RF Cables: The Overlooked Satellite Component

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ABSTRACT

In comparison to the difficult work of payload design and system integration, specifying the correct RF cables seems all-too simple. A passive microwave component, the purpose of an RF cable is simply to transport an analog signal from one physical location on the satellite to another.

However, RF cabling design decisions can mean the difference between mission success and failure. RF cables can represent a potential weak link in overall system design because they are mechanically and electrically exposed. All too often, we find engineers have specified RF cables that either do not optimize for system performance or create mission risk. In this paper, we define three rules for small satellite designers to consider when specifying their RF interconnect.

First, do no harm. We show why, for spaceflight applications, it is critical to specify cables that will not outgas, resist multipaction as appropriate, can withstand the radiation environment, and use materials that are not susceptible to whiskering.

Second, understand how the tradeoffs among different RF cables affect overall system performance. RF cables most often influence system performance through three key RF cable performance parameters: attenuation, return loss, and phase stability. Those tasked with selecting cables must understand the contours of the cable's electrical and mechanical performance trade spaces.

Third, simplify your satellite assembly. Thoughtful cable assembly specification can reduce overall system mass, simplify cable management during the integration process, and reduce the risks of installation errors. Engineers should consider how to introduce requirements such as connector keying, cable marking, and appropriate minimum bend radii. Furthermore, new styles of connector interfaces such as TLMP address the electrical and mechanical weaknesses of traditional mil-spec interfaces such as SMP/SMPM for high frequency spaceflight applications.

Often, cables are defined late in the overall satellite design process, with little time to consider the impacts of cable design choices. Applying these three rules will reduce risk and ensure that even the smallest of components support overall mission success.

INTRODUCTION

In comparison to the difficult work of payload design and system integration, specifying the correct RF cables seems all-too simple. A passive microwave component, the purpose of an RF cable is simply to transport an analog signal from one physical location on the satellite to another.

However, this deceptively simple purpose can pose challenges which are unique and unlike any others in a space environment. Designers call for cables when they need to move a signal to a remote location, away from the relative safety of the circuit board, antenna, or power electronics box. The distance that a cable traverses can present risks to the electrical, mechanical, and environmental performance of the interconnect.

The risks of poor RF interconnect design are real. Prior authors have found that the communications subsystem is responsible for approximately 17% of failures in the first 100 cubesat missions and a suspected instance of cable failure leading to mission loss.[1,2]

At the outset, it is worth recognizing two terms of art within the RF cabling industry. An *RF cable* is defined as the bulk coaxial transmission line. An *RF cable assembly* is a length of coaxial cable terminated with a connector on each end. Some suppliers focus only on the manufacture of bulk RF cable, others specialize in the installation of connectors on procured bulk cable, and some manufacture both bulk cable and cable assemblies. For the purposes of this paper, the terms RF cable and RF cable assembly will be used interchangeably, as the product of interest for satellite applications is always an RF cable assembly.

This paper will primarily focus on RF cabling for satellites, though the principles are also relevant for launch vehicle designers, who face similar environmental exposures and are also critically focused on minimizing size, weight, and power (SWaP).

HOW A COAXIAL CABLE WORKS, AND FAILS

A coaxial cable serves the simple function of transmitting an RF wave from one point to another. Electrically, system designers care about several performance parameters, most notably: impedance, attenuation, return loss (match efficiency), electrical phase, and RF leakage. Furthermore, the cable must be able to withstand the mechanical and environmental conditions without degradation to its electrical performance.

A coaxial cable has three essential elements: a center conductor, a dielectric, and an outer conductor. Beyond these three electrical materials, cable manufacturers often will add layers of shielding and jacketing to improve the robustness and performance of the cable. A generic coaxial cable is shown and annotated in Figures 1 and 2.

Figure 1: A cut-away view of a high-performance coaxial cable

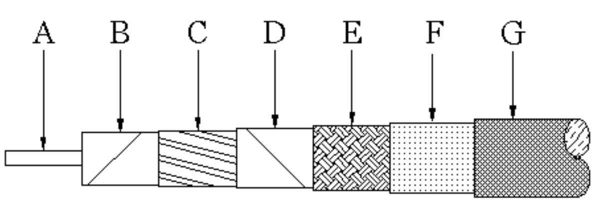

Figure 2: The basic coaxial cable construction elements are A: center conductor, B: dielectric, C: outer conductor, D: interlayer, E: braid, F: jacket, G: armor/abrasion shield

A coaxial cable's electrical performance is defined by its materials, and the choice of materials determines how a cable will perform under mechanical and environmental stress. A review of the basic transmission line equation clarifies the contribution of several elements to a coaxial cable's performance:

$$\alpha = \left[\frac{.4343}{Z_0 * D} * \left(\frac{D}{d * k_s} + F_{bd}\right) * \sqrt{f}\right] + \frac{2.78 * df * f}{\upsilon_p} \qquad (1)$$

Where α = attenuation per unit length, Z_o = characteristic impedance, D = diameter of outer conductor, d = diameter of inner conductor, k_s = strand factor of inner conductor, F_{bd} = braid factor of outer conductor, f = frequency of operation, df = dissipation factor of the dielectric, and υ_p = velocity of propagation.

Fundamentally, the key characteristics that define the performance of the cable are the dielectric constant of the insulator, the conductivity of the metal or wires, and whether the conductors are continuous cylindrical surfaces or are composed of multi-strand braids. The impedance of the cable can be arbitrarily selected, given a specific dielectric, through the relative diameters of the inner and outer conductor. The diameter of the cable at a given impedance also defines its maximum operating frequency. An impedance of 50 ohms is typical for microwave applications as a compromise between attenuation and power handling.[3]

A cable can fail by a separation in the transmission line (known as an "open"), a short between the center and outer conductors, or exceeding its tolerances on impedance, attenuation, return loss, electrical phase, or leakage. Beyond electrical failures, an additional notable failure mode is the creation of foreign object debris (FOD) such as flaked plating or outgassing from the cable assembly, which poses a risk to other elements of the system.

Mechanical and environmental factors can provoke any of these failure modes and must be considered. These factors include, but are not limited to:

While the specific failure mechanisms of each of these mechanical and environmental factors goes beyond the scope of this paper, each is well-characterized and can be managed through judicious selection of materials and manufacturing techniques.

With this basic description of how a coaxial cable functions in mind, let us now consider three rules for specifying RF cables for spaceflight.

RULE 1: DO NO HARM

Four performance standards are critical to consider when selecting an RF cable: materials outgassing, multipaction resistance, radiation resistance, and tin-whiskering susceptibility.

Outgassing

Many non-metallic materials outgas when exposed to a vacuum environment. This includes plastics commonly found in coaxial cable manufacture, such as PTFE, PVC, and PE. Outgassed materials can recondense on critical components such as camera lenses, degrading performance. As a result, NASA and ESA have developed standards to define outgassing rates and databases to compile the performance of various materials.

For small satellite designers, outgassing remains a critical parameter to consider even if outgassed materials would pose no harm to their satellite due to its specific mission and payload design. Rideshare operators often will require compliance to NASA outgassing standards to avoid risks to any other rideshare participant.[4,5,6]

Multipaction Resistance

Multipaction (also known as the multipactor effect) is an electron resonance effect that occurs when RF fields accelerate electrons in a vacuum and cause them to impact with a surface, which depending on its energy, release one or more electrons into the vacuum. When the electrons released and timing of the impacts are such that a sustained multiplication of the number of electrons occurs, the phenomenon grows exponentially and can lead to loss/distortion of the RF signal and even result in damage to the RF components or subsystems. The risk of multipaction is a function of the distance between the conductors, the frequency of the signal, the power levels involved, and the ionizing dose rate, meaning each application must be analyzed individually.

In RF assemblies, multipaction can occur at the connector between the inner and outer conductors. Connector designers mitigate multipaction risks by designing mating connectors with overlapping dielectrics to ensure there is no free path between conductors. TNC connectors are typically a good choice for situations in which multipaction may pose a concern.

Radiation Resistance

Radiation exposure can ultimately lead to the degradation of the cable jacket, causing a FOD concern, but more importantly can cause a change in the dielectric constant of the cable dielectric, degrading electrical performance. The sensitivity of a cable to radiation exposure depends greatly on the cable's location. Often, designers are managing radiation exposures within the satellite bus carefully for the protection of other components, and these levels are below the exposure limits for even common coaxial cable plastics. However, one of the critical roles of a cable is to interconnect remote functions, meaning RF cables often must exit the safety of the bus to reach a remote antenna. In these scenarios, radiation resistance can become critical.

Cable designers have approached radiation resistance through two philosophies: shielding and materials selection. Through the first philosophy, radiation-tolerant materials such as Tefzel® are used as the cable jacket. Generally, Tefzel®-jacketed cables can withstand a TID of up to 100 MRad in a vacuum environment. These high-tolerance materials shield the more radiation-sensitive plastics often used as cable dielectrics. In the second philosophy, cable manufacturers select radiation-hard materials for the dielectric, such as silicon dioxide (SiO2). These products can withstand radiation exposures above 100 MRad. It is critical to note that factors such as dose rate and dose orientation play critical roles in the overall TID performance, so very high-radiation missions (E.g., deep space) should analyze their situation carefully.

Whiskering

Metals such a pure tin are known to grow whiskers in vacuum and/or high temperature environments, leading to shorts or FOD, and as a result are generally prohibited from spaceflight use.[7] Tin is commonly used in solder for coaxial connectors and the plating of semirigid coaxial cables. To avoid whiskering, designers should specify tin/lead alloys for solder or plating. It is also useful to note that though leaded solders may have their RoHS exemption, 6(c), phased out, items designed for spaceflight are permanently exempted from control under RoHS.

In summary, vacuum and radiation pose specific risks to RF cable performance. RF system designers must consider outgassing, multipaction, radiation exposure, and whiskering when specifying coaxial cables.

RULE 2: UNDERSTAND RF CABLE TRADE-OFFS

Once a designer defines a set of cable designs that will meet the minimum electrical, mechanical, and environmental requirements, the next step is to select the optimum design for the application from a trade space of multiple performance measures.

Attenuation vs. Mechanical Performance

In general, a larger diameter cables provide lower attenuation per unit length than a comparable smaller diameter cables, but this comes at the cost of increased mass and a wider minimum bend radius. This tradeoff is defined by the three properties that define the attenuation of a coaxial cable: the conductivity of the conductors, the dielectric constant, and the diameter of the cable.

High-conductivity materials such as copper and silver provide low attenuation per unit length, but are heavy or expensive. Lighter-weight materials such as stainless steel and aluminum reduce overall mass, but are relatively poor conductors. Cable manufacturers frequently optimize their conductor designs by cladding or plating a lightweight and low-cost base metal with higher-conductivity copper or silver for the RF path.

For a given dielectric material, increasing diameter cable will yield lower attenuation per unit cable length. However, larger cables are heavier. Furthermore, larger cables cannot be bent as tightly smaller cables. An overly-tight bend will cause the cable to become oblong or, at worst, kink, causing an impedance mismatch and excessive return loss. The primary decision for designers is to balance the contribution of cable loss to their RF link budget with the mechanical considerations for system size and mass.

The third contributor to cable performance is the dielectric constant. All else equal, a lower-loss dielectric generally will be lighter because it incorporates more air into the media. For the purposes of coaxial cable design, the dielectric constant for air at STP, 1.00059, is an effective substitute for the permittivity of free space. More air in the dielectric material lowers the effective dielectric constant of the total media and brings the loss closer to the ideal performance of a wave travelling in a vacuum.

The tradeoff for low loss dielectric materials usually is cost, given the processing controls required to effectively manufacture these products.

Figure 3**Error! Reference source not found.**, below, illustrates the loss per unit length for various dielectric materials at different cable diameters.

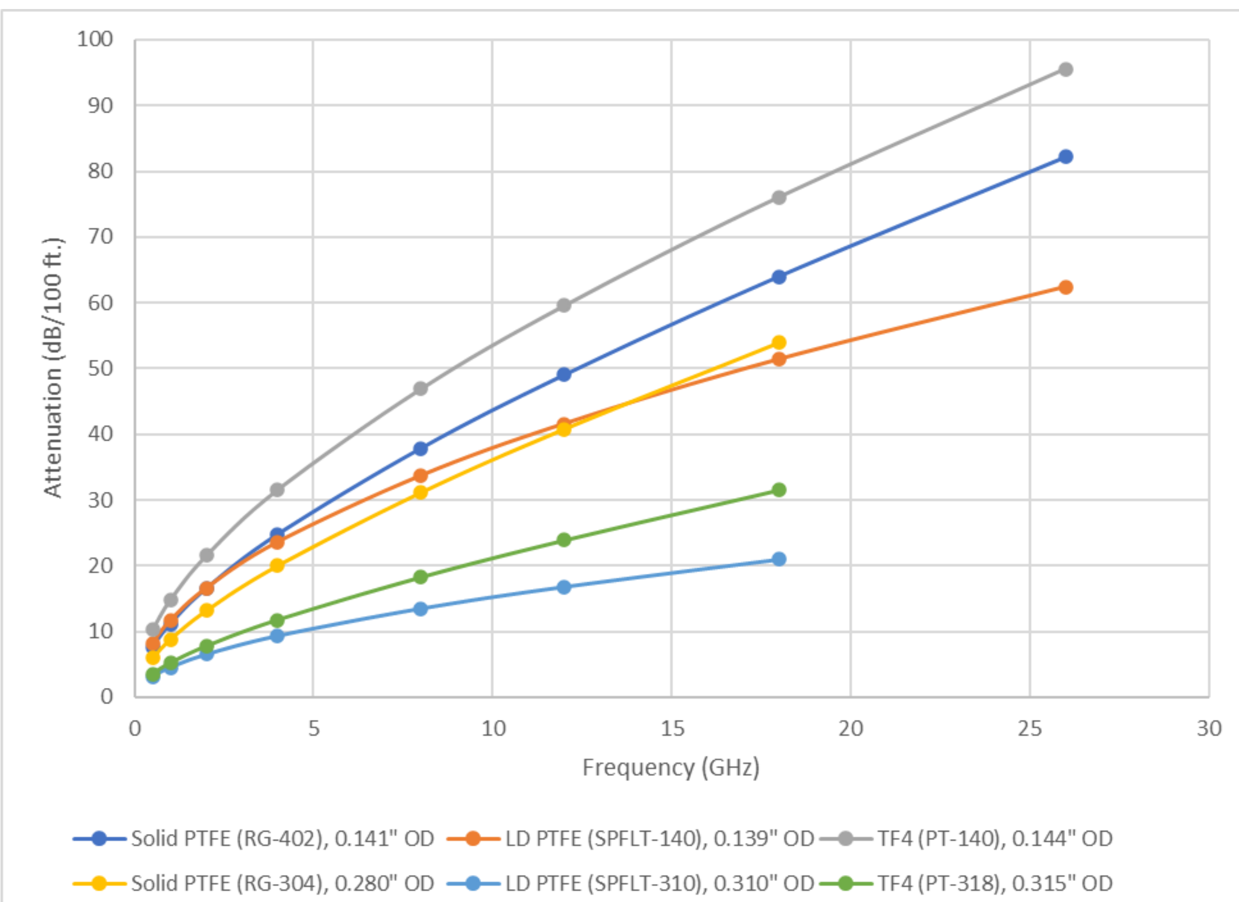

Figure 3: Attenuation of various RF cable materials and constructions

Electrical vs. Environmental Performance

As noted above, the three most common critical electrical performance parameters for a coaxial line are attenuation, return loss, and phase stability. In spaceflight, these parameters are frequently compared across temperature ranges and radiation exposures.

PTFE exhibits an electrical property known as the "knee" at approximately +19 C, at which point the electrical length per unit temperature undergoes a non-linear transition. The basis of this property is the nature of PTFE itself. PTFE is a long chain molecule with crystalline sites connected by amorphous chains, arranged in a helical fashion. Below +19 C there are 13 CF_2 groups per 180-degree twist of the molecule. At +19 C transition point there is sufficient energy imparted to the molecule to unwind it slightly, leading to 15 CF_2 groups per twist. Unwinding the molecule makes it longer, reducing the volume. Electrically, this leads to a higher velocity for the signal in the cable and a smaller electrical length per unit mechanical length. Graphically, this non-linear change in electrical length vs. temperature looks like a "knee".

For phase-sensitive systems, compensating for this this change multiple times per orbit at the spacecraft moves through its operating temperature range is at minimum challenging and at worst a limitation on overall system performance.

Other dielectric materials, such as Times Microwave's TF4 dielectric and SiO2 do not exhibit a similar non-linear change. Figure 4 illustrates the scale of the chase change for solid and low-density PTFE relative to other dielectric materials at a given cable diameter and frequency of operation.

The attenuation of non-PTFE materials can be somewhat (~10-20%) higher per unit length for a given cable diameter at Ku and Ka band frequencies, but this is often a worthy tradeoff to significantly improve phase stability and not a meaningful loss penalty on short cable runs.

In addition to controlling overall phase change vs. temperature, designers may need to characterize the hysteresis of the phase change across the operating temperature range. For applications requiring low hysteresis, an SiO2 dielectric provides linear phase change with exceptional repeatability.

For spaceflight applications, the second major environmental consideration is electrical performance over radiation exposure. Plastics such as PTFE and TF4 will degrade over time, increasing loss. For short-duration or risk-permissive missions, these long-term concerns may not be compelling. For long duration, high exposure, or high reliability missions, using a radiation-tolerant material such as SiO2 is often a better approach than attempting to shield a plastic. The primary tradeoff is cost, with specialty SiO2 cables generally priced higher than an equivalent plastic-dielectric cable due to the specialty manufacturing steps involved.

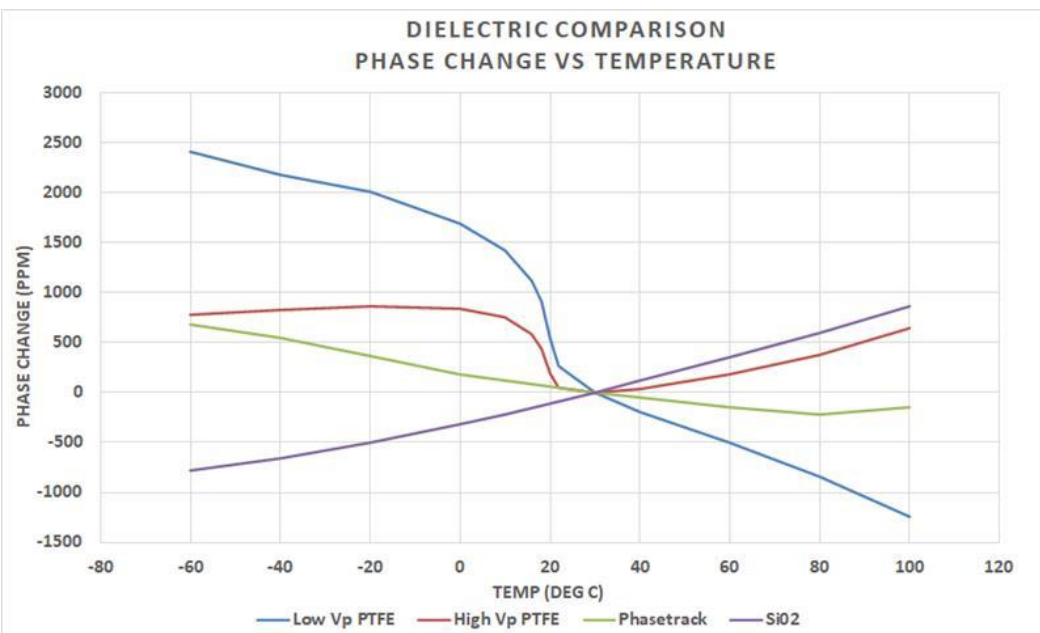

Figure 4: Phase change vs. temperature for various coaxial cable dielectrics

Mission-Specific Considerations

- The tradeoffs described above are not exhaustive. Depending on the mission, other critical considerations include:

- Thermal stability of the cable: will the cable conduct heat between two components intended to be isolated?

- Magnetic moment performance: will the magnetization of connector components from machining processes create a meaningful magnetic moment on the spacecraft? Replacing nickel with tri-metal plating can be an effective solution.

RULE 3: SIMPLIFY ASSEMBLY

Thoughtful cable assembly specification can reduce overall system mass, simplify cable management during the integration process, and reduce the risks of installation errors.

Cable Management

Prior authors have described optimization strategies for SmallSat wiring harnesses.[8] Single point-to-point lines support system iteration but have higher cost and increase the number of potential failure points. Multi-cable harnesses often can be lower weight but cannot be readily modified.

Many operators find it helpful to add custom marker bands (see Figure 5) to each end of the cable so the installer can visually confirm that the cable is wired correctly through the unique designator printed on that cable marker band and an identical marking on the surface of the matching component. For spaceflight applications, marker bands should be made of low/no-off-gassing materials.

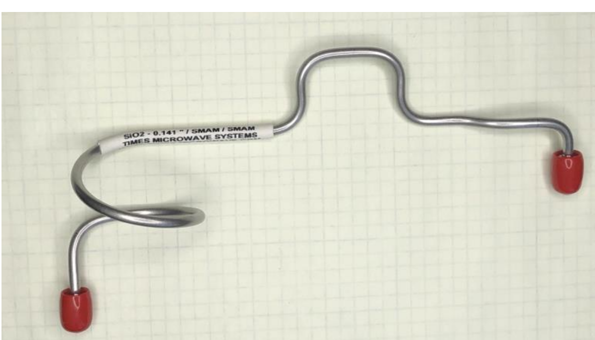

Figure 5: Example customer marker band on an SiO2 cable

To protect cables in flight, designers should ensure that cables are restrained with tiedowns. A typical rule of thumb is a tiedown at least every 200mm, though this can vary based on routing and cable mass. It is also critical to consider whether the tiedowns will cause chafing on the cable, and whether protective sleeves are a valuable feature.

Installation Errors

Installation mistakes can create problems from testing headaches to catastrophic failures. Practically speaking, ensuring that the correct cable is mated to the correct port can become a challenging endeavor in a tight environment.

To provide assurance beyond a visual inspection of marker bands, designers can specify unique keying for each connection, making it impossible for connectors to be cross-routed. Since the keys require some physical space, they are readily implementable on larger connectors such as TNC interfaces or multiport shells. With creative design, keyed concepts can also be applied to smaller interfaces.

Once routed correctly, it is also critical to ensure that the cable is mated correctly to ensure effective RF performance. For threaded connectors, RF assembly suppliers should be able to provide recommended connector torque values. Designers should also consider multiport connectors and locking push-on connectors. Multiport connectors will mate multiple contacts simultaneously, reducing the opportunities for error. Locking push-on connectors, such as Times Microwave's TLMP, which visually indicate full engagement by exposing a green ring on the connector body when successfully mated.

Finally, bending a cable tighter than its specified minimum bend radius at any point along the routing path can cause a permanent deformation in the dielectric, leading to higher return loss through a local impedance change and resulting mismatch. The necessary care required when handling an RF cable is not always obvious, especially in a world in which personal electronics cables can be repeatedly flexed and knotted without effect. Building a culture of care among all who handle RF cabling during assembly, integration, and test is essential to reducing scrap.

Supply Chain

Defining the correct technical requirements is only one element of an effective cable procurement. Many other considerations can reduce overall program risk and include:

- Packaging: are the cables supplied in ESD or cleanroom packaging for ready integration? Especially for larger programs or constellations, is the packaging labelled to facility easy stocking and picking from inventory and integration into the spacecraft?

- Heritage: does the product have spaceflight heritage and is there test data available?

- Workmanship and inspection: how does the supplier mitigate FOD and inspect the product prior to shipment?

- Testing: What acceptance testing does the supplier perform on each assembly? For programs in which component qualification is required, what electrical, mechanical, and environmental testing can the supplier perform?

- Manufacturing: how resilient is the production capability? In the event of a facility closure (E.g., pandemic, power outage), does the supplier have alternative means of production to protect flight-critical schedules?

- Financial stability: particularly for long-lived, Maria modular design, and high-reliability programs, can the supplier assure production to avoid costly re-qualifications later?

Conclusion

The humble RF cable is in fact a complicated passive RF component, critical to communications or payload performance and subject to many (at times competing) electrical, mechanical, and environmental performance expectations. Furthermore, due to the nature of satellite design cycles, interconnects are often considered only after the modules they connect are fixed. Failing to consider cable selection tradeoffs early in the system design can force designers into solutions that.

As the satellite industry trends towards commercial products based on mission risk, it is critical to recognize that not every RF cable requires the pedigree of the interconnects commonly found on legacy systems. System designers should seek cable manufacturing partners who can effectively juggle the many elements of technical performance necessary for mission success alongside price, lead time, quality, and responsiveness.

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