Space Tethers: Design Criteria

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TECHNICAL MEMORANDUM

SPACE TETHERS: DESIGN CRITERIA

I. INTRODUCTION

The purpose of this document is to provide a systematic process for the selection of tethers for space applications. Criteria are provided for determining the strength requirement for tether missions, as well as for mission success from tether severing due to micrometeoroids and orbital debris particle impacts. Also, background information of materials for use in space tethers includes electricity-conducting tethers and dynamic considerations for tether selection. Finally, safety, quality, and reliability considerations are provided for a tether project. This is a living document that will be updated as additional design criteria are provided for tethers.

II. STRENGTH CRITERIA FOR TETHERS

Tethers are potentially single-point structural failures and play a critical structural role in the experiment. Generally speaking, strength should not be a driving parameter in tether design, i.e., they should possess enough inherent durability and robustness to support a "normal" amount of mishandling and damage. Tethers are usually very long, providing increased opportunities for something to go wrong. This may be due to crimps, pulley pinches, vibration, rubbing, or contact with other spacecraft elements. In order to establish durability, a qualification tether should be tested in an off-nominal (tight knot or slice through one-half the load-carrying element(s)) condition. The flight tether should be proof-tested (end-to-end), and tests should be conducted at flight temperature. If this is impractical, the test levels should be adjusted to account for strength degradation due to temperature. In order to avoid fragile tethers, all should have an ultimate tensile strength of at least 100 pounds. During manufacture, the structural element(s) should be inspected and anomalous conditions assessed by engineering. Repair methods should be qualification-tested and repairs on the flight article proof-tested. Tensile strength should be established using a minimum of 10 samples, and breaking strength of the flight tether should be verified using end samples.

Tether use should, in general, be limited to one mission. Any reflight or reuse of a tether should be evaluated on a case-by-case basis with consideration given to strength and performance degradation due to space exposure, loading, and any other conditions which would alter the tether's characteristics. Reinspection and reproofing should be performed on all portions of tether that were exposed to any potentially degrading conditions.

The following factors of safety are to be verified by test on the maximum predicted tether load and in the appropriate environment.

Qualification test:
$$FS \ ult = 5.0 \quad \text{Basic tether, splice, and repair methods}$$
$$= 2.0 \quad \text{Off-nominal tether condition}$$

Proof-test of flight article:
$$PF = 2.0 \quad \text{End-to-end}$$

III. METEOROID AND ORBITAL DEBRIS

During the early Apollo days, many studies were conducted to determine the effects of meteoroid impacts on spacecraft. As more and more spacecraft were launched into low-Earth orbit (LEO), the generation of manmade orbital debris increased dramatically. Now the threat of orbital debris is greater than that of meteoroids to most long-life orbiting spacecraft, while the meteoroid environment remains the larger threat to some spacecraft components such as space tethers.

The meteoroid environment consists of particles of natural origin, and most are generated by comets and asteroids. The average mass density for a meteoroid is 0.5 g/cm^3. There are approximately 200 kg (440 lb) of meteoroids within the 2,000 km (1,080 nm) altitude. There is an estimated 1.5 to 3 million kg (3.3 to 6.6 million lb) of manmade orbital debris as of mid-1988 within this same altitude range. Most of this orbital debris is in high inclination. The orbital debris environment consists of about 1,500 spent rocket stages, inactive payloads, and a few active payloads. The average mass density for the orbital debris is 4 g/cm^3. It is the nature of these environments that smaller particles are greater in number than larger ones, and the densities are a function of the particle sizes. Figure 1 shows this relationship for representative meteoroid and orbital debris (M/OD) environments. Not only particle size and mass determine the damage capability of a meteoroid or orbital debris particle—the impact velocity of the particle must be considered as well. The average impact velocity of a meteoroid relative to an orbiting spacecraft is 19 km/sec; the impact velocity for orbital debris is 10 km/sec.[1] These average velocities are recommended for the M/OD damage analysis of the spacecraft and its components.

Inadvertent tether severing poses great risks for any space tether missions in LEO. These risks include loss of mission, loss of satellite, and end-body entanglement due to recoil of the tether remnant. This is especially critical for missions where the safety of end-bodies is of paramount importance, such as those involving manned spacecraft like the space shuttle or space station. The potential causes of the inadvertent tether severing include manufacturing defects, system malfunctions, material degradation, and collision with spaceborne matter. Most of these causes can be controlled through design, quality control, and perhaps collision avoidance maneuvering. However, since practical space tethers are generally quite small in cross-sectional diameter, their main threat is from collision with space matter too small to be detected or avoided, such as small meteoroid and orbital debris. For example, the tether diameters for the Small Expendable Deployer System (SEDS) and Tethered Satellite System (TSS) programs were less than 0.25 cm (0.1 in); however, the tether lengths were 20-km (12.5-mi) long when they were fully deployed. The tether lengths for some future space tether missions are proposed to be well over 100-km (62.5-mi) long. Thus, the space tethers have substantial surface areas exposed to M/OD environments. Another concern is the characterization of materials for the effects of hyper-velocity impacts by either meteoroid or orbital debris particles. Many new materials and unique combinations of materials like the ones used for the TSS and SEDS tethers have not been thoroughly characterized for these effects, although the results of the early studies of meteoroid effects on structures and materials are generally applicable to current M/OD impact physics.
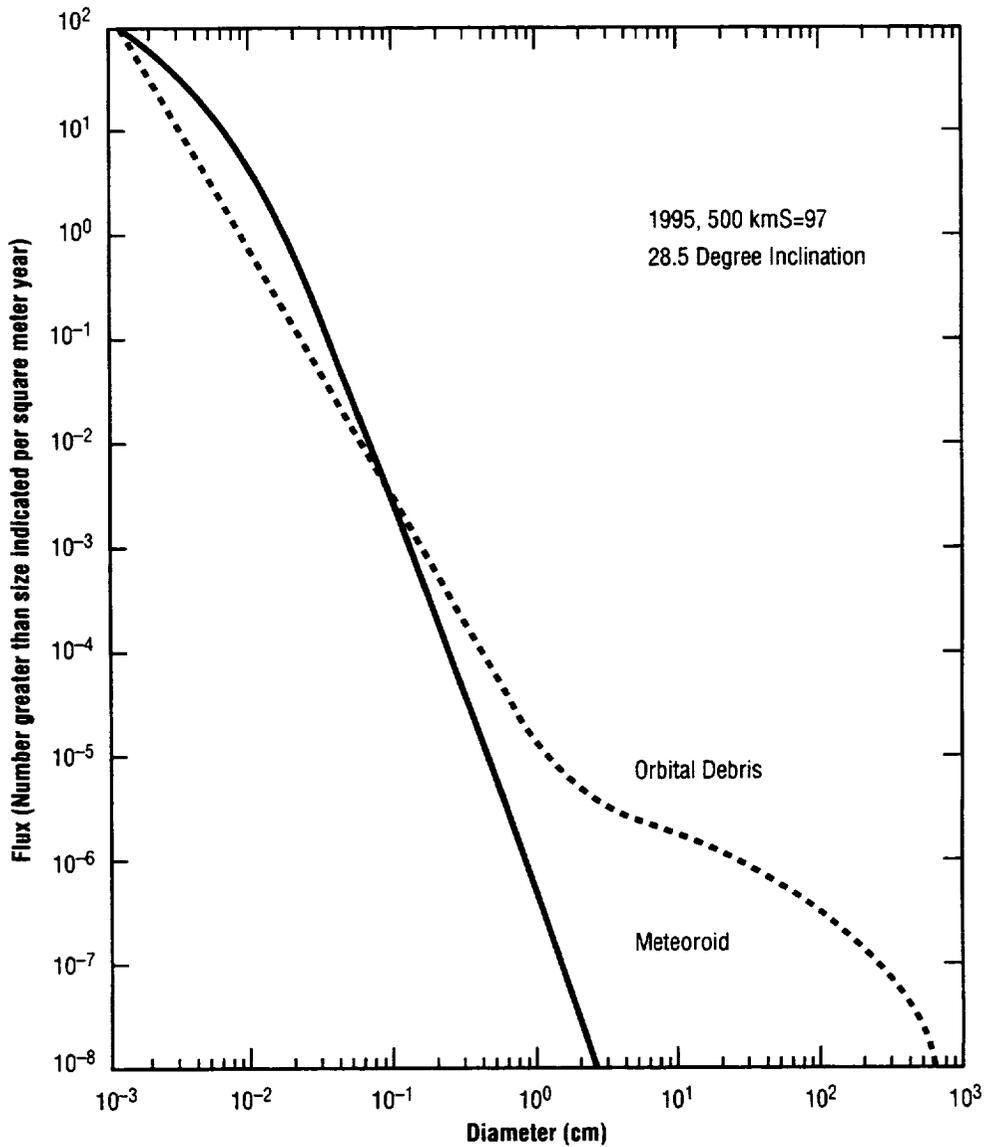
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FIGURE 1.—Meteoroid and orbital debris flux as a function of diameter.

Upon inadvertent tether severing, a tension unloading stress wave propagates from the break point and travels in each remnant toward the tether attach points. The tether behind this wave immediately goes slack and develops a velocity toward the end-bodies. This recoil velocity is related to the tether material properties and the tension in the tether prior to the break. The end-body entanglement due to recoil of the tether remnant posed a safety hazard for some tether missions such as the TSS–1 and TSS–1R (reflight), both of which involved the Space Shuttle. This dynamic mechanism for the TSS–1R mission is discussed in detail in reference 2.

Determining the probability of no random M/OD particle impact occurrences is best done using the Poisson Distribution.[1] The equation used for determining the probability of no critical failure is:

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$$P_{\text{no critical failure}} = e^{-(\text{particle\_flux}*\text{area}*\text{time})} . \tag{1}$$

Then, the probability of critical failure is:

$$P_{\text{critical failure}} = 1 - P_{\text{no critical failure}} . \tag{2}$$

Here, a critical failure for the space tether is defined as tether severing, and a critical particle size for either meteoroid or orbital debris is the particle size which will sever the tether. The critical particle size can only be determined by the hypervelocity impact test results. The exposed areas and times for any tether missions are specified in or derived from their mission profiles. The orbital debris particle flux is a function of the actual year of the mission, the solar flux of the previous year, the mission altitude and inclination, and the critical particle size. The meteoroid particle flux is a function of the particle size since the meteoroid model has been integrated to include all sporadic and stream meteoroids which occur throughout the year. The exposed area of the tether will vary as the tether is being deployed and retracted. The exposed area will also be different for the orbital debris damage analysis than for the meteoroid damage analysis since orbital debris is directional and meteoroids are not. Reference 3 discusses the M/OD damage analysis performed for the TSS–1 mission, and reference 4 the analyses for the three SEDS missions.

The *NASA Safety Standard*,[5] recently published in order to limit the generation of the orbital debris, discusses how to limit the orbital debris and how to perform the assessment. The space tether is one of the topics covered by this safety standard. Manned missions where a severed tether could result in loss of mission and crew but is not an immediate hazard should have a 95-percent probability or better of no severed tether. Manned missions where a severed tether results in an immediate hazard to the crew should have less than one chance in a million of a tether severance. Missions where loss of mission success could result from tether severance (no hazard to crew) must be assessed on an individual basis regarding the allowable probability of tether severance. Engineers should endeavor to design all safety hazards out of their systems.

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IV. MATERIALS

A. Materials Selection

All metallic and nonmetallic materials specified for use in construction of the tether shall be controlled by MSFC–STD–506. System design and functional and reliability requirements shall be considered for possible tailoring of MSFC–STD–506, where appropriate. Materials with acceptable ratings per MSFC–HDBK–527 (computer data base version) will be selected where possible. If the design requires the use of any material with a rating that does not meet the acceptance criteria of MSFC–STD–506, it shall be dispositioned in accordance with MSFC–PROC–1301. Tethers which contain electrical conductors have special considerations in order to prevent arcing or discharge of electricity from the tether.

B. Materials and Processes

The materials and processes employed in the tether design shall be selected to assure maximized reliability and performance in the specified environment within the diameter and weight constraints. Physical, chemical, and electrical property characterization data, as required by a cognizant materials engineer, shall be developed for all materials and processes applicable to electromechanical conducting tethers and structural tethers.

C. Workmanship

The tether shall be fabricated in a thoroughly workmanlike manner. Particular attention shall be given to freedom of defects, contaminants, and blemishes. The engineering organization is required to define the manufacturing and storage environment and workmanship acceptance criteria in the engineering specification prior to manufacturing.

D. Radiation

The tether shall be compatible with all space radiation environments, which are: (1) Galactic Cosmic Radiation, as defined by the CREME model (or CREME96 when it becomes available); (2) geomagnetically trapped radiation, as defined by the NASA models AE–8 (trapped electrons) and AP–8 (trapped protons); and (3) solar proton events (solar flares) as defined by the JPL 1991 model during the active portion of the solar cycle. [6-9]

E. Atomic Oxygen

The tether shall be designed to withstand the degradation effects of atomic oxygen at orbital velocities and altitudes.

F. Residual Reel Storage Effects

The tether components shall be designed to ensure the tether will operate smoothly through the mechanisms following a 6-month storage period on the reel.

G. Hygroscopic Characteristics

The tether should be designed so that variations in water content due to space environment will not degrade tether components during the mission.

H. LEO Plasma

The tether and its components should be compatible with the conductive LEO ionospheric plasma.

I. Particulate Contamination

The necessary steps should be taken during the manufacturing and testing of all tether components, tether control mechanisms, and tether deployment mechanisms to eliminate particulate contamination.

J. Tethers Containing Electrical Wires

Because of the high voltage developed using electrodynamic tethers and the hazards associated with these high electrical potentials in space, this section has been dedicated to the requirements for these tethers.

1. Electrical insulation selection.

    a. The required insulation thickness shall be calculated based on the insulating materials dielectric strength (volts/mil) and maximum voltage (V) generated by the tether. This calculation should be done with the understanding that the dielectric strength for most insulating materials decreases as the material thickness is increased.

    b. The electrical insulation should possess characteristics that prevent external debris and internal braided wire from puncturing the insulation.

2. Static electricity generation should be eliminated.

    a. Static electricity caused by tether reeling operations should be eliminated on pulleys.
    b. Internal friction between insulating layers should not generate static electricity.

3. Corona and arcing events caused by outgassing of the tether and pressure buildup in any enclosure containing the high voltage tether should be eliminated by proper venting of enclosed volumes or pressurizing with SF_6 or other suitable insulating gas.

4. A spark test will be performed as the final test on the tether because of the potential loss of mission if even the smallest pinhole in the insulation exposes the conductor to the ionospheric plasma. A destructive test—twisting and hocking—would be helpful to determine the robustness of the tether against pinholes. The results of these tests should be used to develop final manufacturing handling requirements.

5. Eliminate debris in enclosures that contain the tether to prevent puncturing of the electrical insulation.

6. Tether handling during deployment and storage for extended time periods on the reels or spools should not contribute to breach of the insulation.

7. Electrical characteristics of materials used in tethers should be examined as potential culprits in insulation failures.

8. Materials with a tendency to collect and harbor harmful contamination should be avoided.

9. The tether path through the deployer system should be free from conducting paths which could lead to electrical arcing.

10. The designer should endeavor to produce a pristine length of continuous tether.

11. Trapped gasses in the tether should be avoided because they can be excited and ionized by radio frequency or alternating current in the tether. This could lead to a breach in the insulation, causing mechanical failure of the tether.

The TSS–1R tether demonstrated that a breech in the insulation will cause the conductor to short to the conductive plasma. Molecular outgassing of materials, a common phenomena of materials in space vacuum environments, will sometimes produce conductive atmospheres. Materials and processes selections employed for conducting space tether applications should minimize vacuum outgassing. Any breech in the electrical insulation applied to a conducting tether will likely result in a structural failure of the tether. The health of electrical insulation shall be evaluated prior to and/or during flight integration activities. In order to verify insulation integrity, spark testing shall be performed on all conducting tethers in a final flight tether checkout during flight spooling activities.

V. DYNAMIC CONSIDERATIONS

Tether selection will affect the vibration between the two end masses and the damping of the vibration. Since the tether's temperature changes significantly as it passes in and out of the sunlight each orbit,[10] the tether expands and contracts, resulting in significant changes in length.[11] With proper selection of tether material, the dynamics will be reduced to a reasonable level. Tethers have an inherent twist torque which can be mitigated if the tether is handled properly prior to flight.

A. Tether Longitudinal Flexible Body

The tether's cross-sectional area (A) and Young's modulus of elasticity (E) of the tether's material provide the information to determine the strain of the tether per unit load:

$$\in = \frac{T}{AE} \, , \tag{3}$$

where T is the tether tension. The spring constant (k) of the tether between the two bodies is provided by:

$$k = \frac{AE}{L} \, , \tag{4}$$

where L represents the tether length. The stretch (w) of the tether between the two bodies is:

$$w = \frac{TL}{AE} \, , \tag{5}$$

where T is the average tension in the tether. If the end masses are rigid bodies, the bobbing frequency (f) of the end mass can be estimated from:

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{M}} \, , \tag{6}$$

where M is the reduced mass of the end bodies, that is:

$$M = \frac{m_1 m_2}{m_1 + m_2} \, . \tag{7}$$

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TSS and SEDS tether missions have operated at tension levels that are a small fraction of the strength capability of their tethers. Large variations of AE have been noted when operating at low tension fractions and AE increases significantly as operating tension increases. AE increased on TSS and SEDS tethers as temperatures decreased and vice versa.[12–14] A longitudinal wave travels in the tether at a speed of:

$$S = \sqrt{\frac{AE}{\rho}} \, ,$$

(8)

where ρ is the mass per unit length of the tether. If the tether is severed, the velocity of the tether remnants toward the end masses is:

$$V = \frac{T}{\sqrt{AE\rho}} \, ,$$

(9)

where T is assumed constant over the length of the tether prior to the break and no reduction in the velocity is assumed due to natural forces. When the tether is severed due to a micrometeorite, for example, a wave travels at the speed (S) along the tether, relieving the stress in the tether while imparting the velocity (V).

B. Thermal Expansion

The TSS tether had a thermal coefficient of expansion (CTE) of –0.0000098 per degree Centigrade according to reference 13. The manufacturer, DuPont, reports that the Kevlar alone has a CTE of –0.000002 per degree Centigrade which was less than reference 13's finding for the composite. Although all the materials except Kevlar had a positive CTE, the strength member, Kevlar, dominates. It is not known why the magnitude was greater.

C. Tether Twist

All tethers will have a small twist torque when deployed in space regardless of how they were handled prior to flight; however, the torque can be mitigated. If the deployment adds twists to the tether, it can be pretwisted on the spool so the net twist is zero when deployed. If the deploy adds no twist, there should be no twists on the spool. The purpose here is to prepare engineers for any potential problem. The longer the tether, the greater the twist can be, and the greater the effect tension can have on the twist. It is not yet known how to predict torque in the tether preflight. Tests of the TSS tether were performed preflight in an attempt to understand and predict the torque, but the results provided little information about the conditions during flight. The torque, however, is expected to be small and may unwind a short time after deployment. Solar heating and cooling may alter the equilibrium position, but the effects are expected to be small.

D. Skip Rope Motion

When a tether of length (L) containing a conductor is traveling at a velocity (V) in the Earth's magnetic field of strength (B) an electromotive force (EMF) is created between the ends of the tether, which can be approximated by:

$$\text{EMF} = L \; V \; B \; \sin \theta \; , \tag{10}$$

where θ is the angle between the B field vector and the velocity vector. If an electric current (I) flows in the tether by providing the lower end of tether with a way to release electrons, a force (F) is created on the tether which can be approximated by:

$$F = I \; L \; B \; \sin \phi \; , \tag{11}$$

where ϕ is the angle between the length vector and the B field. Generally, the force is in the westerly direction for orbits that are from west to east and the B field lines are along the longitudes of the Earth. This force will cause the tether to move, and oscillating current variations can cause the motion to grow or damp, depending on the phasing or the current flow and the motion of the tether. The motion will be planar initially, but due to B field variations, the oscillation becomes like an elliptical skip rope motion. If the tether is to be retrieved, the skip rope motion will most likely be required to be removed, since angular momentum will for the most part be conserved. With the conservation of angular momentum, the amplitude of skip rope grows as the tether is retrieved. Due to the tether's centrifugal force, this can cause the satellite to be drawn into the deployer before all the tether is retrieved. The skip rope may be damped as the tether is retrieved by flowing current at times when the tether force opposes the skip rope velocity; this requires knowledge of the skip rope motion.

VI. SAFETY AND MISSION ASSURANCE

The tether shall be fabricated to NASA-approved drawings, specifications, and procedures. Prior to starting fabrication, the tether manufacturer will supply a quality plan to NASA for approval. NASA will survey the manufacturer prior to and during fabrication to ensure the manufacturer is following the approved quality plan, workmanship requirements, procedures, and specifications. All materials used to fabricate the tether shall be traceable from the manufacturer throughout the fabrication process. Traceability records shall be maintained on a log during fabrication. These records will be maintained throughout the life of the tether. A controlled and clean environment as defined by the approved specification shall also be maintained. All testing, handling, storage, packaging, and shipping activities will be NASA approved. The aforementioned activities will be inspected and stamped by a responsible quality assurance organization. Where government Mandatory Inspection Points are defined, NASA or other government-delegated agency quality assurance personnel will be present to inspect and accept these points in the fabrication.

For space flight missions with no crew, where ground processing and range safety are the only concerns, tethered missions are fairly easy to manage for safety. However, for human space flight missions, tethers can present some unique catastrophic hazards which require rigorous hazard controls and verifications. Collision and safing for reentry are hazards that are the most difficult to control. All nominal and off-nominal tether deployer operating conditions must be assessed for potential loss of stability of the tether end mass which can result in spacecraft and end mass collision, or slack tether. Slack tether has the potential to impact the spacecraft or to cause a snag which could prevent safing for reentry. Tether breakage by micrometeoroid or space debris is another cause of slack tether which has to be controlled to an acceptable level by designing the tether to resist impact damage and to limit exposure to the space environment. The required fault tolerance must be built into the deployer system to prevent these hazards.

Typically it is very difficult to design a tethered system that is "fail safe;" crew actions will be required to safe the system. Sufficient crew reaction time and notification of hazards will be designed into the deployer system. An operational hazards analysis is a good tool that could be used to evaluate operations safety. A tether-cutting safing system is required for all tether systems. This safing system must be designed to ensure proper fault tolerance for both activation and inadvertent activation.

A failure modes and effects analysis shall be developed in the concept phase and updated as the design progresses for the entire tethered system. This analysis will be used to identify critical failures that could impact safety or mission success. Other analysis tools, such as fault trees or event trees, should also be considered. Missions where a severed tether could result in loss of mission and crew but is not an immediate hazard should have a 95-percent probability or better of no severed tether. Missions where a severed tether results in an immediate hazard to the crew should have less than one chance in a million of a tether severance. Missions where loss of mission success could result from tether severance (no hazard to crew) must be assessed on an individual basis regarding the allowable probability of tether severance. Engineers should endeavor to design all safety hazards out of their systems.

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The Safety and Mission Assurance Office at Marshall Space Flight Center will establish a risk assessment and hazard analysis for all proposed tether systems and ensure compliance with all applicable safety policies and requirements. This office will participate in design reviews.

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APPROVAL

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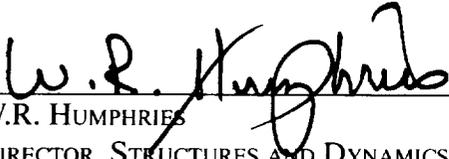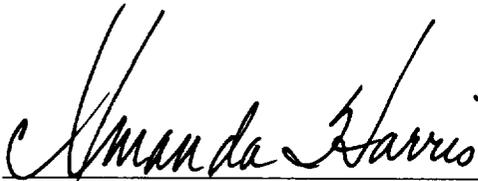
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13. ABSTRACT *(Maximum 200 words)*

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