TIN WHISKERS: A CASE STUDY

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Abstract

This paper discusses the experiences of one Air Force space program with the growth of "whiskers" on tin-plated electronic components. The known characteristics of whiskers and whisker growth are presented alongside the methodology adopted by the Air Force to determine when tin-plated components are acceptable, and when they are not. It has long been known that pure tin is capable of growing fibrous whiskers with current-carrying capacity, a source of potentially fatal short circuits. Tin whiskers grow straight with occasional abrupt changes in direction; and though reports vary widely, these whiskers may reach several millimeters in length and up to seven micrometers in diameter. Unlike dendrites, whose growth is induced by electro-magnetic fields, tin whiskers are induced strictly by mechanical stresses in pure tin. Whisker growth depends on many factors, including the nature of the underlying substrate, the level of impurities in the tin plating, and the thickness of the plating. Whiskers have been known to grow in both ambient and vacuum conditions, and no temperature dependence has been established. Most insidious of all, a pure tin plating may remain dormant for many years before spontaneous whisker growth begins. The process of determining when pure tin plating is acceptable in already-built flight hardware is tedious, and is based on the specific details of each usage: reflow of the tin plating; lead or other impurities in the tin; thickness of the plating; conformal coating of the tin; and, the susceptibility and consequences of short circuits in the local area of the tin-plated component. The methodology for applying these factors, and some acceptable "thresholds" adopted by the Air Force, are presented.

I. INTRODUCTION

Tin plating of electrical and mechanical components is common in both commercial and high-reliability hardware. Tin provides excellent solderability and electrical conductivity; it is non-toxic; it resists oxidation and other forms of corrosion; and, it produces an aesthetically pleasing shine. Unfortunately, electro-plated pure tin can grow "whiskers," single crystal extrusions with a high degree of internal and external perfection, which are a source of potentially fatal system impacts. Electrical shorting has been attributed to growing whiskers, "floating" whisker particles which have broken away from their producing surfaces, and transient "vacuum metal arcs" created by the vaporization of whiskers under current load. Whiskers also have the potential to interrupt the smooth functioning of micromechanical systems.

Despite the fact that tin whisker growth has been well-documented since 1946, tin plating is still common in both commercial and defense hardware. No less than fifty military piecepart specifications permit the use of pure tin [11], notable among them MIL-M-38510, the general specification for microcircuits, and MIL-S-19500, the general specification for semiconductor devices. Presently there is a significant movement within the Air Force and NASA to rectify this situation.

The first part of this paper discusses what is known about tin whiskers: their physical and electrical properties, and conditions and reasons for growth. The second part is a discussion of the methodology adopted by one Air Force program to disposition the use of tin in existing high-reliability space hardware.

II. THE TIN WHISKER PHENOMENON

Whisker growth is associated with many pure metals, including tin, cadmium, zinc, antimony and indium, and less frequently lead, iron, silver, gold, nickel, and palladium [9]; the surface and dimension morphologies for each type of whisker are remarkably similar [3]. While there is general agreement on the attributes of whiskers, especially tin whiskers, considerable controversy exists concerning the conditions and reasons for growth; indeed, much conflicting evidence has been reported in the last twenty years (for example, contrast [2] and [3]). Controversy stems from the fact that the precise cause of whisker growth is not understood; consequently, potentially crucial variables have not been controlled during experimentation [8]. Aggravating the situation is the fact that spontaneous whisker growth has begun as late as twenty years after the plating operation was performed [7], forcing meaningful experiments to span decades. What follows is a review of data concerning the physical and electrical attributes of tin whiskers, the conditions for whisker growth, and current theories for whisker growth.

Physical Properties

Tin whiskers are single, perfect crystals which grow spontaneously from the base of tin-plated surfaces and rotate outward (Figure 1). Typical whisker diameters range from 3–4 microns, though diameters as small as 6 nm and as large as 7 microns have been observed [3,9]. Whisker lengths near 2 mm are common, but individual whiskers have reached 5 and 9 mm [7,8]. Reported growth rates range from 0.03–9.00 mm/yr [9], though whiskers rarely grow for more than about 200 days [3]. Whisker density falls in the range of 3–500 whiskers/mm^2 [3].

Primary whisker growth is associated with tin nodules on the surface of plated tin, and often whiskers appear to grow out of these nodules (Figure 2). Whiskers may be solid, hollow, or perforated [8], and striations along the axis of growth are common. Striations and other textures have been attributed to the shape of the producing orifice [3] and the growing together of two or more whiskers [8]. Whiskers grow very straight, but with abrupt kinks which may be caused by the imperfect crystal of the tin plating or by collisions between multiple whiskers at their extrusion

Fig 1. Tin whiskers growing from the metal casing of a transistor. Whiskers grow straight with occasional abrupt changes in direction, and they appear to maintain a uniform cross section throughout their length. *(SEM photo courtesy of the Aerospace Corporation)*

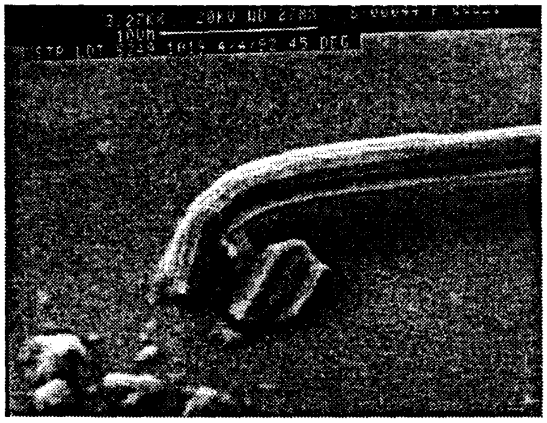

Fig 2. Primary whisker growth is associated with eruptions of tin nodules, and often whiskers appear to grow out of these nodules. Note the striations along the body of the whisker. *(SEM photo courtesy of the Aerospace Corporation)*

point. In addition, there is no unique crystallographic direction for whisker growth [3]. Interestingly, no thinning or depression of the tin plating is observed in regions of high whisker growth, indicating that whiskers are "fed" by a long-distance diffusion process.

Because they are pure crystals, unstressed and free of internal defects, whiskers are quite strong, capable of withstanding elastic strains 100 times that of bulk tin [8]. Some evidence indicates that whiskers are so strong they cannot be broken by mechanical shock or vibration [9]; other researchers disagree and claim that even moving air can break whiskers [8]. There is little dispute, however, that tin whiskers are strong enough to grow through conformal coating [7], though a resin thickness of 1.5 mm or greater might inhibit their growth [2]. Experts warn that when applying conformal coating to dense assemblies, the resin should not bridge the gap from one surface to another, providing a direct path for potential whiskers [7]. Conversely, many agree that if a gap does exist between coated surfaces, a whisker will not be able to penetrate the opposing surface after already growing through one layer of coating.

Perhaps the most insidious aspect of tin whiskers is their dormancy, or incubation period. Whiskers have sprouted spontaneously after years of dormancy, in some cases after 8–10 years [3] and in others after as long as 20 years [7]. The type of substrate bears a close relation to the length of incubation, as will be discussed. In addition, some research shows that longer incubation periods result in slower whisker growth [2], while the opposite has also been claimed [3]. There is evidence that whiskers appearing after a prolonged dormancy period are more likely to be pointy or pyramid-like, and do not grow from nodules [3].

Electrical Properties

The current-carrying capacity of a tin whisker at a given base-plate temperature approaches its maximum value as the whisker approaches its melting point. Assuming cooling along the length of the whisker by conduction only, this relationship has been shown to be [9]:

$$i_{\text{melt}} = 0.076 \times \frac{A}{L} \text{mA}$$

where A is the cross-sectional area of the whisker in micron^2 and L is the whisker's length in cm. For a whisker whose diameter is 2.8 microns and whose length is 0.8 mm, this value is 5.85 mA. The actual measured capacity of a whisker with these dimensions was 22 mA [3]. The discrepancy between the predicted and actual values is due to idealization in the predictor equation, and the fact that area measurements of whiskers are complicated by their fluted cross-sections. Observe that current-carrying capacity is inversely related to whisker length.

Based upon their cross-sectional area and length, whiskers which create short circuits fall into three categories: those which sustain current flow indefinitely, those which burn out within seconds or micro-seconds, and those which burn out instantly. A statistically significant, empirical mapping between whisker dimensions and these three categories does not exist; however, hard failures due to shorting tend to occur in high-impedance, low-current applications, while transient failures tend to occur in medium-power circuits drawing between 1–60 mA of current [7].

At atmospheric pressures of 0.5 torr and below, electric fields around the sharp tip of a whisker can accelerate electrons in the surrounding gas, resulting in a discharge capable of melting the whisker tip. When this blunt whisker makes contact with an opposing surface, a transient conducting path with a current-carrying capacity of several hundred amps may appear. This phenomenon has been termed "vacuum metal arcing." Experiments have revealed that vacuum metal arcs will not appear when there is less than 12 volts of potential across the whisker, but they may appear when the potential exceeds 18 volts [7]. Current levels of 15 amps and above have sustained vacuum metal arcs across 30 volts [7]. The arcs will persist until all available tin has been consumed, or until no additional current is available.

Conditions for Whisker Growth

Whisker growth from surfaces electro-plated with pure tin is impossible to predict with absolute certainty. Some actions, such as reflowing an electro-plated tin deposit, will greatly reduce the probability of whisker growth, but many additional factors complicate the situation. Key parameters governing whisker growth are: substrate metal, tin fusing, tin purity, plating thickness, external stress, temperature, pressure, and plating process. Additional factors may also be important.

Substrate Metal. Whisker growth dependence on various types of substrate metal has been clearly established. In one study, normal tin plating over brass and copper substrates exhibited whisker growth after two days, while the same plating on steel lay dormant for several months before the onset of whisker growth [3]. One author listed substrate metals in terms of their likelihood of producing whiskers, from most likely to least: brass, electro-deposited copper, sheet copper, steel, electrodeposited nickel, electro-deposited lead, and tin-nickel alloy [2]. Despite the preponderance of evidence that tin-on-copper creates whiskers, tin-coated copper wire has never exhibited whisker growth [7]. Substrate surface roughness and coefficient of thermal expansion differences between the substrate and tin do not appear to be contributing factors [1].

Tin Fusing. Fusing, or melting, the electro-deposited tin significantly decreases the chances for whisker growth. One notable study observed no whisker growth on fused tin, regardless of the substrate metal [3]. The success of fused tin in preventing whisker growth has been attributed to the fact that high temperature produces regular polygonal grains of tin, which are less likely to recrystallize and produce stresses internal to the tin plating [5].

Tin Purity. If pure tin is alloyed with small amounts of lead before electro-deposition, the risk of whisker growth is substantially reduced. Elongated nodules with lengths of 50 microns have been observed on tin-lead platings with a 30% lead content, but they are much less threatening than whiskers several millimeters in length [8]. Many observers believe that 1% lead is satisfactory to inhibit whisker growth [1,9], but 2% is often recommended to provide margin in the case where non-uniform deposition might create a tin-rich region. New revisions of some military standards may require as much as 3% lead. Of course, alloys of tin may not provide the same advantages of pure tin: when nickel is added to tin in quantities sufficient to prevent whisker growth, soldering becomes difficult [1].

Plating Thickness. Whiskers are not seen on bulk tin or on coatings less than half a micron in thickness [8,9]; it follows that there must be some "threshold" plating thickness above which whiskers will not grow. Military specifications presently require a minimum plating thickness of 200 micro-inches (5 microns); various authors set the threshold between 8–10 microns [2,3].

Thickness appears to relieve lattice strain with tin deposits, hindering whisker growth [2].

External Stress. Some authors believe that high compressive stress from an external source stimulates whisker growth in a matter of hours [2] due to local grain distortions [5]; others claim that whisker growth is completely independent of external macro-stresses, even to the point that heavily torqued nuts on the tin surface will not enhance whisker growth [3].

Temperature. An exact temperature dependence has not been demonstrated for whiskers; however, whisker growth slows considerably above 121 degrees C and halts completely above 150 degrees C. One author claims that 52 degrees C is the optimal temperature for whisker growth [8]. Another believes that temperatures between 25–50 degrees C do not affect the susceptibility of tin to whisker growth, but may impact the speed of growth. Interestingly, higher temperatures will stimulate atom diffusion within tin by a factor of $e^{-Q/kT}$, promoting whisker growth; but higher temperatures will also anneal the tin, relieving internal stresses and obviating the theorized need for whiskers. Finally, there is some concern that temperature cycling might create stresses which lead to whisker growth [3].

Pressure. Whiskers have been known to grow in high vacuum as well at ambient pressure and when submerged in dielectric liquid [9]. High relative humidity may enhance whisker growth [8].

Plating Process. There is disagreement as to whether bright tin finishes are more or less likely to produce whisker growth than matte finishes. Some studies indict brighteners as whisker enhancing, especially at high current densities [2]; more recent studies differ [11].

Other Factors. It is possible that static charging and irradiation stimulate whisker growth [3,8]. Other suggested causes of whisker growth are high frequency vibration [8], moisture [2], and corrosion [1].

Theories for Whisker Growth

Tin whiskers are a purely mechanical phenomenon, unlike dendrites which are induced by electro-magnetic fields in solution. The exact reason for whisker growth is not known, but theories evolving since the early 1950's cite growth of internal crystal dislocations as a root cause. The first complete theory [4] suggested that whisker growth begins with a dislocation in tin which is fueled by stress-inducing oxidation on the surface of the plating; however, this theory failed to explain whisker growth under vacuum conditions, where oxidation is not possible. A second major theory [6] postulated long range diffusion of tin atoms to feed a *screw dislocation* near the surface of the plating. The limiting assumption behind this theory was that externally applied macro-stresses, such as those induced during electro-plating, provided the impetus for tin diffusion. The most recent theory [3] is based on empirical evidence that external macro-stresses do not induce whisker growth, but rather micro-stresses internal to the tin plating create the conditions for whisker growth. The hypothesized micro-stresses are created over time in reaction to a dense intermetallic layer which forms between the tin plating and the underlying metal substrate. In the case of tin-on-brass, this intermetallic layer would be Cu_6Sn_5 created from the diffusion of copper into the tin. In the case of tin-on-steel, the diffusion of iron into tin is much slower, thereby explaining the paucity of whiskers on tin-plated steel. The internal stress created by the density difference between tin and Cu_6Sn_5 aggravates dislocations near the surface and creates nodules, from which the primary whiskers later emerge. Lateral expansion at the tin-substrate interface leads to the growth of secondary whiskers which do not nucleate from nodules and are more pointed in character.

III. THE AIR FORCE APPROACH

The resounding conclusion from the foregoing discussion is that pure electro-plated tin should not be used in high-reliability systems. The uncertainties associated with whisker growth make it impossible to predict with absolute certainty when whiskers will appear. Especially disturbing are claims that whisker growth may be induced by elements of the standard spacecraft acceptance test, such as thermal cycling and high frequency vibration. New revisions of the military standards are in work. They promise to eliminate the use of pure electro-plated tin, but they may permit tin-lead alloys in ratios sufficient to hinder whisker growth. Little is known about the impact of these new requirements on vendors who use tin today. There is some concern that vendors will require new equipment in order to meet safety regulations associated with lead; also, the increased use of lead might complicate steam-aging corrosion problems created by lead-oxide formation.

The presence of tin in existing high-reliability applications poses special problems, especially if it is discovered late in the system integration and test cycle. The obvious option of removing and replacing tin-plated components can carry tremendous cost: risk of damage during rework, non-availability of replacement parts in a timely manner, and impacts to overall program cost and schedule. An Air Force space program faced with this dilemma reviewed the available information on whisker growth and formulated a decision tree based upon acceptable areas of risk (Figure 3). At the root of the decision tree is the assumption that three types of tin-plating are acceptable: pure electro-plated tin which has been reflowed by fusing; electro-plated tin with a lead content above 1%; and, electro-deposited pure tin with a thickness equal to or greater than 10 microns. Under each of these conditions, tin is unlikely to produce whiskers. The decision tree also assumes that a tin whisker, having grown through one layer of conformal coat, will not be able to penetrate a second coat. This assumption exonerates the use of tin-plated components under a layer of conformal coating, with one exception: flush-mounted parts on conformal coated boards require special analysis to ensure that whisker growth from the bottom of the part is not possible, or not a concern. The decision tree permits a "use-as-is" disposition when any of the baseline assumptions has been satisfied. It also allows "use-as-is" if the circuit can provide enough current to destroy the whisker without sustaining permanent damage, or if geometries are such that no whisker will be capable of producing a short. Components which are not dispositioned "use-as-is" must either be removed and replaced, or repaired. Removal and replacement is preferred, but the repair option is necessary when replacement parts are not available, or when removal is unusually difficult. The method of repair involves brushing (or air-blowing) and vacuuming the tin surface to break and remove all whiskers, followed by conformal coating of the area. This approach has been used successfully in the past [2], and the conformal coating provides protection against the risk of whisker regrowth in sensitive areas [10].

The decision tree was applied to thousands of electrical components with special concern for leads and metal-encased components. It was also applied to mechanical components, such as fasteners, lugs, nuts, and washers, where a whisker at ground potential could be fatal. Fortunately, the vast majority of assemblies produced by the program were conformal coated, significantly reducing tin whisker concern. The program policy to solder-dip all electrical leads also proved

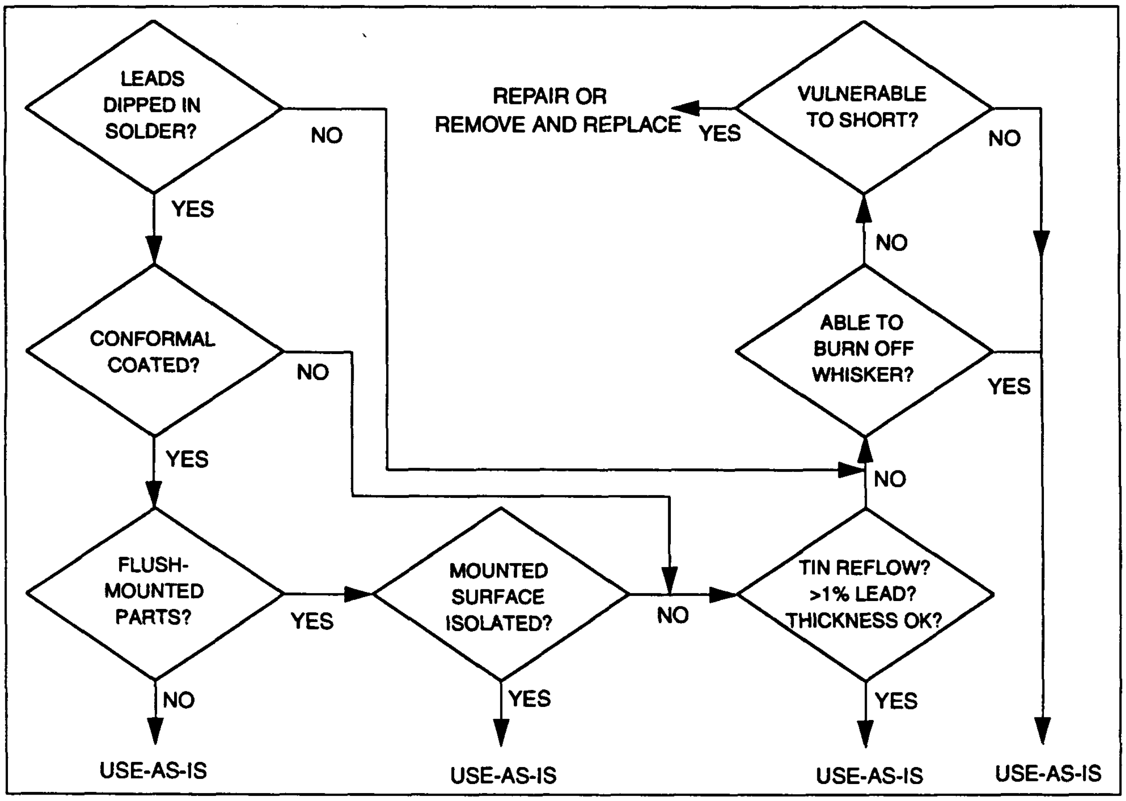

Fig 3. Decision logic adopted by an Air Force program to disposition the use of tin-plated electronic components in existing flight hardware. This logic was applied at the card and piecepart level for hundreds of assemblies and thousands of parts.

beneficial to the disposition process. Most occurrences of tin were deemed "use-as-is," but the analyses leading to these conclusions were extensive. Three sample dispositions follow:

Case 1. One TO-18-type transistor in an electronics assembly is known to be electro-plated with pure tin which has not been reflowed. The assembly is not conformal coated. The transistor case is sleeved by an insulator, with only the 1.3 mm-wide circular rim exposed. The transistor case is tied to the collector potential, but a whisker spanning the 2–3 mm distance from the rim to the base or emitter would be fatal. On the other hand, all three leads are insulated to within a small, but unspecified, distance from the can. Twenty-six identical transistors in stores are examined, revealing lead content at the rim between 0.00–1.33%, and an average rim plating thickness of 8.25 microns. None of stored transistors, which have been in stores for two years, exhibit whisker growth. *Analysis*: Lead content and thickness fall just short of the accepted thresholds, but the absence of whiskers on the parts in storage is encouraging. Ultimately, the government and contractor decide that the probability of a whisker growing from the narrow rim to the non-insulated portion of a lead is acceptably small. *Disposition*: Use-as-is.

Case 2. A TO-3-type power transistor used by another space application develops a whisker shorting the collector to the structure and turning an electrical unit on with no command being sent. When the unit is later commanded on and off in sequence, the anomalous behavior ceases. Vacuum metal arcing is suspected. The transistor is identified as coming from a lot of pure tin-plated transistors. A lot date code search reveals two uses of the same transistor within a critical power converter for the program described here. *Analysis*: A clear case for removal and replacement. *Disposition*: Remove and replace both transistors. Subsequent destructive physical analysis of the transistors revealed the presence of dense whisker growth, including a 1.2 mm whisker spanning the glass meniscus between the transistor can and the base lead (Figure 4).

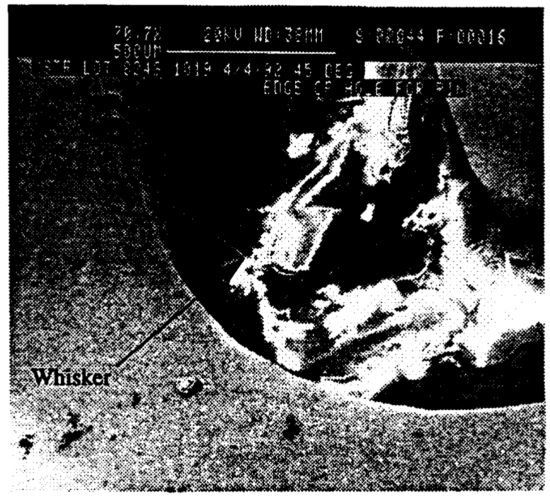

Fig 4. A 1.2 mm tin whisker bridges the gap between the transistor case and the base lead. ***(SEM photo courtesy of the Aerospace Corporation)***

Case 3. A conformal coated printed wiring board is found to contain one flush-mounted transistor which is tin-plated. In normal operations, the emitter-collector current is approximately 260 mA. Metallurgical analysis of identical parts in storage reveals a lead content of 1% and a plating thickness of 10.1 microns. *Analysis*: Adequate lead content and sufficient plating thickness indicate a low probability of whisker growth; moreover, 260 mA is more than sufficient to burn out any whisker. *Disposition*: Use-as-is.

IV. CONCLUSION

Pure electro-plated tin is susceptible to the growth of fibrous whiskers which can produce short circuits and, under some conditions, vacuum metal arcs capable of sustaining hundreds of amps. Typical whiskers are 3–4 microns in diameter and approach 2 mm in length; they are strong enough to penetrate one layer of conformal coating. Whiskers may lie dormant for many years before growing spontaneously. Many experts agree that fused tin, tin containing at least 1% lead, and tin platings over 10 microns thick are unlikely to produce whiskers. Some substrates, such as brass, are much more likely to induce whisker growth than others. Whiskers grow at ambient pressure and in vacuum conditions. They do not grow above 150 degrees C, but their temperature dependence is not well understood. Other growth-inducing factors have been suggested, including external stress, plating brighteners, moisture, thermal cycling, and irradiation. The exact reason for growth is not understood, but has been convincingly attributed to stress internal to the plating. Military regulations are being rewritten to disallow the use of pure tin plating.

The methodology adopted by one Air Force program to disposition the use of tin in existing spacecraft hardware has been presented. It permits the use of tin when growth conditions are strongly adverse, or when the tin plated components are conformal coated. In cases where whisker growth is considered possible and problematic, removal and replacement, or careful cleaning and conformal coating is required.

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