EASA
European Aviation Safety Agency

Certification Memorandum

The integrity of nickel powder metallurgy rotating critical parts for gas turbines

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Log of issues

Issue	Issue date	Change description
001	27.10.2017	First issue.

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1. Introduction

1.1. Purpose and scope

The purpose of this Certification Memorandum is to provide additional guidance when establishing the integrity of nickel powder metallurgy rotating critical parts, as identified under CS-E 510, when showing compliance with CS-E 515.

1.2. References

It is intended that the following reference materials be used in conjunction with this Certification Memorandum:

Reference	Title	Code	Issue	Date
CS-E 515	Engine Critical Parts	CS-E	---	---

1.3. Abbreviations

AMC	Acceptable Means of Compliance
CM	Certification Memorandum
CS	Certification Specification
GM	Guidance Material
IFL	Inclusion Fatigue Life
PFL	Pore Fatigue Life
POF	Probability of Fracture

2. Background

CS-E 515 requires that the integrity of Engine Critical Parts be identified via the establishment of an Engineering Plan (CS-E 515 (a)), a Manufacturing Plan (CS-E 515 (b)) and a Service Management Plan (CS-E 515 (c)).

The Engineering Plan of CS-E 515 (a) requires in part that an Appropriate Damage Tolerance assessment must be performed to address the potential for failure from material, manufacturing and service – induced anomalies within the Approved Life of the part.

EASA Certification Memorandum CM – PIFS – 007 provides guidance for assessing surface damage tolerance in critical rotating parts.

As described in the AMC to CS-E 515, material anomalies consist of abnormal discontinuities or non-homogeneities introduced during the production of the input material or melting of the material. Some examples of material anomalies that should be considered are hard alpha anomalies in titanium, oxide/carbide stringers in nickel alloys, and ceramic particulate anomalies in powder metallurgy materials that are unintentionally generated during the powder manufacturing.

Such inherent anomalies, whilst small, may result in the nucleation of cracks when tested in fatigue. The determination of the Approved Life therefore needs to recognise the possibility of an anomaly occurring at a highly stressed location in the rotating part and nucleating a fatigue crack.

Considerable industry experience has been gained in managing the anomalies found in titanium, for example FAA AC 33.14-1 provides one such example of a probabilistic process evaluation for hard alpha material anomalies in titanium alloy rotor components.

While assessments are made for the rare occurrence of a melt anomaly in traditional cast and wrought material, the likelihood of occurrence is so low in such materials that establishing the probability of the presence of such an anomaly is based on a combination of in-service finds and detection in manufacture and supply.

By contrast the inherent nature of the inclusions and porosity in powder metals is such that a more systematic approach may be taken. This CM developed in conjunction with the members of the AIA Rotor Integrity Steering Committee (RISC), Aerospace and Defence Industries Association of Europe, the Federal Aviation Administration Engine and Propeller Directorate, and Transport Canada discusses the ways in which a systematic approach to inherent anomalies in powder metals can be addressed. In addition the elements of a test programme to establish the capability of the material are considered, recognising that it is unlikely that an extreme size of anomaly such as one that can occur in production quantities will be present in the limited volume of material tested. A method for determining the fatigue capability of powder material is developed from these tests which can be used to demonstrate the integrity of parts.

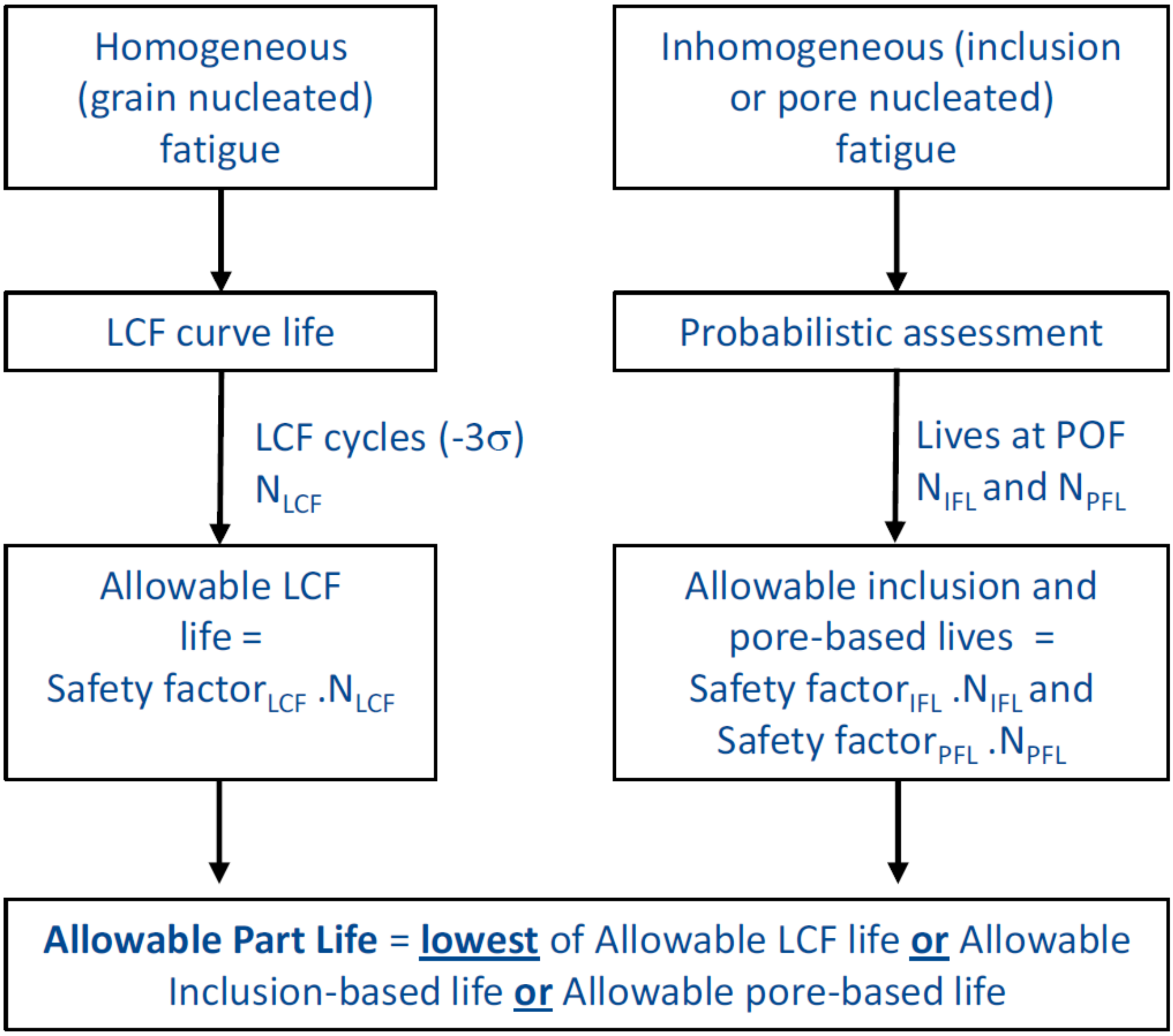
3. EASA Certification Policy

3.1. EASA Policy

3.1.1. Introduction

Nickel powder materials have been introduced to allow the use of highly alloyed materials which would be difficult, if not impossible, to produce through a conventional melt route due to segregation, which is the non-uniform distribution of alloying elements in the forging. Instead small particles of the material are produced which cool so quickly that levels of segregation are extremely small, producing consistency in alloy composition. The powder particles are then consolidated into a single monolithic piece of material. However the process of producing the particles and consolidating the material introduces anomalies such as small inclusions and porosity (from trapped gas), both of which are therefore inherent to the material. While fatigue tests on components made of powder metallurgy will often fail from grain facet features similarly to conventional cast and wrought alloys, there will also be occasional failures initiating from the inherent inclusions or, under some circumstances, porosity. When establishing the Approved Life it is necessary to consider not only the possibility of fatigue fracture from grain facets but also from anomalies that can be missed during non-destructive inspections. Further discussion of issues identified when lifing powder alloys are discussed in McClung et al. 2011 (McClung, Enright, & Wuwei, 2011).

Figure 1 Lifing assessments performed on powder nickel materials



3.1.2. The processing of powder materials

A powder alloy is produced from the molten state. A quantity of alloy is melted with the desired chemical composition and the liquid metal is poured through a nozzle and atomised into a fine spray of droplets by inert gas. These droplets solidify very quickly and are cooled in a collection vessel. The particles are then passed through a sequence of sieves to eliminate the larger ones, thus ending up with a uniform distribution of finer powder.

Inclusions arise because the molten metal is confined during the melting and pouring processes. Repeated use of the melting crucible, in particular, erodes the ceramic refractory linings by the passage of high temperature liquid metal and thus small particles of the ceramic material are released and are collected with the powder particles. Generally such inclusions are very small, normally measured in microns, but occasionally larger inclusions can arise up to a size which can get through the sieve. These may be bigger in one dimension than the sieve gauge because the particle can be acicular and pass through by its minimum cross section. In addition, inclusion particles larger than the sieve dimensions are found on rare occasions at frequencies similar to those of anomalies in conventional cast and wrought materials. These larger (rogue) inclusions often appear as a unique individual distribution relative to the inclusion sizes which can still be present after the sieving process. Their potential effects on component life should also be evaluated.

The consolidation of powder materials is achieved by hot compaction methods at sufficiently high temperatures and pressures that plastic flow and diffusion will occur, bonding the particles and producing a material structure suitable for subsequent processing. After compaction the consolidated material may be subjected to significant additional hot deformation by shearing the compact through a die to produce an extrusion or through tightly controlled forging to produce billet followed by isothermal forging to a shape close to the final component. This breaks up and elongates the ceramic inclusions and porosity present. The material may also be used in an as-compacted form (such as post Hot Isostatic Pressing (HIP)) to manufacture components, however industry practise in recent years is to apply hot deformation to the HIP compact to ensure a billet of fine grain size.

After heat treatment, the forging or as-compacted form is then machined to remove the surface through a succession of shapes to allow inspection before being finally machined to the required profile for engine use. Ultra-sonic inspection can usually achieve a high standard because the processing route delivers a uniform small grain size with low noise levels, although the detectability of anomalies is dependent on whether or not there is cohesion between them and the matrix material. Etch inspection and fluorescent penetrant inspections are routinely applied to check the microstructure and to confirm the absence of cracks or crack-like anomalies on the surface within the determined probability of detection (POD). When the POD has been appropriately determined, inspections can verify that cracks exceeding the POD criteria are not present in the part with a given confidence. Because etchants can adversely affect the finished material surface integrity at smooth or notched features, work to understand the impact of the etchant should be included within the fatigue programme.

Ensuring that the powder produced is traceable and of a consistent high quality via an approved material specification and fabrication process is a pre-requisite for a reliable lifing system for powder alloys.

3.1.3. Development of a lifing system for powder metallurgy rotating parts

The first step in the development of a lifing system is to characterise the different mechanisms of crack nucleation in the material, which can typically be from:

- Grain facets (similar nucleation mechanism to conventional alloys)
- Anomalies such as inclusions (both inherent and rogue inclusions) and porosity resulting from inert gas trapped in the powder

The characterisation of the active crack nucleation mechanisms can only be done by fractographic examination of the failure surfaces of a sufficient number of fatigue specimens tested at component-representative strains and temperatures.

The declarable component life will be the lowest result from separate life assessments performed for the mechanisms shown earlier in Figure 1.

For each nucleation mechanism, the significant parameters driving the LCF life should be examined. Cycle-related parameters may include:

- Applied stress or strain levels, their degree of multiaxiality and any resulting non-linear deformation through plasticity and/or creep.
- Cycle temperature and its phasing with the applied component loads. It would be expected that nucleation of a propagating crack will depend on the peak stress, but may also be influenced by whether the peak temperature occurs simultaneously or at some other point in the engine cycle. This will influence the crack propagation phase after crack nucleation.

For nucleation from grain facets, the significant parameters are usually consistent with those of a conventional cast and wrought alloy with the same chemistry. Consequently the same type of lifing models may be applied when assessing the nucleation from grain facets.

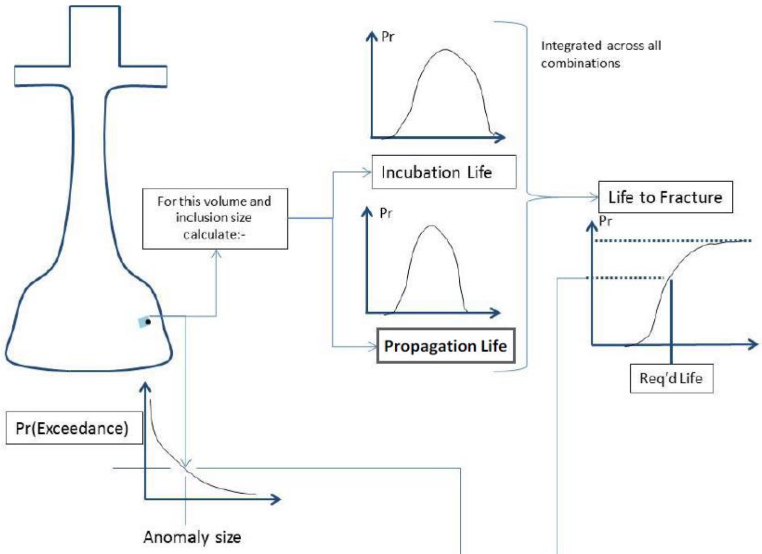
In addition to the cycle-related factors described above, the fatigue behaviour of inclusions may also depend on:

- The size of the inclusion, including its aspect ratios and orientation.
- The composition of the inclusion and its effect, if any, on the substrate material.
- The proximity of the inclusion to a surface of the component because this affects the balance of the stresses in the microstructure around the inclusion and hence how easily it can incubate a propagating crack.
- The surface treatment of the component because the shot peening process, for example, will distort the microstructure at surface or very near surface inclusions and the residual stresses may affect potential crack nucleation and propagation.

The simplest approach would be to treat all inclusions as initial cracks of a size equal to the projected area normal to the largest principal tensile stress. In practice, especially for smaller inclusions, a nucleation life before the inclusion gives rise to a propagating crack may be determined.

A probabilistic component lifing model is considered an appropriate approach when assessing fatigue failures originating from inclusions and porosity, with the aim of demonstrating that the probability of a fracture from an extreme size of anomaly present in a highly stressed portion of a component is acceptably low. This evaluation follows the same lines as an assessment for melt anomalies in conventional cast and wrought materials and is outlined in Figure 2.

Figure 2 Probabilistic assessment method for fracture from inclusions



$$\text{Pr(fracture)} = \int_{all\ volumes} \int_{all\ inclusion\ sizes} Pr(size) Pr(fracture)$$

The probabilistic model will be based on a two-stage representation of fatigue life consisting of:

- Crack propagation life as a function of the above engine cycle variables and considering, if near a surface, residual stresses from machining and/or surface treatment.
- Nucleation life as a function of size and type of anomaly and proximity to a surface, and as a function of cycle and material variables such as applied strain or stress, temperature (peak and its phasing with the applied loads), loading multiaxiality and inelastic (creep and plastic) strain levels if applicable.

Another key input is the size and frequency distribution of the powder material anomalies (inclusions and porosity). Methods for determining the anomaly distributions and nucleation lives are discussed in sections

3.1.4 and 3.1.5. Although these sections are focused on inclusions, the same principles may be used to provide the information required to assess the risk of porosity-related failure with some minor differences.

3.1.4. Characterising the inclusion size distribution in powder materials.

All powder materials will be characterised using the same mechanical and physical measurements as used for conventional cast and wrought materials. In addition, it is necessary to extract data to make a prediction of the largest size of inclusion which could occur in a given volume of material. Predicting the largest size is based on measuring inclusions above a detectable limit in known volumes of material. If the number of inclusions found using a particular inspection process is known and a size distribution is fitted to those found, then the likelihood of finding a large inclusion in any volume of material may be determined. However consideration should be given to the following factors:

- There is a lower detectable limit below which inclusions may simply be missed. This may be because:
    1) the inclusion size is small, in which case the inclusion is unlikely to be life limiting; or
    2) the shape and orientation of the inclusion is such that the area presented to the inspection plane is small, in which case the inclusion could be life limiting. Consequently, the inspection plan should be defined to maximize inspection capability, accounting for the deformation of the material during forging and the inspection limits should be recognized when fitting the anomaly rate, size and orientation distributions.
- Sieving is designed to remove larger inclusions, but may still let through long acicular inclusions with a lower cross sectional area. The size distribution at powder creation may be smooth but will become less populated at large sizes due to sieving.

Furthermore methods for detecting and measuring the sizes of rogue anomalies will be required in order to take appropriate account of them in the lifing process.

Because of the above challenges in gathering inclusion distribution information, methods for detecting and measuring inclusion sizes and orientations should include processes such as:

- <u>Fractographic examination of powder material.</u>

  This would be performed in the forged state and would therefore include the effects of forging on the inclusions. This is desirable since the inclusions may deform and become elongated during the forging process depending on their position relative to the forging flow lines. However, due to the effort required to section and polish material, only a relatively small volume of material can practically be examined using this approach and hence there is a degree of extrapolation up to a volume representative of all the highly stressed material in production quantities of components.

- <u>Large bar tensile tests.</u>

  It is assumed the test bar will fail at the largest inclusion. If enough large tensile specimens are tested, each with a known volume at the ultimate stress, then the largest inclusion can be measured on the fracture surface. This assumes that the critical dimension is normal to the direction of the tensile stress. This method can be used to examine a relatively large total volume of material, comparable to a small number of engine discs. The specimens are usually cut from billet material but may be taken from forgings. The only information that can be obtained from these tests is the size of the largest inclusion in each volume. Gumbel statistics may be employed in deriving the underlying rate and size distribution for forward extrapolation up to larger volumes.

- <u>Large specimen fatigue tests.</u>

  Another possible method for detecting and measuring inclusion sizes and orientations is to systematically test fatigue of powder alloys on larger specimens than used for conventional alloys. These large specimens should be extracted from forgings and their size should be chosen taking into account forging size and fatigue test machine capability. In this manner, the volume of material tested in fatigue is increased and the probability of failure from a large inclusion is also increased. When the specimen fails from an inclusion, this inclusion is considered to be the most detrimental for fatigue resistance in the tested volume and this can be related to its size plus appropriate additional scatter coming from its interaction with the local microstructural environment. By measuring the size of the inclusion at the fracture origin on each specimen and testing enough large specimens, the underlying rate and size distribution of inclusions can be derived using similar techniques as described for large bar tensile tests. In addition, these large specimen fatigue test results can also be used to characterize the nucleation life from inclusions.

- Heavy liquid separation.

  By passing the basic powder through a liquid with a density between those of the alloy and the inclusions, the inclusion particles will float while the alloy will sink. This examines the material before consolidation and forging so a model is required which relates the sizes of particles found to what will be missed and therefore could remain in the forged component. However the examination and measurement of the particles is relatively easy and can include all three dimensions, which is not easily achieved by the other methods. Depending on local health and environmental regulations, the use of heavy liquid separation may however be restricted due to the toxicity of the material necessary to reach an intermediate density between the ceramic inclusions and the nickel alloy powder. Alternative techniques such as water separation are also available. Further aspects of heavy liquid separation are discussed by Roth et al. (Roth, Murray, Morra, & Hyzack, 1994).

- Acid digestion.

  This is accomplished by using an acid to remove metallic material while the inclusions are not attacked and left as remnant particles at the end of the process. Tungsten-bearing alloys, however, have proven difficult to evaluate by this technique due to the formation of tungstic acid and its subsequent effect on laboratory hardware.

- Cut-up characterization of ultrasonic indications.

  2D and 3D characterization of the anomalies detected by the ultrasonic inspection are performed. This also gathers information relating to porosity and other issues such as proximity of anomalies and the rogue size population.

More than one of the above approaches should be used both for initial determination of the inclusion size distribution and continued monitoring of the powder production process to confirm that the initial size distribution remains appropriate and conservative for lifing throughout the life of the product. The engineering plan of CS-E 515 (a) should account for the assumptions made, and treatment of these distributions in establishing the Approved Life of the part.

3.1.5. Fatigue test strategy to characterise the nucleation life from inclusions in powder materials

Testing small specimens of powder materials in fatigue can give rise to widely varying results. If the tested volume is free of inclusions the behaviour will appear significantly better than when a relatively large inclusion is present. As the volume of material under high stress increases, it becomes more likely that fracture will nucleate at an inclusion, but even large discs may not always fracture from inclusions. To establish the fatigue implications of inclusions, the approach selected for testing must consider how a sufficient number of failures can be generated to demonstrate that the fracture during service operation of powder materials can be avoided.

The simplest approach would be to test very large volumes of material such that a significant number of fractures from inclusions are generated. This may however be impractical, as noted above, even large discs do not always fracture from inclusions. Tests should also be conducted at a wide range of temperatures and load levels to ensure that the material behaviour has been characterised appropriately through the full service usage envelope.

An alternative approach is to use “seeded material” where artificial inclusions of a known size and rate are introduced at the powder stage. Such seeds should be representative of the actual inclusions in composition and behaviour. Specimens and components manufactured from seeded material are much more likely to fail from the artificial seeds than through conventional LCF. This allows a fatigue model for the inclusions to be generated based on a relatively modest test programme.

However the tests are performed, it will be necessary to define an equivalent crack size that corresponds to the end of the nucleation phase of life and the start of crack growth. This could be represented in a number of ways:

- Engineering crack size (0.762mm x 0.381mm (0.030”x.015”)) for surface cracks,
- The actual size of the anomaly from which the fatigue failure nucleated (determined by fractography).
- The actual size of the anomaly from which the fatigue failure nucleated plus an allowance for diffusion or other interaction between the anomaly and the surrounding material.

Determination of the nucleation life is likely to involve back calculations using fracture mechanics of the number of cycles from either test piece failure or crack detection (of a known size) to the equivalent crack size at the end of the nucleation life.

For crack nucleation from porosity, the same questions should be addressed. It may be possible to show that the size and frequency distribution for porosity can be determined directly from conventional specimens because pores are often more frequent than inclusions and have a lower scatter in size. The stress component (von Mises or worst principal, for example) which best describes crack nucleation is also to be defined and it should be noted that it may be different for a pore, an inclusion or a grain facet.

3.1.6. Calibration and Validation of the probabilistic system for inclusions

As this is a probabilistic system that integrates a significant number of parameters (related to the size distribution and life model) which are often identified independently, it is important to verify that it produces sensible results once these are combined together. As part of achieving this, the inclusion size distribution may be slightly adjusted in the domain which is too small to be easily characterised experimentally.

The confirmation of the accuracy of the probabilistic system for inclusions can be made using fatigue test results from specimens or components made from unseeded material. Although only a fraction will fracture from inclusions, these occurrences should be sorted to correlate the various probabilities that the probabilistic system can calculate:

- Conditional probabilities of failure from surface, sub-surface and internal inclusions.
- Probabilities of failure from inclusions within a given size interval.
- The global failure probability distribution from inclusions as a function of cycles at a given loading condition.

It is important to run a test campaign to show the accuracy or at least the conservatism of the probabilistic system. This should include, in addition to fatigue specimen tests, tests that represent the behaviour of components. Spin tests are useful in such campaigns to provide information on how to account for component characteristics such as volume of material under stress, multiaxial loading and residual stresses.

The results from the component-representative tests should fall within the population of predicted lives at the test conditions.

3.2. Whom this Certification Memorandum affects

This Certification Memorandum is applicable to engine type certificate holders and engine manufacturers.

4. References

McClung, R. C., Enright, M. P., & Wuwei, L. (2011). Integration of Nasa-developed lifing technology for PM alloys into DARWIN. *NASA/CR-2011-216977.* NASA.

Roth, P. G., Murray, J. C., Morra, J. E., & Hyzack, J. M. (1994). Heavy liquid separation: a reliable method to characterize inclusion in metal powder. *Characterization, testing and quality control advances in powder metallurgy and particulate materials*, Vol2.

5. Remarks

1. Suggestions for amendment(s) to this EASA Certification Memorandum should be referred to the Certification Policy and Safety Information Department, Certification Directorate, EASA. E-mail CM@easa.europa.eu.

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