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INTERNATIONAL ELECTROTECHNICAL COMMISSION

GUIDANCE FOR THE INTERPRETATION OF OTDR BACKSCATTERING TRACES

FOREWORD

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 62316, which is a technical report, has been prepared by subcommittee 86A: Fibres and Cables, of IEC technical committee 86: Fibre optics.

This second edition cancels and replaces the first edition published in 2003. It constitutes a technical revision. In this edition,

– polarization effects are discussed in case of unidirectional trace;
– a new clause dealing with uncertainties, deviation and resolution has been introduced.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86A/1090/DTR	86A/1114/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

GUIDANCE FOR THE INTERPRETATION OF OTDR BACKSCATTERING TRACES

1 Scope

This Technical Report provides guidelines for the interpretation of backscattering traces, as obtained by an optical time domain reflectometer (OTDR).

A full description of the test measurement procedure can be found in Annex C of IEC 60793-1-40.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60793-1-40, *Optical Fibres – Part 1-40: Measurement methods and test procedures – Attenuation*

3 Backscattering phenomenon

3.1 Rayleigh scattering

Rayleigh scattering or backscattering originates from fluctuations in the density, and hence in the index of refraction, of the material constituting the wave-guide. Optical fibres are made of amorphous silica and density fluctuations are a consequence of the manufacturing process.

3.2 Fresnel reflections and dead zone fibres

When a light ray reaches a surface at an angle of incidence from the normal to that surface and that surface separates two media of different index of refraction, part of this light ray is refracted in the second medium and part of it is reflected backward into the first medium. This is the Fresnel reflection, which can be very high, depending on the difference in the index of refraction of the two media, on the aspect of the surface, the surface roughness, the angle of incidence and the surface defects. In some situations, the detected Fresnel reflection is very intense, which can bring the receiver to saturation (flat response vs. time). The corresponding section of the OTDR trace defines the so-called dead zone, i.e. a length of the fibre where the backscattered signal is lower than the reflector's saturated signal, hence not detectable and visible on the OTDR trace. The effect of the dead-zone connected to the Fresnel reflection at the input end of the fibre is often reduced by adopting a short length of a fibre positioned between the OTDR output and the fibre under test. This dead-zone or buffer fibre should preferably be at least one tenth (1/10, in m) of the OTDR pulse-width (in ns), e.g. for a 1 000 ns pulse the dead zone fibre should be ≥100 m long.

4 Measurement of the backscattered power (OTDR)

The power backscattered by an optical fibre is measured by means of OTDRs. They are based on the principle of sending one pulse or typically a train of pulses from one fibre end, and measure the power back-reflected from the fibre (the optical echo) at the same end. In OTDR traces, space and time are completely equivalent through the relation

$$\frac{z}{t} = \frac{c}{n_g(\lambda)} \tag{1}$$

where z is the distance (in m), t is the time (in s), c is the speed of light in vacuum (299 792 458 m/s) and n_g (as a function of the wavelength) is the group index of refraction. This parameter, to be supplied by the fibre manufacturer, takes into account the wave-guiding properties of the fibre and the different materials used for the cladding and the core. It also adjusts the speed of light in the studied material. The group index of refraction n_g is related to the phase index n or n_p (which is measured on a fibre and its fundamental attribute) by using the following expression

$$n_g = n_p - \lambda \frac{dn_p}{d\lambda} \tag{2}$$

4.1 Representation of the backscattered power

A possible schematic representation of the OTDR power P(z) at wavelength λ backscattered by a point z along an optical fibre is:

$$P(z) = C \frac{\lambda^2}{(\omega(z))^2} P_i \tau_w 10^{-\frac{2}{10}\alpha z} \tag{3}$$

where

- P_i is the input OTDR pulse power;
- τ_w is the input OTDR pulse width;
- z is the distance from the origin;
- α is the attenuation coefficient of the fibre (assumed constant to simplify the equation);
- ω(z) is the fibre mode field diameter (MFD) at point z;
- C is a proportionality factor, which depends on several parameters such as the fibre material or the refractive index value.

Equation 3 shows the relation between the backscattered power, the pulse-width, the attenuation coefficient and the MFD. The optical echo, as given by Equation 3, is conventionally represented on a logarithmic graph: it therefore appears as a (theoretically) straight line, whose slope is the attenuation coefficient of the fibre, α, as better explained in Clause 5 below.

4.2 Noise and perturbations

Normally, the noise and fluctuations of fibre parameters affect the backscattering traces; the trace will therefore appear as a perturbed line. The signal decreases rapidly, in an exponential way (as from Equation 3); the signal-to-noise (S/N) ratio is therefore rapidly degrading as a function of the distance. Backscattered traces of long fibres show inevitable oscillations. A practical way to reduce this problem is to average data collected from repeated measurements: OTDR evaluations of long fibres therefore take a longer time to be completed. If this is not sufficient, longer pulse-widths have to be used, correspondingly increasing the backscattered power (see Equation 3), hence the S/N ratio.

Macrobending and microbending effects can also perturb the OTDR trace; typically they appear as local losses, and macrobending is more evident at longer wavelengths (e.g. 1 550 nm or 1 625 nm vs. 1 310 nm), far from the cut off wavelength, where the MFD is larger and the confinement of the light into the fibre is reduced.

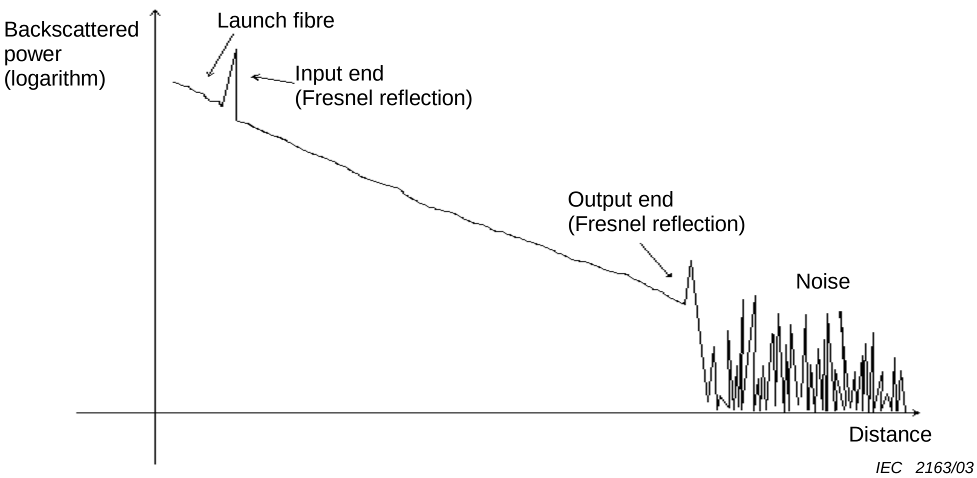

Figure 1 – Unidirectional OTDR trace

Figure 1 shows a typical OTDR trace of an optical fibre. The reflection at the input face is exaggerated for clarity; normally it is reduced by means of suitable index matching fluid between the launch and the measured fibre.

5 Interpretation of a backscattering trace

5.1 Unidirectional trace

OTDR traces obtained by the processing of the optical echo collected from one end only of the fibre are called unidirectional traces. They are very useful to quickly evaluate the optical continuity of a fibre and to estimate its attenuation coefficient. Their reliability can however be affected by several effects (such as noise in the fibre, MFD variations, polarisation ghost peaks or others). Where possible, use the bi-directional approach described below.

5.1.1 Slope as the attenuation coefficient of a fibre

Starting from Equation 3 for the backscattered power, taking logarithms on both sides, one obtains:

$$10LogP(z) = const. + 20Log\left(\frac{\lambda}{\omega(z)}\right) - 2\alpha z \tag{4}$$

The constant in the equation includes some numerical factors and the logarithm of the parameter C:

$$const. = 10(\log C + \log P_{\mathrm{i}} + \log \tau_{\mathrm{w}}) \tag{5}$$

Equation 4, plotted on a logarithmic scale as a function of z, will appear as a straight line with slope α (taking properly into account the factor 2).

Due to the S/N characteristics described in 4.2, the evaluation of the attenuation coefficient is better undertaken with the best-fit straight line.

5.1.2 Impurity and discontinuity

If an impurity, or any discontinuity, is present within the fibre (in the MFD region), the light can suffer a Fresnel reflection (see 3.2), and will appear on the OTDR trace as a peak, the amplitude of which depends on the size of the discontinuity (in some situations, the receiver may saturate). It is possible to locate the position of the discontinuity by Equation 1. A peak can be detrimental to link performance when its backscattered energy content is large enough to interfere with the source . The Optical Return Loss (ORL), as defined and used for the characterization of the connectors, can be envisaged as the right parameter to evaluate the peak.

NOTE Further discussions on the same subject can be found in C.3.6 of IEC 60793-1-40.

5.1.3 Pulse width

It is important to understand that the pulse width affects the amplitude of the reflected peak: the larger the pulse, the smaller the peak (the reflection is averaged over a longer time). The choice of the appropriate pulse is the result of a careful trade off between the resolution and the available power (i.e. fibre length, see 4.2).

NOTE Further discussions on the same subject can be found in C.1.5 of IEC 60793-1-40.

5.1.4 Polarization effects

The OTDR includes a splitter that can act as a polarizer on the output pulses and an analyzer on the receive side of the reflected pulses. Other elements can also polarize the light. As a result of polarization mode dispersion (PMD) in the fibre, the Stokes vector of polarized light rotates about the Poincaré's sphere as it propagates through the fibre in both the forward and reflected directions. It also rotates with optical frequency or wavelength.

If the temporal OTDR pulse width and/or spectral width is sufficiently broad, the OTDR receiver yields the average of many Stokes vectors and the effect of varying polarization states is not seen. If these widths are reduced in comparison to the fibre PMD, or if the fibre PMD is low enough compared to these widths, fewer Stokes vectors are averaged and the apparent pulse magnitude can appear to vary with position along the fibre in a ripple pattern.

These apparent ripples can be reduced by rapidly varying the polarization of the source or by using a polarization scrambler or other appropriate devices.

5.2 Bi-directional trace

Bi-directional traces are obtained by suitably combining measurements taken by the two single ends of the fibre.

Starting from the expression of the backscattered optical trace (Equation 4), it is straightforward to calculate the bi-directional OTDR traces, applying the co-ordinates transformation *z*' = *L* - *z*, (where *L* is the total fibre length and *z*, *z*' indicate the same point taken on the two traces), thus obtaining:

$$10LogP_1(z) = const. + 20Log\left(\frac{\lambda}{\omega(z)}\right) - 2\alpha z \tag{6}$$

$$10LogP_2(z') = const. + 20Log\left(\frac{\lambda}{\omega(z)}\right) - 2\alpha L + 2\alpha z \tag{7}$$

P_1 and P_2 are the traces obtained from the two ends of the fibre. The two equations can be then summed or subtracted side-by-side, and the results, respectively *S* and *D*, are

$$S \propto 4Log\left(\frac{\lambda}{\omega(z)}\right) \tag{8}$$

$$S \propto 4Log\left(\frac{\lambda}{\omega(z)}\right) \tag{9}$$

Equations 8 and 9 show that the bi-directional approach allows, in principle, the separation of contributions due to variations of geometrical parameters of the fibre (the MFD ω) from contributions due to changes in the attenuation coefficients (α) of the fibre. Further details for the computation of S and D can be found in 5.2.1 and 5.2.2 below.

5.2.1 Attenuation uniformity[1)]

Attenuation uniformity is based on the bi-directional backscattering technique. The bi-directional back-scattering trace can be represented as a function, y(z), with y being the trace (in dB) and *z* being the position (in km). It is computed by reversing the position of each location of one of the uni-directional traces and computing the difference between the two uni-directional traces, divided by two, for each position. The bi-directional trace may be derived from multiple measurements or from appropriately filtered data having the same effect.

5.2.1.1 Sliding window

The uniformity parameter, X_A, is defined in terms of the sliding window (SW) algorithm, in which the attenuation coefficient is evaluated across a fixed sub-length, *SL*, (sliding window width) of the fibre, ideally sliding along the fibre starting from each of a set of positions: z_1, z_2. The attenuation coefficient values at those positions can be represented as:

$$A(z_i;SL) = \frac{y(z_i) - y(z_i + SL)}{SL} \tag{10}$$

Alternatively, the fitted slope of the trace at the defined positions may be substituted for the values of $A(z_i;\ SL)$. The uniformity parameter is the difference between the maximum of the

1 The text of this paragraph is an extract from Clause 7 of the more detailed Technical Report IEC 62033, *Attenuation uniformity in optical fibres*.

$A(z_i, SL)$ values and the average attenuation coefficient of the whole fibre, given by its end-to-end attenuation coefficient, α, as determined by any method in the IEC 60793-1-40:

$$X_A = \max[A(z_i; SL)] - \alpha \tag{11}$$

5.2.1.2 Generalised sliding window

The generalised sliding window (GSW) algorithm will provide coefficients, α_r, and ε_r such that for a defined range of SL:

$$Max\{A(z_i, SL)\} = \alpha_r + \frac{\varepsilon_r}{SL} \tag{12}$$

α_r is a baseline attenuation coefficient and ε_r is a loss penalty parameter that allows scaling non-uniformity with variable SW lengths. The GSW parameters may be used to compute the sliding window maximum in Equation 12 for a variety of sub-lengths, SL.

5.2.2 MFD uniformity

Combining the two traces P_1 and P_2 in the half-sum S(z)

$$S(z) = \frac{10Log_{10}P_1(z) + 10Log_{10}P_2(L-z)}{2} \tag{13}$$

the MFD as a function of the position, $\omega(z)$, can be easily calculated, inserting a reference fibre before the fibre under test with a known MFD, $\omega(z_0)$, at the position z_0, and neglecting longitudinal variations of α:

$$S'(z) = S(z) - S(z_0) = 20Log_{10}\frac{\omega(z_0)}{\omega(z)} \quad \Rightarrow \quad \omega(z,\lambda) = \omega(z_0,\lambda)10^{-\frac{S'(z,\lambda)}{20}} \tag{14}$$

5.2.3 Splice loss evaluation

It is difficult to evaluate a system loss budget by measuring splice losses, since there exist several different approaches and some of them can sometimes lead to misunderstandings.

One traditional method for measuring link loss is by an end-to-end light source power meter (LSPM) measurement, but note that this method does not provide fault location. For that type of problem or trouble shooting the OTDR plays an important part in evaluation of systems.

The basic backscattering principle makes the OTDR very sensitive to fibre MFD dependent light-coupling properties (see equation 3 above). Different fibres will intrinsically capture more or less backscattered light resulting in varying signal levels back to the OTDR.

Different here means different geometrical properties and not the manufacturing method. This means that the same fibre type can be manufactured by different technologies and are easy to splice to each other, provided the geometry is well controlled.

When two fibres with different MFD values are joined and measured with an OTDR, either an apparent loss or "gain" appears at the interface as shown from the following picture:

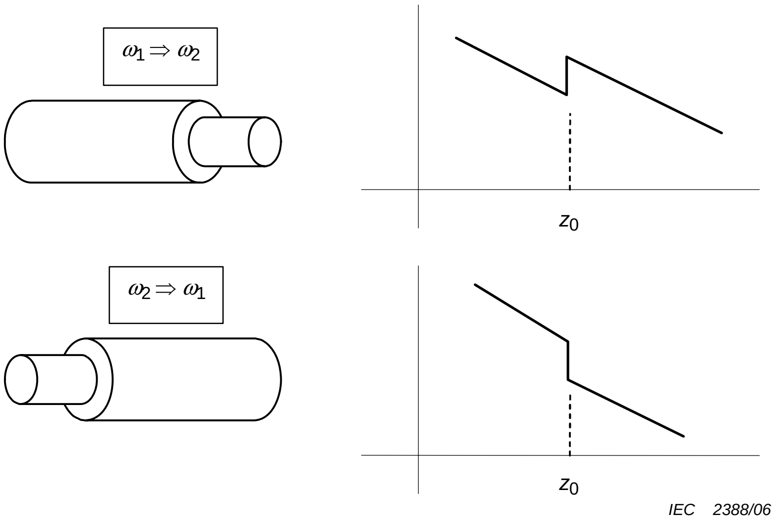

Figure 2 – OTDR traces for fibres with different MFD

This commonly known phenomenon is an artefact of the unidirectional OTDR measurement. The error component of measured loss is governed by the following equation,

$$\alpha_{\mathrm{OTDR}} = 10 \cdot \mathrm{Log}[\omega_2 / \omega_1] \qquad (14a)$$

ω_1 is the mode field radius for the first fibre (upstream) and ω_2 for the second fibre (downstream). For example, when the MFD's of the spliced fibres are 9,0 µm and 9,2 µm an apparent unidirectional loss/gain is present of 0,1 dB. This apparent loss does not have an effect on the system loss budget and should not be considered as splice loss. MFD differences do add a minimal additional loss to the splice but can be typically ignored due to its small order of magnitude. The actual loss contributed by the different MFD's is given by

$$\alpha_{\mathrm{mfd}} = -20 \cdot Log\left[\frac{2\omega_1\omega_2}{\left(\omega_1^2 + \omega_2^2\right)}\right] \qquad (14b)$$

For example, when the MFD values of the spliced fibres are 9,0 µm and 9,2 µm, the actual loss due to this MFD mismatch is only 0,002 dB.

Next equation shows each loss contributor to the unidirectional OTDR measured loss, where α_{others} includes attenuation due to core to core offset, tilt, and other loss mechanisms,

$$\alpha_{\mathrm{measured}} = [\alpha_{\mathrm{others}} + \alpha_{\mathrm{MFD}}]_{\mathrm{splice\ loss}} + \alpha_{\mathrm{otdr}} \qquad (14c)$$

To a first approximation and for MFD mismatch up to about 1 µm, α_{MFD} can be considered negligible, so the equation reduces to

$$\alpha_{\mathrm{measured}} = [\alpha_{\mathrm{others}}]_{\mathrm{splice\ loss}} + \alpha_{\mathrm{otdr}} \qquad (14d)$$

The most effective way of overcoming this measurement error is by taking bidirectional OTDR measurements. Therefore, the evaluation of a splice loss is carried out according to the following steps:

- Obtain the backscattering trace from the two opposite sides of the spliced fibres;
- Evaluate the step/gain G_1 and G_2 in the point z_0 where the splice is located: as shown above, G_1 and G_2 are composed by a term ($\Delta w = \alpha_{\mathrm{otdr}}$) depending on the MFD mismatch of the two fibres, and a term which is the proper splice loss ($\delta = [\alpha_{\mathrm{others}}]_{\mathrm{splice\ loss}}$);

- To extract the significant value, δ, compute

$$Splice - loss = \frac{G_1 + G_2}{2} = \frac{(\Delta w + \delta) + (-\Delta w + \delta)}{2} = \delta \tag{15}$$

Therefore, splice losses must be evaluated through the bi-directional average of the OTDR traces. This approach is however not always feasible in the field due to location and access restraints. If unidirectional OTDR measurements are to be used for splice loss evaluation, corrections based on the MFD's of each fibre must be used to offset the effect of α_{otdr}.

6 Uncertainties, deviation and resolution

Attenuation coefficient measurements and fault location with an OTDR can be characterised in terms of uncertainties, deviation and resolution, generally defined as follows:

- One part of uncertainties is the spread of values, resulting from repeated measurements, around a target value; for a large number of measurements following a Gaussian distribution, it is the standard deviation around the average.
- Deviation indicates the difference between the measurement output (or the average for multiple measurements) and the true, or accepted, or reference, value. Deviation can be corrected with calibration, see IEC 61746.
- Resolution is the ability to separate fine details in the measurement

6.1 Attenuation coefficient measurements

Uncertainties associated to the attenuation coefficient measurements with an OTDR can be affected by the duration of the measurement (i.e. the number of averaged backscattered signals) and in general by the amount of backscattered power, in turn depending on the fibre length and the coupling loss (see also 4.2). Under appropriate conditions, the uncertainties of a measured attenuation coefficient can be as low as few thousandths of dB/km.

Accuracy of attenuation measurements depends on the calibration status of the equipment. It should also be noted that different OTDR can have different source wavelengths, and their measurements will therefore be different.

Resolution of attenuation coefficient measurements can be associated with the minimum significant decimal place of the measurement, i.e. 1 thousandth of dB/km.

6.2 Fault locations

A break or impurity in a fibre, or a coupling between two fibres, may appear in the OTDR trace as either a feature with higher reflectivity, a higher loss, or both. By means of the relation between the back-and-forth propagation time ($\tau/2$) and the distance (x) through the speed of light in the fibre (v):

$$\frac{\tau}{2} = \frac{x}{v} \tag{16}$$

it is possible to identify the location (x) of the defect. It must be noted also that $v = c/n$, where n is the effective group index of the fibre.

Deviation and uncertainties of a measured fault location can be affected by the quantity of backscattered power and by the uncertainties related to the fibre group index which is only approximately known: however, for typical applications, an approximate evaluation of the defect position is acceptable.

Resolution can be considered as a combination of the capacity to detect a “small” fault and the minimum possible distance between two detectable consecutive defects. Generally speaking, a defect so small as to be negligible to the OTDR will also be negligible to system operation. For two detectable consecutive defects, more consideration is necessary.

We consider the schematic drawing of a fibre with two consecutive defects 1 and 2:

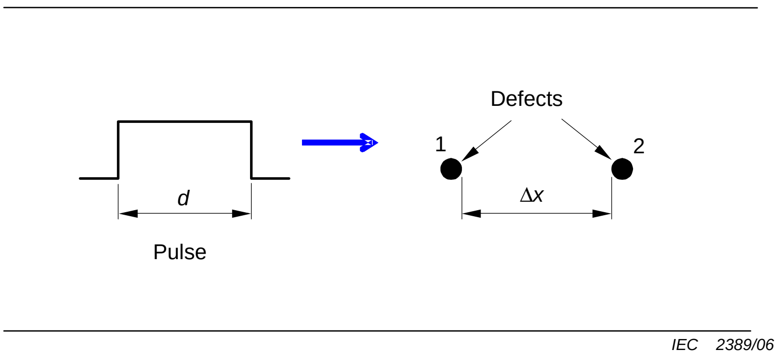

Figure 3 – Schematic drawing of a fibre with two consecutive defects 1 and 2

The pulse duration *d* can be expressed, in the time co-ordinate, as

$$\Delta t = \frac{d}{v} \tag{17}$$

v being the light velocity in the fibre; the time which the light takes to go from 1 to 2 is

$$\tau = \frac{\Delta x}{v} \tag{18}$$

In order to make the two defects detectable, the pulse back-reflected by 2 must reach the OTDR when the pulse back-reflected by the defect 1, which persists for a time Δt, has been totally received by the OTDR; this condition can be expressed as

$$2\tau > \Delta t \tag{19}$$

The factor 2 in this expression appears because the incoming pulse must arrive to the second defect before being reflected back: therefore it has to cover the distance Δx two times. Remembering that $v = x/t$, the previous expression can be easily translated in the following space-domain relation:

$$2\Delta x > d \tag{20}$$

which is interpreted as: “*two consecutive defects are detected separately by an OTDR if, and only if, their distance is larger than half the OTDR pulse-width*”; for instance, in a measurement using a 10 µs pulse, which covers a length d ~ 2 km, two consecutive defects are separated on the OTDR trace if their distance is greater than (or equal to) 1 km.

NOTE This value comes from $d = \Delta t \cdot v = \Delta t \cdot (c/n)$ where c is the vacuum light speed, approximatively 3 x 10^8 m/s, and n is the refractive index of the fibre, approximatively 1,5; therefore d~10 x 10^{-6} · 3 x 10^8 / 1,5 = 2 x 10^3 m = 2 km.

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IEC 62033:2000, *Attenuation uniformity in optical fibres*

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