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The Influence of Coatings on the Fracture Behaviour of Optical Waveguides

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The life of optical waveguides (OWG) has not been dealt with any great length in the fibre-optics literature, but has cropped up repeatedly in discussions over the past 15 years. Indeed, no reliable calculation method has yet been put forward that could be adequately corroborated by experimental results. This leads to considerable problems in designing communication cables with optical waveguides, since a life expectancy of 20 to 30 years must be specified for these. The problem complex here lies in the OWGs, which are made of glass and are hence fragile.

The loads on a communication cable can be readily understood, if we consider that a so-called duct cable must be pulled into ducts, and that considerable tensile forces must often be exerted, of which about half is permanently retained as a result of friction. Aerial cables suspended between poles are not only permanently under stress of gravity, but are also additionally stressed by temporary wind and ice loads.

The difficulty of predicting the life of OWG cables lies in our ignorance of the flaw distribution over the length of an OWG. This is a statistical problem, for the probability of the existence of a flaw is greater, the longer the OWG.

In practice, OWG lengths of many hundreds of kilometers must be taken into account. This is shown by the examples of a local subscriber cable with a mean length of 5 km and 50 OWGs = 250 km and of a submarine cable containing 10 OWGs and bridging 150 km without repeaters, resulting in OWG lengths of 1500 km. These figures immediately show that life expectancy cannot be determined directly by experiment. Investigations are necessary, from which it is possible to extrapolate. To obtain initial information about the strength of OWGs, tensile testing is often performed. OWG specimens are stressed at a constant rate until breakage occurs. With 100 specimens, 100 values for forces at break are obtained, which are scattered be-

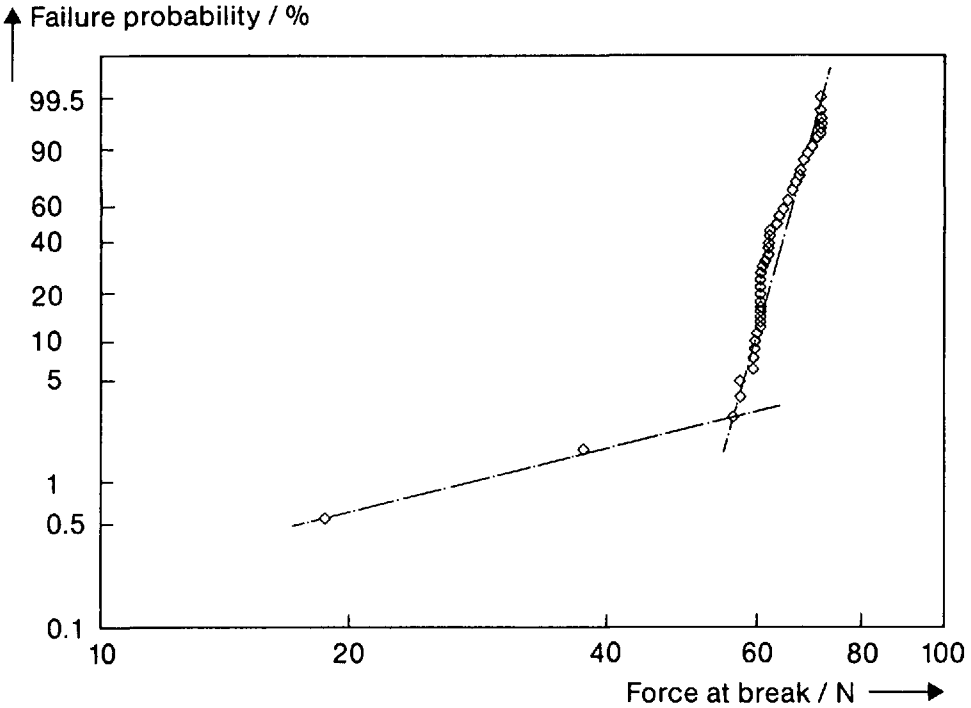

Fig. 1. *Tensile test with OWG* l = *20 m*. Test velocity: 800 mm/min.

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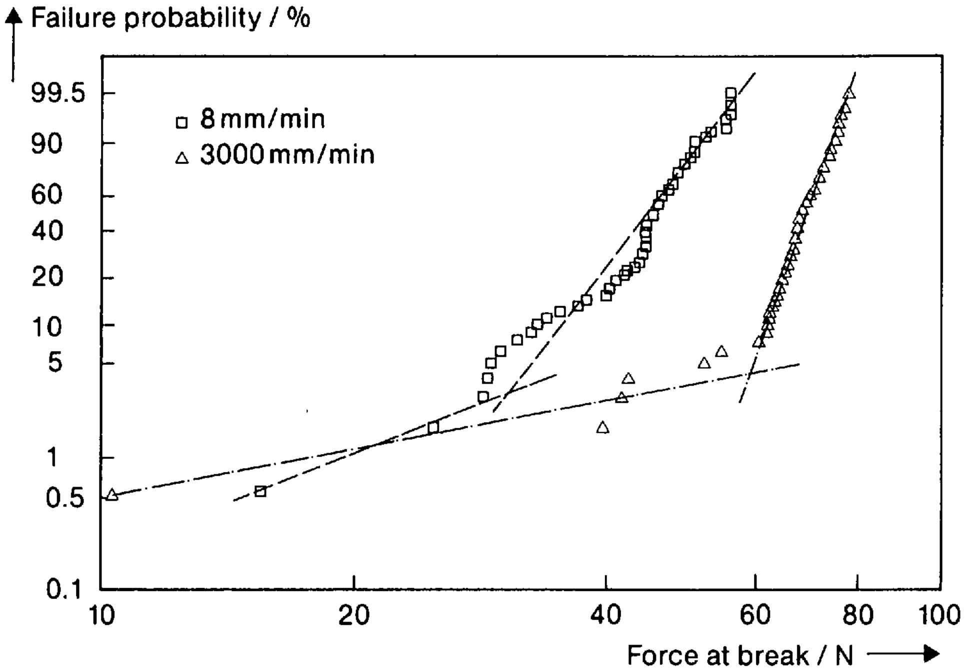

Fig. 2. *Tensile test with OWG* l = *20 m.* Influence of test velocity.

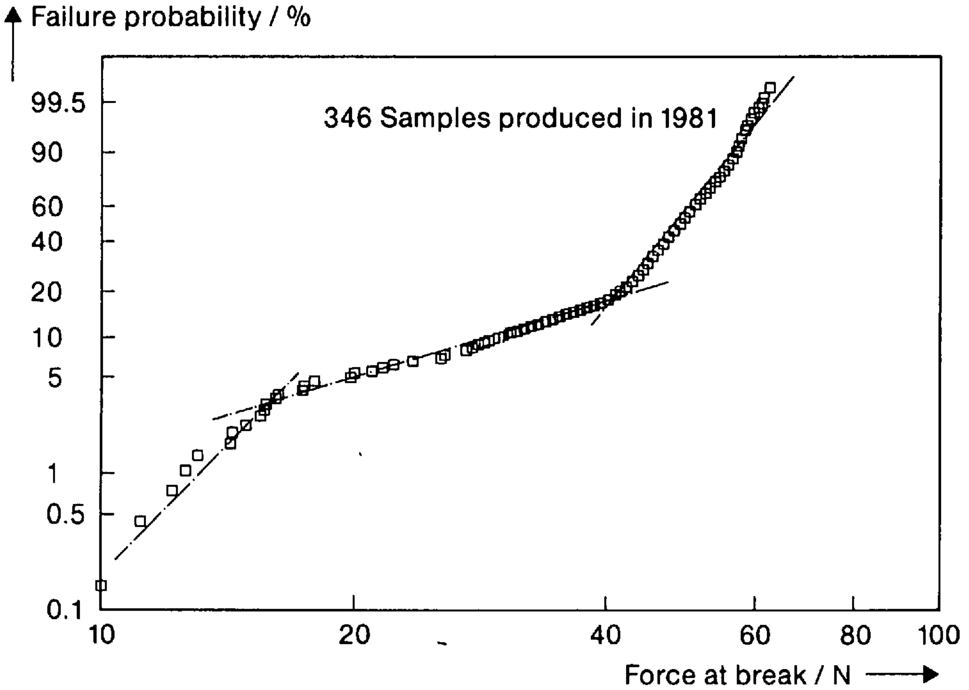

Fig. 3. *Tensile test with OWG* l = *0.9 m.* Test velocity: 45 mm/min.

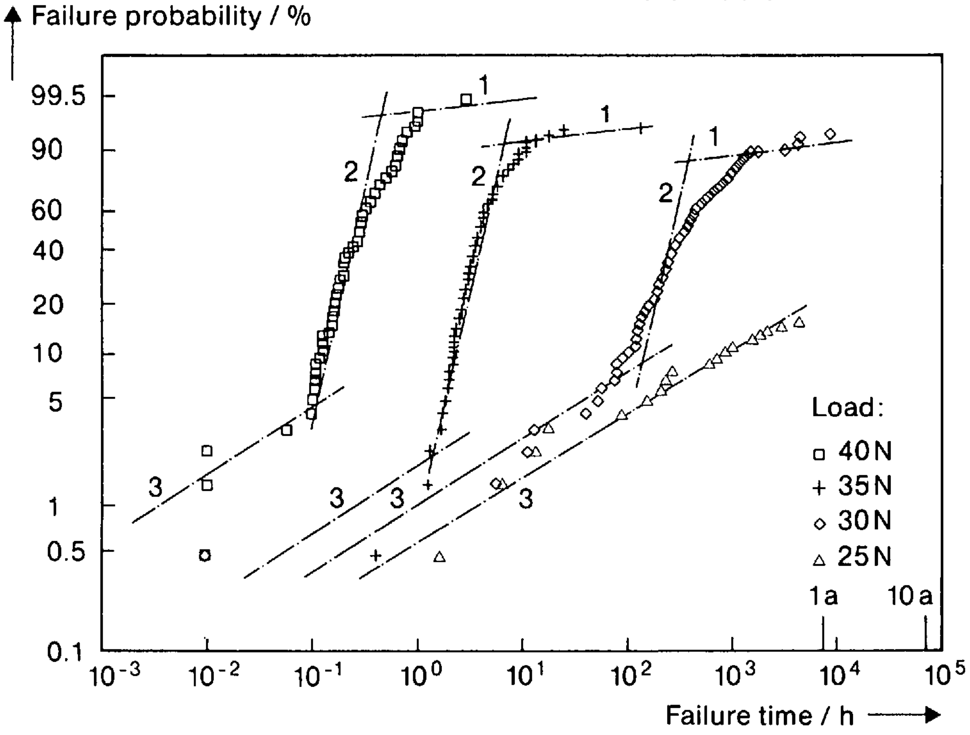

Fig. 4. *Static fatigue of OWG in air 8-m samples*

tween a minimum and a maximum. These forces at break must be handled by statistical methods. Since this is a breakage process, it is appropriate to apply *Weibull* statistics. *Weibull* developed a statistical method for breakage processes, by which the failure probability, plotted against the force at break, gives a straight line. The *Weibull* equation states:

$$P = 1 - \exp - ((l/l_0) \cdot (F/F_0)^m \cdot (t/t_0)^{(m\,n)}) \quad (1)$$

where
P = failure probability
l = length of OWG
F = force at break
t = time to fracture
l_0 = length of test specimen of the experimental distribution
F_0 = 63.2% force at break of the experiment distribution
t_0 = time to fracture of the 63.2 force at break
n,m = exponents for matching to the experimental distribution, where n is the so-called stress corrosion constant.

To represent the dependence on the force at break by a straight line, *i.e.* linearly, the equation (the fracture time is initially not taken into account and the OWG length l is made equal to the test specimen length l_0) is twice logarithmated to obtain

$$\log \ln 1/(1 - P) = m \cdot \log (F/F_0) \quad (2)$$

The failure probability P is calculated by

$$P = (2i - 1) / (2 \cdot N) \quad (3)$$

where i is the consecutive number of the ordered forces at break and N is the number of test specimens.

An experimental graph for 100 test specimens with a length of 20 m, fractured with a test rate of 800 mm/min is shown in *Fig. 1*. For high failure probabilities, the test points form a straight line in first approximation. For low failure probabilities, the straight line bends away and forms what could be imagined to be a second straight line with a much lower slope. This formation of a second straight line does not make itself known in most publications, as their results are based on too few test specimens. Distributions with a sufficiently large number of specimens, however, always exhibit different slopes, as is

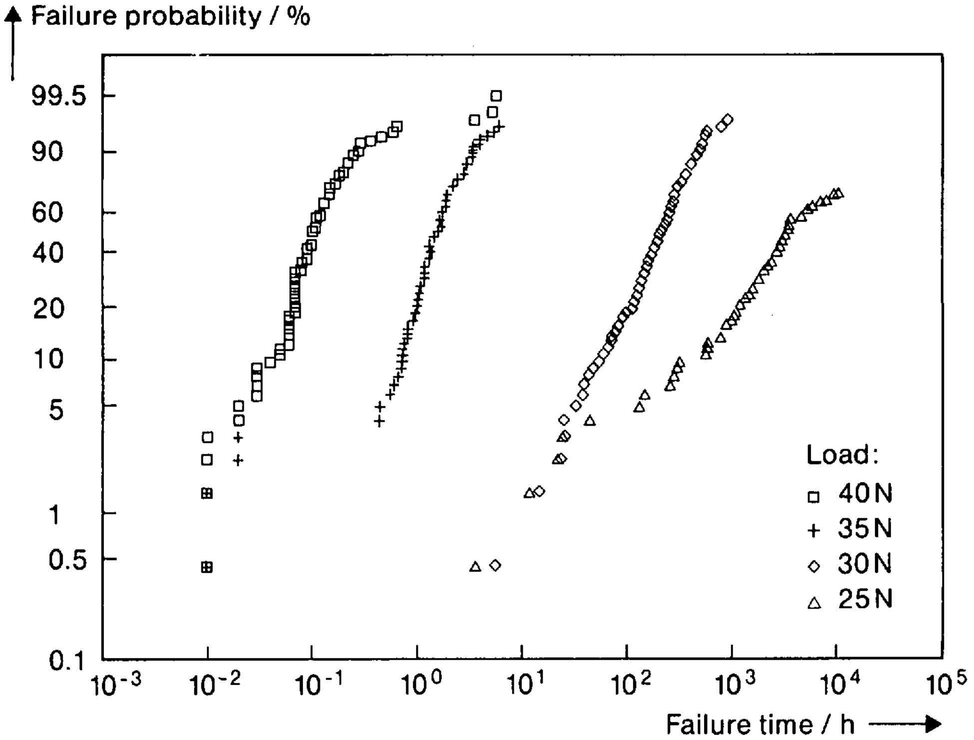

Fig. 5. *Static fatigue of OWG in H_2O 8-m samples*

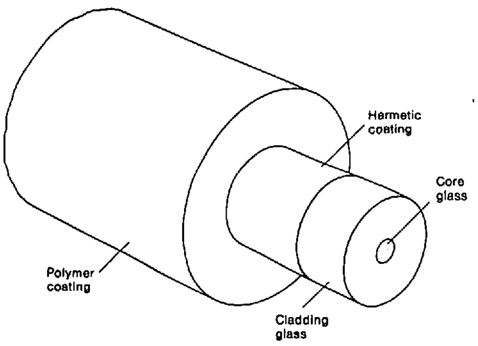

Fig. 6. *Structure of cornings hermetic coated fiber*

evident from *Fig. 2* for tensile tests with two different testing rates. For experiments with an even larger number of specimens, there follows, with very low failure probability, another region with a high slope (see *Fig. 3*, distribution of older OWGs, which illustrates this curve shape). The total distribution forms an S-shaped curve that can be divided into three linear regions. These three regions embody different crack growth mechanisms, which are examined in detail in the following. *Fig. 2* clearly shows that the forces at break decrease at lower test rates, *i.e.* an OWG stressed for a longer time breaks due to crack growth during the stress time at lower forces at break than a briefly stressed OWG.

The mechanisms of crack growth can be studied better with fatigue tests; these are tests in which constant weights are suspended from OWGs, and the time until breakage is measured. These test results are shown in *Fig. 4*. Here, groups of 110 test specimens each with a length of 8 m were stressed with weights between 25 N and 40 N. The ambient medium is air. The plotted values, even though plotted according to *Weibull*, do not form straight lines. As in the tensile tests, an S-shaped curve is again perceptible, which, with a little imagination, can be approximated by three straight lines (*Fig. 4*). The straight lines for low failure probabilities have low slopes (this region shall be designated region 3), for medium failure probabilities hish slopes (region 2) and for high failure probabilities again low slopes (region 1). For the distribution for 25 N load, only region 3 is pronounced. The majority of test specimens did not break, and will after a period of years form the two other branches of the distribution (regions 2 and 1). It can be assumed that the slope of region 3 of the 25-N distribution can be transferred to the other loads.

Wiederhorn and coworkers [1] have performed crack velocity measurements on solid glass specimens (not OWGs) and have likewise ascertained three regions with different crack growth mechanisms. In region 1, which is characterized by low stresses and small flaws, crack growth is governed by a chemical process. This occurs at the crack tip with water, which chemically reacts here and widens the crack [2]. It is assumed that in region 1 the cracks are not deep and the crack growth rate is low, so that there is always enough water at the crack tip. In region 2, characterized by medium stresses and flaws, the crack growth rate is higher than the rate of transportation of water by diffusion to the crack tip. Crack growth is here governed by the diffusion and, hence, delayed. In region 3, characterized by high stresses and

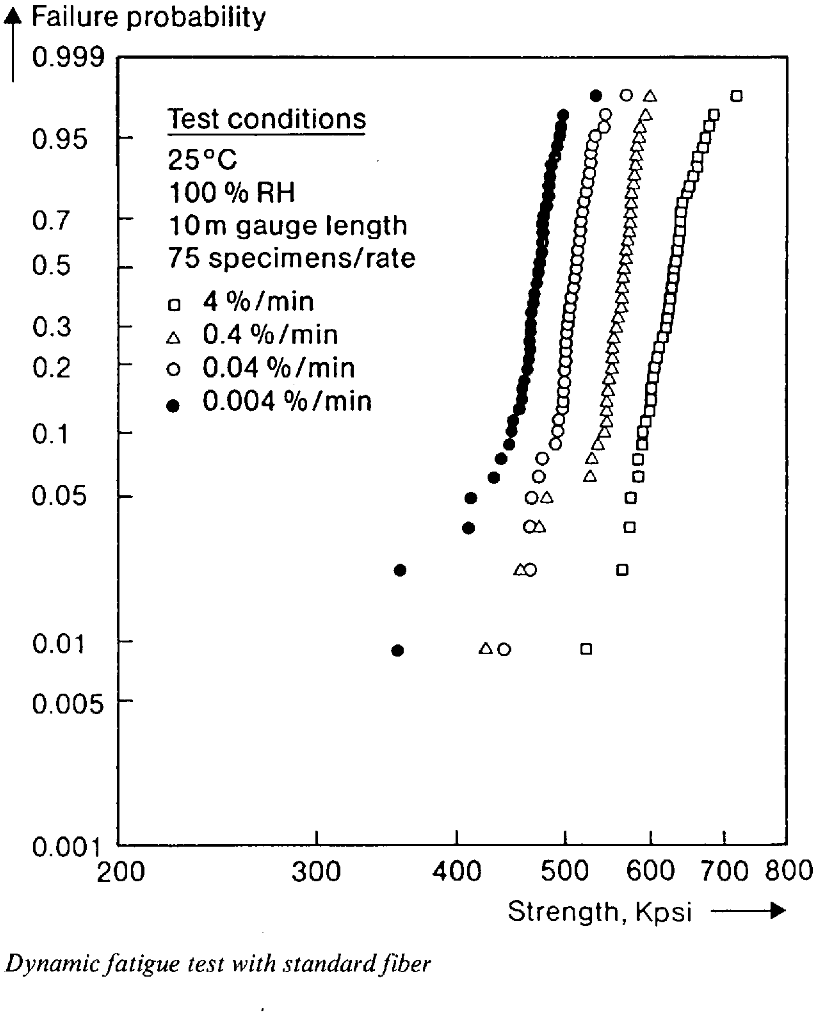

Fig. 7. *Dynamic fatigue test with standard fiber*

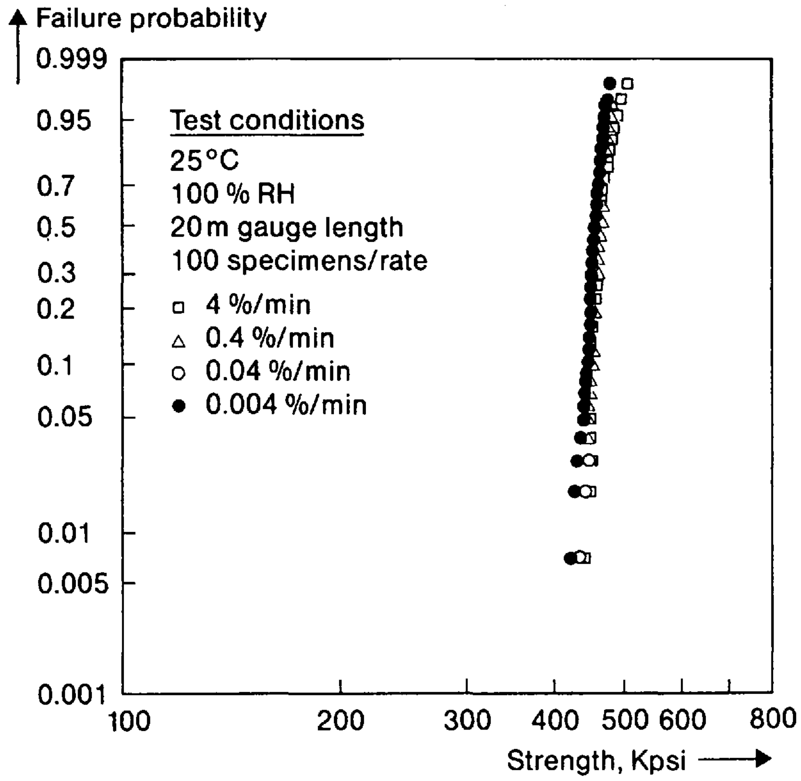

Fig. 8. *Dynamic fatigue test with hermetic coated fiber*

coarse flaws, breakage occurs – independently of chemical reactions and diffusion – probably due to electrostatic processes, a so-called forced rupture.

In parallel with the fatigue tests in air, fatigue tests were also performed on samples stored in water (tap water). The test results are similar to those obtained from the creep tests in air, with the difference that the curves are shifted towards shorter fracture times (*Fig. 5*). This can be explained by the circumstance that the liberal supply of water – absorbed by the plastic coating of the OWG – that waits in front of the crack to be transported by diffusion, accelerates the crack growth. With this in mind, it can now well be imagined that by applying a coating that absorbs no water, or allows no water to permeate, crack growth can be considerably delayed, or even prevented. With application of a hermetic coating, crack growth can only be promoted by the water enclosed under the coating, which reaches the incipient cracks by transportation along the OWG. If the coating is applied direct to the silica glass structure, which, for reasons of optical conductivity, must contain extremely little water, it must be possible to keep crack growth negligibly low.

Such an OWG with hermetic coating was developed by the industry [3] [4]. The design of the hermetic fiber developed by *Corning*, USA (*Fig. 6*), differs from the standard fiber only in its water-vapour impermeable (hermetic) coating of amorphous carbon with a thickness of about 1000 Å, which is applied direct to the cladding glass of the OWG. The plastic coating is retained for mechanical protection of the OWG surface. To check the effectiveness of the hermetic coating, tensile tests were performed with different test rates. For fast breakage, where the water was allowed no time to penetrate to the crack tip, and for slow breakage, where the water was allowed sufficient time to reach the crack tip by diffusion, there must have been evidence of fracture-force differences in the presence of water. In the absence of water – excluded by the hermetic coating – no fracture-force difference must have occurred. The experimental results, shown in *Figs. 7* and *8*, show exactly this situation. The fracture forces of the hermetic fiber for tensile tests with widely different test rates are constant. There is no crack growth during the stress period. Fatigue tests with the hermetic fiber would probably lead to great difficulties, for it may be assumed that, under severe stresses, they would show very short fracture times due to forced rupture, and, under low stresses, they would lead to practically immeasurable, theoretically infinitely long fracture times, if not even hitherto unknown fracture mechanisms come to light.

The investigations have shown that the breakage behaviour of OWGs depends on the crack growth of incipient cracks, caused by a chemical reaction with water at the crack tip. By excluding water with a hermetic coating, the crack growth can be minimized.

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