TWO - STAGE MECHANISM OF STRIATED DISINTEGRATION OF FUSE - WIRE

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Abstact: Up to now in the open literature there is a conviction that fuse-wire shows one stage disintegration by striation. It is not the case in reality. The paper pushes forward an idea about a two stage striation. Each stage: primary and secondary, has got its own modulus. For primary striation that modulus is several times shorter than for secondary one. In the paper a developed analitical explanation of both stages is given and compared with experimental observations. An analitical approch is based on MHD equations plus an equation of state of the liquid conductor metal.

1 Introduction

Investigations show clear, that interrupting a short-circuit the fuse-wire disintegrate by striation [1,2,5,6,10,11,12,13,14]. On the other hand, drop, segment and chaotic disintegrations have taken place due to the overload and moderate short-circuit currents breaking [5,10,12]. Hitherto research does not give a univocal identification of the striation [2,9,10,12,13,14]. Hibner's experiments [5,6] suggest that such striation occurs if the maximal current density in the fuse element fulfils the conditions:

- for wire fuse-elements

$$j_m \geq \frac{4.3}{d^{0.68}} \quad \left[\mathrm{kA/mm^2}\right] \tag{1}$$

- for strip fuse-elements

$$j_m \geq \frac{4.6}{A^{0.29}} \quad \left[\mathrm{kA/mm^2}\right] \tag{2}$$

in which: d - wire diameter in mm, A - cross - sectional area of strip in mm^2.

The main feature of striation is modulus, which established experimentally is:

- Nasiłowski's for wires [10,11]

$$h_w = 0.555 + 2.08\,d \quad [\mathrm{mm}] \tag{3}$$

- Hibner's for strips [5,6]

$$h_s = k_c\,A^{0.3} \quad [\mathrm{mm}] \tag{4}$$

where: $k_c = 3.1\ \mathrm{mm^{0.4}}$ - empirical constant.

Both relations (3) and (4) are based on sand fuse fulgurite inspections, which on the other hand does not exist if a striation in the open space occurs. In such case on ultra rapid X - ray photography [3,4], shows that striation appears if $j_m \approx 5 \div 1000\ \mathrm{kA/mm^2}$. The modulus in the last case is several times smaller than one suggested by (3) and (4) (**Table 1**). The reason of so greate differences is in different kind of that modulus determination. Namely, the instants of modulus observation in sand fuses and in open space in experiments are dramatically shifted: in fuses the observation is statical after final current interruption, whereas in open space the observation is dynamic and has just taken place before wire disintegration. Arai investigations [1,2] indicate, that striation in the wire fuses demonstrate 2-stage process (**Fig. 1**). During the first one, which is over the pre-arcing period, primary striation arises within modulus analogous to that but if a wire disintegrates in the open space. The second stage, during arcing in a fuse. Now arise a secondary distribution within cousiderably longer modulus. The last one led on to the fuse-wire distribution moduli described by (3) and (4). 2-stage process distincly demonstrated in Fig. 1 has got more complicated nature than that up to now has been considered.

So, the aim of the paper is to make an attempt in explanation of 2-stage wire striation.

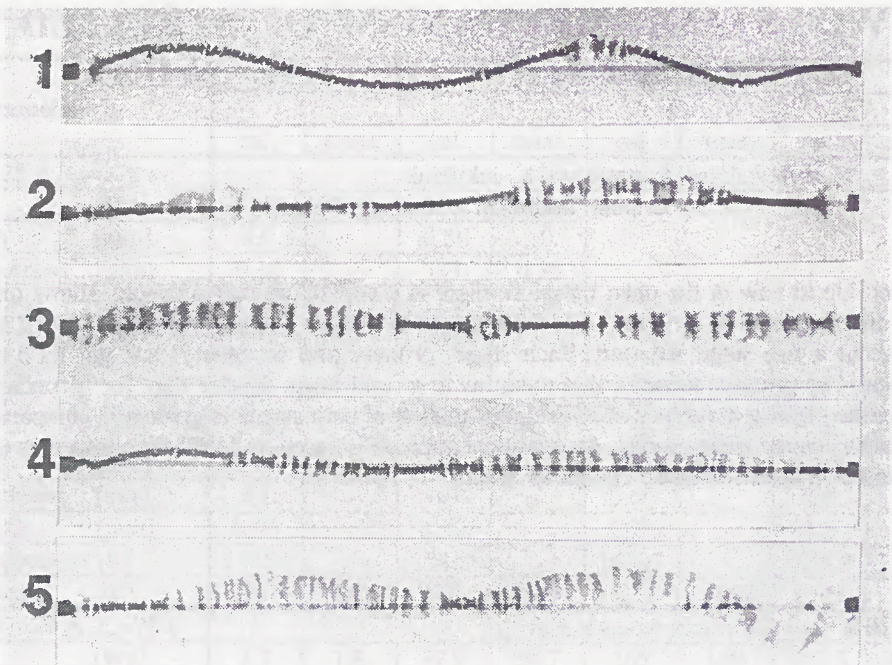


Fig. 1 X-ray photography of consecutive phases of striation disintegration, Ag - wire d = 0.4 mm, l = 50 mm in sand, $j_m = 11\ kA/mm^2$ [1,2]. Pictures shots are taken 1 ms later than disintegration peak voltage. Time distances from that peak are: 1 - 7 μs, 2 - 17 μs, 3 - 21 μs, 4 - 24 μs, 5 - 28 μs.

2 Physical and mathematical models of striation

2.1 Primary striation

Primary striation, arising during pre-arcing period, runs along there consecutive periods disintegration it self. The heating up process last from the current beginning up to the complete wire liquifaction. Due to in homogeneous geometry and structure of a conductor and unequality in its melting, along that conductor are arising stochastically distributed surface perturbations. The perturbations indicate small amplitude, of order 1% of the dimension of the cross-sectional area, - and can be analysed as Fourier's series [9,16]

$$r_p(z, t_0) = R + \sum_{n=1}^{\infty} \delta R_n(t_0) \cos(k_n z + \psi_n) \tag{5}$$

in which: R - radii of wire, t_0 - instant of the complete wire liquifaction, $r_p(z,t_0)$ - equation of the conductor side surface in instant t_0, $\delta R_n(t_0)$ - disturbance amplitude of wave number k_n in instant t_0, ψ_n - phase of angle of wave number k_n.

In turn, the deformation lasts since complete conductor liquifaction up to the arriving in it thermodynamic parameters of a spinodal. This parameters $\frac{\partial p}{\partial V}|_T > 0$ means termodynamic instability of overheated conductor liquid. In doing several simplifications of the MHD-equations relating to the liquid displace of conductor one can formulate them as fallows [9,16]:

- equation of uncompressible liquid continuity

$$\nabla \cdot \mathbf{v} = 0 \tag{6}$$

- displacement equation (Navier-Stokes)

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \eta \nabla^2 \mathbf{v} \tag{7}$$

- energy equation

$$\rho \frac{d}{dt}\left(cT + \frac{v^2}{2} \right) = \frac{j^2}{\sigma} \tag{8}$$

• equations of electromagnetic field

$$\nabla^2 \mathbf{B} + \mu\sigma\left[\nabla\left(\frac{1}{\mu\sigma}\right) \times (\nabla \times \mathbf{B})\right] = 0 \tag{9}$$

$$\mathbf{j} = \frac{1}{\mu} \nabla \times \mathbf{B} \tag{10}$$

where: ρ - density, p - pressure, **v** - vector of velocity, **B** - vector of magnetic induction, **j** - vector of current density, η - absolute viscosity, σ - conductivity, μ - magnetic inductive capacity, c - specific heat, T - temperature.

The equations (5) -(10) ought to be completed by the equation of the liquid metal state and by relation of the metal properties: c (T), η (T) and σ (T) on the temperature.

In this manner the problem formulated was solved by finite-diffrence method using Crank-Nicolson approach [8,15]. The position of free conductor surface was defined by marked particles method [9,15]. The equations set (5) - (10) was solved many times for initial surface perturbations defined by the consecutive k_n (5) numbers. The exemplary results are shown in Fig. 2.

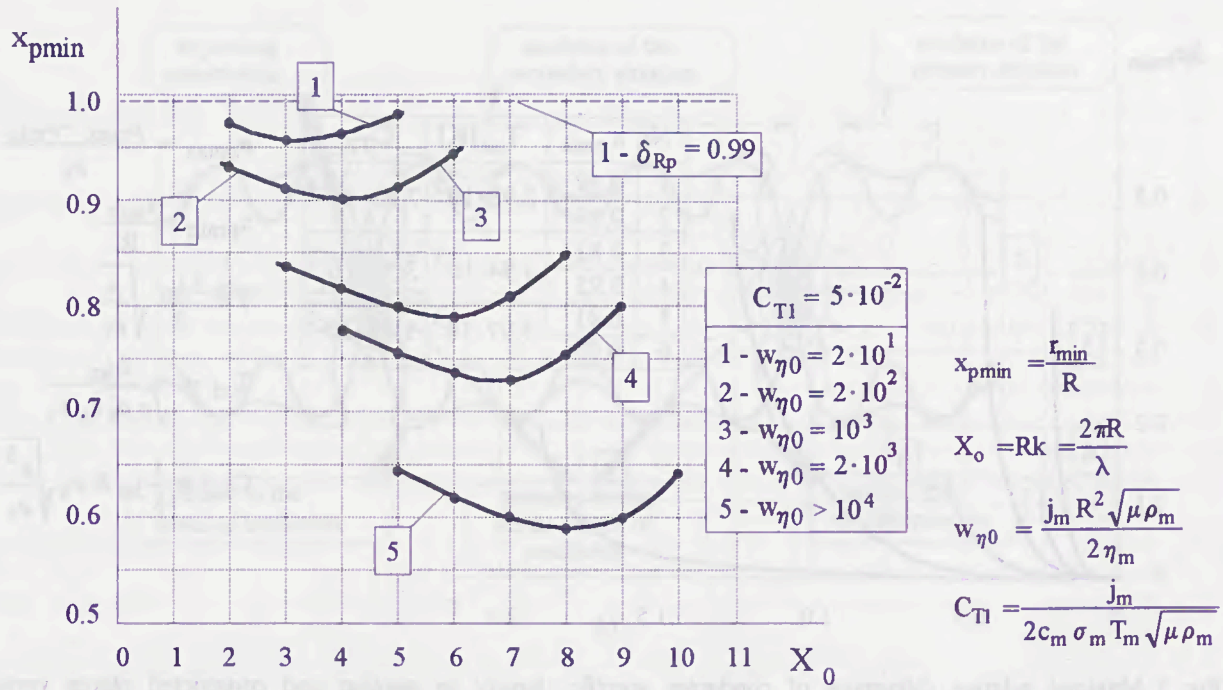


Fig. 2 Minimal radii of deformed conductor versus wave number of different values of p.n. parameters $w_{\eta 0}$ and C_{T1} and various initial perturbations $\delta_{Rp} = \delta Rp/R = 0.01$ calculated for instant of reaching of parameters of spinodal

The calculation demonstrate, that, for a given current density j_m as well for a defined radius R and metal properties ρ_m, η_m, σ_m in the melting temperature T_m, there is a distinguished perturbation wave lenght of which amplitude rises most quickly. For current densities $j_m \approx 5 \div 50$ kA/mm^2 the conductor deformation can be so significant, that in constrictions the radius is approaching zero.

When arriving spinodal parameters the metal gets instability and starts a disintegration lasting up to the maximum overvoltage across the conductor. Now begins the disintegration according to the MHD low. Assuming, as in many eleborations on the wire explosions, e.g. [9], that the disintegration velocity is given by

$$v(r,t) = v_R(t)\frac{r}{R} \tag{11}$$

in which: v_R - liquid velocity on the wire surface,

the MHD equations one can present in a simplifie from [9]:

- equation of uncompressible liquid continiuity

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot \mathrm{v} = 0 \tag{12}$$

- Navier - Stokes equation

$$\rho \frac{\partial \mathrm{v}}{\partial t} = -\nabla p + \mathbf{j} \times \mathbf{B} \tag{13}$$

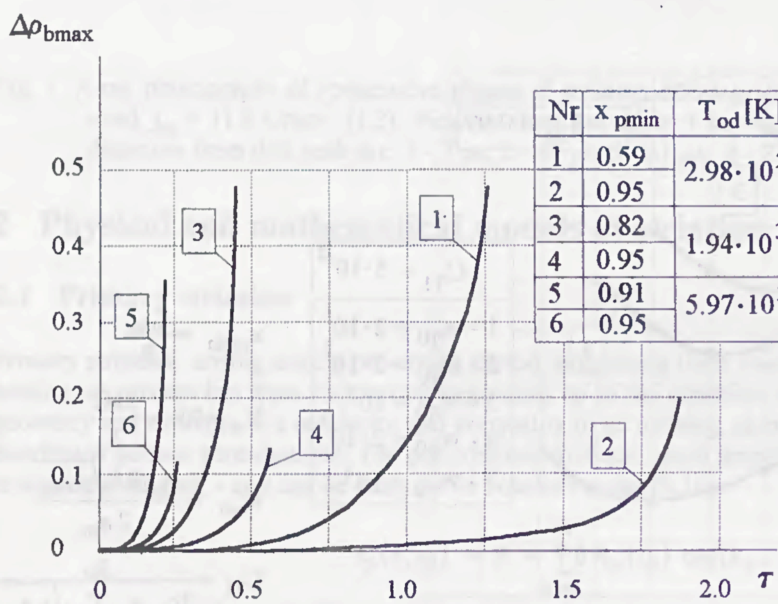
- energy equation

$$\rho \frac{d}{dt}\left(c\,T + \frac{v^2}{2} \right) = \frac{j^2}{\sigma} \tag{14}$$

- electromagnetic field equation

$$j = \frac{i_m}{A} \tag{15}$$

Of course, above equations shall be completed by the equation of state and relations on conductivity versus temperature and density [9]. Bearing in minde the relation (11) the last four equations one can rewrite in form of normal nonlinear differential equations. Finally the equations (12) - (15) were solved by predictor - corrector method with iterations [8,15]. Exemplary results are given in the **Fig. 3**.



Nr	x_{pmin}	T_{od} [K]	C_{T2}
1	0.59	$2.98 \cdot 10^2$	$7.10 \cdot 10^{-4}$
2	0.95		
3	0.82	$1.94 \cdot 10^3$	$3.55 \cdot 10^{-3}$
4	0.95		
5	0.91	$5.97 \cdot 10^3$	$1.42 \cdot 10^{-2}$
6	0.95		

$$\rho_{bmax} = \frac{\rho_{max} - \rho_{min}}{\rho_s}$$

$$x_{pmin} = \frac{r_{min}}{R}$$

$$\tau = \frac{t\, j_m}{2} \sqrt{\frac{\mu}{\rho_s}}$$

$$T_{od} = \frac{2\, j_m}{\sqrt{\mu\, \rho_s}\, c_s\, \sigma_s}$$

$$C_{T2} = \frac{1}{8} j_m R\, \sigma_s \sqrt{\frac{\mu^3}{\rho_s}}$$

Fig. 3 Maximal relative diferences of conductor specific density in swollen and constricted places versus time for exemplary parameters x_{pmin}, T_{od} and C_{T2} (s - property of spinodal parameters)

Table 1 Juxtapposition of experimental and analytical results

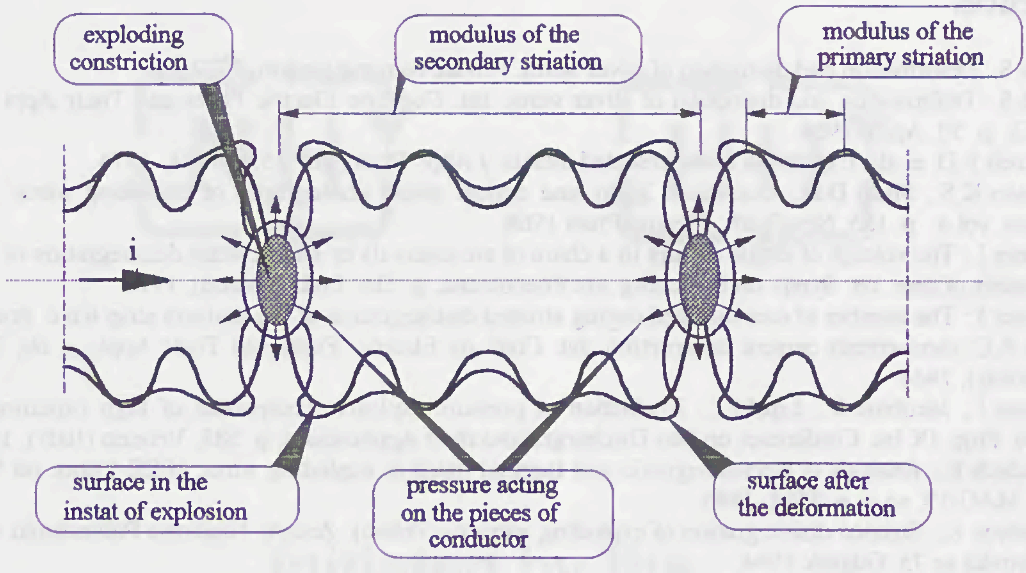
Material	Diameter [mm]	j_m [kA/mm^2]	Primary modulus of experimental [mm]	Kind of striations	Source	Calculation modulus of primary striation [mm]	Modulus calculated after the formula (3) [mm]
Ag	0.3	8.2	0.31	primary ,secondary	[2]	0.27	1.18
Ag	0.5	6.0	0.36	primary, secondary	[2]	0.38	1.60
Ag	0.5	12.0	0.24	primary, secondary	[1]	0.28	1.60
Cu	0.625	170.0	0.23	primary	[4]	0.22	1.85
Cu	0.625	260.0	0.20	primary	[3]	0.19	1.85

Results show that, as a result of deformation, the constrictions fulfil the condition $x_{pmin} < 0.95$, at current densities $j_m \approx 5 \div 50$ kAmm^2, the relative density differences in Fig. 3 are at least 45 %. It can be considered as the primary disintegration.

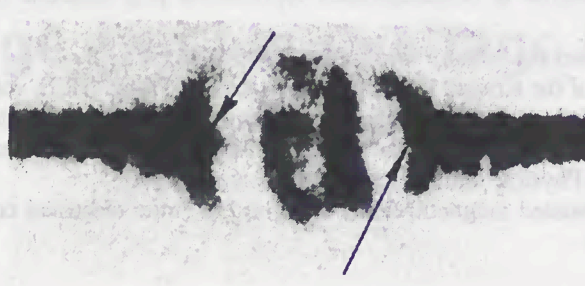
Comparisons the results of experiments with the results of calculations by presented method and with the results of calculations after the formula (3) are given in the table 1.

2.2 Secondary striation

Obove analyses and experiments [1,2,9] suggest at that $j_m \approx 5 \div 50$ kA/mm^2 the conductor deformation is considerable. It can even get a local break in the continuity of conductor. Because of densities are not relatively so great the deformation lasts relatively long. As a result the constrictions are not arising simultaneously [1,2,9], consequently the spinodal parameters are ariving first in the smallest cross - sections whereas the disintegration starts earlier. During the explosions of such smallest cross - sections it generates a significantly higer pressure [7]. Finally in here arcs are ignited. Two pressures now are acting on the pieces of conductor: just mentioned exploding pressure and arcing one (Fig. 4). Demonstrated secondary striation in Fig. 4a, seems, that it is confirmed by the X - ray image in Fig. 4b. Secondary striation modulus is two to five times longer than modulus of primary striation.



a)



b)

Fig. 4 Secondary striation mechanism:
a) sketch for explanation of mechanism,
b) magnified fragment of X - ray image on Fig. 1(3)

Carried out endeavourings to eleborate an analytical model of just mentioned processes gave not yet a satisfactory result, because physical phenomena are very complicated. The problem is still under considerations.

3 Conclusions

- A reason, why striation moduli defined experimentally (3) and (4) and hitherto by theoretical approaches, is a very simplified disintegrating mechanism taken into account. In those approaches only one mechanism was taken as deciding on striation. Above considerations show clear that in reality decides a combination of various phenomena leading in fact to two - stage striation.
- Two - stage striation is valid for maximal current densities in the range $j_m \approx 5 - 50$ kA/mm^2. The stage one appears over post - arcing period, whereas the second one during arcing. The secondary striation modulus is much longer ($2 \div 5$ times) than that of primary one.
- By the curent density $j_m \approx 5 - 1000$ kA/mm^2 striation is limited to one - stage only. It can be observed in exploding conductors in open space. The final modulus of striation is exactly as one - stage modulus.
- Primary striation is due to MHD deformation of liquifield conductor. In this the main phenomena are: magnetic pinch, mass inertia and viscosity of metal. Reaching spinodal parameters an overheated metal gets a thermodynamical instability and disintegrates.
- The secondary striation arises on the base of the primary striation. Deciding factor is an interaction between exploding constrictions and burning arcs between the fuse - element fragments being in an overheated state

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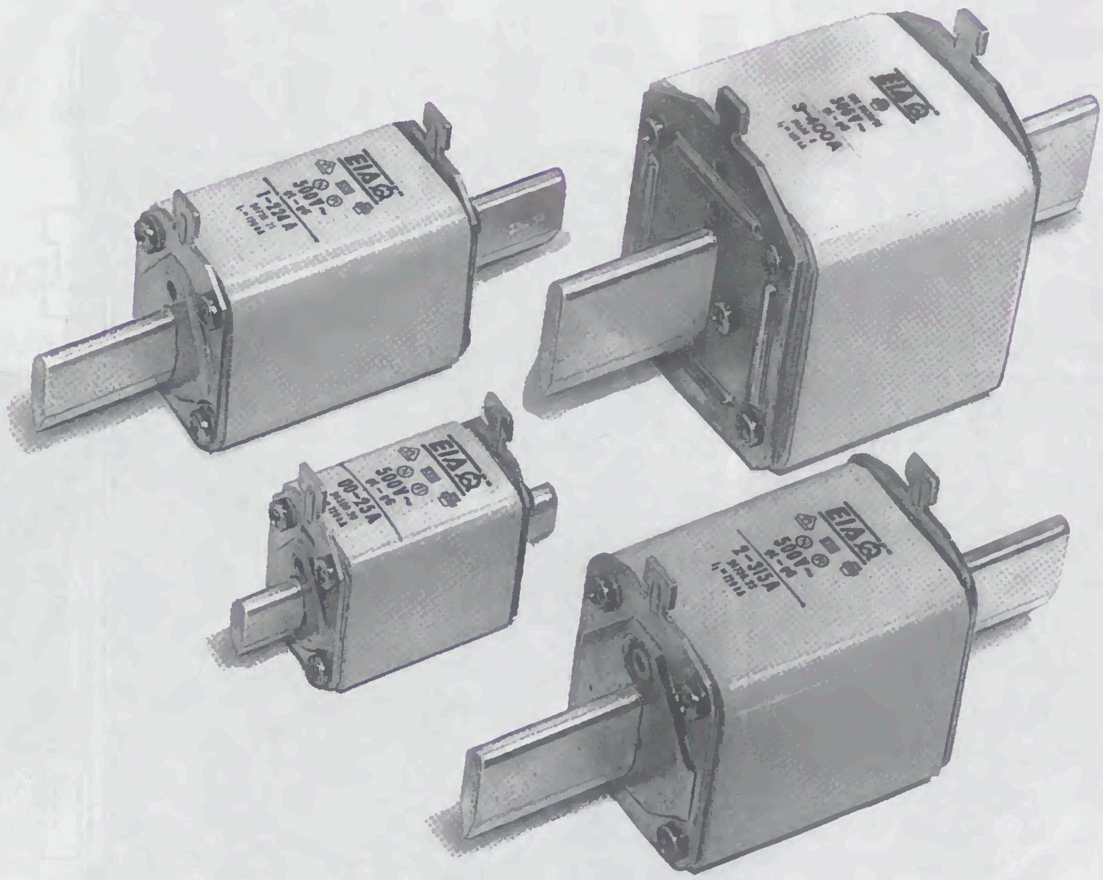

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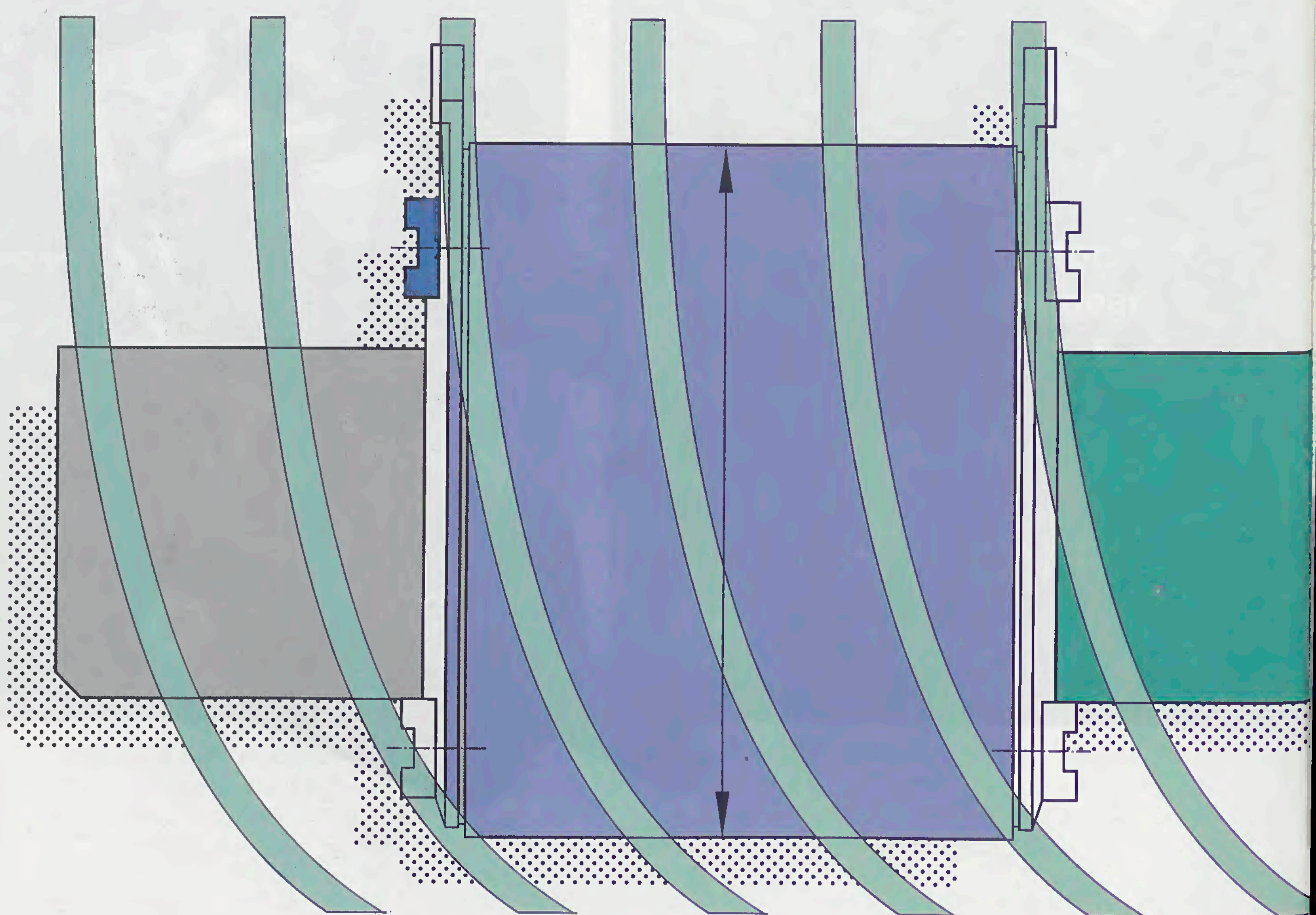

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