EXPERIMENTAL INVESTIGATIONS OF CAVITATION EROSION IN THE INCUBATION PERIOD

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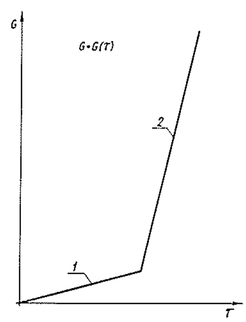
Introduction

Cavitation erosion investigations carried out by various methods, using the conventional hydrodynamic principles (flow devices) or the accelerated methods (magnetostriction devices) are primarily aimed to classify the relative cavitation erosion properties of different materials. Such experimental investigations involve the measurement of weight or volume losses of different materials as the function of the arbitrarily choosen experimental time, at a given state of cavitation. Considering that the weight or volume loss per unit time does not represent a constant value but changes with the time and furthermore the physical state of the material will similarly change as the damage continues, none of the different measurements used to characterize erosion damage is perfect and we are obliged to search for the available criteria.

In carrying out a large number of experimental studies of this type, little attention was paid to the more minute investigation of the so-called "incubation" period. Materials exposed to cavitation effect will exhibit considerable damage only after the incubation period. In that stage the collapse energy of the bubbles produce only the fatiguing on the surface of the test specimen, without the appearance of appreciable damage and hence loss of weight. Isolated small pits are found on the surface only. Beyond that stage at the same cavitation condition it will produce a quick destruction of the test specimen. This character of cavitation erosion damage is confirmed repeatedly.

This nature of cavitation erosion damage process brought about the necessity of subjecting the incubation period to a close examination. A few results of these investigations will be discussed below. The experimental investigations have been carried out in a test section built into the closed circuit water tunnel in which the cavitation—produced behind circular cylinder model—acted upon lead test specimens arranged on the side wall of the test section. The test equipment has already been discussed in detail in earlier papers [1], [2], [3].



1/ Loss of weight (G) due to cavitation damage plotted versus the time (τ) of experiment. — 1. The incubation period. — 2. The period of total destruction.

Perte de poids (G) provoquée par la cavitation, en fonction de la durée (τ) de l'expérience. — 1. Période « d'incubation ». — 2. Période de destruction totale.

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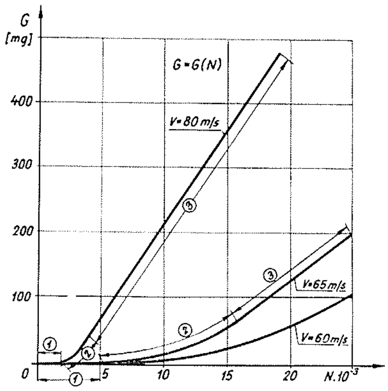
The critical damage period

A number of earlier experimental studies carried out with different flow velocities have confirmed the statement that the curves of weight loss versus time, in the early stages of testing are composed of two clearly distinct zones (apart from a short transition section). An idealized weight loss versus time curve is illustrated in Figure 1. The zone marked 1 in the Figure is the incubation period, in which the deformation of the test specimen surface is predominant, accompanied by a moderate loss of weight. Zone 2 of the curve is the period of quick destruction, the so-called "total destruction" or accumulation zone. The intersection point of the two lines represents the end of the incubation period. In the following it will be referred to as the critical point, and the whole period as the critical damage period (τ_{crit}). The weight or volume loss pertaining to it will be called the critical weight (or volume) loss. The adjective "critical" involves the statement that from the point as the damage continues the physical state of the material and similarly the mechanical strength properties of the test specimens are changing, and therefore, the resistance of the test specimen to cavitation erosion decreases.

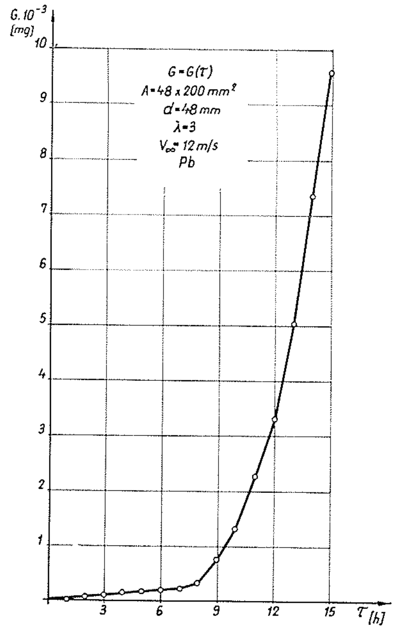
There is a concept according to which the "pure" effect of cavitation erosion manifests itself during the incubation period only because the damage becomes cumulative after a major damage occurs on the surface. It may well be assumed that the physical state of the material does not undergo any basic change within the incubation (critical damage) period, consequently the incubation period might be considered as the true cavitation damage phase without any secondary phenomena. It may furthermore be assumed that the so-called contraction work [4] i. e. specific fracture energy (the energy absorbed per unit volume of the material up to fracture) at the end of the critical damage period would be exhausted. This is confirmed by the fact that small cracks appear under the surface of the test specimen as was verified by electron-microscopic investigations [5]. Such an interpretation of the critical point offers a basis for comparing the resistance of different test specimens to cavitation damage.

In the literature the division of the weight-loss curves into typical zones frequently appears. Kozirev [6] divides the curves obtained with the rotating-disk equipment into three zones. He calls the first zone with no loss of weight, incubation period which is followed by a short transition section featuring slight loss of weight. The third zone is the period of rapid destruction (Fig. 2). Bogatchev and Mints [7] in agreement with Figure 1 divide the weight-loss curves into two sections also obtained by accelerated method. Leith [8] defined the incubation period as the time interval during which considerable plastic deformation of the test specimen takes place without any apparent weight loss. Govinda Rao [9] approaches the subject from the energetical point of view stating that the incubation period is characterized by an energy level causing plastic deformation. Thiruvengadam [10] defined



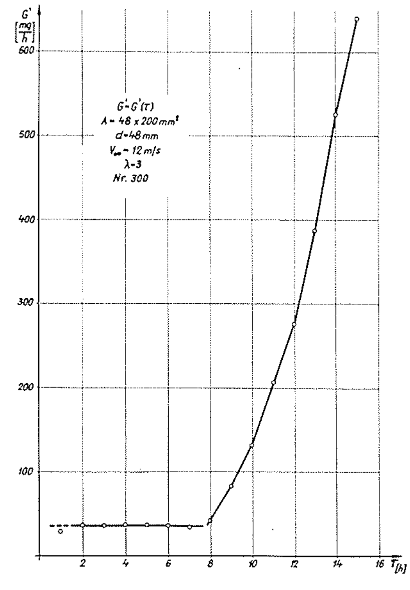
2/ Weight loss (G) as the function of impacts (N) on the test specimen, at different specimen speeds. Based on Kozirev's paper. — 1. Incubation period. — 2. Transition zone. — 3. Stage of rapid destruction.

Perte de poids (G) en fonction des chocs (N) subis par l'échantillon d'essai, pour des vitesses d'échantillon variables. Données basées sur le mémoire de Kozirev. — 1. Période « d'incubation ». — 2. Zone de transition. — 3. Phase de destruction rapide.



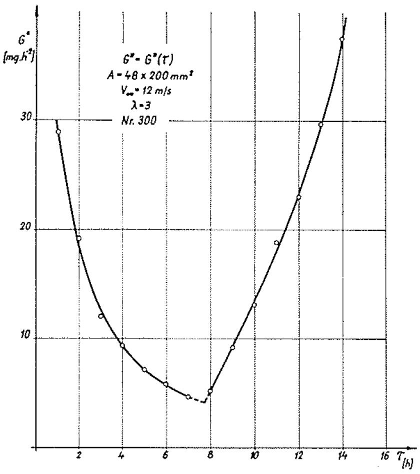
3/ Weight loss (G) plotted versus the time (τ) of experiment. Dimensions of the test section are 48×200 sq.mm, the flow velocity is $v_\infty = 12$ m/sec., the relative length of the cavitation zone is $\lambda = 3$.

Perte de poids (G) en fonction de la durée (τ) de l'essai. Les dimensions de l'échantillon d'essai sont 48×200 mm², la vitesse d'écoulement est $v_\infty = 12$ m/s, et la longueur relative de la zone de cavitation est $\lambda = 3$.



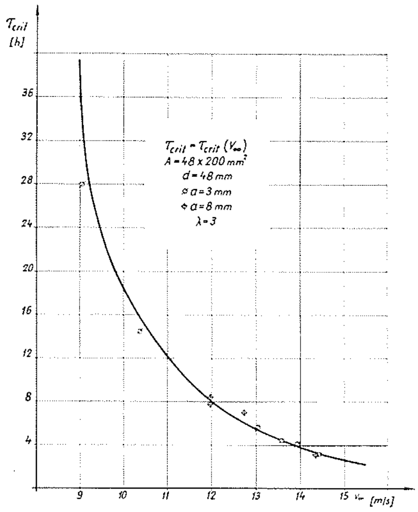
4/ Weight loss per unit time (G') versus the time (τ) of experiment.

Perte de poids par unité de temps (G') en fonction de la durée (τ) de l'essai.



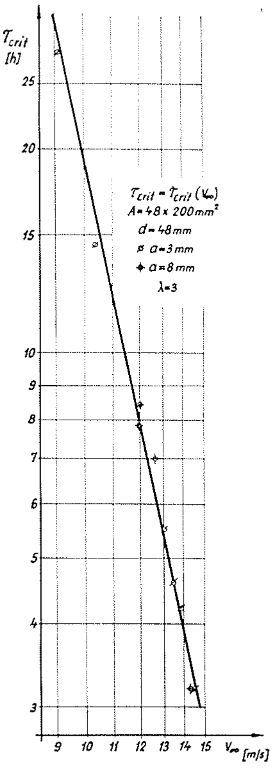
5/ Variation of $G'' = G/\tau^2$ as the function of the time (τ) of experiment.

Variation de $G'' = G/\tau^2$ en fonction de la durée (τ) de l'essai.



6/ Critical period of cavitation erosion damage ($\tau_{crit.}$) versus the flow velocity (v_∞). The thickness of the lead sheets are $a = 3$ and 8 mm.

Période critique destructive par l'érosion due à la cavitation ($\tau_{crit.}$), en fonction de la vitesse de l'écoulement (v_∞). Les épaisseurs des plaques de plomb sont $a = 3$ et 8 mm.



7/ Critical period of cavitation damage ($\tau_{crit.}$) versus the flow velocity (v_∞).

Période critique de la destruction due à la cavitation ($\tau_{crit.}$) en fonction de la vitesse de l'écoulement (v_∞).

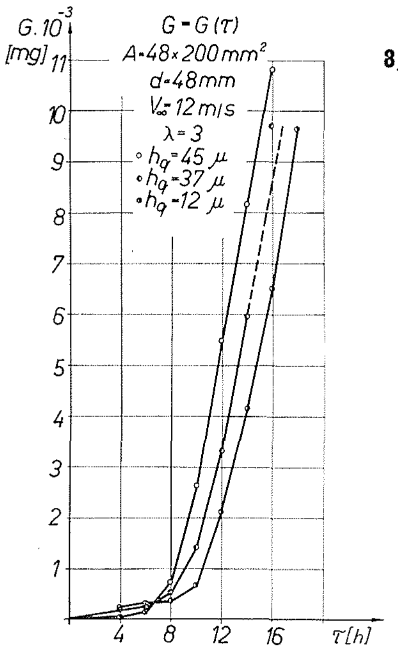
the incubation period as that period after which the first permanent plastic dent is formed. It is also evident from the statements of the above authors that the opinions are not uniform in connection with the incubation period. The authors who claim that the incubation period involves no weight loss at all, are probably unable to measure the very small weight losses involved.

The determination of the critical time

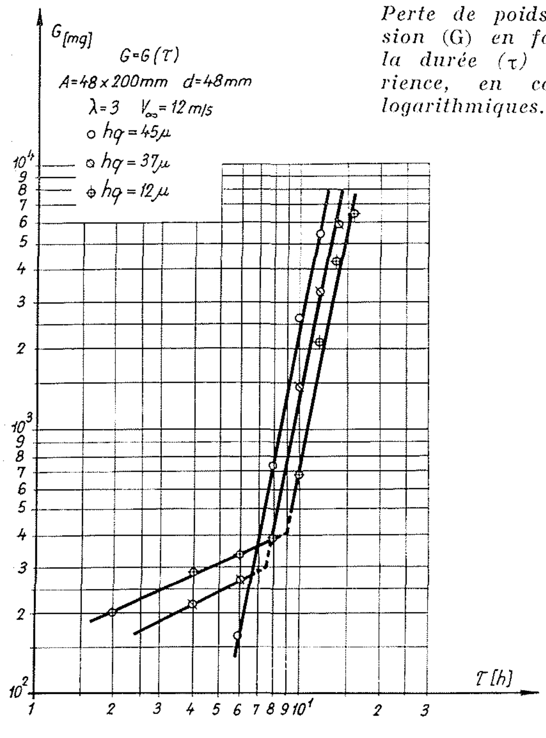
It is difficult to determine the critical time from weight-loss curves plotted versus time of experiment because the curves differ from the idealized curve of Figure 1 just by the presence of a short transition period between the incubation period and the zone of total destruction (Fig. 3). Thus the intersection point of the two curves cannot be determined unambiguously. In view of this, a method of evaluating the experimental results has been sought for permitting the determination of critical weight loss and critical time with satisfactory accuracy. The transition point between the two curve sections may be regarded the one to which a tangent circle of minimum radius can be relegated. However, it cannot be unambiguously determined because the test points are usually not available in the desired density; even if more points were plotted, the accuracy could not be increased on account of the unavoidable scattering of the test results. Therefore, a more accurate method was searched for to determine the critical value. Plotting the quantity of material eroded during unit time versus the time of experiment, the curve of Figure 4 will be obtained. Here the incubation period appears in the form of a straight line parallel to the abscisse. The critical point can be determined even more perfectly and accurately by carrying out the same procedure with the points of Figure 4. Thus, the curve of Figure 5 will be obtained from which it is possible to locate the critical point with satisfactory accuracy.

Influence of the flow velocity on the critical period

Plotting the critical periods (obtained by the above methods) versus the speeds pertaining to them, the curve of Figure 6 will be obtained. Plotting same in a co-ordinate system of logarithmic scale, a straight line can be laid across the test points (Fig. 7) that can be described by the equation $\tau v^m = \text{const.}$ in which the power exponent is $m = 5$. This relationship is identical with the one found in a previous paper [11] for the accumulation zone following the incubation zone with a given constant quantity of material eroded. The points plotted in Figure 7 represent the test results with two different thicknesses ($a = 3$ mm and 8 mm) of lead test specimens. Obviously, the critical period is the same with both types of test spe-



8/ Erosional weight loss (G) versus the duration (τ) of experiment.
Perte de poids par érosion (G) en fonction de la durée (τ) de l'expérience.



9/ Erosional weight loss (G) versus the duration (τ) of experiment in logarithmic co-ordinate system.
Perte de poids par érosion (G) en fonction de la durée (τ) de l'expérience, en coordonnées logarithmiques.

cimens. It may be noted here that the experiments on the total destruction (accumulation) period have also been made with the above test specimens of two different thicknesses and the same results have been obtained. On the other hand, oddly enough, the critical quantities of material pertaining to the critical times differ with the thickness of the test specimen (see Table 1). It is evident from the Table that with experiments carried out at a constant cavity length ($l_z = 3\ d$),

$G_{crit} = 290$ mg on the average with a lead sheet of 3 mm,

$G_{crit} = 420$ mg on the average with a lead sheet of 8 mm.

To explain this phenomenon requires further experiments to be carried out.

Apart from the data given in the Table, it could be ascertained in a large number of tests that the critical quantity of material may be regarded as independent of the flow velocity under constant cavitation conditions, i.e. constant cavity length. The critical material quantity depends only on geometrical dimensions such as model diameter, test section dimensions and cavity length, which appear to represent a unique function of cavitation number [12]. This was verified by experiments conducted with lead and aluminium test specimens. It may be noted that earlier the authors [11] had found in their experiments conducted in order to determine the velocity-damage exponent, that the exponent value was shown to be less than 5 and of variable value in the period of incubation and to reach the constant value 5 only by the end of critical period.

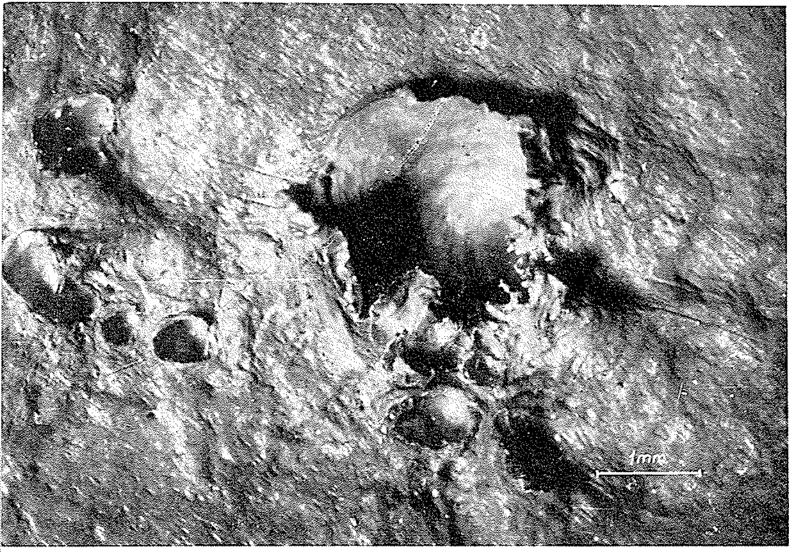
Influence of surface roughness on the incubation period

The literature of cavitation research includes only a small number of papers dealing with investigations on the relationships between the surface roughness of hydraulic machines and cavitation erosion. In this respect, the experiments by Shalnev [13] and, more recently, Numachi et *al.* [14] deserve mentioning.

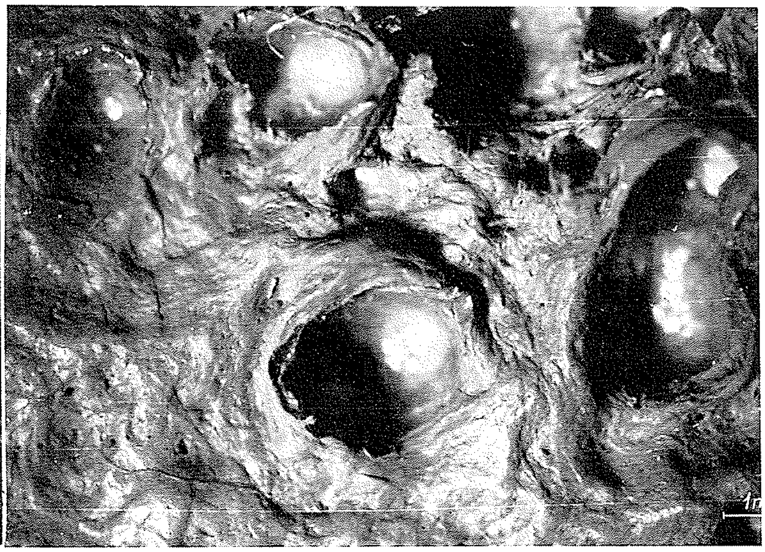
In our experimental studies, the objective was to determine the influence of the roughness of test specimen on the intensity of cavitational erosion. The tests were carried out by the methods discussed in the Introduction. Also, the quality of test specimen was the same. The surfaces, initially smooth, have been made rough by rolling a weight-loaded screwed spindle over them. Then the precise value of roughness was measured using a profilometer-type instrument. The grooves were set at right angles to the direction of flow. The value of roughness was expressed in conventional rms terms. The roughness values of the three test specimens were $h_q = 12\ \mu$, $37\ \mu$ and $45\ \mu$.

The weight losses of test specimens of three different roughness values are shown (versus the time of experiment) in Figure 8. The graphs will be made clearer by plotting those weight-loss curves in a logarithmic co-ordinate system (Fig. 9). From the Figures, and from comparisons with experiments involving smooth-surface test specimens, the following conclusions can be drawn:

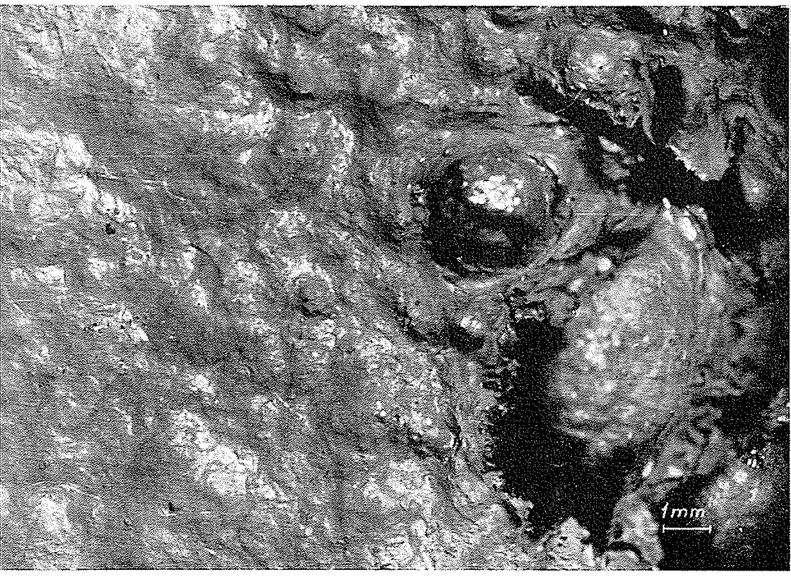
1. Roughening the specimen surface shifts the location of the critical point, its value decreasing with roughness (under the same flow conditions) — i.e. the critical period becomes shorter;



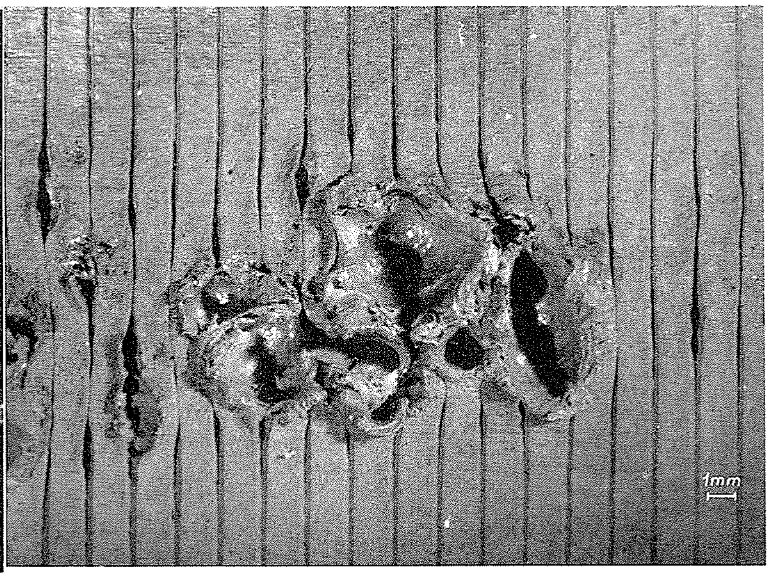
10/ Photograph of eroded surface on a smooth test specimen.
Photographie de la surface d'érosion sur un échantillon lisse.



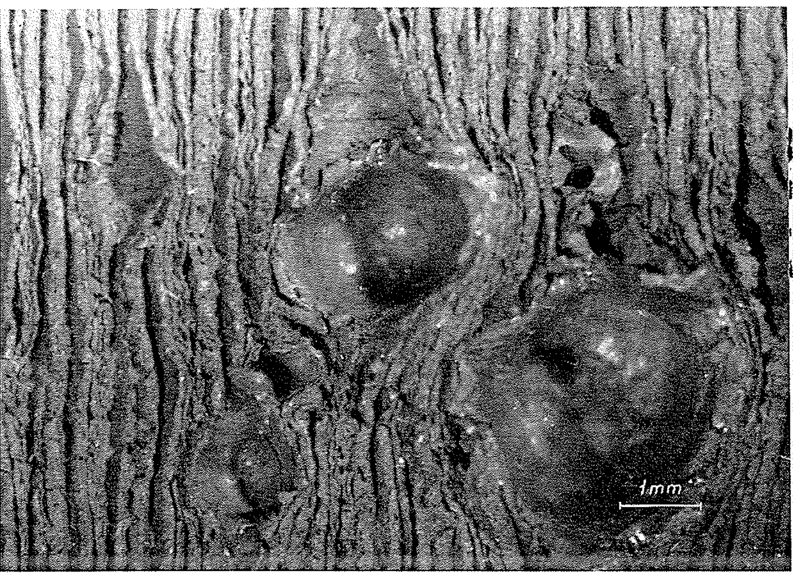
11/ Photograph of eroded surface on a smooth test specimen.
Photographie de la surface d'érosion sur un échantillon lisse.



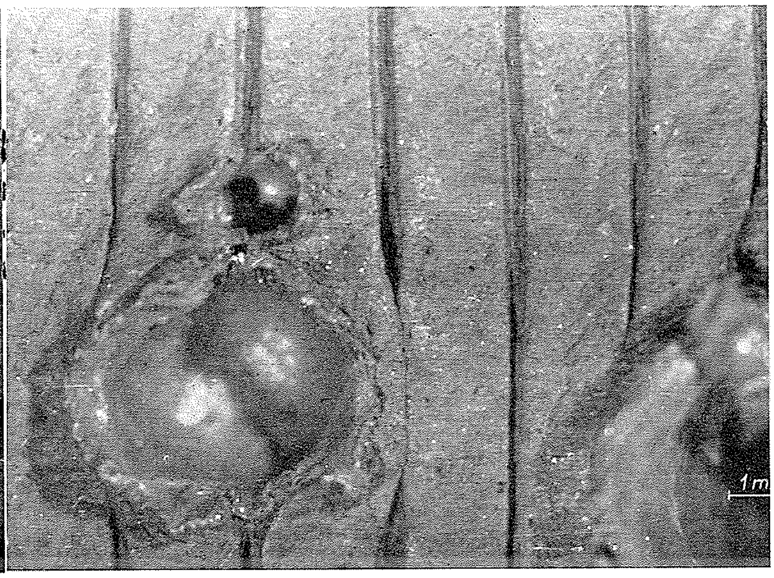
12/ Photograph of eroded surface on a smooth test specimen.
Photographie de la surface d'érosion sur un échantillon lisse.



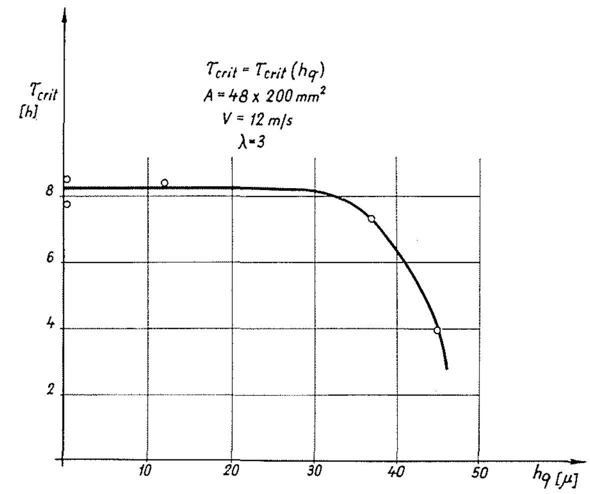
13/ Photograph of cavitational caverns on a grooved test specimen.
Photographie de cavités de cavitation sur un échantillon rainuré.



14/ Photograph of cavitational caverns on a grooved test specimen.
Photographie de cavités de cavitation sur un échantillon rainuré.



15/ Photograph of cavitational caverns on a grooved test specimen.
Photographie de cavités de cavitation sur un échantillon rainuré.



16/ Variation of incubation period ($\tau_{crit.}$) with surface roughness (h_q).

Variation de la période « d'incubation » ($\tau_{crit.}$) en fonction de la rugosité superficielle (h_q).

Table 1

Number of test specimen	v_∞ (m/s)	τ_{crit} (h)	G_{crit} (mg)	a (mm)	h_q (μ)
200	13,60	4,5	340	3	< 1
201	14,43	3,2	275	3	< 1
204	13,95	4,2	305	3	< 1
205	10,40	14,5	270	3	< 1
206	13,05	5,7	265	3	< 1
207	9,05	28,0	290	3	< 1
			average 291		
300	12,00	7,8	320	8	< 1
301	14,35	3,2	430	8	< 1
303	12,74	7,0	480	8	< 1
304	12,00	8,4	450	8	< 1
			average 420		
310	12,00	7,3	430	8	37
311	12,00	8,4	450	8	12
312	12,00	4,0	53	8	45

2. In the period of total destruction following the incubation period, the curves are practically parallel to one another. Hence, the conclusion can be drawn that at this stage the surface roughness has no longer influence on weight losses due to erosion.

The above statements are confirmed by some additional observations. During the experiments, it was found that the erosion pits occur invariably along the grooves. The rougher the surface is, the sooner will the pits appear. This phenomenon may be conceived in such a way that the effect of cavitational erosion is increased by additional effects coming from the grooved surface. Figures 10, 11 and 12 illustrate the cavitation damage of smooth test specimens; Figures 13, 14 and 15 illustrate the eroded surfaces of grooved test specimens. It is evident from the latter figures that the pits develop primarily in the grooves.

The variation of incubation period as the function of surface roughness is shown in Figure 16. The Figure suggests the conclusion that, under the conditions of our experiments, roughness up to $h_q = 35\ \mu$ has no appreciable influence on the length of incubation period. At a roughness higher than that, the incubation period tends to shorten rapidly followed by total destruction.

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