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Investigation of the Scale Effects of Cavitation Erosion

K. K. Shal'nev, I. I. Varga and D. Sebestyen

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XXIII. Investigation of the scale effects of cavitation erosion

By K. K. Shal'nev,† I. I. Varga‡ and D. Sebestyen‡
† *Institute of Mechanical Problems, Academy of Sciences of the U.S.S.R.*
‡ *Hungarian Academy of Sciences*

[Plates 52 to 54]

A great variety of methods for the evaluation of cavitation erosion are now available. However, because of a lack of correlation with the hydromechanics of cavitation, they fail to provide a solution to the problem of scale effects. Studies are described of the hydromechanical aspects of cavitation erosion induced in the wake of a circular profile model for plane flow conditions in a water tunnel. An energy parameter for the estimation of resistance of materials to cavitation damage will be introduced. An explanation of cavitation effects will be reached by varying the parameters likely to affect the intensity and development of erosion. These parameters include: the state and structure of the cavitation zone, relative dimensions of the model, cavitation layer thickness, the characteristic model dimension, flow velocity, specimen erosion volume, experimental duration, and Reynolds and Weber numbers.

The energy parameter is derived in terms of the erosion volume and the work done by the cavitation drag forces. The reciprocal value of the energy parameter gives the erosion resistance of the material in terms of the amount of work done in damaging unit volume of the material. This parameter is used to explain the power law obeyed by dimensional and velocity scale numbers. It will be shown that erosion volume is proportional to flow velocity to the fifth power, and to the characteristic model dimension to the third power. The conditions for prognosis of erosion volume from the experiments with models will be specified.

1. The state of the problem

From the point of view of modern hydraulic engineering and structural design, the effect of scale numbers, particularly those of flow velocity and model dimensions, on the volume of cavitation erosion is of primary interest. Knowledge of these effects will enable an engineer to forecast the period of possible cavitation damage of the prototype on the basis of tests on models. But so far only investigations into the effect of flow velocity on the intensity of erosion have become well known (Schröter 1932, 1934; Knapp 1955, 1958; Kerr & Rosenberg 1958; Rata 1960). As to the effect of the model dimensions, the only data available are from pump-operation practice (Ackeret & Haller 1936).

Observations of the following factors have been used previously to estimate the intensity of erosion of solid materials: (1) the appearance of erosion pits, in particular the depth and other dimensions of the pitted area (Parsons & Cook 1919); (2) the weight loss of specimens over a specified test period (Kerr 1937); (3) the volume loss of specimens over a certain test period (Mousson 1937); (4) volume loss per unit area per unit time (rate of erosion) (Shal'nev 1954*a*); (5) the same as (4) but with respect to weight loss (Gavranek 1957); (6) the number of erosion pits (Knapp 1955); (7) the depth of pitting in the case of a sharply localized erosion area (Plesset & Ellis 1955); (8) the duration of testing of a specimen up to a definite degree of damage, determined visually (Schröter 1932). Noskievic (1956) examined possible similarity criteria and proposed the following parameter of erosion:

$$V = G/\gamma d,$$

where G is the weight loss of the specimen, γ the specific weight of the specimen material, and d a characteristic dimension of the cavitation zone. Rata (1960) evaluated the intensity of erosion from the drop of ohmic resistance in the specimens being tested. Gowinda Rao & Thiruvengadam (1961) proposed as a nondimensional parameter of cavitation erosion the ratio of the energy required to displace the volume of material discovered during the tests to the energy of the collapsing bubbles producing the damage effects. The energy was determined by a theoretical method.

Considering the aforementioned parameters of cavitation erosion with respect to their possible use in the evaluation of scale effects, we see that neither of them is in any direct way related to the hydromechanical factors in cavitation erosion, such as the degree of cavitation, the flow velocity and the dimensions of the cavitation zone.

In previous papers by one of us (Shal'nev 1956*a*, *b*, 1958) it was proposed to take as a parameter of cavitation damage the ratio of the volume of the material damaged to a certain part of the flow energy lost due to the cavitation drag on bodies producing the cavitation. The following 'energy parameter' of cavitation erosion was suggested as a specific volume of erosion (Shal'nev 1961*a*):

$$\Delta V = \frac{10^7 \Delta V}{36 \Delta C_x dh\, q_\infty v_\infty \gamma} \left[\frac{\mu\text{m}^3}{\text{Kg}}\right], \tag{1}$$

where ΔV is the volume of erosion in $\text{mm}^3\,\text{h}^{-1}$, and $\Delta C_x = \eta(C_{xc} - C_x)$, C_x being the drag coefficient of the model in the absence of cavitation, C_{xc} the drag coefficient of the model in the presence of cavitation, and η an activity coefficient indicating the amount of cavitation drag expended in damaging the material, assumed as $\eta \approx 1$. Here also d is the characteristic dimension of the profile (e.g. diameter of a circular cylinder, chord of a wing profile), γ is the specific weight of the fluid, and v_∞ is the flow velocity which takes into account the reduction of the cross section of the working chamber. Further,

$$v_\infty = kv, \quad k = \frac{b}{b-d}, \quad q = \frac{v^2}{2g},$$

where b is the width of the working chamber, and g is the acceleration due to gravity. The inverse value of the specific volume of erosion gives the absolute resistance of material to erosion in terms of the quantity of work spent in damaging a unit volume of the material.

2. Methods of testing

Methods in current use for the investigation of cavitation erosion include: (1) vibratory treatment with sound waves; (2) impacts between a liquid jet and a solid body; (3) the method of rotating tested specimens in relatively still water. These belong to the category of accelerated test methods. Scales of relative resistance of materials to cavitation erosion are created with their help, but they do not establish a direct connexion between the erosion intensity and hydromechanical aspects of the flow. The most suitable for this purpose is the method of flow-type cavitation.

Several variations of this method are known: (1) the specimen is placed in a zone of cavitation created by another body (Parsons & Cook 1919; Hammitt 1963); (2) the specimen itself produces the cavitation. In tests of the second kind, use has been made of the model of a wing profile (Föttinger 1932), axisymmetrical body (Parsons & Cook 1919; Knapp 1955), diffuser walls (Schröter 1932), circular cylinder (Schröter 1932), circular cylinder between two parallel walls (Rasmussen 1949, 1950). Again, the specimen may be placed in the wall adjacent to the cavitation zone created by a sharp-edged body, e.g. a sill (Schröter 1932, 1934; Mousson 1937), a cylindrical projection (Haller 1933), or a cylinder between two parallel walls (Shal'nev 1954*b*) (see figure 1). Experiment has shown that the position of cylinder and of the cavitation zone in the space has no effect on the erosion intensity. An idea of the structure of the cavitation zone and position of erosion pits is given by the photographs in figure 2 (plate 52).

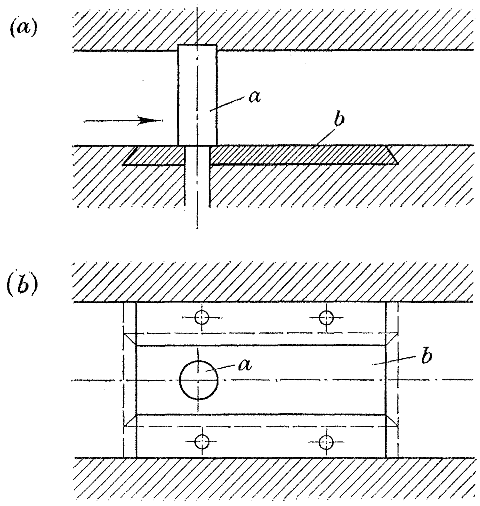


FIGURE 1. Scheme of cavitation erosion tests using the method of flow-type cavitation: (*a*) model, (*b*) specimen.

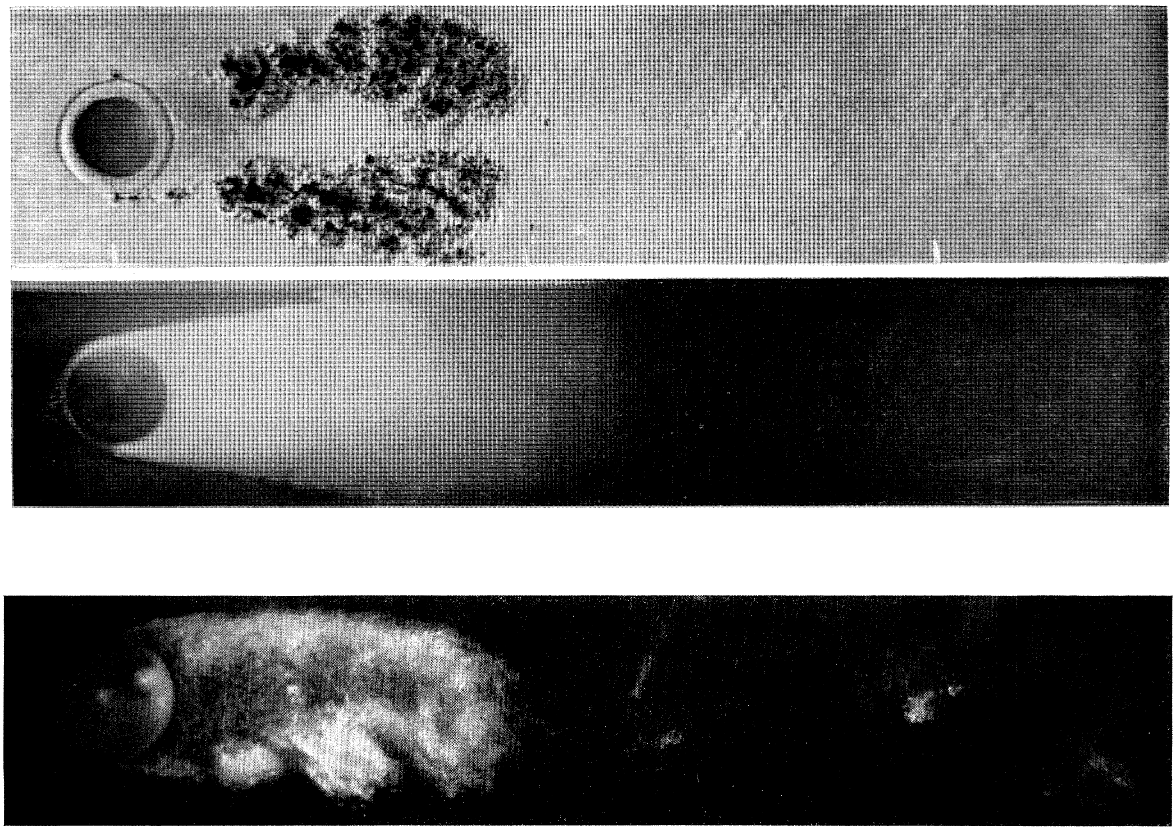
This last method allows one to connect in the simplest way the cavitation drag of a body and its characteristic dimension with the flow velocity, physical properties of the fluid and volume of erosion.

Results of experiments described here were obtained mostly in the working sections of cavitation tunnels at the Institute of Mechanical Problems of the Academy of Sciences of the U.S.S.R., and of the Hungarian Academy of Sciences in Budapest University (Varga, Tchernjavsky & Shal'nev 1963). The dimensions of the working sections, $a \times b$, had the following variants: 70×200, 48×200, 24×100, 12×50 and 6×25 mm^2. The flow velocity and pressure could be controlled independently of each other over a range of $V = 0$ to 25 m/s, and $p = -0{\cdot}8$ to 6 atm. Used as material for specimens was a rolled lead of commercial quality, containing 99·98 % Pb. This material was chosen as the least resistant to cavitation erosion in order to reduce the period of tests.

3. HYDROMECHANICAL PARAMETERS

Relative dimensions of the model

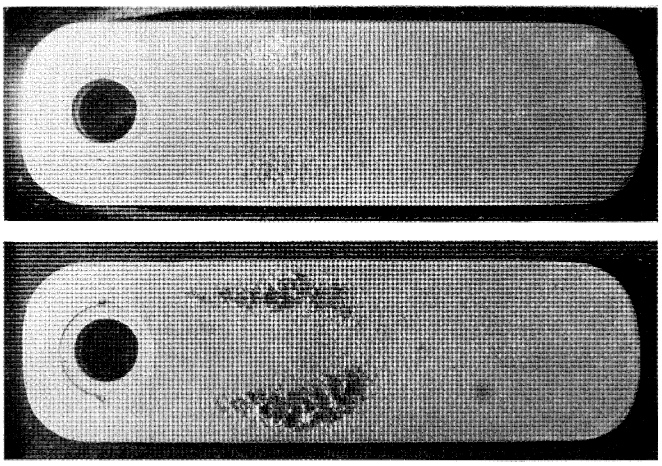
The erosion experiments should be carried out in geometrically similar chambers, of a height equal to the diameter of cylinder, $h/d = 1$. Tests have shown (see figure 3) that at



(*a*)

(*b*)

FIGURE 2. Cavitation zone and erosion zone of the lead specimen: (*a*) at a long exposure; (*b*) at a short exposure.



(*a*)

(*b*)

FIGURE 7. Cavitation erosion of a lead specimen: (*a*) at the initial stage of damage, up to $\Delta G_{cr.}$; (*b*) at the developed stage of damage.

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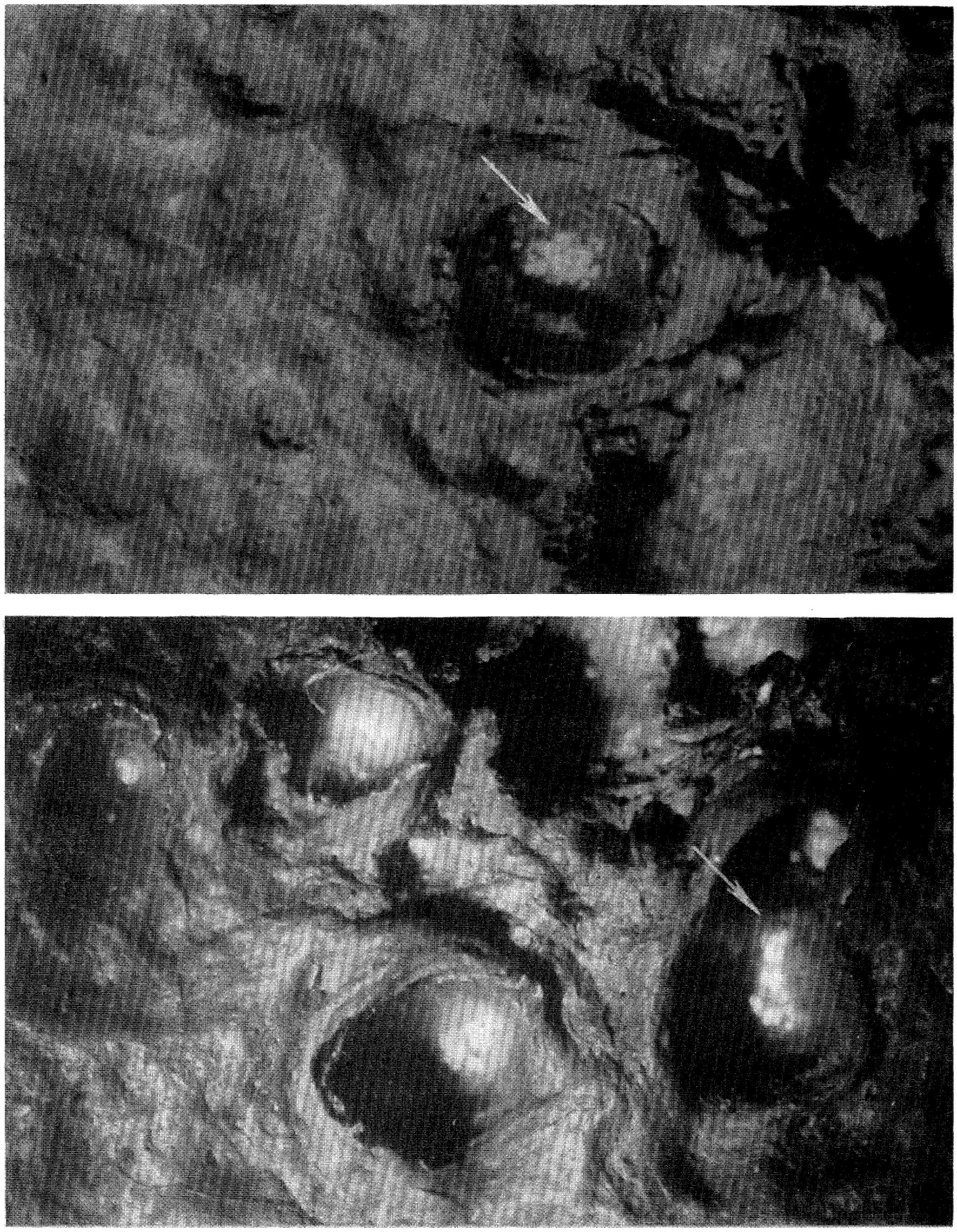

FIGURE 10. Erosion pits in the initial stage and in the developed stage. Arrow shows the accumulation of copper particles. (Magn. ×30.)

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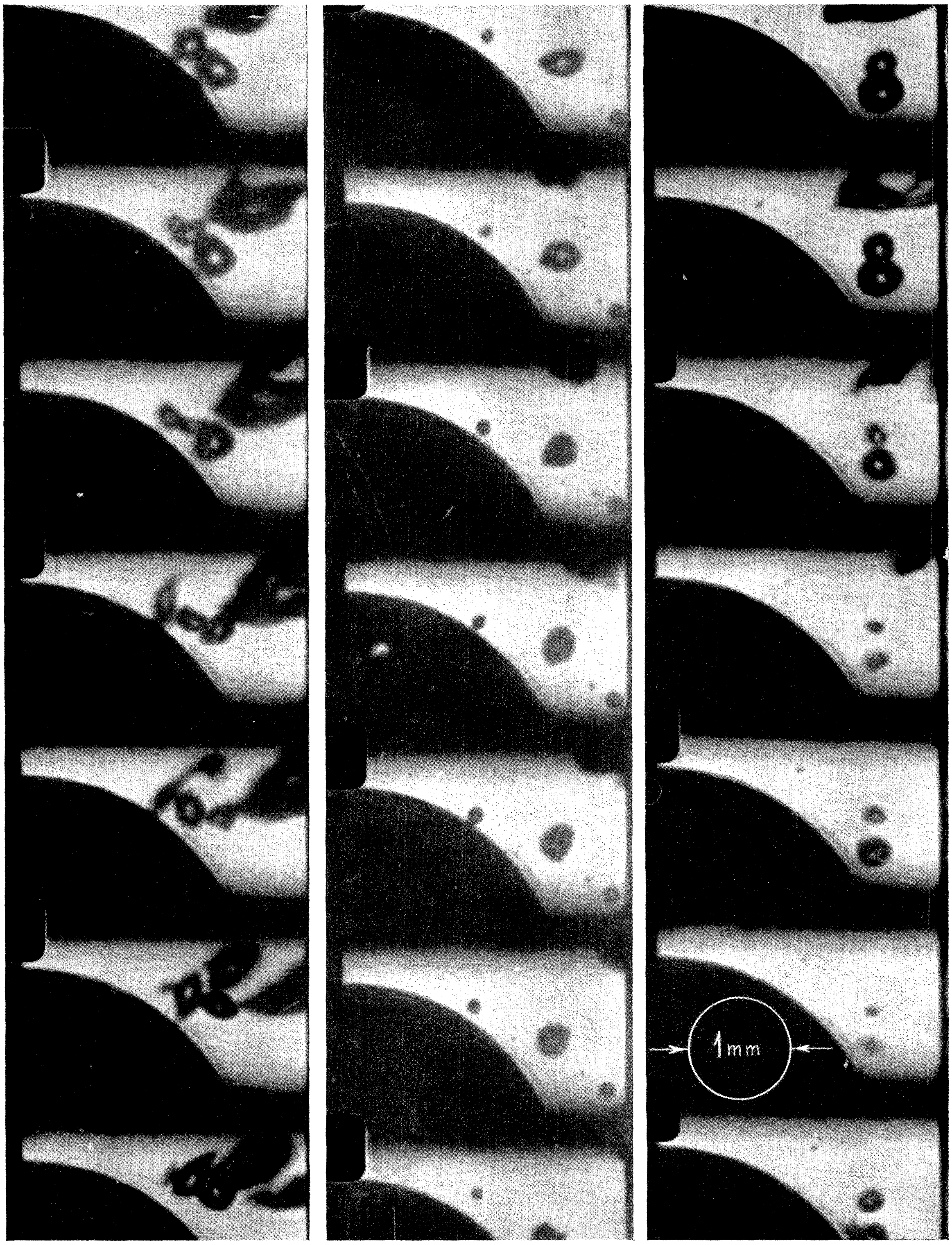

FIGURE 11. Several successive sequences of a high-speed ciné film of a small part of the cavitation zone in the wake of a cylinder. Pulsating bubbles are seen.

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this value of h/d the erosion volume is at its maximum (Shal'nev 1958). At $h/d = 2$ to 3, the erosion during the same period of experiment is almost undetectable. Probably this phenomenon is due to the change of structure of the cavitation zone.

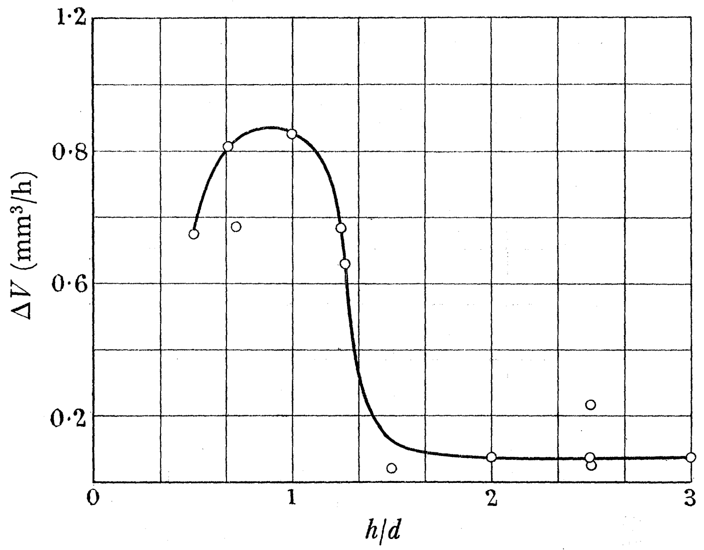

FIGURE 3. Influence of relative dimensions of a model, h/d, on the erosion volume ΔV at v = const. and λ = const.

Stage of cavitation development

Similarity between the development of the cavitation stages and the geometrical similarity of the cavitation-zone lengths should be preserved. The cavitation-zone length characterizes its kinematic structure, as has been shown by high-speed photography. At the cavitation stages $\lambda = l_c/d = 1$ to 4, the cavitation zone consists of cavities periodically arising and carried away by the flow. The frequency of cavity formation obeys the Strouhal law, $S = fd/v_\infty$, but the number S depends on the cavitation stage (Shal'nev 1954*a*, *b*; Iljichev 1961). In so far as the main frequency of the pressure pulsations in the erosion zone is equal to the frequency of separation of cavities, determined from the Strouhal formula $f = Sv_\infty/d$ (Shal'nev 1954*b*; Shal'nev & Rubina 1964), similarity of the pressure-pulsation frequency could be achieved by preserving the similarity of the cavitation zone lengths. Experiments set up to show the dependence of erosion on stage have shown that when the Reynolds numbers Re is small, the erosion volume $\Delta V_{\text{max.}}$ is observed at $\lambda = 2{\cdot}5$ to 3, and at large numbers Re it is displaced toward $\lambda = 1{\cdot}5$ (figure 4). In the present investigation, ΔV was determined at $\lambda = 2{\cdot}5$ to 3.

Cavitation drag ΔC_x

The data of several authors can be used for the determination of ΔC_x. All these data were obtained by different methods of experiment. Martyrer (1932) communicated the results of experiments in a water-tunnel with open circulation of water in the working chamber (61×200 mm²) with cylinders of $d = 5$ to 24 mm and at $\text{Re} = 6 \times 10^3$ to 4×10^3. The drag C_x and C_{xc} was determined by means of a hydrodynamic balance. Correction for wall effects was not introduced. Konstantinov (1946) describes results obtained in a working chamber 60×200 mm² with the models of $d = 5$, 10, 30, 50 mm at $\text{Re} = 4 \times 10^4$ to

$4{\cdot}3\times10^5$, and in a working chamber 80×640 mm² with models of $d = 30$ and 100 mm, and $\mathrm{Re} = 1{\cdot}75\times10^5$ to 8×10^5. The drag was determined from the pressure distribution at the middle section of the models. The wall effect was taken into account by means of the continuity of flow equation, allowing for the local loss of pressure in the working section due to a contraction of flow. Correction for the wall effect was not introduced in the values. Results of the experiments by Konstantinov are reproduced in figure 5, which shows the dependence of C_x, C_{xc} and ΔC_x on We; there is also plotted the relation of the erosion

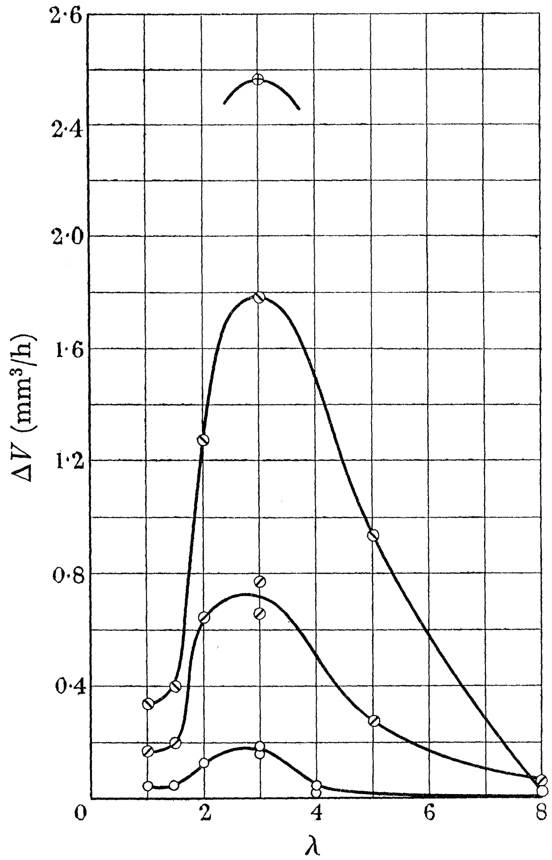

FIGURE 4. Influence of the cavitation state λ on the erosion volume ΔV. Values of v_0 (m/s): ⊕, 23; ⦸, 20; ⊘, 17; ○, 14.

volume ΔV (We), where We is the Weber number: $\mathrm{We} = \rho v_\infty^2 d/\sigma$, ρ being the density and σ the surface tension of the liquid. The scattering of experimental points can be explained by the different methods of defining a wall-influence correction, also by differences in the turbulence level and pressure gradient along the working chambers (Shal'nev 1961 *b*). An approximate function ΔC_x (We) for the range under consideration can be represented by means of a straight line, making an α_0 angle with the abscissa axis.

Weber number

The use of a Weber number for evaluation of the similarity of cavitation phenomena is justifiable by the fact that the cavities comprise an accumulation of a multitude of bubbles, in the development and closure of which an important role may be played by surface tension forces. Thus the volume of erosion can be represented by the function $\Delta V \sim \sigma + k\sigma^2$, where k is a constant (Nowotny 1942).

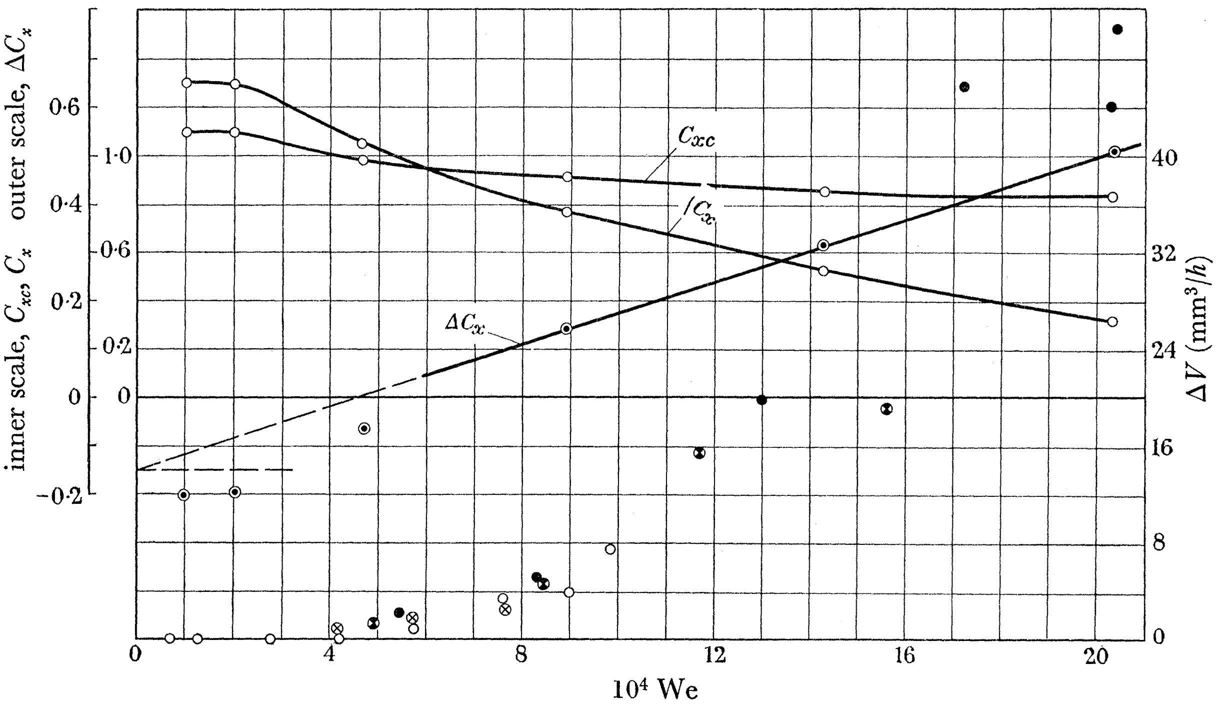

FIGURE 5. Combined graph of variations of cylinders drag ΔC_x and ΔV with the Weber number We at $\lambda = 3$.

	○	⊗	●	⦿
$a \times b$ (mm²)	6 × 25	7·5 × 25	12 × 50	15 × 50
d (mm)	6	6	12	12

4. Erosion parameters

Volume of erosion

According to definition, the volume of erosion is

$$\Delta V = \Delta G / \tau \gamma_p, \tag{2}$$

where ΔG is the weight loss of the specimen from the influence of cavitation during time τ, and γ_p is the specific weight of the specimen material. The weight loss is established by weighing the specimen before and after the test.

The problem arises, how long should the test duration be made to give a correct evaluation of the cavitation damage of material. The function $\Delta G(\tau)$ for many materials is characterized by two periods of damage at least: the initial, somewhat delayed period and the subsequent, more intensive one (figure 6). The initial period is called also the incubation period (Nowotny 1942; Mathison & Hobbs 1960; Thiruvengadam 1962). The incubation period is not taken into account usually when evaluating ΔV, and thus the evaluation of material loss is made for the second period, or the sum of the two. However, there is a great difference in the processes of damage during the first and the second period (see figure 7, plate 52).

A cumulative effect influences the damage in the second period. But in the initial period of erosion, the damage persists owing to the formation of small shallow pits on the grain boundary, and in this case it is difficult to imagine the presence of a cumulative effect, or it is rather small. The presence of a critical point is clearly shown by the graph of $\Delta G/\tau^2$ against ΔG in figure 8, to some extent similar to the acceleration of a moving body.

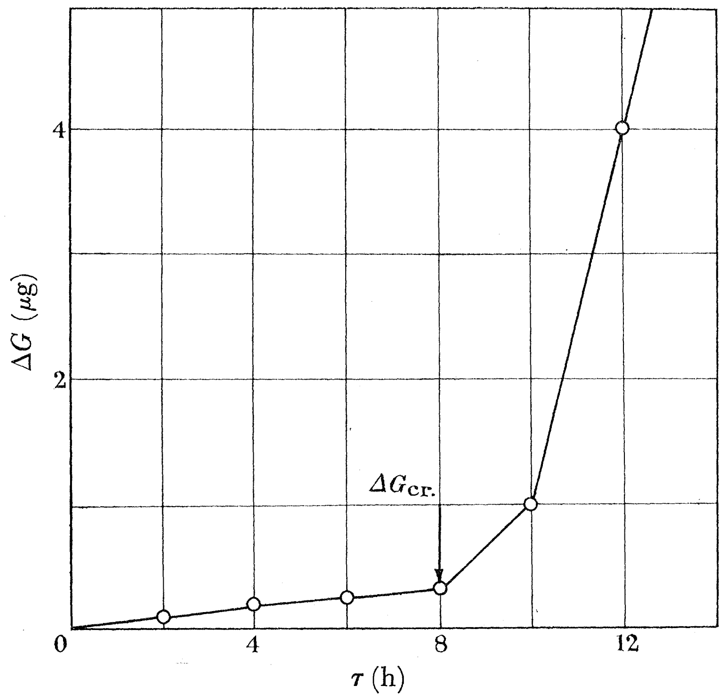

FIGURE 6. Graph of $\Delta G(\tau)$ showing a clearly demarked incubation period. Working chamber, 48×200 mm^2; d = 48 mm; v = 12 m/s.

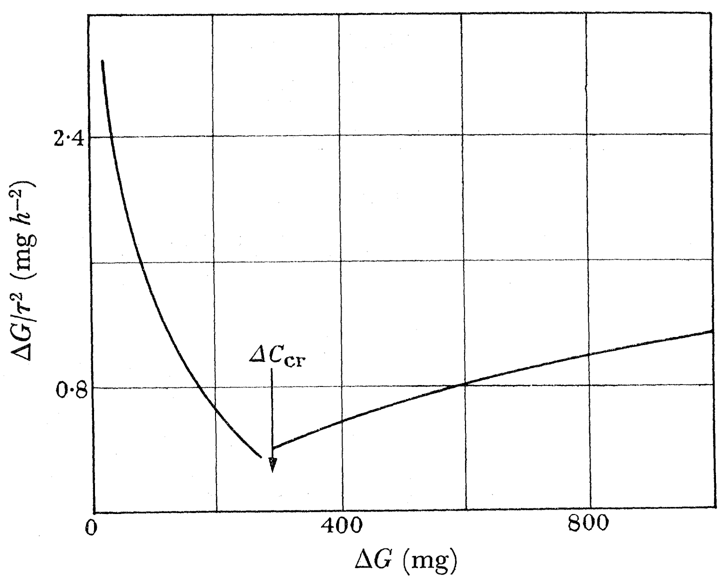

FIGURE 8. Determination of critical $\Delta G_{cr.}$. v = 12 m/s; working chamber, 48×200 mm^2.

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Specific volume of erosion

Determinations of the specific volume of erosion are shown on the graph of $\Delta V_0(\mathrm{We})$ in figure 9. Some of these experimental results, namely for cylinders with d = 6, 7·5, 12, 15 mm, were obtained during two periods of the damage of the specimen. Deviations of single data from the mean value $\Delta V_0 = 60\times10^3\ \mu\mathrm{m}^3\ \mathrm{kg}^{-1}\ \mathrm{m}^{-1}$ reach more than 50%. Nevertheless, it can be seen that the mean value ΔV_0 can be expressed by a straight line parallel to the abscissa. The scattering of test points can be explained by the uncertainty in relation to the selection of the ΔG value. On the same graph are plotted ΔV_0, obtained for $\Delta G_{\mathrm{cr.}}$ from the data of tests with cylinders of d = 24 and 48 mm. Deviations from the mean value $\Delta V_0 = 3{\cdot}0\times10^3\ \mu\mathrm{m}^3\ \mathrm{kg}^{-1}\ \mathrm{m}^{-1}$ do not exceed 20% and are explained by the usual experimental errors.

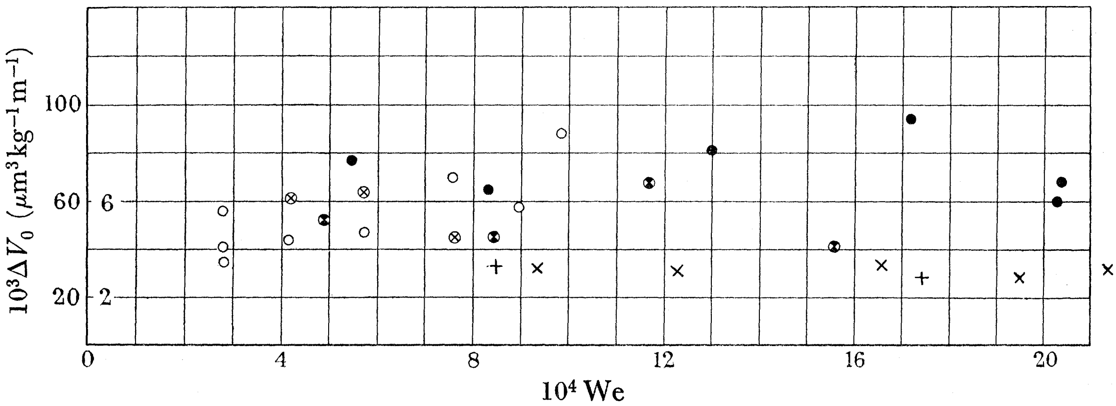

FIGURE 9. Relation between specific volume of erosion and Weber number for several series of tests at λ = 3 and h/d = 1.

	○	⊗	●	◉	+	×
$a\times b$ (mm^2)	6 × 25	7·5 × 25	12 × 50	15 × 50	24 × 100	48 × 200
d (mm)	6	6	12	12	24	48

5. INTERPRETATION OF SCALE NUMBERS

The notion of the energy parameters of cavitation erosion can be used now to study the effect on the intensity of damage of the principal hydromechanical parameters: i.e. the velocity and characteristic dimensions of geometrically similar bodies and channels. In transition from the model (index m) to the prototype (index n) in the case of similar materials, we must assume, according to figure 9, that

$$\Delta V_0 = \frac{\Delta V_n}{\Delta C_{xn}\, d_n\, h_n\, q_{\infty n}\, v_{\infty n}\, \gamma_n}$$

$$= \frac{\Delta V_m}{\Delta C_{xm}\, d_m\, h_m\, q_{\infty m}\, c_{\infty m}\, \gamma_m} = \text{const.};$$

hence

$$\Delta V_n = \Delta V_m \frac{\Delta C_{xn}\, d_n\, h_n\, q_{\infty n}\, v_{\infty n}\, \gamma_n}{\Delta C_{xm}\, d_m\, h_m\, q_{\infty m}\, v_m\, \gamma_m}. \tag{3}$$

According to the graph of ΔC_x against We (figure 5), we can assume

$$\Delta C_{xn,\,m} = (\mathrm{We}_{n,\,m})\tan\alpha_0 = \frac{\rho_{n,\,m}\, d_{n,\,m}\, v^2_{\infty n,\,m}}{\sigma_{n,\,m}}\tan\alpha_0.$$

For liquids with similar physical properties, $\rho_n = \rho_m$, $\sigma_n = \sigma_m$, $\gamma_n = \gamma_m$. For geometrically similar models, $d_n/d_m = h_n/h_m = 1$. After the substitution of the above-mentioned values in (3), we have

$$\Delta V_n = \Delta V_m L^\alpha V^\beta, \tag{4}$$

where $V = v_{\infty n}/v_{\infty m}$; $\alpha = 3$ and $\beta = 5$.

If the tests are carried out at $d_n = d_m$, then we have $h_n = h_m$, as for example in the tests of the effect of flow velocity on the intensity of erosion in one and the same chamber. Thus

$$\Delta V_n = \Delta V_m V^5. \tag{5}$$

If the tests are carried out at $V_{\infty n} = V_{\infty m}$, but with different sizes of models, then

$$\Delta V_n = \Delta V_m L^3. \tag{6}$$

Let us consider the results of an experimental study of the influence of a flow velocity and characteristic dimension of the model on the erosion intensity. Knapp (1955) has found from experiments on erosion of axially symmetric bodies made of aluminium that the exponent for the scale number of velocities can be accepted as $\beta = 6$. Rata (1960), in his tests of thin zinc and brass plates in a working chamber of the Schröter–Walcher type, obtained in five tests $\beta = 4{\cdot}05$ to $6{\cdot}0$, and in seven tests $\alpha = 8$ to $8{\cdot}3$. The flow velocity varied within the range $v = 30$ to 40 m/s. In the experiments of Gowinda Rao & Thiruvengadam (1961), $\beta = 3$ to 8. In tests where the results were independent of test duration, Hammitt (1963) obtained $\beta = 5$, as the limiting value. The great diversity of test data pertaining to the value β can be explained by the peculiarities of the method of evaluating the erosion intensity (Knapp 1955), an insufficient number of tests (Gowinda Rao & Thiruvengadam 1961), or a small range of velocities (Rata 1960). In our investigations we came to the conclusion that $\beta = 5$, if the identity of test conditions is carefully observed (Varga, Tchernyavsky, Shal'nev 1963; Varga & Sebestyen 1964). Kerr & Rosenberg (1958) on the basis of field tests also accept $\beta = 5$.

We are not aware of any investigations of scale number for the characteristic dimensions of models. A discrepancy of experimental values of α was observed in our previous tests with cylinders of various diameters. The present studies have shown that $\alpha = 3$, when the value $\Delta G_{\text{cr.}}$ is used.

6. Conclusion

As explained here, the inverse value of the specific volume of erosion is a measure of the work required to damage by erosion a unit volume of material. Its comparison with the damage work produced by well known mechanical forces of pressure or tension is of great interest. In the case of equality of both kinds of work, the identity of forces may be presumed.

There is a reason to suppose the manifestation of a special cumulative effect. The damage of deep erosion pits occurs by damage of the side walls of the pits. This can be seen from the photographs (shown in figure 10, plate 53). At the bottom of some pits deposits of copper particles are present, carried by the ion flow from the copper cylinders to the lead. Copper particles in the form of globules are settled at the pit bottom as small heaps and stay undisturbed, while the side walls are pulled outwards.

When the energy parameter is being calculated, it is necessary to know the value of a certain part of the model drag spent on the damage. This problem needs a deep theoretical study and precise experiment. It is necessary to have a correct idea about the kinematic structure of the cavitation zone when investigating this problem. Results of our high speed photographic observations of the cavitation zone in the wake of a cylinder near the point of burbling cavitation (figure 11, plate 54) show that the cavitation bubbles pulsate with a very high frequency, while the form and volume of bubbles drastically change from frame to frame during a time of 10^{-4} s. Probably the frequency of pulsation wholly conforms to the frequency of resonant pulsations determined by Mineart's formulae (1933). Moreover, we notice that the bubbles do not close on the surface of the body. It is doubtless, however, that further investigations of the erosion intensity at other stages of cavitation and over a greater range of the Reynolds numbers should help the solution of this problem.

An idea is given of the limiting velocities at which no erosion occurs and which are characteristic of each material. For example, is not the flow velocity 1 m/s a limiting velocity for the lead, when it would be damaged by cavitation only after 1000 years (Shal'nev 1961 *a*)?

The causes giving rise to a cavitation need to be carefully studied when prognosis is given as to the volume of erosion in field conditions on the basis of model tests. Such causes could be the projections of identical size on the surface of the model and prototype. Then the scale effect should depend only on the velocity scale.

For a correct evaluation of cavitation-erosion resistance of materials according to tests on models, the tests should be carried out at velocities exceeding the field velocities, but in conditions of similarity of the type of cavitation stage and relative dimensions of the model and channel.

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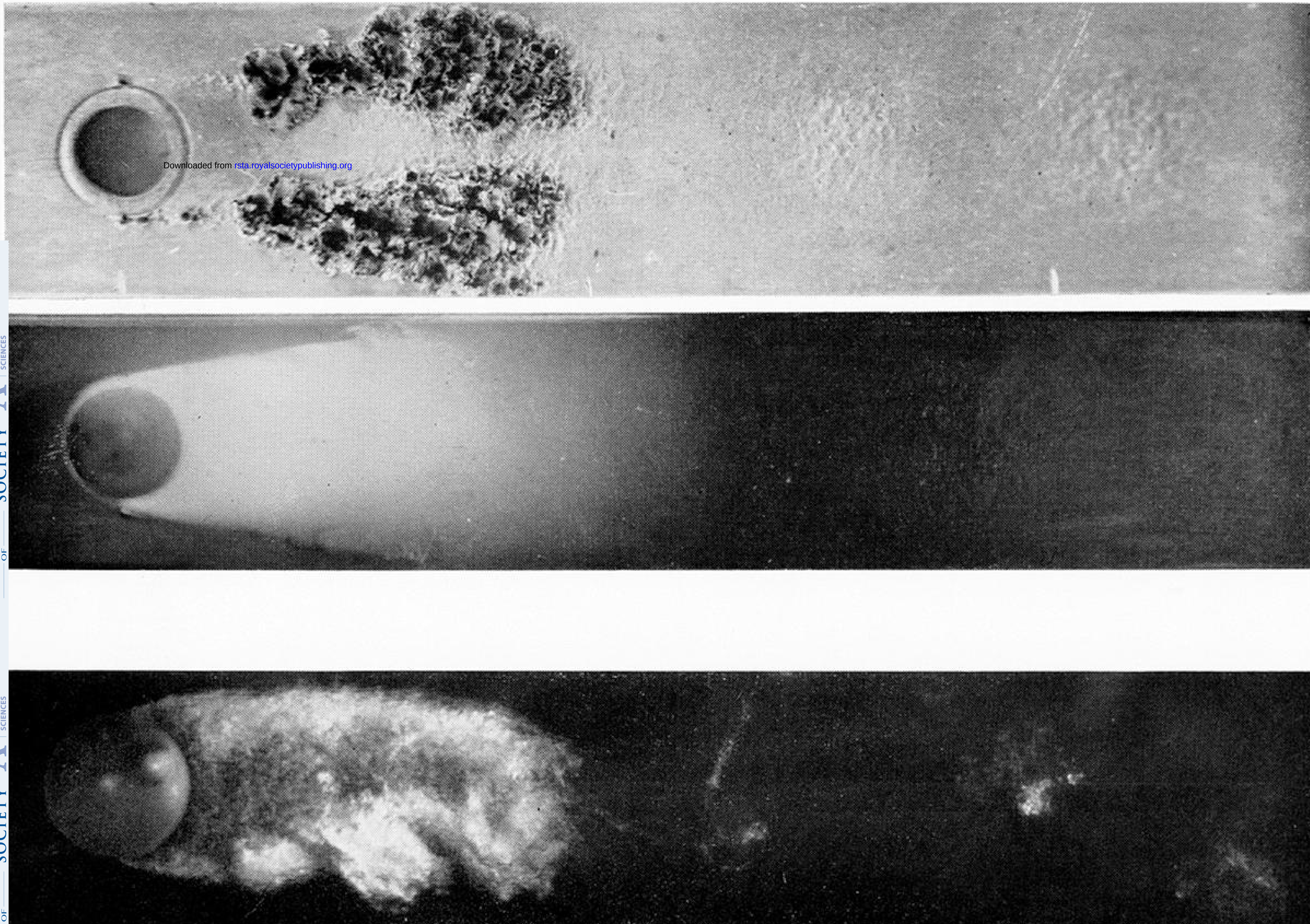
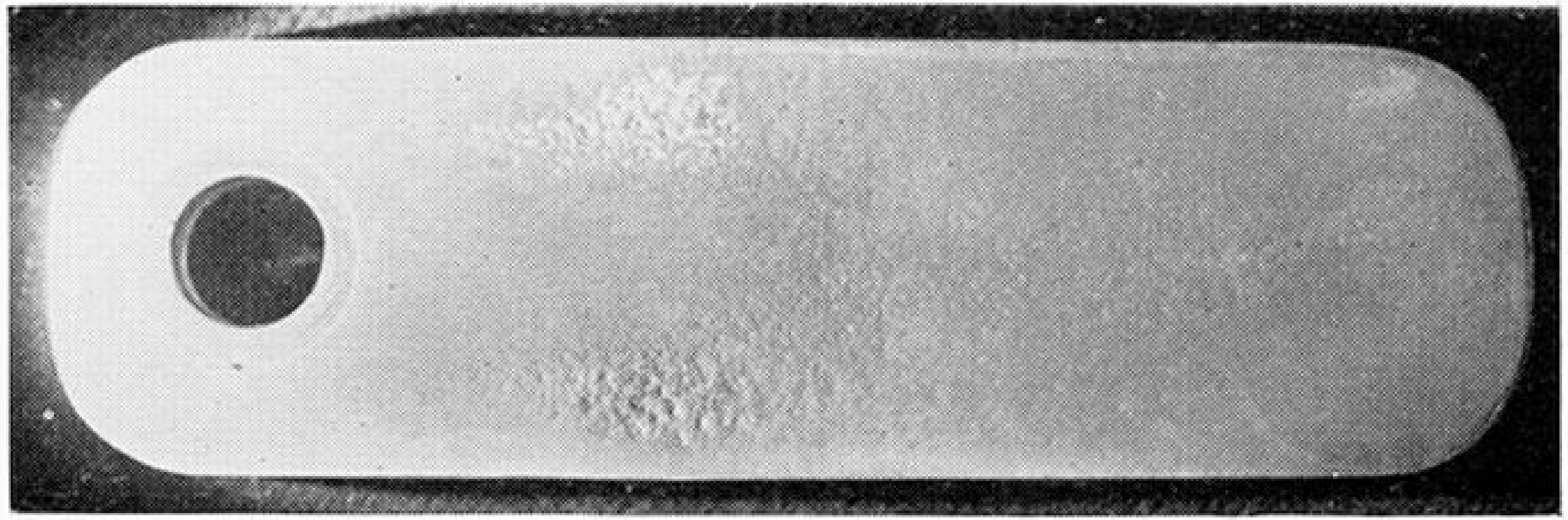


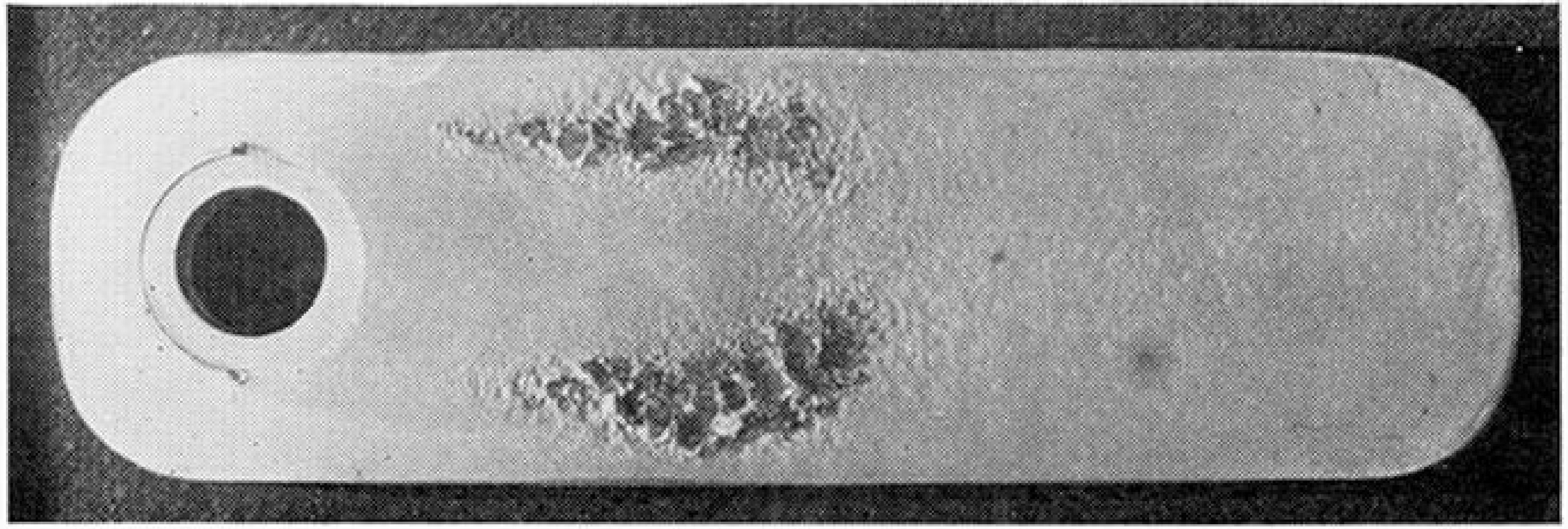
(a)

(b)

FIGURE 2. Cavitation zone and erosion zone of the lead specimen: (a) at a long exposure; (b) at a short exposure.



(a)



(b)

FIGURE 7. Cavitation erosion of a lead specimen: (a) at the initial stage of damage, up to $\Delta G_{cr.}$; (b) at the developed stage of damage.

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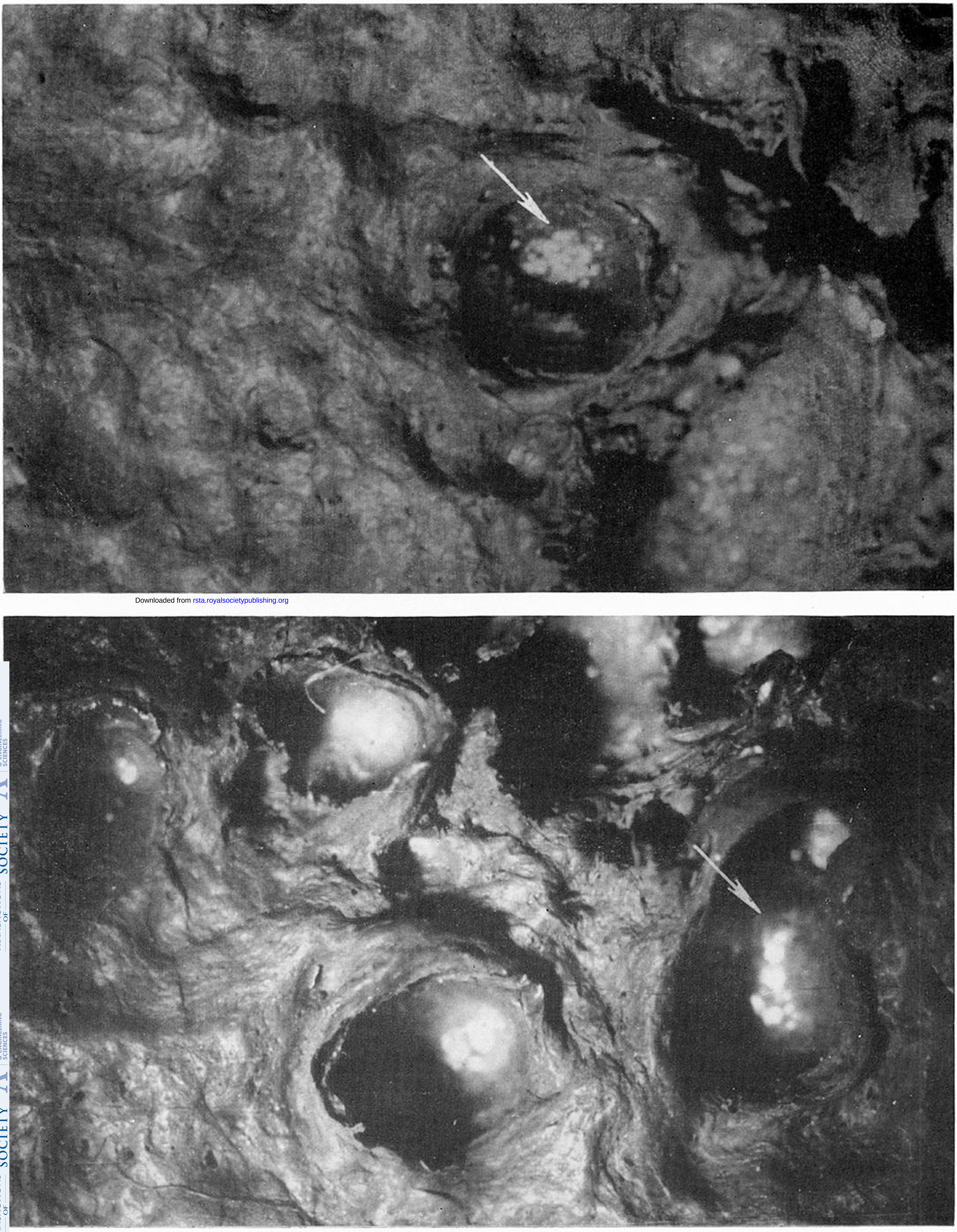

FIGURE 10. Erosion pits in the initial stage and in the developed stage. Arrow shows the accumulation of copper particles. (Magn. ×30.)

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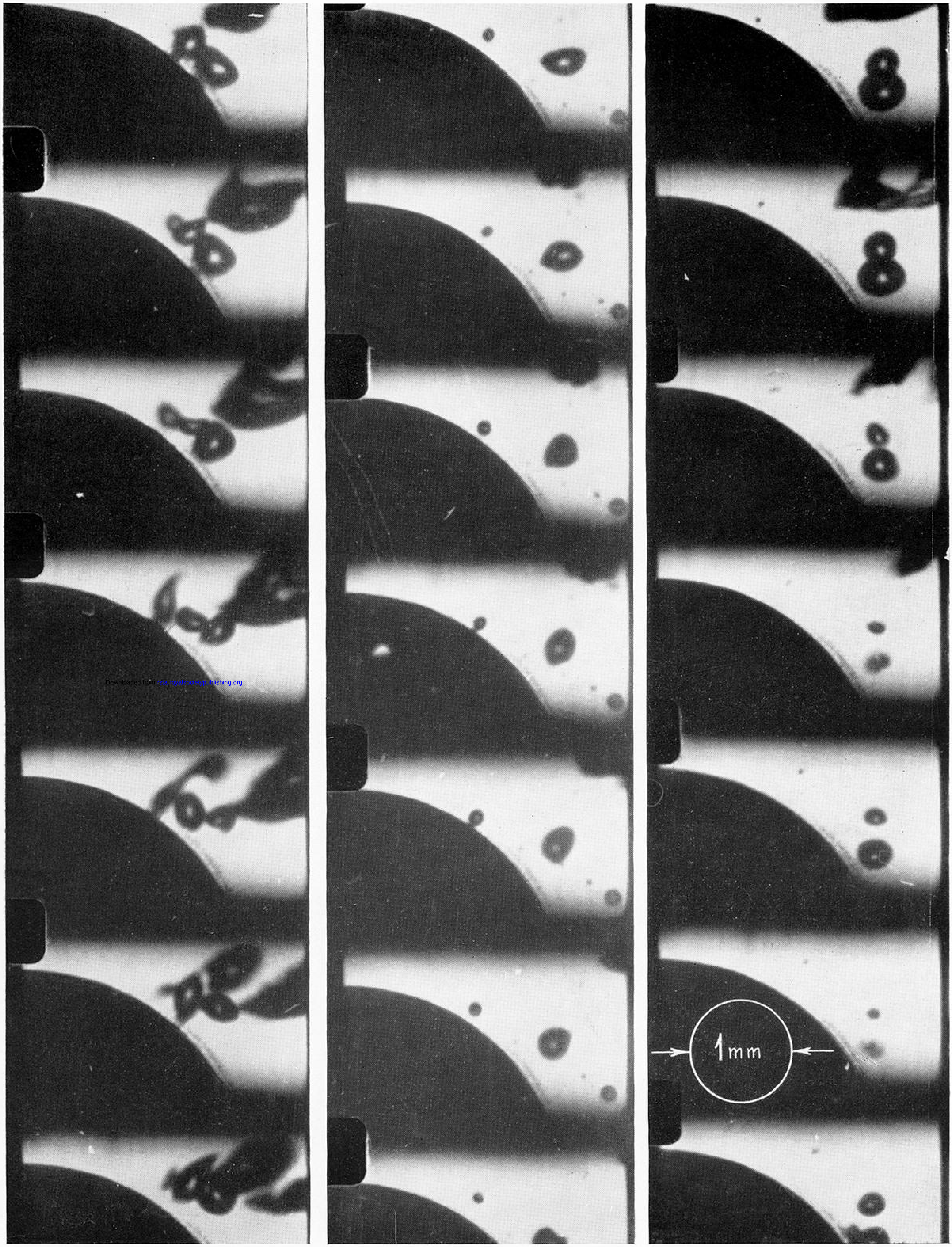

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FIGURE 11. Several successive sequences of a high-speed ciné film of a small part of the cavitation zone in the wake of a cylinder. Pulsating bubbles are seen.