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ON CAVITATION AND SUB-COOLED BOILING BUBBLE COLLAPSE

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by

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ABSTRACT

The possibility of the applicability of spherical symmetry to cavitation and highly sub-cooled bubble collapse is considered in the light of present photographic and theoretical evidence, and it is concluded that such symmetry is unlikely in situations of engineering importance. Rather an asymmetry which generates a high-velocity microjet is a more likely mode of collapse. The present evidence relative to the importance of microjet impact as opposed to the classical spherical shock-wave model for cavitation damage is examined and some new experimental evidence presented. It is concluded that the microjet model is most likely of predominent importance in cavitation damage. Some estimates for the pertinent parameters of such microjets are presented.

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I - INTRODUCTION

For many years, since the pioneering analysis of Rayleigh, in 1917, it was assumed that bubble collapse under conditions where the liquid pressure is substantially in excess of the saturation pressure could be adequately treated if spherical symmetry were assumed for the entire process. In addition the damage resulting from such collapses was assumed to be the result of the imposition of spherical shock-waves propagated through the liquid upon the material surface. However, evidence gathered over the past few years indicates more and more strongly that in most real cases involving this phenomenon the assumption of a collapse which is spherically symmetric is not realistic. The resultant non-symmetries appear then responsible for the generation of high-velocity liquid jets which are associated with the collapse, and the impact of which on adjacent surfaces may well be responsible for the observed cavitation pitting. It is the purpose of this paper to review the evidence pertinent to these questions, and to present some new evidence which has been generated in the writer's laboratory at the University of Michigan.

II - APPLICABILITY OF SPHERICAL SYMMETRY TO BUBBLE COLLAPSE

A - General considerations

Practically all analyses of cavitation or sub-cooled boiling bubble collapse from that of Rayleigh[1] up until very recent years have assumed spherical symmetry. This was of course made necessary by the severe mathematical complexities of the problem if other than "ideal fluid" parameters were to be considered. In fact the major effort in the years following Rayleigh was to improve his ideal fluid analysis so that more meaningful numbers for pressure wave magnitudes and velocities propagating through the fluid away from the collapse could be obtained, since Rayleigh's assumption of an inviscid, incompressible fluid might be expected to lead to unreasonably high estimates for these quantities. it was not actually possible to acheive such realistic analyses of the collapse with spherical symmetry until the advent of modern electronic computers. Theoretical exploration of the problem of non-spherical collapse is at present only in its infancy.

The possible importance and probable existance of non-spherical collapses was first discussed in the literature by Kornfeld and Suvorov[2] in 1944. However, the present interest in the possibility of this mode of collapse stems from the excellent photographs obtained by Naude and Ellis[3] in 1961. In fact most of the evidence pertinent to the question of the suitability of the assumption of spherical symmetry for bubble collapse analysis is that of high-speed photography, using equipment which has generally been available only over approximately the last decade. A review of this evidence [4,5,6,7,8,9] indicates that a substantially spherical bubble collapse is not at all likely in ordinary engineering situations where turbulent flow, pressure gradients, and the proximity of walls exist. If great care is taken to remove all non-symmetric influences including that of gravity it is possible to obtain approximate spherical symmetry over a large ratio of volume reduction [7,8], although even so it is unlikely that the symmetry will persist until the termination of the collapse.

B - Theoretical considerations

On theoretical grounds there are several reasons to doubt the applicability of the assumption of spherical symmetry. In 1956 Plesset and Mitchell [10] showed that a spherical collapse was unstable in the sense that a small perturbation of the spherical symmetry might be expected to increase after a certain volume reduction had been acheived, whereas the inverse case of bubble growth was stable. While this result is interesting as indicative of the likelihood of non-spherical bubble collapse even in cases of apparent symmetry, there are obvious asymmetries inherent in most real situations which are probably of greater importance.

In any situation involving damaging cavitation damage or sub-cooled boiling from a heated wall, it is almost certain that the presence of the wall will be an important asymmetrical influence. The validity of this statement can be demonstrated on very simple grounds.

If spherical symmetry is to apply it is necessary that the pressure and velocity must not be functions of angle at any time during the collapse. If the bubble collapse starts with the nearest bubble wall no more than the order of the bubble diameter away from a wall, it is intuitively obvious that flow to the side of the bubble adjacent to the wall will be proportionately restricted so that both radial velocity and pressure on this side of the bubble will be less during the collapse than the same quantities on the opposite side at the same distance from the collapse center. It is then obvious, due to the non-uniformity of radial velocity, that the collapse cannot remain symmetrical about the original collapse center, and it would be merely fortuitous on intuitive grounds if the bubble shape remains a sphere.

It is also clear that the bubble centroid will move during collapse toward the wall, as has been long recognized and more recently shown photographically[7,8,11]. This translatory motion will then induce further asymmetries in the pressure field around the bubble. Thus spherical symmetry cannot strictly be applied to a collapsing or growing bubble moving relative to the surrounding liquid, as has sometimes been done [12]. The converse of the above statements also applies in that a growing bubble will be repelled from a wall.

In addition to wall proximity and relative velocity there is also the asymmetrical effect of a pressure gradient, which in most flowing situations of interest will exist. These effects for a flowing system are shown in Fig. 1 and 2 from experiments in the writer's laboratory on cavitation bubbles collapsing in the diffuser of a cavitating venturi. It will be noted that the bubble flattens on the high pressure side and in one case appears to involute into a ring vortex formation (Fig. 1).

Various at least approximate analyses[11, 12, 13, 14,15] of bubble motion near walls and in pressure gradients now exist in the literature although the complete problem for non-ideal fluid parameters has not yet been solved.

III - EVIDENCE RELATIVE TO SHOCK WAVE AND JET CAVITATION DAMAGE MECHANISMS

A - General considerations

As previously mentioned it was generally accepted up until the last few years that cavitation damage was the result of the impingement of spherical shock waves transmitted through the liquid and emanating from the center of bubble collapse onto the surface to be damaged as postulated by Rayleigh[1] The experimental and theoretical study of Naude and Ellis[3] then indicated the possibility of damage being the result of the impingement of a high velocity microjet resulting from an asymmetrical bubble collapse near a wall. A somewhat similar but later experiment by Shutler and Mesler[5] indicated the further possibility that shock waves from the collapse of the toroidal vortex which forms around the central microjet might also be damaging, perhaps more so than the jet itself. However, neither experiment resembles a conventional flowing system in that a cavitation bubble was generated in each case in a static system by the discharge of a spark between electrodes separated by a small gap and close to the surface to be damaged.

At the moment there is no concrete evidence regarding the relative importance of the various possible damaging mechanisms for flowing systems. However, various bits of circumstantial evidence are available, several from tests in the writer's laboratory which will be here summarized. The venturi and vibratory cavitation facilities which were used have been previously described[16] .

B - Detailed Structure of Cavitation Pits.

Fig. 3 shows cavitation pits presumably from individual bubble collapses from the venturi[17] (operating with mercury) on stainless steel coated with a 0,6 μm layer of electro-deposited chromium.

The chromium plate, when submitted to cavitation, was removed over small central craters and partially removed over somewhat larger surrounding areas. This behavior is very consistent with the concept of a high velocity microjet impacting the center of the crater and giving rise to an even higher radial velocity which "washes off" the chromium plate entirely near the point of impact and partially at larger distances. It is not at all consistent with the concept of a spherical shock front impinging at this point, since this would merely press the chromium plate down into the surface. To test this hypothesis, a small steel ball was fired at a similar chrome-plated surface with a velocity of the order of 100 m/s. It was found that a small crater was formed but that the chromium plate was not removed.

Fig. 4 shows individual cavitation pits in plexiglass exposed in our venturi to water cavitation, while fig. 5 shows a crater in the same material caused by a jet from a 1.7 mm diameter nozzle with velocity of about 700 m/s, also obtained in our laboratory. As has been previously demonstrated by Brunton[18] and others also, liquid jet impact on plexiglass in this velocity range produces a relatively non-damaged area around the point of impact surrounded by a damaged ring. This can be explained on the basis that plexiglass is weaker in tension than compression. While the loading at the point of impact is essentially compressive, that in the damaged ring is tensile, opening permanent deformation cracks.

Examination of Fig. 4 and 5 demonstrates a striking similarity between the craters created in plexiglass by cavitation and by jet impact. The complex cavitation damage pattern of Fig. 4 is hardly consistent with the concept of the impingement of a spherical shock front in this region, being much more consistent with the concept of a high-velocity microjet impacting in the center pit. Since damage under the presumed point of impact does exist for the cavitation case, presumably the jet velocity is somewhat higher than that used with the jet impact device. Thus it might be assumed that the cavitation microjet velocity is in the order of 1000 m/s, consistent with Brunton[18]. It is believed that the polygonal shape of the central pits is a result of the microstructure of the material. Note that the diameter of these pits is about 10 μm.

The outer damaged ring of the cavitation pits can be explained in the some manner as for the jet impact pits. However, its appearance is also consistent with Shutler and Mesler's hypothesis[5] that damage results from the collapse of the toroidal vortex as well as from the central jet.

Fig. 6 and 7 show that the shape of the cavitation pits generated in the venturi is a function of throat velocit[19]. For the lower throat velocity of about 20 m/s the pits are generally approximately circular with a raised lip which is symmetrical (Fig. 6). For the higher velocity of about 60 m/s the pits are generally drastically elongated in the direction of flow and the raised lip is predominently on the downstream side, as may be seen from examination of the photomicrograph of the craters and the corresponding profilometer traces. This large dependence of surface and depth profiles of the pits on throat velocity can only be explained in terms of the microjet mechanism wherein the direction of the jet is presumably a complex function of the velocity profiles, etc. Though the angle with the surface cannot be forecast, it is capable of acheiving substantial values as is apparently the case in these tests. The apparent "tipping" of the craters in the high velocity tests cannot be justified in terms of the vector triangle which would be formed by the sonic velocity in the liquid (the approximate velocity of shock wave propagation) and the stream velocity, since only a very small angle would thus result.

Fig. 8 compares the profiles of conventional liquid impact craters[19] with cavitation craters. The shapes are very similar although the sizes are quite different.

C - Number Ratio between Craters and Collapsing Bubbles

Several test estimates exist[19] starting with Knapp[20] of the ratio between number of bubbles actually collapsing very close to a surface, both in flowing and vibratory cavitation systems, and the number of craters actually created. This ratio appears to be of the order of 10^3 or 10^4. This is confirmed by another very recent estimate[21] Thus a highly selective mechanism must exist which separates the very small number of damaging bubbles from the large proportion of non-damaging bubbles. This situation seems more consistent with the microjet than with the shock wave model, since an additional parameter, i.e., direction of jet, is added to those of bubble position and size in a given flow regime for the microjet model.

D - Detailed Microjet Characteristics

Much excellent photographic evidence of the formation of microjets in asymmetrical bubble collapse has been obtained and already discussed [3,5,6,7,8,9]. In addition a close examination of the negatives from the high-speed motion picture frames from our own laboratory composing Fig. 2 show the same indications. Fig. 9 is a photograph from our vibratory facility showing a toroidal bubble collapse on the face of the vibratory horn [22]. The jet appears to be impinging on the surface of the horn and deflecting radially. Fig. 10 is a typical photograph of the bubble field on the face of this horn showing the gross non-symmetry of most of the bubbles [22].

As previously mentioned a microjet velocity of the order of 1000 m/s was estimated on the basis of the appearance of cavitation pits in plexiglass (Fig. 4). This is also consistent with estimates based on a comparison of the profiles of impact and cavitation pits in various metals and with various fluids [19]. On this same basis it was estimated [19] that the microjet diameter lay between about 1 and 25 μm, and the microjet diameter was about 1/4 the pit diameter.

The diameter of the area of the central region on the cavitation pits on chromium-plated stainless steel (Fig. 3) from which the chromium was completely removed is about 50 μm, and the diameter of the central damaged region in the plexiglass cavitation craters (Fig. 5) is about 20 μm. Using the above estimate of 1/4 for the ratio of microjet to pit diameter, the probable microjet diameter from this new data would lie between 5 and 12 μm, thus being consistent with the previous estimate.

E - Results of Analytical Treatments

Two recent detailed numerical analyses of spherical bubble collapse, one including the effects of compressibility but using an "exact" calculation of the pressure propagations into the liquid[23], and the other, done in our own laboratory[24], which considered viscosity and surface tension as well as compressibility but used the Kirkwood-Bethe approximation for the calculation of pressure propagation into the liquid, each showed that the pressures developed in a spherically-symmetric collapse, even if the bubble were initially tangent to the wall, were not sufficient to account for the observed pitting in some of the stronger materials. However, pressures generated on rebound from a gas or vapor core were sufficient under these conditions. A later analysis[21] also included the effects of thermal restraint and finite condensation time on such bubble collapse as well as the other parameters listed above, and concluded that the bubble wall velocities computed in the earlier analyses[23, 24] were essentially correct. No calculation of the pressures propagated through the liquid were made in this case. None of the analyses has included the effect of the motion of the collapse center (which might be expected to increase the pressures upon the wall) and asymmetry due to the proximity of the wall into the calculation of shock pressures imposed upon the wall. Hence the calculations presently available neither prove nor disprove the possibility of cavitation damage resulting from liquid shock waves.

With regard to the microjet impact mechanism, if the estimated order of velocity of 1000 m/s (previously discussed) is correct, there is no doubt of the capability of this mechanism to produce the observed damage.

F - Microjet Direction

Photographic evidence[3,5,6,7,8,9] generally indicates that the microjet is projected in the direction of decreasing pressure where the pressure effect is predominent, or toward an adjacent wall where the wall effect is more important. It has been postulated on grounds of the conservation of linear and angular momentum that the jet must be in the direction of the relative velocity with respect to the fluid which exists before collapse starts, and that a toroidal vortex must be formed before collapse is complete [7]. These arguments have also been confirmed by a small perturbation analysis of the bubble collapses shown in our venturi diffusor[15](Fig. 1 and Fig. 2). When the bubble collapse starts in the diffuser the bubble of course exhibits "negative slip" with respect to the liquid so that the microjet is projected in the upstream direction according to the analysis, and as can be seen from close examination of Fig. 2. However, recent observations on flow in a centrifugal pump volute appear to disagree with these general concept[12]. Hence it is of value to consider a very simple model of the flow around a collapsing or growing bubble to provide an easily credible explanation of the anticipated microjet velocity with respect to the surrounding fluid.

For this purpose we will assume a "virtual mass" of liquid accompanying the bubble such that the momentum of the bubble system with respect to the frame of reference of the surrounding liquid at large distances from the bubble is correct. We will further assume that this virtual mass system has a relative velocity distribution, with respect to the frame of reference, normal to the direction of bubble motion. This distribution is symmetrical about the axis of such motion and is a maximum along the axis of motion, falling to zero at larger distances from this axis. If we assume potential flow and uniform pressure for the purpose of the present approximations, there will be no drag on the virtual mass system and hence the linear momentum of the mass making up this system must be conserved. If the bubble now begins to collapse and we assume for simplicity that it maintains its spherical shape, the virtual mass will decrease in proportion to the bubble volume so that portions of the system at largest distance from the axis of motion will become lost to the moving system,and a portion of the stationary system. Thus, since the lowest velocity portions are first to be lost from the moving system, the average velocity of the moving system must increase, if conservation of linear momentum for the original virtual mass system is to be observed. This process will continue as long as the bubble collapse continues, so that the bubble will continue to accelerate with respect to the fluid at large distances in the direction of its original relative motion.

By entirely analogous reasoning the relative velocity of the bubble will decrease for the case of bubble growth.

IV - CONCLUSIONS

The following major conclusions may be drawn :

1 - Spherical symmetry is not a realistic model for bubble collapse in most engineering situations. Still, calculations based on this assumption may be of value in comparing the relative pressures to be anticipated from the collapse of cavitation bubbles in various fluids, temperatures, pressures, etc.

2 - The preponderance of present evidence indicates the likelihood of the asymmetric collapse microjet mechanism being of primary importance in the production of cavitation damage.

3 - Typically such a microjet may have a diameter roughly in the range of 1 to 25 μm and a velocity of the order of 1000 m/s. The microjet will proceed in the direction of the relative motion of the bubble at the time of its formation.

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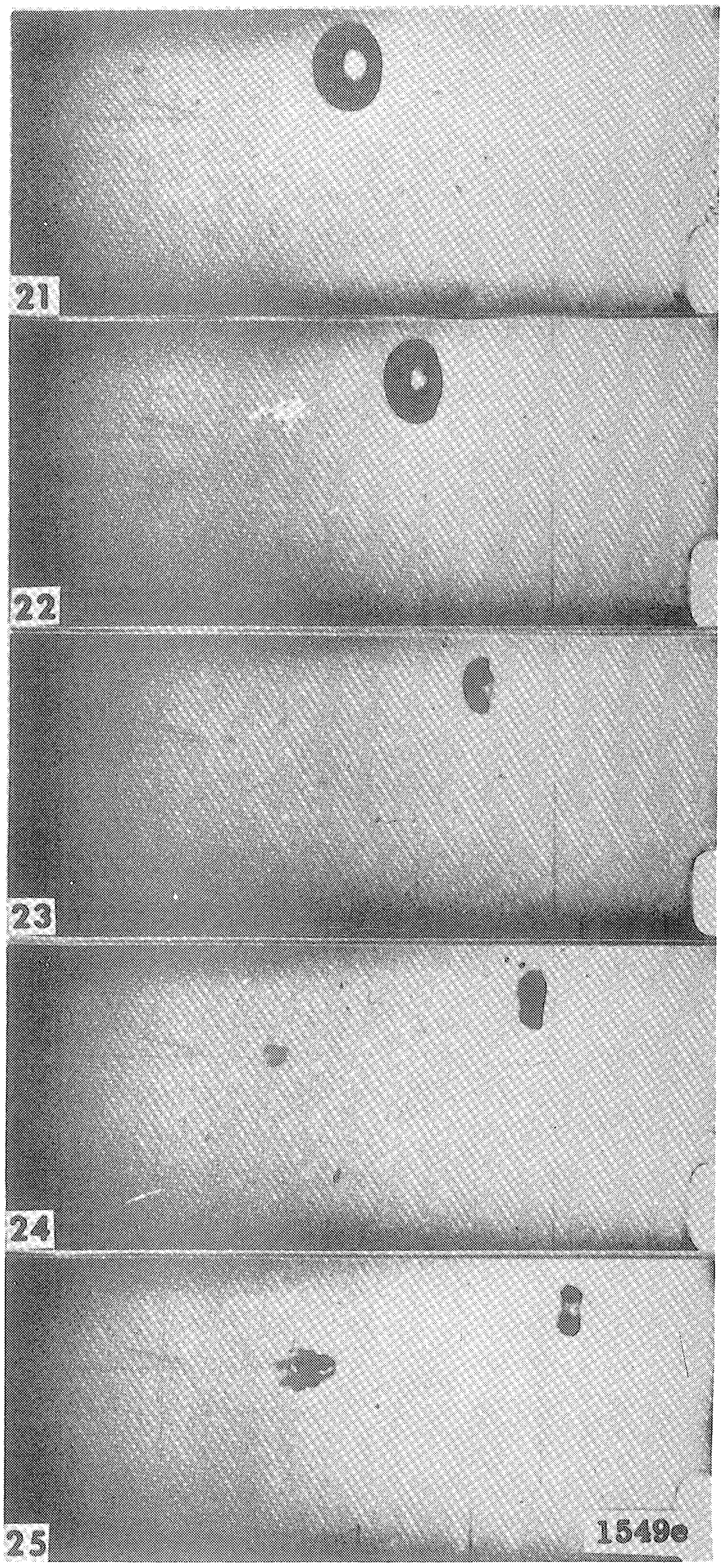


Figure 1

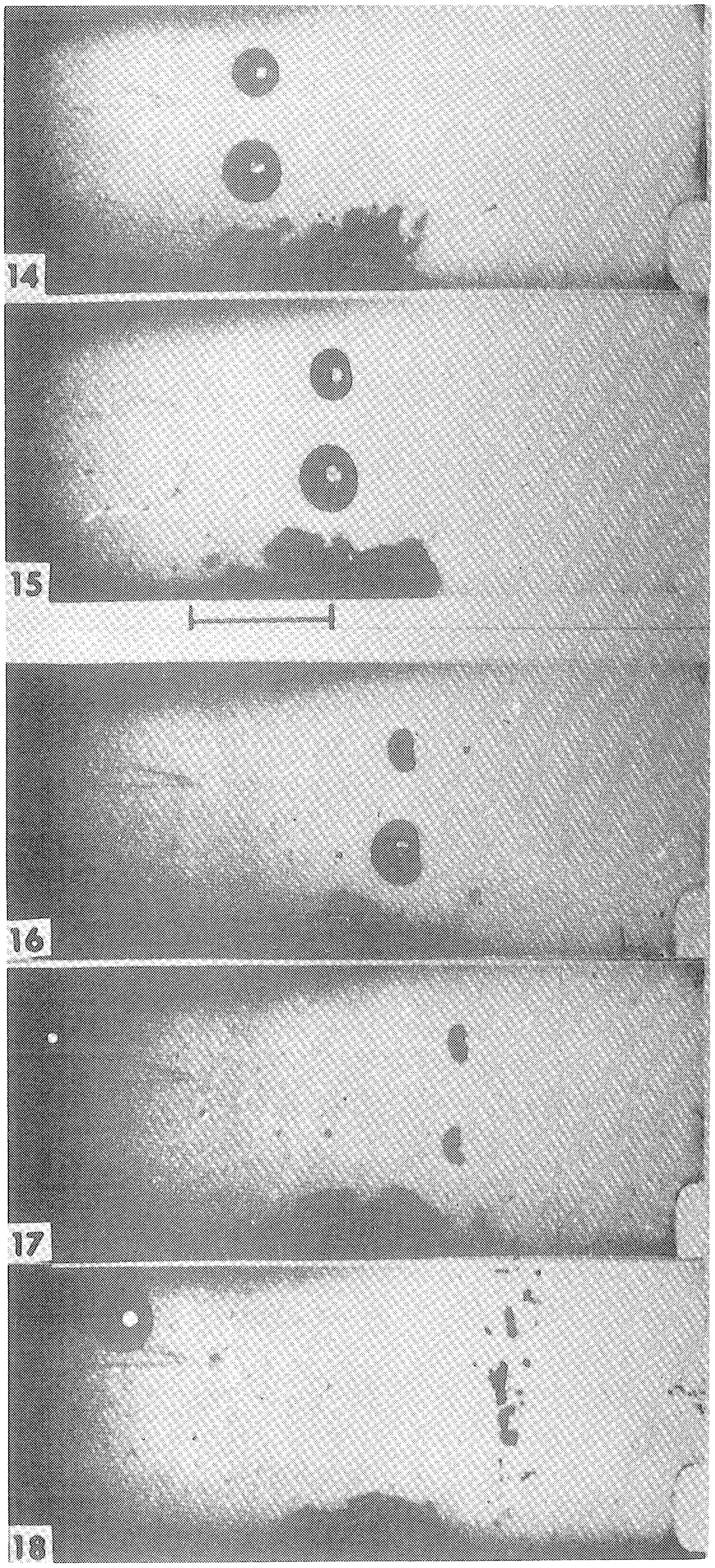


Figure 2

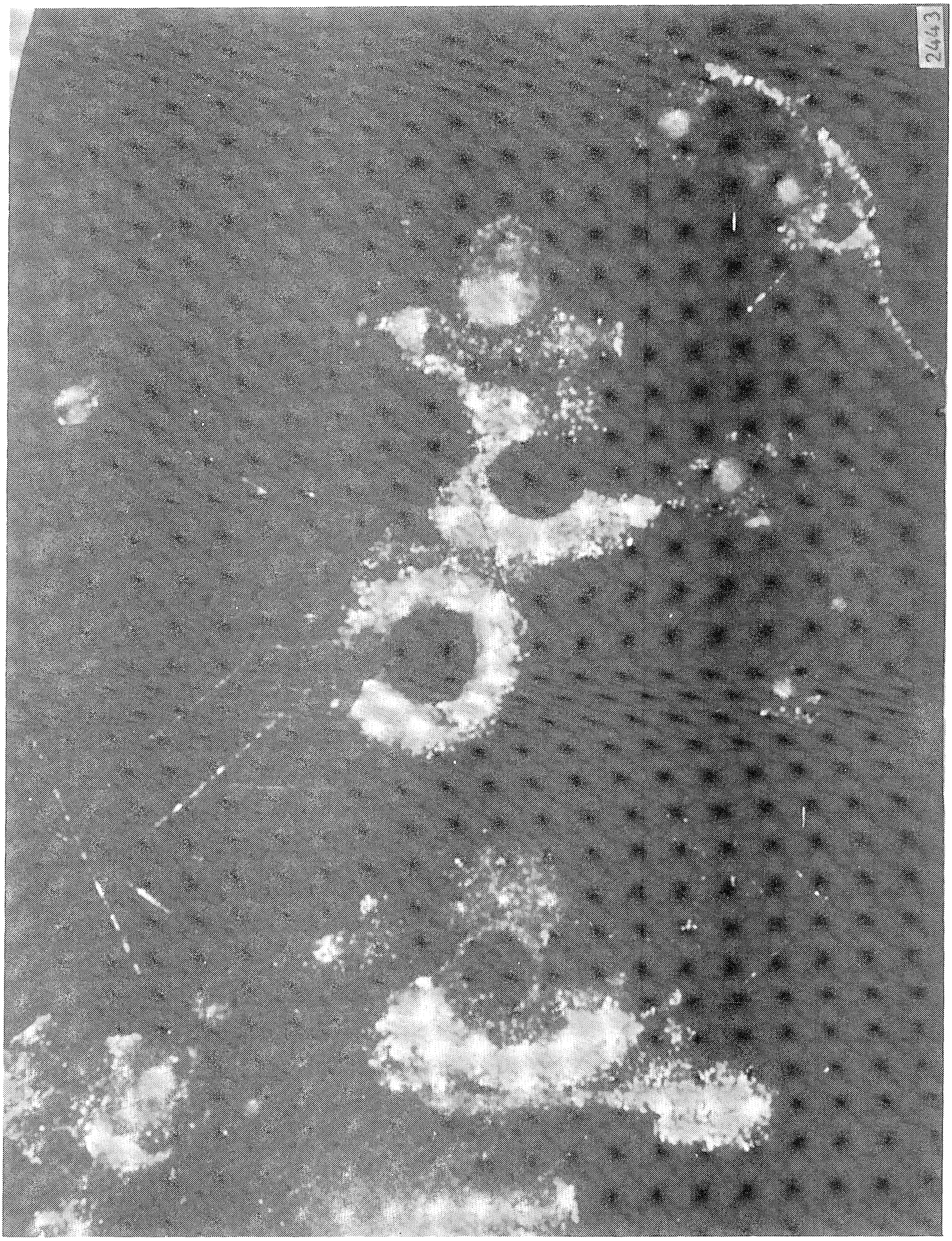


Figure 3

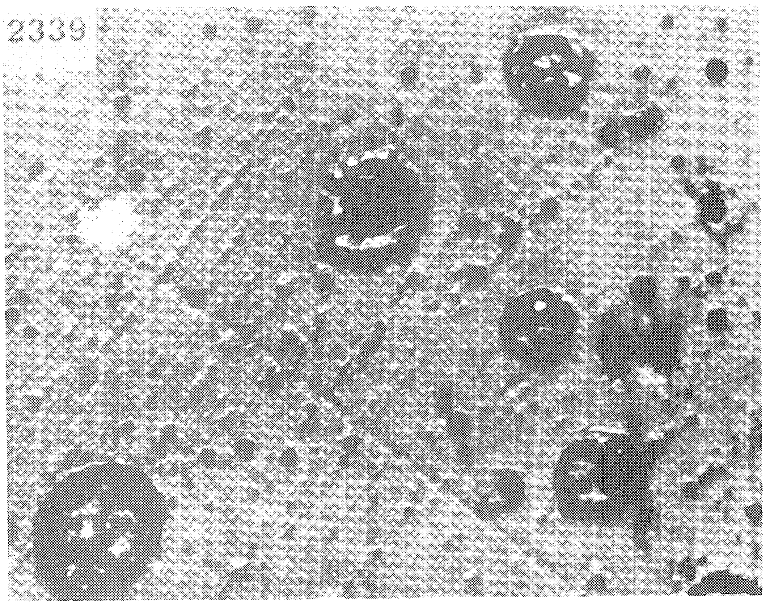


Figure 4a

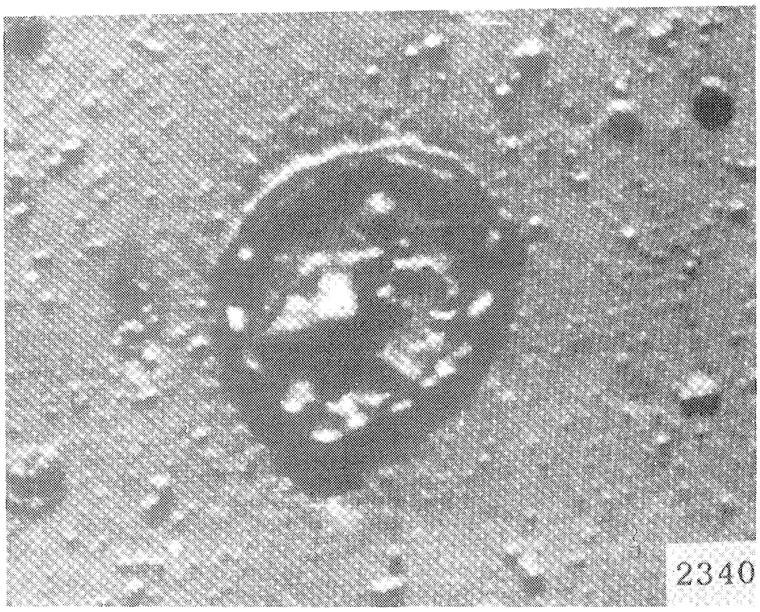


Figure 4b

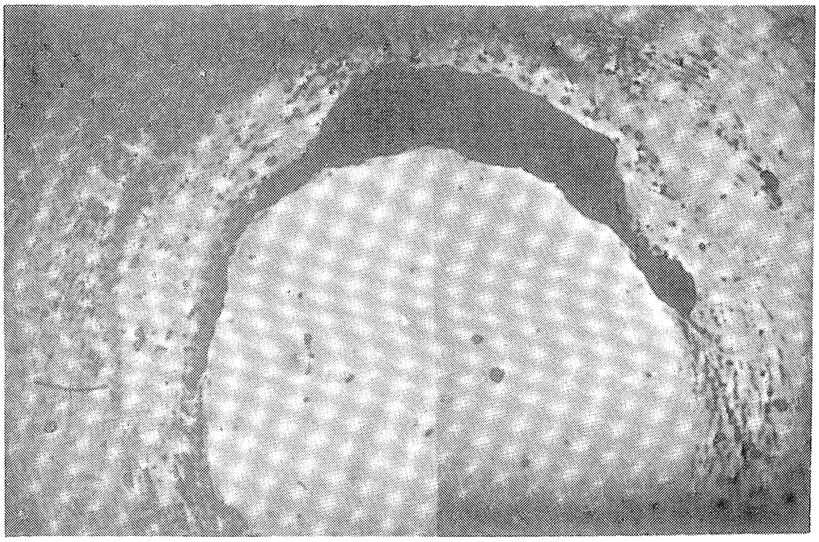
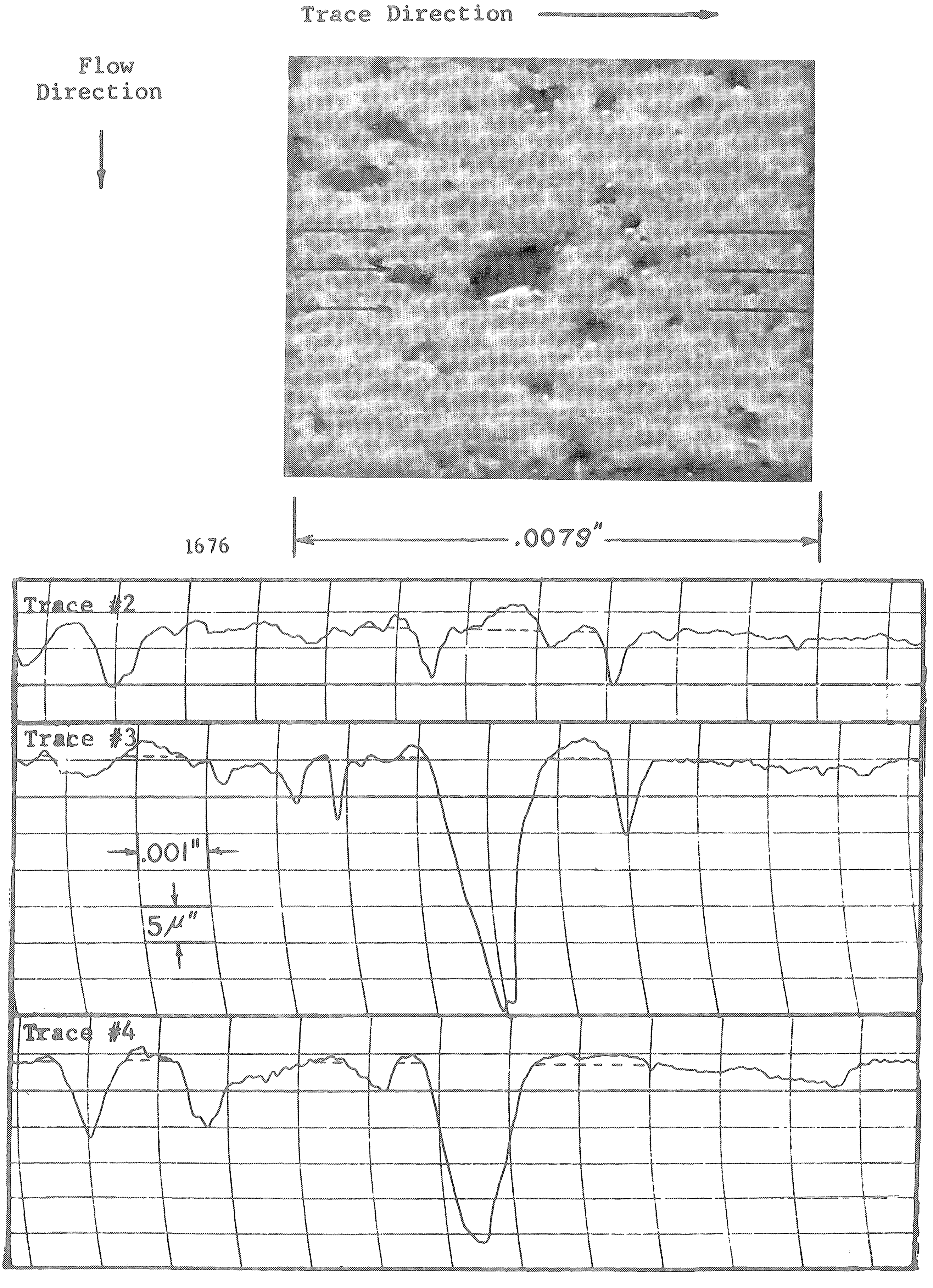


Figure 5

Figure 6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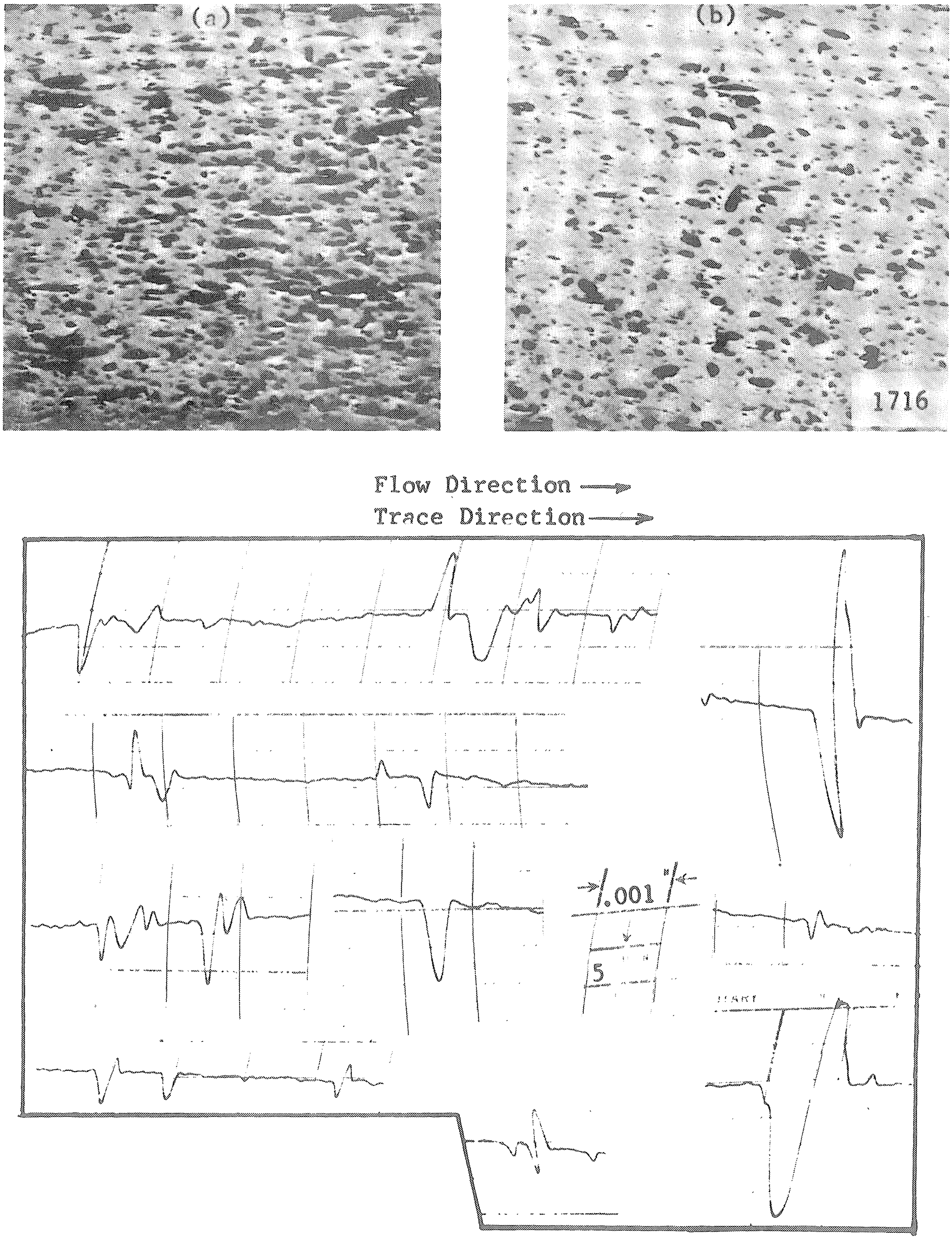
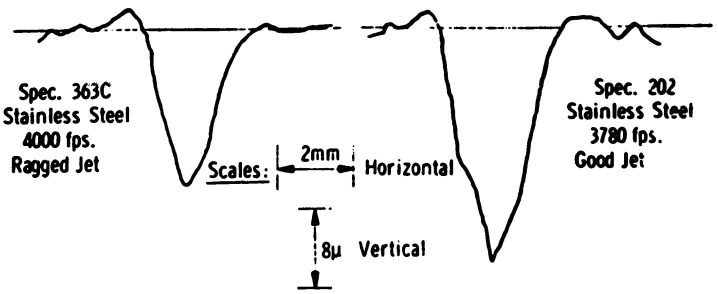
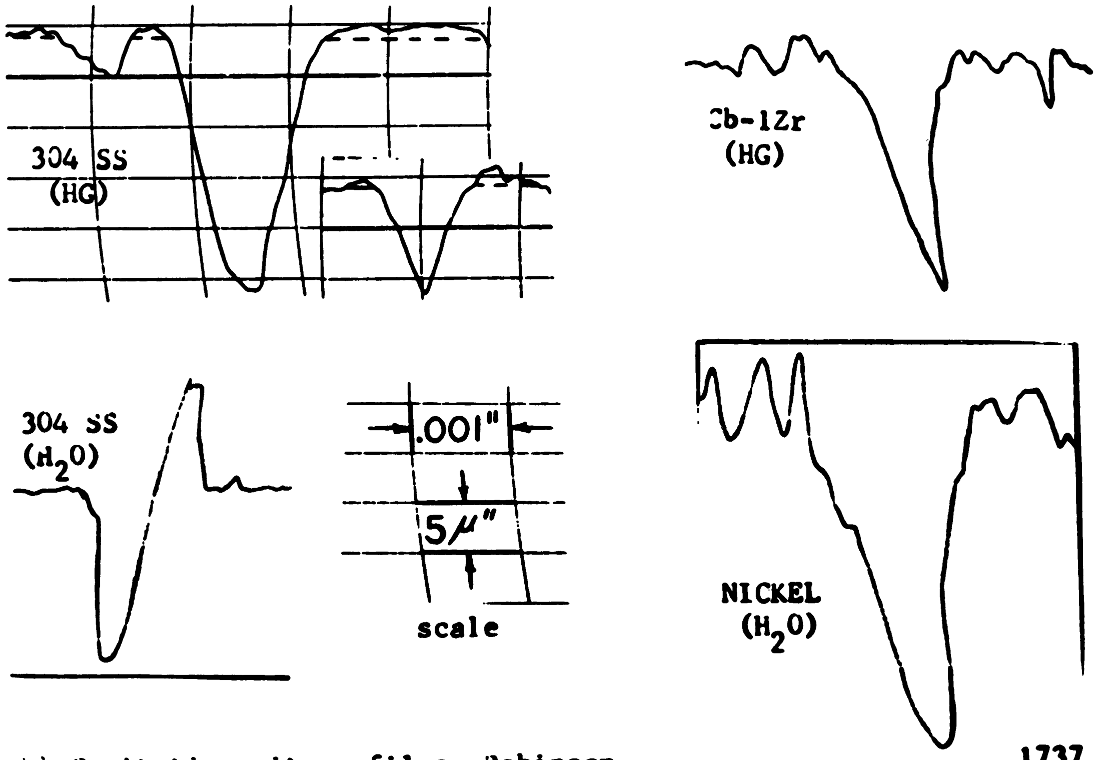


Figure 7



a) Water impact pit profiles from DeCorso .



b) Cavitation pit profiles, Robinson .

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Figure 8

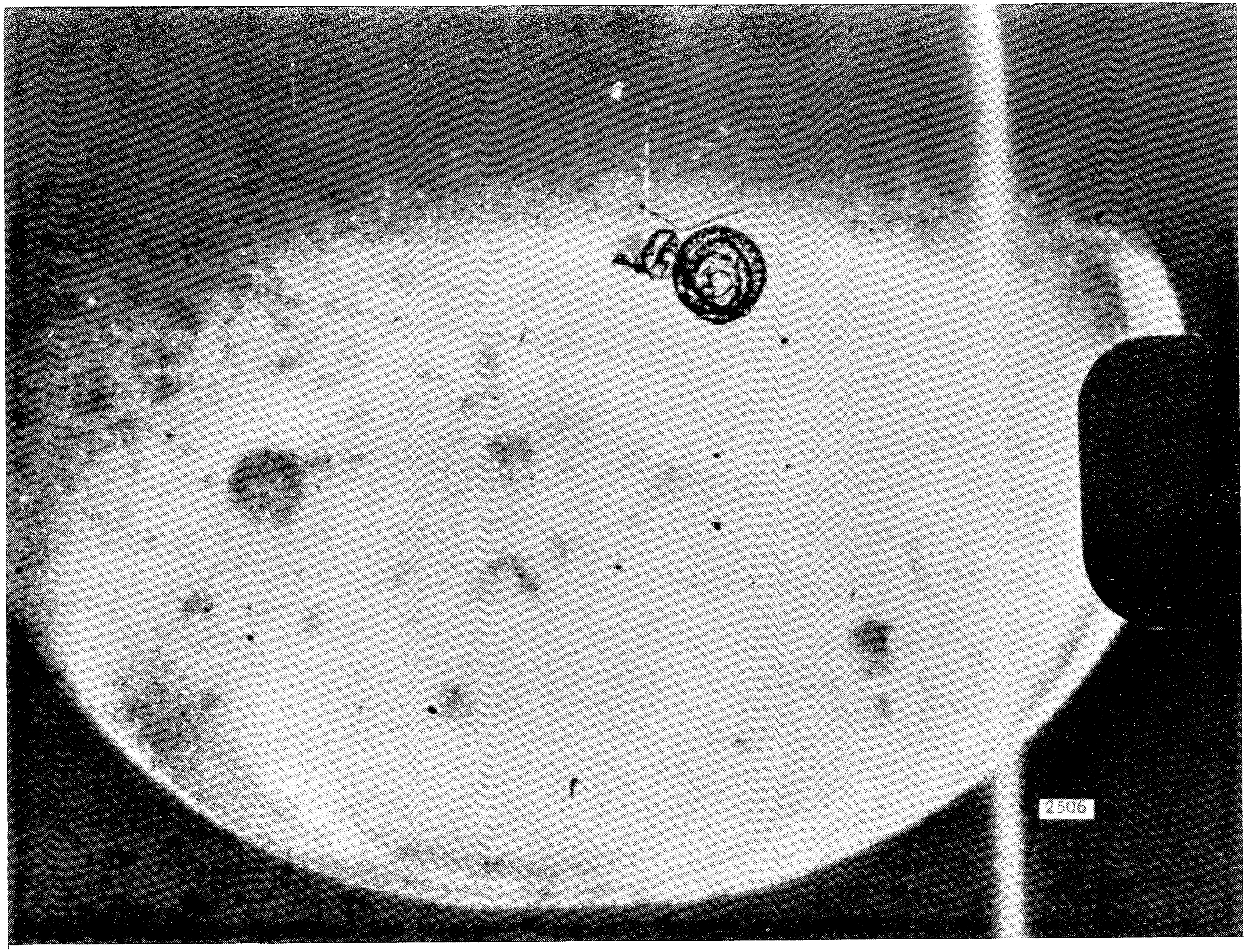

Fig. 9.--The result of the collapse and apparent rebound of large bubble in water at an approximate diameter at rebound of 1 mm.

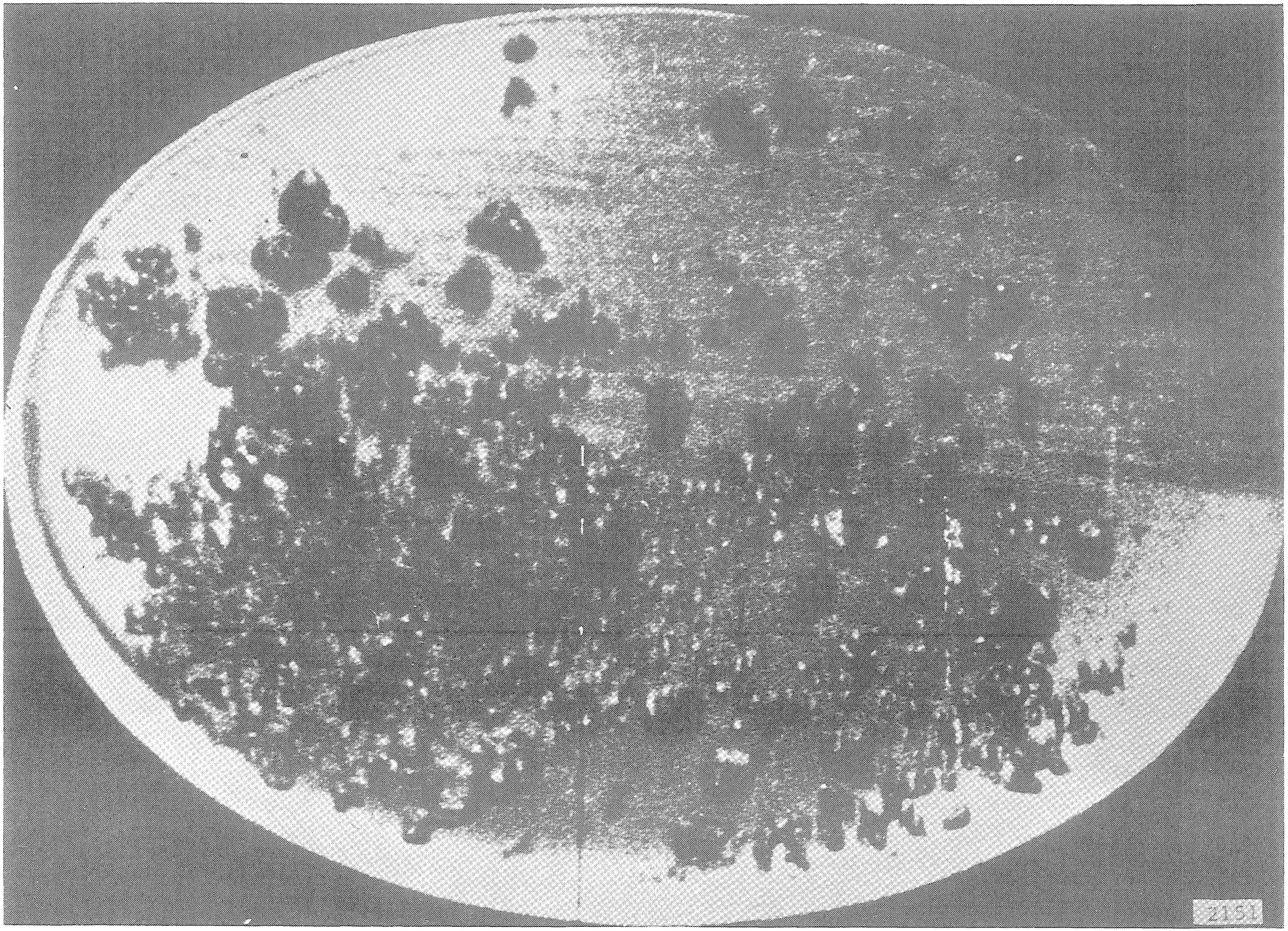

Figure 10