The final stage of the collapse of a cavitation bubble close to a rigid boundary

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The final stage of the collapse of a laser-produced cavitation bubble close to a rigid boundary is studied both experimentally and theoretically. The temporal evolution of the liquid jet developed during bubble collapse, shock wave emission and the behavior of the "splash" effect are investigated by using high-speed photography with up to 5 million frames/second. For a full understanding of the bubble–boundary interaction, numerical simulations are conducted by using a boundary integral method with an incompressible liquid impact model. The results of the numerical calculations provided the pressure contours and the velocity vectors in the liquid surrounding the bubble as well as the bubble profiles. The comparisons between experimental and numerical data are favorable with regard to both bubble shape history and translational motion of the bubble. The results are discussed with respect to the mechanism of cavitation erosion. © 2002 American Institute of Physics. [DOI: 10.1063/1.1421102]

I. INTRODUCTION

Upon the collapse of a cavitation bubble in the neighborhood of a rigid boundary, a liquid jet is observed to form and threads the bubble.1–3 Eventually, in the final stage of the collapse, a liquid–liquid impact occurs between the front of the reentrant jet and the opposite side of the bubble with the jet penetrating the slower-moving liquid close to the rigid boundary. The most significant parameter affecting the dynamical properties of the liquid jet is the nondimensional stand-off, defined as the distance of the initial location of the bubble from the boundary scaled by the maximum bubble radius, which is denoted by $\gamma$. Comprehensive descriptions of the effect of the stand-off parameter $\gamma$ may be found in the above-mentioned papers. Philipp and Lauterbon4 experimentally investigated the damage of rigid surfaces induced by single laser-generated bubbles as a function of the stand-off parameter $\gamma$. They observed two distinct damage patterns—a shallow pit damage and a circular damage pattern, and concluded that damage generated during first bubble collapse will occur for $\gamma<0.7$, whereas for $0.9<\gamma<1.7$ cavitation erosion is due to the second collapse when the bubble is directly attached to the material surface.

Recently, the interaction between a cavitation bubble and a rigid boundary occurring during the first bubble collapse for values of the stand-off parameter $\gamma=1$ has been the object of active research.5–7 This has been mainly provoked by the observation of a "splash" effect which was found to occur after the liquid jet impact onto the boundary. The temporal development of the "splash" effect is strongly dependent on the thickness of the liquid layer between bubble and boundary. When the liquid jet threads the bubble and impacts onto this layer, the closeness of the boundary results in a radial flow away from the jet axis. This flow collides with the flow induced by the still contracting bubble and a "splash" is projected away from the boundary, in a direction opposite to the liquid jet motion. The jet impact thus induces drastic changes in the flow field, including the formation of an impact interface between the jet flow and the flow induced by the contracting bubble that leads to the generation of high transient pressures and to the transformation of the bubble into a mushroom shape. Since one of the most important consequences of cavitation is its effect on nearby boundaries, the lack of a detailed investigation of the final stage of bubble collapse with high temporal and spatial resolution was considered to be a shortcoming of the previous work.

In this article we present both experimental and theoretical results on the final stage of the first collapse of a bubble near a rigid boundary for two values of the stand-off parameter $\gamma=1.1$ and $\gamma=0.9$ (see earlier papers5,6 for a wider range of values). In this choice we have been guided by the observation that the "splash" effect is very pronounced providing very interesting features of the bubble dynamics. The experimental work was conducted by using high-speed photography with 1 million and 5 million frames/second, and
parallel illumination for the observation of shock-wave emission upon bubble collapse. Numerical calculations were conducted by using a boundary-integral method, initially developed by Best, which allows us to compute the motion of the bubble including the impact and the penetration of the reentrant jet into the liquid close to the boundary. The results of the numerical simulations include the bubble profiles as well as velocity and pressure fields in the liquid surrounding the bubble which are not easily accessible through experiments.

In the following, the experimental methods used for the investigation of bubble collapse near a rigid boundary are presented in Sec. II. The mathematical statement of the problem and the numerical procedures are briefly introduced in Sec. III. The results and discussions are presented in Sec. IV, and the conclusions are drawn in Sec. V.

II. EXPERIMENT

A schematic diagram depicting the experimental arrangement used for investigating the behavior of a laser-induced cavitation bubble near a rigid boundary (aluminum 99.9% purity) is shown in Fig. 1. The bubbles were generated in a glass cuvette filled with doubly distilled water by using a Q-switched Nd:YAG laser (Continuum YG 671-10). The laser delivered light pulses at a wavelength of 1064 nm with energies of up to 250 mJ and a pulse duration of 6 ns. The laser beam was first expanded by a biconcave lens (focal length in air f = −40 mm) to allow a large focusing angle together with a large distance between focus and cuvette walls. To minimize spherical aberrations, Nd:YAG laser achromats were used for the beam collimation (f = 200 mm) and focusing (f = 125 mm), and an ophthalmic contact lens corrected for an air–water transition (Rodenstock RYM) was built into the cuvette wall. Aiming was facilitated by a helium–neon laser beam coupled into the beam path of the Nd:YAG laser. During each laser exposure, the pulse energy was measured using a pyroelectric energy meter (Precision Rj 7100). The pulse-to-pulse fluctuations of the laser energy were in the range of ±3%. The direction of the laser light was perpendicular to the rigid boundary.

The dynamics of the cavitation bubble were recorded with a high-speed image converter camera (Hadland Photonics, Imacon 792). Framing rates of 1 million and 5 million frames/second were selected to investigate the final phase of bubble collapse. The image on the fluorescent screen was recorded with a slow scan CCD camera system (Photometrics AT200A) with a 1317×1035 pixel array. The signal from the CCD camera was then digitized with 8-bit resolution and passed to a computer. The pictures were taken at 2.4 times original magnification at both framing rates. This corresponds to a spatial resolution in object space of 24 μm. Parallel illumination was used to observe the shock waves emitted upon bubble collapse. The shock waves become visible because they deflect the illuminating light out of the imaging lens, changing the brightness of the corresponding region on the photograph (shadowgraph method). The triggering of the devices was done electronically with controlled delay times for taking specific sequences out of the overall bubble motion.

For all values of γ, the maximum equivalent spherical bubble radius was held constant at $R_{\text{max}} = 1.55 \pm 0.05 \text{mm}$, corresponding to a laser pulse energy of 8 mJ. At the very high framing rates used in the present experiment, where only the final phase of bubble collapse was photographed, the maximum bubble size was determined through hydrophone measurements of the oscillation period of the bubble, $T_{\text{osc}}$. The pressure signal of the hydrophone (Ceram; rise time 12 ns) was displayed on a digital oscilloscope (Tektronics TDS 540), and the value of $T_{\text{osc}}$ was determined by measuring the time interval between the pressure pulses emitted at optical breakdown and bubble collapse. The calibration between the oscillation period of the bubble and the maximum bubble radius was done using photographic series obtained with 50,000 frames/second. A full account of the method can be found in a previous paper.

III. THEORY

The liquid volume $\Omega$ surrounding the bubble is assumed inviscid and incompressible, and the motion irrotational. The effects of gas diffusion and heat conduction through the bubble wall, gravity, surface tension, and viscosity are neglected. The diffusion of the gas in and out of the bubble has significant dynamical effects only at very low ambient pressures, when the small quantity of the gas diffusing into the liquid is an appreciable fraction of the total amount of gas contained in the bubble. This effect, however, can be ignored at higher pressures. A further consequence of diffusion manifests itself over timescale much longer than that associated with the typical oscillatory period of bubble motion. This process, which, in the case of an oscillating bubble, is termed rectified diffusion, results in a slow change of parameters such as the total gas content of the bubble, and again has negligible dynamical consequences. Accordingly, we shall disregard diffusion altogether and assume the bubble boundary to be impervious to the gas. Heat conduction through the bubble wall may influence the bubble dynamics very strongly, and is in fact a controlling factor in boiling. However, when the equilibrium vapor density is relatively small (“cold liquid”), the thermal effects can be neglected. Such is the case for a laser-generated cavitation bubble produced at room temperature; we thus neglect
thermal effects in the present work. Furthermore, due to the small lifetime and volume associated with the growth and collapse of a cavitation bubble, the effects of gravity can also be neglected. Finally, for bubbles with a maximum radius of the orders of millimeters the Reynolds number associated to the bubble motion is so large and bubble lifetime so short in comparison to viscous diffusion times that the motion is essentially inertial and the effect of viscosity can also be neglected. Despite the desirable theoretical refinements that would be necessary to provide a complete description of bubble motion, the present formulation still gives a fairly reasonable quantitative picture of bubble dynamics, and thus provides an essential practical connection between theory and experiment.

Under the above assumptions, we may represent the liquid velocity $u$ as the gradient of a potential $\phi$

$$u = \nabla \phi,$$  

(1)

with $\phi$ satisfying Laplace’s equation in the liquid:

$$\nabla^2 \phi = 0.$$  

(2)

The pressure inside the cavity is assumed to be uniform and consists of a constant vapor pressure and a volume-dependent noncondensable gas pressure. A simple adiabatic model is used for the variation of cavity pressure, $p_v$, giving

$$p_v = p_r + p_0 (V_0 / V)^\kappa,$$  

(3)

where $p_r$ is the vapor pressure, $p_0$ is the initial pressure of the noncondensable gas inside the bubble (corresponding to a bubble volume $V_0$), and $\kappa$ is the ratio of specific heats. This assumption is justified when the bubble undergoes low-amplitude oscillations as in the case of laser-generated bubbles close to a rigid boundary.

Lengths are scaled with respect to the maximum bubble radius, $R_{\text{max}}$, time with respect to $R_{\text{max}} (\rho/\Delta p)^{1/2}$, and $\Delta p \approx p_{\infty} - p_v$ is the pressure scale, where $\rho$ is the density and $p_{\infty}$ is the ambient pressure of the liquid surrounding the bubble.

The dynamic boundary condition on the bubble surface, $\partial \Omega_b$, can be written as

$$\frac{D \phi}{Dt} = \frac{1}{2} | \nabla \phi |^2 - \alpha \left( \frac{V_0}{V} \right)^\kappa + 1,$$  

(4)

where $\alpha = p_0 / \Delta p$, while the kinematic condition stipulates that

$$\frac{D x}{Dt} = \nabla \phi.$$  

(5)

The solution of (2) may be written in terms of an integral equation

$$\frac{1}{2} \phi (x') = \int_{\partial \Omega} \left( \frac{\partial \phi (x)}{\partial n} G (x, x') - \phi (x) \frac{\partial G (x, x')}{\partial n} \right) dS,$$  

(6)

where $S$ is the bubble surface and $G (x, x')$ is the Green’s function

$$G (x, x') = \frac{1}{4 \pi |x - x'|} + \frac{1}{4 \pi |x - x'|}.$$  

(7)

with $x, x' \in \partial \Omega$ and $x''$ the image of $x'$ reflected about the boundary. This form of the Green’s function satisfies the no-flow condition through the rigid boundary. Once jet-liquid impact occurs, this formulation fails due to the transformation of the bubble from simply connected region to a doubly connected region (toroidal bubble). The jet impact process is assumed to begin with impact at a single point, $q$ [see Fig. 2(a)], which implies that the normal derivative of the potential derivative after impact, $\phi''$, is equal to that of the potential before impact, $\phi'$, on $\partial \Omega_c$. In the numerical scheme the surface around the impact is smoothed and a cut $C$ is introduced across the jet to define a simply-connected domain [Fig. 2(b)]. Velocities on both sides of the cut are equal, but there will be a jump in the potential $\Delta \phi$ corresponding to the circulation around the bubble. The new modified integral formula now becomes

$$\frac{1}{2} \phi (x') = \int_{\partial \Omega} \left( \frac{\partial \phi (x)}{\partial n} G (x, x') - \phi (x) \frac{\partial G (x, x')}{\partial n} \right) dS,$$  

(8)

$$- \Delta \phi \int_{C} \frac{\partial G (x, x')}{\partial n} dS,$$

where $n_+$ denotes the normal directed into the liquid on the surface $C$ away from the rigid boundary. The value $\Delta \phi$ is obtained from the difference between $\phi$ at the tip of the liquid jet and opposite cavity surface. A detailed description of the numerical method can be found in Best and Tong et al.

To close the mathematical formulation we need the precise initial conditions for computations in order to match with experiment. The bubble is assumed to originate from a small spherical nucleus with radius $R_0$, wall velocity $v_0$, and internal pressure $p_0$ which subsequently grows to many times its initial volume. The values of $R_0$ and $v_0$ were estimated from the photographic sequences at a time $t = 1 \mu s$ after laser breakdown, while the value of $p_0$ was determined from the condition of equal maximal volume of the bubble in computation and experiment. The constants in the above equations are: density of water $\rho_0 = 998 \text{ kg/m}^3$, polytropic exponent $\kappa = 1.4$, vapor pressure $p_v = 2.35 \text{ kPa}$, and static ambient pressure $p_{\infty} = 100 \text{ kPa}$. With this values we obtain the following nondimensional values of the initial conditions in the computations: $R_0 = 0.171$, $v_0 = 11.1$, and $\alpha = 7.5$. 

![Fig. 2. Bubble geometry for the numerical computation before (a) and after (b) the impact of the reentrant jet on the opposite bubble wall. The cut $C$ is introduced to define a simply connected computational domain.](https://example.com/figure2.png)
IV. RESULTS AND DISCUSSION

A. Bubble motion and flow field for $\gamma=1.1$

Figure 3 shows the final stage of bubble collapse near a rigid boundary for a value of the stand-off parameter $\gamma=1.1$. Part (a) illustrates a high-speed photographic record taken at a framing rate of 1 million frames/second. The bubbles were generated near a vertical aluminum plate which served as a rigid boundary. To make optimal use of the image format provided by the Imacon camera, the image was rotated by 90° by using a Dove prism inserted in front of the camera. Therefore, in this and all the following photographic sequences, the rigid boundary is visible in the upper part of the photographic frames. The first frame was taken 310\,µs after the moment of optical breakdown. Since the main features of the bubble–boundary interaction, including the jet impact process, take place inside a toroidal bubble, the photographic images do not yield all necessary information. Therefore, to assist in the interpretation of the experimental results, part (b) of the figure shows a series of snapshots of the bubble profile which are computed numerically. The time elapsed between successive images is constant at a value of $6.38\times10^{-3}$ dimensionless units (corresponding to 1\,µs). The liquid jet, formed in an earlier stage of bubble collapse, hits the far bubble wall in the final stage of the collapse and penetrates the bubble, causing a protrusion on its side closest to the boundary (frame 3). The jet flow through the bubble changes the topology of the cavity and the bubble becomes toroidal. Two cavities can be seen after jet penetration (frames 6–10) with the cavity situated far away from the boundary collapsing approximately 1\,µs before the second cavity. The calculation successfully predicts the temporal evolution of the cavity shape during the final stage of the collapse and the translating motion of the bubble towards the rigid boundary. The calculation also predicts a maximum jet velocity of 90\,m/s which is approximately 15% larger than the corresponding value measured (averaged over an interframing time of 1\,µs) experimentally ($v_{\text{max}}=78\pm24$\,m/s). We note, however, that the high-velocity tip of the liquid jet is difficult to observe in experiment, because it is eroded by residual gas in the bubble and by more slowly converging liquid on the opposite side of the bubble.

The temporal resolution of the picture series taken with 1 million frames/second presented above is not sufficient to resolve the final collapse phase. Therefore, Fig. 4 shows the final stage of bubble collapse at a framing rate of 5 million frames/second, i.e., with an interframing time of 200\,ns. The shock waves emitted upon bubble collapse become clearly visible at this framing rate because of the relatively short exposure time of 40\,ns. Analysis of the distances traveled by the individual shock waves at the time of exposure allows one to deduce the bubble behavior with an even better time resolution.
resolution than that given by the interframing time. The part of the bubble far from the boundary collapses first accompanied by the emission of shock waves and the main bubble splits in two (frame 12) with the formation of two toroidal cavities. Not later than 200 ns a second set of shock waves is emitted. The position of the shock waves center indicates that the emission center is located in a region where the bubble splitting occurs. The cavity situated closer to the rigid boundary collapses approximately 800 ns later, emitting only a relatively weaker shock wave. This is because a large part of the kinetic energy of the radial flow into the main bubble is transformed into kinetic energy of an outflow around the toroidal cavity next to the wall. This assertion is supported by the observation that the size of the toroidal cavity closer to the wall is nearly constant during the final collapse stage of the bubble [frames 13–16 of Fig. 4(a)]. The content of this cavity becomes, therefore, less compressed and the sound emission is diminished. This feature together with the observation that the bubble does not touch the boundary at the moment of the first collapse leads to the conclusion that the damage potential of the bubble is small at this $\gamma$-value. In fact, experiments by Vogel et al.\textsuperscript{3,14} show that the collapse pressure is minimal around this $\gamma$-value, and the experiments of Philipp and Lauterborn\textsuperscript{7} and Isselin et al.\textsuperscript{15} show only minor damage of the nearby boundary. As before, it should be noted the good agreement between the experimental and numerical results with respect to the temporal development of the bubble shape before the conclusion of the collapse. However, the computations are currently restricted to $t = 2.0213$ because they have not yet been extended to multiple toroidal bubbles using vortex sheet methods.

The experimental results suggest that the jet flow has vorticity around its axis—like the outflow of a bathtub. The slightly thicker structure between the bubble parts situated nearer and farther from the boundary that is visible in frames 10 and 11 of Fig. 4(b) is in the photographs twisted like a spiral. The vorticity is the result of instabilities which are probably induced by a slight asymmetric impingement of the reentrant liquid jet onto the opposite bubble wall. These instabilities cannot be portrayed in the numerical calculations which assume radial symmetry.

The pressure contours and the velocity field for three different times in the liquid surrounding the bubble for $\gamma = 1.1$ are presented in Fig. 5. During the initial phase of the jet penetration process the liquid near the boundary has not yet sensed the jet and is still moving along the boundary [plot (a)]. In a later stage, the flow surrounding the bubble side nearer to the boundary has changed direction and is now moving radially outward and away from the boundary [plot (b)]. The maximum velocity of this flow is about half that of the reentrant jet. Obviously, the mechanism that brings about this sudden change in the flow field is the redirection of the jet flow by the solid boundary. The redirected jet flow collides with the radial inward flow visible in plot (a), and this collision produces a flow directed away from the boundary that induces an involution of the main part of the bubble, resulting in a mushroom-like shape of the bubble. Starting from the involution, the bubble surface reconnects around the region of the jet nearer to the boundary [plot (c)], which finally leads to the formation of the two toroidal cavities from the main bubble as seen in Figs. 3 and 4. In the left part of each plot, one can see that two high-pressure regions are located on the axis of symmetry above and below the bubble just after the liquid jet has touched the boundary [plot (a)]. The maximum pressure above the bubble is 15 (approximately 1.5 MPa in absolute value), as compared to 10 below the bubble. The further development of the pressure fields is given in plots (b) and (c). It can be seen that the pressure reaches more than 70 at the rigid wall, compared to 55 at the opposite bubble side. We also note that the high-pressure region on the rigid boundary covers only a small area localized around the jet tip. Similar observations have been reported by Tong et al.\textsuperscript{8} for a stand-off distance of $\gamma = 1.2$.

**B. Bubble motion and flow field for $\gamma=0.9$**

Figure 6 illustrates the final stage of bubble collapse for a stand-off distance $\gamma=0.9$. The frame interval in the photographic sequences is 200 ns, with the first frame taken 314...
μs after laser breakdown. As in the previous case, the bubble assumes a mushroom-like shape before the conclusion of collapse. However, now the bubble almost touches the boundary during collapse and the bubble part nearer to the boundary (the foot of the mushroom) is larger. Again, the bubble part farther from the boundary collapses first. During collapse, it separates from the bubble (frames 11–15) and forms a torus. Shock waves are emitted from the area covered by this torus. The torus disintegrates into several separately collapsing parts; about seven different shock waves are discernible in frame 12. Examination of the photographic frames covering later times (not shown in the figure) showed that no shock waves are emitted during the collapse of the bubble part next to the boundary. The explanation is similar as for the case of $γ = 1.1$: A large part of the kinetic energy of the radial flow into the main bubble is transformed into kinetic energy of a rotational flow. The content of the cavity next to the wall is, therefore, not very strongly compressed and the sound emission is weak. A good agreement between experimental and theoretical results with regard to bubble shape history is obtained over the last few percent of the collapse phase. It should be noticed here that since the numerical model is limited to incompressible flow it gives no information about shock wave emission upon bubble rebound.

Figure 7 contains plots of the pressure fields and velocity vectors around the bubble for $γ = 0.9$. In this case, the maximum velocity of the reentrant jet is 105 m/s, which is almost equal to the measured value in experiment ($v_{\text{max}} = 112 \pm 24$ m/s). Just after the impact of the reentrant jet, a high-pressure region with a magnitude of 14 is located on the boundary [plot (a)]. The proximity of the rigid boundary redirects the flow induced by the reentrant jet as a radial flow outwards from the jet axis. This flow collides with the flow induced by the contracting bubble and, as a result of this collision, a “splash” is projected away from the boundary, leading again to the formation of a mushroom-like shape of the bubble. The liquid velocity along the exterior bubble wall is even larger than that of the reentrant jet. The circulation in the velocity field subsequently manifests itself in a flow around the toroidal cavity surface. The important feature of this motion is the instantaneous jump in the peak liquid pressure from above the bubble to beneath the bubble. The action of this high-pressure region is to decelerate the liquid flow through the toroidal bubble and spread the bubble part nearer to the boundary along the rigid boundary, resulting in an hour-glass shape of the bubble. A second, ring-shaped, region of high pressure with a magnitude of 34 is generated on the boundary around the impact interface between jet flow along the boundary and in-rushing flow induced by the collapsing bubble [plots (b) and (c)] (see also Ref. 6). Another important observation is that, near the conclusion of collapse, the pressure gradient acting on the bubble surface is now directed away from the boundary. This can explain the detachment of the bubble wall from the rigid boundary observed in the last four frames of the photographic sequence shown in Fig. 6.

Even though the ring shape of the high-pressure region developing due to the splash effect resembles the damage patterns observed by Philipp and Lauterborn for $γ = 0.9$, it is highly unlikely that the pressure of about 3.4 MPa predicted by the numerical calculations can overcome the yield strength of metals. The dynamic yield strength of pure aluminum, for example, was reported by Lush to be 1300 MPa. Philipp and Lauterborn deduced from their observations that the second collapse of the bubble is responsible for the erosion pattern of the boundary. This result is also supported by the present experiments. Figure 8 shows the sec-
ond collapse of the bubble for a value of the stand-off parameter $g = 0.9$. It can be seen that the toroidal cavity formed during the first collapse of the bubble separates into several individual bubbles, each of them collapsing separately (frames 5–10). The size of the collapsed bubbles is very much smaller than the size of the toroidal cavity formed during the first collapse (Fig. 6), indicating that the pressure inside the collapsed bubbles is much higher during second collapse. This observation is in agreement with the observed annular damage pattern and relates it to the second collapse.

V. CONCLUSIONS

The final stage of the collapse of a cavitation bubble near a rigid boundary has been investigated both experimentally and theoretically. The behavior of laser-produced bubbles was investigated by using high-speed photography with up to 5 million frames/second and parallel illumination for the visualization of the shock waves emitted upon bubble collapse. To get a clearer picture of the bubble–boundary interaction, numerical simulations were also conducted by using a boundary integral method which provided velocity fields and pressure contours in the liquid surrounding the bubble. The method allows for the simulation of the jet impact that occurs toward the end of the collapse.

The interaction of a cavitation bubble with a rigid boundary is particularly interesting for $g \approx 1$ because, due to the proximity of the bubble to the rigid boundary, the liquid jet formed during bubble collapse flows along the boundary and collides with the flow induced by the still collapsing bubble. As a result, the flow is redirected along the bubble wall away from the boundary. This leads to a rapid motion of that part of the main bubble situated nearer to the boundary and to the formation of a mushroom-like shape of the bubble. This behavior was observed in the present experiments for $g$-values down to 0.52, and Shaw et al. reported similar results. The part of the bubble situated furthermost from the rigid boundary (the cap of the mushroom) collapses first accompanied by shock wave emission. During the final stages of collapse, a large part of the kinetic energy of the radial flow into the main bubble is transformed into kinetic energy of a rotational flow around the cavity next to the wall. Because the radial collapse of the bubble part closer to the boundary is strongly attenuated, only a relatively weaker shock wave emission was observed, in agreement with previous results of hydrophone measurements reported by Vogel et al. This way, the damage potential of the bubble is diminished even when the bubble is in direct contact with the boundary at the moment of the first collapse. This scenario may explain the results of Philipp and Lauterborn, who found a considerably reduction of the damage generated by single laser-produced bubbles for $0.5 < g < 1.1$.

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