Electric Field Effect on the Rise of Single Bubbles during Boiling

N. Masoudnia, M. Fatahi

***Abstract*—**An experimental study of saturated pool boiling on a single artificial nucleation site without and with the application of an electric field on the boiling surface has been conducted. N-pentane is boiling on a copper surface and is recorded with a high speed camera providing high quality pictures and movies. The accuracy of the visualization allowed establishing an experimental bubble growth law from a large number of experiments. This law shows that the evaporation rate is decreasing during the bubble growth, and underlines the importance of liquid motion induced by the preceding bubble. Bubble rise is therefore studied: once detached, bubbles accelerate vertically until reaching a maximum velocity in good agreement with a correlation from literature. The bubbles then turn to another direction. The effect of applying an electric field on the boiling surface in finally studied. In addition to changes of the bubble shape, changes are also shown in the liquid plume and the convective structures above the surface. Lower maximum rising velocities were measured in the presence of electric fields, especially with a negative polarity.

***Keywords*—**Single bubbles, electric field, boiling, effect.

I. Introduction

BOILING heat transfer is characterized by high dissipated heat fluxes under low wall superheats. It relies on the combination of two mechanisms: Latent heat transfer and enhancement of convection by the movement of bubbles. Therefore, fundamental study of bubbles nucleation, growth, detachment, and interactions, as well as liquid and bubbles motion, are required in order to fully understand boiling phenomenon. Although boiling heat flux can be high, industry and particularly electronic industry always search for higher and higher cooling performance. Applying an electric field on the boiling surface is known as an active heat transfer enhancement technique, and is the object of investigation of many researchers as it has been summed up by Laohalertdetcha et al. [1].

This paper aims at presenting a fundamental study of single bubble boiling with the application of a uniform D.C. electric field on the boiling surface.

Bubble dynamics in boiling has been the focus of both academic and practical interest for decades. The study of boiling particularly gain in intensity from the early fifties, years from which we get most of our actual theories. Bubble rise trajectories have been the interest of Haberman and Morton [2] and of Harmathy [3]. They described three different kinds of trajectories: linear, helicoidally and zigzag.

Niloofar Masoud Nia is with the Islamic Azad University of Mahshahr, Iran, Islamic Republic Of (e-mail: N.masounia68@gmail.com).

When the bubble Reynolds number is low, bubbles trajectory is linear. For higher Reynolds number, trajectories are helicoidally or zigzagging, and for even higher Reynolds number corresponding to big bubbles, the trajectories are linear again.

Keshock and Siegel [4] have shown that when the bubble trajectory is linear, the bubble accelerates suddenly after detachment and then stabilizes at a constant terminal velocity. Harper [5] adds that the drag coefficient differs for a unique bubble or for successive bubbles from the same nucleation site.

Several correlations for the value of the terminal velocity have been suggested, for example by Haberman and Morton [2] or by Harmathy [3]. Peebles and Garber [6] have suggested four different correlations covering a large range of Reynolds numbers.

Study of the application of an electric field on the boiling surface is more recent. Different works under terrestrial and microgravity conditions, and usually on raw surfaces have been published. Laohalertdecha et al. [1] review most of what has been already done. To the authors' knowledge, no specific work on the effect of an electric field on bubble rise has yet been published.

II. Experimental Setup and Procedure

Boiling is performed in very pure n-pentane. This fluid is not toxic, not polar and with a low permittivity: ε_l = 1.8371. It is a comfortable fluid as its boiling point is 36.07 °C at atmospheric pressure.

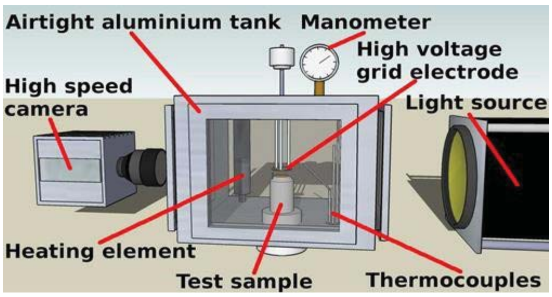

Fig. 1 Schematic of the experimental setup

The experimental apparatus is shown in Fig. 1. A parallelepiped airtight tank contains pentane at thermodynamic saturation: liquid is at equilibrium with its vapor through a free surface. After filling the tank, the fluid has been heated to a temperature corresponding to a pressure higher than the atmospheric pressure, and several degas sings have been performed to ensure the absence of dissolved air. The fluid is maintained at the desired working temperature and pressure with a regulated heating element and cooled by heat losses, i.e. natural convection all around the apparatus. Four thermocouples are used to ensure the temperature homogeneity in the vapor phase and the liquid bulk.

An experimental sample, shown in Fig. 2, is placed inside the tank. This test sample is made of a 20 mm copper cylinder, heated by a cartridge heater. The heat flux is then conducted through a 5 mm diameter copper pin, equipped with six Ktype thermocouples, and isolated in PTFE. These thermocouples allow calculating the total longitudinal heat flux as well as the radial heat losses and the top surface temperature. A 40 µm thin and 18 mm diameter copper plate is soldered on the top of the pin. The plate is mirror-polished to avoid nucleation on its surface, and its thinness results in a radial temperature drop that prevents nucleation on its edges. This meticulous surface processing allows having more than 30 K of wall superheat without having any bubble nucleation.

A single artificial nucleation site is made by mechanical indentation at the center of the plate. The site has been visualized with a confocal white light microscope (Fig. 3). It is parabolic, 500 µm deep and has a diameter of 180 µm. In the experiments, bubbles will only nucleate on this site.

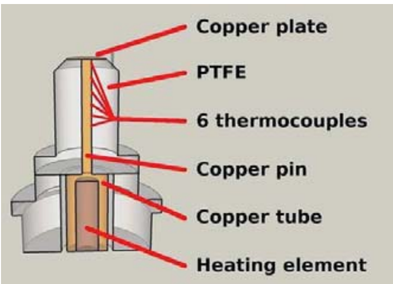

Fig. 2 Schematic of the test sample

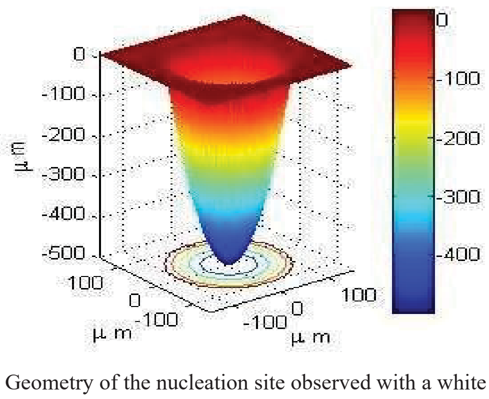

Fig. 3 Geometry of the nucleation site observed with a white Light confocal microscope

In order to apply a uniform DC electric field on the boiling surface, the test sample is wired to the ground and a plane grid is placed above the surface (see Fig. 1) and wired to a high voltage source. In all experiments, the distance between the grid and the test sample is cm. The high voltage generator can supply a DC voltage from 0 to 30 kV.

Boiling takes place in the middle of the tank at the center of the copper plate. After detachment, bubbles rise more or less vertically in the liquid, pass through the grid and reach the free surface. A high speed camera (Photron Fastcam 1024 PCI) records the bubble growth and rise over 12 mm. The typical image acquisition frequency is 1000 to 3000 fps.

An automatic image processing software has been developed. It allows determining the volume of the bubble and the position of its gravity center. Bubble contour is detected by locating maximum grey gradient using Sable method. The bubble's volume is measured as if the bubble was a stack of 1 pixel thick vapor cylinders. To evaluate the position of the bubble's gravity center, the vapor pressure is supposed to be homogeneous inside the bubble at each time, and we assume that the time-evolution of the pressure (and hence vapor density) in the bubble remains low.

III. Result and Discussion

A. Activation of the Nucleation Site

When heating the experimental sample, the copper plate temperature rises. The liquid surrounding the plate is then superheated, causing natural convection. This convection has been observed with a backward light and a wall superheat of 30 K (Fig. 4), in the absence of any artificial nucleation site. Large convective structures rise at the center of the plate at a speed of 5 to 10 mm/s.

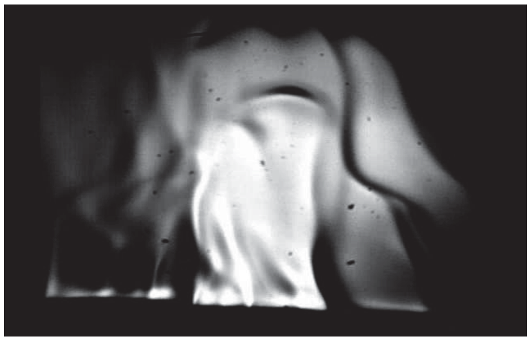

Fig. 4 Natural convection above the experimental sample with A wall superheat of 30 K

In the presence of an artificial nucleation site, the site can be activated with a sufficient wall superheat. The threshold for initial site activation was between 20 and 40 K of wall superheat in our experiments. At such wall superheats, successive bubbles are growing so fast that they form a vapor column. Therefore, once the nucleation is activated, the heat flux is reduced so as to maintain the wall superheat between 1.5 and 8 K. If the wall superheat is higher, then successive bubbles sometimes merge, and if the wall superheat is lower, the nucleation site can get deactivated. Between these two values, single bubble growth and rise can be observed.

B. Bubble Growth without Electric Field

Bubble growths are observed with different wall superheats. Bubbles first have the shape of a sphere, and then a neck appears at the end of the growth (Fig. 5). As detaching bubbles are far from being spherical, it is preferred that the size parameter of the bubble should be its volume, and not its equivalent radius. The bubble always remains attached to its nucleation site during the full growth period: the bubble base diameter is 180 µm. The bubble base shape does not show any thin micro layer beneath the bubble. The bubble size at detachment is around 1 mm.

It has been shown in a previous paper [7] that the bubble frequency rises linearly with the wall superheat whereas the bubble's volume at detachment is invariant and equal to 0.55 ± 0.02 mm^3.

Fig. 5 Bubble just before detachment

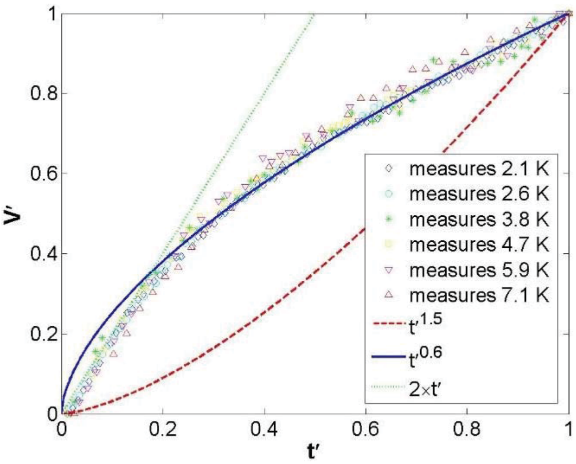

Fig. 6 Normalized bubble growths for various wall superheats

As the latent heat transfer is proportional to f x V (frequency multiplied by volume at the moment of detachment), this means that the mechanism for the increase of the latent heat flux is only due to the bubble frequency. Bubbles growth curves have then been normalized in Fig. 6 by dividing the time by the total growth time and the volume by the departure volume, in order to compare the growths for several wall superheats. It is shown that for any wall superheat in the range of the study, the normalized bubble growth is the same and can be described by a non-dimensional growth law.

$$V' = 2\,t' \text{ for } 2\,t' < 0.2 \quad V' = t'^{0.6} \text{ for } 2\,t' > 0.2 \tag{1}$$

This empirical growth law, which was obtained from a large number of observations and with a high video acquisition frequency, is noticeably different from growth laws deriving from theoretical models that can be found in the literature. Indeed, these models usually yield to V' = t'1.5. They are in fact most of time expressed in terms of equivalent radius as Req ∝ t0.5. The most important difference between the models and the present empirical low appears when deriving the volume with respect to time to express the evaporation rate. The experimental results yield to an evaporation that decreases with time during the bubble growth, while the theoretical models predict an increase of the evaporation rate with time. It has been suggested in [7] that the detached bubble draws hot liquid in its wake. The new growing bubble is thus surrounded with superheated liquid, which could be the cause for a high evaporation rate at the beginning of the bubble growth. The liquid around the bubble is then cooled down by phase change, which progressively leads to a lower evaporation rate. This explanation still needs proofs, particularly as regards the liquid motion. Studying here the bubble motion after detachment will give clues to support this suggestion.

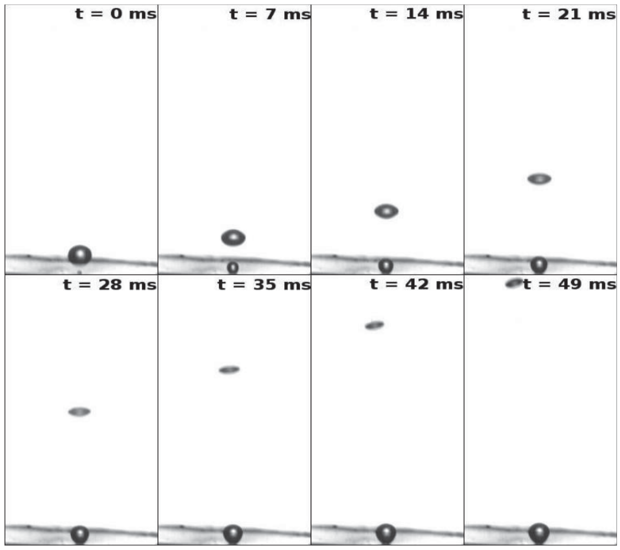

Fig. 7 Rise of a bubble

C. Bubble Rise without Electric Field

When the bubble is about to detach, a neck is formed as shown in Fig. 5. This neck then breaks up, and the free bubble oscillates due to the neck breakage. The bubble then slowly accelerates vertically, and eventually changes its direction after a few millimeters, as it is shown in the pictures of Fig. 7. The movement of the bubbles in the two directions available with the pictures (vertical z and lateral x directions) has been studied. The position of the center of gravity of the bubbles has thus been computed.

The height of the center of gravity of the bubble shown on Fig. 7 is plotted in Fig. 8 as a function of time. These measurements are fitted with an appropriate polynomial function. The bubble vertical velocity is obtained by deriving this polynomial function (Fig. 9). The bubble accelerates in the vertical direction until reaching a maximum vertical velocity.

This velocity can also be expressed in terms of a critical Reynolds number.

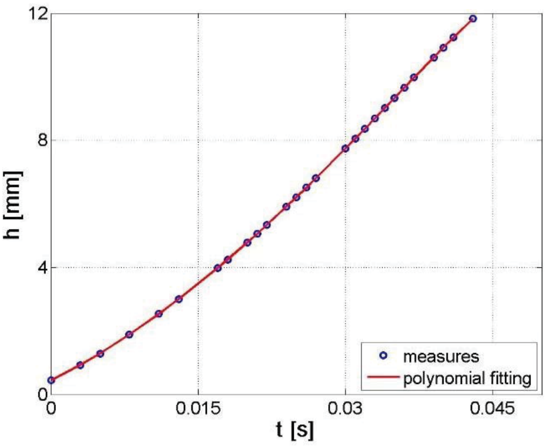

Fig. 8 Height of the gravity center of the bubble versus time during its rise

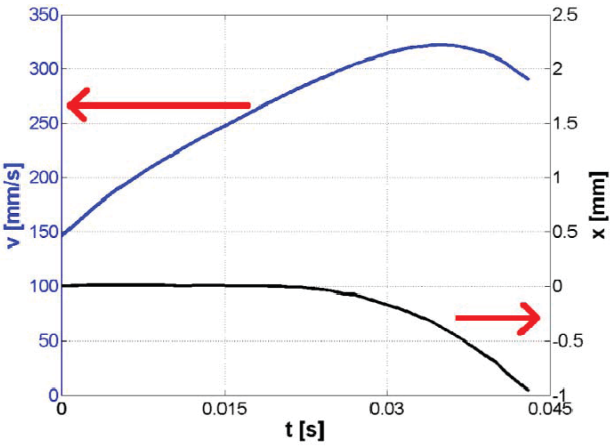

Fig. 9 Vertical velocity (blue) and x position (black) of a Bubble during its rise

When the critical Reynolds number is reached, the bubble randomly changes its direction. As described for the sample bubble on Fig. 9, the horizontal position x remains the same during the acceleration of the bubble and eventually changes at the moment when the maximum vertical velocity is reached. An analogous behavior was explained by Jenny et al. [8] for a free ascending sphere: the sudden change of direction would occur when an instability would break the axisymmetric of the sphere's wake and would impose to the sphere a plane oblique trajectory.

The bubble rise study has been done for 20 different bubbles for different wall superheat between 1.5 and 8 K. The wall superheat has shown no influence on bubble rise. In all cases, the bubble accelerates until it reaches a maximum velocity in the vertical direction, and then turn to another random direction: sometimes to the left, sometimes to the right, and sometimes the bubbles vertical speed decreases and the bubble seems to be moving toward the direction perpendicular to the picture plane.

The mean bubble volume at detachment was 0.55 mm^3 with a standard deviation of 0.02 mm^3. This volume is assumed to be constant during the bubble rise, as the bubble is moving in a saturated bulk liquid. The mean maximum velocity was 331 mm/s with a standard deviation of 12 mm/s. This velocity has been compared with Peebles and Garber [6] model.

The characteristic length used for the Re, We and Fr in the model is the equivalent radius of the bubble Req. The maximum velocity calculated with this model is 299 mm/s with a Reynolds number of 2.49. This maximum velocity is of the same order of magnitude as the measured maximum velocity. Beyond the question of the accuracy of the correlation, a difference between the present experiment and that of Peebles and Garber lies in the fact that this experiment is non adiabatic.

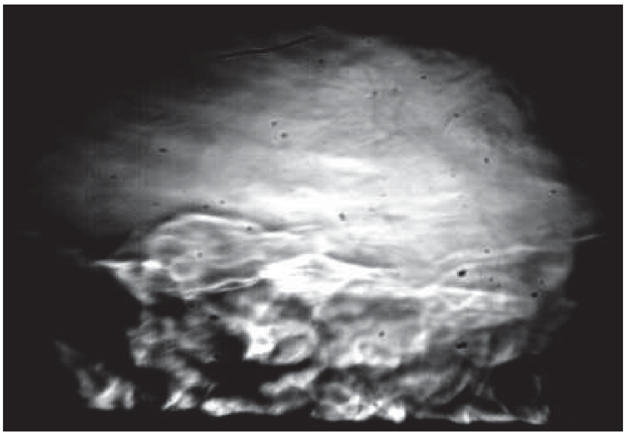

Fig. 10 Convection above the experimental sample with a Wall superheat of 30 K and an electric field of 30 kV/cm

The measured velocity is in fact the velocity of the bubble compared to the boiling surface and not to its surrounding liquid. This speed is thus the sum of the bubble's velocity relative to the liquid plus the liquid velocity relative to the boiling surface, assuming that the liquid surrounding the bubble is moving in the same direction as the bubble. This assumption seems to be verified by observing convection images like that of Fig. 4.

D. Bubble Rise in the Presence of an Electric Field

When a uniform D.C. electric field is applied above a heated surface in a dielectric liquid, convective movements are strongly modified. Little convection cells appear and stay within three millimeters above the heated surface. In Fig. 10, these convective structures have been recorded in the same conditions as in Fig. 4, but with an added electric field.

When growing on the artificial nucleation site in the presence of an electric field, the bubble is distorted by the electric field (Fig. 11). The bubble is elongated in the direction of the electric field. This is due to interfacial forces created by the strong difference between the electric properties (mostly permittivity) of the liquid and vapor phases. Nevertheless, although being distorted, the bubbles have the same volume at detachment with or without the application of an electric field, namely about 0.55 mm^3.

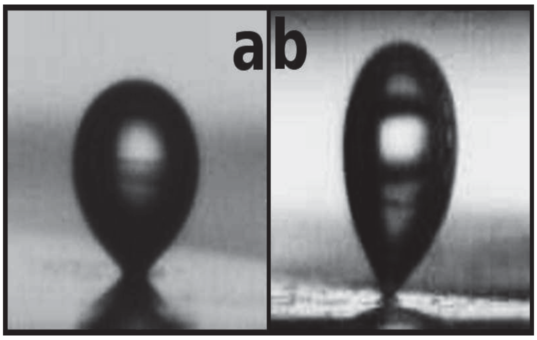

Fig. 11 Bubble close to detachment under no electric field (a) And a 30 kV/cm electric field (b)

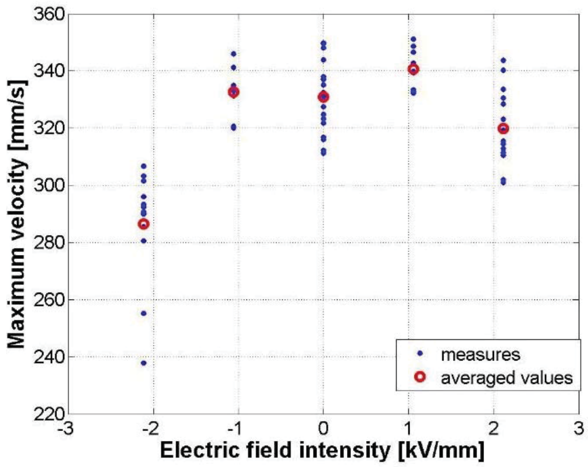

Fig. 12 Maximum vertical velocity of the bubbles in the Presence of an electric field

After detaching, the bubble rises in the liquid the same way as without any electric field. It accelerates vertically in the liquid until it reaches its maximal velocity, and then turns to another direction. This maximal velocity has been compared for various electric field intensities, as well for a positive or a negative polarity in Fig. 12.

It is shown experimentally that the maximum vertical velocity of the bubbles decreases when increasing the absolute value of the electric field intensity. The effect of the electric field is stronger with a negative polarity (i.e. a negative voltage on the grid electrode while the boiling surface is linked to the ground).

This decrease of the bubble velocity in the presence of an electric field can be partially due to the convective motion of the liquid. Indeed, as explained above, the measured bubble velocity is the sum of the bubble velocity relative to the liquid plus the liquid velocity relative to the heated wall. Comparing Fig. 4 and Fig. 10 shows that the motion of the liquid is very different in the presence of an electric field. With an electric field, the plume at the center of the boiling surface can no longer be observed. The liquid velocity contribution to the measured bubble velocity thus seems to be lowered, or even equal to zero.

The difference between the positive and the negative polarity is not yet explained. Its explanation requires a deeper study of charges injection in a dielectric fluid. This effect of polarity is in fact even not clear for pool boiling on raw surfaces, as contradictory results are found in the literature.

IV. Conclusion

The main results of this paper concern the growth, departure and rise of single bubbles, as well with or without the application of an electric field on the boiling surface. They are useful for a better understanding of pool boiling and electro hydrodynamic enhancement of pool boiling, which will lead to a better design of systems that need the use of boiling, especially for electronic cooling.

Bubble growths have been observed with various wall superheats and a non-dimensional experimental growth law has been established. It has been found that the evaporation rate is decreasing during the bubble growth, which shows the need to take into account the liquid motion created by the preceding bubble. Bubble detachment volume has been found constant because the bubbles always keep attached to the nucleation site. Rises of bubbles have also been studied. After detachment, bubbles accelerate vertically until reaching a maximum velocity in good agreement with the correlations found in literature. The bubbles then turn to another direction. This change of direction has been interpreted by analogy with numerical simulations of a free sphere ascending in a liquid performed by Jenny et al. [8].

Some results concerning the application of an electric field were also obtained. The effect of electric fields on the liquid plume and on the convective structures has been shown. Electric fields also distort the bubbles by elongating them in the vertical direction. The application of an electric field lowers the maximum vertical velocity of the bubbles, especially with a negative polarity. Some elements concerning the change of convective structures have been suggested, but much is still needed to explain this effect of the electric field on the rise of bubbles.

Nomenclature

Latin Symbols

f	*Bubble* frequency	Hz
Fr	*Froude* number	v^2/gL
g	*Gravitational* acceleration	m/s^2
h	*Height* of the gravity center of the bubble in m the vertical direction	
L	Length	m
R_{eq}	Equivalent radius of the bubble (i.e. radius m of a sphere that has the same volume)	
Re	Reynolds number	$\rho vL/\mu$
t	Time	s
t'	Non dimensional time (i.e. time / total bubble growth time)	
v	Bubble's vertical velocity	m/s

vmax	Bubble's maximum velocity	m/s
V	Bubble's volume	m^3
V'	Non dimensional volume (i.e. bubble's volume / bubble's volume at detachment)	
We	Webers number	$2Lv^2\rho_l/\sigma$
x	Bubble's horizontal position in the pictures m plane	

Greek symbols

ε_l	Relative permittivity of the liquid	
μ_l	Dynamic viscosity	Pa s
ρ_l	Liquid density	kg/m^3
σ	Surface tension	N/m

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