Behavior of Nucleation Sites in Pool Boiling

The behavior of active boiling site populations was monitored for pool boiling on an electrically heated 1-mil stainless steel sheet. The boiling sites were located using a high-speed infrared camera focused on the underside of the boiling surface. Experiments were conducted to determine factors affecting the origin, concentration, and lifetime of active sites.

J. E. SGHEIZA and
J. E. MYERS
Department of Chemical and Nuclear Engineering
University of California
Santa Barbara, CA 93106

SCOPE

Most experimental studies of nucleation sites in pool boiling are limited either to single, artificial sites or to sparsely distributed sites found on surfaces boiling at low heat fluxes. At fluxes of even moderate value the two-phase turbulence in a boiling system prevents direct observation of the behavior of the individual sites. In the investigation reported here real-time detection of the presence of active sites on the upper surface of a heated plate was done using a high-speed infrared camera to scan the temperature field on the underside of the heater.

It has been known for over two decades that the nucleation and growth of a bubble in pool boiling causes a rapid drop in the temperature of the heater surface. When the surface is an electrically heated 1-mil sheet of stainless steel, the drop in the temperature on the upper side is transmitted to the underside within a few milliseconds. Thus, the nucleation, growth, and departure of bubbles in the liquid can be followed using an infrared scanning camera to detect the temperature behavior on the underside. This noninvasive technique allows studies to be made of individual sites and whole populations of sites under the influence of such variables as heat flux and the nature of the heating cycle.

CONCLUSIONS AND SIGNIFICANCE

Transient and permanent boiling sites were identified and counted with a high-speed infrared camera during saturated pool boiling of water and four organic liquids on a horizontal heated surface at one atmosphere, at heat fluxes between 6.0 and 30.0 W/cm^2. The behavior of active boiling site populations was monitored with the infrared camera during steady and pulsed boiling tests. Infrared camera displays of boiling site activity were recorded on 16 mm film at 60 pictures/s. Frame-by-frame analysis of these films produced counts of active sites and the number of movie frames showing active boiling during two-second intervals. From these counts the average lifetime per site and the fluctuation in average lifetimes was determined. Temperature profiles of several active sites were photographed from the IR camera displays at 1,000 pictures/s, and the fluctuation in bubble nucleation periods analyzed.

Pulsed boiling tests with water indicated that at heat fluxes up to 17 W/cm^2 only 50 to 60% of potentially active sites nucleated and that less than 30% of all active sites nucleated consistently. Site-lifetime results showed that some sites, referred to as transient sites, nucleated in a highly irregular manner with vigorously active periods alternating with periods of few nucleations. Other sites, which are referred to as permanent sites, nucleated consistently over the entire test interval. As heat flux increased, transient sites tended to transport a higher percentage of the total heat. Irregular nulceation behavior was further demonstrated in fluctuations arising in the temperature-rise period during bubble growth.

Examination of a boiling surface with an optical microscope at 800× revealed more potential boiling sites than are likely to nucleate during boiling. No differences based on cavity size and shape were noted between surface sites that produced bubbles and those that did not.

From these experimental results, a mechanism for activating potential boiling sites, based on circulating microbubbles, was postulated which could account for apparent time-dependent behavior exhibited by active boiling site populations.

INTRODUCTION

Nucleate-boiling heat transfer rates are dependent on both the concentration of boiling sites and the bubble formation rates at these sites. Previous investigations have been made of spatial distributions of active sites, the relation of site density to cavity size distribution, and the effect of surface roughness, system pressure,

Correspondence concerning this paper should be addressed to J. E. Myers.

and surface tension on measured site distributions. These, plus studies of bubble growth and surface temperature changes at single boiling sites, have led investigators to describe nucleate-boiling heat transfer using models such as bubble agitation, vapor-liquid exchange, latent-heat transport, transient conduction, and microlayer evaporation. Although many of these models have merit, they have not satisfactorily explained how active site populations interact with other boiling parameters, nor have they adequately explained hysteresis, secondary bubbles, site seeding, and transiently active sites. One shortcoming of many prior boiling site studies has been their reliance on surface data taken after boiling has ceased. In the present work, measurements were taken during the time that boiling was actually occurring. The resulting picture of how active sites behave is somewhat different from what has been concluded from examination of a surface after boiling on it has ceased.

Counting Active Sites

Most early attempts at counting active boiling sites were performed visually through the boiling liquid and were limited to relatively low heat flux. Jakob and Fritz (1931) were among the first to investigate active sites, finding a maximum site density of 0.31 sites/cm^2 at 5.69 W/cm^2 in water. Concluding that heat transfer rates depended on surface conditions, Jakob (1949) proposed that heat flux was related to site density according to the equation

$$(q/A) = a(n/A)^b \quad (1)$$

where the exponent b was equal to 1.

The effect of surface roughness on heat transfer rate was investigated by Corty and Foust (1955) and by Kurihara and Myers (1960). Recognizing the need to study boiling site populations at higher heat fluxes, Gaertner and Westwater (1960) employed an electroplating technique to count active sites and found the exponent b in Eq. 1 to have a value of 0.49. From population data at 63.1, 92.8, and 100 W/cm^2, Gaertner (1963) determined that the local site density for boiling water containing nickel salts fitted a Poisson distribution. Studying surface nucleation properties, Gaertner related active site population to liquid-surface properties and surface temperature using classical nucleation theory. Hsu (1964) investigated the gradual transition from discrete bubbles to multibubbles and found that the area fraction of heater covered by multibubbles is a Poisson function of the product of the instantaneous population density and the average single-bubble influence area. Gaertner (1965) photographed vapor-formation characteristics while boiling water on a 4/0 polished copper surface at atmospheric pressure and visually counted active sites up to 6.5 sites/cm^2 at 18.5 W/cm^2. He found that Eq. 1 relates active site population and heat flux, but the exponent in this case, $b = 0.67$, was between the extremes found by Jakob (1949) and Kurihara and Myers (1960).

Kirby and Westwater (1965) sought to avoid turbulence-imposed limits to viewing active site populations from above the heated surface by boiling carbon tetracholoride on a 5.1 cm square ground-glass heater coated with a transparent, electrically conductive material, while photographing the active sites from below. Although Kirby found heat flux to depend on site density according to Eq. 1, with the exponent $b = 0.73$, he noted one case in which he counted twice as many active sites after increasing the number of movie frames analyzed from 100 to 1,500 frames. Heled and Orell (1967) utilized extremely thin scale deposits to identify and locate naturally-occurring active boiling sites. Still another novel approach was employed by Iida and Kobayasi (1970) who detected vapor-void areas above a copper surface with a small, electrically conductive probe. They found heat flux to vary with site density according to the results of Gaertner and Westwater (1960).

A recent study by Sgheiza and Myers (1977) avoided many of the limitations encountered in earlier investigations. Their study used a fast-scanning infrared (IR) camera to observe the temperature field on the bottom of a thin, electrically heated stainless steel plate while water boiled on the upper side at heat fluxes up to 33.3 W/cm^2. Positioning the IR camera under the boiling surface allowed an unimpeded view of active site population behavior at heat fluxes well into the bubble interference region. In addition, this setup did not require any special treatment of the surface or liquid as needed in other studies. The present paper represents a continuation of the infrared camera work.

Cavity Size and Site Density

Examinations of surfaces used in boiling experiments show a distribution of cavities of various size and geometry. Although system pressure, surface tension, and heater properties are known to affect the boiling performance of a surface, some observers believe that cavity size distribution is the most important parameter in fixing the nucleation characteristics. This section discusses how cavity size distribution affects active boiling site populations. A summary of several studies is given in Table 1. A detailed analysis is provided by Sgheiza (1981).

Assuming that equilibrium exists between liquid and vapor at a spherical interface, and that the vapor at a curved interface is nearly at the saturation temperature and pressure of a flat interface, many investigators have related the size of a nucleating cavity to

TABLE 1. REPORTED CAVITY SIZES AND SITE DENSITY FOR WATER

Source	r_c μm	n/A cm^{-2}	q/A W/cm^2**	Surface† Type	Notes
Griffith and Wallis (1960)	2.54	10.1	—	Copper	29°C subcooling
Hsu (1962)	1.27–25.4	—	60	Strip	—
Han and Griffith (1965)	2.21–9.30	2.8	31.8	Gold-plated	5.6–18.5°C subcooling
Hatton and Hall (1966)	25.4–127	26.9	9.15	Chrome-plated tube	—
Lorenz et al. (1974)	2.5–6.4*	4.4	<7.0	Copper	320 grit finish
Shoukri and Judd (1975)	3.16*	80	16.7	Copper	—
Eddington et al. (1978)	2.5–3.0*	9.3	11	Brass	3°C subcooling 0.15 m/s flow
Eddington and Kenning (1978)	1–4	71	21	Stainless Steel	3–6°C subcooling 0.15–0.30 m/s flow
Singh et al. (1978)	3.1–5.3	3.6	<7.0	Copper	

* Cavity radii measured.
** Heat fluxes are at the reported site density.
† Heaters are flat, horizontal plates except where noted.

boiling system parameters using the well-known equation:

$$r_c = \frac{2\sigma T_{sat}}{h_{fg}\rho_v \Delta T_{sat}} \tag{2}$$

In developing a heat transfer model that proposed transient conduction as the primary contributor to nucleate-boiling heat transfer, Mikic and Rohsenow (1969) assumed that the number of sites with radii larger than r_c, as given in Eq. 2, can be expressed in a power law relation:

$$(n/A) = C_1(r_s/r_c)^m \tag{3}$$

where r_s is a radius for which (n/A) would be one per unit area, and C_1 is a dimensional constant. One consequence of the transient-conduction boiling model is that the boiling heat flux is linearly related to active site density.

Boiling water and methanol on polished copper surfaces at one atmosphere, Lorenz et al. (1974) visually counted active boiling sites in the isolated bubble region at heat fluxes less than 7.0 and 2.0 W/cm^2, respectively, while measuring the surface superheat. Equation 1 was found to relate heat flux to site density with the exponent b equal to one. Combining Eqs. 2 and 3 to relate active site density to the superheat temperature,

$$(n/A) = C_2(\Delta T_{sat})^m, \tag{4}$$

Lorenz concluded that the exponent m is determined by the distribution of active sites and that the transient-conduction boiling model of Mikic and Rohsenow (1969) will predict the nucleate pool boiling performance of a surface once r_s, the power-law index m, and the liquid contact angle ϕ for the surface are known

Two recent studies indicate that the power-law exponent m can vary greatly for apparently similar surfaces. Results reported by Shoukri and Judd (1975) while boiling water at atmospheric pressure on various copper surfaces indicated that m increased from about 2.0 to 2.5 as the CLA surface roughness decreased. On the other hand, Singh et al. (1978) observed m to increase from 10 to 25 as the RMS surface roughness increased in tests with water and methanol at nearly the same conditions reported by Shoukri and Judd. Site density and heat flux, however, changed in the manner reported by Shoukri and Judd. These findings show that surface roughness measurements do not reliably predict the distribution of active boiling sites on a surface.

Heater Surface Temperatures

During nucleate pool boiling of liquids, significant temperature fluctuations occur at specific locations on the heating surface where vapor bubbles grow, detach, and move into the bulk liquid. Although several early investigators observed temperature fluctuations during nucleate boiling, they were not analyzed in detail until Moore and Mesler (1961) observed repeated rapid temperature drops of 10–15 K in 2–3 ms. Their tests were performed with water boiling at atmospheric pressure on a nickel-plated nichrome strip. From the nature of the measured temperature fluctuations, Moore and Mesler postulated that they were caused by the evaporation of a thin film of liquid at the base of each bubble. Hendricks and Sharp (1964) reached a similar conclusion after simultaneously photographing bubble growth and recording the surface temperature profile at an artificial boiling site. Rogers and Mesler (1964) confirmed both findings when they photographed isolated bubbles growing near surface thermocouples at an artificial site. In their study, rapid temperature drops of about 11 to 17 K occurred within 1–5 ms. No significant cooling was apparent as liquid returned to the surface after bubble departure.

Cooper and Lloyd (1966) boiled toluene on glass heaters at low pressure and described four stages in bubble growth. In addition to an initial drop and subsequent temperature rise (stages 1 and 2), a second, smaller drop (stage 3) was seen to occur when the bubble lifted from the surface. Stage 4 was the final rise in temperature. One unexpected result was that none of the recorded temperatures reached the saturation temperature. In a preliminary phase of a study measuring transient surface temperatures near the peak heat flux of water, Yu and Mesler (1977) compared experimental and predicted surface temperatures beneath an evaporating microlayer. Their findings agreed with the four stages of bubble growth postulated by Cooper and Lloyd (1966).

Hysteresis, Secondary Bubbles, and Transient Sites

Hysteresis effects in plots of boiling heat-transfer coefficient vs. degree of superheat have been observed for many years. Myers and Katz (1953) reported that at low heat flux, boiling coefficients increased over a period of three or four hours before becoming reproducible, but that stable operating conditions could be reached much more quickly at high heat transfer rates. This phenomenon occurred when boiling propane and n-butane but not when boiling Freon-12, methylchloride, or sulfur dioxide.

Corty and Foust (1955) observed hysteresis effects associated with site activation while boiling n-pentane, ether, and Freon-113 on horizontal surfaces of nickel and copper. When the boiling heat flux was decreased to a level where all active sites disappeared and then increased after 10 to 15 minutes, the first sites to reactivate would appear at a superheat much higher than the superheat at which the last site disappeared. On the other hand, if some sites still existed when the heat flux decrease was interrupted, no such superheat elevation was seen.

Reviewing the findings of researchers who had encountered hysteresis effects, Orell (1967) claimed that all such experiments used electrically heated surfaces where heat flux is the controlled parameter. Although Orell proposed that hysteresis would not happen with steam-heated boilers where wall temperature is the independent variable, no tests were reported to confirm this idea.

In a discussion of hysteresis effects, Madejski (1972) noted that as heat flux increased, surface superheat rose very little or even dropped once nucleate boiling began. Only when heat flux decreased did he find reproducible boiling curves. In contrast, Rallis and Jawurek (1964) emphasized that they obtained their unusual boiling curve as heat flux decreased and that similar tests performed at higher pressures did not exhibit the abnormal behavior.

One possible explanation for hysteresis is the presence (or absence) of high concentrations of circulating microscopic bubbles that have been observed near heating surfaces. Westwater (1956) cited experiments that showed suspended inert gas bubbles, too small to be seen individually, had a strong effect on the nucleate-boiling curve. A similar idea was advanced by Elrod et al. (1967), who noted that a milky cloud formed near their boiling test section and that it resembled a cloud of minute bubbles.

Renewed interest in site seeding has been exhibited in several recent boiling studies. In tests with water boiling on stainless steel, Eddington and Kenning (1978) postulated that the natural nucleation sites on their plate included both stable and seeded unstable sites and that thermal interference and the temperature-pressure history of the surface affected site populations. Boiling site populations were 10 to 25% higher than expected from gas nucleation experiments. To account for the increase, site seeding was thought to occur when the microlayer under a bubble dried out, causing vapor to cover an adjacent site and activate it. Eddington and Kenning also found that some boiling sites unexpectedly deactivated as heat flux increased in their stainless steel tests. Since their system had been carefully degassed, they dismissed the possibility that sites deactivated as noncondensable gas in the cavities became depleted. Instead, they suggested thermal interference as the cause since each deactivated site lay within 0.4 cm of a new site, and the sites reappeared when the heat flux was later lowered.

Raad and Myers (1971) advanced the idea of permanent and transient boiling sites when they investigated the length of time specific sites actively boiled on a 0.00254 cm thick stainless steel heater at 2.72 W/cm^2. From high-speed movies of site population patterns, Raad observed that although active site population decreased to a constant level in less than one second, some sites remained active indefinitely, others had relatively short lives, while a third group exhibited repeated periods of rapid bubbling separated by periods of inactivity.

Circulating Microbubble Mechanism

In a succeeding paper in this series, Myers (1984) has postulated a mechanism in which fluid motion transports microbubbles of a certain size range from the liquid bulk into the superheated liquid of the thermal boundary layer adjacent to the heater surface. There the microbubbles can grow and create an active boiling site which might exist for a short time only or which might become a stable nucleation center if adjacent to a cavity with the proper geometry. The size range of microbubbles which might recirculate and grow increases markedly with increasing superheat temperature.

A consequence of having circulating microbubbles in a boiling liquid is that boiling sites would exhibit a range of nucleation lifetimes. A single microbubble penetrating the superheated liquid near the heater surface might simply grow and depart without further consequence. On the other hand, it might in its growth displace liquid from a nearby cavity and create a long-lived boiling site. As shown in earlier sections, many investigators have studied the size and shape of cavities that will effectively trap gas and nucleate. They have shown that some sites might exist in which the gas in the cavity is easily dislodged by advancing liquid. These sites would be active for only a short time. If more circulating microbubbles exist as the superheat temperature increases, one would observe a wider range of boiling site lifetimes at high heat fluxes than at low heat fluxes.

Another indication that circulating microbubbles can affect active boiling site behavior is if different cavities are active in different boiling runs at the same heat flux. A series of boiling tests run under the same conditions, as indicated by constant total site counts, might show some sites to be active in every test while other sites would be active in fewer tests. The sites active in every test would presumably consist of cavities that have the most suitable geometry or are suitably positioned so that microbubbles can readily activate them. These would correspond to the long-lived sites discussed above. On the other hand, sites active in only some tests might have less favorable geometric conditions to be readily stimulated to nucleate by microbubbles. These sites would correspond to the short-lived sites referred to above.

This study tests to see if the hypothesis that boiling sites are activated by circulating microbubbles is consistent with the results of experiments that count active boiling sites and measure site lifetimes as functions of heat flux and elapsed heating time. Pulsed heat flux tests are performed to see how many different sites can be activated at one heat flux. Heater surface temperatures and nucleation times are measured to determine if sites nucleate intermittently and how intermittent sites might be activated. Finally, one boiling surface is analyzed to compare bubble site and surface-cavity positions.

APPARATUS AND PROCEDURE

This study used an Inframetrics, Inc., model 209A thermographic camera and display unit to analyze on a real-time basis the thermal radiation emanating from the bottom surface of a heater plate while liquids were boiling on the top surface. Utilizing a liquid nitrogen cooled HgCdTe crystal array that detects thermal radiation at wavelengths between 8 and 14 microns, this device displayed televisionlike video images of the heated surface at 30 and 60 frames/s with the scanning rate fixed at 3,000 Hz. These visual mode images consisted of light and dark patterns that represented warm and cool areas on the heater surface. Sometimes the IR camera operated in a line-scan mode by selecting a single line from the visual mode display and continuously scanning it at 3,000 Hz. This mode produced a temperature profile of the selected line whose amplitude was proportional to temperature gradient. The IR camera was limited to targets having surface temperatures between −20 and +150°C, although special apertures are available from the manufacturer to extend the operating range.

Visual-mode images and line-scan displays were photographed with a Redlake Corp. HYCAM 16 mm high-speed, rotating-prism movie camera for data storage and analysis. An electronic control system used to synchronize video and filmed images is described in detail by Sgheiza (1981). For all filmings the HYCAM was equipped with a 55 mm Pentax lens mounted on a 2.54 cm C-mount adapter. Focusing distance was 82.5 cm (32.5 in) with the lens iris set at $f/2.8$. Most movies were taken with Kodak no. 7278 Tri-X film (ISO/ASA 200). When the movie camera was in use, all room lighting was turned off. Adjustment of the *Background* control on the display unit front panel brightened the CRT sufficiently for filming. Frame-by-frame analysis of films was performed with a Kodak Analyst 16 mm projector.

The boiler consisted of a 15.2 cm square vessel made of 0.32 cm thick stainless steel, 25.4 cm high. Boiling took place on a 0.00254 cm (1 mil) thick horizontal sheet of 302 stainless steel. Two 0.15 cm stainless steel frames, four 0.051 cm asbestos gaskets, and a 1.3 cm transite frame attached the heater to the vessel. The stainless steel frame conducted heat away to prevent overheating of the plate. Teflon tape and silicone glue sealed connections and joints. Details are given by Sgheiza (1981).

Closing the top of the boiler during boiling runs, a stainless steel shell-and-tube condenser provided venting to atmospheric pressure with 24 1.1 cm ID tubes. Babcock and Wilcox Kaowool ceramic-fiber blanket, 2.5 cm thick, minimized heat losses from the boiling vessel and flange. An S-80210B E.H. Sargent and Co. total-immersion thermometer, positioned 1.0 cm above the heater, measured bulk-liquid temperatures up to 101 ± 0.01°C. For higher boiling liquids, the thermometer was replaced with a chromel-alumel thermocouple immersed in naphthalene and contained in a sealed glass tube.

Two copper electrodes, 1 cm wide by 12.5 cm long, spaced about 8.5 cm apart, were soldered to the bottom of the boiling plate. An Electronics Measurements, Inc., model SCR 10-500 high-current power supply provided power from a three-phase, 220-volt outlet over a range of 0 to 10 volts DC and 0 to 500 amperes. Between the power supply and the copper electrodes, heavy duty copper bars, 0.7 cm square, were employed to reduce resistance heating at high current loads. All fixed connections were silver-soldered. A John Fluke, Inc. model 8000A digital multimeter read voltage to ±0.01 volts. Current was recorded to ± 2 amps from the power supply ammeter.

During boiling runs, a 0.1 cm thick stainless steel temperature reference plate equipped with four chromel-alumel thermocouples provided indirect estimates of the heater-surface temperature. Attached to the transite frame, this plate was positioned between the electrodes and suspended about 0.5 cm below the heated plate. A 4.5 cm × 8.0 cm hole cut in the reference plate gave the IR camera an unobstructed view of the heater bottom. The thermocouples were silver-soldered in pairs to the reference plate on both sides of the hole near the middle of the heated plate. They were monitored by a Leeds and Northrup model 8690 student potentiometer. All surfaces normal to the IR camera were painted with a colloidal graphite solution called Aquadag® to provide a uniform surface emissivity. An alignment grid of white dots was painted at 0.5 cm intervals on the Aquadag® coated heater surface so the IR camera could be accurately positioned under the boiler.

In these experiments, heating surfaces were prepared by first cutting a 15 cm × 15 cm sheet from a 183 cm roll of Precision Steel Warehouse 1 mil, type 302 stainless shim steel. After cleaning with acetone, each sheet was annealed at 300°C for one hour in an oven. Copper electrodes were soldered to the sheet after cooling.

After the boiler was cleaned with acetone and dried, approximately two liters of fresh liquid were placed in the vessel for a boiling test. In tests with water, the liquid pool was preheated at 80 to 90°C for a minimum of 6 hours to eliminate dissolved gases. For the organic liquids, the preheat time was at least 3.8 hours. In addition, before site counts were taken the liquid was

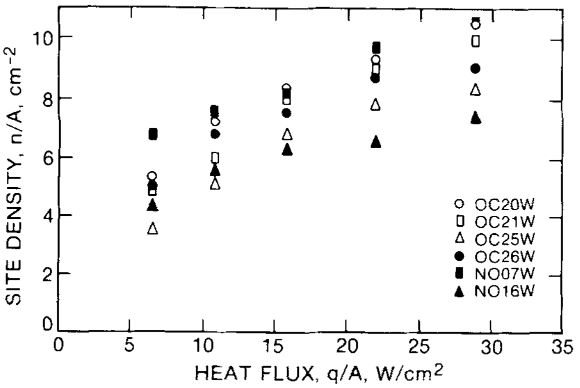

Figure 1. Site density vs. net heat flux for water on plate 77-18.

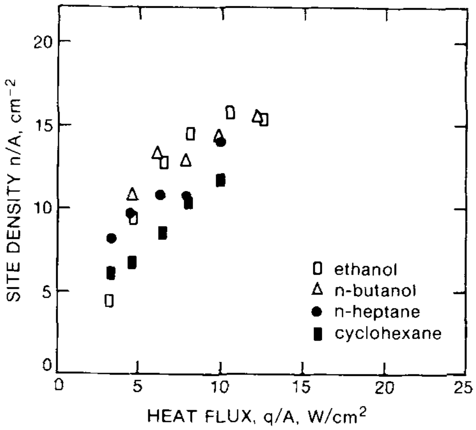

Figure 2. Site density vs. measured heat flux for organic liquids; plate 78-05.

boiled at the maximum heat flux for at least three hours. During boiling tests liquid volume was maintained between 1,500 and 2,000 ml by periodically adding fresh liquid preheated to the saturation temperature. Liquid depth stayed between 6.0 and 9.0 cm above the heater surface. In several experiments liquid samples were taken before and after boiling and tested for purity by gas chromatography.

Direct Site Counts

Direct site counts were taken at different times during a boiling run by marking active site locations and alignment grid points on acetate sheets placed on the IR camera video display. After the acetate sheets were photocopied, the number of sites appearing inside a 6.0 cm^2 count area on the paper was recorded. Site densities, such as those shown in Figure 1, were taken in sequences in which heat flux decreased in steps after the three-hour boiling period. Site-plot marking was done at each power level 10 minutes after each decrease in heat flux.

Figure 1 shows how measured site density varied in different boiling runs for water on heater plate 77-18. Although all runs show an increase in site density with heat flux, the runs show considerable variation from one another. Some investigators have suggested that differences in surface pressure or surface tension might account for such variations. However, pressure differences between runs in this study were always less than 1%; in addition, careful cleaning of the system was always done to eliminate that as a possible source of error.

In several series of boiling runs made at constant heat flux, active site density increased somewhat with elapsed time. For example, in four out of five tests with plate 78-05 at 24 W/cm^2, site density increased up to 19% over a three-hour interval, although most of the change seemed to occur during the first hour. The same trend was observed at 11.8 W/cm^2 in run OC10W. Similar results were obtained with plate 77-18 in 7 out of 8 boiling tests run for three hours. At measured heat fluxes between 28.6 and 29.0 W/cm^2, the number of active sites increased an average 10.0%. By comparison, plate 78-05 averaged a 10.3% increase in site density during the same elapsed time interval. Just as site density was observed to increase with time after heat flux was increased to and held at constant level, active site counts for water showed comparable decreases with time at constant heat flux after a decrease in heater power. Again, most of the site density change seemed to occur in the first hour.

Time effects in nucleate boiling of water have been noted by at least two other investigators. Nix et al. (1970) noted that the superheat of a Teflon-coated stainless steel surface decreased as heat flux increased and speculated that additional sites were activated by seeding from existing adjacent sites or that the necessary conditions for site activation arose in some random manner with time. Witzke (1977) observed the number of active sites to increase 23% during the fitrst three hours of boiling at 27.5 W/cm^2. During the next five hours the site count changed less than 5%. Witzke obtained similar results at 34.2 W/cm^2.

The time-dependent changes in active site density noted by other researchers and recorded in direct site counts in this study could be explained by a site-activation mechanism based on circulating microbubbles. When heat flux increases, sites which are already producing bubbles now nucleate more rapidly and new sites become active. Some newly active sites appear immediately after the heat flux increase, while other new boiling sites appear over a period of time and may actually represent less desirable locations which have been stimulated into nucleating by the increasing concentrations of microbubbles that are carried in the liquid sweeping over the heater surface. In addition, the temperature in the thermal boundary layer increases, which allows growth of smaller bubbles. After a decrease in heat flux the process reverses. Some boiling sites cease bubbling immediately, others nucleate less rapidly, while a third group deactivates slowly with time. These sites are probably in less stable locations that are subject to easy deactivation by random eddies of liquid sweeping by. That sites might be deactivated easily was shown in a test where, after steady boiling was established in a pool boiler and many active bubble sites were observed with the IR camera, stirring the liquid vigorously swept away the temperature patterns of the bubble sites from the video display.

Figure 2 shows how site density varied for four organic liquids on plate 78-05. Measured site densities for the organic liquids were significantly higher than for water at the same heat flux. Higher site densities might be expected since Eq. 2 indicates that liquids with low surface tension can retain stable microbubbles smaller in size than can water and that, as a result, more nucleating sites may be available at the same heat flux. A comparison of cavity radii calculatd from Eq. 2 at $T_w - T_{sat} = 10$ K for water and the four organic liquids used in these experiments shows values of r_c ranging from 0.85 to 1.2 μm for the organic liquids compared to a value of 3.2 μm for water. Active sites were counted in the same manner as in the water tests using acetate sheets to mark the nucleating sites from the IR camera video display. Degassing times ranged from three to 26 hours and included one to four hours boiling at the maximum recorded heat flux.

Filmed Site Counts—Pulse Tests

The permanence of active boiling sites was tested by boiling water at 11.3 W/cm^2. Counts were made of the boiling sites that remained active after momentarily shutting off the heater power and then turning it on. When power was restored, some sites initially active resumed nucleating. Other sites remained dormant, and several new sites not seen before became active. Figure 3 shows that the cumulative number of sites active in at least one test increased from 27 to 43 in four pulse tests, while the number of sites persistently active in each of the four tests decreased from 27 to 11. In contrast, the number of active sites counted after each power change varied less than 8% from the steady state count of 27. Degassing for 25.7 hours followed by boiling at the test heat flux for more than three hours established steady conditions for a run. Next, the heater power was pulsed momentarily by setting the input voltage at zero for 5 seconds to deactivate the boiling sites and then resetting the voltage at the original level. After a 1-minute delay, the HYCAM movie camera was switched on for 4 to 5 seconds at 60 frames/s to record the active sites appearing in the 3 cm × 2 cm viewing areas monitored by the IR camera. From frame-by-frame viewing of the developed movie film, active sites were counted.

These results extend the work of Raad (1970), who observed both per-

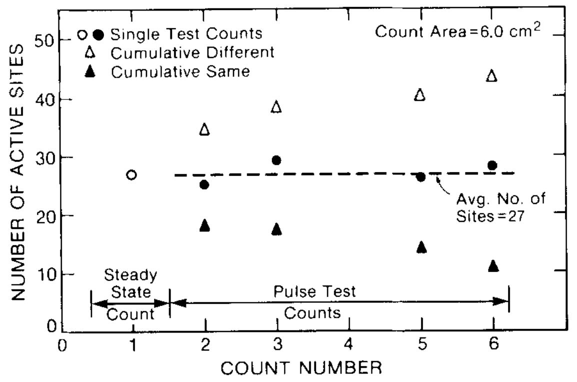

Figure 3. Number of active sites vs. pulse test number for run MY07W at 11.3 W/cm²; plate 79-01.

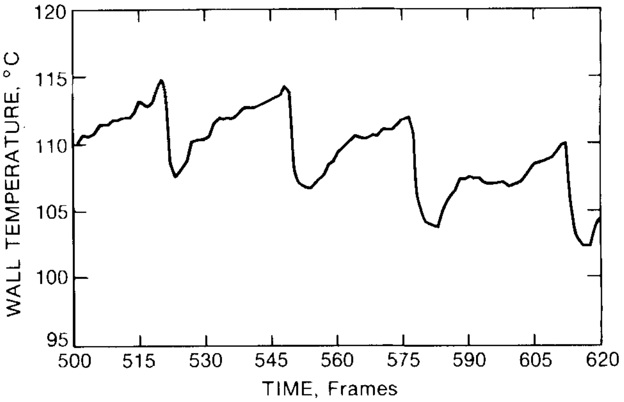

Figure 4. Heater surface temperature vs. time at site M0.7 for plate 78-05, water at 24.0 W/cm²; film speed 988 frames/s.

manent and nonpermanent sites while boiling methylene chloride. The finding that many inactive sites exist on a boiling surface has indirect support in the literature. For example, Eddington and Kenning (1978) discovered that up to five times more sites nucleated on a surface in gas diffusion tests than were active in boiling. The pulse-boiling test results reported in this section imply that established nucleation theory is not sufficient to predict which sites will nucleate at a given heat flux or superheat temperature. Although the persistently active sites behaved as expected, the majority of sites were only sometimes active, indicating that some mechanism exists which determines between sites which ones to activate. This finding is consistent with the idea that circulating microbubbles stimulate inactive boiling sites. The persistently active sites presumably have the most desirable shape or location to trap microbubbles. The sometimes-active sites would be those less capable of trapping microbubbles.

Filmed Site Activity

Boiling activity at individual sites was studied by examining projections of motion-picture photographs of a 1 cm × 3 cm area of plate on which water was boiling at one atmosphere. Filming was done at 60 frames/s; the film strips examined in each case consisted of two-second segments (120 frames).

The results of counts of film strips from seven runs were recorded in which a total of 43 nucleation sites were identified. Measurements were taken at three different heat fluxes (12, 17, and 24 W/cm²). The results tabulated from a strip for each site during each run consisted of the number of frames (maximum 120) during which the site showed activity on the screen, and the number of sequences of consecutive appearances each site made during the two-second clip. The most persistently active site was one which appeared in seven sequences and whose cumulative appearance time varied from 44 to 114 frames. The least active site appeared in only 15 frames after boiling for three hours at 24 W/cm² and disappeared when the heat flux was decreased.

Seven of the 43 sites were active in all seven runs, four sites were active in only single runs, and no more than 31 sites were active in any single test. As found earlier, the concentration of sites tended to increase with power input. The average length of a burst of boiling activity ranged from 1.47 frames/burst at the lowest heat flux (11.9 W/cm²) to 2.53 frames/burst at the highest (24.2 W/cm²). The length of these periods tended to increase with time at constant heat flux, as well as with power input. It is to be expected that the average length of a burst of boiling activity at a site would increase with heat flux if the number of active sites were fixed.

HEATER SURFACE TEMPERATURES

Temperature Profiles and Change

During several boiling runs the heater surface temperature beneath individual sites was monitored by the IR camera in the line-scan mode at 3,000 Hz and recorded on 16 mm movie film at 1,000 frames/s. Figure 4 shows how heater surface temperature changed with time at site M0.7 on plate 78-05 at 24.0 W/cm². These temperature profiles, along with similar ones developed for other sites from the same boiling run, show the four stages of bubble growth and departure described by Cooper and Lloyd (1966) and confirmed by Yu and Mesler (1977).

Table 2 relates the size and duration of the temperature changes that occurred during three of the four stages of bubble growth. The values shown for these chnges are averaged from 8 to 16 data points calculated from the temperature profiles developed for four sites, including site M0.7. The bubble growth stages represented in Table 2 are stage 1, an initial temperature drop, corresponding to the start of bubble growth, stage 2, an initial temperature rise, and stage 4, a final temperature rise. Stage 3, a second temperature drop believed to occur when a bubble departs from the heater surface and cooler liquid again covers the bubble site, tended to be very small in magnitude and duration relative to the other changes and is not recorded here. Because stage 3 was generally small, the initial temperature drop was found to be approximately equal to the sum of the two temperature rises. The rate of the initial temperature drop was in all cases much greater than either of the temperature rises.

These findings are very different from those reported by Jakob (1949), who indicated that the bubble growth (stages 1 and 2) and

TABLE 2. SURFACE TEMPERATURE CHANGES DURING BOILING RUN OC10W/PLATE 78-05

Test	Growth Stage	No. of Changes	$\overline{\Delta T}$ K	$\overline{\Delta \theta}$ ms	$\overline{\Delta T}/\overline{\Delta \theta}$ K/ms
M14*	Initial Drop (1)	16	6.5	4.3	1.6
M14*	Initial Rise (2)	12	3.6	9.0	0.41
M14*	Second Rise (4)	8	3.0	32.9	0.099
M17**	Initial Drop (1)	13	7.4	4.2	1.9
M17**	Initial Rise (2)	13	3.9	8.5	0.51
M17**	Second Rise (4)	11	3.1	14.7	0.22

* For test M14, q/A = 11.8 W/cm², ΔT_{sat} = 12.3 K.
** For test M17, q/A = 24.0 W/cm², ΔT_{sat} = 14.7 K.

TABLE 3. OVERALL NUCLEATION BEHAVIOR FOR SITES M0.7, M0.4, P0.4, AND P0.9 IN RUNS OC10WM14 AND OC10WM17 ON PLATE 78-05

Run	Site	Number of Nucleations During 1st 400 Frames	2nd 400 Frames	3rd 400 Frames
OC10WM14	M0.7	3	2	4
OC10WM14	M0.4	3	3	1
OC10WM14	P0.4	4	7	9
OC10WM14	P0.9	6	4	7
OC10WM17	M0.7	10	11	10
OC10WM17	M0.4	11	9	9
OC10WM17	P0.4	13	18	13
OC10WM17	P0.9	10	12	10

waiting times (stage 4) were equal. Later, Hatton and Hall (1966), Roll and Myers (1964), and Hsu and Graham (1976) refuted Jakob's finding and established that the waiting period varies between sites and that the ratio of waiting period to growth period varies greatly, as Table 2 confirms.

The magnitude and duration of the temperature changes measured here are similar to reported values measured with thermocouples at artificial boiling sites. Rogers and Mesler (1964) reported temperature drops of 6 K in 2 ms at 10.4 W/cm^2 and 10 K in 1.6 ms at 15.9 W/cm^2. Their tests were performed with water on a narrow, 0.16 cm thick chromel F strip at one atmosphere. Using the same boiling system as Rogers and Mesler, Hospeti and Mesler (1969) found temperature drops of 4.4 to 6.2 K that took from 1.5 to 2.8 ms at 7.9 W/cm^2 for three bubbles. At heat fluxes from 5.3 to 10.4 W/cm^2, the cooling times (stage 1) reported by Rogers and Mesler (1964) showed no consistent trend with heat flux. On the other hand, their heating times, which include stages 2 and 4 and which varied from 6.8 to 34.4 ms, decreased markedly as heat flux increased, while the heating rate which ranged from 0.17 to 0.97 K/ms increased in accordance with Table 2.

Nucleation Period Fluctuations

Although the surface temperature changes (Table 2) at active boiling sites are important in indicating the heat transfer mechanisms involved in vapor-bubble growth, the amount that these changes fluctuate in magnitude and duration can also provide valuable information. For example, based on the mechanism for microbubble circulation postulated here, it might be expected that boiling sites stimulated by microbubbles would nucleate less regularly than sites where bubble growth depends only on superheat temperature and site geometry. If a boiling site nucleated irregularly, large variations in nucleation period size should be expected even though the number of nucleations during equal time intervals might be constant.

TABLE 4. OVERALL VARIATION OF NUCLEATION PERIODS DURING BOILING RUN OC10W ON PLATE 78-05

Test	q/A W/cm^2*	Site No.	No. of Periods in 1 s run (Approx.)	$\overline{\Delta\theta}$ ms	$CV(\overline{\Delta\theta})$ %
M14	11.8	M0.7	8	139.9	51.7
M14	11.8	M0.4	6	168.7	60.9
M14	11.8	P0.4	19	60.8	52.8
M14	11.8	P0.9	16	78.8	60.4
M17	24.0	M0.7	30	37.4	28.3
M17	24.0	M0.4	28	41.4	47.7
M17	24.0	P0.4	43	26.3	37.5
M17	24.0	P0.9	31	38.0	46.2

* At q/A = 11.8 W/cm^2, ΔT_{sat} = 12.3 K; at 24.0 W/cm^2, ΔT_{sat} = 14.7 K.

TABLE 5. SCATTER IN AVERAGE TEMPERATURE CHANGES DURING BOILING RUN OC10W ON PLATE 78-05†

Test	Growth Stage	$CV(\overline{\Delta T})$ %	$CV(\overline{\Delta\theta})$ %	$CV(\overline{\Delta T}/\overline{\Delta\theta})$ %
M14*	Initial Drop (1)	35.6	35.7	26.3
M14*	Initial Rise (2)	36.1	29.4	31.6
M14*	Second Rise (4)	47.1	49.6	41.3
M17**	Initial Drop (1)	19.6	27.6	27.2
M17**	Initial Rise (2)	19.5	26.3	40.6
M17**	Second Rise (4)	26.1	39.3	23.0

† Average temperature changes calculated in Table 2.
* For test M14, q/A = 11.8 W/cm^2, ΔT_{sat} = 12.3 K.
** For test M17, q/A = 24.0 W/cm^2, ΔT_{sat} = 14.7 K.

Tables 3 and 4 indicate that intermittent nucleation behavior occurred at sites M0.7, M0.4, P0.4, and P0.9 in boiling runs OC10WM14 and OC10WM17. Table 3 shows that the number of nucleations at each site stayed relatively constant over three time intervals of 400 movie frames (405 ms). In contrast, Table 4 shows large variations in individual nucleation periods for these sites. The parameters used in Table 4 to describe the variation or scatter in a set of data is the coefficient of variation (CV), defined as the percentage ratio of the standard deviation of the mean for n data elements.

The coefficients of variation in Table 5 for the temperature changes shown in Table 2 indicate that the temperture and time changes recorded for the second temperature-rise period (stage 4) fluctuated considerably more than did corresponding values for the initial drop and rise periods (stages 1 and 2). CV values for the temperature rise rates show less consistency because a large ΔT divided by a large $\Delta\theta$ will give the same quotient as a small ΔT divided by a small $\Delta\theta$.

The finding that stage 4 bubble growth varies more than the other stages was corroborated by calculating the coefficient of variation for a set of growth and waiting times reported by Han and Griffith (1965). They measured times for 20 single bubbles at an isolated site while boiling water at ΔT_{sat} = 10 K on a gold-plated surface with 3.9 K subcooling. Although Han and Griffith used a different boiling system from the one used here, average growth (stage 1 and 2) times of 16.0 and 51.0 ms from their data are consistent with growth and waiting times of 13.3 and 32.9 ms taken from Table 2 at 11.8 W/cm^2 and ΔT_{sat} = 12.3 K. Coefficients of variation of 16.6% and 61.0% calculated from their growth and waiting times agree with the finding in Table 5 that stage 4 bubble growth times varied much more than growth times in stages 1 and 2.

The findings that nucleation times and magnitudes fluctuate by large amounts and, more exactly, that most of these fluctuations are concentrated in the fourth stage of bubble growth—the waiting period—are in accord with the view of boiling nucleation in which vapor bubble nucleations occur randomly. On the other hand, if bubble nucleations only depend on cavity size distribution, which is fixed before boiling starts, and surface superheat temperature, which changes relatively slowly with time, most active boiling sites ought to exhibit relatively constant nucleation periods and constant temperature changes. In contrast, it has been shown here that the nucleation behavior of active boiling sites fluctuates markedly.

Liquid Dryout and Site Seeding

The preceding two parts of this section presented evidence that intermittently active boiling sites exist and that irregular nucleation behavior can be detected by measuring the amount that nucleation periods fluctuate. Although seeding by circulating microbubbles could account for intermittently active boiling sites, another nucleation mechanism, site seeding by nearby active sites, could also explain intermittent behavior. Site seeding was first proposed by Eddington and Kenning (1978), who observed active boiling sites which were inactive in gas nucleation experiments and stable gas nucleation sites which did not nucleate in boiling tests.

According to Judd and Lavdas (1980), a new bubble nucleus can be created when a bubble from an adjacent nucleation site covers a potential nucleation site with its "dryspot." Bubble emission can be terminated when a bubble interferes with the nucleus at a nearby active site. Photographic evidence of both occurrences was taken from Judd and Hwang (1976) for dichloromethane boiling on glass at 4.1 and 6.0 W/cm^2 and 5.3 K subcooling.

In contrast, van Stralen (1979) concluded from dryspot radius calculations that dryspots are exclusively generated at pressures less than atmospheric. When system pressures are low, vapor bubbles grow to a large hemispherical size and stay on the heated surface for a relatively long time. At pressures equal to or greater than atmospheric, van Stralen concluded that hardly any dryspot will be present beneath hemispherical bubbles in pure liquids. The experiments of Judd and Lavdas (1980) were performed at 0.5 atmosphere, which would support the conclusion of van Stralen.

To determine if dryspots form during nucleate boiling of water at one atmosphere, the temperature rise for the second stage of bubble growth was calculated and compared to the experimentally measured temperature rise. From a lumped analysis of the heater surface temperature under a bubble, the energy loss from the plate to the bubble was represented by a heat-transfer coefficient, h_ℓ, times the temperature difference between the heater surface and the bulk liquid, $(T - T_{sat})$. Varying h_ℓ from 0.001 to 4 $W/cm^2 \cdot K$ produced temperature rises that simulated a range of surface conditions up to dryout ($h_\ell \leq 0.1$ $W/cm^2 \cdot K$). Experimental temperature rises were taken from Table 2 for boiling runs OC10WM14 at 11.8 W/cm^2 and OC10WM17 at 24.0 W/cm^2.

The results indicated that no dryspots were formed during boiling runs OC10WM14 and OC10WM17. At 11.8 W/cm^2, a liquid heat-transfer coefficient of about 2 $W/cm^2 \cdot K$ gave the best agreement between calculated and experimental temperature rises. At 24.0 W/cm^2, a liquid heat-transfer coefficient greater than 4 $W/cm^2 \cdot K$ was needed to match temperature rises. These values of h_ℓ indicate that liquid stayed between the vapor bubble and the heater surface until the bubble departed.

Visual mode displays of boiling site patterns also confirmed that no dryspots formed when water was boiled at heat fluxes up to 30 W/cm^2. On the other hand, a potential dryout condition was observed in boiling test JA29B with n-butanol at 11.3 W/cm^2 on plate 78-01. Visual mode displays exhibited unusually bright spots at active site locations indicating a local surface temperature that was higher than the surrounding temperature. In the line-scan mode small, sudden temperature rises were noted that were equal in magnitude and nearly as fast as the temperature drops. When the heat flux was reduced, the bright spots and rapid temperature rises disappeared.

Heater Surface Analysis

When the stainless steel boiling surface was examined under an optical microscope at magnifications up to 800×, many locations were found which might be thought to be suitable as boiling sites. In a 2 cm^2 area 176 pits were counted, a number far in excess of the 10 to 20 active boiling sites observed at 16.5 W/cm^2. Pits were almost always part of a groove. Groove widths generally were around 5 μm in diameter, while pits ranged up to 18 μm in diameter. Concentric circular rings of different colors were often observed around the pits. The outermost ring diameter ranged up to 40 μm.

Because they were also found on surfaces that had been annealed but not yet used for boiling, it was believed that the pits and grooves were caused by inclusions of extraneous material in the stainless steel and that the concentric colored rings may have resulted from annealing the cold-rolled steel sheets. The sizes of the pits were of the same magnitude as the diameters of stable bubbles at the superheats involved, so it is possible that some served as boiling sites. In addition to the 176 locations with pits, another 39 locations were found with ring-type coloration but without pits. These were considered also likely to be the results of occurrences during manufacture and annealing.

ACKNOWLEDGMENT

The National Science Foundation provided support for part of this work under grant ENG75-06560.

NOTATION

A	= area
a, b	= constants
c_1, c_2	= dimensional constants
h_{fg}	= latent heat of vaporization
m	= constant
n	= number of boiling sites
q	= power input
r_c, r_s	= cavity radius
T_{sat}	= liquid saturation temperature
ΔT_{sat}	= superheat

Greek Letters

θ	= time
ρ_v	= density of vapor
σ	= surface tension

LITERATURE CITED

Cooper, M. G., and A. J. P. Lloyd, "Transient Local Heat Flux in Nucleate Boiling," *Proc. 3rd Int. Heat Tr. Conf.*, **3**, 193, Chicago (1966).

Corty, C., and A. S. Foust, "Surface Variables in Nucleate Boiling," *Chem. Eng. Prog. Symp. Ser.*, **51**, (17), 1 (1955).

Eddington, R. I., and D. B. R. Kenning, "The Prediction of Flow Boiling Bubble Populations from Gas Bubble Nucleation Experiments," *Proc. 6th Int. Heat Tr. Conf.*, **1**, Paper FB-1, 275, Toronto (1978).

Eddington, R. I., D. B. R. Kenning, and Q. I. Korneichev, "Comparison of Gas and Vapour Bubble Nucleation on a Brass Surface in Water," *Int. J. Heat Mass Tr.*, **21**, 855 (1978).

Elrod, W. C., et al., "Boiling Heat-Transfer Data at Low Heat Flux," *J. Heat Tr.*, **89**, 235 (1967).

Gaertner, R. F., "Distribution of Active Sites in the Nucleate Boiling of Liquids," *Chem. Eng. Prog. Symp. Ser.*, **59** (41), 52 (1963).

———, "Photographic Study of Nucleate Pool Boiling on a Horizontal Surface," *J. Heat Tr.*, **87**, 17 (1965).

Gaertner, R. F., and J. W. Westwater, "Population of Active Sites in Nucleate Boiling Heat Transfer," *Chem. Eng. Prog. Symp. Ser.*, **56** (30), 39 (1960).

Griffith, P., and J. D. Wallis, "The Role of Surface Conditions in Nucleate Boiling," *Chem. Eng. Prog. Symp. Ser.*, **56** (30), 49 (1960).
Han, C. Y., and P. Griffith, "The Mechanism of Heat Transfer in Nucleate Boiling. I and II," *Int. J. Heat Mass Tr.*, **8**, 887 (1965).
Hatton, A. P., and I. S. Hall, "Photographic Study of Boiling on Prepared Surfaces," *Proc. 3rd Int. Heat Tr. Conf.*, **4**, 24, Chicago (1966).
Heled, Y., and A. Orell, "Characteristics of Active Nucleation Sites in Pool Boiling," *Int. J. Heat Mass Tr.*, **10**, 553 (1967).
Hendricks, R. C., and R. R. Sharp, "Initiation of Cooling Due to Bubble Growth on Heating Surface," NASA TN-D-2290 (1964).
Hospeti, N. B., and R. B. Mesler, "Vaporization at the Base of Bubbles of Different Shape During Nucleate Boiling of Water," *AIChE J.*, **15**, 214 (1969).
Hsu, Y. Y., "On the Size Range of Active Nucleation Cavities on a Heating Surface," *J. Heat Tr.*, **84**, 207 (1962).
———, "Gradual Transition of Nucleate Boiling from Discrete Bubble Regime to Multibubble Regime," NASA TN-D-2564 (1964).
Hsu, Y. Y., and R. W. Graham, *Transport Processes in Boiling and Two-Phase Systems*, McGraw-Hill, New York (1976).
Iida, Y., and K. Kobayasi, "An Experimental Investigation of the Mechanism of Pool Boiling Phenomena by a Probe Method," *Proc. 4th Int. Heat Tr. Conf.*, **5**, Paper B1.3, Paris (1970).
Jakob, M., *Heat Transfer*, Vol. 1, Wiley, New York (1949).
Jakob, M., and W. Fritz, "Experiments in the Evaporation Process," *Forsch. Geb. Ingenieur.*, **2**, 435 (1931).
Judd, R. L., and K. S. Hwang, "A Comprehensive Model for Nucleate Pool Boiling Heat Transfer Including Microlayer Evaporation," *J. Heat Tr.*, **98**, 623 (1976).
Judd, R. L., and C. H. Lavdas, "The Nature of Nucleation Site Interaction," *J. Heat Tr.*, **102**, 461 (1980).
Kirby, D. B., and J. W. Westwater, "Bubble and Vapor Behavior on a Heated Horizontal Plate During Pool Boiling Near Burnout," *Chem. Eng. Prog. Symp. Ser.*, **61** (57), 238 (1965).
Kurihara, H. M., and J. E. Myers, "The Effects of Superheat and Surface Roughness on Boiling Coefficients," *AIChE J.*, **6**, 83 (1960).
Lorenz, J. J., B. B. Mikic, and W. M. Rohsenow, "The Effect of Surface Conditions on Boiling Characteristics," *Proc. 5th Int. Heat Tr. Conf.*, **4**, Paper B2.1, Tokyo (1974).
Madejski, J., "Improved 'Three-Component' Theory of Nucleate Pool Boiling," *Int. J. Heat Mass Tr.*, **15**, 503 (1972).
Mikic, B. B., and W. M. Rohsenow, "A New Correlation of Pool Boiling Data Including the Effect of Heating Surface Characteristics," *J. Heat Tr.*, **91**, 245 (1969).
Moore, F. D., and R. B. Mesler, "The Measurement of Rapid Surface Temperature Fluctuations During Nucleate Boiling of Water," *AIChE J.*, **7**, 620 (1961).
Myers, J. E., "Short-Lived Sites in Nucleate Boiling", *AIChE J.*, (1985).
Myers, J. E., and D. L. Katz, "Boiling Coefficients Outside Horizontal Tubes," *Chem. Eng. Prog. Symp. Series*, **49** (5), 107 (1953).
Nix, G. H., R. I. Vachon, and D. M. Hall, "A Scanning and Transmission Electron Microscopy Study of Pool Boiling Surfaces," *Proc. 4th Int. Heat Tr. Conf.*, **5**, Paper B1.6, Paris (1970).
Orell, A., "On S-Shaped Boiling Curves," *Int. J. Heat Mass Tr.*, **10**, 967 (1967).
Raad, T., "A Study of Nucleation in Pool Boiling," M.S. Thesis, Univ. of California, Santa Barbara, CA (1970).
Raad, T., and J. E. Myers, "Nucleation Studies in Pool Boiling on Thin Plates Using Liquid Crystals," *AIChE J.*, **17**, 1,260 (1971).
Rallis, C. J., and H. H. Jawurek, "Latent Heat Transport in Saturated Nucleate Boiling," *Int. J. Heat Mass Tr.*, **7**, 1,051 (1964).
Rogers, T. F., and R. B. Mesler, "An Experimental Study of Surface Cooling by Bubbles During Nucleate Boiling of Water," *AIChE J.*, **10**, 656 (1964).
Roll, J. B., and J. E. Myers, "The Effect of Surface Tension on Factors in Boiling Heat Transfer," *AIChE J.*, **10**, 530 (1964).
Sgheiza, J. E., "Behavior of Nucleation Sites in Pool Boiling", Ph.D. Dissertation, Univ. of California, Santa Barbara (1981).
Sgheiza, J. E., and J. E. Myers, "Infrared Studies of Nucleate Boiling," *Chem. Eng. Prog. Symp. Ser.*, **73** (164), 244 (1977).
Shoukri, M., and R. L. Judd, "Nucleation Site Activation in Saturated Boiling," *J. Heat Tr.*, **97**, 93 (1975).
Singh, A., B. B. Mikic, and W. M. Rohsenow, "Relative Behavior of Water and Organics in Boiling," *Proc. 6th Int. Heat Tr. Conf.*, **1**, Paper PE-9, 163, Toronto (1978).
van Stralen, S., "Combined Effect of Relaxation and Evaporation Microlayers," *Boiling Phenomena*, Vol. 2, Ch. 15, S. van Stralen and R. Cole, Eds., Hemisphere Publishing, Washington, DC (1979).
Westwater, J. W., "Boiling of Liquids," *Advances in Chem. Eng.*, Vol. 1, 2, Academic Press, New York (1956).
Witzke, M., "Nucleate Boiling Site Formation from Microbubbles," M.S. Thesis, Univ. of California, Santa Barbara (1977).
Yu, C. L., and R. B. Mesler, "A Study of Nucleate Boiling Near the Peak Heat Flux Through Measurement of Transient Surface Temperature," *Int. J. Heat Mass Tr.*, **20**, 827 (1977).

Manuscript received Apr. 9, 1984; revision received July 17, 1984, and accepted July 23.