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# BOILING SONGS AND ASSOCIATED MECHANICAL VIBRATIONS

By
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June 30, 1960

Nuclear Development Corporation of America
White Plains, New York

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NDA 2131-12
PHYSICS

# BOILING SONGS AND ASSOCIATED MECHANICAL VIBRATIONS

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June 30, 1960

Work Performed under Contract AT(30-1)-2303(IX)
for the United States Atomic Energy Commission

NUCLEAR DEVELOPMENT CORPORATION OF AMERICA
White Plains, New York

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# 1. INTRODUCTION

All boiling generates some sounds. Under certain conditions, which,. fortunately, are not frequently encountered, the intensity of the sounds can become extremely high and can be accompanied by severe vibrations of equipment and supports. Not much is known about the conditions under which these ''boiling songs'' and associated vibrations occur.

Because of the possible damage resulting from the vibrations, it is important that nuclear reactors be operated outside the regions in which these phenomena occur. The present study was undertaken to define these regions.

The study is based entirely on observations which have been made at a number of different installations at which boiling songs and vibrations were noted during heat transfer experiments. The sources of this information consist of an initial survey (NDA 10-68),[1] a review of recent literature, and discussions with personnel at Columbia University, University of Illinois, Savannah River Project (SRP), Argonne National Laboratory (ANL), and Westinghouse Atomic Power Division (WAPD).

# 2. CONCLUSIONS AND RECOMMENDATIONS

## 2.1 CONCLUSIONS

1. Under certain conditions of local boiling, which includes a boiling-like mechanism at supercritical pressures, intense sounds (boiling songs) and mechanical vibrations can be generated.
2. The occurrence of these intense sounds and mechanical vibrations are intimately related to the operating conditions in the heated portion of the loop.
3. The boiling songs and associated vibrations are accompanied by large-amplitude pressure and flow fluctuations, although such fluctuations may occur without the generation of sounds or vibrations.
4. When these unusual phenomena occur in a system, the condition is reproducible and reversible.
5. These unusual phenomena exhibit a threshold condition, generally occurring about 70-80% of the burnout heat flux.
6. In the case of intense sound generation, increasing the heat flux, while maintaining a constant inlet subcooling and flow rate, results in an increased intensity which maximizes and then decays as burnout is approached.
7. The intensity of the associated vibrations may show the same pattern as the sound generation phenomena, or may persist until the burnout condition.
8. During vibration, and probably during sound generation, the heated surface exhibits a periodicity in bubble formation; that is, all bubbles are synchronized and grow and collapse simultaneously.
9. The occurrence of boiling songs and associated vibrations appears to be confined to local (subcooled) boiling systems. There has not been a recorded occurrence of these phenomena in bulk boiling (net vapor generation) systems.
10. The unusual phenomena result from pressure waves and/or flow fluctuations which induce variable heat transfer in the system. The variability in the heat transfer rate and energy dissipation of the pressure wave results in the intense sounds and vibrations.

11. The pressure waves may be initiated by "bumping."

## 2.2 RECOMMENDATIONS

The severity of the vibrations and intensity of the sounds indicate a possible limiting condition for some boiling systems. Because of other more immediate needs in cases where these phenomena were observed, they were considered to constitute a nuisance condition and, thus, were not investigated systematically. It is recommended that some systematic investigation of these phenomena be initiated, directed at obtaining an understanding of the cause and effect relations, and discovering methods for eliminating the occurrences.

## 3. DESCRIPTION OF THE PHENOMENA

### 3.1 NORMAL BOILING, CAVITATION, AND CONDENSING SOUNDS

Before describing the unusual high intensity boiling sounds – "boiling songs" (see Section 3.2), the present state-of-the-art of normal boiling, cavitation, and condensing sounds is briefly reviewed.

Everybody is familiar with frequently encountered sounds of boiling, such as those emitted from a pot filled with water on a hot stove, or a sizzling steak. However, nobody seems to have undertaken a systematic investigation to determine whether these sounds are caused by the growth of bubbles, by their collapse, by their penetration through liquid-air interfaces, or by any other action.

Although the source of the sounds is uncertain, attempts have been made to recognize the difference in sound levels and frequencies associated with different modes of boiling such as nucleate, transition, and film boiling. Examples of practical significance of this are the housewife's determining whether her iron is at the right temperature by spraying water on it and listening for the "right" sound; the operator of a chemical plant judging the performance of evaporators and reboilers by the sounds emitted from the equipment; and the metal worker getting an indication of the degree of completion of a quenching process by listening for the changes in pitch and intensity.

Some frequency and level measurements were made for these normal boiling sounds by Boyd and Cummerow[2] (see Fig. 1) and by Westwater, et al.[3] (see Fig. 2). While their observed frequency range is similar to that of the "boiling songs," their reported levels are significantly lower. The measured frequencies of 1000 to 4000 cps at peak intensities correspond well with bubble lifetimes of 0.5 to 0.8 msec reported by Gunther and Kreith[4] and Gunther.[5]

Other familiar sounds which one may expect to be related to boiling sounds are cavitation, and steam condensing noises. Practical uses of cavitation noises have been made in detecting submarines, and in warning of cavitation-induced failures. Condensing noises are a familiar nuisance in steam-heated buildings, and around process equipment in which large volumes of liquid are heated by the direct introduction of live steam. The intensity of cavitation[6] and steam condensing noises can be quite high, although their frequencies are usually much lower than those encountered in boiling sounds.

Less familiar, but probably also related to the aforementioned sounds, are the "boiling songs" which have been heard during heat transfer experiments with water at subcritical and supercritical pressures. It is these boiling songs and associated mechanical vibrations which are of interest to the present study.

## 3.2 HIGH INTENSITY SOUNDS – BOILING SONGS

Boiling songs have been heard during "boiling" of greatly subcooled liquids at very high heat fluxes. The intensity of the boiling songs has been variously described by investigators as "singing," "howling," "high frequency screams," "a wailing banshee," or "ultrasonic generator-type noise." Measurements of the sound frequency indicate an approximate range of 1000 to 20,000 cycles/sec, although the higher frequencies may be caused by dominant harmonics other than the fundamental frequency. From the descriptions given of these boiling songs, the intensity may be "guesstimated" to be between 120 to 140 db, that is, the range between a disturbing and a painful noise. These sounds appear to exhibit a frequency spectrum which changes continuously with parameters such as heat flux, flow rate, and inlet subcooling. A threshold condition has been observed somewhat below burnout, the sounds maximizing in intensity and then subsiding as burnout is approached.

## 3.3 MECHANICAL VIBRATIONS

Large amplitude, high frequency vibrations sometimes accompany the boiling songs. The frequency of one such occurrence of mechanical vibrations was measured at Columbia University to be 10,000 ± 4000 cps. These vibrations have a threshold condition at/or near that for sound generation, but may persist up to the point of burnout.

Depending on the flexibility of supports and on means for pressure balancing thermal expansion joints, mechanical vibrations may be restricted to the test section or they may be transmitted to other equipment and, in some instances, they have been felt throughout a building. The principal causes for these vibrations are believed to be the pressure and flow fluctuations associated with the boiling songs.

## 3.4 PRESSURE AND FLOW FLUCTUATIONS

Large amplitude pressure and flow fluctuations have been observed concurrently with the boiling songs. Measurements of these fluctuations showed, as would be expected, a threshold condition. Variations of the exit pressure of ±100 to 200 psi have been measured on Heise gages. Flow fluctuations have been recorded, using turbine-type flow meters and showed a diverging oscillation of as much as ±70% of the nominal flow rate[7] prior to burnout. However, because of instrument inertia and time constants of the recorders the measured frequencies and amplitudes of these oscillations are only indicative of the actual fluctuations occurring in the system.

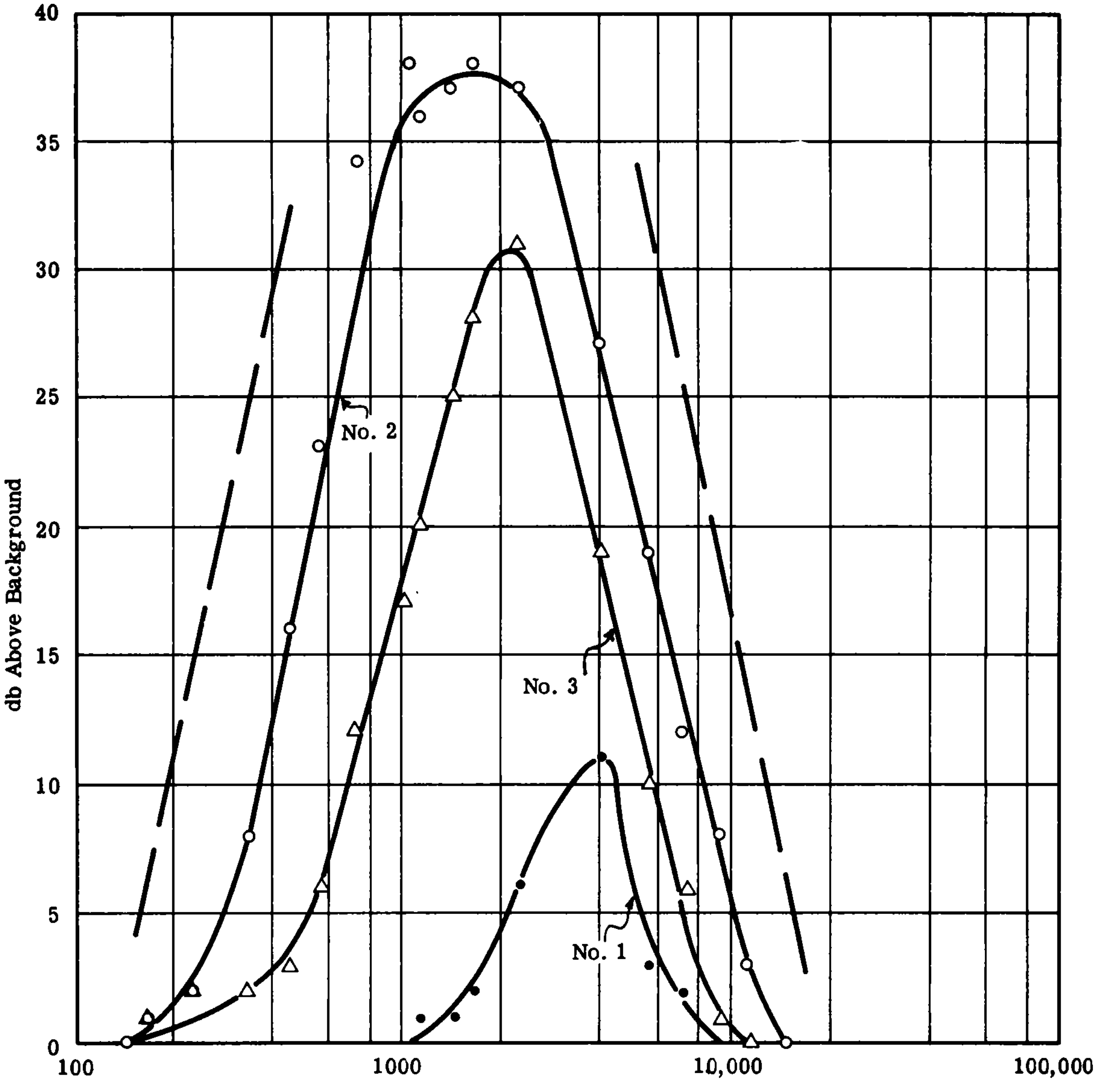

Fig. 1 — Nucleate boiling experiment. No. 1: 840 watts, 60 cycles, 18°C; No. 2: 840 watts, 60 cycles, 53°C; No. 3: 368 watts, 60 cycles, 53°C. (Reference 2)

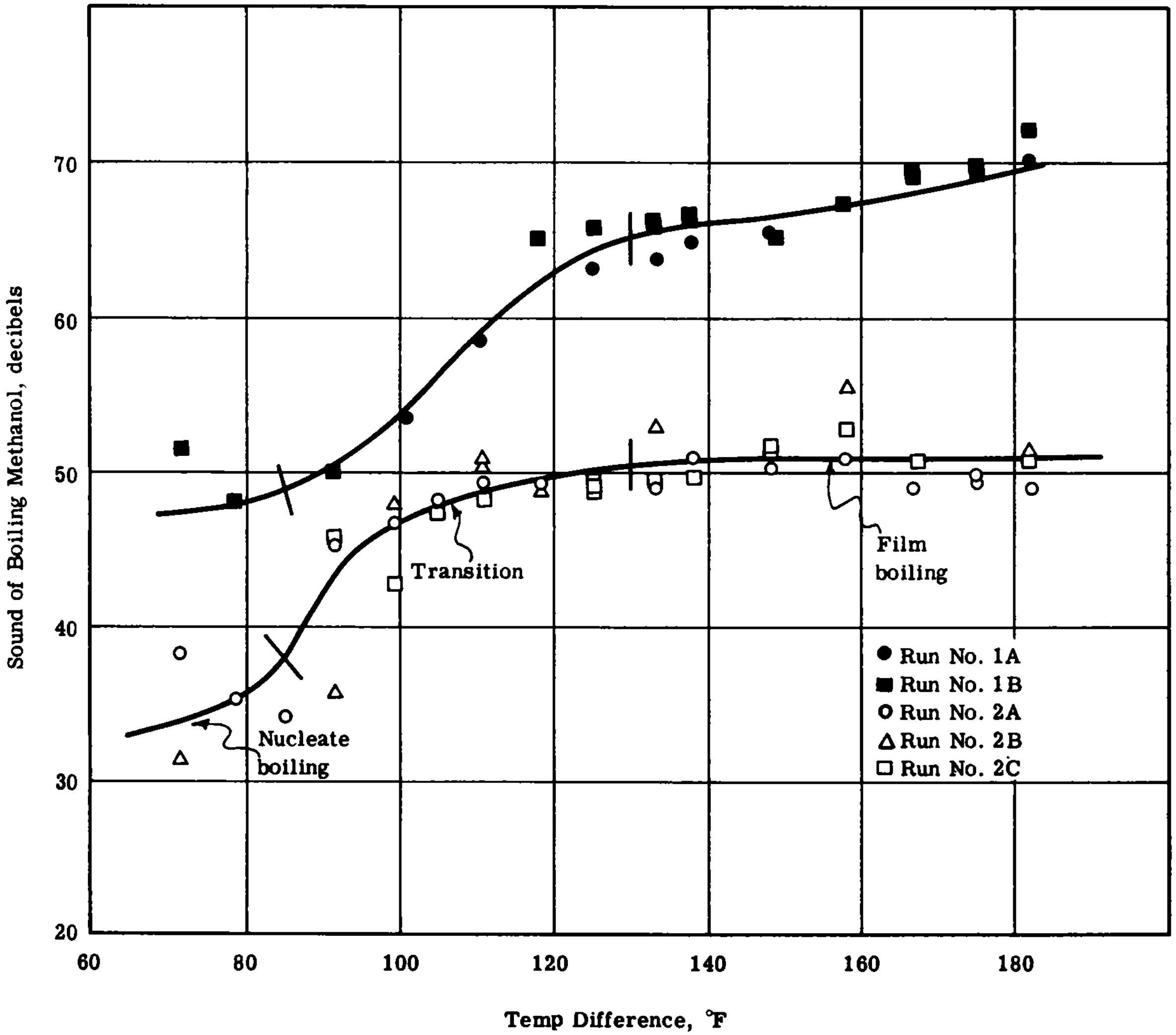

Fig. 2 — Effect of temperature driving force on the sound of boiling methanol (Reference 3)

# 4. OCCURRENCES OF BOILING SONGS AND SALIENT SYSTEM PARAMETERS RELATED TO THESE OCCURRENCES

## 4.1 HISTORICAL BACKGROUND

Interest in boiling songs was first aroused during heat transfer studies with water at supercritical pressures. It had been observed that whenever the longitudinal temperature profile of the test section resembled the boiling-like profile encountered at subcritical pressures the test sections emitted high intensity, audible sounds. It was hypothesized[1,8] that these sounds were produced by a boiling-like mechanism* occurring at supercritical pressures. As an indirect verification of the hypothesis, installations were visited and investigators working in boiling heat transfer studies were questioned. The accumulated facts gathered from these interviews indicated that numerous occurrences of boiling songs, in subcritical boiling systems, had been observed. A summary of these observations was given in NDA 10-68.[1]

Since the issuance of NDA 10-68, additional observations of boiling songs have been described in the literature[10-16] or obtained by interviews with personnel at various installations.

Of particular interest in this recent study were the severe mechanical vibrations encountered at Columbia University[11-13] and visual observations of the system hydrodynamics during the occurrence of these phenomena,[17,18] which are discussed in Section 4.3.

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* The existence of a boiling-like process at supercritical pressures has since been confirmed by the photographic studies of Griffith and Sabersky[9] on Freon 114A. Bubble-like aggregates have been photographed, but no abrupt change was noted in the heat transfer rate.

## 4.2 SALIENT SYSTEM PARAMETERS RELATED TO THE OCCURRENCE OF BOILING SONGS AND ASSOCIATED MECHANICAL VIBRATIONS

A summary of all the known observations of boiling songs and associated mechanical vibrations obtained from the previous study,[1] a review of the literature, and visits to various installations is given in Table 1 (Section 6). The data point out some salient conditions at which these phenomena were encountered. The more evident characteristics are:

1. "Subcooled" boiling at subcritical and supercritical pressures.
2. High surface heat fluxes, which in subcritical systems are generally in the range of 70 to 80% of the burnout heat flux.
3. Concurrent occurrence of pressure and flow fluctuations.
4. Vibration of the test equipment.

It is noteworthy that no instance of the occurrence of boiling songs has been recorded in rectangular channel geometries. For audible sound generation it is necessary that some surface vibrate between the source of the disturbance and the receiver. The intensity of the audible sounds will depend on the rigidity and inertia of the vibrating member interposed between the disturbance source and the receiver. The heavy backup housings employed in burnout studies with rectangular channel geometries probably provides sufficient damping to reduce the intensity of the sounds well below those heard with round tubes or annuli.

## 4.3 VISUAL OBSERVATIONS OF SYSTEM HYDRODYNAMICS DURING THE OCCURRENCE OF THE BOILING SONGS

At Columbia University, Fastex pictures were taken during operation of a test loop at low pressures (Table 1, Index Nos. 22, 23, 24, and 25.)[17] (See Section 6.) The films were made during "normal" operation of the loop and while the loop was vibrating. As would be expected, during normal operation the surface exhibited the general characteristics of subcooled nucleate boiling. Bubbles were observed to grow and collapse at or near the heating surface in a random manner characteristic of nucleate boiling. However, during operation within the "zone of vibration" the section of the surface viewed showed a different appearance. Complete periodic cessation of vapor bubble formation was observed to occur on the surface section viewed. This period of no-visible-bubbles was followed by a period of bubble growth quite similar to that observed in nucleate boiling. Cursory estimates indicated that a definite frequency was associated with the phenomena and that the periods of suppressed nucleation and bubble growth were approximately the same with a duration of one or two bubble lifetimes. Another interesting point concerning these experiments was the recorded variation of the wall temperature as the loop started and ceased vibrating (see Section 6). When vibrations started, a decrease in the wall temperature was noted, although the heat flux had been increased. However, the wall temperature markedly increased when the vibrations ceased; the increase being larger than could be attributed to the corresponding increase in heat flux.

At the University of Illinois, Westwater and Kirby[18] observed a reproducible phenomenon on an apparatus designed to study pool boiling burnout from a horizontal surface. After each burnout run, room temperature water was added to the system to prevent failure of a sealing gasket. When this procedure was followed, strange sounds would be generated and the apparatus would shake violently. They viewed this occurrence numerous times and noted that the smooth mirror-like film, which covered the heating surface, changed to an erratic, foggy-type film when the cold water was added. The phenomenon ceased when stable nucleate boiling was evident.

## 5. CAUSES OF THE BOILING SONGS

The similarity of the general system operating conditions (Section 4.2), whenever boiling songs and/or mechanical vibrations were observed, intimately relates the "disturbance source" to the heated section of the loop, and the boiling process. In this section, we will attempt to construct a plausible "cause and effect" relation, necessarily of a speculative nature, for these phenomena.

### 5.1 POSTULATED MECHANISM FOR GENERATION OF BOILING SONGS

Consider a small section of a heated surface operating in the subcooled, nucleate boiling regime at about 70 to 80% of the burnout heat flux. The appearance will be that of discrete bubble growth and collapse at/or near the surface in an overall timewise random process.[4,5,17,19] If a pressure disturbance (wave) is superimposed on the system, then as the disturbance is propagated through the system the general nucleating characteristics will be altered. If the pressure disturbance is of sufficient amplitude, then nucleation of bubbles may be completely suppressed. The duration of suppressed boiling will depend on those parameters important in the bubble nucleation-growth-collapse processes, and the frequency and amplitude of the perturbed pressure. Any section of the surface selected for observation will, therefore, exhibit a periodic cessation of vapor formation, followed by a period of normal nucleate bubble formation as the disturbance moves past the section. Furthermore, this forced suppression of vapor formation will move subcooled liquid against the surface, thereby inducing variable heat transfer. The forced vibrations produced by the pressure disturbance and variable heat transfer can generate sounds.

The occurrence of such a phenomenon may be inferred from the visual studies at Columbia University (Section 4.3), the measurements of the surface temperatures during vibration (Section 6), and the observed concurrent occurrence of pressure and flow fluctuations.

The measured frequency and intensity of the sounds produced by the above-mentioned phenomena will necessarily depend on the phase relations between the primary pressure disturbance, the secondary pressure disturbances produced by the collapse of vapor bubbles on the heating surface, and the induced variability in heat transfer. One would expect that altering the thermal or flow characteristics would affect the frequency and intensity of the sounds generated.

For example, increasing the surface heat flux, $\phi$, will increase the wall superheat since $T_W = T(\phi)$. For a sinusoidal pressure disturbance the variation of the saturation temperature is also sinusoidal with time. For nucleation and growth of bubbles it is necessary that $T_W > T_S$. Fig. 3 shows the variation of the saturation temperature, $T_S = T(P)$ at any point in a system in which there is a sinusoidal pressure variation with time. Since some wall superheat is required for bubble growth, a dashed line, marked $(T_{min})_{bubbles}$, is shown above $T_S$ in Fig. 3 to indicate the minimum temperature at which bubbles can grow. A straightline above the mean saturation temperature, $(T_S)_{P_{mean}}$ represents the mean wall temperature, $(T_W)_{mean}$ for a given heat flux. As the pressure disturbance moves past the point of interest, the minimum wall temperature required for bubble growth will approach the wall temperature (for positive pressure disturbances), and at point A, nucleation of bubbles can no longer be supported. This condition of suppressed boiling (cross-hatched areas) will continue until the disturbance amplitude returns to a level corresponding to point B. The duration of suppressed boiling, $(\tau)_{no\ bubbles}$ will depend on the frequency and amplitude of the disturbance, and the wall superheat. By next considering the disturbance to be constant and changing the surface heat flux from $\phi$ to $\phi'$, the location of the points for incipient suppression and initiation of boiling will shift from A to A′ and B to B′, respectively. The duration of the suppressed boiling $(\tau')_{no\ bubbles}$ at the new surface heat flux must necessarily change such that $\tau' < \tau$; if $\phi' > \phi$. Thus, one may expect variations in heat transfer rates to lead to time varying wall temperatures which, in turn, will affect the amplitudes and propagation velocities of the pressure waves. It should be noted that a qualitative explanation is given by Fig. 3 for the cessation of the boiling songs prior to burnout. When the surface heat flux is so high that the mean wall temperature is greater than the minimum wall superheat temperature, then bubbles can grow at all times and pressure waves cannot be enforced by the simultaneous growth and collapse of all bubbles. However, the pressure fluctuation initiated by other causes may continue to induce mechanical vibrations.

The actual processes which cause the observed frequency-intensity spectrums of the boiling songs will be considerably more complicated in their interactions than the example given. However, there is implicit in the process a condition which leads to changes in frequencies and intensities of the source disturbances for the boiling songs, and may lead to sound generation patterns consistent with the observed dependency on the system thermal and flow conditions. The differential pressure measurements of Addoms[20] (Fig. 4) are a case in point, where a "loud whining noise" was heard when the differential pressure fluctuations increased in magnitude.

Estimates were made of the amplitude of the pressure wave necessary to produce the phenomena observed at Columbia (Section 4.3). Without accounting for variability in the heat transfer rate, a minimum amplitude of 125 psi was calculated. Pressure fluctuations of ±5 to 25 psi were noted on a Heise gage. Because of damping in the lines and the inertia of the gage, the maximum amplitude of the pressure waves may well have been in excess of the 125 psi calculated as required for suppression of bubble growth.

## 5.2 POSTULATED MECHANISM FOR INITIATION OF PRESSURE WAVES

Numerous sources for periodic pressure fluctuations exist in a boiling system, each of which may produce high frequency, large amplitude disturbances. One such mechanism, somewhat related to the phenomenon of "bumping," has the distinct merits as the source of the requisite pressure waves described in Section 5.1.

Bumping of liquids is a phenomenon generally associated with laboratory experiments and seldom, if ever, experienced in industrial operations. Wismer[21] has demonstrated that "training-up" of a system may lead to excessive superheating of liquid without formation of a vapor phase. This liquid will be in metastable equilibrium until a condition favorable for nucleation occurs. At such a time, the liquid rapidly approaches thermodynamic equilibrium by flashing into vapor. Thus, a violent eruption of vapor occurs in the liquid, producing large pressure pulses capable of shattering glassware.

Westwater, during photographic studies of boiling methanol from a horizontal copper tube, observed the violent eruption of vapor from the heated surface. When such a vapor burst, or "bump," occurred a "shock wave (seemed) to rush along the solid-liquid interface. The appearance (was) that of a series of minor bursts set-off by a major one."[19]

Bradfield[22] also photographed the occurrence of explosive generation of vapor while studying the effect of a vapor film on the drag resistance of solids in water. When graphite was employed for the test specimen, the "bump" was apparently violent enough to cause surface disintegration. On metallic specimens, these bursts were observed to occur locally on the surface after substantial cooling of the specimen.

In viewing the films obtained by Westwater[19] the bumps were observed to originate on the lower portion of the horizontally oriented 3/8 in. diameter tube (viewed length of 3.5 in.) and occurred within 0.25 msec (film speed 4000 frames per sec). The average frequency of these vapor bursts was estimated to be 0.5 bursts/msec on the 3.5 in. section photographed. Since the bumping occurred on the underside of the tube it is possible that this phenomenon may have occurred in the nucleate boiling regime rather than in the transition boiling regime (see Section 6.3).

By extrapolating the average bump frequency obtained in a saturated methanol system to a subcooled water system permits some estimate (admittedly crude) of the attainable frequencies of the pressure wave by such a mechanism. The initial bumping process has a frequency of approximately 500 bumps per sec. However, the violent nature of the bump will force the vapor into the subcooled liquid and will result in rapid condensation. Harrison[6] has shown that such a cavitation phenomenon can give rise to very large local pressure pulses. Therefore, it is possible for the combined frequency of the bump and cavitation phenomena to be 1000 cps. In NDA 10-68[1] sound frequencies between 1000 to 2000 cps were reported, which are in fair agreement with the estimated frequency of the aforementioned mechanism. Taylor and Steinhaus[16] measured a frequency range of 2500 to 20,000 cps for the boiling songs heard in their apparatus (Fig. 5). Since these frequencies at the upper end of the range are somewhat higher than the frequencies measured at other installations, one may speculate that these higher frequencies were due to dominant harmonics other than the fundamental frequency.

Other mechanisms can be hypothesized to account for the occurrence of large amplitude pressure waves. As an example, in any forced convection system, external sources of pressure fluctuations are always in existence, such as pumps and valves. If a resonance condition can occur between these externally produced pressure fluctuations and the pressure fluctuations generated by boiling processes, then the required conditions for sound generation outlined in Section 5.1 would be satisfied. However, such sound generations would always have to be at the resonant frequency (or a higher harmonic). Since the observed frequences vary continuously with heat flux and other parameters, it is very unlikely that a resonance with disturbances in the external system is the cause of the vibrations.

That these phenomena (boiling songs and mechanical vibrations) can present serious design and operating problems during subcooled boiling is manifestly illustrated by their occurrence at numerous facilities. At present, the available information permits only qualitative and speculative conclusions and points to a real need for a systematic investigation. Such a program had been started at Columbia University. However, further analysis and probably more experimental data are needed to obtain a fuller understanding of the cause and effect relations underlying these phenomena, and the remedial measures necessary to prevent their occurrence in reactors.

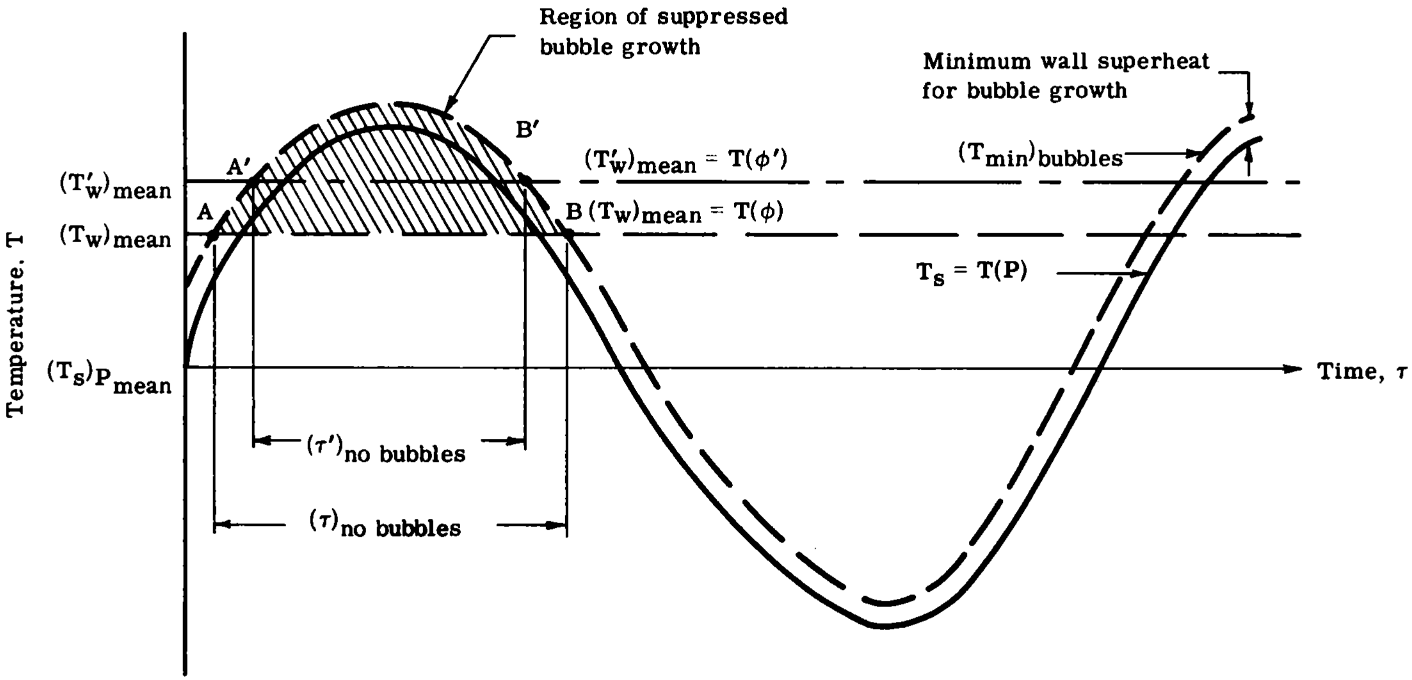

Fig. 3 — Effect of a pressure wave on the suppression of bubble growth

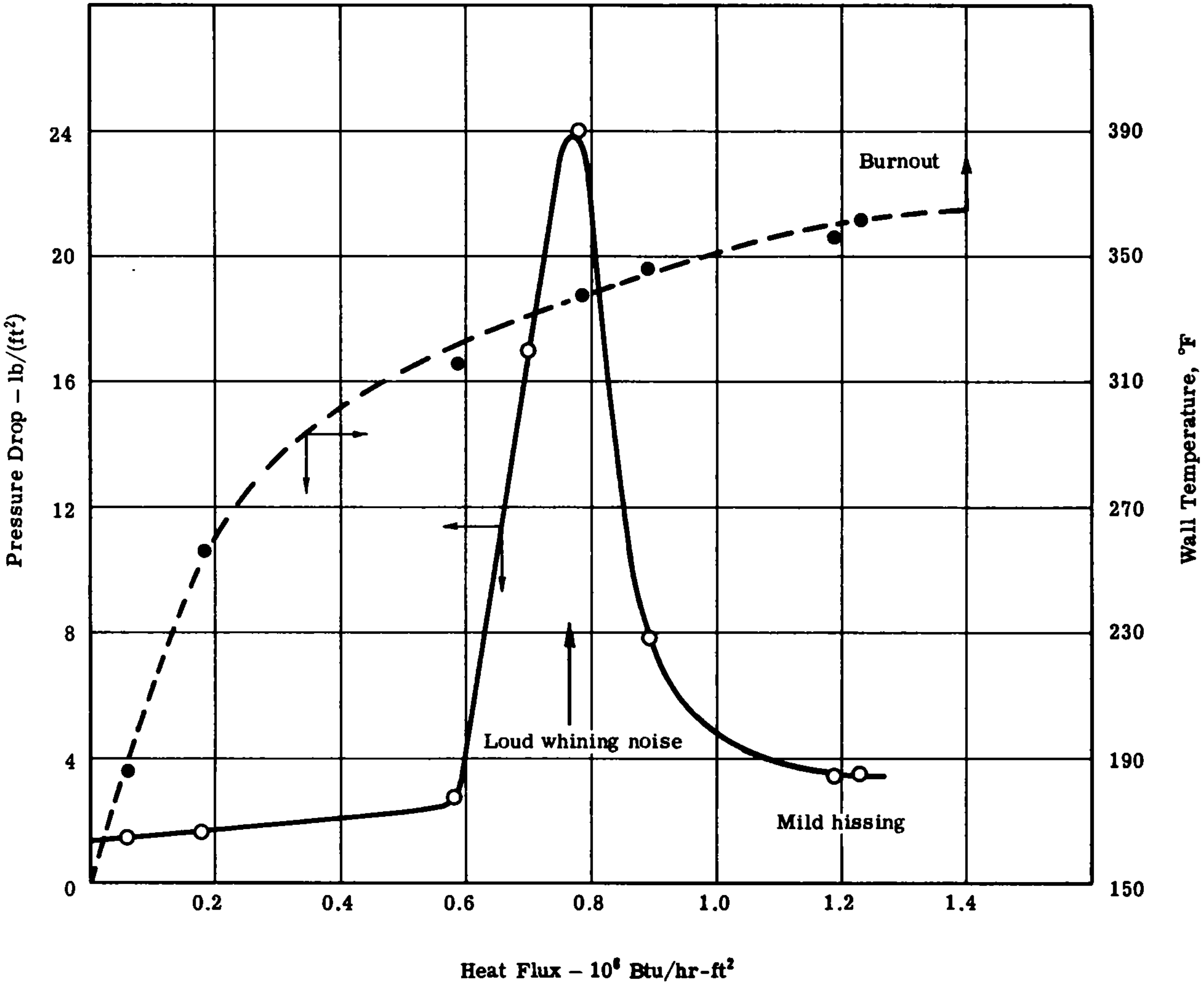

Fig. 4 — Pressure drop in annulus – pressure = 30 psia, velocity = 4 ft/sec, bulk temperature = 145°F (Reference 20)

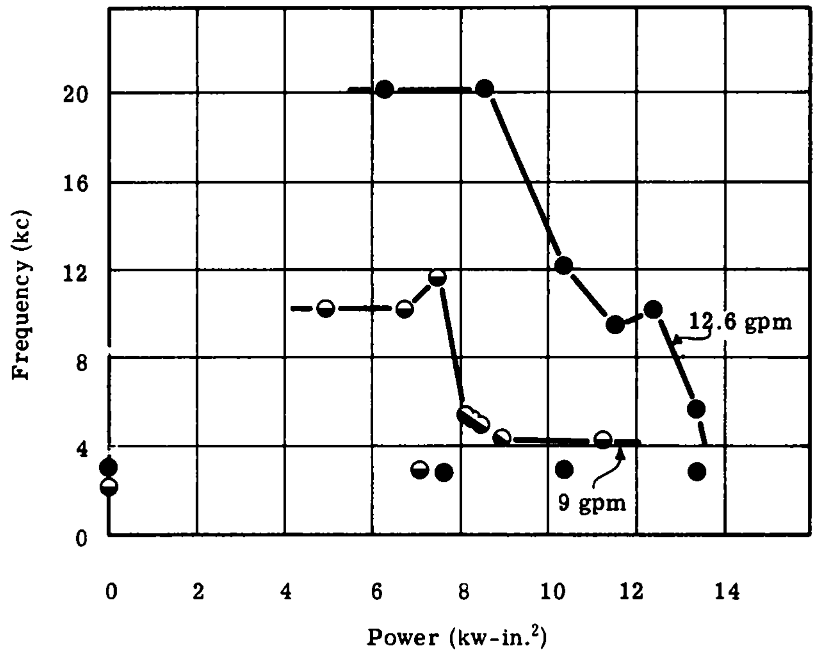

Fig. 5 — Frequency of boiling sounds as a function of heat flux (Reference 16)

# 6. INSTALLATIONS VISITED

A summary is given of discussions at the installations visited during this study, with specific details given in Table 1 as to the conditions at which boiling songs and associated vibrations were observed. The following installations were visited on the dates indicated:

February 2, 1960 – Columbia University
February 29, 1960 – Savannah River Project (SRP)
March 16, 1960 – University of Illinois
March 17, 1960 – Argonne National Laboratory (ANL)
March 18, 1960 – Westinghouse Atomic Power Division (WAPD)

## 6.1 COLUMBIA UNIVERSITY – ENGINEERING RESEARCH LABORATORIES

W. Begell and M. Gutstein have been involved in subcooled burnout studies in annular and round tube geometries with vertical up- and down-flow. Seven incidents of severe mechanical vibrations were observed (Table 1, Items 15 to 21) during this study, all in annular flow geometries. The severest incidents occurred during the first four of five experimental runs performed on an existing high pressure loop (Table 1, Items 15 to 19). The original loop was dismantled after five tests and replaced. Only two further incidents of vibrations were recorded on the new loop (Table 1, Items 20 and 21). A. Bendler discussed the only known systematic investigation of the occurrence of these phenomena. The loop was designed with an annular flow channel and a viewing port was provided for photographing a small section of the heating surface. Fastex pictures were taken while the loop was operating smoothly and during vibratory operation (Table 1, Items 22 to 25). A review of these photographic studies is given in Section 4.3. In addition, measurements were made of the longitudinal temperature profile of the test section. When the loop entered the zone of vibration, a drop in the wall temperature was observed. This was followed by a marked increase in the temperature when the system passed the upper limits of the "zone of vibration." The following tabulation is typical data taken during an experimental run:

Table 1 –– Boiling Songs and Associated Mechanical Vibrations (Part 1)

| Index Number | Reference Number | Nominal Pressure, psia | Nominal Velocity, fps | Flow Direction | Flow Path | Equivalent Diameter, in. | Heater Diameter, in. | Heated Length, in. | Inlet Subcooling, °F | Exit Subcooling, °F | Exit Flow Quality, w/o | Water Conditions | Heat Flux,† Btu/hr-ft$^2$ | Heat Flux,§ Btu/hr-ft$^2$ | Intense Sounds | Vibrations | | Fluctuations | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | Test Section | Loop | Pressure, psi | Flow Rate, fps |
| 1 | | 5000 | ~28 | Down | Tube | 0.062 | 0.062 | 6 | Inlet temp, 120 | Exit temp, 565 | —— | G | $2.2 \times 10^6$ | | X | | | ±25 | |
| 2 | | 4000 | ~28 | Down | Tube | 0.062 | 0.062 | | Inlet temp, 100 | Exit temp, 580 | —— | | $1.97 \times 10^6$ | | X | | | | |
| 3 | | 4000 | ~28 | Down | Tube | 0.062 | 0.062 | | Inlet temp, 200 | Exit temp, 605 | —— | | $1.68 \times 10^6$ | | X | | | | |
| 4 | | 5000 | ~28 | Down | Tube | 0.062 | 0.062 | | Inlet temp, 100 | Exit temp, 590 | —— | | $2.13 \times 10^6$ | | X | | | | |
| 5 | | 5000 | ~28 | Down | Tube | 0.062 | 0.062 | | Inlet temp, 200 | Exit temp, 605 | —— | | $1.78 \times 10^6$ | | X | | | | |
| 6 | | 5000 | ~28 | Down | Tube | 0.062 | 0.062 | | Inlet temp, 200 | Exit temp, 690 | —— | | $1.81 \times 10^6$ | $2.14 \times 10^6$ | X | | | | |
| 7 | | 5000 | ~28 | Down | Tube | 0.062 | 0.062 | | Inlet temp, 400 | Exit temp, 740 | —— | | $1.27 \times 10^6$ | $1.73 \times 10^6$ | X | | | | |
| 8 | | 4100 | ~10 | Horizontal | Tube | 0.094 | 0.094 | 25 | Inlet temp, 595 | Exit temp, 680 | —— | | $0.54 \times 10^6$ | | X | | | | |
| 9 | 10 | 100 | 20 | Down | Tube | 0.250 | 0.250 | $3\frac{1}{8}$ | 280 | | —— | Tap water | $2.5 \times 10^6$ | Burnout | X | | | | |
| 10 | 1 | 1500 | 17 | Up | Tube | 0.1805 | 0.1805 | 9.4 | 206 | 166 | —— | 30 ppm NaCl | Approaching burnout | | X,<br>2000 cps | | | | |
| 11 | 1 | 30 | 4 | Up | Annulus | ~0.500 | 0.250 | | 105 | | —— | | $0.6 \times 10^6$ | $0.9 \times 10^6$ | X | | | | |
| 12 | 1 | | | Up | Tube | 0.143 | 0.143 | 3.0 | | | —— | | | | X | | | | |
| 13 | 1 | 14.7 | 1-10 | Up | Tube | 0.03-0.04 | 0.03-0.04 | 8.0 | | ~180 | —— | | $1\text{-}5 \times 10^6$ | | X | | | | |
| 14 | 1 | 2000 | 13.6 | Up | Tube | 0.174 | 0.174 | | | | —— | | $1.24 \times 10^6$ | | X,<br>1070 cps | | | ±3.6-4.0 | |
| 15 | 11 | 500 | 0.98 | Up | Annulus | 3.64 | 2.125 | 70.56 | 286 | 167 | —— | DG | $1.31 \times 10^6$,<br>$1.47 \times 10^6$ | | X | X | X | ±100 | ±0.05, ±0.29 |
| 16 | 11 | 500 | 0.98 | Up | Annulus | 3.64 | 2.125 | 70.31 | 266 | 131 | —— | DG | $1.43 \times 10^6$ | | X | X | X | ±30 | |
| 17 | 11 | 500 | 1.08 | Up | Annulus | 3.64 | 2.125 | 70.31 | 153 | 37 | —— | DG | $1.32 \times 10^6$ | $1.38 \times 10^6$ | X | X | X | ±100 | ±0.01 |
| 18 | 11 | 500 | 3.3-3.5 | Up | Annulus | 3.64 | 2.125 | 70.50 | 53-65 | 23-50 | —— | DG | | | | X | X | | |
| 19 | 11 | 500 | 14.7 | Down | Annulus | 0.78 | 2.125 | 70.25 | 179 | 33 | —— | DG | $0.97 \times 10^6$ | $1.384 \times 10^6$<br>(burnout) | X | X | X | ±40 | ±0.05 |
| 20 | 12,13 | 500 | 15.7 | Down | Annulus | 0.78 | 2.125 | 70.00 | 72 | 31 | —— | DG | $0.95 \times 10^6$ | $1.013 \times 10^6$<br>(burnout) | X | X | X | ±30,<br>0.5-6.0 cps,<br>20-60 cps | |
| 21 | 12 | 650 | 11.0 | Down | Annulus | 0.78 | 2.125 | 70.00 | 198 | 131 | —— | DG | $0.905 \times 10^6$ | $1.946 \times 10^6$<br>(burnout) | X | X | X | ±5-20 | |
| 22 | 17 | 16.7 | 0.13 | Up | Annulus | 3.326 | 0.500 | 6.0 | 174 | | —— | DG | $0.275 \times 10^6$ | $0.525 \times 10^6$ | X | X | X | | |
| 23 | 17 | 248 | 0.24 | Up | Annulus | 3.326 | 0.500 | 6.0 | 150 | | —— | DG | $0.150 \times 10^6$ | | X | X | X | ±25 | |
| 24 | 17 | 93 | 0.47 | Up | Annulus | 3.326 | 0.500 | 16.0 | 147 | | —— | DG | $0.240 \times 10^6$ | $0.55 \times 10^6$ | X | X | X | ±3-5 | |
| 25 | 17 | 17.2 | 0.13 | Up | Annulus | 3.326 | 0.500 | 16.0 | 170 | | —— | DG | $0.150 \times 10^6$ | | X | X | X | | |
| 26 | 14 | 49.9 | 18.8 | Down | Annulus | 0.500 | 0.500 | 24.0 | 142 | | —— | | | | | X | | | |
| 27 | 14 | 47.9 | 25.5 | Down | Annulus | 0.500 | 0.500 | 24.0 | 139 | | —— | | | | | X | | | |
| 28 | 18 | 14.7 | —— | Pool | —— | —— | Horizontal heater | —— | —— | | —— | D | —— | —— | X | X | X | | |
| 29 | | 2000 | 35.5 | Up | Tube | 0.184 | 0.184 | 18.0 | 71, 35 | | —— | DG | $1.56 \times 10^6$,<br>$1.60 \times 10^6$ | | X | | | ±200 | +20, -30 |
| 30 | | 2000 | | Up | Tube | 0.187 | 0.187 | 12.5 | | | —— | CDG | | | X | | | | |
| 31 | | 2000 | 10-45 | Up | Tube | 0.135 | 0.135 | 12 | | 61-76 | —— | CDG | $0.72\text{-}1.74 \times 10^6$ | | X | | | | |
| 32 | 15 | | | Up | Tube | 0.587 | 0.587 | 17.5 | | | —— | | | | | X | X | Differential pressure | |
| 33 | 7 | 2000 | 55 | Up | Tube | 0.304 | 0.304 | 18 | 364 Btu/lb* | -103.5 Btu/lb* | —— | DG | | $1.62 \times 10^6$ | X | | X | | |
| 34 | 7 | 2000 | 55 | Up | Tube | 0.304 | 0.304 | 18 | 372 Btu/lb* | -109.5 Btu/lb* | —— | DG | | $1.63 \times 10^6$ | X | | X | | |
| 35 | 7 | 2000 | 48 | Up | Tube | 0.304 | 0.304 | 18 | 428 Btu/lb* | -113.5 Btu/lb* | —— | DG | | $1.64 \times 10^6$ | X | | X | | |
| 36 | 16 | Variable | Variable | See General Comments | | | | | | | | | | | X | | X | | |

*$\Delta h_{sub} = h_f - h_{in}$.
†$\Delta h_{sat} = h_{BO} - h_f$.
‡Heat flux at which boiling songs and/or vibrations start.
§Heat flux at which boiling songs and/or vibrations stop.

Water Conditions
- D – Deionized water used to fill system.
- G – Degassed water used to fill system.
- DG – Deionized-degassed water used to fill system.
- CD – Continuous deionization of process water.
- CG – Continuous degassing of process water.
- CDG – Continuous deionization-degassing of process water.

Table 1 — Boiling Songs and Associated Mechanical Vibrations (Part 2)

| Index Number | Test Section Surface Condition | Reproducibility and Reversibility of Phenomenon | Installation | Reference | General Comments |
|---|---|---|---|---|---|
| 1 | Not recorded | Reproducible | NDA-P&WA | | In all cases of sound generation at supercritical pressures, the temperature profiles resembled those for boiling at subcritical pressures. Increasing the inlet temperature the heat flux necessary to produce whistling decreased. Reduction of flow had the same effect. Whenever the heat flux was reduced, the frequency of the whistling decreased. |
| 2 | Not recorded | Reproducible | NDA-P&WA | | |
| 3 | Not recorded | Reproducible | NDA-P&WA | | |
| 4 | Not recorded | Reproducible | NDA-P&WA | | |
| 5 | Not recorded | Reproducible | NDA-P&WA | | |
| 6 | Not recorded | Reproducible | NDA-P&WA | | |
| 7 | Not recorded | Reproducible | NDA-P&WA | | |
| 8 | Not recorded | Reproducible | NACA | | |
| 9 | Not recorded | Noises started at ~50% of burnout heat flux | NDA | 8 | Rotational flow was induced by twisted metallic ribbons. At ~50% of burnout, loud whistling started, increasing in intensity and decreasing in pitch as the power was increased. At incipient burnout, noise became steadily composed of rattling, whining, and whistling sounds. |
| 10 | Water color – tan. No surface discoloration. | | MIT | 1 | High frequency screams first observed at a velocity of 17.0 fps. Reducing flow to 13.5 fps, resulted in a frequency of 2000 cps. |
| 11 | Substantial scale deposition | | MIT | 1 | As heat flux increased, pressure drop increased. Peak noise-intensity corresponded to peak pressure drop. Noise reduced to mild hissing as burnout was approached. |
| 12 | Scale deposits | | Purdue | 1 | Noise started at ~80% of burnout heat flux. |
| 13 | Not recorded | Reproducible | NACA | 1 | Noise was described as a ''humming sound'' which disappeared by increasing or decreasing flow or power. |
| 14 | Light tan discoloration | | ANL | 1 | Whining sound began at $1.24 \times 10^6$ Btu/hr-ft$^2$. At $1.76 \times 10^6$ Btu/hr-ft$^2$, velocity of 13.6 fps, the frequency of the noise was measured at 1070 cps. |
| 15 | Not recorded | Reproducible | Columbia | 10 | Vibrations, which were very severe, reduced by decreasing heat flux to $0.76 \times 10^6$ Btu/hr-ft$^2$. |
| 16 | Not recorded | Reproducible | Columbia | 10 | Test section was damaged so that $N_2$ may have leaked into system. Increasing or decreasing heat flux caused system to enter and leave vibrating zone. |
| 17 | Not recorded | | Columbia | 10 | |
| 18 | Not recorded | | Columbia | 10 | |
| 19 | Not recorded | | Columbia | 10 | Vibrations continued to burnout. |
| 20 | Not recorded | | Columbia | 11,12 | Vibrations similar in magnitude to Index No. 19. |
| 21 | Not recorded | | Columbia | 11 | Vibrations similar in magnitude to Index No. 19. |
| 22 | Olive-green to black discoloration which was eliminated by using deionized distilled water. Vibrations noted with clean surfaces. | Reproducible and reversible | Columbia | | Moving into, and out of, the vibrating zone was achieved by changing the heat flux and/or the bulk inlet temperature. The sensitivity of the phenomenon to system conditions was demonstrated by the repetitive starting and stopping of vibrations with a 1.0°F change in the bulk inlet temperature. Thermocouples indicated that a marked decrease in temperature, at the surface, occurred when the system began to vibrate, and a marked increase occurred when the system ceased to vibrate. |
| 23 | Olive-green to black discoloration which was eliminated by using deionized distilled water. Vibrations noted with clean surfaces. | Reproducible and reversible | Columbia | | Moving into, and out of, the vibrating zone was achieved by changing the heat flux and/or the bulk inlet temperature. The sensitivity of the phenomenon to system conditions was demonstrated by the repetitive starting and stopping of vibrations with a 1.0°F change in the bulk inlet temperature. Thermocouples indicated that a marked decrease in temperature, at the surface, occurred when the system began to vibrate, and a marked increase occurred when the system ceased to vibrate. |
| 24 | Olive-green to black discoloration which was eliminated by using deionized distilled water. Vibrations noted with clean surfaces. | Reproducible and reversible | Columbia | | Moving into, and out of, the vibrating zone was achieved by changing the heat flux and/or the bulk inlet temperature. The sensitivity of the phenomenon to system conditions was demonstrated by the repetitive starting and stopping of vibrations with a 1.0°F change in the bulk inlet temperature. Thermocouples indicated that a marked decrease in temperature, at the surface, occurred when the system began to vibrate, and a marked increase occurred when the system ceased to vibrate. |
| 25 | Olive-green to black discoloration which was eliminated by using deionized distilled water. Vibrations noted with clean surfaces. | Reproducible and reversible | Columbia | | Moving into, and out of, the vibrating zone was achieved by changing the heat flux and/or the bulk inlet temperature. The sensitivity of the phenomenon to system conditions was demonstrated by the repetitive starting and stopping of vibrations with a 1.0°F change in the bulk inlet temperature. Thermocouples indicated that a marked decrease in temperature, at the surface, occurred when the system began to vibrate, and a marked increase occurred when the system ceased to vibrate. |
| 26 | | | SRL | 13 | Intentionally roughened surface: longitudinal knurls 0.005 in. deep. |
| 27 | | | SRL | 13 | Intentionally roughened surface: longitudinal knurls 0.005 in. deep. |
| 28 | | Reproducible | University of Illinois | | Cold water, ~70°F, added to system to protect gasket resulted in an unstable condition at the heating surface. The apparatus generated sounds and vibrated severely each time this procedure was followed. |
| 29 | | Reproducible | ANL | | Howling persisted in test section after a series of quality burnout runs followed by subcooled burnout runs. High frequency sounds were accompanied by vibrations and pressure and flow fluctuations. Test section was finally removed since it was impossible to run without howling. |
| 30 | | Not checked for reproducibility | WAPD | | Sounds appeared in some runs but not others. If any reproducibility existed, it was associated with high fluxes and high inlet subcooling. |
| 31 | | | WAPD | | Sounds heard with either an exponential or top-hat heating of the test section. |
| 32 | | | JPL | 17 | At high heat fluxes, when the wall superheat exceeded 55°F and the bulk temperature near the outlet approached within 60 to 80°F of the boiling point, the test section began to vibrate and the differential pressure oscillated considerably. |
| 33 | | | ANL | | |
| 34 | | | ANL | | |
| 35 | | | ANL | | |
| 36 | | | Livermore | 14 | Burnout studies were conducted on a vertical copper disc. High intensity sounds were heard and the frequencies measured between 2.5 to 20 kc/sec. |

| Heat Flux | Notes | Changes in Wall Temperature | | | |
|---|---|---|---|---|---|
| | | $\Delta T_1$ | $\Delta T_2$ | $\Delta T_3$ | $\Delta T_4$ |
| $2.25 \times 10^5$ Btu/hr-ft$^2$ | No vibration | -2.3°F | -2.0°F | -2.0°F | -1.0°F |
| $2.51 \times 10^5$ Btu/hr-ft$^2$ | Vibration | | | | |
| $5.11 \times 10^5$ Btu/hr-ft$^2$ | Vibration | +7.0°F | +5.0°F | +5.0°F | +7.0°F |
| $5.68 \times 10^5$ Btu/hr-ft$^2$ | No vibration | | | | |

The subscript, on the differential reading of the thermocouples, $\Delta T_1$, corresponds to a longitudinal position on the test section ($\Delta T_4$ corresponds to the position closest to the end of the tube). The temperature changes indicated are for the increase in heat flux given.

## 6.2 SAVANNAH RIVER PROJECT (SRP)

S. Mirshak, N. Dinos, W. Durant, and R. Towell conducted experiments on low-pressure, subcooled burnout on roughened surfaces in vertical downflow. Two occurrences of vibration were encountered with a test specimen roughened by longitudinal knurls 0.005 in. deep (Table 1, Items 26 and 27). Specific conditions at which these vibrations occurred could not be recalled.

Discussions were also held with A. H. Peters pertaining to quenching experiments. During quenching of vapor in a large tank, audible high frequency sounds were heard. Differential pressure fluctuations of ±75 psi were recorded by DP-cells. Also, during experiments performed on the condensation of steam by sparging with subcooled water (steam, saturated at 150 psi; water temperature, 16°C) noises and vibrations, characteristic of such operations, were noted. This condition was eliminated by using a nozzle distribution system.

## 6.3 UNIVERSITY OF ILLINOIS – DIVISION OF CHEMICAL ENGINEERING

D. Kirby, under Professor J. W. Westwater, is presently performing pool burnout experiments on the exposed base of a solid copper cylinder. Distilled, deionized water is used in the pool. When burnout is achieved, cold, distilled water (~70°F) is added to the system to prevent failure of the gasket between the heater and holding plate. The first time this procedure was used, the apparatus began to make "strange loud noises and severely vibrated" (Table 1, Item 28). Professor Westwater and D. Kirby observed this phenomenon repeatedly.

Professor Westwater showed films taken during pool boiling of methanol from a horizontal copper tube. In what was termed the transition boiling regime, vapor bursts appeared frequently from the underside of the tube. The bursts appeared from one frame to the next at a film speed of 4000 frames per sec. These bursts induced a very rapid, violent motion of the liquid-vapor interface. Whether these vapor bursts occurred during transition boiling was questioned. It appears that a radial temperature gradient around the tube may permit nucleate boiling to occur at the underside and transition boiling on the topside of the tube. Such a gradient may arise from a thicker liquid condensate film forming on the bottom of the tube, and/or the tendency of vapor to move away, under bouyant forces, from the bottomside of the tube exterior surface thereby allowing solid-liquid contact more readily.

## 6.4 ARGONNE NATIONAL LABORATORY (ANL)

J. Marchaterre and R. Weatherhead were contacted at ANL. R. Weatherhead has been involved in burnout studies in round tube geometries at 2000 psia. Audible, intense sounds were heard during subcooled burnout runs (Table 1, Items 33, 34, and 35) and were noted in an internal memorandum. One of the more interesting occurrences of this phenomenon was observed on a 3/16 in. diameter, 18-in. long nickel tube (Table 1, Item 29). The tube had undergone 14 tests (seven at subcooled exit conditions, and seven with bulk boiling) and started to generate sounds on the 15th run (subcooled boiling). The intensity was described as a "wailing banshee." The noise was first noted when the bulk exit temperature approached 400°F, increasing in intensity as the inlet subcooling was decreased at constant surface heat flux. As the system approached burnout, the sound intensity maximized and then decayed to a level slightly higher than background when burnout was reached. The noises were accompanied by vibrations, diverging flow fluctuations, and measured exit pressure fluctuations of ±200 psi. After operating the test specimen another five or six times, with the reoccurrence of these phenomena, it was discovered that the tube could no longer be operated without generating the high intensity sounds. The noise was extremely annoying to personnel in the laboratory and neighboring offices so that it had to be removed. R. Weatherhead supplied us with this particular test specimen for analysis at some later date.

J. Marchaterre related an experience on some natural convection experiments, which has a great deal of similarity to Bendler's observations. At a heat flux sufficient to initiate subcooled boiling, the surface appeared to be periodically swept free of bubbles. The frequency of this phenomena was estimated to be approximately 1.0 cps. No unusual sounds or vibrations were observed.

## 6.5 WESTINGHOUSE ATOMIC POWER DIVISION – BETTIS FIELD (WAPD)

S. Green, S. Cota, and R. DeBortoli have been involved in WAPD's extensive burnout program. S. Cota remembered the occurrence of high pitch noises during a sequence of burnout runs, but could not recall the geometry of the test specimen. R. DeBortoli believed the sounds were associated with the burnout experiments on round tube (0.187 in. ID) geometries and recalled that the noises were heard in only subcooled runs. Any reproducibility of the phenomena was associated with high heat fluxes and high inlet subcooling.

S. Cota recalled one more recent instance of sound generation in a test specimen with either an "exponential" or "top hat" heat distribution. However, the conditions of the test were uncertain.

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