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A. L. Colomb and F. T. Binford

ABSTRACT

This paper will describe measurements made at ORNL to study the feasibility of boiling detection in a water-cooled nuclear reactor.

The methods selected for the detection of boiling are:

1. Measurement of the acoustical noise produced by the generation of bubbles.
2. Measurement of changes in the reactor-power spectral density produced by bubbles.

Preliminary results indicating that both methods could detect boiling are shown.

INTRODUCTION

One of the mechanisms most likely to cause damage to a water-cooled reactor of the ORR type is overheating of the fuel plates resulting in boiling burnout. The burnout phenomenon has been described in the literature[1,2] and is illustrated graphically in Figure 1. In this figure the heat flux is plotted against ΔT, the difference between the temperature of the heated surface and the saturation temperature of the bulk fluid. The region AB represents that part of the curve where heat transfer occurs by forced convection. The surface temperature at B may be slightly above the saturation temperature. At B boiling commences at the heated surface. Initially, bubbles arise from a few points of nucleation. These nucleation points become more numerous as the heat flux is raised. In the region BC this nucleate boiling enhances the heat transfer because of the heat of vaporization required to cause formation of the bubble. This effect results in an increase in the slope of the curve as shown. As the heat flux is further increased above C, the bubbles begin to become so numerous that they interfere with one another. This coalescing of the bubbles results in the formation of a blanket or film of steam on the heat-transfer surface which insulates it and forces the surface temperature higher. Finally, when the heat flux is increased to D, the steam film is so effective in insulating the fuel surface that the temperature rises sharply even if there is no increase in heat flux and, in fact, will usually continue to rise despite a rather sizable decrease in heat flux.

Strictly speaking, the term "burnout" applies to that point on the curve at which melting or serious structural damage to the fuel occurs. This may actually lie somewhere between E and F; however, since the temperature continues to rise even with a decrease in heat flux once the point D is reached, it seems reasonable to assume that damage will occur in the reactor if the point D is reached. This point will, accordingly, be called the "burnout point".

Reactors such as the ORR, LITR, and HFIR are designed to operate in the forced convection region AB. However, provided the magnitude of the void coefficients are small and the void volume is also small, no serious difficulty should be encountered even if the heat flux is great enough to

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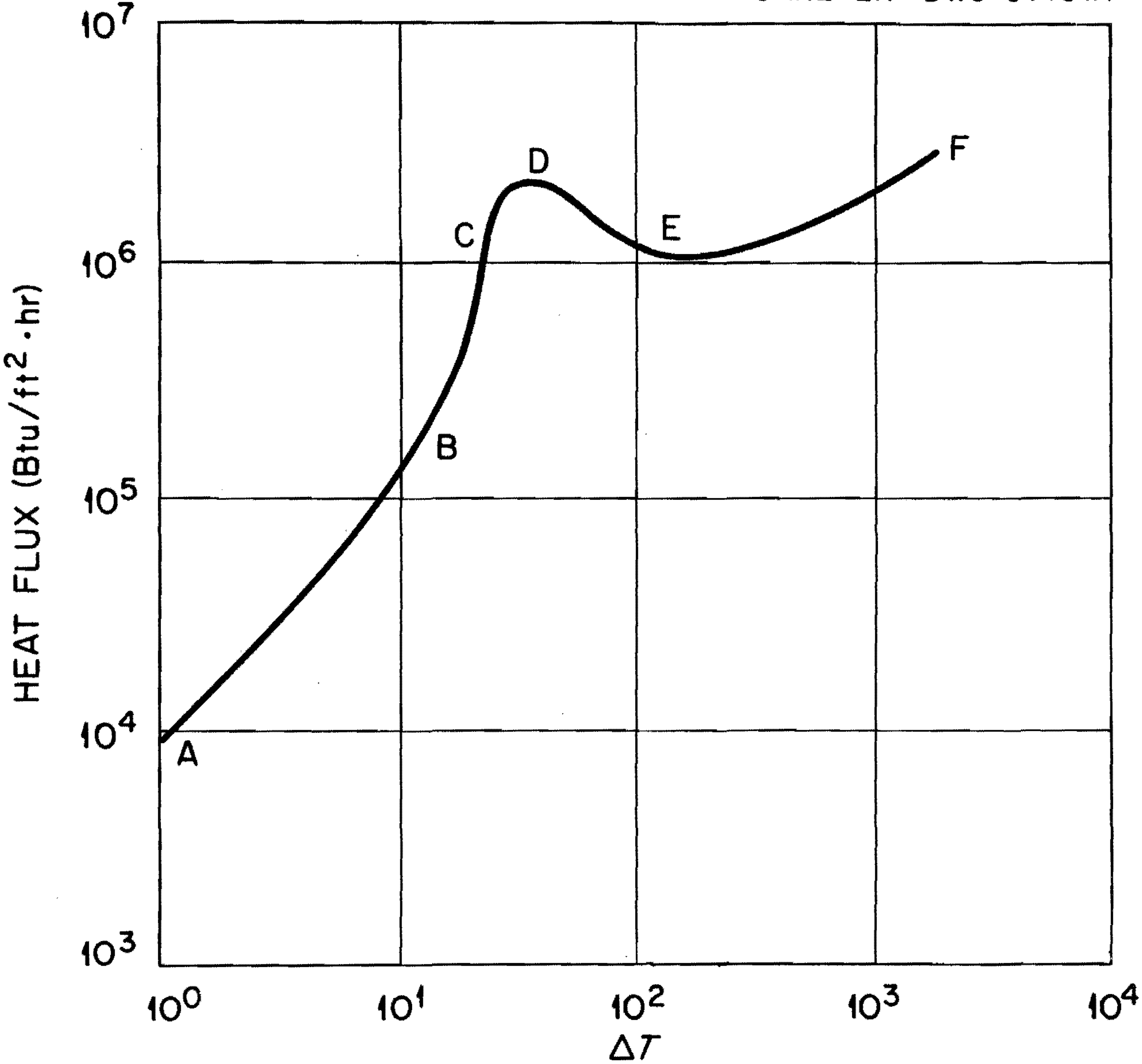

Relationship Between Heat Flux and Temperature Difference Showing the Various Regimes of Boiling.

Fig. 1.

cause some portions of the core to operate in the nucleate boiling region BC. In fact, the most efficient use of the cooling system is realized in this region.

The precise shape of the heat flux-ΔT curve will depend upon a number of parameters including the pressure, the coolant velocity, the subcooling, and the hydraulic diameter. Correlations exist[3,4] which permit the prediction of the burnout heat flux fairly accurately provided these parameters are known. While it is possible to know the nominal value of these parameters, it is very difficult, from a practical standpoint, to know them with sufficient accuracy at every point in the core. Moreover, because of local flux gradients and irregularities in fuel density, it is not possible to predict the exact heat flux at every point in the core. This combination of uncertainties, usually grouped together under the heading of "hot spot factor", opens up the possibility that even though the reactor is designed to operate well down in the forced convection region certain portions of it may be operating in or near the nucleate boiling region. It follows that if the heat flux of the reactor is increased until it is operating nominally in the nucleate boiling region, certain portions of it may be operating dangerously close to burnout. For this reason both the ORR and the LITR are operated well below the point at which nucleate boiling is expected to occur.

In addition to the uncertainties mentioned above, there exists the distinct possibility that the blocking of a fuel channel by a foreign object in the ORR might sufficiently restrict the coolant flow to permit burnout to occur. Moreover, it is recognized that the inadvertant reversal of one of the nonuniformly loaded fuel plates during manufacture would very probably lead to burnout in the HFIR core if that core were brought to full power. For these reasons, it is considered important to develop a device which will warn of the approach to burnout conditions and thus enable corrective measures to be taken before any serious damage is done.

The most promising procedure appears to be the development of a device which will detect the onset of boiling. It would be highly desirable if the device could differentiate between nucleate boiling and film boiling; i.e., could indicate whether or not the condition BC or the condition

CD is obtained. During the initial tests of the ORR, boiling was detected by means of a sensitive fast recorder connected to a neutron monitoring device.[5] The indication of boiling was a characteristic fluctuation of the neutron current reaching the monitoring device because of the variation in moderator density due to bubble formation. In this case, what was actually detected was probably the evolution of non-condensible gases from the heated water; however, the indications of boiling occurred under approximately the conditions predicted by theory. An attempt to refine this method and to differentiate between nucleate and film boiling at the WTR[6] was terminated abruptly by the burnout of a fuel element.

It seems clear that boiling can be detected by observing fluctuations in the neutron density. It is not clear at this point how well developed the boiling must be in order to be observed nor whether what is seen is extensive nucleate boiling or a small region of bulk boiling.

This paper will describe the experimental program now being carried out at ORNL to develop an instrument capable of detecting the onset of boiling in a water-cooled nuclear reactor.

Two methods of detection are being investigated. The first one already mentioned above consists of measuring the spectral density of the reactor power fluctuations to find out if the reactivity variations produced by the boiling bubbles can be observed and used as indication for the amount of bubbles generated.

The second method is completely independent of the nuclear characteristics of the reactor and could be used in any system where boiling occurs on a heated surface. It is an acoustical method consisting of investigation of the acoustical noise generated by the boiling process to determine if it can be discriminated in the presence of the general background noise produced by the reactor hydraulic system.

In order to test these two methods quantitatively, some boiling has to be generated in the reactor, the ORR. This can be done in two ways, nuclear heating or electrical heating.

The second method was chosen because, although quite involved, it has the advantage of producing at will, and without changing the reactor power, a controllable amount of boiling at a well-defined position in the reactor.

BOILING GENERATOR

An instrumented electrical heater was built to generate boiling in the reactor core. The heater consists of a 1 in.^{2}, 50-mil thick nichrome plate connected to a 6-kw, AC power supply by large aluminum electrodes. The heater is assembled in a core box having the same external dimensions as an ORR fuel element and, therefore, can be accurately positioned in the core.

The power generated by the heater section can be computed from measurements of the total circuit current and of the voltage drop across the nichrome plate.

The heater wall temperature is measured by three chromel-alumel thermocouples brazed on the plate center line.

In order to achieve boiling at a reasonable power, the water flow along the heater faces had to be limited by a calibrated orifice to five ft/sec at maximum reactor flow.

The boiling generator was first tested without forced cooling. Figure 2 shows a wall temperature versus power measurement definitely indicating the change in heat-transfer characteristics due to the onset of boiling at approximately 1 kw. No attempts were made to compare this measurement with existing correlations because, under natural convection conditions, the coolant flow moves in a direction opposite to that for which the orifice was designed; and the coolant flow cannot become well established.

The measurements of wall temperature versus power for forced convection are reported in Figure 3. There, the behavior of the measured points compare well with the calculated curve. This curve was calculated by using Colburn's correlation for a flow rate of five ft/sec and a pressure of 30 psia. The almost constant discrepancy between the measured and the calculated curves is ascribed to a systematic error in the measurement of heater power. The voltage drop measured across the heater is equal to the drop across the nichrome plate plus the drop across the nichrome-aluminum contacts. The heat generated at this contact is certainly conducted away by the aluminum; and, therefore, the power generated in the nichrome will be smaller than that indicated by the instruments. This measurement was

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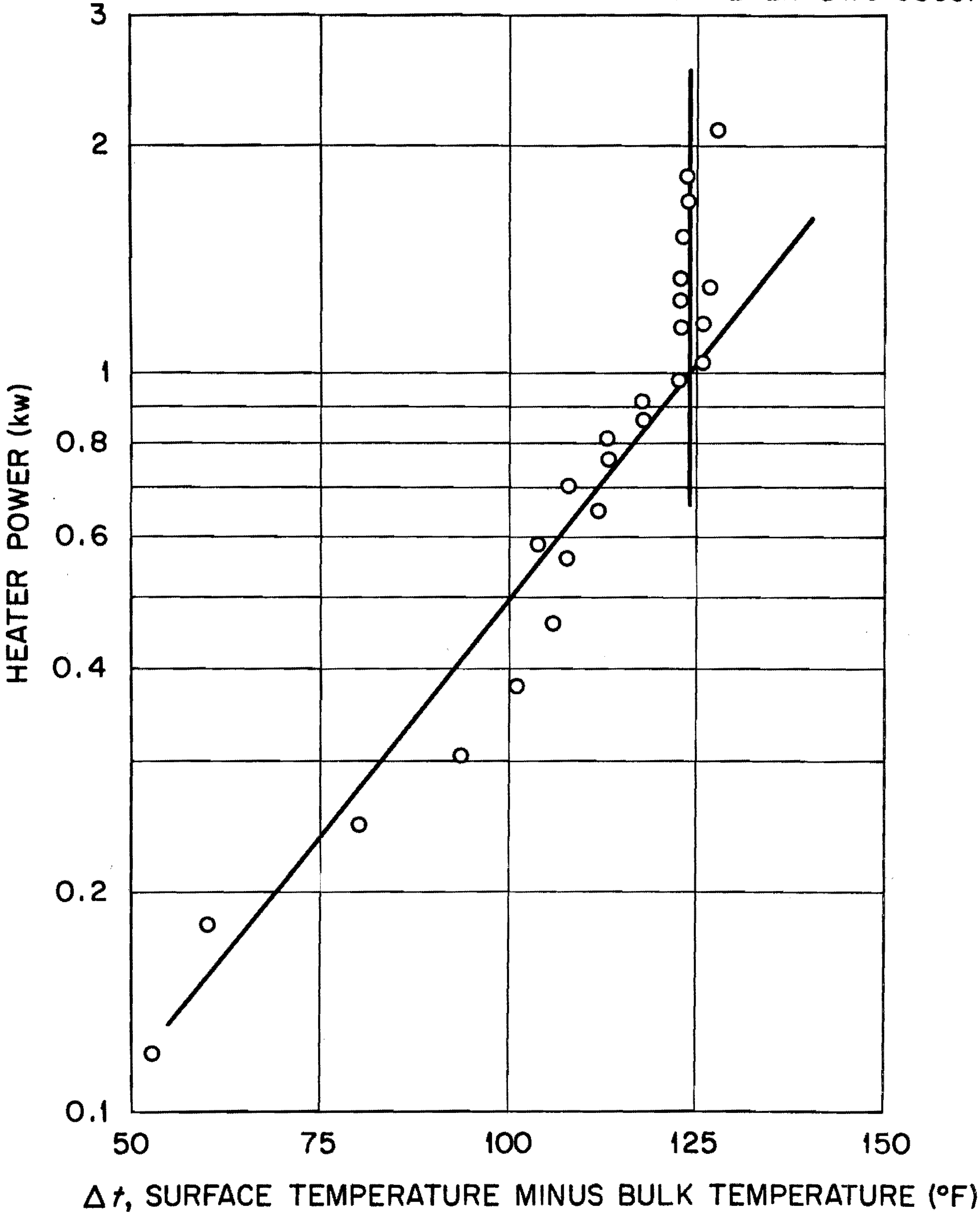

Measured Temperature vs Power Curve for Natural Convection.

Fig. 2.

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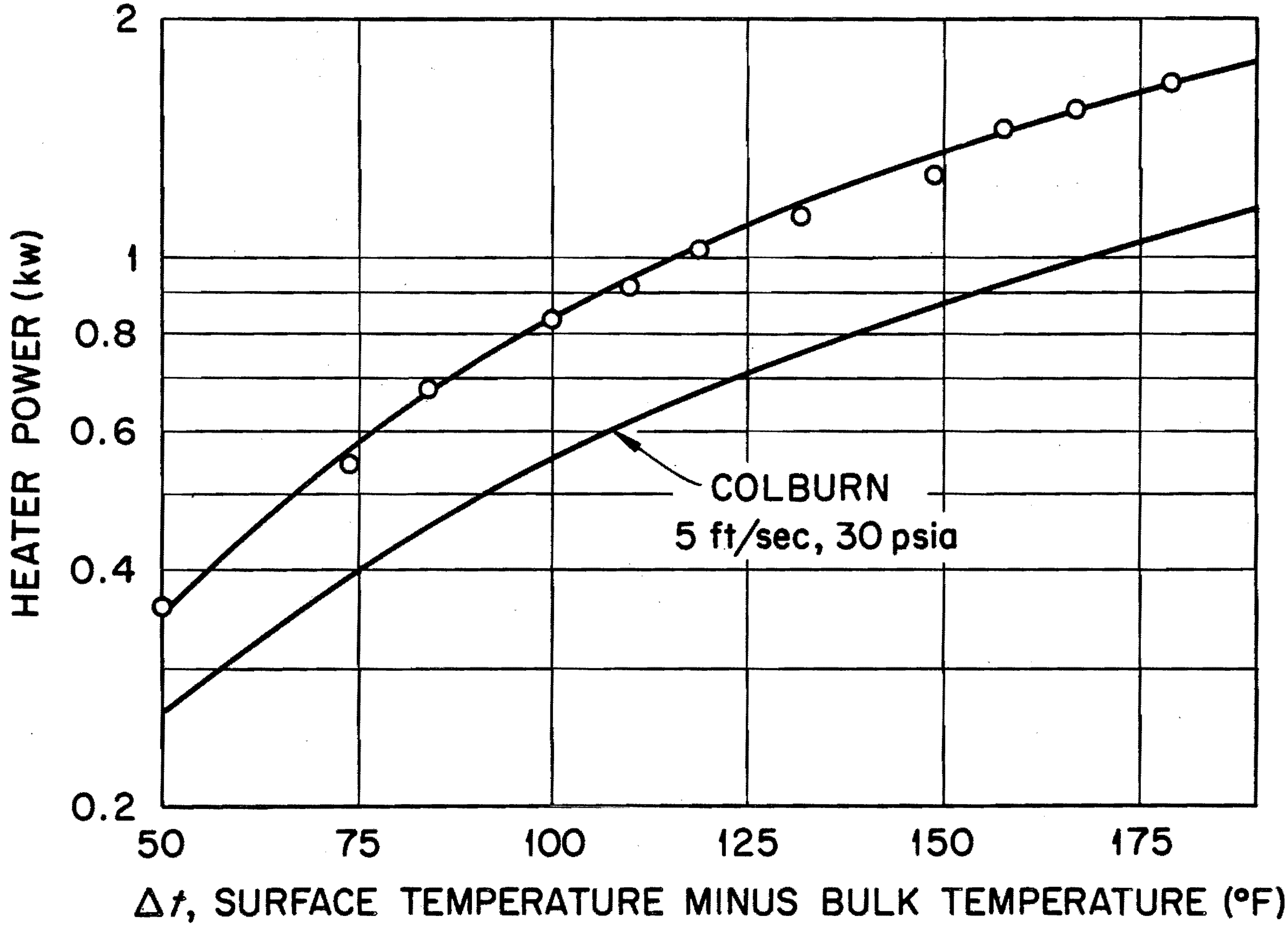

Measured Temperature vs Power Curve for Forced Convection.

Fig. 3.

interrupted before boiling was achieved by the failure of the thermocouples. It was found later, upon examination of the heater in a hot cell, that the nichrome-aluminum contact at one end of the heater must have had too high a resistance and therefore produced a hot spot. The effect of this hot spot was first to burn the thermocouple leads that passed very close to it and, after approximately one week of operations, to burn the nichrome at the contact, resulting in a complete failure of the heater.

The thermocouple failure made any qualitative measurements of boiling effects impossible. Nevertheless, it was possible to estimate, with the existing experimental values and the available correlations, that the onset of boiling would occur between 2 and 3 kw.

The partial results presented in the next paragraphs were obtained in the period of time between the failure of the thermocouples and the heater failure.

ACOUSTICAL NOISE ANALYSIS

An underwater microphone was installed alongside the heater electrodes at approximately 10 ft from the reactor core. The output of this microphone was fed into a Hewlett-Packard wave analyzer and the output of the wave analyzer was smoothed out by a passive integrator with a 240-sec time constant.

This apparatus was used to measure acoustical spectra, and Figure 4 is a plot of the background noise and of the boiling spectrum in the absence of reactor coolant flow showing that boiling produces a detectable amount of noise. Figure 5 indicates that the boiling noise varies proportionally with the power generated in the heater. It is interesting to note that the abrupt change in amplitude behavior occuring at 0.86 kw corresponds fairly well with the value of 1 kw found previously (Figure 2) for the onset of boiling.

Comparing Figure 4 with Figure 6, a plot of the hydraulic noise measured with a reactor coolant flow of 18,000 gpm indicates that the peaks measured in the boiling spectrum at 0.82 and 1.87 kilocycles could be due to resonance effects in the reactor tank. The fact that two different noise sources produced peaks at the same frequencies strongly supports this interpretation. On the other hand, it appears that the

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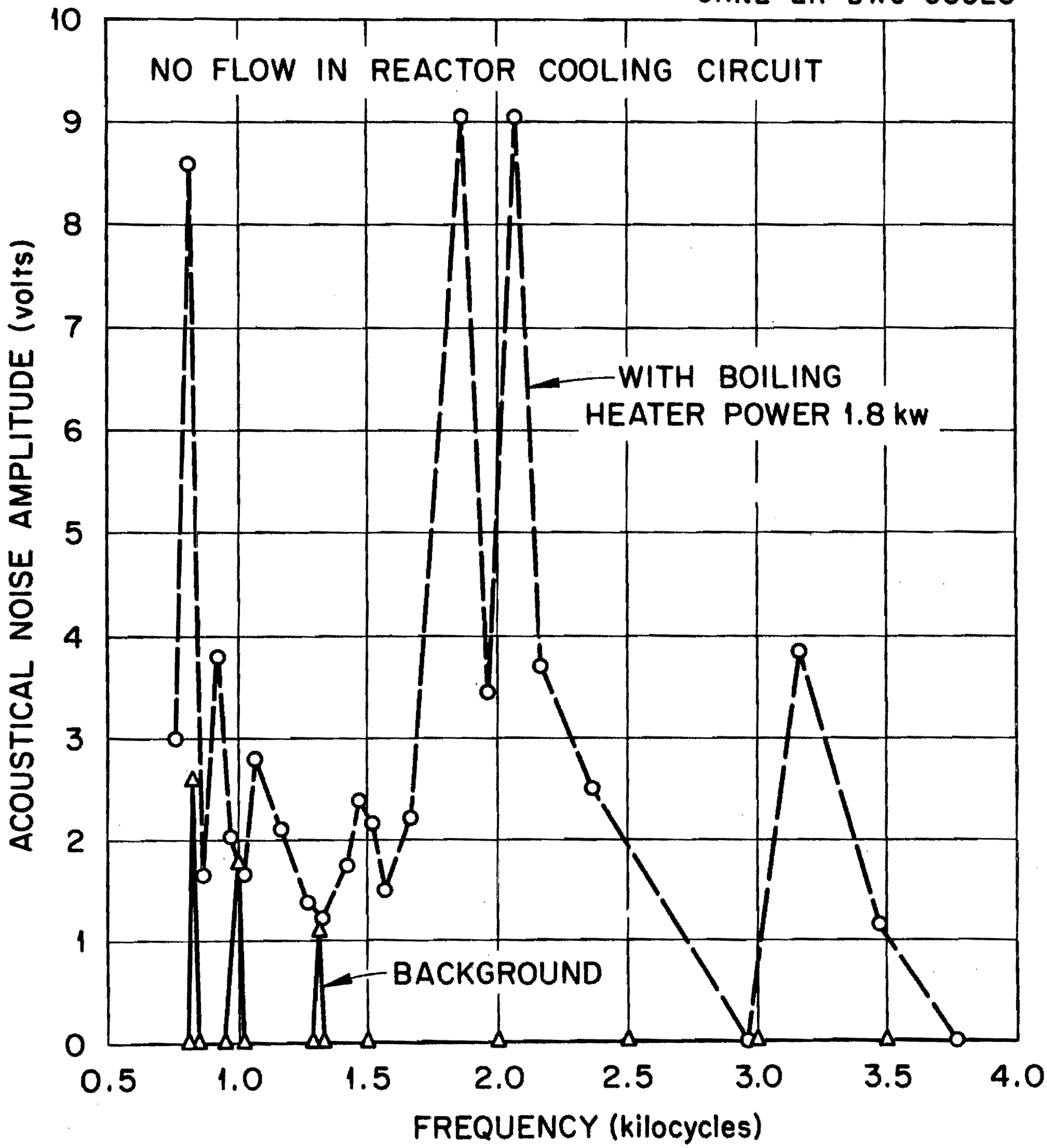
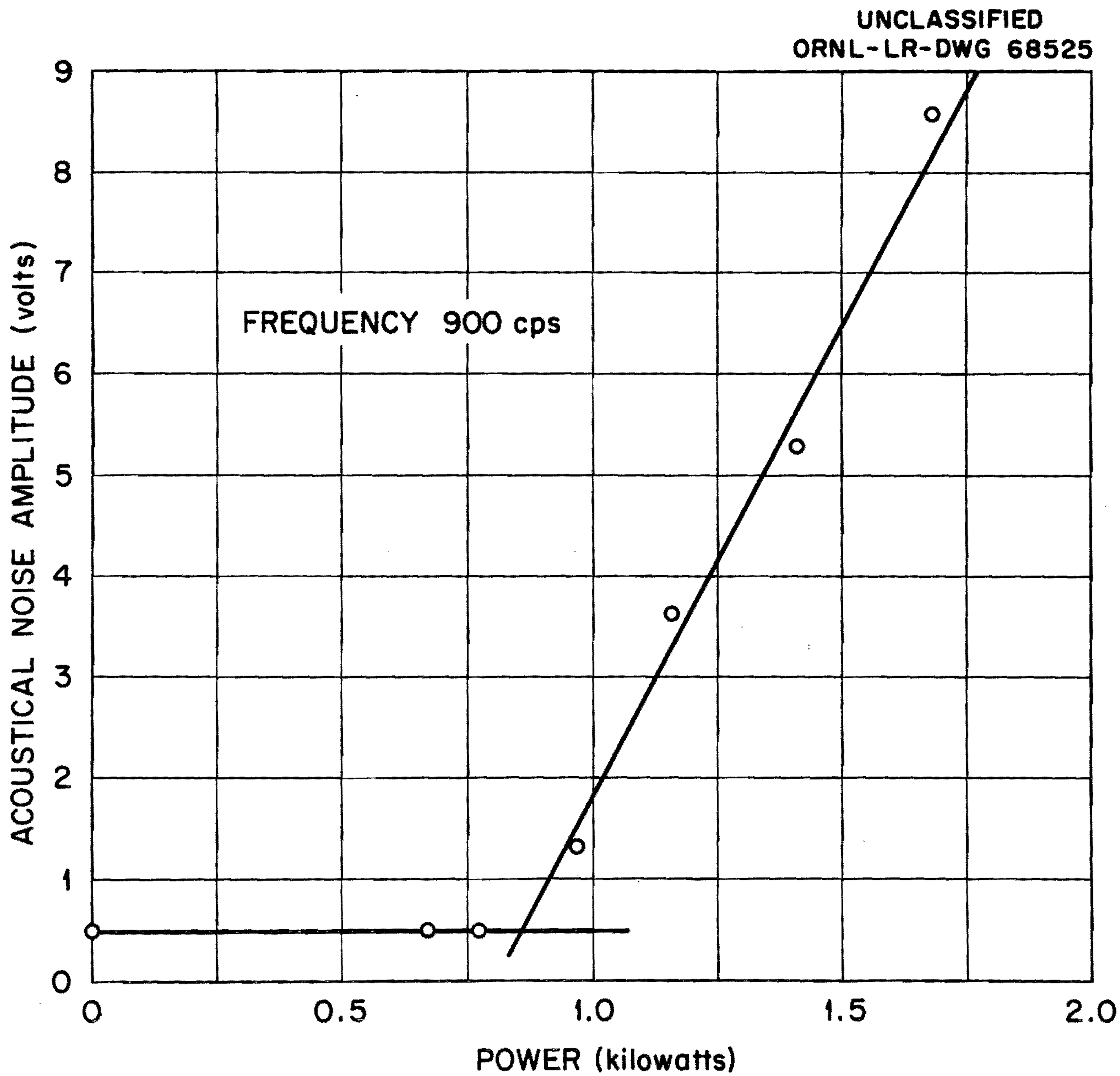


Acoustical Noise Spectrum; No Reactor Coolant Flow.

Fig. 4.



Acoustical Noise Amplitude as a Function of Heater Power.

Fig. 5.

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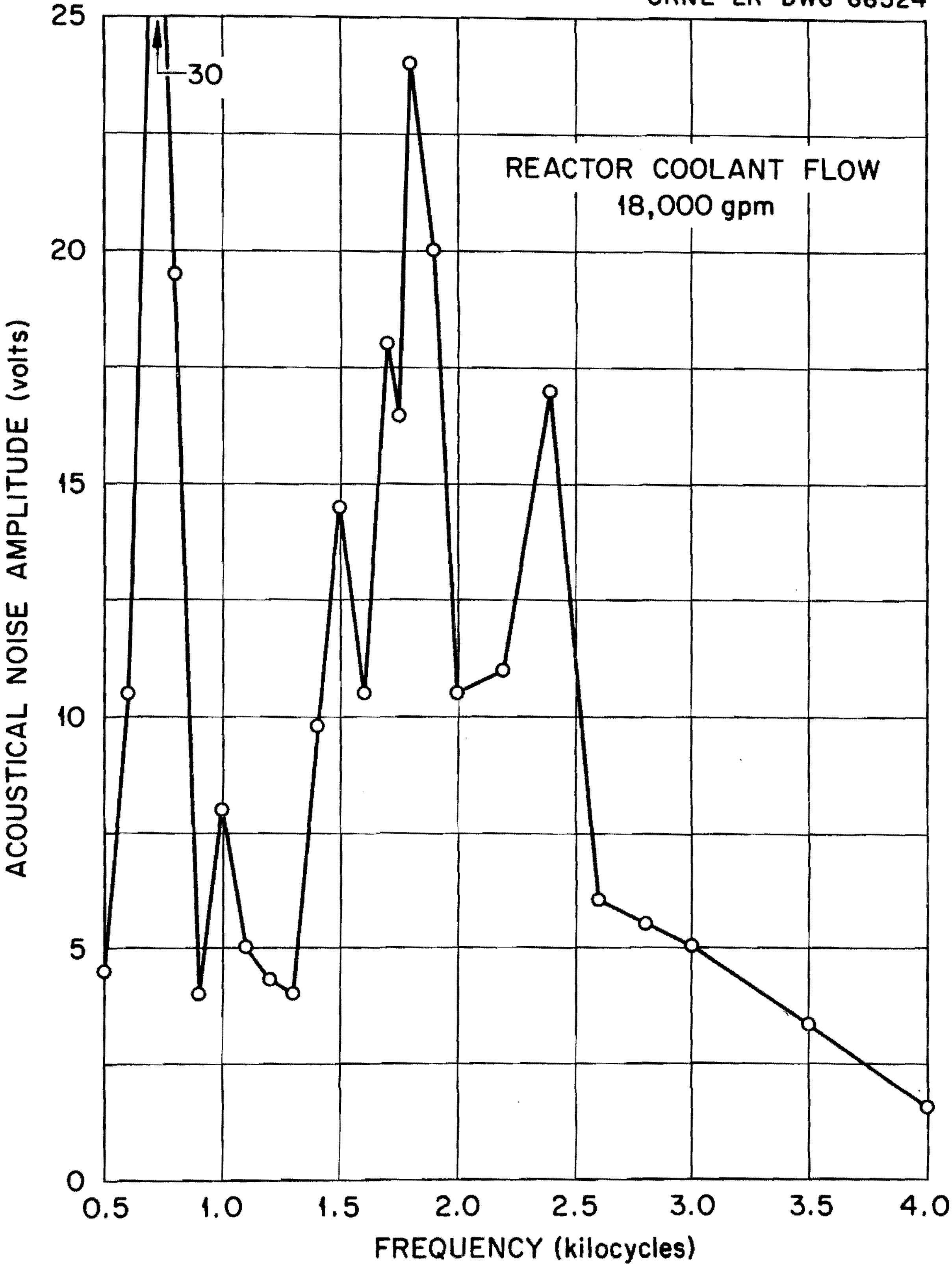

Acoustical Noise Spectrum; Reactor Coolant Flow 18,000 gpm.

Fig. 6.

boiling spectrum peaks at 0.92, 2.07, and 3.17 kilocycles are characteristics of boiling because they are located at frequencies where the background noise has low values.

This series of observations indicates that at a pressure of 30 psia the acoustical noise produced by boiling can be detected and that if the background noise is not too great it can be detected at the onset of boiling.

Nevertheless, this noise has a relatively small amplitude compared with the amplitude of the hydraulical noise (Figure 6). An attempt was made to discriminate the boiling noise against the hydraulical background noise in the region of the 0.92-kilocycle boiling peak. Figure 7 is a plot of the noise amplitude with and without power in the boiling generator. As one approaches the maximum of the peak the ratio of boiling noise to background noise increases rapidly. The fact that the boiling noise amplitude becomes smaller than the background noise at low frequencies is ascribed to the effect of the magnetic field of the heater electrodes on the microphone. This explanation still needs confirmation. Unfortunately this test was interrupted by the failure of the boiling generator before the maximum of the 0.92 kilocycle could be reached.

Future work with an improved boiling generator will use the information obtained up to the present to improve the sensitivity of the detector. The microphone will be installed far away from the heater conductors to avoid magnetic effects. The microphone will also be moved as close to the reactor as radiation permits in order to increase the boiling-noise-to-background-noise ratio. This ratio should be quite sensitive to distance. The boiling noise, being generated by a point source, will decrease at least with the square of the distance between source and detector. On the other hand, the background noise, being generated throughout the system, will have a relatively constant effect on the microphone wherever it is located.

POWER FLUCTUATIONS SPECTRAL DENSITY

To measure and analyze the reactor fluctuations a neutron sensitive ionization chamber was placed in one of the standard chamber locations close to the reactor core.

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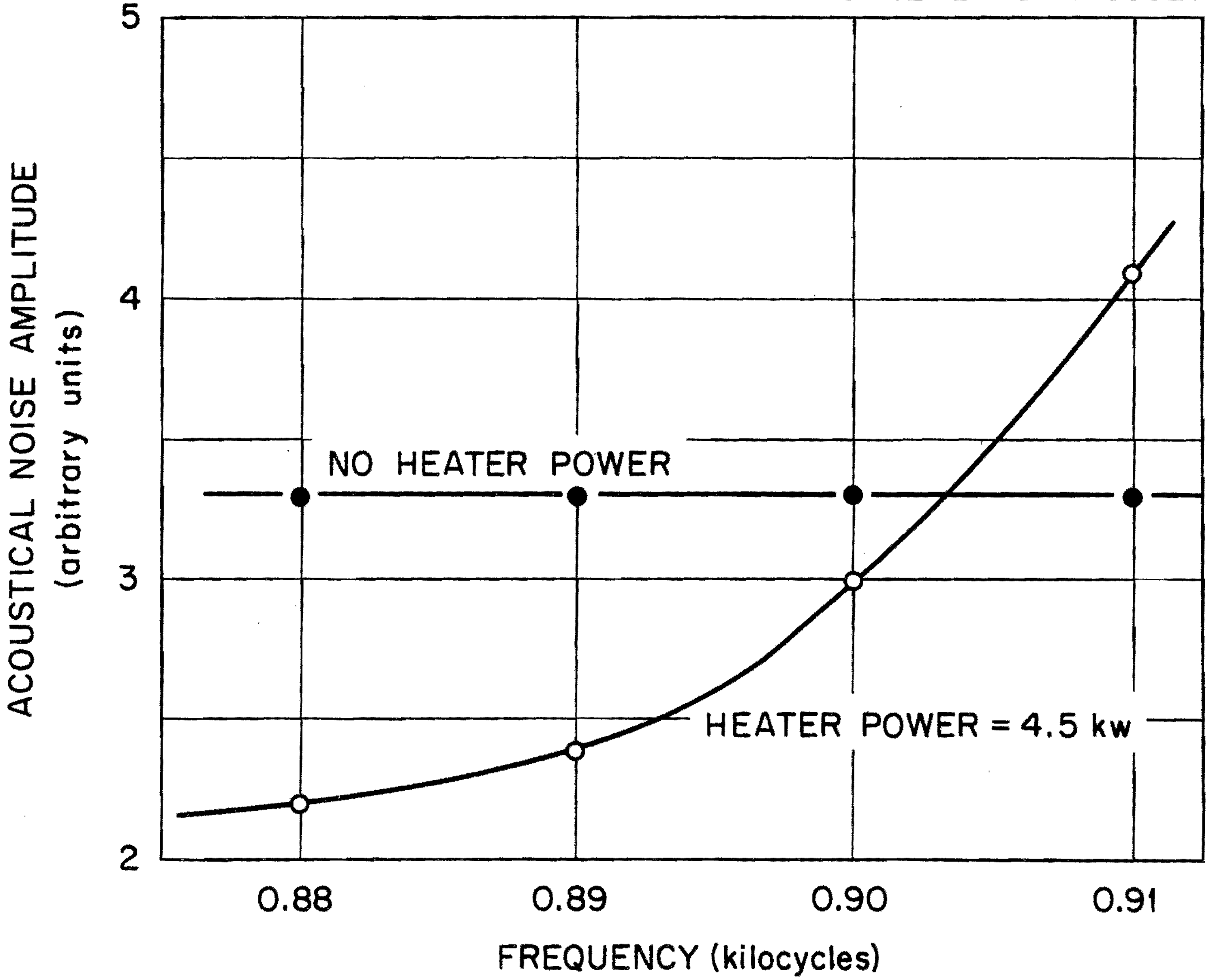

Boiling Noise Amplitude in the Vicinity of a Resonance.

Fig. 7.

The current output of the chamber was 200 μ amps and the total amplitude of the current fluctuations 0.2 μ amps. This indicates that at a reactor power of 30 Mw the power fluctuations have an amplitude equal to 0.1% of the operating power or 30 kw.

These current fluctuations are converted to a voltage on a 1 M-Ω load resistor and then amplified by a factor of 100 in an AC coupled amplifier having a flat frequency response from 0.1 to 1000 cps.

The amplifier signal is recorded on a tape recorder and digitalized at a rate of 128 numbers per second by playing back the tape at a lower speed than that used during the recording. The numbers obtained are punched on an IBM card deck, and the auto-correlation function and the spectral density of the signal are computed on a 7090 IBM computer.

The complete system was checked for frequency response by analyzing the fluctuations produced by a gamma-ray source, and the spectral density was found to be flat within the frequency range of interest.

Four 10-sec observations both with and without power on the heater were taken and analyzed. The average auto-correlation functions obtained from these samples are plotted in Figure 8. The standard deviation of these curves is 22%. The cosine Fourier transform of the auto-correlation functions (i.e., the spectral densities of the samples) are plotted in Figure 9. Here the standard deviations were found to be 45%.

Both the auto-correlation functions and the spectral densities indicate a difference between the samples with boiling and those without boiling, but the failure of the heater unit did not allow sufficient time to obtain measurements sufficiently accurate to allow a good interpretation of the results. One conclusion can be drawn from this test. It was found that for a given measurement duration the standard deviation of the auto-correlation function is much smaller than that of the spectral density. This indicates that a change in the reactor behavior could be detected more rapidly from an observation of the auto-correlation function than from an observation of the spectral density.

At this point, the results obtained, although not complete, indicate that both methods, the acoustical noise analysis and the power fluctuations analysis, could be used as a boiling-indicating device. It is not

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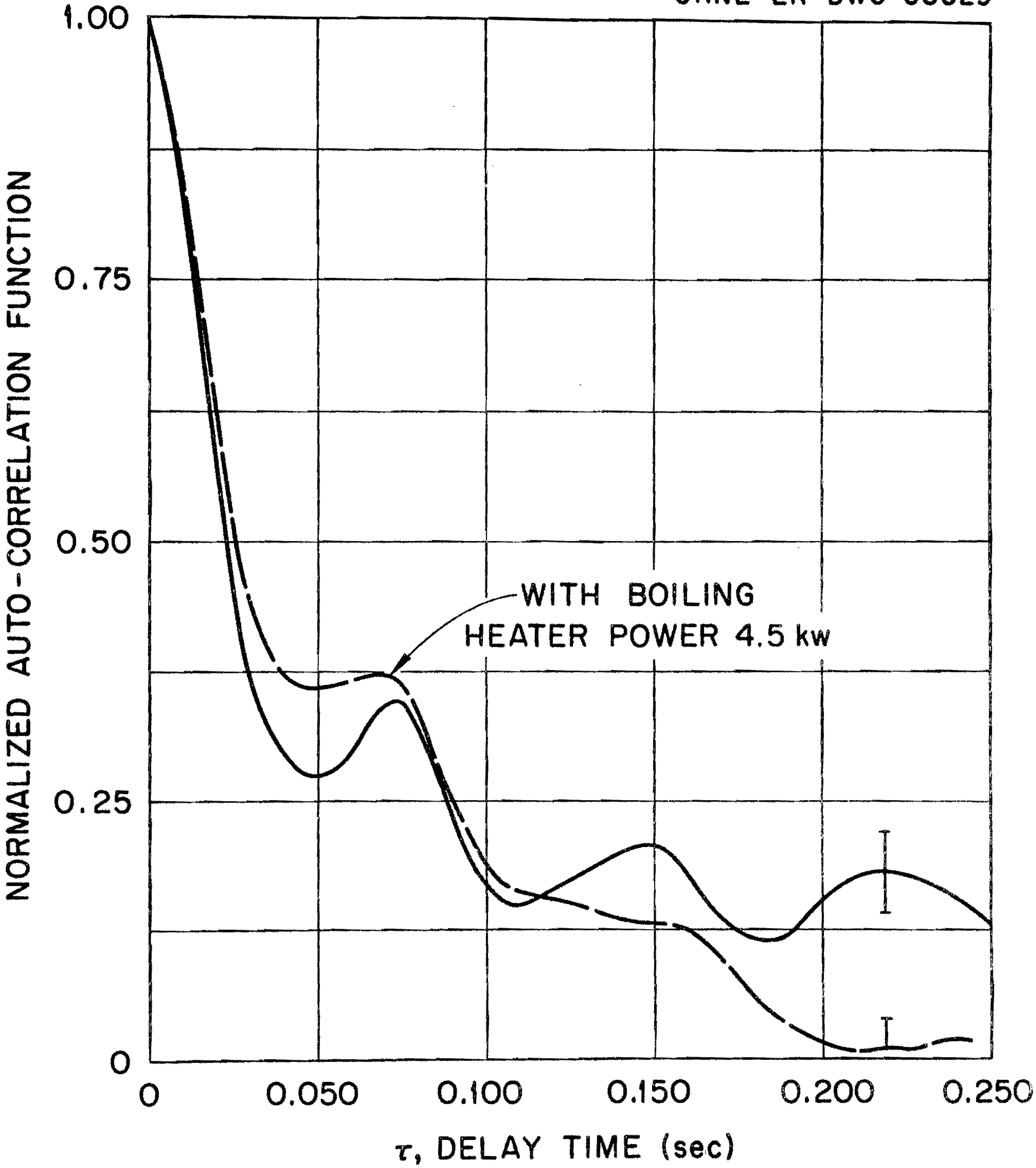
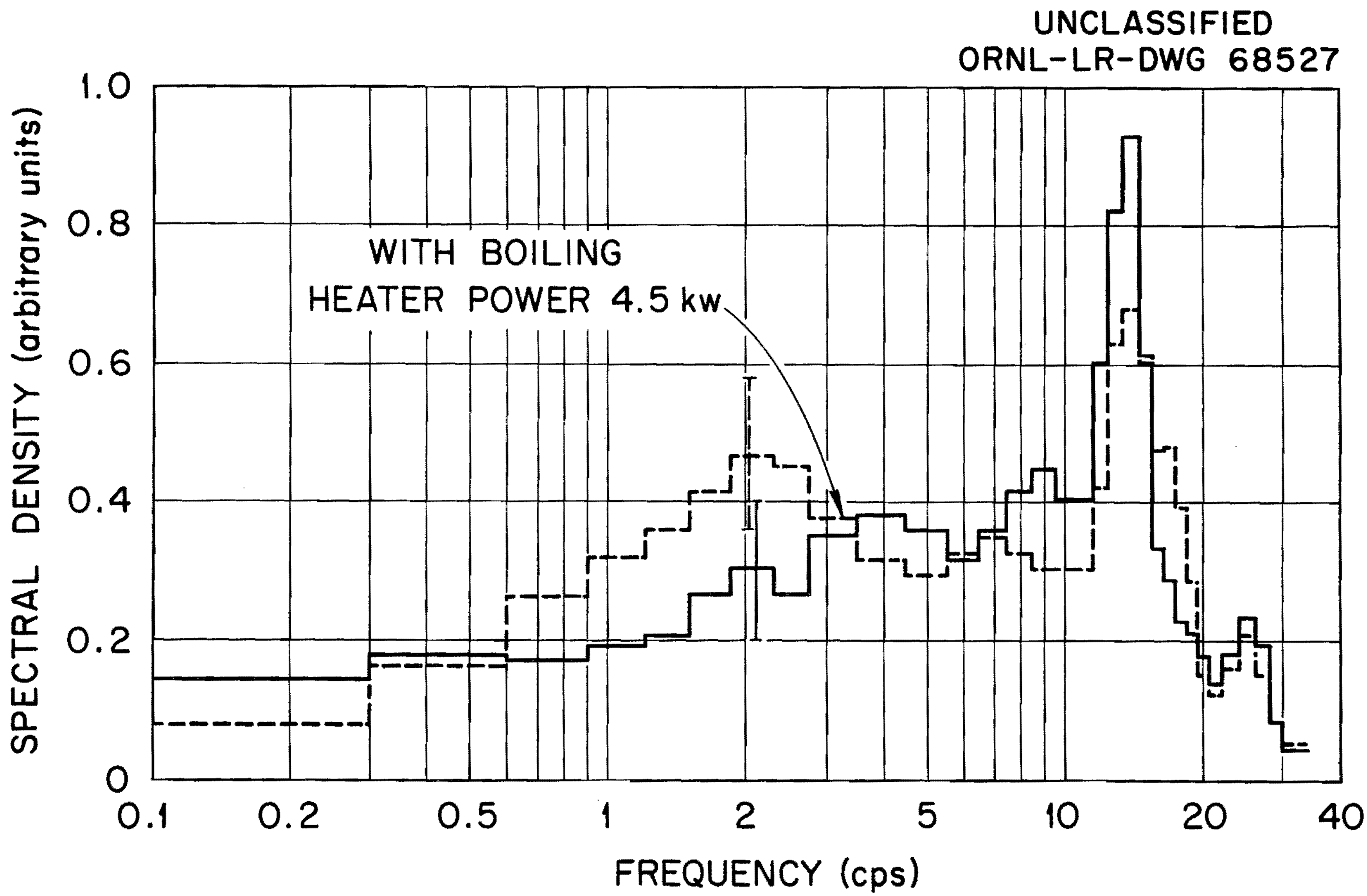


Power Fluctuations Auto-Correlation Functions.

Fig. 8.



Power Fluctuations Spectral Densities.

Fig. 9.

known what sensitivity could be achieved and what amount of time would be required to obtain the desired information with sufficient accuracy.

An improved boiling generator is being built to pursue this investigation of the effects of boiling; and, as soon as sufficient knowledge of this phenomenon is obtained, an instrument will be developed which is capable of indicating when boiling occurs in a small part of the reactor core.

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