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SURVEY AND STATUS REPORT ON APPLICATION OF ACOUSTIC-BOILING-DETECTION TECHNIQUES TO LIQUID-METAL-COOLED REACTORS

by

T. T. Anderson, T. P. Mulcahey, and C. Hsu

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April 1970

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NOMENCLATURE

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Symbol	Definition	Units
a	radius of cylindrical tank	cm
c	sound velocity	cm/sec
d	piezoelectric charge coefficient	C/N
f	frequency	Hz (cycles/sec)
f_r	geometrical resonance frequency	Hz
g	piezoelectric voltage coefficient	Vm/N
J_m	Bessel function of mth order	
ℓ	rectangular dimension	cm
n	integer denoting order of spatial mode	
p	system pressure	atm
q/A	heat flux	$Btu/hr\text{-}ft^2$
R	vapor bubble radius	cm
Z	characteristic acoustic impedance	$g/cm^2\text{-}sec$
Z_i	characteristic acoustic impedance of medium i	$g/cm^2\text{-}sec$
α_{mi}	ith zero of the mth-order Bessel-function equation $\partial J_m(\pi\alpha_{mi})/\partial a = 0$	
γ	ratio of specific heats, c_p/c_v	
Γ_R	acoustic energy reflection coefficient	
ρ	fluid density	g/cm^3

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ABSTRACT

Boiling in the core of Liquid Metal Fast Breeder Reactors can be detected by either of two principal methods, acoustic or neutron monitoring. This report summarizes literature through June 1967 concerning acoustic methods. In the acoustic monitoring method for boiling detection, either acoustic waveguides or high-temperature acoustic sensors are recommended.

I. INTRODUCTION

Sodium boiling in future Liquid Metal Fast Breeder Reactor (LMFBR) cores may be hazardous for two principal reasons. The first is the present limitations on core and structural materials. For example, the effect of sodium-vapor blanketing on heat-transfer characteristics is such that material temperatures may exceed their yield points and incur severe damage to the core. The second reason, although not applicable to all core configurations under study in the LMFBR program, is that the presence of voids in the coolant will result in a positive reactivity, with a resultant increase in power. This increase in power will aggravate the situation by forming more vapor, thus giving rise to a positive-feedback effect. For these reasons, all LMFBR's need a safety device that will initiate an alarm and/or corrective action at the first trace of coolant boiling during operation. If uncorrected, vapor generation would cause partial or complete core destruction.

There is a third reason for having a boiling detector on an LMFBR. For example, should an incident occur in which a reactor scram has been initiated but not yet carried out, the changing flow, power, and heat-transfer conditions may result in some uncertainty as to possible damage to the core. A boiling detector may provide some indication of a potential fuel meltdown.

There are various techniques for detecting boiling in a nuclear reactor. Of these, the two most promising are: (1) the acoustic detection technique, in which the sonic and ultrasonic noises generated in the core are monitored; and (2) the neutron-flux detection technique in which boiling-induced fluctuations in the neutron-flux spectrum are monitored. This status report covers the development and perfection of the acoustic technique.

II. PHENOMENA ASSOCIATED WITH ACOUSTIC DETECTION OF BOILING

A. SUMMARY OF BOILING-DETECTION EFFORT

Since 1965, a number of unclassified reports have been published on acoustic boiling detection as applied to thermal- and fast-reactor systems. By far, the majority originated in the United Kingdom, reflecting the effort devoted to the detection of sodium boiling in their Prototype Fast Reactor (PFR), which is under construction. On the other hand, reports from two installations [1,2] in the United States indicate that pump noise would completely obscure any boiling noise for the particular conditions in water-cooled reactors. The British, too, are concerned about pump noise, as reflected in a report on sodium-pump cavitation [3]. If the problem of pump noise is not too severe, Saxe [4] indicates that the acoustic technique may be more sensitive than neutron methods, which involve spatial averages and time integration of the void reactivity [5].

The various advantages and problems associated with acoustic boiling detection can be obtained directly from the literature. However, several factors common to most experiments may influence the results and bias the conclusions. The first factor is the qualitative nature of reporting sound intensities. Most investigators express sound spectra in terms of intensities relative either to a voltage level at the receiver or to a quiescent noise level. In only one case [6] was the sound intensity of boiling expressed relative to a

mechanical energy or pressure level. Absolute sound intensities are useful for design criteria, for sound-measuring systems, and for comparison of results by different investigators. But in all fairness to the experimenters, when an accelerometer or contact microphone is placed on a vessel wall or on an acoustic waveguide, the equivalent sound-pressure amplitude can be determined only by a rather involved calibration process, using secondary sound-standard transmitters and receivers for that geometry.

The second factor is that most of the spectra reported are limited to 20 kHz or less by the electronic equipment, by the transducer system, or by both. Higher-frequency components obtained with broad-response detectors may be a factor of 10 or 100 (20 or 40 dB) below the low-frequency components, but are much less susceptible to mechanical noise (other than bearing chatter or gas leaks) and hence may be of more use than the lower-frequency components.

The third factor is the difficulty in comparing the results of different investigations cited. Most investigators vary one or two parameters of many, using different measurement techniques; therefore the general conclusions obtained from one experiment may have only limited application to the others.

In the following survey of the literature, various investigations are reported simultaneously and, whenever possible, the differing conditions and their results are compared using similar units on reduced-size plots. The units were chosen to make the plots meaningful to both heat-transfer specialists and sound specialists. For example, for sound intensity versus heat flux, the sound intensity is plotted in decibels (dB), where -20 dB is a factor of 10 in pressure or voltage below the reference level of 0 dB (or unity gain factor), and -40 dB is a factor of 100 below the reference level. For spectra, unless absolute mechanical units were furnished for sound pressure, the decibel scales have been replotted, using zero decibels (0 dB) for the peak amplitudes. Heat flux per unit area of heater surface is expressed in conventional units of Btu/hr-ft^2; this quantity can be converted to W/cm^2 by multiplying by 3.14×10^{-4}.

B. BUBBLE DYNAMICS AND BOILING SOUND SPECTRA

The earliest investigations of bubble dynamics were by Rayleigh [7] and Minnaert [8]. Rayleigh considered the collapse of a cavitation bubble and estimated both the collapse time and the extremely high shock pressure generated at the bubble interface. He presented a simplified version of the analysis by Besant by equating the kinetic energy of the collapsing bubble to the work necessary to collapse it.

Osborne [9] of the U.S. Navy Underwater Sound Laboratory, New London, reported that his measurements in water agreed with Rayleigh's prediction of collapse time, but that the bubble "rebounded" several times with a period approximately double the collapse time. In addition, there were high-frequency components. This would correspond roughly to a frequency of bubble appearance times bubble radius of

$$fR = 5(p \text{ atm}/\rho \text{ g/cm}^3)^{1/2} \text{ kHz-mm.}$$

Hence for a bubble radius of 1 mm in water at atmospheric pressure, the rebound frequency would be 5 kHz (kilocycles per second).

Minnaert [8] treated a somewhat different problem: the volume oscillation of a gas bubble in water. He equated kinetic energy to the potential energy of adiabatic volume change and obtained the expression

$$fR = \frac{1}{2\pi}\sqrt{\frac{3\gamma p}{\rho}},$$

where p is the system pressure, ρ is the density of the liquid, and γ is the ratio of specific heats. Substitution of values of subcooled water at 1 atm yields fR = 3.28 kHz-mm.

More recent investigators have considered the growth rate of bubbles in superheated liquid [10-12]. We will not discuss these papers here, but, in general, they evidence the progress in a closely related area. Bree [13] at Risley has performed an analysis of bubble oscillations, taking into account the conduction of heat across the boundary of the bubble. His predictions are plotted as power-spectral-density curves, which for water have maxima given approximately by fR = 2.1 kHz-mm. For sodium, the plots show the influence of conductivity in that medium, where the maxima are given by fR = 0.3 kHz-mm. Apparently, subsequent investigators in the U.K. have not compared his theoretical predictions with their measurements.

The best comparisons to the above predictions of bubble resonances would be measurements in which effects of geometry are minimized. For example, boiling sound spectra in large bodies of water would be acceptable. The three references indicated in Fig. 1 give experimental results, all for boiling in rivers or a reservoir and for boiling in containers. There is a broad maximum for each infinite medium. The figure from Osborne [14] shows a peak at 5 kHz; he reports bubble radii ranging from 0.02 to 0.5 mm. Walton's [15] curve peaks at 1.8 kHz, whereas that of MacLeod [16] shows a broad maximum from 0.9 to 3 kHz. Hence there is agreement within a factor of two

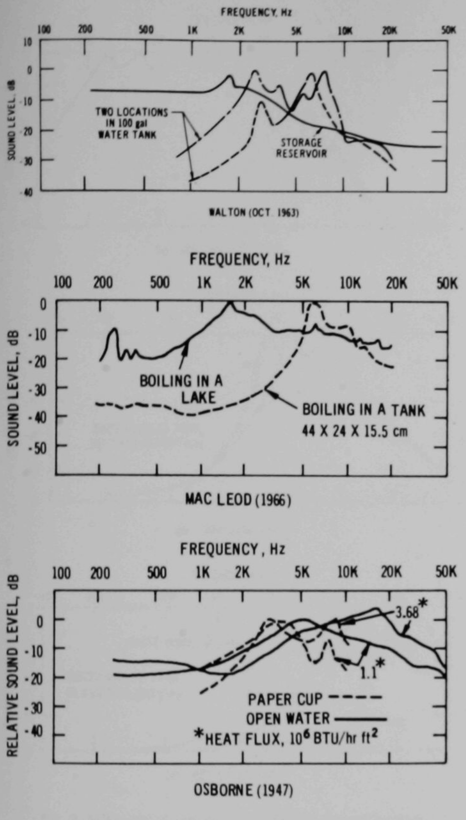

Fig. 1. Comparison of Boiling-water Sound Spectra in Large and Small Geometries

between these references, and also general agreement between experiment and the three predictions.

Another area of investigation in underwater acoustics is the problem of cavitation noise. Similarities to boiling noise, especially at high subcooling, can be seen in the papers by Harrison [17] and Mellen [18]. Actually, cavitation is a type of boiling characterized by a sudden change in pressure energy, rather than by a change in thermal energy.

C. GEOMETRY AND BOILING SOUND SPECTRA

One difficulty in predicting when boiling noise is being generated, as compared to any other source of noise (say the random white noise), is the excitation of acoustic resonances within a finite container. The wall-liquid and gas-liquid interfaces reflect sound waves and sustain a frequency component whose half-wavelength is an integer multiple of a rectangular length. The fraction of the sound reflected from a boundary can be determined by a "characteristic acoustic impedance," which is simply the product of density ρ and sound velocity c; or algebraically stated,

$$Z = \rho c.$$

From the development by Babikov [19], the fraction of sound energy reflected back into medium 1 after striking medium 2 is given by

$$\Gamma_R = \frac{Z_2 - Z_1}{Z_1 + Z_2}.$$

Table I lists the acoustic impedances for various materials found in water- and sodium-cooled reactors [20,21]. The table indicates that structural members will reflect 90% or more of the incident energy back into the coolant.

The frequency of a resonance can be obtained as follows: For a rectangular container of dimensions $\ell_1 \times \ell_2 \times \ell_3$ at the rigid wall, the sound pressure would have a maximum value and the sound velocity would be zero. For these boundary conditions, Beranek [22] gives resonance frequencies in terms of integers n_1, n_2, and n_3 as

$$f_r(n_1, n_2, n_3) = \frac{c}{2}\left(\frac{n_1^2}{\ell_1^2} + \frac{n_2^2}{\ell_2^2} + \frac{n_3^2}{\ell_3^2}\right)^{1/2},$$

where c is the velocity of sound within the container. For a long container, only one dimension is dominant to produce the familiar equation for the closed organ pipe,

$$f_r(n) = \frac{cn}{2\ell}.$$

MacLeod [16] has experimentally verified these tank resonances, as shown in Figs. 2b and 2c. The organ-pipe resonance should occur in a subassembly with walls, as demonstrated by Walton [15] and plotted in Fig. 2a. Thus geometrical resonances can play an important part in

TABLE I. Acoustic Impedances of Structural Materials and Coolants

Material	Velocity of Sound (c), 10^5 cm/sec	Characteristic Acoustic Impedance, 10^6 g/cm^2-sec
Sodium	2.420	0.2131
Nickel	4.785	4.95
Steel	5.790	4.56
Water (20°C)	1.5	0.15

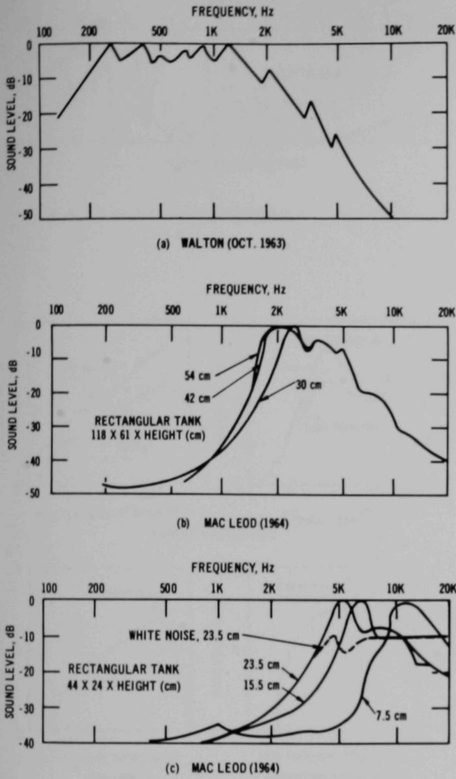

Fig. 2. Influence of Geometry on Boiling Sound Spectra

determining magnitudes and frequencies of any detected boiling spectrum. Walton demonstrates that in the audio range to 20 kHz, the spectrum of white noise (i.e., purely random fluctuations over the complete frequency range) is modified by geometry to be indistinguishable from the original boiling noise. This result shows there can be a definite limitation of acoustic boiling detection, with respect to obtaining a sufficient signal-to-noise ratio. Similar results are shown (Fig. 3) by Randall and Logan for a boiling sodium loop [23].

To complete the discussion on geometrical resonances, we should include the resonance-frequency formula [24] for a right circular cylinder of radius a and length ℓ, which is the more common configuration for a liquid-filled reactor tank. For the rigid wall, in terms of zeros of the derivative of Bessel functions, $dJ_m(\pi a_{mi})/da = 0$, the resonance frequency is

$$f_r(a_{mi}, n) = \frac{c}{2}\left[\left(\frac{n}{\ell}\right)^2 + \left(\frac{a_{mi}}{a}\right)^2\right]^{1/2} .$$

The lowest zeros are $a_{10} = 0.5861$, $a_{20} = 0.9722$, and $a_{01} = 1.2197$.

Thus far, we have shown that acoustic boiling sound is a broad-band noise, with most of the sound occurring in the audible range of frequencies. Resonance peaks of the spectrum for infinite media apparently are related to bubble size, whereas the acoustic spectral peaks for finite media are definitely determined by geometrical resonances.

D. SOUND INTENSITY FROM BOILING

In this section, the heat-transfer process will be examined in relation to sound production in an attempt to link thermal-energy considerations to the previous mechanical considerations.

Sound production from boiling could be a useful tool to the heat-transfer specialist in determining the transition from nucleate to film boiling; two investigations have been made involving this technique.

Schwartz and Siler [25] measured sounds emitted by the boiling of water from the outside surface of an 0.093-in.-diam, electrically heated tube. The tube was immersed in a water-filled glass carboy of about a 1-ft diameter. Most of the spectrum (Fig. 4) lies below 1 kHz, which is somewhat low compared to U.K. investigators or Osborne (Fig. 1); their results show increasing sound level with heat flux. A double point of heat flux or sound versus wall temperature occurs. Thus the sound curve (Fig. 5) has the same form as the familiar Nikuradse heat-transfer curve.

Data by James [26] and by Osborne and Holland [6], when plotted to a similar scale, refute the increasing sound level in the film-boiling region. The information by James mentions only a vertical pin in water and gives no dimensions or temperatures. Osborne and Holland plot absolute sound-pressure level, but give heat flux in terms of

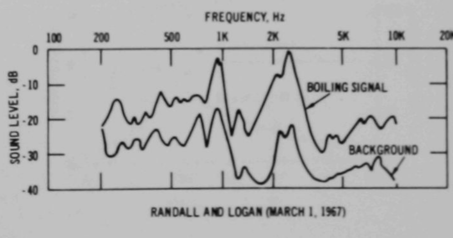

Fig. 3. Sound Spectra from Boiling Sodium

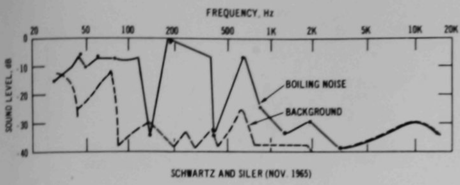

Fig. 4. Boiling-water Sound Spectrum in a Glass Carboy

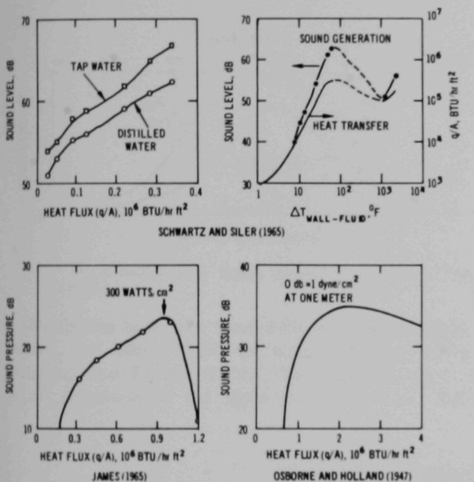

Fig. 5. Sound Intensity versus Heat Flux and Wall-fluid Temperature Difference for Boiling Water

heater power for their tests of small horizontal wires in river water at 5°C. However, for 3/4-in. through 3-in. lengths and 22 AWG through 30 AWG wire sizes, the various curves of sound intensity versus power nearly coincide when plotted against heat flux. The curve shown (Fig. 5) is for a 1-1/2-in.-long, 28 AWG wire. Osborne [14] shows the double-valued nature of nucleate and film boiling through resistance curves of the "cold" or "red-hot" wire. Westwater, Lowery, and Pramuk [27] demonstrate that for boiling methanol (Fig. 6) the sound spectrum is a single-valued function of the wall-to-fluid temperature difference, which is contrary to the results reported for water. Only in the nucleate-boiling region do all four references agree. Hence it appears reasonable to conclude that for nucleate-boiling heat transfer, the sound level of the boiling increases with heat flux.

E. ASSOCIATED PROBLEMS

An associated problem of acoustic boiling noise is the coupling of mechanical resonance of the boiling hydrodynamics to a resonance in thermal transport and heat transfer. Some studies, including those of combustion instability and pulsating flow [28], have proposed mechanical models of the phenomena. The conditions are similar to some of those reported rather early by Goldman [29] and later by Firstenberg [30].

F. APPLICATIONS OF BOILING DETECTION TO NUCLEAR REACTORS

Two applications of acoustic boiling detection to water-cooled reactors were unsuccessful; pump noise masked the boiling signal. According to Colomb and Binford [1], pump noise at their hydrophone exceeded by 10 dB the boiling signal from the Oak Ridge Research Reactor (Fig. 7). Hogan and Boyd [2], in a Bettis-KAPL collaboration, performed tests and came to the same conclusion, but did not publish data in support of their findings. Both groups have since relied upon ion chambers for detecting boiling [31]. However, in early work by Boyd and Cummerow [32], feasibility of measuring boiling sound was demonstrated in a water loop, as shown in Fig. 8.

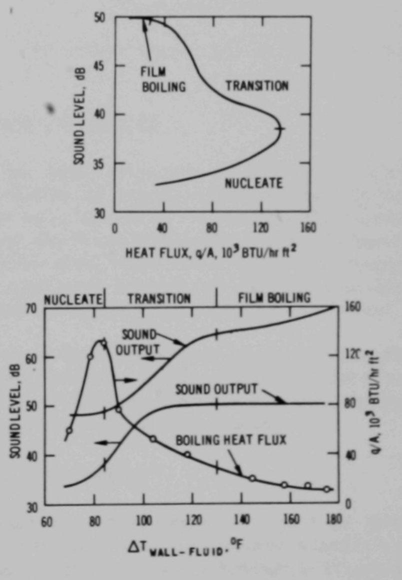

Fig. 6. Sound Intensity versus Heat Flux and Wall-fluid Temperature Difference for Boiling Methanol

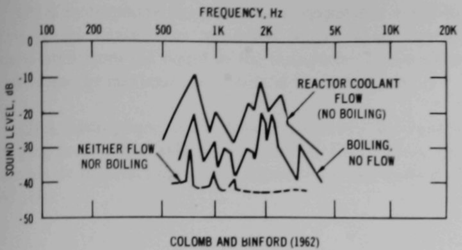

Fig. 7. Boiling-water Sound Spectra in the Oak Ridge Research Reactor

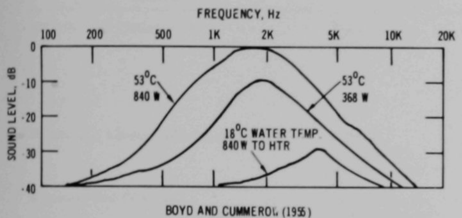

Fig. 8. Boiling-water Sound Spectra in Support of the STR Program

Waveguides have been successfully used by Ledwidge, Parnell, and Adam [33,34] for boiling detection in the Dounreay Fast Reactor (DFR). They report as much as 30-dB separation of the signal and background noise (Fig. 9). Keep in mind, however, that the NaK-cooled reactor uses electromagnetic pumps, which are much quieter than mechanical pumps. With the advent of large fast reactors using centrifugal pumps (including PFR), combined acoustical flow noise of the pump-coolant interaction may be detrimental to the capability for acoustically detecting boiling.

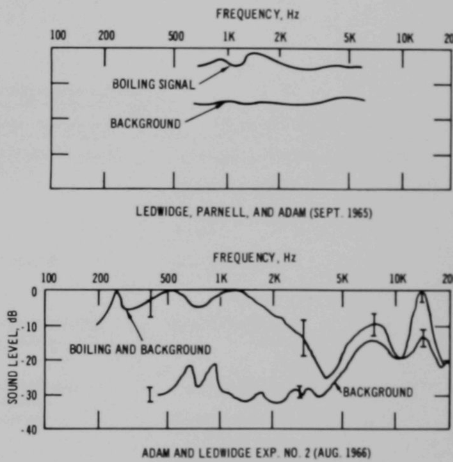

Fig. 9. Boiling-NaK Sound Spectra in the DFR 4-in. Loop

III. ACOUSTIC-BOILING-DETECTION TECHNIQUES

A. DETECTION

Boiling in a liquid can be detected acoustically in different ways, since bubble formation and motion in the liquid generate sound waves, and the sound waves, in turn, cause disturbances in the liquid. In principle, a sound wave passing through a point in the liquid will cause variations in pressure, velocity and liquid density. Pressure variations can be measured by deflection or compression of a solid body immersed in the liquid; velocity variations by the measurement of the changes in the heat-transfer coefficient of an electrically heated film on a probe; and density variations by measuring the bending of light beams in optically transparent liquids. These variations can be directly related to the characteristics of the sound waves and, in turn, to boiling in the liquid. Similarly, a sound wave impinging on a solid induces vibration of the solid; this vibration can be measured by the resulting displacement, velocity, or acceleration of the surface. The measurements also can be related to boiling in the liquid.

These methods rely upon the sound waves internally generated by the boiling. However, externally introduced sound waves also can be used to detect the presence of boiling, since the gas bubble changes the sound-transmission properties of the liquid. In this instance, the intensity of the sound waves measured after they travel through the medium is compared to that of the input sound waves.

Two of the above methods are directly applicable to acoustic detection of boiling in liquid-metal-cooled nuclear reactors: (1) detection of pressure variations in the liquid, and (2) detection of vibrations of solids.

1. Use of Hydrophones

Sound-wave-induced pressure variations are detected through the use of a pressure transducer. A specific type of pressure transducer, termed a hydrophone in underwater acoustics [21], is used in the general liquid-boiling detection work for the following reasons:

(1) A hydrophone has an acoustic impedance equal to that of the liquid; thus maximum sound energy can be transferred from the liquid to the transducer. This enables one to use the maximum sensitivity of the transducer.

(2) A hydrophone could have a frequency bandwidth ranging from a few kHz up to 15 MHz. This enables the transducer to detect the boiling sound waves that extend to 60 kHz.

Table II summarizes the work on application of hydrophone transducers to acoustic boiling detection. More recent work on a boiling detector for the ATR reactor has been presented in a preliminary report by Clayton and Morrison [35]. In this application, they are using the lead zirconate-titanate composition PZT 5a, with a Curie temperature of 365°C, in a hydrophone transducer of their own design.

TABLE II. Comparison of Sound-detection Techniques

Source	Technique	Frequency Response	Electronics and Comments
Osborne and Holland [6]	Hydrophone (crystal)	Hydrophone; flat to 40 kHz	(1) Heterodyne analyzer, 8-50 kHz. (2) Sound analyzer, 200 Hz to 10 kHz. (3) High-pass filter and Ballantine meter.
Westwater, Lowery and Pramuk [27]	Crystal microphone outside heater	25-7500 Hz	Sound-level meter.
Schwartz and Siler [25]	"Hydrophone" microphone in the balloon	20 Hz to 20 kHz on analyzer	Tape recording.
Hogan and Boyd [2]	Accelerometer, hydrophone with silicon rubber sheath	Hydrophone; unknown response	(1) Band-pass analyzer, 0.5-200 kHz. (2) Tape recorder, 30 Hz to 20 kHz. (3) Heterodyne listening unit near 20 kHz (could not detect boiling noise).
Walton [15]	No description of experimental equipment		
MacLeod [16]	Lead zirconate or barium titanate crystal in a hydrophone-type transducer	Flat in the audio range	B & K Type 2107 analyzer, 20 Hz to 20 kHz.
Ledwidge, Parnell, and Adam [33]	Waveguide coupled to transducers	Not reported	(1) Tape recording of signals definitely showed boiling easily detected. (2) Analyzed spectrum was very noisy, perhaps due partly to method of analysis as well as to spasmodic signals.
Adam and Ledwidge [34]	Crystal accelerometer on acoustic waveguide	Mounted resonant frequency 27 kHz; not meaningful beyond 20 kHz	(1) On-line spectrum. (2) Tape recording.
Colomb and Binford [1]	Hydrophone	Not reported	(1) Hewlett-Packard wave analyzer (most likely 20 Hz to 20 kHz). (2) Very narrow spectrum observed. (3) Pump noise much in excess of boiling noise.
Boyd and Cummerow [32]	Pressure transducer; temperature limited to 60°C	50 Hz to 50 kHz	(1) Wave analyzer, 20 Hz to 20 kHz. (2) Boiling near saturation temperature at atmospheric pressure. (3) Spectra erratic.

2. *Use of Accelerometers*

Sound-wave-induced vibrations in solids are used to detect boiling by inserting a rod into the liquid and measuring vibration at the end, or by mounting a sensor onto the liquid-filled tank. To detect sound through solid vibration, an accelerometer is commonly used. Commercially available accelerometers [36,37] can produce signal levels of 4 mV/g with a mounted resonant frequency of 125 kHz, or 390 mV/g with a mounted resonant frequency of 16 kHz.

To properly assess the frequency response of an accelerometer, one should note that the unit consists of a mass-and-spring system with very low damping. This mass-spring coupling causes the response voltage to be directly proportional to acceleration up to about one-third of the mass-spring resonance frequency. Above one-third of the resonance frequency, the response voltage climbs to a peak at resonance, and then drops off quickly at higher frequencies.

Of interest is the 27-kHz resonance accelerometer used by Adam and Ledwidge [34]. They reported, as of August 1966, placing an order for accelerometers with 125-kHz mounted resonances. In the U.K., the problems of high-temperature in-core detectors and lead wires have been circumvented through the use of acoustic waveguides coupled to a transducer. These have been described briefly in the previous references; Redwood [38] has published a comprehensive treatise on the mathematical analysis and design of waveguides.

3. *Other Techniques*

During the investigation of hydrophones for acoustic boiling detection in a nuclear reactor, several other methods of performing the same task were encountered. These methods are summarized and compared in the following paragraphs.

The measurement of void fraction in a boiling loop by using attenuation of sound has been proposed [39]. Although this technique may pose extremely difficult problems in a reactor, analysis of the attenuation of sound waves due to the presence of bubbles may prove of some value in calculating change in noise level from a boiling source. Since minute bubbles can reflect, refract, and attenuate sound, considerable attention has been focused on this technique in underwater acoustics [21,40].

As an extension of the concept of injecting sound into the liquid to detect voids, an ultrasonic generator could be used to determine the boiling threshold in a liquid. This is the basis of work performed by DePrisco *et al.* [41], with a further application reported by Kartluke, Wichner, and Hoffman [42]. The technique could be used to detect tendency to boil at one point in a reactor coolant system, but it would not detect tendency to boil elsewhere in the system.

Since sound waves produce variations in velocity, it is conceivable to make a detector that responds to rapid, small variations of velocity. In aerodynamics, for instance, a very sensitive flow-measuring device, called a hot-wire anemometer, has been used for this purpose [43]. At Argonne, a demonstration test was made to determine if boiling noise in water was detectable [44]. The results apply to boiling from a 1-1/2-in.-long, 30 AWG Nichrome wire in 20°C water. When immersed in a 50-cm-diam, 50-cm-deep cylindrical container, both a 100-kHz response hydrophone and the anemometer indicated boiling spectra with similar sound resonances, which agreed with calculated resonance frequencies of 5, 10, and 15 kHz. For the anemometer, the signal-to-noise level ratio was only 3-to-1 (10 dB) for a source-to-detector distance of 20 cm. The anemometer was able to detect 100-kHz signals, demonstrating that frequency response can be exceptionally high for this technique. Use of anemometers in LMFBR's is doubtful, however, since, for the necessary acoustic sensitivity, the measuring element would be extremely fragile.

B. HIGH-TEMPERATURE PIEZOELECTRIC BOILING DETECTOR

The method of acoustical measurement for acoustic boiling detection could be based on a high-temperature piezoelectric hydrophone, which, unlike other types of hydrophones, when immersed in liquid sodium will still retain a broad frequency response and fairly high sensitivity.

Table III lists piezoelectric materials applicable for high temperatures. The first line gives the Curie temperature (i.e., the temperature at which piezoelectric effects disappear). Note that only two materials, tourmaline and lithium niobate, are useful near 1000°F. The third line refers to crystallographic orientation of force and charge, and all coefficients listed below that line refer to the crystal orientation. The relative dielectric constant indicates how much charge capacity can be stored within a given size of crystal; the coupling coefficient gives a measure of the crystal efficiency in converting one form of energy to another (i.e., mechanical to electrical for a pickup). The piezoelectric charge coefficient gives the charge in coulombs per newton force applied to the crystal. Lastly, the piezoelectric voltage coefficient denotes the electrical field (V/m) per unit stress (N/m^2). The property definitions are described more completely in Goldman [45] and Frederick [46].

TABLE III. Properties of Piezoelectric Materials Useful above 200°C

Piezoelectric or Ferroelectric Material	*a* Quartz, X-Cut (SiO_2)	PZT-4 (Commercial preparations of lead zirconate-titanate)	PZT-5A	HDT-31	Lead Metaniobate, Pb $(NbO_3)_2$	Lithium Tantalate	Lithium Niobate	Tourmaline Z-Cut
Curie temp, °C	576	328	365	325	570	660	1210	~980
Max useful temp, °C	550	200-250	250-290		500		Transducer operated at 1050°C	
Mode (crystal axes)	11	33	33	33	33	33	33	33
Relative dielectric constant	4.5	1200-1300	1500-1700	1300	225	43	29	7.1-7.5
Coupling coefficient, %	11	64-70	68-70	65	38-39	33	30-50	
Piezoelectric charge coefficient (d), 10^{-12} m/V or C/N	2.3	256-289	320-374	260	85-290	8	6	1.83-1.9
Piezoelectric voltage coefficient (g), 10^{-3} Vm/N	58	24	24-25	23	13-37	21	23	

The choice of a piezoelectric material depends to a large extent on the application as well as on the environment. However, several conclusions can be made on the basis of material properties. Table III shows that lead zirconate-titanate excels in nearly all areas but temperature. The niobates and tantalates have moderate sensitivity; quartz and tourmaline have low sensitivity. For initial development of a high-temperature, high-sensitivity transducer, lithium niobate would be a logical material to use in view of its high Curie point and moderate sensitivity.

Background material on piezoelectricity and related ferroelectricity is available from many sources. As a basic reference, see the definitive treatises by Cady [47] and Mason [48]. For specific materials, see: (1) ferroelectric behavior of lithium tantalate by Matthias and Remeika [49]; (2) ferroelectricity of lithium niobate by Nassau and Levenstein [50]; and (3) the application to mechanical stress at radio frequencies for laser modulation by Spencer, Lenzo, and Nassau [51]. Further work along these lines was reported by Lenzo *et al*. [52].

Applications relevant to boiling-detector requirements were reported by Fraser and Warner [53]. They used a plate of lithium niobate crystal as a shear transducer mounted on a test specimen, and measurements were taken to 1050°C in an oxygen atmosphere. This material, if incorporated into an acoustic transducer, may enable monitoring within an LMFBR core environment.

In general, the design of any transducer requires a source of information on the various constants. This information is available for lithium niobate and lithium tantalate from the work by Warner, Onoe, and Coquin [54]; their results are included in Table III.

When ferroelectrics are irradiated in a nuclear reactor, anomalous voltage pulses can occur, as reported by Lefkowitz *et al.* [55]. Of the 80 samples exposed, 80% evidenced minor sensitivity, 5-10% major sensitivity, and the remainder no sensitivity to radiation. Lefkowitz *et al.* recommended that the applications be restricted to fuses and capacitor dielectrics. However, since organic constituents can cause some of those ionizing effects, inorganic constructions should be used in future irradiation tests.

C. CALIBRATION OF THE ACOUSTIC BOILING DETECTOR

Since the measurements will extend over a broad frequency range, the detector must be calibrated both statically and dynamically. Static calibration provides a precise, absolute measurement of the low-frequency pressure sensitivity. To perform the calibration, a static pressure is released suddenly to produce a step change in detector signal. The ratio of detector output signal to pressure is the sensitivity of the detector at zero frequency. This calibration procedure, called the closed-tank pressure-calibration technique [56], requires a pressure vessel, a hydrostatic pump, a pressure gauge, and a quick-opening valve.

Dynamic calibrations are necessary to determine the frequency response of the detector to sound waves. Sound calibrations are usually performed by the reciprocity-calibration technique [57,58]. Here, the hydrophone under test is compared against a reversible standard hydrophone (which can either transmit or receive sound) and against a sound projector. The liquid-filled container may be a long tube, a large acoustically baffled tank, or a deep pond.

IV. CONCLUSIONS

Operation and safety of future LMFBR's would be enhanced by adding to the instrumentation and control systems new devices for detecting boiling sodium within the core region. Acoustic methods can be fast and sensitive to detect boiling sodium by monitoring the mechanical energy produced by the growth and collapse of vapor bubbles. An acoustic-boiling-detection system is operational on the Dounreay Fast Reactor in Great Britain; however, acoustic boiling detection on U.S. water-cooled reactors has been hampered by excessive background noise. Studies are recommended to determine the amount of sodium boiling that can be detected successfully in the presence of prototype-reactor flow and pump noise.

Acoustic emissions from boiling in water systems contain characteristic frequency spectra corresponding to bubble-volume resonances, to container resonances, and to small-amplitude high-frequency components. The acoustics of boiling has a random-noise appearance, whose amplitude increases as the amount of boiling increases.

Technology exists for detecting boiling in a reactor by acoustic waveguides, which consist of rods or tubes extending from the core region out through vessel penetrations to a room-temperature environment. Thus, conventional vibration sensors can be attached to the upper ends of the waveguides. With the recent availability of a new, high-temperature man-made material, lithium niobate, acoustic sensors can be developed for immersion in reactor sodium, thus advancing still further the measurement capability of in-reactor instruments.

Based on these considerations, acoustic boiling detection is feasible in future LMFBR's, provided that boiling can be detected acoustically at a threshold far enough below conditions of irreversible overheating. Quantitative studies are still lacking on these decisive parameters for successful application of acoustic detection to boiling of sodium within an LMFBR core.

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