THE ACOUSTIC DETECTION OF BOILING IN THE
SODIUM LOOP SAFETY FACILITY IN-REACTOR EXPERIMENT P1

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BASE TECHNOLOGY

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NOMENCLATURE

C	Sonic velocity (m/sec)
d	Diameter (m)
$f_o; f_c$	Center frequency (Hz)
l, L	Length (m)
n	Integer constant
r, R	Radius (m)
s, S	Cross-sectional area (m^2)
t	Time (sec)
Δt	Time difference (sec)
T	Temperature ($^{\circ}C$)
ΔT	Temperature difference ($^{\circ}C$)
V	Volume (m^3)
λ	Wave length (m)

Abbreviations

ALIP	Annular Linear Induction Pump
CT	Components Technology
ETR	Engineering Test Reactor
FTR	Fast Test Reactor
LOPI	Loss of Piping Integrity
RAS	Reactor Analysis and Safety
RTA	Real Time Analyzer
SLSF	Sodium Loop Safety Facility

ABSTRACT

Acoustic data were obtained from two high-temperature lithium niobate^{1,2} microphones on the loop background noise and transient pressure pulses during the Sodium Loop Safety Facility (SLSF) P1 in-reactor experiment.^{3,4} This experiment simulated an LMFBR loss-of-piping-integrity (LOPI) transient on a nineteen element, end-of-life, enriched-UO₂ fuel assembly. Experimental conditions required that all sensors be capable of operating at an elevated temperature in a sodium environment with internal sensor pressures of 1.4 MPa. Lithium niobate transducers normally require oxygen venting; however, pre-thermal conditioning and oxygen impurities in the helium were sufficient to enable the transducers to function for a period exceeding ninety days. During this period of time, the microphones were exposed to liquid sodium at a distance 4.85 meters above the reactor core at temperatures between 315° and 590°C. The distance and location of the microphones in the P1 Test Train provided an attenuative transmission path which was undesirable for optimum acoustic detection of sodium boiling and fuel failure. The data gathered on the loop background noise was observed to be dominated by pump and electrical noise at frequencies below 1.5 KHz and appeared to be dominated by flow induced local turbulence noise at higher frequencies. During the four low-power transients, acoustic events were observed to occur within 1 sec after the annular linear induction pump (ALIP) power trip and after 3 sec. These events appear to be the result of control rod motions. During the final 130 MW loss-of-piping-integrity (LOPI) transient, a ringing mechanical sound was observed with a peak-to-peak pressure of 30 kPa. During the period of time that the sodium in the fuel assembly was at its saturation temperature 943°C (1730°F), as indicated by the wire wrap thermocouples, several discrete pulses were observed

with peak-to-peak pressure between 3.3 kPa and 7.9 kPa and center frequencies between 360 and 550 Hz. The pulses occurred at two separate gradually increasing repetition rates. These observations appear to be consistent with the result of an impulsive forcing function interacting with a band passed Helmholtz resonator. These data are consistent with the hypothesis that sodium boiling occurred in the P1 fuel assembly, resulting in the formation of individual voids that collapsed upon reaching the subcooled sodium. These data provide pertinent information regarding the feasibility of sodium boiling detection and may provide additional insight into the dynamics of the void behavior.

1.0 Introduction

This report represents a continuation of a series of studies performed by the Acoustic Surveillance Group of the Components Technology Division (CT) on several safety oriented experiments being conducted by the Reactor Analysis and Safety Division (RAS).

The Acoustic Surveillance Group has as its prime objective the development of acoustic surveillance methods, transducers and instrumentation for Liquid Metal Fast Breeder Reactors (LMFBRs). In particular, the subject of boiling detection in an LMFBR is being addressed. To assess the feasibility of boiling detection, one needs a firm understanding of the characteristic sounds associated with bubble collapse, the reactor ambient noise background and the transmission properties of the particular system being considered. The Sodium Loop Safety Facility In-reactor P1 Experiment was conducted from the Acoustic Surveillance point of view to obtain data pertinent to the understanding of sodium boiling and the sounds produced during bubble collapse.

The SLSF in-reactor experiments are being conducted by the ANL/RAS division in response to the needs and priority safety problems of the LMFBR program³. These experiments are designed to provide data under realistic conditions on the behavior of fast reactor fuel elements and subassemblies during postulated off-normal or hypothetical accident scenarios. The P1 experiment was the first in a series and had as its primary objective the verification of loop and component performance, loop qualification and the calibration of loop analytical models. This particular experiment was a simulation of the behavior of a nineteen pin enriched-UO₂ fuel pin assembly under a loss-of-piping-integrity scenario.

In this report, the acoustic data acquisition and analysis are presented. By analysis, the characteristics are determined for sodium vapor bubble sounds observed in the P1 experiment. The report is organized to present an overview

of the experiment, a summary of the experimental results, a discussion of the results and a concise summary and presentation of conclusions.

The authors of this report acknowledge the valuable and additional work of Pete Gavin, Dean Pedersen, and John Janicek for their work in fabrication, calibration and testing of the high temperature microphone used during this experiment.

2.0 Description of the Experiment^{3,4}

This section of the report shall provide an overview of the overall SLSF in-reactor P1 experiment. The SLSF in-reactor P1 experiment was conducted in the Engineering Test Reactor (ETR) at the Idaho National Engineering Laboratory. The SLSF P1 loop is schematically illustrated in Fig. 1. This loop is a doubly contained concentric design. Sodium flow is controlled by the annular linear induction pump (ALIP). The sodium flow is down through the helium heat exchanger and then through an outer annulus to the bottom of the loop. The flow continues back up through the bypass annulus and the fuel subassembly. This bypass flow and primary flow are then recombined and flow proceeds to the upper plenum. Also shown on this schematic are the approximate locations of the acoustic sensors, in the mixed mean flow stream 4.85 meters above the reactor core, midplane.

The P1 experiment consisted of a test subassembly with a double wall hex can (inside across-flats dimension of 3.245 cm (1.287 in.) housing nineteen full-length, wire wrapped FTR fuel elements. These fuel elements were arranged in a standard triangular grid with U-235 enrichments of 93% for the center element, 86% for the six elements in the second row and 72% for the twelve elements in the third row. This enrichment variation was to ensure that a flat radial power distribution existed. The spacing of the inner rows of fuel pins was accomplished by using 1.42 mm (0.056 in.) dia. wire wrap spacer wire. Each wire wrap spacer contained a thermocouple. The outer row of twelve pins was wire wrapped with .71 mm (.028 in.) dia. spacer wires with thermocouples. This was to maintain a hex can to fuel pin spacing of .71 mm (.028 in.), and reduce coolant flow streaming at the element shroud interface. The element spacing between the third and second rows was accomplished by the use of sleeves at appropriate locations. Furthermore, radial heat transfer through the hex can to the bypass flow wall was minimized by a 3.175mm (0.125 in.) argon-filled

FIG. 1 SLSF P1 Test Loop Schematic

gap between the concentric hex cans. This also ensured a flattened radial temperature distribution across the subassembly. The design of this test section was thus intended to simulate fuel element radial surface temperatures, radial sodium temperatures, and radial flow distribution typical of the uniform conditions expected in the center of an FTR fuel subassembly. Shaping of the ETR flux in the SLSF portion of the core was also done to produce a typical axial power and temperature profile within the test section. Finally, the test section above and below the core region was designed to have FTR prototypic hydrodynamic resistances.

2.1 The SLSF P1 Acoustic Data Acquisition

During the SLSF P1 experiment, the acoustic portion of this experiment involved the acquisition of flow, temperature, neutron level, ALIP power and acoustic data.

Flow data was obtained for the inlet of the fuel bundle, the outlet of the fuel bundle, and the total test section flow.⁴ The fuel bundle inlet flowmeter was a permanent magnet flowmeter while the outlet and total flow were of the eddy current type. All three sensors were recorded on calibrated strip chart recorders and the fuel bundle outlet flowmeters were recorded on the wideband Bell and Howell CPR 4010 tape recorder.

Thermocouple data were recorded from the fuel bundle inlet sensor, fuel bundle outlet sensor and the mixed mean temperature sensor. These data were recorded periodically on magnetic tape as well as continuously on calibrated strip chart recorders.

Five fuel subassembly wire wrap thermocouples were also recorded on the RAS analog backup tape system and final transient results were plotted out on a calibrated strip chart. In addition to these parameters, the ETR neutron level sensor and the ALIP, pump power (KW) was monitored. Finally, the outputs of the two ANL high temperature lithium niobate microphones were amplified with

Endevco 2730 charge sensitive amplifiers. The charge sensitive amplifiers were used with a high pass 200 Hz filter and exhibited a flat response to 33 KHz. These acoustic signals were redundantly recorded on a CPR-4010, Bell and Howell tape recorder. Tape recordings were made at 60 IPS with wideband Group 1 FM channels and wideband direct channels.

Calibration data furnished by the RAS research group were utilized on all except the acoustic sensors. These sensors were calibrated prior to the test in a standard navy G-19 calibrator. Calibration of the charge sensitive amplifiers was accomplished with an oscillator and a 1000 pf capacitor. Calibrations on all strip chart recorders were periodically checked. The CPR4010 tape recorder was calibrated at the ETR and calibration signals placed on each magnetic tape. In all instances, data obtained in this experiment can be referenced to a calibrated value.

During the ninety days of testing, comparisons of the acoustic sensor broad band responses were made for a variety of flow, temperatures, and sensor shunt resistances. While a post calibration of the microphones was not possible, the response of the microphones during the test was not observed to change appreciably.

In summary, data necessary to determine the flow, temperature, and acoustic levels in the SLSF P1 test loop were obtained.

2.2 Experimental Scope

The SLSF in-reactor P1 experiment consisted of a series of steady state tests, thermal-hydraulic tests, natural circulation tests, decay heat source test, low-power transient test and the final LOPI transient.

While these tests were primarily performed by RAS to verify loop performance, calibrate loop models and evaluate sensor performance, the acoustic group obtained data during each major testing sequence. The purpose of this data acquisition was to provide an understanding of the acoustic background noise of the loop and to evaluate the response of the ANL/CT high temperature microphones. Thus, the acoustic portion of this experiment was the observation of each major loop checkout test to obtain the acoustic characteristics of the P1 test loop under a variety of flow, temperature and reactor power conditions. In particular, low-power transients were observed to provide acoustic characteristics of the transients which could be the basis of comparison for the high power LOPI transient.

3.0 Experimental Results

During the P1 test, data were obtained continuously on twelve channels of strip chart recorders and on a fourteen-channel wideband magnetic tape recorder. The data recorded were the outputs from the two acoustic sensors, the inlet, outlet, and total flowmeters, the ALIP power, five wire wrap thermocouples, and the mixed mean thermocouple and the ETR neutron sensor. The acoustic data were redundantly recorded to insure a wide dynamic range and band width. This section shall summarize the results of this data acquisition and analysis and shall concentrate on that experimental data pertinent to sodium boiling detection.

The loop background noise was characterized as a function of flow and the variance of the broadband levels established. Table I represents a summary of the four non-boiling transients and the final 130 MW transient. Only during the last transient (the loss-of-piping transient) did temperatures observed by the wire wrap thermocouples reach the saturation temperature of the sodium. In each transient, the test sequence called for a reduction in flow by tripping the ALIP power followed by an ETR scram. Broadband acoustic levels were observed to decrease by 10 dB after the flow coastdown. This noise background was composed of pump and electrical noise below 1 kHz and was dominated by local turbulent effects at higher frequencies. No acoustic evidence was observed which could be attributed to rubbing or loose components. In the first transient, spurious signals were observed on microphone PE9-1 which appear to be of an electrical nature. During the five transients, acoustic events were observed to occur within 1 sec after the linear induction pump power trip and after 3 sec which appear to correspond with control rod motions.

The second 30 MW transient which occurred on October 30, 1975, is illustrated in Fig. 2. This figure is a real time strip chart recording of the actual transient. The ALIP pump power provides a clear indication of the beginning of

TABLE I
P1 TRANSIENT SUMMARY

	Nonboiling Transient 1	Nonboiling Transient 2	1st 30 mw Transient	2nd 30 mw Transient	130 mw Transient
ALIP (kw)	95 to 10	95 to 10	100 to 1	100 to 5	82.5 to 5
Bundle Flow (gpm)	40 to 10.5	40 to 16.85	40 to 6.5	41 to 8	38 to 9
Wire wrap max temp. °F	1150°F	1015°F	1100°F	1150°F	1730°F
Δt (sec)	1.00 sec	1.08 sec	1.32 sec	1.6 sec	1.3 sec
ETR Scram Δt (sec)	0.53	0.58	0.54	0.60	0.52
Acoustic be- fore/after dB re μPa	170/160	170/160	170/160	169/160	175/165
Evidence of rod drop	X	X	X	X	X
Spurious spikes on one channel	PE9-1	--	--	--	--
Boiling	No	No	No	No	Yes
Flow coast- down pressure pulse	No	No	No	No	Yes
High frequency sounds	No	No	No	No	Yes

Fig. 2 Second 30mw Transient October 30, 1975, Real Time Recording, Bandpass 1.2 to 40 kHz

the flow coastdown. The reduction in pump power is followed by a decrease in flow as illustrated by the inlet flowmeter trace. Due to the decay heat, the wire wrap temperature experienced a modest rise to 546°C (1015°F) approximately 1.08 sec after the ALIP power trip and 0.4 sec after the ETR scram. Due to the mildness of this transient the mixed mean temperatures show virtually no variation. Also shown in the figure is the strip chart recording of the logarithmic RMS broad-band (1.2 to 40 KHz) acoustic output. Both acoustic sensors were observed to respond to the change in the local turbulence noise field that resulted from the flow reduction. Also shown are several small irregularities prior to 1 sec and after 3 sec from the beginning of the transient. These irregularities are considered to be associated with ETR control rod motions. The first is coincidental with the ETR scram. This transient was typical of the other three non-boiling transients and is included here as a basis of comparison for the LOPI transient.

The analogous real time recording for this LOPI transient is illustrated in Fig. 3. As in the simulated 30 MW transient the ALIP power trip indicates the beginning of the transient and is followed by the inlet flow reduction. At 0.5 sec following the ALIP power trip the reactor was scrammed and at approximately 0.8 sec after the scram the sodium, as observed by a wire wrap thermocouple (TE5-5), reached a saturation temperature of 943°C (1730°F). This is illustrated by the flat top of the TE5-5 thermocouple trace. Note that the mixed mean temperature of the sodium at the microphones does not increase. The two acoustic broadband (1.2 K to 40 kHz) RMS logarithmic outputs showed appreciable acoustic energy coincident with the flow coastdown, weak indications of control rod motions (before 1 sec after 3 sec) and a weakly observed (via a loud speaker) boiling event. The immediate concern with these data was that the audible indication of boiling was much clearer than the real

Fig. 3 Final Transient November 7, 1975, Real Time Recordings, Bandpass 1.2 to 40 kHz

time trace.

As the acoustic output was being averaged with a logarithmic converter which has a response time of approximately 50 millisecc, these data were played back at a slower speed thus effectively decreasing the frequency of occurrence of the events by a factor of four. The playback is illustrated in Fig. 4. The net decrease in response time of the system enables one to clearly show that acoustic energy was observed during the period of time (0.8 sec) that the wire wrap thermocouple indicated that sodium boiling had occurred.

The acoustic data obtained in this test were analyzed in the following manner. Peak hold spectra before, during, and after the transient were obtained to determine the bandpass of optimum signal to noise ratio. The data were bandpassed and examined with a selective amplifier, square law detection scheme, and a tuned filter. Both detectors were examined simultaneously and coincident pulses of sounds were identified with the ALIP power trip and during that period of time that the sodium in the fuel bundle was at its saturation temperature. These individual pulses of sound were then subjected to a transient analysis. Transient power spectra and real time photographs were examined to determine pulse bandwidth, center frequency, ring down time, and the optimum bandpass for the test signal to noise ratio. The results of this analysis are summarized in Fig. 5. Here shown on one plot is the acoustic intensity in the 300 to 900 Hz bandpass, the real time pressure fluctuation in this bandpass and the variations of pump power, inlet flow and wire wrap thermocouple variations with time.

This summary clearly indicates that boiling occurred in the LOPI transient at 1.3 sec after the ALIP power trip, that discrete acoustic pulses were observed during this period of time and that ample signal to noise ratio existed for the identification and characterization of these pulses. Also shown in Fig. 5 are enlargements of the first pressure pulse and one of the boiling pulses.

Fig. 4 Final Transient November 7, 1975, Playback at 15 IPS, Bandpass 1.2 to 40 kHz

Fig. 5 The SLSF LOPI, Acoustic Experiment Summary

The pulses are also shown in more detail in Figs. 6 and 7. Referring to Fig. 6, one observes the obvious damped mechanical ringing characteristic of this pulse. The ringing serves to identify the pulse as being a real mechanical phenomenon. Transient analysis of this pulse revealed that the peak-to-peak pressure was 33.5 kPa and center frequency was 531 Hz. As the pulse of sound was associated with the beginning of the flow coastdown, one might expect that it is related to a weak sodium hydraulic hammer effect. However, no appreciable difference in the flowmeter responses were observed.

Fig. 7 illustrates one of the eleven observed pulses coincident with the wire wrap thermocouple indication of sodium boiling. The characteristic of a bandpassed damped resonator is readily apparent and was observed in all bubble collapse pulses. The data have been bandpassed in the 300 to 900 Hz band to improve the signal-to-noise ratio. Referring to Fig. 8, one observes in the background spectra before the transient and after the transient a strong 1 kHz band which was a loop characteristic. As both the initial pulse and bubble collapse pulses are broadband with a decrease in acoustic energy above 1 kHz, and as appreciable noise existed in the background spectra below 300 Hz, the 300 to 900 Hz bandpass was chosen. Based on these considerations and the coincident output of the RTA (SD 301 D) used as a tuned filter with a bandwidth of 150 Hz, center frequency of 450 Hz and integration time of .01 sec, eleven individual bubble collapse sounds were identified as shown in Fig. 9 and Table II.

These results may be summarized by saying that wire wrap thermocouples were observed to indicate that sodium at the top of the fuel pin assembly reached its saturation temperature of 943°C (1730°F) at 1.3 sec after the ALIP power trip and 0.8 sec after the ETR scram. This flat top condition was observed to last for

FIG. 6 THE COINCIDENT PRESSURE PULSE WITH ALIP POWER CUTOFF

FIG. 7 BAND PASSED (300 Hz to 900 Hz) REAL TIME ACOUSTIC SIGNAL BETWEEN 1.560 AND 1.660 SEC FROM THE ALIP POWER TRIP, A REPRESENTATIVE COLLAPSE PULSE.

FIG. 8 PEAK HOLD SPECTRA OF THE SLSF P1 LOPI TRANSIENT

a. Sensor PE9-1

b. Sensor PE9-2

Fig. 9 RTA Filter (Center Frequency 450 Hz, Bandwidth 150 Hz, analysis time .01 sec) Output Versus Time

0.8 sec and was observed on a sufficient number of wire wrap thermocouples to establish that boiling encompassed the center seven fuel pins. The axial extension of this boiling is not know. However, during this period of time the two acoustic sensors observed eleven discrete sound pulses which had peak-to-peak pressures between 3.3 and 7.9 kPa with center frequencies between 364 and 548 Hz. Furthermore, these pulses had characteristics of a bandpassed resonator and appeared at regular alternating times which gradually increased as the heat flux and temperature dropped. These data are consistent with the premise that sodium vapor collapsed in the upper portion of the fuel pin assembly.

4.0 Discussion of the Results

As previously discussed, data obtained during the SLSF in-reactor P1 experiment are consistent with the fact that the boiling occurred and sodium vapor voids formed and collapsed. During the LOPI transient, eleven pulses were observed between 1.297 and 1.987 sec after the initiation of the flow coastdown; during this period of time, wire wrap thermocouples indicated that sodium within the fuel subassembly had reached a saturation temperature of 943°C (1730°F) and that boiling had occurred. The sound pulses attributed to bubble collapse are listed in Table II and indexed 1 through 11. These pulses were all observed to have a characteristic shape with center frequencies between 364 and 548 Hz. The pulses also appear at gradually increasing repetition times of .03 and .06 sec, with no apparent amplitude relation.

The acoustic data are consistent with the hypothesis that a fast rise time impulse is produced during a bubble collapse and that this impulsive forcing function is then multiplied by the dynamic transfer function of the test loop; thus, the experimental observations must reflect this transfer function. The acoustics of the SLSF test loop were determined by the specification of a free surface boundary condition in the upper plenum and a fixed boundary condition in the lower melt cup. Between these two regions the effective mechanical impedance (ρCs) was determined as a function of loop elevation. The resulting schematic is shown in Fig. 10. The fuel assembly, bypass, and down comer annulus appear as a constriction just ahead of the melt cup region. This constriction and small volume have the characteristic shape of a Helmholtz resonator. The analysis of this segment of the loop may be accomplished by the use of a lumped parameter model as long as the length is less than a wave length of sound. Thus, the volume V is connected to a small diameter tube of length l

TABLE II

ACOUSTIC DATA SUMMARY

Pulse No.	Δt_o , sec	Δt_{p-p} , sec	P_{p-p} , m bars	f_o , Hz	SL* dB re μ bar	SL* dB re μ Pa
0	0		335+8	531	105	205
1	1.297		46+7	364	87	187
2	1.327	.030	33+2	364	84	184
3	1.387	.060	56+8	414	89	189
4	1.417	.030	71+9	405	91	191
5	1.472	.055	56+16	548	89	189
6	1.502	.030	39+5	379	86	186
7	1.582	.080	79+5	386	92	192
8	1.602	.020	68+6	394	91	191
9	1.672	.070	41+7	471	86	186
10	1.677	.005	63+6	500	90	190
11	1.987	.310	44+3	400	87	187

*Rounded off to the nearest dB.

FIG. 10 THE ACOUSTIC SCHEMATIC OF THE SLSF P1 TEST LOOP

and cross sectional area S which has a resonant frequency defined as follows:

$$f = \frac{C}{2\pi} \sqrt{\frac{S}{\ell V}} \quad \text{where} \quad \begin{array}{l} \ell < \lambda \\ d \ll \lambda \end{array}$$

This resonant condition arises from the stiffness of the volume combined with the inertance of the fluid within the tube to produce the lumped parameter resonator. The calculation performed on this loop yields resonant frequencies of between 400 and 550 Hz. These calculations are based on the premise that the resonator sees a large open space, and as this is not actually the case, some modifications to the resonance observed should be expected. Nevertheless, the calculated resonance frequencies are close to those from the acoustic observations. The upper part of the loop, as shown in Fig. 10, has expansions and contractions in the cross-sectional area and consequently has a variation in the mechanical impedance of the loop as a function of elevation. This 4.9m section of the loop resembles a classical low pass filter. This problem has been solved for the case of repeated volumes (expansions) and lengths (constrictions). Although the case presented here is not an even repetition of equal volumes and lengths, it is interesting to estimate the cutoff frequencies from such a filter. These cutoff frequencies for interconnecting tubes of length (ℓ) and cross-sectional area (S) with expansions of volume (V) may be determined by

$$f_c \doteq \frac{1}{\pi} \sqrt{\frac{C^2 S}{\ell V}}$$

For the case of the P1 test train one calculates cutoff frequencies between 1.6 and 2.2KHz depending on the representative volume and length sizes. An exact analysis will not be attempted as it is sufficient to say that with this kind of a structure the higher frequency components associated with the bubble collapse will be severely attenuated. The calculated cutoff frequencies are consistent with the fact that little data was observed above 1.5kHz.

Finally, the microphones are located approximately 1.28 meters below the free surface in the upper plenum, corresponding to a distance of $\lambda/4$ at a frequency of 458 Hz. It is reasonable to assume that the output of the damped band-passed resonator is added to the inverted reflection off the free surface to modify the wave form as observed by the microphone.

The conclusion of this discussion is that the data are consistent with this model: an impulsive bubble collapse (forcing function) interacted with the test loop (which behaved as a damped Helmholtz resonator and a low pass acoustic filter). The subsequent observations by a microphone located at a distance $\lambda/4$ below a free surface results in the characteristic shapes observed.

The analysis will next include the consideration of standing wave resonance, acoustic reflections and coupled fluidic - elastic propagations. The relationships for closed and open tubes are $f = nc/4l$; $nc/2l$. The data in this instance are at the most 1.5 cycles in duration and at 400Hz one would require at least 2.5 cycles. Thus it is unlikely that a standing wave resonance would explain these results especially in the absence of higher harmonics.

As the data are observed to have a somewhat regular appearance, the question as to whether these pulses could represent acoustic reflections was considered. The traversal time of the loop by the acoustic pulse is of the order of milliseconds and for collapses occurring near the top of the fuel assembly one would expect arrivals at 2.3, 4.9, 9.4, and 12 milliseconds respectively. These times are much less than the repetitive 30 and 60 millisecond time intervals observed. Furthermore the data do not show a series of pulses with decreasing amplitudes representative of reflected signals.

Finally, one possible explanation could be that the acoustic pulses are travelling at a propagation velocity less than the speed of sound. Coupled

propagations can exist between thin walled elastic cylinders and fluids.

However, for stainless steel and sodium these propagation velocities are high (3×10^3 FPS) and cannot explain this distribution of pulse arrivals and amplitudes. Thus, the conclusion of this analysis is that without doubt there are eleven discrete observations associated with bubble collapse phenomena.

During the LOPI transient, the wire wrap thermocouples 30 cm above the fuel midplane gave indications that the sodium had reached its saturation temperature. The fuel bundle outlet thermocouple did not reach the saturation temperature; thus, the maximum length of a sodium void may be taken as the distance to the outlet thermocouple (144.15 cm) while the minimum length may be taken as the height of the wire wrap thermocouples that observed the saturation temperature (6 cm). As wire wrap thermocouples indicate that boiling encompassed the seven center pins of the nineteen pin fuel assembly, the maximum radial extent is taken as coverage of the center seven pins, while the minimum radial extent is the annular area between the center pin and the first row of six pins. Thus the minimum and maximum void volumes and equivalent spherical bubble ratio may be estimated as follows:

$$\begin{array}{rclcl}
 11.94 \text{ cm}^3 & \leq & V_{\text{bubble}} & \leq & 288 \text{ cm}^3 & \text{seven pins} \\
 (1.4 \text{ cm}) & \leq & r_{\text{bubble}} & \leq & (4.1 \text{ cm}) & \\
 \hline
 2.39 \text{ cm}^3 & \leq & V_{\text{bubble}} & \leq & 57 \text{ cm}^3 & \text{center pin} \\
 (.98 \text{ cm}) & \leq & r_{\text{bubble}} & \leq & (2.4 \text{ cm}) &
 \end{array}$$

Judd (1967, 1968)^{6,7} has done some interesting calculations on the growth and collapse of sodium vapor bubbles at low super heats. Below are some representative growth times to a particular radius with the corresponding initial bubble super heat.

$$\begin{array}{l}
 \Delta t = .03 \text{ seconds} \quad \left\{ \begin{array}{ll} \Delta T_{si} = 5^{\circ}\text{C} & r_b = 0.5\text{cm} \\ \Delta T_{si} = 10^{\circ}\text{C} & r_b = 1.3\text{cm} \\ \Delta T_{si} = 20^{\circ}\text{C} & r_b = 2.5\text{cm} \end{array} \right. \\
 \\
 \Delta t = .06 \text{ seconds} \quad \left\{ \begin{array}{ll} \Delta T_{si} = 5^{\circ}\text{C} & r_b = 1\text{cm} \\ \Delta T_{si} = 10^{\circ}\text{C} & r_b = 1.9\text{cm} \\ \Delta T_{si} = 20^{\circ}\text{C} & r_b = 3.6\text{cm} \end{array} \right.
 \end{array}$$

As collapse times are short compared to bubble growth times, one may qualitatively say that the observed repetition of the pulses associated with bubble collapse during the SLSF P1 transient are consistent with the growth rates one might expect at low superheats in the range of possible bubble volumes.

Judd^{6,7} calculated for a bulk sodium temperature of 750°C (1382°F), a vapor saturation temperature of 880°C (1616°F), 130°C subcooling at one atmosphere of pressure, the following acoustic energy in the collapse of vapor bubble:

R_b	E_{AC}	Potential Energy
1 cm	.09 Joules	0.42 Joules
3 cm	1.6 Joules	11.3 Joules
10 cm	18.2 Joules	420 Joules

This corresponds to a collapse of a bubble in 130°C subcooling at one atmosphere of pressure. During the LOPI transient the bulk sodium temperature as observed by the bundle outlet thermocouple was 682°C and the sodium saturation temperature was 943°C. The observed energy in the acoustic pulses associated with bubble collapse were found to range between 1.4 and 8 millijoules with an average energy of 4.25 millijoules. These energies cannot be directly compared with Judd's calculation; nevertheless, their reasonableness is apparent from this comparison, where the effective 600 Hz bandwidth is considered.

5.0 Summary and Conclusions

During the SLSF in reactor P1 experiment, a loss of piping integrity experiment, eleven individual sodium vapor bubble collapse pulses were observed. The detection of these pulses was verified by wire wrap thermocouple indications that boiling had indeed occurred. These pulses were characterized by their peak acoustic pressure, their center frequency, bandwidth and rate of occurrence.

The observed data were found to be consistent with the product of an impulsive forcing function and the dynamic transfer function of the loop. This was established by performing a lumped parameter modeling of the P1 test loop.

The rate at which collapses occurred was found to be consistent with the approximate growth times to produce sodium vapor in the gross regions defined by wire wrap thermocouple observations.

The observed acoustic energy observed during this experiment was also found to be consistent with bubble collapses of equivalent volume under slightly different thermodynamic conditions, when the 600 Hz analysis bandwidth is considered.

The characteristics of the collapse sounds and the transfer function of the loop were accomplished and sound source levels between 186 and 192dB re μ Pa were observed. The conclusions to be drawn from this experiment are that the observations of bubble collapse phenomena in experiments such as this one may be useful to the determination of sound source levels associated with realistic accident scenarios only if one can interpret the product of the impulsive forcing function and the dynamic transfer function. Furthermore, bubble collapses that occur in an operating LMFBR fuel subassembly will produce a sound pulse which is the product of the collapse impulse and the subassembly/reactor plenum transfer function. If in experiments such as the SLSF P1 experiment one can demonstrate an ability to describe analytically this process, then one may be able to extrapolate these results to a realistic reactor geometry.

A qualitative approach to this problem has been demonstrated in this experiment. Furthermore, the P1 experiment again demonstrates that sufficient acoustic energy is available in the collapse process to enable one to detect boiling providing that additional noise sources can be accounted for. The scenario observed in this experiment produced eleven large bubbles which collapse at low repetition rates of .03 and .06 sec respectively. Cavitation on the other hand produces small bubble collapses in a rapid but random manner. For accident scenarios such as the loss of piping integrity, this rate of occurrence may provide a means for differentiating between these two phenomena. Finally, it is to be concluded that for accident scenarios such as those which produce pulses of sound as the result of the collapse of bubbles in 2.39 cm^3 to 288 cm^3 with a slow repetition rate, neutronic/acoustic cross correlation may be an important and valuable tool.

APPENDIX A

DATA APPENDIX

APPENDIX A

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Fig. A1 Real Time Acoustic Data Band Passed 300 to 900 Hz Between
.05 Seconds After Trigger to 1.05 Seconds

Fig. A2 Background Noise Real Time Signals Band Passed 300 to 900 Hz,
Between 0.5 and 1.5 Seconds After Trigger.

Fig. A3 Real Time Acoustic Signals Band Passed 300 to 900 Hz
Between 1.0 and 2.0 Seconds After Trigger.

Fig. A4 Band Passed (300 to 900 Hz) Background Signals from PE9-1 and PE9-2 Between 2.2 and 3.2 Seconds

Fig. A5

PE9-1 Acoustic Sensor, 1.3 sec After Beginning of Transient.
 a. Real Time Waveform, b. Tuned Filter Output Center Frequency 450 Hz,
 Bandwidth 150 Hz. Analysis time .01 Sec. (Delay Time From Trigger Pulse
 is 1.3 sec.)

Fig. A6 Sensor PE9-2, a.) Real Time Acoustic Signal Band Passed 300 to 900 Hz, b.) Tuned Filter Output, Center Frequency 450 Hz, Bandwidth 150 Hz, analysis time is .01 sec

Fig. A7 Tuned Filter (Center Frequency 450 Hz, Bandwidth 150 Hz, analysis time .01 sec) Output Versus Time

Fig. A8 First Pressure Pulse Observed at 175 Millisecond After Trigger, Band Passed (300 to 900Hz)

Fig. A9 Band Passed (300 to 900 Hz) Real Time Acoustic Signal Between 1.5375 sec and 1.6375 sec.

Fig. A10 Band Passed (300 to 900 Hz) Real-Time Acoustic Signal Between 1.60 and 1.70 sec

Fig. A11 Band Passed (300 to 900 Hz) Real Time Acoustic Signals Between 1.725 Second and 1.825 Second

Fig. A12 Band Passed (300 to 900 Hz) Real-Time Acoustic Signals Between 1.80 and 1.90 sec

Fig. A13 Sensor PE9-1, a) Broad Band Channel Number 9 Band Passed 300 to 900 Hz, Tuned Filter Output with Center Frequency 450, Bandwidth 150 Hz), b) Band Passed (1.2 kHz to 40 kHz) Channel #5, Tuned Filter Output, Center Frequency 450, Bandwidth 150 Hz.

Fig. A14 High Frequency Tuned Filter Output. Center Frequency 1350 Hz, Bandwidth 150 Hz.

APPENDIX B: Units, Dimensions and Conventions

This report utilizes the recently adapted international system of units. Several of the more important of these units are tabulated as follows:

Quantity	Name	Symbol	Expression	Dimensions
Frequency	Hertz	Hz		s^{-1}
Force	Neutron	N		$m \cdot Kg \cdot s^{-2}$
Pressure	Pascal	Pa	N/m^2	$m^{-1} \cdot Kg \cdot s^{-2}$
Energy	Joule	J	$N \cdot m$	$m^2 \cdot Kg \cdot s^{-2}$
Power	Watt	W	J/s	$m^2 \cdot Kg \cdot s^{-3}$

Thus the standard reference acoustic pressure used this report is the μPa (10^{-6} Pa). The pascal is equal to 10^{-5} atmospheres or 10^{-5} bars. Secondly, pressures in this report are referred to as source levels referenced to 1 μPa . This dB notation may be explained as follows:

The acoustic intensity level of a sound of intensity I referenced to an intensity I_0 is

$$\text{Intensity level (dB)} = 10 \log(I/I_0)$$

As for plane waves this intensity is proportional to the acoustic pressure (P) squared, one has a sound pressure level or sound level as follows:

$$\text{Sound pressure level} = 10 \log(I/I_0) = 20 \log(P/P_0)$$

If one chooses the μPa as the reference pressure level, then a peak pressure of 1 ATM = 10^5 Pa results in a sound pressure level of

$$SPL = 20 \log(10^5 Pa / 1 \mu Pa) = 220 \text{ dB re } \mu Pa.$$

To aid in the interpretation of these quantities referenced to 1 μPa Table B-I is presented.

TABLE B-I: dB Conversion Table

P (ATM)	dB re Psi	dB re μb	dB re dyne/cm ²	dB re μPa
10	43.35	140	140	240
1	23.35	120	120	220
10 ⁻¹	3.35	100	100	200
10 ⁻²	-16.65	80	80	180
10 ⁻³	-36.65	60	60	160
10 ⁻⁴	-56.65	40	40	140
10 ⁻⁵	-76.65	20	20	120
10 ⁻⁶	-96.65	0	0	100

REFERENCES

1. A. P. Gavin and T. T. Anderson, *High Temperature Acoustic Sensors for Boiling Detection*, IEEE Trans. Nucl. Sci. NS-18C11, February 1971.
2. A. P. Gavin, T. T. Anderson and J. P. Bobis, *Irradiation of Microphones in the EBR-II Core*, ANL-CT-76-20, May 1976.
3. C. H. Gartside, W. A. Bezella and D. H. Lennox, *Research Program for the Sodium Loop Safety Facility*, Transactions, 1976 Annual Mtg., Toronto, June 14-18, 1976, p. 319.
4. J. E. Herceg, R. D. Pierce, T. T. Anderson, et. al., *Sodium Loop Safety Facility In-Pile Experiment P1*, Transactions, 1976 Annual Mtg., Toronto, June 14-18, 1976, p. 319.
5. I. T. Hwang, P. Y. Wang and J. H. Tessier, *Heat Transfer for the SLSF P1 Hexcan*, Transactions, 1976 Annual Mtg., Toronto, June 14-18, 1976, p. 321.
6. A. M. Judd, *Sodium Boiling and Fast Reactor Safety Analysis*, AEEW-R-561, 1967.
7. A. M. Judd, *The Condensation of Sodium Vapor Bubbles*, AEEW-R-813, May 1968.