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AN INTERIM REPORT ON THE FEASIBILITY
STUDY OF ACOUSTIC LEAK LOCATION FOR
WTD STEAM GENERATORS

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SUMMARY

1.0 INTRODUCTION

- 1.1 Objective of Study
- 1.2 Program Plan
- 1.3 Organization of Report

2.0 WTD STEAM GENERATOR DESIGN DESCRIPTIONS

- 2.1 Intermediate "A" Steam Generator Design
- 2.2 Low Temperature Steam Generator Design
- 2.3 Operating Conditions During Location
- 2.4 Design Changes

3.0 RESULTS OF ANALYTICAL STUDIES

- 3.1 Geometric Effects
- 3.2 Localization Criteria
- 3.3 Jet Noise
- 3.4 Electronic Hardware Design Criteria
- 3.5 Portable System
- 3.6 Ultrasonic Leak Location

4.0 RESULTS OF EXPERIMENTAL INVESTIGATIONS

- 4.1 Accelerometer and Attachment
- 4.2 Array Geometry Limitations
- 4.3 Gas Injection Noise Powers

5.0 ASSESSMENT OF RESULTS

- 5.1 Major Conclusions from Analytical Tasks
- 5.2 Areas of Concern and Methods for Resolution
- 5.3 Major Conclusions from Experimental Tasks

6.0 WORK PLAN

7.0 ACKNOWLEDGEMENTS

REFERENCES

LIST OF ILLUSTRATIONS

FIGURE

1. Intermediate "A" Steam Generator
2. Low Temperature Steam Generator
3. Acoustic Power Transmission Across Plates
4. Sound Power as a Function of Axial Distance
5. Sound Spectrum as a Function of Strouhal Number
6. Effect of Geometric Obstruction
7. Reference Acoustic Leak Detection System
8. System Performance.
9. Example of Curve (Developed for CRBRP)
10. Amplifier Noise
11. Attenuation of Longitudinal Waves.
12. Comparison of Accelerometers
13. Visual Display Output (No Leak)
14. Location of SIDE Leak - Leak in Plane
15. Location of EDGE Leak - Leak in Plane
16. Location of Leak Displayed 42 cm Below Plane
17. Location of Leak of $S/N \approx -25$ dB
18. Calibration of SONAR Vessel
19. Signal Level
20. Major Areas of Uncertainty
21. Schedule - WTD PHASE 1

LIST OF TABLES

1. Feasibility Study Tasks
2. Design Characteristics for Steam Generators
3. Task 1 Summary: Geometric Effects
4. Task 2 Summary: Localization Criteria
5. Task 3 Summary: Jet Noise (Ultrasonic and Acoustic)
6. Task 4 Summary: Hardware Design Criteria
7. Digital Signal and Data Processing Requirements
8. Task 5 Summary: Portable System
9. Task 6 Summary: Ultrasonic Leak Location
10. Accelerometer Specification
11. Small Leak Location in MATOI.

SUMMARY

This interim report summarizes the current status of a feasibility study of an acoustic leak location system for two Westinghouse-Tampa Division (WTD) double-wall steam generators. The primary WTD design requirement is that a leak of helium gas into sodium be located to within a cluster of seven tubes at hot standby conditions.

The report documents the results of an extensive analytical assessment, outlines areas of concern resulting from the analyses which will require experimental validation, and presents results of experiments thus far completed. The conclusion of the study at this time is that acoustic leak location is feasible, pending the results of the remaining experimental tests.

The acoustic leak location system operates on the same principles as the acoustic leak detection system being developed under SG027, Subtask X2. Analyses indicate that, in general, the location system will use similar design parameters to the acoustic leak detection system. Much of the hardware can be identical, in particular the accelerometers. It is recommended that a minicomputer/software approach be employed rather than the custom-designed hardware approach used for the detection system.

1. INTRODUCTION

1.1 Objectives of Study

The objective of this study is to assess by analytical studies and experimental programs, the feasibility of acoustic leak localization for the Westinghouse Tampa Division (WTD) steam generator designs. To the extent possible, technology from acoustic leak detection system development under Base program SG027 will be utilized and applied.

The principal WTD design requirements call for a leak of helium gas into sodium to be located to within a cluster of seven tubes. The system is to have the sensitivity to locate a leak from a 0.002 inch diameter hole (with a helium gas pressure of 300 psig) within 4 hours after hot standby conditions are achieved. Although not a firm requirement, WTD has requested that strong consideration be given to using a portable leak location system which could be attached to any steam generator within the plant.

1.2 Program Plan

The feasibility study consists of an analytical assessment comprising six areas and five experimental investigations of geometric regions or problems associated with the steam generator designs. These are summarized in Table 1 below.

TABLE 1

FEASIBILITY STUDY TASKS

Analyses

1. Geometric effects
2. Localization criteria
3. Jet noise
4. Electronic hardware design
5. Portable system
6. Ultrasonic leak location

Experimental Investigations

7. Accelerometer attachment
8. Array geometry limitations
9. Helium jet noise character
10. Transmission across annulus
11. Ultrasonics

1.3 Organization of Report

The structure of this interim report is as follows. Brief descriptions of the two steam generator designs and their operating conditions are given in Section 2. Results of the analytical studies are presented in Section 3 followed by results of the completed experimental studies in Section 4. An assessment of results with major conclusions is given in Section 5. The report concludes with a description and schedule for the work remaining to be completed in Section 6.

The study to date concludes that there is every indication that acoustic leak location can be achieved and the design requirements met. However, the remaining experimental tests must be completed before this conclusion can be considered firm. A final report on the feasibility study is scheduled for June 1979.

2.0 WTD STEAM GENERATOR DESIGN DESCRIPTIONS

Brief descriptions of the two WTD steam generator designs are given in this section. More complete design information can be found in References 9 and 10.

2.1 Intermediate "A" Steam Generator Design

The sodium-heated steam generator is a vertical straight shell and tube heat exchanger employing double-wall tubes as a double barrier between the potentially reactive heat transfer fluids, shell-side sodium and tube-side water/steam. The design, with key dimensions, is shown in Figure 1. The double-wall tube is a prestressed concentric double-tube assembly which has four longitudinal grooves located on the inside surface of the outermost tube for containment of the helium leak detection fluid.

There are three steam generator units per loop operating in parallel each with a thermal rating of 292 MWt. The mode of operation is once-through with low temperature feedwater (465°F) heated to superheated steam (855°F) in one pass through the unit.

Secondary loop sodium from the IHX enters the tapered inlet nozzle located near the top of the unit, flows in and around the inlet flow shroud, and is turned 90° to pass through the flow distributor before entering the active tube bundle volume. The sodium is then turned an additional 90° to flow downward in crossflow and parallel flow patterns over the tubes. After passing through the active tube bundle, the sodium is turned 90°, flows through the outlet flow distributor, and flows up and around the outlet flow shroud before exiting the outlet nozzle located near the bottom of the unit.

Double tubesheets are provided near the top of the steam generator. These are joined by a leak-tight cylindrical shell and dished head complex which contains the helium leak detection fluid. The outer tube of the double wall tube assembly ends in this plenum such that the helium can enter the four longitudinal grooves of each tube. The outer tube is welded to the front face of the sodium tubesheet using a fillet weld to

Figure 1. Intermediate "A" Steam Generator

boss configuration. The inside tube alone passes through the upper water/steam tubesheet and is also welded on the front face using a fillet weld to boss configuration. Three 16-inch manways are provided in the chamber for access during manufacture and inservice inspection. Two 2-inch helium fill and leak detection nozzles are provided on the cylindrical portion of the complex joining the double tubesheets.

A single tubesheet is employed at the bottom of the unit with the outside tube welded both to the back face and the front face of the tubesheet using the boss fillet weld configuration. The tube is expanded throughout the entire tubesheet thickness in this tubesheet.

2.2 Low Temperature Steam Generator Design

The steam generator design for the low temperature, saturated steam cycle is quite similar to that for the Intermediate A cycle with the exception of moisture separating equipment mounted in the upper shell attached to the upper tubesheet. Minor dimensional changes also exist. The low temperature design is shown in Figure 2.

For the low temperature cycle there are two steam generator units per loop operating in parallel, each with a thermal rating of 364 MWt. The mode of operation is recirculation with low temperature feedwater (425°F) mixed with saturated water (532°F) and recirculated through the tube bundle. The wet steam exiting the tubes then flows through the moisture separating equipment mounted in the upper shell.

2.3 Operating Conditions During Location

During sodium side leak location the plant will be operating on N-1 loops with the down loop at refueling temperature (approximately 400°F). Primary flow in the affected loop will be essentially zero (probably less than 30 gpm through the check valve), with the secondary loop operating at pony motor flow (7%). Pony motor flow is required to maintain the steam generator at 400°F (the steam generators will most likely not be electrically heated) and can be interrupted periodically to facilitate listening. The waterside of the unit can be drained or filled at the steam generator vendor's option. During the process the unaffected loops will be operating at full flow.

2.4 Design Changes

A series of design changes have been made to the steam generators since this analysis was initiated. These design changes are reported in References 9 and 10.

Table 2 gives the approximate values used during the analysis of both designs. Values shown in brackets are design revisions as given in References 9 and 10. The most significant changes for the leak location feasibility study is a 75% He-25% argon gas mixture as the third fluid rather than the original 100% helium, and the increase in reservoir pressure to 345 psf. The convoluted bellows section of the shell has been thickened and the diameter of the convolutions increased. Tests of this section will be made using the updated dimensions; analyses were performed on the pre-change dimensions.

TABLE 2
DESIGN CHARACTERISTICS FOR THREE STEAM GENERATORS

	W Intermediate A	W Low Temperature	CRLMFBR
Outer Diameter			
Flanged + Dished Head	143.00"	141.00"	
Convolute Section	103.62"	101.63"	
Main Body	92.12"	90.13"	
Length			
Head Outlet	123.75"	130.00"	
Head Inlet	154.75"	159.62"	
Convolute	100.00"	100.00"	
Shell	189.25"	366.87"	
Wetted	768.00"	756.00"	551.18"
Shell Thickness			
Head Outer	2.5"	2.0"	
Inner	1.0"	1.0"	
Convolute Outer	.5"	.5" (0.6)	NA
Inner	.25"	.25"	NA
Radius of Convolutions		2.75" (5")	
Number of Convolutions		6 (4)	
Shell	1.5"	1.5"	2.24
Internal Structure			
Stayrods Diam	.75"	.75"	
Number	5	17 (21)	
Pipe Skid	NA	2" (Removed)	
Support Plates Width	.75"	.75"	1.49"
Number	26	25	21
Tubeplate Outlet Width	25.12"	19"	
Inlet Width	13.0"	12.5"	
Flow Shroud	NA	NA	.47
Tubes			
Type	Double Wall	Double Wall	Single Wall
Outer Diam #1	.817"	1.0" (1.0)	5/8"
Outer Diam #2	.665"	.90" (0.88)	NA
Inner Diam	.542"	.74" (0.702)	
Number	3338 (3350)	2500 (2188)	757
Pitch		1.625" (1.703)	
Leak			
Type	He to Na	He to Na	H ₂ O to Na
Min. Size	2 MIL Eq. Diam	2 MIL Eq. Diam	10 ⁻² gm/sec
Pressure	300 psig	300 psig	1600 psig
Operation Condition			
Localization to 7	Hot Standby	Hot Standby	All Conditions to Full
Localization to 1	No Water Optional	No Water Optional	NA Power
	No Na	No Na	
Function Required	Localization	Localization	Detection
Localization			
7 Tube Area	13.08 in ²	16.69 in ²	18.62 in ²
Diameter	4.08"/10.36 cm	4.60"/11.7 cm	4.86"/12.36 cm

3.0 RESULTS OF ANALYTICAL STUDIES

The six analytical tasks are discussed in order as presented in Table 1.

3.1 Geometric Effects

Calculations were made to determine the frequency limitations, homogeneity and isotropic limitation for both WTD steam generator designs. Reflection and transmission characteristics of the internal structures, such as tube supports, tubesheet/fluid interface, inlet and outlet annuli, flow distribution plates, and tube supports were determined. Results from this task are summarized in Table 3.

The frequency band for leak location will be chosen using the following criteria [3]:

- a) The vessel wall must respond in a mass controlled mode.
- b) The attenuation of the signal as it passes over the internal structure should be minimized.
- c) The signal power must be significant in the selected frequency bandwidth.

The lowest frequency is chosen by considering the natural resonant vibration characteristics of the vessel and components. Most flexural and extensional resonant vibration frequencies are below 1 KHz. It is not until higher harmonics are reached that frequencies approach this value. Experience indicates that most far-field noise is also below about 1 KHz. If the low cut-off frequency is increased above this value there is a danger that significant signal noise power will be lost. It is therefore recommended that the lowest frequency be 1 KHz. MATOI and SONAR tests [4] have shown that above this frequency the wall motion is essentially mass controlled, rather than stiffness controlled. Mass controlled wall motion is essential to the operation of the acoustic system as it implies that each accelerometer on the wall will respond only to the internal pressures impinging on that local section of the wall.

An upper frequency limit is set by the critical coincidence frequency. Above this frequency the impinging energy enters the wall and will cause a bending, or stiffness controlled, wave. Such waves can cause the accelerometer outputs to become coherent; that is, the accelerometers move in unison and can

TABLE 3. TASK 1 SUMMARY

GEOMETRIC EFFECTS

MAJOR QUESTIONS

1. WHAT IS THE BEST BANDWIDTH FOR ACOUSTIC LEAK LOCATION?
2. CAN THE VESSEL INTERNALS BE CONSIDERED HOMOGENOUS AND ISOTROPIC?

RESULTS OF ANALYSIS

1. NO SIGNIFICANT RESONANCES OR STIFFNESS CONTROLLED VIBRATIONS IN THE RANGE 1 KHz to 10 KHz ARE EXPECTED.
2. THE STEAM GENERATOR AND ITS CONTENTS MAY BE TREATED AS HOMOGENOUS AND ISOTROPIC.
3. SIGNAL ATTENUATION DUE TO THE TUBE STRUCTURE SHOULD BE MINIMAL.

AREAS OF CONCERN

1. SOUND TRANSMISSION ACROSS 2 FT. ANNULUS, AND THE INLET FLOW DISTRIBUTION BAFFLE.
2. RESPONSE OF THE BELLOWS SECTION OF THE VESSEL WALL TO ACOUSTIC PRESSURES.
3. CONFIRM NO ANISOTROPIC EFFECTS WHEN ACOUSTIC VELOCITY IS MEASURED IN PLANE AND ALONG AXIS.
4. HIGH FREQUENCY ATTENUATION IN INLET AND OUTLET ANNULI MAY BE SIGNIFICANT.

not be used to locate a leak. Calculations indicate that this frequency is ~ 10 KHZ.* Therefore, this the upper frequency limit selected for the location system.

The attenuation of the signal from the leak site to the wall has been calculated. In the frequency range of 1 KHz to 10 KHz the calculations indicate that the fluid and internal tube bundle produce negligible signal attenuation. The analysis also indicates that it is probable in the frequency bandwidth 1 KHz to 10 KHz that the internal fluid and structures form a homogenous medium with isotropic acoustic properties. This significantly simplifies the design of an acoustic leak location system.

When the signal is transferred across a plate structure, such as a shroud or tube support, attenuation can occur. The attenuation is a function of the plate thickness and the signal frequency. Figure 3 shows the attenuation for plates of three different thicknesses as a function of frequency. In the frequency range of 1 KHz to 3 KHz, where most of the power of the gas injection signal is generated, the attenuation is not excessive even for a 2.54 cm thick plate. At higher frequencies the attenuation can be severe, especially for thicker plates.

A geometric area of concern within the steam generator identified by this task is the 2 ft. annulus in the sodium outlet and inlet regions. Sound transmission across these annuli cannot be accurately predicted due to the following factors.

- a) The wall is $3/4$ inch (1.9 cm) thick. High frequencies may be attenuated significantly, thus reducing the resolution in the tube bundle.
- b) The size of the gap approaches the same magnitude as the acoustic wavelengths. In the CRBRP design the gap between the shroud and the wall is a small part of an acoustic wavelength. Calculations and test experience from the detection program are not directly applicable to this situation.

*NOTE: A critical coincidence frequency of ~ 8 KHz was calculated for the Intermediate A plant.

Figure 3. Acoustic Power Transmission Across Plates
(Power Transmission Versus Frequency for
Normal Incidence)

- c) The fluid/shroud/bundle structure may not be homogenous because of the liquid annulus. Acoustic properties may not be isotropic.

A further complication is introduced by the variable porosity hole structure of the flow control region. It will be necessary to obtain experimental data for the inlet and outlet regions before a final assessment of feasibility can be made.

3.2 Localization Criteria

Calculations leading to localization criteria, specifically cell size and expected resolution, were made. One of the most important parameters in leak localization is the acoustic velocity. The effects of operating parameters such as sodium temperature and pressure on acoustic velocity were estimated. Potential errors due to signal reflection or attenuation by the injected gas were examined. Array configurations for leak location were considered, and the approximate array pattern calculated.

A summary of the localization criteria assessment is given in Table 4.

The design requirement is leak localization to within a cluster of seven tubes. This is equivalent to a resolution of 4.09 in. (10.4 cm) for the "Intermediate A" WTD design and 4.61 in. (11.7 cm) for the "Low Temperature" design. Based on this resolution requirement it was estimated that the steam generator volumes would have to be divided into 80,000 and 50,000 volume elements respectively. (For comparison a CRBRP steam generator has ~ 20,000 volume elements).

In order to achieve such resolution the noise source bandwidth will have to be ~ 10 KHz or higher. Experimental data to be presented later (Section 4) indicate that this bandwidth is produced by leaks of small diameter and high pressures. However, with larger leak orifice sizes, the bandwidth may be as low as 2 KHz to 4 KHz. This would increase the resolution width to ~ 7.9 in. (20 cms) and definition would be to a cluster of ~ 50 tubes. Therefore, if low bandwidth noise is produced by the leak, the array processing techniques will have to be changed from that used for the CRBRP detection system. An over-sampling technique is contemplated. This will have the practical impact of increasing processing time.

TABLE 4. TASK 2 SUMMARY

LOCALIZATION CRITERIA

MAJOR QUESTIONS

1. HOW SENSITIVE IS THE ACOUSTIC VELOCITY TO OPERATING PARAMETERS?
2. WHAT IS THE ARRAY CONFIGURATION?
3. CAN ROUGH LOCALIZATION FOLLOWED BY FINE TUNING BE USED?

RESULTS

1. VELOCITY EFFECTS DUE TO THE MEDIUM DO NOT APPEAR TO BE A PROBLEM.
2. THE NUMBER OF ACCELEROMETERS REQUIRED IS ABOUT THE SAME AS FOR CRBRP. (80%)
3. LOCALIZATION TO WITHIN 7 TUBE CLUSTER MAY BE POSSIBLE IF SUFFICIENT ANALYSIS TIME IS AVAILABLE. (FUNCTION OF S/N RATIO)
4. ROUGH LOCALIZATION FOLLOWED BY MORE PRECISE LOCATION HAS POTENTIAL.

AREAS OF CONCERN

1. CAN TOTAL INTERNAL REFLECTION OF PRESSURE WAVE OCCUR? (WOULD LIMIT THE AXIAL DISPLACEMENT TO $\pm 1/2$ METER). ISSUE IS CLOUDED BY NEAR FIELD-FAR FIELD AND WAVELENGTH LIMITS
2. WHAT IS THE ULTIMATE SPATIAL RESOLUTION OF AN ARRAY?

If the angle of impact of the pressure wave onto the wall exceeds a critical value, the wave will be totally internally reflected and the wall will not "see" the pressure wave. For a semi infinite solid and semi infinite fluid system, the critical internal reflection angle for sodium is $26^{\circ} 36'$. (For water the angle is $\sim 17^{\circ}$). If the leaking tube is in the center of the vessel diameter, then the maximum distance at which an accelerometer off the plane containing the leak would sense the resulting pressure waves would be ± 21.7 in. (55 cm). Correspondingly, for the water filled MATOI vessel the maximum distance would be ~ 7.09 in. (18 cm). However, tests show that on MATOI, significant signal levels are received by accelerometers at 9.45 in. (43 cm) axially displaced from the center leak. (These tests are discussed in more detail in Section 4). It is concluded that the hypothesis of semi-infinite media is not a valid representation of the actual steam generator geometry.

An error in measuring the position of a leaking tube results from using an incorrect acoustic velocity. This error is maximum for leak locations furthest from the accelerometer and minimum for locations closest to the accelerometer. The acoustic velocity is a function of the medium (composite of liquid sodium, tube bundle, etc.), and changes when operating conditions are changed. Analyses indicate that the effect of refraction, convection, sodium velocity, and sodium pressure are negligible. However, changes in sodium temperature of 100°C will produce an error of ~ 5 cms in the leak position. The effect of operating temperature changes or temperature distribution along the vessel can be adequately compensated by the incorporation of a correction factor into the location system logic.

An array consisting of a repeating pattern of eight accelerometers arranged in a multi-start helical pattern, with each accelerometer axially displaced by 4.72 in. (12 cm), is considered to be a reasonable conceptual design. This system should be suitable for all conditions which give a signal-to-noise ratio better than -20 dB. With this criteria, a total of ~ 170 accelerometers will be required for the WTD steam generator designs. (This is about 80% of the number required for the CRBRP steam generator design). The use of a wider pattern of accelerometers to provide a rough leak location, followed by an optimized array to locate the leak position accurately may be economically attractive. This approach requires more information on transfer functions and

signal-to-noise ratio estimates before a complete assessment can be made. A further assessment of feasibility will be made for the final report in June 1979.

3.3 Jet Noise

A literature search on the acoustic characteristics of gas jetting into a liquid was completed. Two major classifications of noise generation were identified: (1) the noise due to turbulence induced by the high velocity jet and (2) noise due to formation and oscillation of gas bubbles. Turbulence noise is of importance in considering high frequency leak detection, such as ultrasonic monitoring. Bubble noise is of importance to acoustic leak location, being much lower in frequency. It is associated with the physical dimensions of the bubbles formed.

A summary of the jet noise study is given in Table 5.

3.3.1 Characterization of Jets (Turbulent Noise)

The nature of the jet is characterized by a Reynolds Number defined as:

$$N_{Re} = \frac{r_o u_o}{\nu}$$

where r_o is the radius of the jet orifice, u_o is the flow velocity through the orifice, and ν is the kinematic viscosity. For $N_{Re} < 500$ the bubble size (r_b) is approximately constant [$r_b = 0.693 r_o^{0.3}$]. As the flow rate increases the bubble frequency increases. Surface tension effects are important in this range. At higher N_{Re} ($N_{Re} < 2100$), the bubble size increases [$r_o = 0.09 d^{0.5} N_{Re}^{0.33}$] while the number of bubbles remains relatively constant. The maximum bubble size is reached when bubbles begin to coalesce, and the induced turbulence breaks up the bubbles.

A transition regime exists for $2100 < N_{Re} < 10,000$, with fully developed turbulent jets for $N_{Re} > 10,000$. In these regimes a characteristic jet cone is formed. The gas liquid dispersion within the cone consists of small bubbles, the size of which depends upon the orifice diameters and N_{Re} .

TABLE 5. TASK 3 SUMMARY
JET NOISE (ULTRASONIC & ACOUSTIC)

QUESTIONS

1. CAN THE JET NOISE BE ANALYTICALLY PREDICTED?
2. HOW SENSITIVE IS THE JET NOISE TO CHANGES IN PARAMETERS?
3. WHAT IS THE FREQUENCY BAND FOR ULTRASONIC LOCATION?
4. WHAT IS THE EFFECT OF AN OBSTRUCTION?

RESULTS

1. IF JET IS TURBULENT, RELATIVE NOISE LEVELS CAN BE ANALYTICALLY PREDICTED. EQUATIONS ARE AVAILABLE TO PREDICT PARAMETRIC EFFECTS.
2. THE FREQUENCY BAND FOR ULTRASONIC DETECTION IS 100 KHz to 300 KHz.
3. AN OBSTRUCTION CAN EITHER INCREASE OR DECREASE THE ACOUSTIC POWER DEVELOPED BY JET.

AREAS OF CONCERN

1. THE EFFECT OF NON-CIRCULAR ORIFICES IS NOT KNOWN.
2. THE EFFECT OF THE DOUBLE WALL TUBE STRUCTURE IS NOT KNOWN.
3. THE RUSSIAN DATA ON EFFECT OF JET IMPINGEMENT ON AN OBSTRUCTION IS AMBIGUOUS. NO OTHER TEST DATA HAS BEEN FOUND.

Acoustic noise is generated very close to the orifices, usually within $10 d_o$. High frequency noise is generated closest to the orifice, and low frequencies preferentially downstream. The sound power generated as a function of axial distance is shown in Figure 4. The sound source distribution has a broad peak over the first four orifice diameters, falling rapidly after six diameters to become almost insignificant at ten diameters from the orifice. The noise spectrum of a turbulent jet is shown in non-dimensional form in Figure 5. The spectral density curve is shown as a function of Strouhal Number ($f d_o / u_o$), where f is the frequency, d_o is the orifice diameter, and u_o is the jet velocity. For a flow velocity of 984 ft/sec (300 m/sec) and an 8 mil (0.2 mm) diameter orifice, the maximum spectral density appears at ~ 150 KHz.

The basic theory of sub-sonic jet noise generation was developed by Lighthill^[5]. Although the formulas developed do not give absolute power levels, the parametric dependencies have been experimentally verified. The total acoustic power generated by a jet (P) is given by:

$$P \propto \frac{\rho_o^2 u_o^8 d_o^2}{\rho_m c_m^5}$$

Where ρ_o , u_o , d_o are jet density, velocity and orifice diameter, respectively, ρ_m is the surrounding medium density and c_m the acoustic velocity. This equation was developed using non-dimensional theory, and the exponent powers were checked experimentally.^[5]

Based on the above considerations, the frequency band for ultrasonic investigations has been chosen as 100 KHz to 300 KHz. In this frequency band a gas jet into sodium will generate the maximum high frequency power.

For reservoir pressures greater than ~ 60 psig, giving a minimum of 30 psi pressure across the orifice, the stream velocity is constant. Increases in reservoir pressure would increase the jet density giving slightly increased noise generation but the main parameters controlling noise generation is the choked flow velocity through the orifice. If the jet orifice size is increased, the total acoustic power generated also increases. The effect of non-circular orifices would increase the turbulence and therefore generate higher noise levels.

Figure 4. Sound Power as a Function of Axial Distance

Figure 5. Sound Spectrum as a Function of Strouhal Number

The effect of temperature on jet noise is to change the velocity by about +14% for a change of 360°F (200°C). This change would give a 2.85 times increase in noise power.

3.3.2 Characterication of Bubble Noise

Most of the noise generated by gas bubbles is caused by volume oscillation, although a small contribution from changes in bubble shape is possible. Volume pulsations are produced when there is a change in the pressure differential across the bubble surface. This change in pressure can be caused by flow past a fixed body, or along a hydrodynamic pressure gradient. Sound is also emitted when bubbles split or coalesce. If bubbles greater than 1 mm are formed in water and rise, it has been observed that they generate a continuous sound of relatively low amplitude.

For a 4 mil (0.1 mm) radius orifice, bubble diameters are about 60 mils (1.5 mm), and for very high N_{Re} approach 200 mils (5 mm). Frequencies associated with bubbles of this size are in the range of 1 KHz to 3 KHz and can be utilized by the proposed acoustic system.

When an alternating pressure wave is transmitted through a fluid containing bubbles severe attenuation can result. The bubbles absorb and scatter the acoustic energy. However, experience in MATOI, TILT and SONAR^[4] indicates that injection of a gas does not cause significant attenuation. Attenuation and/or acoustic velocity changes associated with two-phase mixtures are usually examined in a volume containing a homogenous two phase mixture. In the case of a gas injection into the steam generator only direct paths from the leak to the wall are of importance. In general these paths do not pass across the rising bubble stream. If the sound path was to follow the bubble path, attenuation would result.

3.3.3 Local Geometric Structures

If a jet impinges onto a local geometric structure the total power and spectrum can be changed^[2]. As an example Figure 6 shows the dependence of noise power for a gas leak into water as a function of the distance to an obstacle in the form of a 20 mm diameter tube.^[6] Note that the power is either increased or decreased depending upon the distance to the obstacle. (Unfortunately, the translation of this Russian paper does not make it clear whether the noise is higher or lower when the obstruction is close to the orifice).

Dependence of Noise Power on Distance Between Nozzle and Obstruction for:

1. A Nozzle Diameter of 0.35 mm
 2. A Nozzle Diameter of 0.25 mm
 3. A Nozzle Diameter of 0.35 mm (Power Level for a Free Jet)
- a - A, Relative Units

Figure 6. Effect of Geometric Obstruction

3.4 Electronic Hardware Design Criteria

Analyses leading to the formation of hardware design criteria were made. The hardware and software approaches of the acoustic leak detection program (under SG027, Subtask X2) were examined for application to this study. Areas where changes might be required for use in an acoustic leak location system in the two WTD steam generator designs were identified. A summary of the areas analysed is given in Table 6.

3.4.1 Design of Acoustic Detection/Location System

An acoustic leak detection system based on techniques similar to those of SONAR and RADAR has been developed [1]. Accelerometers are fitted in a predetermined pattern to the outside surface of the steam generator vessel. Electronic circuitry selects a number of accelerometers, forms them into an array which focuses within the vessel, and measures the acoustic power at each focal point. The volume of the vessel is sequentially scanned to map the acoustic field with a resolution of ~ 12 cms for a frequency bandwidth of 10 KHz. The resolution is a direct function of the frequency bandwidth, and maximum signal-to-noise ratios are achieved when the resolution grid matches the signal bandwidth. Localization is detection of which focal point has an acoustic power exceeding a given threshold level.

The concept design for an acoustic leak detection system based on CRBRP steam generator parameters is shown in Figure 7. Note that two approaches are indicated for digital signal processing. One uses a custom designed processor which operates in real time; the other is a minicomputer/software system. An acoustic leak location system for the two WTD designs would have a very similar design to that indicated in Figure 7. The similarities and differences between the detection system and a location system will be developed in the following sections.

3.4.2 Signal-to-Noise Ratio

The single most important parameter defining the performance of an acoustic location system is the ratio of the acoustic power of the gas jet to the background noise: the signal-to-noise ratio. The power of the gas jet has been discussed in an earlier section (3.3), and measured in the SONAR

TABLE 6. TASK 4 SUMMARY

HARDWARE DESIGN CRITERIA

QUESTIONS

1. HOW DO $\bar{W}$ LOCATION SYSTEM REQUIREMENTS DIFFER FROM CRBRP DETECTION SYSTEM REQUIREMENTS?
2. WHAT IS THE BACKGROUND NOISE LEVEL, AND THE SIGNAL LEVEL?
3. CAN CURRENT HARDWARE BE ADAPTED FOR $\bar{W}$ DESIGNS?

RESULTS

1. NUMBER OF CHANNELS OF DATA IS SAME OR LESS THAN FOR CRBRP, BECAUSE UNDER-SODIUM VESSEL LENGTH IS SHORTER.
2. NUMBER OF RESOLUTION CELLS INCREASES OVER CRBRP

CRBRP	=	20,000
INTER. A.	=	80,000
LOW TEMP.	=	50,000

THEREFORE, THE TIME IS INCREASED FOR SIMILAR S/N RATIO.

3. FRONT-END AMPLIFIER ELECTRONIC NOISE AND REVERBERENT NOISE FROM THE LEAK-ITSELF ARE LIKELY TO BE THE MAJOR SOURCES OF BACKGROUND NOISE AT STANDBY CONDITIONS.
4. ANALOG SIGNAL PROCESSING AND MULTIPLEXING ARE SIMILAR FOR BOTH DETECTION AND LOCATION SYSTEMS.

AREAS OF CONCERN

1. A CUSTOM DESIGNED SIGNAL PROCESSOR WILL HAVE TO BE DEVELOPED FOR EACH DESIGN.

REFERENCE ACOUSTIC LEAK DETECTION/LOCATION SYSTEM

Figure 7. Reference Acoustic Leak Detection/Location System

vessel. The measurements give an estimate of the acoustic pressure at the vessel wall, and the expected bandwidth.

The background noise will be the resultant of the contributions from several sources. The most important of these are amplifier electronic noise, sodium flow noise, far field noise and the reverberent noise component of the gas jet. For small leaks at hot standby conditions, the major component of background noise is expected to be electronic noise. The electronic noise is equivalent to an acoustic pressure of $\sim 12 \mu\text{bar}$ at the inside wall of a 5 cm thick wall. For larger gas jets, also at hot standby conditions, the probable source of background noise will be the reverberent or multiply reflected pressure waves generated by the jet itself. Based on tests in SONAR and MATOI this noise is a factor of 2 to 6 times higher than the direct path component. At standby conditions the sodium flow component is expected to be negligible. Far field noises can be isolated and are expected to be negligible.

The data that must be analysed as a function of signal-to-noise ratio are shown in Figure 8. If these data are collected and analyzed in real time, the left-hand axis corresponds to location time. If sub-arrays are formed to monitor the vessel, the location time is the length of time that is required to accumulate the data, since each level is monitored sequentially*. A typical curve developed for CRBR is shown in Figure 9.

3.4.3 Accelerometers

The specification developed for the accelerometers to be used in the acoustic detection system^[1] is also suitable for use in the location system. It is possible that at some later time parts of the specification could be relaxed, for example, bandwidth and temperature limitations. Ceramic waveguides, as used in the detection system, will also be required for the location system.

3.4.4 Array and Cell Structure

For the acoustic detection system, accelerometers are mounted in a multistart helix pattern on the outside of the vessel. Each is assumed to have an axial separation of 12 cm, giving a total inventory of ~ 190 accelerometers. At any given time, eight accelerometers form an array which is focused onto a plane containing ~ 500 volume elements or cells. This basic design is

* These times are less than the total location time. As defined by the WTD design requirements, total location time includes the time to setup and install the the necessary acoustic location equipment.

FIGURE 8. SYSTEM PERFORMANCE

LOCATION TIME IS A FUNCTION OF

- SIGNAL LEVEL (S)
- BACKGROUND LEVEL (N)
- PROBABILITY OF FALSE ALARM (F)
- PROBABILITY OF MISSING LEAK (M)
- VESSEL SWEEP TIME (T)

$\frac{S}{N}$ RATIO

Figure 9. Example of Curve (Developed for CRBRP)

applicable to the location system as well.

3.4.5 Amplifier Design and Noise

The amplifier specification developed for the acoustic detection system will also apply to an acoustic leak location system. Since the accelerometer is a charge generating device a charge pre-amplifier design has been selected. The noise generated by the amplifier is a function of the cable length as shown in Figure 10. A typical length connecting the accelerometer and amplifier is ~ 30 ft.

3.4.6 Digital Signal Processing

The main change in hardware design between the acoustic detection and location system is in the digital signal processor. It will be necessary to custom design a signal processor for each WTD steam generator design. Requirements are summarized in Table 7.

3.4.7 Display and Alarm

The display system developed for the acoustic detection system is similar in concept and design to that required for an acoustic leak location system.

3.5 Portable System

Although the use of a portable location system is not a requirement, WTD requested that strong consideration be given to such an approach. A summary of the task results is given in Table 8.

The two major questions on the feasibility of using a portable system are the method of attaching sensors and the use of permanently installed transducers.

3.5.1 Sensor Attachment

The reference design of sensor attachment is that developed, tested and proven during field measurements at Hengelo^[1]. If a permanent transducer

FIGURE 10. AMPLIFIER NOISE

TABLE 7

DIGITAL SIGNAL AND DATA PROCESSING REQUIREMENTS

Digital processing is used to:

1. Focus the signals received from eight accelerometers on the 500 resolution cells in each level;
2. Accumulate the signal power samples to improve the estimates of the acoustic signal power in each cell;
3. Test for leaks in each cell by comparing the acoustic signal power estimates to predetermined threshold levels.

From the point of view of implementing the system, the concerns are:

1. The number of samples that must be stored to perform the focus operation;
2. The rate at which the squaring circuit must operate;
3. The memory required for the detection accumulators, and
4. The detection test rate.

TABLE 8. TASK 5 SUMMARY
PORTABLE SYSTEM

QUESTIONS

1. SHOULD A HARDWARE OR SOFTWARE APPROACH BE USED FOR THE $\bar{W}$ STEAM GENERATOR?
2. CAN THE SYSTEM BE MADE TRANSPORTABLE?
3. WHAT TECHNIQUE WILL BE USED TO INSTALL ACCELEROMETERS?
4. CAN "4 HOUR" CRITERIA BE REACHED?

RESULTS

1. MOST LIKELY APPROACH IS TO USE SOFTWARE, BECAUSE OF ITS INCREASED FLEXIBILITY, RATHER THAN CUSTOM DESIGNED HARDWARE.
2. TRANSPORTABILITY HAS BEEN DEMONSTRATED AT HENGELO, (BUT WITHOUT THE POSSIBLE RESTRICTIONS AT A POWER PLANT).
3. SOME SUCCESS HAS BEEN ACHIEVED WITH CEMENTING STAND-OFFS TO COLD SURFACES.
4. LOCATION CAN POSSIBLY BE ACHIEVED IN FOUR HOURS WITH A PERMANENT TRANSDUCER INSTALLATION.

AREAS OF CONCERN

1. INSTALLATION MAY TAKE MORE THAN FOUR HOURS.
2. NO SOFTWARE PROGRAMS YET DEVELOPED.
3. NO PROCEDURES HAVE BEEN DEVELOPED.
4. ACCELEROMETER ATTACHMENT TO A HOT VESSEL BY A CEMENT IS UNCERTAIN.

installation is used, this mechanical attachment is recommended. However, the concept of portability can be applied to include the installation of transducers, requiring that the transducers be installed onto a specific vessel after the leak is detected.

Two approaches are currently being examined for a relatively temporary ($\sim$ one month) transducer attachment. Limited success has been achieved using a ceramic cement to attach waveguides to a cold vessel wall, but application to a 400°F surface has not been successful. Use of a magnetic attachment appears feasible, provided the accelerometers are attached to a vessel not exceeding $\sim 600^{\circ}\text{F}$. This technique is still under development and test. Developmental test results will be included as part of the June 1979 final report.

There are two main advantages to the use of a permanent transducer installation. Should a leak be detected, the sensors on that particular vessel can be quickly attached to a single leak location system. The second advantage is that the exact location of the transducers are known, reducing the error in position, and the need to make measurements of accelerometer location before making a location prediction. It is estimated that with a permanent transducer installation the location prediction can be made within ~ 4 hours, whereas a temporary transducer installation may require up to ~ 200 hours prior to a location prediction. The saving in time is important not only from an economic viewpoint, but also in reducing the probability of the defect plugging prior to location.

3.5.2 Software -vs- Hardware Approach

The acoustic leak detection system uses a signal processor which is custom designed to match the geometry of a particular vessel. A detection system is required to operate on each vessel in the plant and to provide coverage at all times. Detection is required in the shortest possible time to allow corrective action to be taken by the operator prior to damage propagation. To achieve the maximum detection speed, reliability and lowest cost, the detection system uses a hardware approach.

For leak location the criteria are not as restrictive. Location time can in general take much longer, and the consequences of a false alarm are not as severe. The cost of a software system that is one similar to the

laboratory implementation shown in Figure 7, would be significantly less than the cost of developing and implementing a hardware system. The flexibility of a software system could become a significant advantage during an actual location incident, especially if accelerometer installation is not permanent.

It is recommended that a software approach be implemented for the leak location system.

3.5.3 Transportability

The rapid increase in micro-miniturization, and the development of mini and microcomputers allows even a complex software implementation system to be transportable. A laboratory type system was transported to the Hengelo test site in The Netherlands in several packing cases.^[1] It is not unrealistic to expect a leak location system to be contained in two specially designed cases.

3.6 Ultrasonic Leak Location

Following location of the leak to within approximately seven tubes, by an external acoustic location system, it will be necessary to identify the single leaking tube. There appears to be two potentially feasible techniques for confirming that a leak exists in one tube. Both techniques make use of the ultrasonic portion of the jet noise spectrum. The analysis undertaken as part of the feasibility study is summarized in Table 9.

3.6.1 Leak Signal

The characteristics of an aerodynamic jet were described in Section 3.3. Important characteristics for ultrasonic leak location are:

- a) The spectrum of the noise is broadband, with probable maximum acoustic power generated in the frequency band 100 KHz to 300 KHz for typical hole sizes.
- b) This maximum power is generated close to the orifice, usually within ~ ten orifice diameters.
- c) High frequency noise is attenuated strongly tending to isolate the noise to the immediate vicinity of the leaking tube.

TABLE 9. TASK 6 SUMMARY
ULTRASONIC LEAK LOCATION

QUESTIONS

1. WHAT TECHNIQUES OF ULTRASONIC DETECTION ARE AVAILABLE?
2. WHAT FREQUENCY BANDWIDTH SHOULD BE USED?
3. CAN ULTRASONIC LEAK LOCATION CONFIRMATION BE MADE AT 400°F?

RESULTS

1. TWO POTENTIALLY FEASIBLE TECHNIQUES FOR ULTRASONIC LEAK LOCATION CONFIRMATION HAVE BEEN IDENTIFIED
 - A. - DETECTION OF LONGITUDINAL WAVES AT THE TUBESHEET
 - B. - TRAVERSING A TRANSDUCER ALONG THE TUBE BORE.
2. THE MAXIMUM ULTRASONIC SIGNAL IS EXPECTED TO BE IN THE RANGE 100 KHz TO 300 KHz. FREQUENCIES AS LOW AS 40 KHz HAVE BEEN USED, AND IT IS PROBABLE THAT POWER EXISTS AS HIGH AS 900 KHz.
3. ENVIRONMENTAL DIFFICULTIES WOULD BE MINIMAL USING APPROACH 1(A) AT 400°F, AND RATHER EXTENSIVE USING APPROACH 1(B).

- d) A close-by obstruction can either increase or decrease the noise amplitude.

For a two-phase jet, where most of the noise is generated by bubble dynamics, the frequencies at which maximum power is developed are relatively low. This is the region of the spectrum used for accelerometer array location. It is not expected that this noise can be used to confirm location, although experimental validation of this is required.

3.6.2 Transfer Functions and Leak Location

Two approaches have been considered for locating, by ultrasonics, the leak to a single tube. The first requires that significant sound energy be transferred along the tube to the tubesheet region; the other monitors for sound within the tube bore using a microphone which is lowered through the tube. Both approaches have been used in the field.

In the first approach sound is detected using a transducer mounted at the tubesheet. Sound reaches this transducer either along the gas column in the tube, or by sound waves traveling along the tube wall. Sound waves traveling along the tube wall can be either transverse or longitudinal, but it is considered that only longitudinal wave propagation is feasible for location. The attenuation of a high frequency wave through a column of air within the tube bore is shown in Figure 11. To these losses must be added the substantial losses experienced in coupling the sound from the leak/tube wall into the air column. It appears that a leak signal might be detected if the leak is close to the tubesheet, but the losses are prohibitive for more remote sites. There is evidence that sound waves from the leak site can be transmitted as longitudinal waves to the tubesheet region and be detected. Tests have indicated that a highly trained operator might on some occasions be able to locate the leak position^[8].

The second approach is to lower a microphone through the bore of the tube from the steam chamber. By placing the microphone close to the leak site the prohibitive losses along the air column are avoided. To increase

Figure 11. Attenuation of Longitudinal Waves in a Circular Tube

More difficulties are foreseen with a temporary installation because, in this case, the time required to mount the accelerometers is important. Two alternate techniques are suggested:

- a. Mechanical Attachment - Allow the vessel to cool below a maximum temperature of 480°F (250°C) and then attach accelerometers directly to the vessel wall. This can be a simple mechanical attachment using a single drilled and tapped hole. Such holes would be incorporated into the vessel during design and fabrication.
- b. Attachment with No Prior Vessel Preparation - To install the location system, insulation would be removed from the vessel and accelerometers attached by a bonding technique which might have a relatively short lifetime but would be more than adequate for the four hour time specified for location. Chemical bonding using a ceramic cement such as Aremco 5 has shown promise provided a fairly involved curing process is used. Attempts to bond the ceramic standoff to a hot surface have not been successful. Experiments are in progress to evaluate the use of a magnet which can operate up to ~480°F (250°C).

4.2 Array Geometry Limitations

4.2.1 MATOI Test Rig

The MATOI rig is a foreshortened duplicate of a CRBRP steam generator. The MATOI vessel is 4.2 ft (1.28m) in diameter, has a wall thickness of 2 inches (5 cm) and contains 757 tubes of .625 inch (15.7mm) diameter on a triangular pitch. For the WTD support tests, eight accelerometers were attached to the vessel wall in a single plane. Short (~4m) cables connected the accelerometers to voltage amplifiers and 330 ft (100m) cables connected the amplifiers to the data analysis system in the Acoustic Laboratory. Argon gas was injected at three radial locations in the same plane as the accelerometers.

Tests were also made using a mock-up Super NOAH tube plate and tube. The tube had a 0.0076 cm hole. When gas flowed from the sodium side into the tube it could be detected using a hand-held portable microphone. The microphone held above the leaking tube gave unambiguous detection. However, if the flow was reversed, and gas was injected into the sodium side, there was no detection. This second result is to be expected based upon the earlier discussion of transfer function through gas columns.

Tests in the 50 MW prototype steam generator in the Hengelo test facility indicate that if a microphone is lowered through the tube, a leak can be located. No details of this procedure have been published, and no information on its sensitivity or frequency bandwidth is known.

Recent work at Atomics International using a frequency band of 200 KHz to 300 KHz shows promise for leak confirmation. The approach is to use transducers located on the tubesheet to detect longitudinal waves generated by the leak.

the coupling to the tube wall, either the tube must be filled with liquid, or a remote clamping/unclamping device needs to be provided. If the coupling losses are small then such a device would not be required, and filling the bore with liquid would also be avoided. It is possible that the jet could excite structural resonances in the tube structure; this would amplify the effect of the jet and might increase the detection capability.

3.6.3 Environmental Limitations

If location confirmation is to be made at hot standby conditions ultrasonic examinations will be made at $\sim 400^{\circ}\text{F}$. This is not an excessive temperature for ultrasonic transducers, although care will be required in the selection of a specific model. Tube bore size is probably the most restrictive limitation in the choice of a transducer. Scaling and corrosion on the inner wall should have a minimum effect on the longitudinal wave transmission, but might become a problem for coupling an ultrasonic transducer to the tube wall.

3.6.4 Data Processing

The long cable connecting an in-bore transducer to the data processing equipment would seriously attenuate any signals. Designing amplifier circuits to directly couple to the accelerometer and drive the cable would be difficult for 400°F operating temperature. If the sodium is drained and the vessel cooled, the temperature limitations on the amplifier design would become insignificant. In order to meet the design requirements, ultrasonic confirmation of the location should be accomplished within ~ 30 minutes for each tube. If a traversing accelerometer device is used, the time might be significantly longer. No specific times can be quoted without a particular design and procedure being available.

3.6.5 Current Experience

Tests were made at Dounreay [8] using detection equipment which examined the ultrasonic longitudinal waves transmitted axially along the tube wall and tubesheet. Noise was generated from a steam side fed leak in a single tube. Results indicated that a highly trained operator might on some occasions be able to locate the leak position. However, the tests were not conclusive enough to guarantee that information could be interpreted with certainty.

4.0 RESULTS OF EXPERIMENTAL INVESTIGATIONS

Experimental investigations as outlined in Table 1 are underway or are in preparation. Key test results obtained to date are discussed in this section. These are in two areas: 1) accelerometers and attachment, and 2) array geometry limitations.

4.1 Accelerometers and Attachment

A major factor in the cost of an acoustic location system is the choice of accelerometers. Previous development tests, in particular the background noise measurements on the Hengelo 50 MWt steam generator^[7], used laboratory-grade accelerometers. Recently a much less expensive accelerometer has been purchased and tested using the same mounting technique and found to be fully satisfactory. A typical accelerometer specification suitable for use with the leak location system is given in Table 10.

A comparison between the two accelerometer models was made using the SONAR vessel. Both accelerometers were mounted on ceramic standoffs and attached in the same manner to the vessel wall. A gas bubbler was inserted in the exact center of the SONAR vessel with its injection nozzle in the same plane as the accelerometers. The similarity of the accelerometer responses can be seen in Figure 12.

The method of attachment of the accelerometer to the vessel wall has a major impact on the time to setup the acoustic leak location system. The accelerometer installation can either be permanent, that is, accelerometers installed on all plant steam generators before startup, or the same installations made on the specific steam generator after the leak has been detected during operation and operating conditions reduced to hot standby. A reference mounting technique using a ceramic waveguide or standoff has been developed for the acoustic leak detection system^[1]. If a permanent installation of accelerometers is chosen, this reference mounting technique is preferred.

TABLE 10. ACCELEROMETER SPECIFICATION

Normal Operating Condition	-30 dB re 1g
Dynamic Range Below Operating Condition	-60 dB
Frequency Range	1 kHz to 10 kHz
Mounted Resonance	~ 40 kHz
Sensitivity	3 pc/g
Temperature of Operation	200°C
Maximum Temperature	250°C
Transverse Sensitivity	> 5%
Life	5 years minimum
Weight and Size	Not specified but should be as small as possible so that a high temp standoff may be used.

FIGURE 12. COMPARISON OF ACCELEROMETERS

The display output of the analysis system is shown in Figure 13. Each of the points in the display can be expanded to form a box, and the display is normalized so that one box always reaches maximum size. Each point shown on the display has an equivalent dimension of 2 inches (5cm). The two parameters POWMAX and MAX are absolute measures of the leak size and the signal-to-noise ratio.

4.2.2 Confirmation of Homogenous, Isotropic Medium

The objective of this test was to validate the hypothesis that the acoustic velocity is the same in all directions within a steam generator vessel and that the tube structure "disappears" when measurements are made in the correct frequency band. It was shown that the acoustic velocity will be reduced from that expected for liquid only to an effective velocity for the composite media. The use of an incorrect velocity value results in an incorrect location.

Using a gas injection at the off-center location labeled SIDE, the injection was correctly located with a velocity 67% that for liquid only (see Figure 14). The leak was then repositioned at the edge location and was correctly located using the same reduced velocity (Figure 15). This reduced velocity also gave correct leak location when the leak was moved 42 cm axially out of the plane of the accelerometers (Figure 16).

It is concluded that the media within a LMFBR steam generator can be considered homogenous and isotropic. The correct acoustic velocity must be known or measured for the WTD steam generator designs to obtain true leak locations.

4.2.3 Demonstration of Small Leak Location

At hot standby conditions the main source of background noise will be the electronic noise of the location system amplifiers. A test was made using the MATOI rig to verify location of a very small leak under these conditions. The argon gas injection pressure was less than 5 psig, the orifice size approximately 8 mils (0.02mm) and the gas flowrate was ~3 ml/sec.

15

FIGURE 13. VISUAL DISPLAY OUTPUT (NO LEAK)

DATE : 13-SEP-78
TIME : 14:10:46
MAX : 0.0310
POWMAX: -81.8700

10

FIGURE 14. LOCATION OF SIDE LEAK - LEAK IN PLANE

DATE : 14-SEP-78.
TIME : 08:07:51
MAX : 0.0230 10
POHMAX: -98.7897

FIGURE 15. LOCATION OF EDGE LEAK - LEAK IN PLANE

FIGURE 16. LOCATION OF LEAK DISPLAYED 42cm BELOW PLANE

Figure 17 demonstrates the ability of the acoustic system to locate this very small leak through a 2 inch thick wall. Using the state-of-the-art laboratory system this location would be achieved in about ten seconds of processing time. If a full accelerometer system was used for location, an entire WTD steam generator could be scanned in less than one hour.

Table 11 gives the electronic signal of an amplifier and accelerometer with and without the gas injection. The signal-to-noise ratio for each channel is also calculated. Its minimum value is -22dB. These electronic noise signals were taken over several minutes and averaged. This leads to the possibility of error since variations in the electronic noise level do occur and the difference in level with and without the leak is small. However, an independent estimate of signal-to-noise ratio of $\sim$ -30dB is obtained from the parameter MAX in Figure 17. These values are close to the lower limit of -25dB claimed for acoustic detection/location.

4.2.4 Focussing Along Axis

The objective in making this series of tests in MATOI was to demonstrate that a leak in the convoluted bellows section can be correctly located by focussing a plane, circular array along the vessel axis. The injector was sequentially moved off the plane of the accelerometers and location attempted. The radial position of the injector was successfully located for displacements up to $\sim$ 16.5 inches (42cm) off the accelerometer plane, (see Figure 16).

A calculation performed in the study questioned whether the acoustic pressure wave would suffer total internal reflection at the interface between the vessel wall and the contained liquid. For the MATOI test this effect is predicted to occur when a central located leak is more than 6.7 inches (17cm) off the plane. Successful location up to 23.6 inches (43cm) demonstrates that the hypothesis used in the calculation is incorrect and shows that total internal reflection is unlikely to be a practical problem in the two WTD steam generators.

LEAK RATE 3ML ARGON/SEC
(STP)

DATE : 14-SEP-78.
TIME : 09:25:30
MAX : 0.0300
POWMAX: -78.9815)

30

FIGURE 17. LOCATION OF LEAK AT S/N $\approx$ -25 dB

Table 11. Small Leak Locations in MATOI

Accelerometer Channel		1	2	3	4	5	6	7	8
Signal+Noise* (with gas injection)	Test #1	0.980	0.805	1.009	0.768	0.786	0.950	0.865	0.797
	#2	0.992	0.818	1.021	0.779	0.794	0.974	0.873	0.815
	Mean	0.985	0.812	1.014	0.773	0.790	0.962	0.869	0.806
Noise* (no injection)	#1	0.946	0.702	0.810	0.708	0.716	0.721	0.760	0.761
	#2	0.951	0.698	0.814	0.711	0.711	0.728	0.762	0.765
	Mean	0.948	0.700	0.812	0.710	0.714	0.724	0.761	0.763
Signal $\Delta\%$		3.8	13.8	19.9	8.2	9.6	24.7	23.9	4.1
S/N Ratio dB**		-38	-27	-24-	-31	-30	-22	-22	-37

* Averaged using 0.010 seconds of data digitized and sampled at 100 KHz. 120 separate values then averaged.

** Based on reverberation to direct signal ratio of 3:1 (Minimum measured on MATOI).

4.3 Gas Injection Noise Power

The SONAR vessel was calibrated by assuming it was a reverberent vessel, but that the power generated close to the source would not be effected by the reverberent component. This hypothesis would be correct if the sound pressure close to the source decays as $1/\text{distance}$. It was found that up to ~ 6 cm from the source this relationship could be verified. (See Figure 18). A confirmatory test was made in which power was generated by a calibrated hydrophone, and measured by the wall mounted accelerometers. Both of these tests indicated that the reverberant pressure waves were generating a power 2.3 times greater than the direct pressure waves.

Test data obtained with argon gas injections at ambient and high cover gas pressure are plotted on Figure 19. Noise levels from helium gas injections are plotted onto the same curve. This data indicates that for similar test conditions and gas flowrates, argon gas produces lower noise levels than helium gas jets. Tests in MATOI with argon gas injection are therefore expected to be conservative representations of helium gas injection.

FIGURE 18
CALIBRATION
OF
SONAR
VESSEL

FIGURE 19. SIGNAL LEVEL

5.0 ASSESSMENT OF RESULTS

5.1 Major Conclusions from Analytical Tasks

The major conclusions of each of the six analytical tasks relative to the question of feasibility and the design of the acoustic leak location system are presented in this section.

5.1.1 Geometry Effects

There are no significant stiffness controlled vibrations of the vessel or internal structures in the range 1 KHz to 10 KHz. In the frequency band of 1 KHz to 10 KHz heat transfer fluids and the vessel internals can be considered homogenous with isotropic properties. Attenuation of the signal will be minimal in this frequency band. Therefore, the acoustic leak location system will be designed to operate in a frequency band lying between 1 KHz and 10 KHz. This is the same frequency bandwidth used for the acoustic leak detection system design, and frequency sensitive technology already developed for leak detection (under SG027, Subtask X2) can be directly applied to leak location in the WTD steam generators.

5.1.2 Localization Criteria

Localization to a seven tube cluster depends primarily upon the bandwidth of the noise from the helium leak. If this is less than 10 KHz special array processing techniques might be required, such as oversampling and, in the visual display, identifying the center of a small group of location squares as the leak proper. While the use of these techniques would mean an increase in the time that the signal is analyzed, they do not have a significant impact on the total time required to locate a leak. Coarse localization followed by fine tuning has potential for decreasing leak localization time. The limit to this technique is the signal strength, being most practical for larger leaks.

Leak resolution to within a cluster of seven tubes requires an accurate knowledge of the effective acoustic velocity within the vessel. The effective velocity is highly dependent on the internal structure. Operating parameters such as temperature, pressure, convection currents, sodium flow, etc., have only a minor effect on the velocity.

For a full localization system, the number of accelerometers required is about 20% less than that for a Clinch River Breeder Reactor Plant (CRBRP) steam generator. However, the number of volume elements to be scanned is about six times larger. Therefore, a longer sweep time will be required to examine the WTD steam generators for the same signal-to-noise (S/N) ratio.

5.1.3 Jet Noise

An ultrasonic technique will be used to locate the individual leaking tube once acoustic localization has restricted the leak to a cluster of seven tubes. A literature search on jet noise and characteristics indicates that ultrasonic noise levels are maximum in the 100 KHz to 300 KHz range. Most of this noise is generated close to the defect, within a distance of ten orifice diameters from the surface. Equations giving relative amplitude of the jet noise intensity varies as the jet stream velocity to the eighth power and as the orifice diameter to the second power. Since the flow through the orifice is choked for reservoir pressures greater than ~60 psig, the jet velocity remains essentially constant and the noise intensity will be primarily a function of the orifice diameter. Noise intensity is predicted to increase 4% for every 100°F (56°C) increase above the hot standby temperature of 400°F (204°C). Although ultrasonic jet noise is well characterized, that due to bubble growth phenomena and two-phase jets is poorly understood.

5.1.4 Electronic Hardware Design

The basic system for location is almost identical to that developed for acoustic leak detection in the CRBRP steam generators^[1]. The most significant change is in the increased memory requirements to handle the larger number of volume elements. Accelerometers chosen for the WTD location system will have similar specifications to those for the CRBRP acoustic detection system. Analogue signal conditioning amplifiers, multiplexers, etc., will also have similar specifications.

The main changes will be in the digital signal processing and beam-former signal processing. With a software/minicomputer approach these changes will be minimized. The signal-to-noise ratio for location systems depends primarily upon the signal from the jet noise, and the electronic noise in the amplifier input stage. Operating noise influence on location will be minimal.

5.1.5 Portable System

It is intended that following leak detection during plant operation an acoustic location system will be mounted onto the specific vessel identified as having the leak. The use of a portable leak location system was evaluated in this task.

Four major areas were examined:

- 1) Method of sensor attachment
- 2) Sensor location
- 3) Time required for location
- 4) Resolution.

The time controlling factor is the attachment of transducers to the vessel. If accelerometers are permanently attached to the steam generators (i.e., attached before the plant goes into operation), then achievement of the design requirement of four hours for location appears feasible. If the accelerometer system has to be installed after a leak is detected, the time required will increase significantly and may be on the order of days.

5.1.6 Ultrasonic Leak Location

Based on the jet noise literature search (see 3.3) the frequency range for ultrasonic investigations will be in the range of 100 KHz to 300 KHz. At these frequencies noise absorption in sodium is high. Thus the highest noise intensity will be in the immediate vicinity of the defective tube.

Two ultrasonic systems are under consideration. In the first, a transducer/microphone would be lowered into the tube end to pick up the jet noise in the vicinity of the leak. This technique requires high frequency acoustic coupling between the transducer and the tube wall for maximum efficiency. This approach would use the gas column in the tube as a waveguide with the tube end being monitored. Initial calculations indicate that this technique might be feasible for leaks close to the tubesheets but is much less certain for more remote sites.

In the second system the tube wall would be used as a waveguide, detecting longitudinal waves at the tubesheet. Initial assessment of ultrasonic leak detection at temperatures up to $\sim 400^{\circ}\text{F}$ suggests this is the most promising approach. This technique is being investigated by Atomics International for acoustic detection of water-to-sodium leaks in steam generators with single-wall tubing.

5.2 Areas of Concern and Methods for Resolution

The analytical investigation identified five areas in which experimental tests are required to supplement or correct the analyses. These areas are outlined in Figure 20 and discussed below.

5.2.1 Sound Transmission Across Annulus

The inlet and outlet annuli are about 2 feet (0.6m) in width, separated from the tube bundle by a 3/4 inch (1.9 cm) thick shroud. Sound transmission from within the tube bundle to the vessel wall cannot be predicted with certainty. In the CRBRP steam generator design the combined thickness of the annulus and shroud is a small fraction of an acoustic wavelength and the effect can be predicted. For the Westinghouse Tampa Division (WTD) design this criteria does not apply.

This concern will be resolved by an experiment in which the TILT rig is placed into a water filled vessel (ANTRAC rig). The annulus between the TILT rig and the vessel will be 2 feet in width. Experimental validation of location will be demonstrated before the final report in June 1979.

5.2.2 Bellows Section Response to Acoustic Pressures

The WTD designs have a convoluted bellows section in the shell to allow for differential expansion. Acceleration of the wall in this section by the acoustic pressure waves cannot be predicted with certainty.

This concern has been resolved by experiments in the MATOI rig, which demonstrated that a ring of accelerometers can be focussed into the bellows section to locate a leak. These are discussed in Section 4.2. In addition, experimental measurement of convoluted wall sections will be made in the ANTRAC rig.

5.2.3 Effect of Flow Distribution Baffles on Sound Transmission

The inlet and outlet annuli have perforated flow distribution plates. Sound transmission characteristics across these plates cannot be reliably predicted. This concern will be resolved by an experiment in the ANTRAC rig similar to that described in Section 5.2.1 above. The tube bundle and shroud (TILT rig) will be replaced by a perforated cylinder to model the flow distribution plate. Experimental validation of leak location will be demonstrated before the final report in June 1979.

- Figure 20. Major Areas of Uncertainty

5.2.4 Ability to Achieve Location to Within Cluster of Seven Tubes

Experiments in which helium gas was injected into water suggest that the acoustic width of the jet exceeds a seven tube cluster. This concern will be resolved by an experimental investigation in MATOI using a helium gas injection. Gas will be injected from a modelled defect and located using oversampled data. From this test the expected resolution in the WTD steam generators will be predicted. Test results and the prediction will be in the final report.

5.2.5 Total Internal Reflection

Analysis indicates that a pressure wave would suffer total internal reflection if the angle of the wave to the vessel wall exceeds a critical value. If this were true a limit would be placed on the separation of accelerometers, and the ability to focus into a section of the vessel as suggested in 5.2.2 above, would be severely limited. For a sodium system this critical angle is 26° and for water it is 17° .

This concern was resolved by the same series of tests described in Section 5.2.2 above and discussed later in Section 5.3.2. Pressure impact onto the vessel wall was significant, even when the angle was a factor of three higher than the calculated critical angle.

5.3 Major Conclusions from Experimental Tests

5.3.1 Accelerometer Attachment

A technique for attaching accelerometers to a vessel wall using a ceramic waveguide has been fully tested and reported.^[4] If a permanent installation of accelerometers is used, then this approach is recommended. An attempt was made to adhere the ceramic waveguide to a metal block (simulating the steam generator vessel wall) using a ceramic cement. This technique has promise for short term (days) application provided the attachment is made to cold metal. Application to 600°F metal was unsuccessful, and it is unlikely that a technique can be developed based on currently available ceramic adhesives. The use of permanent magnets for temporary attachment is still under investigation.

5.3.2 Array Geometry Limitations

A potential problem area is location of a leak within the steam generator section bounded by the convoluted bellows in the vessel wall. One method to locate a leak in this section is by focusing planar arrays of accelerometers mounted axially outside the bellows section. Experiments in the MATOI rig have demonstrated that radial location of a gas jet into water can be accomplished by focussing a planar array of accelerometers axially to at least 48 cm. These data indicate that it is feasible to focus into the convoluted bellows section of the WTD steam generator designs and determine the correct radial position of the leak. The correspondence between acoustic velocities in water and sodium is such that 48 cm "side-focussing" in water corresponds to ~145 cm in sodium.

If an incorrect acoustic velocity is used in the leak location computer calculation, the indicated location does not correspond to the true location. Experiments in MATOI indicate the acoustic velocity needs to be known to ~5%. Consideration should be given to including a noise source (pinger) in the vessel design to allow the true acoustic velocity to be measured during pre-operational tests of the plant. A pinger noise source should definitely be included for any WTD steam generators tested.

With the leak in the plane of the accelerometers the argon gas injection rate was reduced until the flowrate was ~3ml/sec. At this flowrate the predicted signal-to-noise ratio is ~-30dB, the background noise being primarily electronic noise in the amplifiers. Location was easily achieved. For comparison, this matches the noise expected for the flow of helium through a hole size of ~0.0015 inch with a reservoir pressure of 300 psi.

5.3.3 Helium Gas Injection Noise Level

The SONAR vessel has been calibrated by a series of tests so that absolute noise power of gas injections can be accomplished. Helium gas was injected into water at ambient conditions through a nozzle of ~0.2 mm (0.008 inch). The injection rate was varied by increasing the gas pressure. Absolute noise levels were also measured using argon gas. These data indicate that, for similar test conditions and gas flowrates, helium gas jets produce higher noise levels than argon gas jets. Tests in MATOI with an argon gas bubbler are therefore expected to be conservative.

6.0 WORK PLAN

The schedule for the WTD Phase One tests is shown in Figure 21. As indicated by this diagram the balance of the feasibility study is experimental. The final report in June 1979 will give a complete assessment of feasibility and the development needs for an acoustic leak location system for both WTD stream generators designs.

FIGURE 21. SCHEDULE W-TD PHASE ONE

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