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ACOUSTIC LEAK DETECTION/LOCATION SYSTEM FOR SODIUM HEATED STEAM GENERATORS

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ABSTRACT

The design of an acoustic leak detection system to monitor for sodium-water reactions in a LMFBR steam generator is described. The detector is based on similar techniques to passive SONAR. It relies on the only absolute parameters associated with a sodium-water reaction: the leak is stationary in space and generates noise. By forming an array from externally mounted sensors and using statistical processing techniques, signals masked by the general background noise can be recovered. Supporting experimental and analytical investigations are also described. Predictions are made of the detection sensitivity of an acoustic leak detection system for an LMFBR.

INTRODUCTION

This paper describes an acoustic small leak protection system which detects and locates leaks in a liquid sodium heated steam generator. It locates a leak in the heat transfer tube to within 6 centimeters, with a sensitivity to leaks as small as .06 mm equivalent diameter.

Should a leak be detected, the plant is shutdown. The leak must then be located, repairs made by plugging each end of the defective tube(s), and the steam generator returned to service. Location of the defective tube after shutdown can be a time consuming problem. Within a steam generator loop, the total length of heat transfer tubing exceeds 50 kilometers. To find a microscopic hole or crack becomes an almost impossible task. Compounding the problem, a small hole will invariably plug with cement-type reaction products during shutdown of the steam generating system.

This acoustic small leak protection system has the potential for rapid detection of sodium-water reactions, particularly at part load conditions where transit of reaction products to a chemical sampling station can be excessively long. It is also the only known technique for locating a leak while the plant is operational.

DESCRIPTION OF ACOUSTIC LEAK DETECTION/LOCATION SYSTEM

System Overview

A schematic design for the acoustic leak detection system is shown in Figure 1. Approximately 200 accelerometers are mounted on the steam generator vessel. Each accelerometer is connected to an amplifier mounted near the steam generator. A

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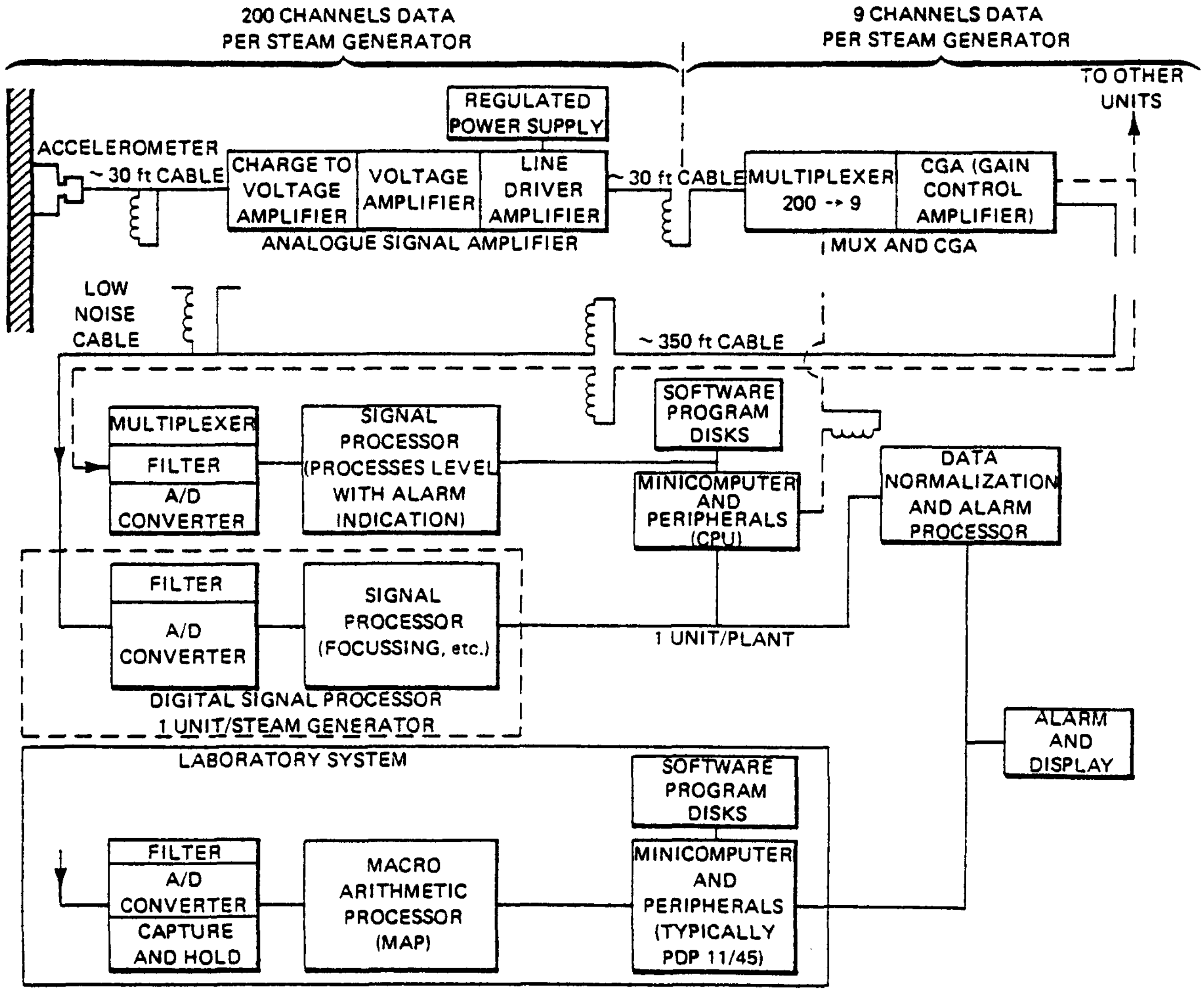


Figure 1. ACOUSTIC LEAK DETECTION SYSTEM

multiplexer is used to select nine of the accelerometer signals at a time, and feed these through an automatic gain control amplifier to the signal processing equipment located in the plant control room. The analog signals are bandpassed and converted to digital form before signal processing. It is assumed that the leak is stationary within a cell so that the acoustic propagation time from the leak to each sensor is constant. Data arriving at the sensors are examined for spatial coherence by a technique known as beamforming. Randomly distributed data are eventually cancelled by the averaging technique, but data associated with the leak site will build up until they are significantly different from the background level.

Control of signal selection, processing, and alarm is provided by a minicomputer functioning as a central processing unit (CPU). It will be noted that two approaches for digital signal processing are indicated in Figure 1. One uses custom designed, hardwired signal processors which operate close to real time. The second approach is a Minicomputer/Macro

Arithmetic Processor (MAP) software based system which provides more programming flexibility than the hardwired system, but sacrifices calculational speed.

Significant reductions in data processing time can be achieved if an additional non-dedicated processor is used for confirming alarm indications before warning the operator. The non-dedicated processor is routed to the level with a leak indication while the first processor continues to sweep the vessel volume level by level. If a leak condition is confirmed, the operator is warned. The non-dedicated signal processor collects data at rates up to 200 times faster, since it remains at the suspect level while the dedicated processor cycles along the vessel.

The performance and design of an acoustic leak detection system are quite dependent upon the geometry of the physical system being monitored. This aspect of the operation of an acoustic detection/location system has been covered in an earlier paper.[2] Based on that report, it is assumed that:

a) The system will operate with a bandwidth of 1 kHz to 10 kHz.

b) Signal pressure amplitude decays inversely as the distance from the source.

c) The vessel wall reacts in an inertia-controlled manner to pressure fluctuations on the inner wall.

d) The spatial distribution of volume focal points is $\sim$12 centimeters.

Analog Signal Processing Subsystem

Two hundred accelerometers, arranged in a predetermined pattern approximating a two-start helix, monitor shell movements resulting from fluctuating acoustic pressures. At any given time, nine contiguous transducers will be transmitting data to the system. Data from eight of these will be used to observe one level of the steam generator. The observed level will be at the axial center of the accelerometers forming the array. For each level change, one "new" accelerometer is added and the "oldest" accelerometer is dropped. This allows the "new" accelerometer to accumulate data for beamforming. Thus, beamforming on the new level is not delayed.

Signals from the accelerometers are amplified and fed to a two-hundred channel multiplexer. Control signals from the processor switch the multiplexer to route nine accelerometer signals onwards. These nine signals are amplified to a level matching the input requirements of the analog-to-digital converter, the gain being controlled by feedback from the CPU.

Digital Signal Processing Subsystem

Data analysis is based on similar techniques to those used in passive SONAR. An array is formed by beamforming the eight channels of data. This is the summation of signal samples from each accelerometer with the signals taken at slightly different times. Digital system processing is used to:

a) Focus the array sequentially onto the 70 volume elements in the steam generator level under observation.

b) Measure the acoustic power at each focal point.

c) Accumulate sufficient data so that a statistically significant estimate is obtained.

d) Compare this estimate with a threshold criteria.

e) Decide if there is reasonable probability that a leak is present.

The focusing operation is performed by delaying the accelerometer signals by an appropriate time, corresponding to the propagation delay from the focal point to the transducer. The accelerometer signals are added and squared to provide an estimate of the acoustic power from the focal point. Data are accumulated for a period of time to give an improved estimate of the noise power. This estimate is compared to a threshold criteria; if there is a significant probability that a leak exists, a signal is sent to the CPU.

Upon receipt of a signal, the central processing unit sends appropriate control signals to a multiplexer which switches the eight accelerometers at the alarmed level to a non-dedicated digital signal processor (see Figure 1). This processor operates in an identical manner to the first, monitoring the cells in the alarmed level while the first processor continues to sweep the vessel volume, level by level. The non-dedicated processor substantially reduces detection time without removing detection capability from the remainder of the vessel volume. To detect very small leaks with a low probability of false alarm, the digitized signals may have to be accumulated for an appreciable length of time, possible an hour.

All digital signal processing, including beamforming, is performed in a microprocessor. There is one microprocessor for each steam generator vessel in a power plant. The microprocessor and its associated memory forms a slave node to the CPU. The CPU performs all necessary bookkeeping and control functions.

Normalization and Alarm Subsystem

There are two approaches to determine if a leak exists in the steam generator. In the first approach, the absolute value of the noise power is compared to a threshold level. In the second, the data from one focal point are compared either spatially or temporally with its neighbors. If an absolute determination is used the focused data will have to be normalized to allow for variations in vessel geometry, transducer variations, signal conditioning factors, and operating conditions. If a relative determination is used, then many of these factors can be ignored. Data from an operating plant indicated that significant acoustic power variations can be measured along the vessel axis, and both this variation and the absolute levels are a function of operating conditions.[3,4] An absolute threshold system would require extensive lookup tables, with the implicit assumption that all operating effects can be accurately predicted. Data normalization is, therefore, the current design approach, and adaptive normalization schemes of data analysis have been developed.

Since the inception of the development of the acoustic leak detection/location system, the operator interface has been considered to be one of the most important aspects of the design. A simple, visual, three-dimensional display has been developed, Figure 2, to summarize many channels of information. Data used to generate such displays will be stored for subsequent display of acoustic history and to provide data trends.

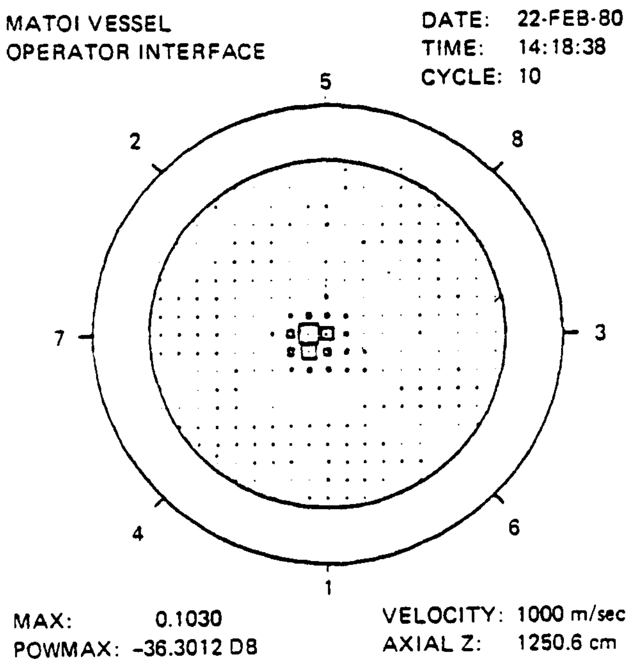


Figure 2. OPERATOR INTERFACE VISUAL DISPLAY

Alarm Criteria

The extreme sensitivity of the detection system increases the potential for false alarms and reduced plant availability. Alarm levels must be set to provide protection while minimizing detection errors. If alarm levels are set too high, then damage propagation to large leak conditions will occur. If the level is set too low, then spurious power plant shutdowns will reduce plant availability and ultimately, plant reliability; since, each scram or rapid shutdown exposes equipment to thermal and mechanical transients. Sufficient estimates of acoustic power from a given focal point are required before a prediction can be made on the probability that a leak exists at that point.

The parameters affecting the acoustic leak detection system sensitivity and response time are signal level, background noise level, probability of false alarm, probability of missing leak, vessel sweep time. For a given physical system, the tradeoff between these parameters becomes one of economic criteria. For example, the system response time could be reduced by a factor of ~200 if a signal processor was provided for each level of the steam generator. However, the cost of the system would increase significantly.

DEVELOPMENT SUPPORTING DESIGN OF ACOUSTIC LEAK DETECTION/LOCATION SYSTEM

Accelerometers

A thermal standoff has been designed and tested to give a reference accelerometer mounting system. Criteria for this design include:

a) Provide a transfer function that is linear and without resonances in the frequency band 1 kHz to 20 kHz.

b) Provide electrical isolation of the accelerometer to eliminate instrumentation ground loops.

This technique of mounting accelerometers on thermal standoffs, shown diagrammatically in Figure 3, was tested and found to give satisfactory vibrational, thermal, and electrical characteristics. Accelerometer replacement while at operating temperatures has been demonstrated, and a lifetime of at least one year has been obtained in a plant environment.

Amplifiers

Accelerometers are generally piezoelectric transducers in which a charge is generated at a rate directly proportional to the wall motion. The source impedance is very high, usually hundreds of megohms. The amplifier, therefore, must operate in a

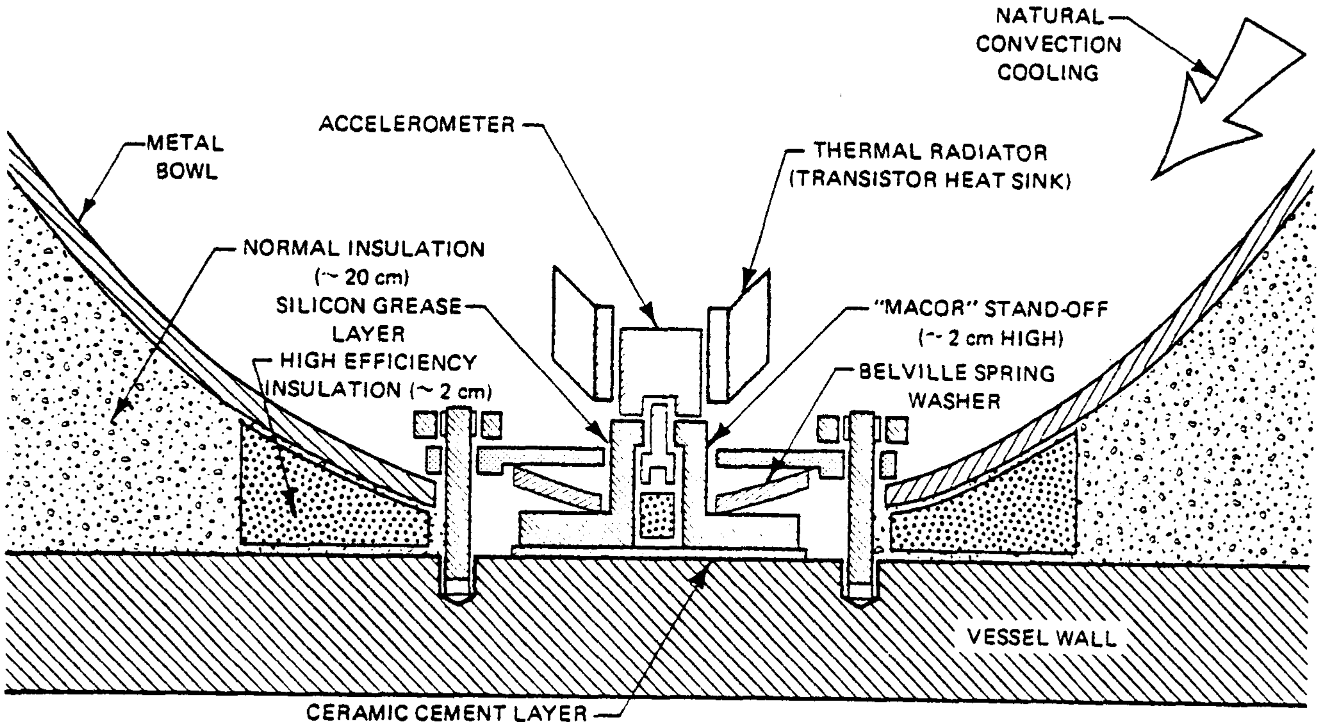


Figure 3. ACCELEROMETER ATTACHMENT CONCEPT

charge sensitive mode or have a very high input impedance in the frequency range 1 kHz to 10 kHz. Several factors, such as small size, frequency range, and acoustic pressure amplitudes, combine to produce a signal level that is electronically small. This implies that the input stage of the amplifier has to be carefully designed, since for many operating conditions, the inherent noise associated with the first stage will constitute the background noise. The amplifier must operate at extremely low input signal levels, but it must also be capable of handling an extremely large dynamic range. At full power, the wall motion approaches levels which give accelerations on the order of 1g compared to less than 1 milli-g at power plant standby conditions.

The acoustic leak detection system is a coherent signal measuring device. Therefore, it is even more important that the coherent noise between the amplifier channels be reduced to extremely low levels. Incoherent noise from the channels forming the array produces only a relatively small change in signal-to-noise ratio, but coherent noise leads to erroneous predictions since it is recognized as a signal. Each steam generator requires approximately 200 amplifiers or about 1800 per plant. With this number of channels, it is essential that the unit cost of the analog amplifier be low. A custom design using commercially available components (operational amplifiers, integrated circuits, etc.) was completed and a breadboard unit fabricated to demonstrate that noise levels were satisfactory.

Multiplexing and Controlled Gain Amplifiers

It is expensive and unnecessary to route 200 channels per steam generator unit to the control room. A multiplexer close to the vessel can be used to reduce this to nine channels. An analog multiplexer performs this sequential selection of sensors, routing the signals to nine cables connecting the multiplexer to the controlled gain amplifiers (CGA). The input to the analog conditioning circuit can change by ~50 dB between quiescent plant operation and operation at power with boiling and flow noise. The signal level transmitted to the control room should be at as high a level as is consistent with the input characteristics of the filters and analog-to-digital converters. This will reduce the significance of e.m. pickup noise in the 120 meters of cable connecting that part of the system in the steam generator cell with the part in the control room. The signal processor maintains the correct data relationships between the nine data channels selected and adjusts the gain of the CGA.

A sixty-four channel input, to eight channel output, multiplexer circuit was designed, fabricated, and tested. Output from the multiplexers fed eight controlled gain amplifiers built in the same package. All circuits were fed from a common power supply. A PDP 11/45 provided multiplexer control logic through an I/O board. Multiplexer output was amplified automatically by computer generated control signals to provide an optimum signal into the analog-to-digital converter (10 v p-to-p maximum). A software program written for the PDP 11/45 provided all control signals. The PDP 11/45 also performed the function of signal processor.

Digital System Processing

Sufficient digital processor system design was completed to provide confirmation that an acoustic detection system could be built using commercially available components. The digitized signals from the nine accelerometers are stored in memory and beamformed using an address processor. After beamforming is completed, the acoustic power is measured and the process data stored in accumulators. These operations will be performed in a digital signal conditioning subsystem constructed of standard ITL logic. Approximately 108 integrated circuits are required to construct this subsystem.

Detection/location of a small signal in a high background noise, both signal and noise having similar spectral character, has been demonstrated using minicomputer/software simulation of the digital processor. Accelerometers were mounted on a full-size water model of the steam generator. Signals were amplified using Tektronix AM502 voltage amplifiers and transmitted over ~75 meters of co-axial cable to Biomation 1015 Waveform Recorders. The cable was deliberately routed alongside electrical power supply busses, experienced temperature gradients, was pulled through conduit, etc., to simulate a power plant environment. The minicomputer (DEC PDP 11/45-RT 11) read the digitized data from the Biomation and performed the appropriate manipulations. Beamforming was accomplished in a similar manner to that used in a hard-wired design. Data were shifted in time within the computers to focus onto the element being interrogated. The acoustic power was calculated by adding the signals from each accelerometer at the correct phasing, and the resultant squared to give the acoustic power.

The DEC PDP 11 minicomputer controlled a 64 to 8 channel multiplexer to give sequential arrays of accelerometers. Gain was set by the computer using a digitally controlled amplifier with a gain variable from 1 to 128. The software program sequentially stepped through twenty array configurations, estimating the noise power in ~450 volume elements per level. The technical concepts used in the minicomputers are identical to those proposed for the hardware approach.

PREDICTED ACOUSTIC DETECTION SYSTEM PERFORMANCE

Signal-to-Noise Ratio

The most important parameter in predicting system capabilities is the signal-to-noise ratio. Measurements have been made of signal levels from the sodium-water reactions, and of the background noise amplitudes associated with sodium flow, water boiling, steam flow, reverberation, farfield noise, and electronic noise.

Signal Levels Associated with Na/H_2O Reactions

A special test rig was designed, built, and calibrated to provide absolute acoustic power measurements of small sodium-water reactions. Tests can be made under similar conditions to those expected under power operation of LMFBR steam generators.

The character and amplitude of the acoustic pressures associated with a sodium-water reaction at different sodium cover gas pressures are summarized in Figures 4 and 5. The first figure shows acoustic pressure amplitudes of the signals are similar, but high cover gas pressure appears to increase the high frequency component. Figure 5 compares the noise for a sodium-steam reaction and a sodium-liquid reaction. The liquid reaction has a lower amplitude and less high frequency components than the steam reaction. The auto correlations confirm the expectations of the spectrum curves. The sodium-steam reaction with high pressure has a noise bandwidth of approximately 7 kHz. The bandwidth for a liquid water injection is approximately 3 kHz with low cover gas pressures. The predicted acoustic pressures on the inside of a steam generator shell are given in Figure 6 for a range of H_2O injection rates.

Background Noise Measurements

In a power plant at hot standby or in a test facility, the leak noise is masked by electronic noise associated with the accelerometer and first stage of the amplifier, and also by reverberation of acoustic energy from the leak within the vessel volume. In an operating plant, process fluids will also produce background noise. The main components can be classified as follows.

a) Sodium flow noise: due to turbulent fluctuation against the vessel wall.

b) Steam flow noise: due to turbulent fluctuations within the heat transfer tubes distributed throughout the vessel volume.

c) Phase change noise (boiling): due to liquid inertial forces resisting bubble formation, noise is generated within the heat transfer tubes.

An investigation into flow and boiling noise amplitudes measured on a prototype of the SNR 300 steam generator has been reported.[3] The noise generated by boiling was measured over a range of operating conditions in a helical coil steam generator. Initially the noise increases as the intensity of nucleate boiling increases. A limiting

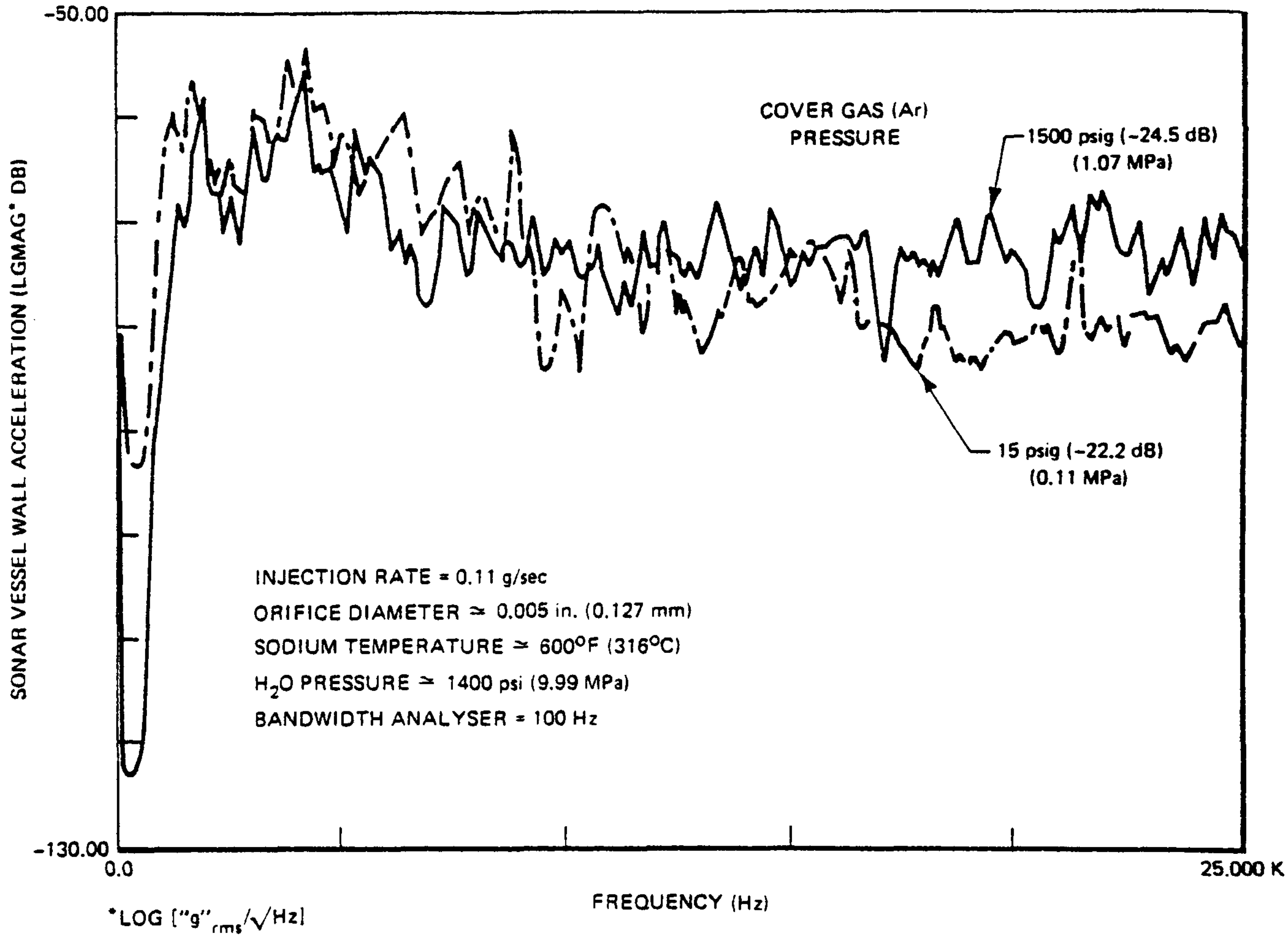


Figure 4. SODIUM-STEAM REACTION – EFFECT OF Na PRESSURE

amplitude results when inertia controlled bubble growth is restricted by thinning of the liquid layer at the tube wall. The noise amplitude then falls sharply as the liquid boundary layer becomes unable to sustain bubble growth. It is expected that maximum boiling noise will be associated with maximum nucleate boiling heat transfer.

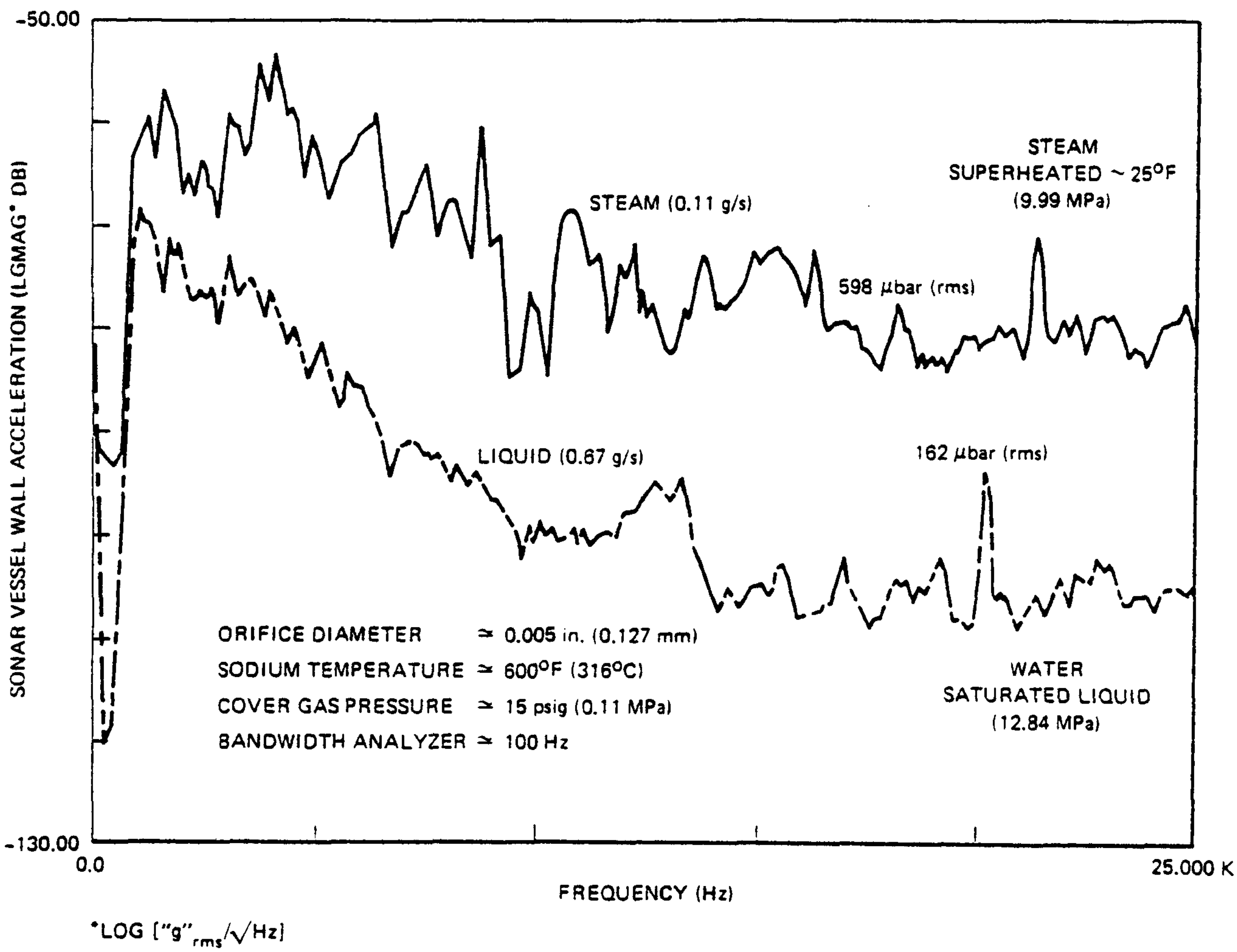
An investigation into sodium flow noise and steam flow noise measured on the EBR-II steam generators has been reported.[4] Tests at isothermal conditions provided measurements of noise generation by sodium flow. Earlier measurements of shell side flow noise had been made using water flow through the hydraulic test model and in a nineteen-tube bundle in the sodium test facility CCTL at ANL. The data from EBR-II matches the data from the HTM and CCTL test facilities. For design purposes, the following equation is used:

$$A_F = 40\ V_{Na}^{3}$$

where A_F = acoustic pressure inside wall of vessel (μbar)

V_{Na} = sodium flowrate (m/sec)

The prime motivation in making measurements on the EBR-II superheater was to investigate noise generation due to steam flow inside the tubes. Steam flow in the



*LOG ["g"$_{rms}$/$\sqrt{Hz}$]

Figure 5. Na/H_2O REACTION NOISE (EFFECT OF PHASE)

tubes is the main source of background noise at full power.

$$A_s = 0.038\ V_s^3$$

where A_s = acoustic pressure inside wall of vessel (μbar)

V_s = velocity of steam (m/sec) in the tubes at the outlet.

Transfer Function Experiments

A series of experiments have been made on a shortened model of an LMFBR steam generator. From the test data, it is concluded that the internal structures blend into the fluids to produce a medium which is homogenous and has isotropic properties in both axial and radial directions. During these tests, measurements were made not only along the tube bundle, but also across the anti-vibration support structure. No significant effects were noticed due to the support structure, as predicted earlier.[2]

Detection Predictions

Using data from signal noise power and background noise power experiments, the detection characteristics were calculated for a typical LMFBR steam generator. Detection times are calculated using statistical theory for the difference in the means of data populations with and without a leak. The predictions indicate substantial protection is provided at hot standby and operating conditions up to ~40% power for both evaporator and superheater units.

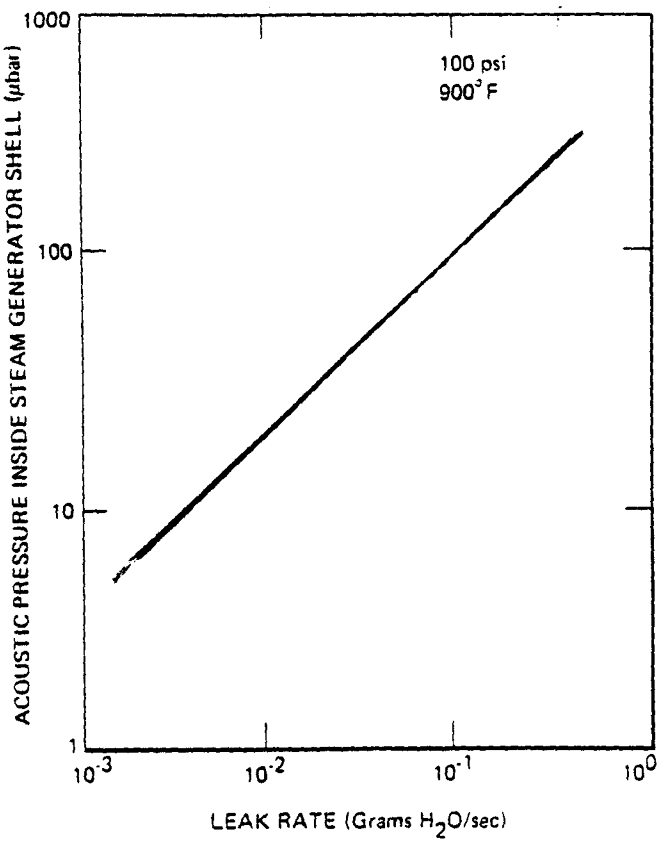


Figure 6. ACOUSTIC PRESSURES GENERATED BY Na/H_2O REACTION

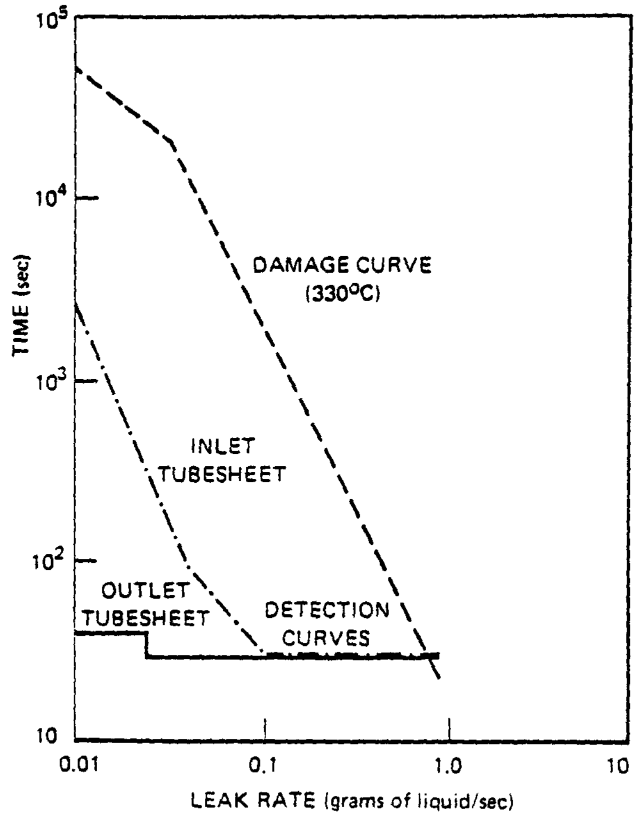


Figure 7. ACOUSTIC LEAK DETECTION FOR LMFBR EVAPORATOR, TUBESHEET AT 40% POWER

Substantial detection capability is also provided for the evaporator units at full power. At 100% power, detection capability in the superheater is limited due to the significant steam flow noise. Typical detection curves are shown in Figures 7 and 8. It is worth noting at this point that detection time (wastage) requirements are a function of operating temperatures.[1] Since the acoustic detector is specific to a region of the vessel, and significant axial temperature variations exist during operation, credit can be taken in cooler regions. A chemical detector must assume that the leak is in the maximum temperature region of the vessel since it is non-specific.

SUMMARY

An acoustic leak detection/location system has been designed and tested. Following a feasibility study, a concept design was completed.[2] A design suitable for use on a LMFBR has been completed and preliminary cost data obtained. It has been demonstrated that low cost accelerometers attached to a specially designed thermal insulating waveguide are suitable for plant operation. Analog signal conditioning equipment has been designed, fabricated, and tested including a special purpose charge amplifier having a wide dynamic range and low noise characteristic and a computer controlled multiplexer and controlled gain amplifier.

Signals from real and simulated sodium-water reactions have been beamformed at the correct sample rates. Hardware systems have been simulated using a mini-

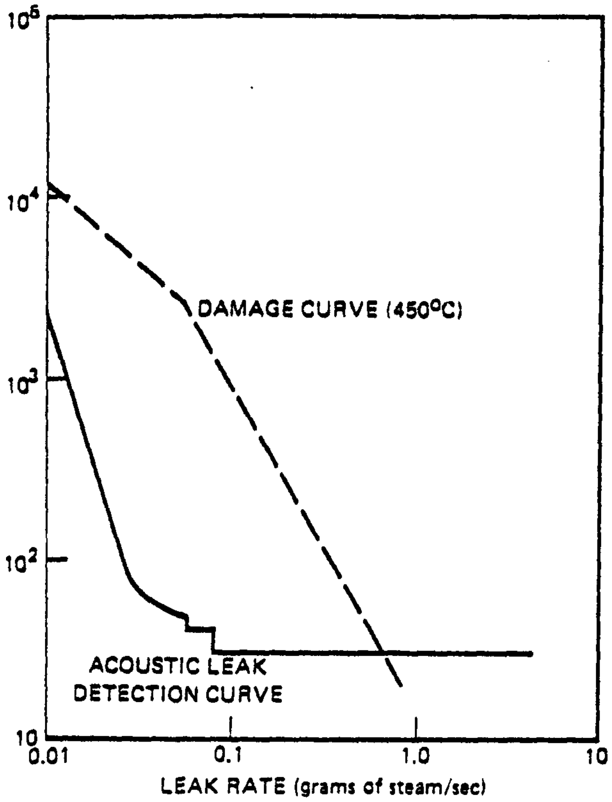


Figure 8. ACOUSTIC LEAK DETECTION FOR LMFBR EVAPORATOR, SODIUM INLET AT 100% POWER

computer. Both time and frequency domain beamforming techniques have been demonstrated using a DEC PDP 11/45 and CsPi MAP float-point processor.

A prototype acoustic leak detection system is operational in the GE-ARSD Acoustic Laboratory. It will shortly be expanded to a multi-channel system which will operate around the clock to provide reliability data. Test data have been obtained which provide estimates of the probable performance characteristics and detection capabilities on an LMFBR steam generator.

ACKNOWLEDGEMENTS

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