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GAAD SYSTEM DEMONSTRATION OF RAPID ACOUSTIC DETECTION OF SIMULATED INTERMEDIATE WATER LEAK IN PROTOTYPE STEAM GENERATOR

D. A. GREENE
J. W. MALOVRH
D. C. GAUBATZ
C. A. CALKINS

U.S. DEPARTMENT OF ENERGY
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AUTHORS: D. A. Greene, J. W. Malovrh, D. C. Gaubatz, and C. A. Calkins

Approved: PR Pluta
P. R. Pluta
Manager, Engineering

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GAAD SYSTEM
DEMONSTRATION OF RAPID ACOUSTIC DETECTION OF SIMULATED INTERMEDIATE WATER LEAK IN PROTOTYPE STEAM GENERATOR

ABSTRACT

Leakage of water into sodium in a Liquid Metal Fast Breeder Reactor (LMFBR) steam generator can rapidly lead to multi-tube failures, with serious economic losses, unless early correct actions are taken. The General Electric Advanced Acoustic Detection (GAAD) system was developed to provide this early warning of leakage. It also provides location of the leak.

Part I of this report describes a successful demonstration test in the Prototype Steam Generator installed in the Sodium Components Test Installation (SCTI) at the Energy Technology Engineering Center. The demonstration test proved the General Electric Advanced Acoustic Detection (GAAD) system will detect and locate intermediate size, water-into-sodium leaks. This will be achieved within 7.5 seconds with only one false alarm in thirty years when the detection algorithm is transferred from the computer to dedicated hardware/firmware.

Part II describes leak detection and alarm requirements for both chemical and acoustic detectors monitoring the prototype steam generator installed in the SCTI. Acoustic detection criteria to meet these requirements were programmed into the GAAD system, with the added requirement of a very low false alarm rate.

SUMMARY

Intermediate water leaks from heat transfer tubes in sodium-heated, steam generators produce severe damage to the tube bundle. An intermediate water leak ranges from approximately 0.01 lbs/sec (5 gms/sec) up to about 2 lbs/sec (1 Kg/sec), or hole diameters from about 0.010 inch (1/4 mm) up to 1/8 inch (2 mm). Water-into-sodium experiments in a full-scale steam generator model showed that this damage could be minimized, if detection of the leak and corrective action occurred within 40 seconds. The timescale is too short for effective operator intervention, and can only be satisfied by an automatic shutdown system activated by suitable leak detection systems. The primary candidates for leak detection are based on monitoring the steam generator for the sounds produced by the sodium-water reaction. Acoustic detection systems have the potential for rapid response, and the added ability to locate the leak within the vessel.

General Electric developed an advanced acoustic detection/location system under U.S. Department of Energy sponsorship. Earlier experimental and analytical programs validated individual aspects of the monitoring system design and algorithms. Testing of a prototype steam generator in the Sodium Component Test Installation (SCTI) at the Energy Technology Engineering Center provided an opportunity to perform a demonstration test on the General Electric Advanced Acoustic Detection (GAAD) System. A gas injection system was installed into the prototype steam generator to simulate a small sodium-water reaction. Test conditions were carefully predefined, and SCTI conditions set to produce a signal-to-background noise which simulated an intermediate water injection under "worst-case" steam generator operating conditions.

The detection algorithm used in the GAAD system is generic in concept, and the successful demonstration test validated the underlying assumptions and algorithms of the GAAD system. The GAAD systems installed on the SCTI facility had one major limitation: the primary beamforming algorithm was implemented in software to provide design flexibility during the system development. As a result, the system did not operate in "real-time." The detection algorithm can be implemented in current hardware/firmware and reach correct operating speed for real-time operation. No change in logic from that tested in the demonstration is needed. [1]

Two demonstration tests were completed, in which two independent GAAD systems monitored the steam generator during the simulated intermediate sized water injection. Both quickly detected and located the injection site in each test. Post-test analysis of the data showed that if the algorithm had been implemented in hardware/firmware the GAAD system would have achieved detection within 7½ seconds. The predicted false alarm rate was one indication in thirty years operation. The test data validated the assumptions and hypothesis underlying the detection/location algorithm, and indicated the generic system design can be applied to most LMFBR steam generator geometries. The demonstration tests showed the GAAD system met the primary objective of the predefined test plan. Data from the demonstration tests suggest the cost of the GAAD system for an LMFBR steam generator protection system will be lower than predicted earlier.

Prior to initiating the thermal-hydraulic test program on the Prototype Steam Generator, the GAAD systems were incorporated into the SCTI small leak protection system. Significant acoustic leak detection system development resulted. In particular long-term data storage, operator interfaces, and off-site monitoring techniques were refined. Detection criteria, protection needs, and facility requirements were analyzed, system performance refined, and an acoustic leak detection system implemented. As a result, the GAAD system rapidly evolved from a developmental system into an operational leak detection system during the SCTI/Prototype Steam Generator program.

Following an initial shakedown period of co-current GAAD system development and implementation as a facility monitor the acoustic system operated without false alarms. Significant facility operating transients and external noise/vibration sources were experienced, including:

a) Blasting activities to form chambers 43 feet deep in the building bedrock foundation.

b) Drilling the bedrock with a four-foot diameter auger to provide piles for the new steam generator cell.

c) Testing of shuttle rocket engines at the nearby Rocketdyne facility for up to several minutes resulting in extensive vibration transmissions to the vessel.

d) Scram of the SCTI facility, normal and fast thermal/hydraulic transients, and control valve operation, etc.

During each of these far-field noise generation events no significant change in detection characteristics occurred, and no false alarms were generated. Normal process operation transients and scrams were accommodated without alarms being generated by the GAAD system.

Experience showed that external, or far-field noise caused a general increase at all locations in the vessel. As a result the local signal-to-noise ratio actually decreases for the duration of the far-field noise; or a slight decrease in the sensitivity of the GAAD system to detect a given size leak.

The only event activating the GAAD system alarm annunciation was steam leakage from the steam generator water/steam flange. The GAAD system detected steam-to-air leakage from the flange approximately twenty-four hours prior to detectable quantities of water appearing external to the flange thermal insulation (i.e., about one cupful of water after twenty-four hours). Indications were generally isolated to accelerometers on the massive tubesheet. Accelerometers a few inches from the tubesheet did not have a strong coherent component from the flange leak. Although it would have been possible to reconfigure the GAAD system to avoid sensitivity to this leak, no changes were made. A unique location diagram resulted when the leak existed. The SCTI operators used this as an early indication and adjusted operating parameters to correct the situation causing the leakage.

A number of leak detection systems, based on different detection mechanisms, have been considered as candidates for installation into an automatic shutdown system to protect against intermediate sized water leaks. The General Electric Advanced Acoustic Detection System appears to meet most requirements. And if the detection algorithm is implemented in hardware/firmware to provide real-time monitoring capability, the resulting integrated advanced acoustic detection (IGAAD) system meets all requirements. The importance of this successful demonstration test of the GAAD system to the overall U.S.-DOE program on automatic leak protection systems for LMFBR steam generators is discussed fully in Section 6 of this report.

GAAD SYSTEM
DEMONSTRATION OF RAPID ACOUSTIC DETECTION OF SIMULATED INTERMEDIATE WATER LEAK IN PROTOTYPE STEAM GENERATOR

PART I

SCTI DEMONSTRATION TESTS

1.0 INTRODUCTION

1.1 Background

A prototype steam generator was tested in a 76 MW_T steam generator test facility at the Energy Technology Engineering Center (ETEC), California. It was installed into the Sodium Component Test Installation (SCTI), and underwent a thermal-hydraulic performance program. An ancillary test program on chemical and acoustic leak detection monitors was completed in conjunction with the prototype steam generator tests.

Operating experience in Liquid Metal Fast Breeder Reactors (LMFBR) power plants and test facilities indicates a rapid leak protection system is needed [1-7]. A series of experiments with intermediate sized leaks in the Large Leak Test Vessel provided criteria for such a protection system [8,9]. Full details of the Prototype Steam Generator test program have been published elsewhere [10].

This report covers the complementary acoustic detection program, and the demonstration test of the General Electric Advanced Acoustic Detection (GAAD) system.

1.2 Test Objectives

Objectives for the acoustic monitor system test were defined prior to the start of the Prototype Steam Generator/SCTI program [Appendix A]. The main objective was to demonstrate the acoustic monitor could meet LMFBR steam generator automatic shutdown requirements. This objective was to be met by detecting a simulated water-into-sodium leak under specified thermal-hydraulic conditions in the prototype steam generator. The objectives specified prior to the test program were:

a) Permit demonstration of the acoustic system's performance.
b) Provide the best acoustic simulation of a leak equivalent to a signal-to-noise ratio of -10 dB (i.e., equivalent to 0.01 lbs H_2O/sec with worst acoustic case plant operating conditions).
c) Allow extrapolation of performance to breeder reactor plant "worst acoustic case" operating conditions for acoustic detection.
d) Detect this "fast shutdown" leak within an equivalent of 20 seconds of real time data.

The General Electric Advanced Acoustic Detection (GAAD) system in successfully meeting these objectives demonstrated its potential for protecting LMFBR steam generators against intermediate sized, water-into-sodium leaks with only one false alarm in thirty years.

1.3 Acoustic Simulation of Leak

The demonstration test provided data which allowed the underlying assumptions of the detection algorithm to be checked out. Earlier experimental and analytical programs validated individual assumptions. The demonstration test was the first in which detection algorithm assumptions and system criteria were integrated, and allowed validation in an environment that approached prototypical conditions of a power plant.

It was impractical to inject water at intermediate leak rates into the sodium in the prototype steam generator. Therefore, the demonstration test was performed with system conditions which acoustically simulated an intermediate water leak into a steam generator operating at full power.

Acoustic similarity required a local signal-to-noise ratio of 0.1, or the signal power was one-tenth of the background noise power (-10dB signal-to-noise ratio).

The sodium-water reaction signal was simulated by injecting inert gas into the sodium in the prototype steam generator. Earlier experimental programs indicated the acoustic energy of the gas injection signal saturated at a lower level than expected for the injection of an intermediate sized water leak. The correct signal-to-noise ratio was produced by adjusting the operating conditions to obtain background noise levels of the correct level relative to the gas injection noise.

1.4 Extrapolation of Acoustic Detection System Performance

The detection algorithm used in the GAAD system is generic in concept. Proving the underlying assumptions will allow extrapolation to any steam generator geometry or operating conditions.

The General Electric Advanced Acoustic Detection (GAAD) system used a detection algorithm based on statistical analysis of data from an array of sensors. Approximately 170 accelerometers were attached to the outside of the steam generator vessel in a double helix pattern. Any eight sequential accelerometers could be chosen to monitor a specific axial plane of the steam generator. Any helix of eight accelerometers covered an axial length of 84 cms or less. The detection algorithm analyzed a single axial plane located within the helical array of sensors; successive planes were treated identically.

The axial plane was considered to be a regular mesh of individual noise generators, each separated by approximately 12 cms. The noise within the vessel resulted from the integrated effect of each of these individual sources on every plane. Each axial plane was separated by approximately 12 cms. The noise amplitude associated with each generator was measured by "focusing" the accelerometer array onto the presumed source locations in each plane.

An analogy can be drawn between the noise amplitude and measurements of an alternating electrical voltage. The average voltage measured over many cycles will be zero, and similarly the average noise amplitude will be zero. If an offset is made to the alternating voltage by adding a small direct voltage, then the average voltage will be the value of the offset. The appearance of a small-sodium water reaction within the plane has a similar effect, causing the data associated with its location to indicate an offset. The offset power is named CORCO.

The assumptions tested were:

a) The mean CORCO value approaches zero as the number of cycles of pressure pulse data analyzed increases. This is true for all locations.
b) The standard deviation of the CORCO measurement is predictable.
c) The mean and standard deviation are independent of the level of the background noise.
d) Data from a leak site has a statistically significant offset from the mean value at other locations.
e) Noise from outside the vessel, such as valve operation, etc., does not increase the mean or standard deviation of the data.

Predictable data statistics allow extrapolation of the detection algorithm to other vessels or operating conditions. The detection time is then predictable from this detection algorithm and the GAAD system configuration. An objective of the acoustic detection program at SCTI was to show that the CORCO data are predictable.

1.5 Structure of Report

The GAAD acoustic system algorithm accuracy is ultimately dependent on the accuracy of the assumed value of acoustic velocity. Analysis and experiment have provided the correction factors for the effect of the tube bundle, etc. Analysis and experiment also show that quite small quantities of bubbles homogeneously mixed in a liquid can severely change the acoustic velocity. A companion report [11] considers the potential impact of gas released from the reaction of sodium and water on the acoustic velocity. This analysis provides an assessment of potential limitations in extrapolating the demonstration test data to other steam generator operating conditions.

Prior to the prototype steam generator starting into the thermal-hydraulic test program the GAAD system was integrated into the facility small leak protection system. Although this restricted some aspects of the GAAD system program, invaluable operating experience was obtained, including the definition of practical requirements for operator interfacing of leak detection criteria and performance. The second part of this report gives details of the leak detection criteria developed for the SCTI small leak protection system.

Full details of the GAAD system are given in the following section, and its integration into the steam generator test at SCTI is described. The demonstration test is then defined in terms of the GAAD system, and full details of the demonstration test are presented. A discussion of the test data leads to conclusions and recommendations.

2.0 TEST EQUIPMENT AND FACILITIES

2.1 GAAD System Operation

The General Electric Advanced Acoustic Detection system (GAAD) will detect and locate a leak of water/steam from a defective tube in a tube-in-shell heat exchanger. When such a tube is filled with high pressure water/steam a localized sodium/water reaction occurs at the site of the defect. This reaction generates hydrogen gas bubbles; the growth of these bubbles produces a localized noise source within the vessel. The leak site is invariant in time. The GAAD system uses statistical processing of random acoustic pressures generated by the sodium/water reaction to assess the probability distribution that a leak exists at a given location within the vessel.

Statistical signal processing is limited to the frequency band of 1 KHz to 11 KHz (approximately). In this bandwidth the vessel wall responds to the acoustic pressure waves in an inertia controlled mode. Or, expressed another way, each element of the vessel wall is uncoupled and is capable of moving independently following the local internal pressure fluctuations [12]. In the same frequency bandwidth the vessel internals and fluids can be considered as a homogeneous medium with isotropic properties and low acoustic noise absorption. These characteristics allow array processing of the signals from vibration sensors attached to the wall [12]. The signals are time delayed to focus within the vessel and measure the acoustic noise power at the focal point (Figure 1).

Accelerometers are placed in a regular double helical pattern covering the total vessel length. Each accelerometer is axially separated by a distance of 12 cm, resulting in about 170 accelerometers attached to the outside of the vessel. An array of eight accelerometers in a double start helical pattern is focused onto the reference plane. The reference plane is at the axial center of one pitch of the helix, four accelerometers above

FOCUSING ONTO SPECIFIC BIN (TRIANGULATION)

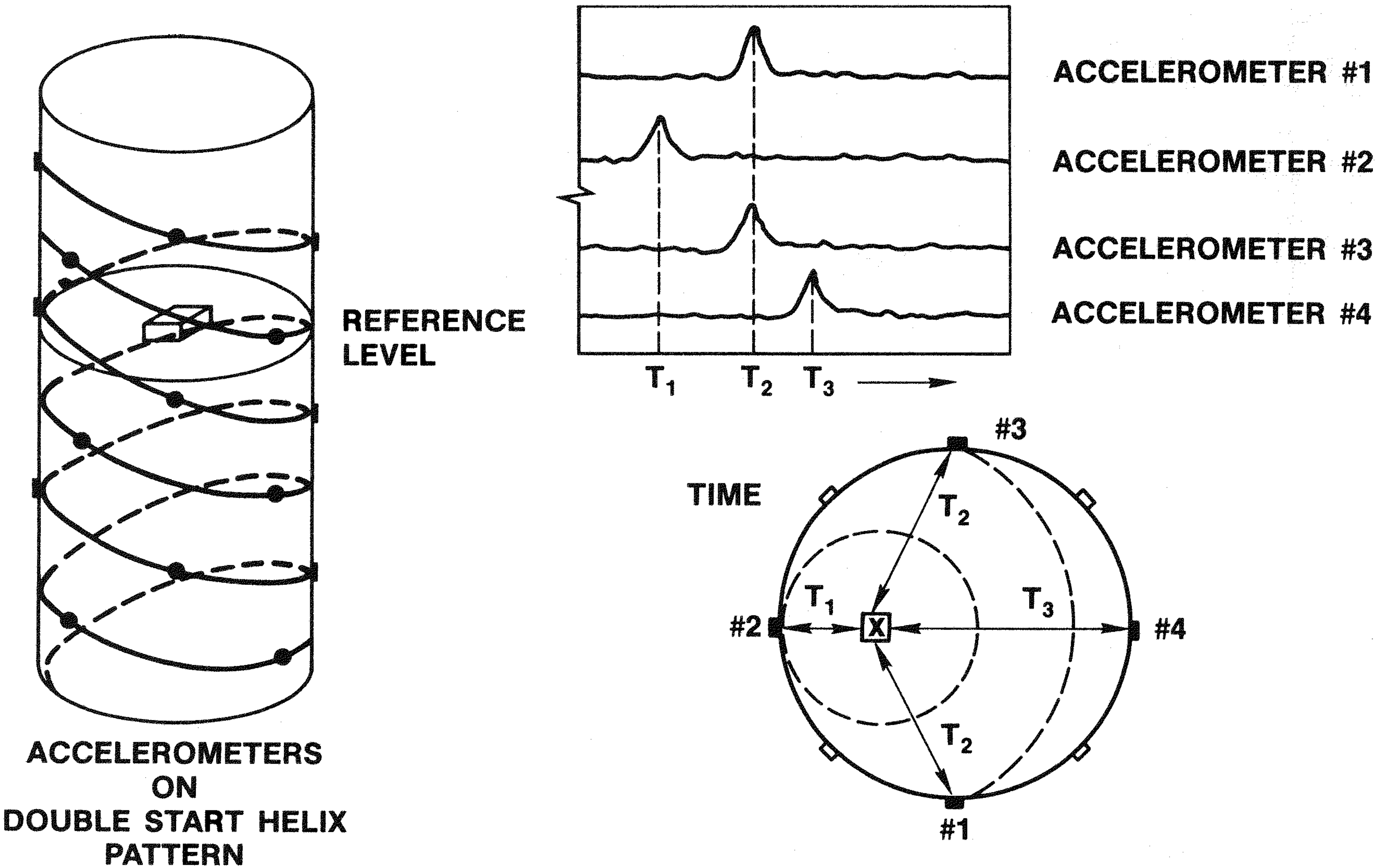

FIGURE 1. TIME DELAY BEAMFORMING

the plane and four below the plane. The array is sequentially focused onto approximately 80 locations (bins) in the plane by time delaying each accelerometer signal by an appropriate amount. The array power is measured at each bin. When this is completed the array is updated by removing the signal from the lowest accelerometer and introducing the signal from the next accelerometer above the original array of eight. The reference plane has now been changed to the next level of bins. This system of bins is shown diagrammatically in Figure 2.

The data processing algorithms divide the steam generator into $\sim$200 levels with each level divided into $\sim$80 cells or focal points (Figure 2). It is assumed that the leak is stationary within the vessel so that the acoustic propagation time from the leak to each sensor is constant. Noise arriving at the sensors is examined for spatial coherence by a technique referred to as "beamforming". Randomly distributed noise is eventually cancelled by the averaging technique leaving the noise from the leak as a unique value greater than the mean value (in general, the mean value is zero).

The process of focusing onto a given cell (bin) by time delay beamforming is illustrated by Figure 1. This figure illustrates the process for an array of four accelerometers. The GAAD system employs eight accelerometers in an array. The signal processor contains a program which will:

a) Focus the array onto a given cell (bin). Each accelerometer's data are delayed an amount corresponding to differences in propagation paths from the focal point to each accelerometer.

b) Measure the acoustic power at the focal point by adding the phased data from the accelerometers.

c) Accumulate measurements for each focal point until sufficient independent observations of the data are obtained to allow a statistically significant test to be made of the acoustic power level.

GE-ARSD ACOUSTIC DETECTION (GAAD) SYSTEM

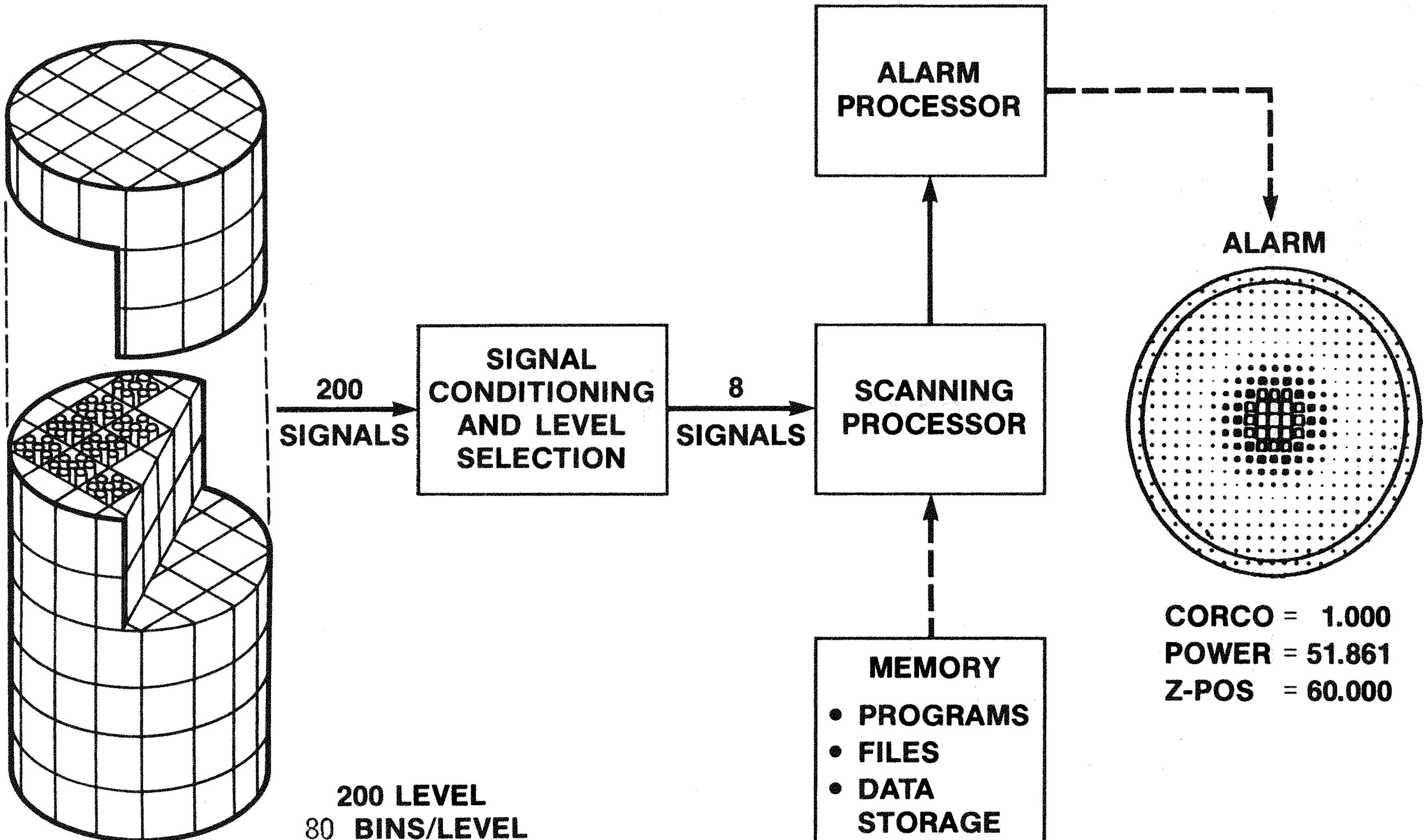

FIGURE 2. GE-ADVANCED ACOUSTIC DETECTION (GAAD) SYSTEM

d) Repeat for all volume elements associated with this particular steam generator level.

e) Test the maximum acoustic power level found in the volume elements for this plane or a dependent parameter, and ascertain if leak detection criteria have been met. If the scanning processor suspects that a large leak exists, a new set of data for the plane is taken and rechecked for the leak indication. Depending upon the detection threshold exceeded an appropriate message is transmitted to the plant operator.

In a Liquid Metal Fast Breeder Reactor (LMFBR) plant the existence of a leak would be further checked by the alarm processor (Figure 2). At the Sodium Component Test Installation (SCTI) the speed of the data reduction computer did not allow the alarm processor to be implemented. Leak detection criteria and thresholds were therefore recalculated specifically for the SCTI/prototype steam generator system. Details are given in Part II of this report.

2.2 GAAD System Design

The GAAD system at the SCTI consists of the following components:

a) Sensor: an accelerometer attached to the outer shell of the vessel.

b) Analog signal conditioning and selection: one or two cabinets of printed circuit cards located in the steam generator cell.

c) Analog-to-digital conversion: the analog signal was filtered to the correct bandwidth and then digitized. These units were in a control room cabinet.

d) Digital signal processing: the digitized voltages were manipulated according to the detection system algorithm. A PDP-11/24 computer with associated peripherals was used, located in the control room.

e) Operator interface: a graphics terminal provided the primary means for the operator to check the integrity of the system. A hardwired link between the GAAD system and the facility DAS allowed information on the leak detection to be stored on tape for archival purposes. Off-site monitoring was provided using a radio accessed Pager. The message to the Pager was generated by the GAAD system computer, and automatically transmitted to the Pager system using the internal auto-dial telephone modem.

A complete description of the GAAD system will be provided in a report to be issued later. The analog system cabinet is shown in Figure 3. It was located next to the prototype steam generator. Accelerometers were installed in the cut-outs in the vessel insulation.

Each accelerometer was connected by microcoax cable to the input of a charge amplifier. The charge amplifiers were close to the steam generator (about five feet); amplifiers were clustered into cabinet subassemblies of approximately 100 channels each at two separate locations (see Figure 3). One set serviced the upper half and the other the lower half of the 80 foot long vessel. The operating environment for the analog equipment was the steam generator cell (75°C temperature). After suitable amplification a multiplexing circuit selected eight sequential accelerometers. These formed the array which scanned the reference plane. All data control and manipulation was under the control of the SCANNING signal processor. A photograph of the signal processing subsystem including the PDP-11/24 minicomputer, is shown in Figure 4.

All system components were designed for an industrial environment. Computer components were manufactured and were serviced by an internationally recognized manufacturer.

The output from the charge amplifiers was parallel connected to three multiplexing subassemblies. This allowed three separate monitoring systems to access the accelerometers on the vessel (Figure 5). The first system

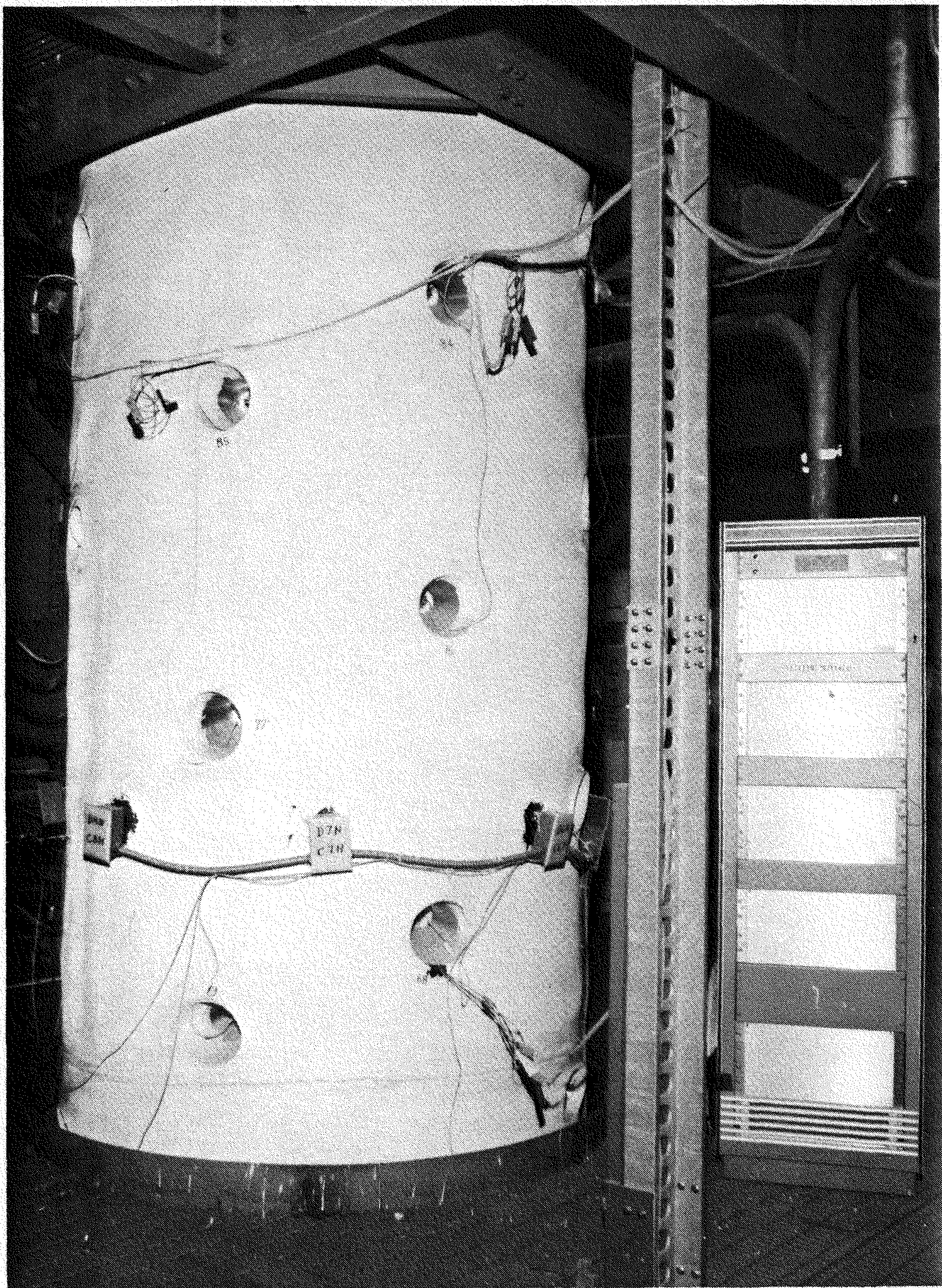

Figure 3. Section of test vessel showing installed accelerometers and GAAD system analog electronics cabinet.

Figure 4. GAAD system digital electronics as installed in the SCTI, ETEC control room.

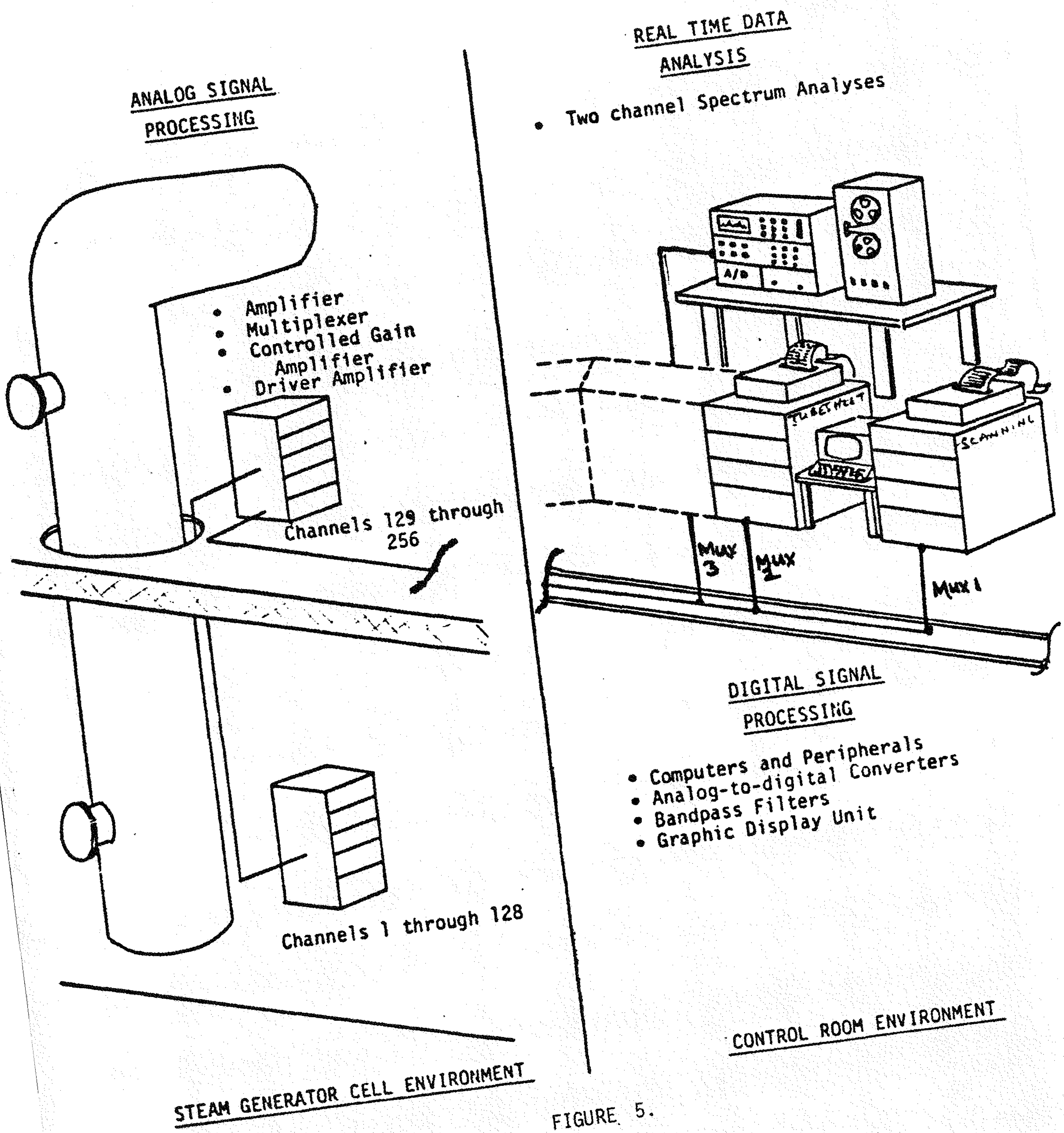

FIGURE 5.

GAAD SYSTEM LOCATION DIAGRAM

was the SCANNING signal processor which scanned the complete vessel volume, or approximately 170 planes. A second system selectively monitored the two tubesheet regions only. The TUBESHEET system monitored five planes at the upper tubesheet, then jumped to the lower tubesheet and monitored an additional five planes. The third (DATA) system was used for audio monitoring, and recording of data on a Sabre III instrumentation recorder.

The scanning system took approximately twenty-five minutes to monitor the total vessel volume. A "real-time" system would be required to monitor the total volume in ten seconds, providing full protection against intermediate leaks. To achieve the ten-second scan time a custom, hardwired, dedicated processor would be required. A decision was made at the start of the leak detection program to simulate the processor by using a software program in the PDP-11/24 computer. This allows flexibility in making design and operating changes, but at the cost of significant increases in processing time.

Originally the acoustic detection system was planned as a "piggyback" experiment on the prototype steam generator test. At the start of SCTI power operation the GAAD system was integrated into the facility leak detection system. An analysis of leak detection requirements showed that the scanning processor would provide protection for leakage rates smaller than approximately 0.01 gm/sec ($2x10^{-5}$ lbs/sec). The tubesheet processor scanned approximately two-foot axial distance from each sodium/tubesheet interface, including the critical sections with tube-to-tubesheet welds. The addition of the tubesheet system to monitor the end regions increased the protection in these critical regions for leaks smaller than approximately 0.1 gm/sec ($2x10^{-4}$ lbs/sec). (See Part II.)

2.3 Description of the Prototype Steam Generator

The prototype steam generator was described in a recent paper [10]. The following descriptions are abstracted from that paper: "It is a shell and tube type heat exchanger, shown in Figure 6. Water and steam enter the tubes at the lower tubesheet, flow upward through the tubes, and exit at

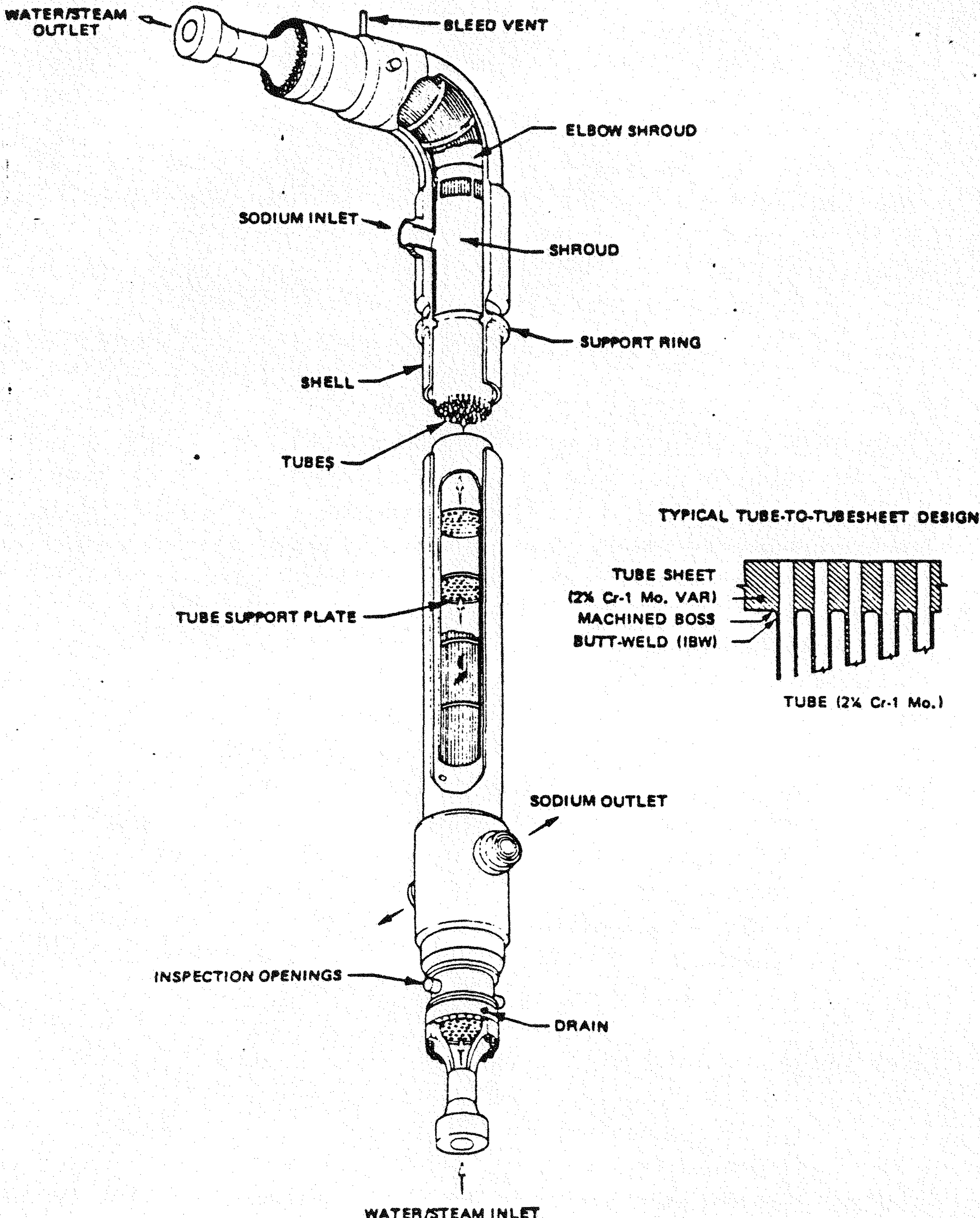

FIGURE 6. PROTOTYPE STEAM GENERATOR WITH SINGLE WALL TUBES AS TESTED AT SCTI, ETEC

the upper tubesheet. The sodium enters the shell side near the top of the unit, flows down through the unit, and exits just above the lower tubesheet. The SG has a "hockey stick" configuration to accommodate differential thermal expansion between tubes and shell. The vertical leg of the hockey stick is approximately 19.2 meters (63 feet) long; the horizontal leg is approximately 2.6 meters (8½ feet) long. The tubes are welded to short nipples or bosses machined on the backside of the tubesheets using a single pass, autogenous welding technique. The tube bundle is enveloped by a shroud cylinder which directs the parallel counterflow of sodium around the tubes. A relatively stagnant annular volume of sodium is provided between the outside diameter of the shroud and the inside diameter of the shell to mitigate the effect of thermal transients on the shell.

"The prototype unit contains ten instrumented tubes plus two leak injection tubes which were used in conjunction with the externally mounted acoustical leak detection devices on the shell. The ten instrumented tubes contain from four to twelve thermocouples, each of which provide temperature readings at various elevations in the tube bundle on the sodium side. In addition to the instrumented tubes, thermocouples were installed at various locations on the shroud and on the inside surfaces of the tubesheets. Several tubes have accelerometers attached to them in the bend region. Leak injection devices positioned in the vicinity of the tube-to-tubesheet welds were used to test the acoustic leak detection devices, which are mounted on the tubesheets.

"The water/steam side is also instrumented with various thermocouples and pressure sensors which are mounted in and/or extend from the steamheads and are inserted into several tube holes. Care was taken while installing or removing the steamheads to ensure that these instruments were properly aligned with the appropriate tube location.

"All of the instrumentation leads on the sodium side of the unit are brought out of the pressure boundary by instrument feed-throughs which are of the freeze tube design with an enlarged head at the end of the tube to accommodate Swagelok fittings."

2.4 Description of the Sodium Component Test Installation *

"The prototype steam generator was tested in the recently uprated SCTI. The capacity of the SCTI facility was increased from 35 MW to its current 70 MW thermal power capability for this test program through the addition of over 80% new components and the refurbishment of existing components. The new SCTI is capable of both steady-state and transient operation from low power conditions up to 70 MW, and it can effectively simulate normal and off-normal test article operating conditions. It is now the world's largest test facility for evaluating thermal and hydraulic characteristics of steam generators and sodium components.

"The design of the SCTI facility is prototypic of standard power plants. It includes a sodium heat transport system for delivering thermal power to the test article through the use of two 35 MW fossil-fueled sodium heaters, each capable of operating on natural gas or fuel oil. It also includes a steam and feedwater system for heat rejection and supporting auxiliary subsystems (e.g., electrical preheat, sodium purification, water purification, inert cover gas). Special design features, such as low-flow bypass lines and staged components, are unique to a test facility and allow operation over an extremely wide range of conditions.

"The SCTI steam and feedwater system is designed for operation in either the recirculation mode with two-phase steam outlet conditions from the test article, or the once-through mode with superheated steam outlet conditions from the test article, thus providing maximum testing flexibility. By operating in the recirculation mode with the recirculation pump off line, natural circulation conditions can also be simulated. The system design includes low-flow bypass for both steam and feedwater to provide optimum control at all power levels.

"The SCTI sodium system includes a cold sodium flow bypass line which bypasses the heaters, allowing excellent control flexibility for providing

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* Taken from Reference 10.

temperature ramps at the test article inlet. A hot sodium flow bypass line which bypasses the test article, and a sodium cooler mitigate thermal shock to the facility under transient conditions. State-of-the-art mixing tees are used to provide efficient mixing of sodium bypass flows.

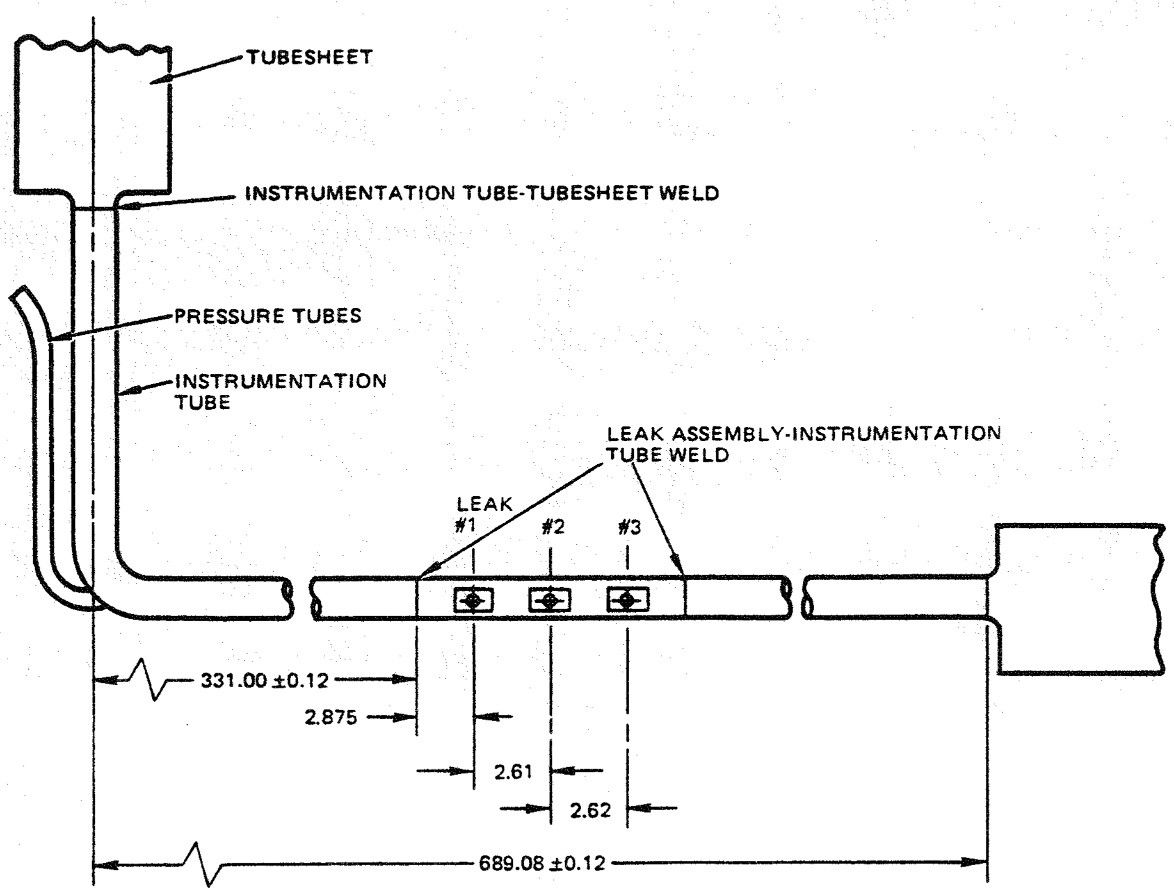
"The sodium system also includes a sodium/water reaction protection (SWRP) system to minimize impact to both the test article and the facility in the event of a sodium/water reaction. As a primary leak detection system for small leaks, in-sodium hydrogen detectors provide continuous monitoring of the test article sodium outlet line and sodium vent line. An oxygen detector is located in the sodium outlet line to provide further leak protection."

2.5 Leak Simulation Devices

Steam generator designers are unwilling in most instances to allow water injections into a steam generator to test leak detection systems. Gas injections were used to simulate the sodium/water reaction noise. Limitations in using simulated leaks are covered in Reference II.

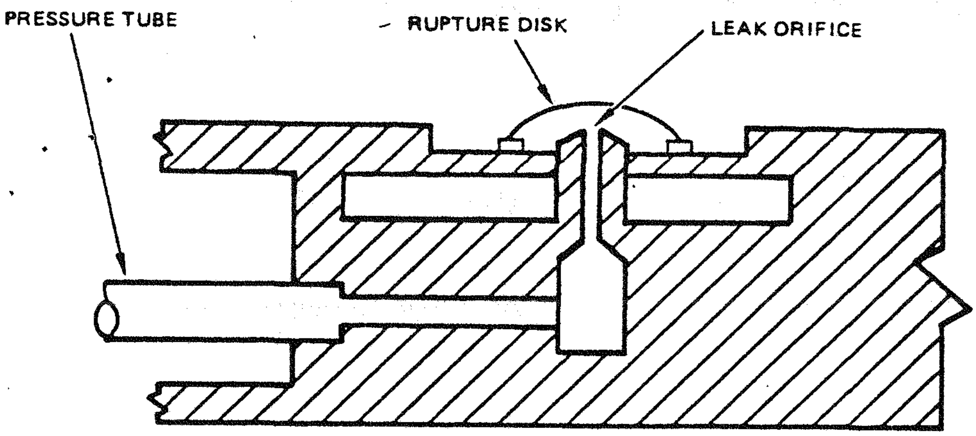
Leak source assemblies were installed in two tubes of the prototype steam generator by Atomics International (Figure 7). Two different designs were used to give redundant sources (Figure 8). The first design utilized small orifices covered by rupture discs. Three such orifices were welded into a tubular assembly that replaced a section of an instrumentation tube in the SG. The three orifices were on 6.65 cm (2.62 inch) centers with the No. 1 leak 848 cm (333.9 in) from the centerline of the tube's short leg. (Each leak orifice was $\sim$0.006 in in diameter.) The rupture leak assembly was installed into instrumentation tube #4071 located on the outside radius of the tube bundle (Figure 7). Pressure tubes were used to rupture the discs and to supply the leak with gas.

During installation of the injectors in tube #4071, leak No. 1 was damaged and was not used. Leaks No. 2 and 3 were available for use during the test. The second injector design, described below, provided a third leak.

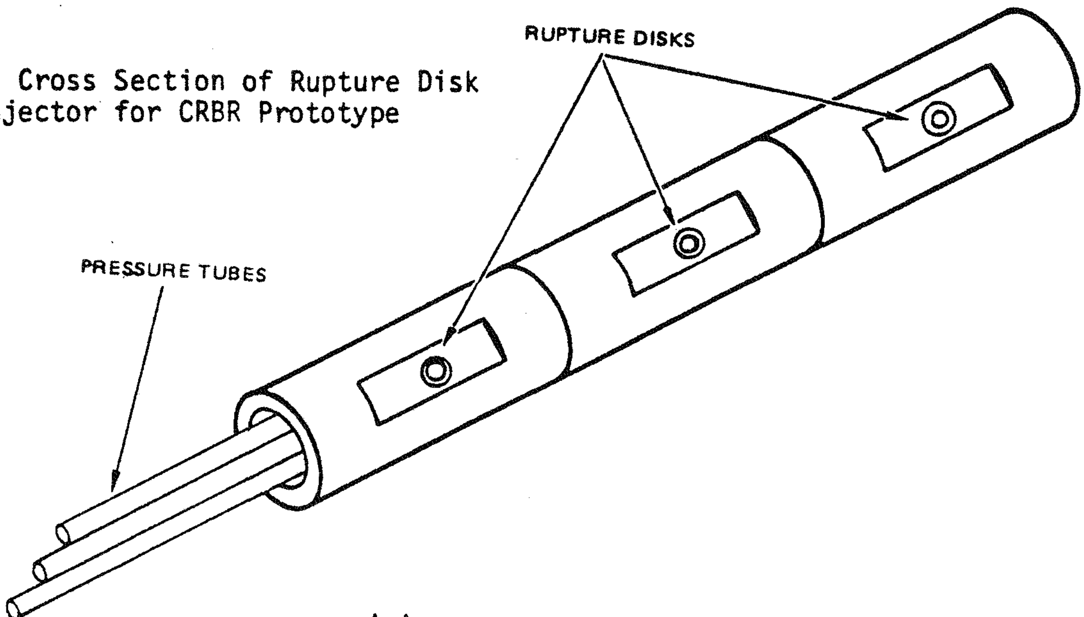


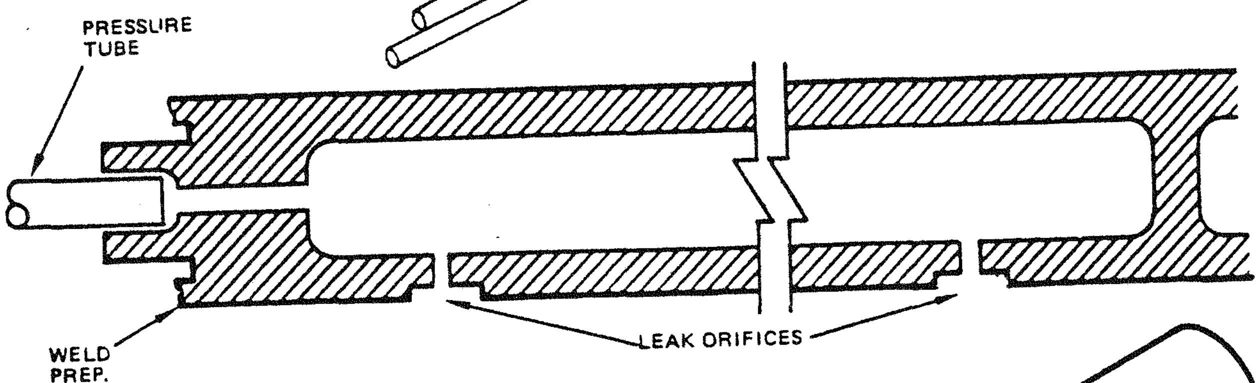
Installation of Rupture Tube Assembly
(Drawing No. N707000107, Steam Tube No. 4071)

FIGURE 7. LEAK INJECTION DEVICE LOCATION DRAWING



Cross Section of Rupture Disk
Leak Injector for CRBR Prototype





Cross Section of Open Orifice Leak Injector

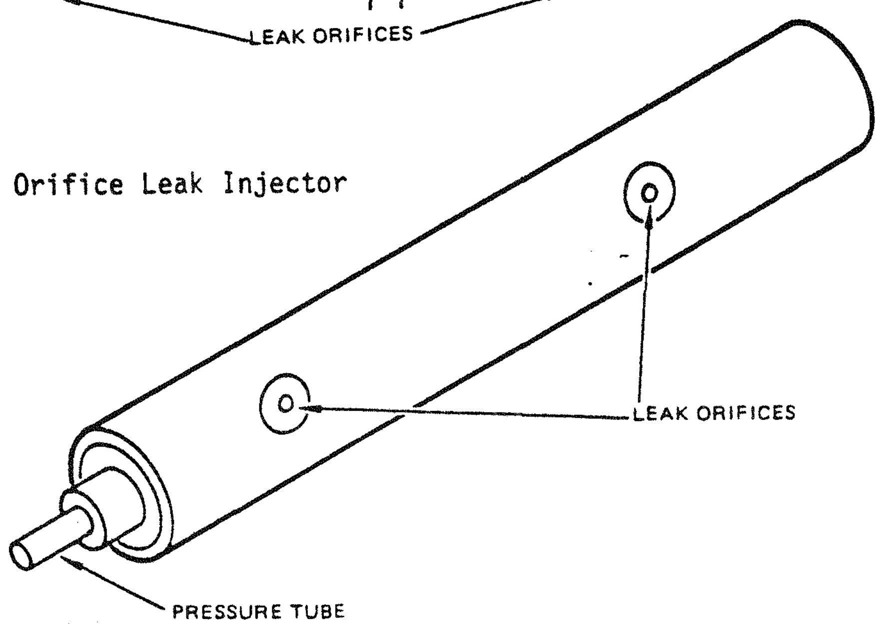


FIGURE 8. DIAGRAMS - LEAK INJECTION DEVICES

The second leak source design installed in the prototype steam generator utilized an open orifice concept. This assembly consisted of two leak orifices, 0.02 mm (0.008-inch) in diameter, that are connected by a common internal cavity supplied by a pressure tube. Although the second leak design has two holes, it was expected that gas would be injected only through one hole during operation. The open orifice assembly was installed with the No. 1 leak 842.3 cm (331.62 in) from the short leg centerline of tube #3058. These differences are the major deviations between the two designs. The open orifice leak source was treated the same as the rupture disk in all other regards. A schematic of the gas injection system is shown in Figure 9.

2.6 GAAD System Data Storage and Alarms

The GAAD system provided an operator interface that simulates the output from the chemical leak detection system. It provided an alarm (CODE 1, 2 or 3) indication if the water leak rate exceeds a predetermined ramp (CORCO-3) or amplitude (CORCO-1 and CORCO-2). See Part II for full details on "CORCO". Upon receiving a low level alarm the operator requires knowledge of the history of the output prior to the alarm, to aid in assessing the appropriate corrective actions. Data were therefore stored for periods both before and after the time of the alarm. Long term data storage was accomplished by transferring a summary of the current indication every two minutes to the SCTI facility data acquisition system (DAS).

A tremendous amount of data was obtained for each focal point, or bin, on each reference plane. Each plane contained approximately 80 bins, and the scanning processor examined 170 planes to give a total of over ten thousand bins. For each bin 200 independent estimates of water injection rate were made during each scan. The GAAD system provided a ramp indication for each bin covering the previous 100 vessel scans; the output for each bin was called "CORCO-3". For each vessel scan, or "PASS", the value of CORCO-3 was updated and the highest value extracted. This value was transmitted every two minutes to the DAS together with the current pass

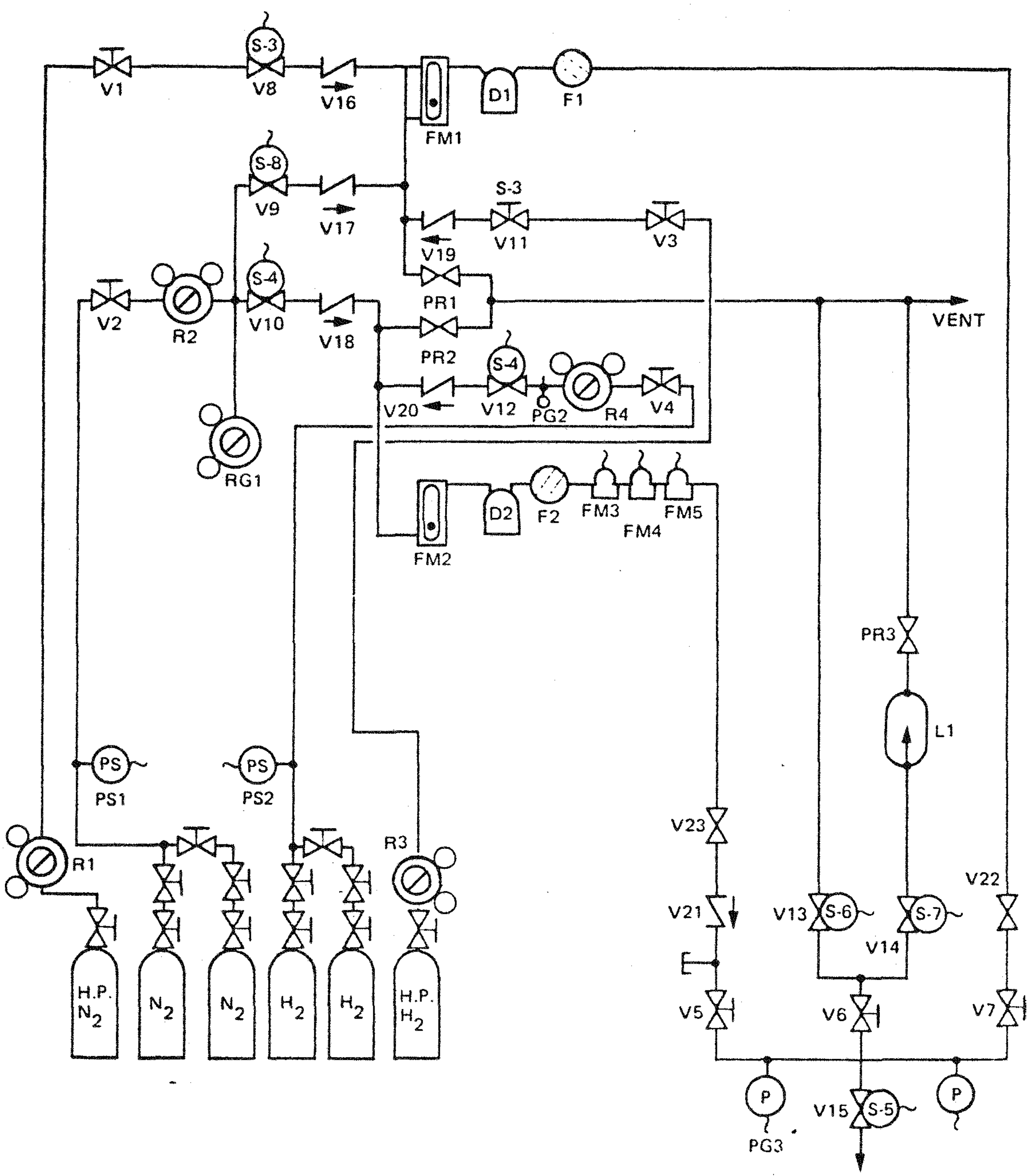


FIGURE 9. SCHEMATIC - GE LEAK INJECTION MODULE

number and location (plane and bin numbers). Within the GAAD system the CORCO-3 values for the previous 90 minutes are in temporary storage. If an alarm criteria threshold is exceeded this 90 minutes of data, plus the subsequent ninety minutes, are transferred to permanent storage for subsequent diagnostic recall.

If a bin exceeded the "CORCO-2" criteria six times on sequential passes an alarm was generated and data transfer initiated. Both CORCO-3 and CORCO-2 alert messages correspond to leaks which cause propagation after a relatively long incubation time ($\sim$15 minutes). These alerts were not transferred directly to the system operator, but to the on-site Operations Engineer. He then monitored the GAAD system, in conjunction with chemical leak detection and process instrumentation, and decided upon corrective action.

After assessing the possible injection rate associated with each bin on a plane the maximum value was compared to the "CORCO-1" alarm threshold. If the threshold was exceeded by any bin the whole plane was remeasured. If the same bin still exceeded the threshold an interrupt signal was sent to the facility DAS and a message transmitted immediately to the operator who initiated a predetermined corrective action procedure. A high CORCO-1 value corresponded to a relatively high leak rate requiring fast corrective action. Data transfer to permanent storage was again initiated.

The GAAD system included an external telephone interface. Twice a day during normal operation a message was transmitted by phone to a paging system. The message was a summary of current operating conditions. The pager/receiver had a one thousand word memory for storing the message. If an alarm level was indicated by the GAAD system, a message was also transmitted to the pager. In this manner, an alarm condition indication was transmitted to the off-site GAAD system specialist. The specialist could then use an external terminal or mini-computer to telephone access the GAAD system on-site and monitor the current data stream. Changes in operating characteristics could also be made to the GAAD system using the telephone interface (Figure 10).

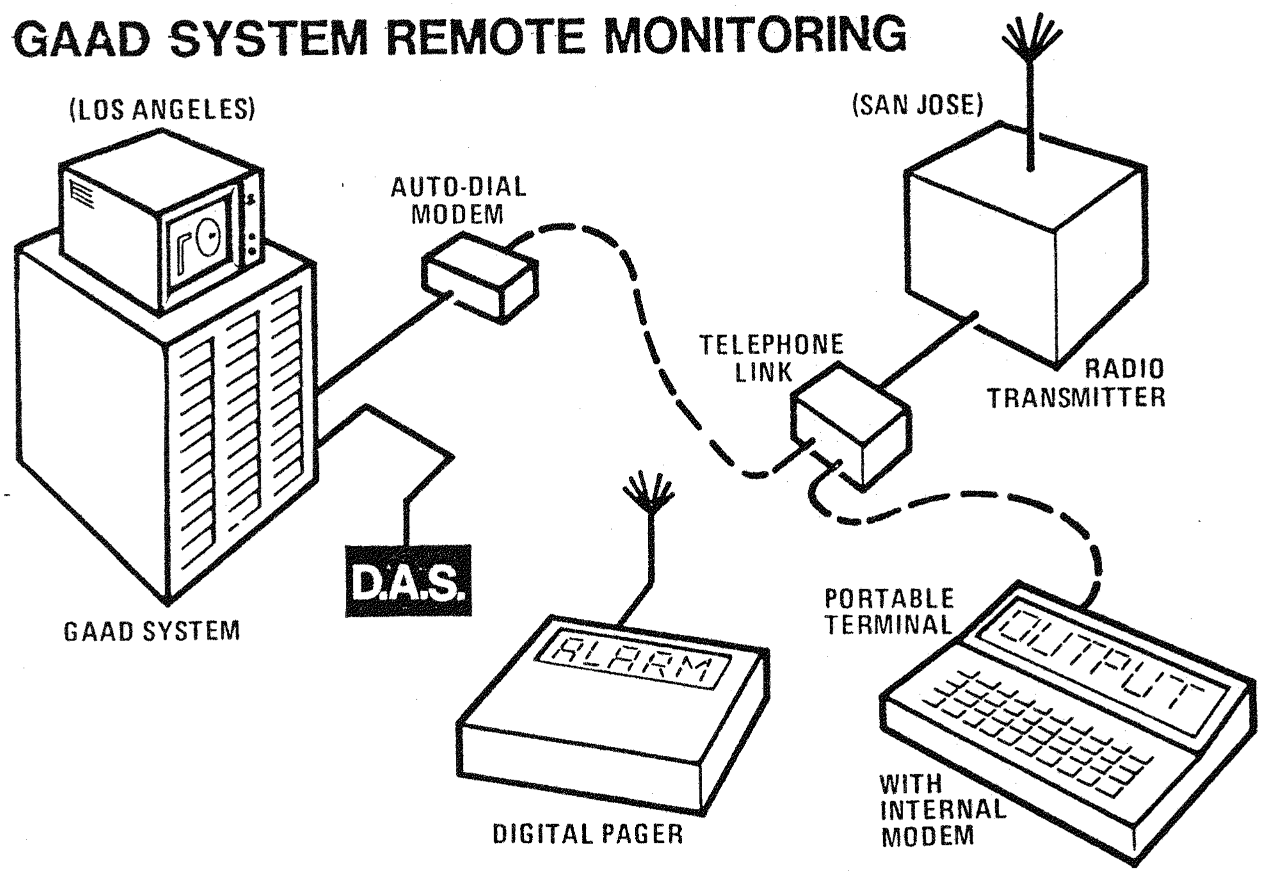


FIGURE 10. TELEPHONE PAGING SYSTEM

2.7 GAAD System/DAS Interface

A forty-conductor ribbon cable connected the GAAD system PDP-11/24 to the SCTI data acquisition HP-1000 mini-computer. Within the PDP-11/24 the cable was connected to a Digital Equipment Corporation input/output card (DR11-W). This card had parallel sixteen bit data lines plus two function bits. One function bit was used to send an interrupt message to the HP-1000, the other was as a handshake to indicate receipt of interrupts and data. The sixteen bit data words transferred are given in Table 1. Two separate interfaces were installed, one between the scanning system and the HP-1000, the other between the tubesheet system and the HP-1000.

Table 1: Interface with Facility DAS

CODE DEFINITIONS:

CODE-1 - Two successive values from the same location with a CORCO exceeding 0.200 ... CORCO-1.

CODE-2 - Six successive values from the same location with a CORCO exceeding 0.070 ... CORCO-2.

CODE-3 - Average of 100 successive values from the same location with a CORCO exceeding 0.036 ... CORCO-3.

POWER - Average background noise amplitude.

Relative word #	Contents
0	177777 (octal) start word.
1	xxxxxx check-sum word.
2	0 code zero message.
3	CORCO 1, Highest value all locations.
4	Bin number for CORCO 1.
5	Plane number for CORCO 1.
6	CORCO 1A, Preceeding CORCO at location of CORCO 1.
7	CORCO 1B,
8	CORCO 1C,
9	CORCO 1D
10	CORCO 1E, Fifth preceeding value at location of CORCO 1.
11	CORCO 3, Highest lont term average CORCO.
12	Bin number for CORCO 3.
13	Plane number for CORCO 3.
14	CORCO 2, Highest six pass average CORCO.
15	Bin number for CORCO 2.
16	Plane number for CORCO 2.
17	Previous CORCO2 at same location.
18	CORCO 2B,
19	CORCO 2C,
20	CORCO 2D,
21	CORCO 2E, Fifth preceeding value.
22	POWER 1, Total power at CORCO 1 plane.
23	POWER 2, Total power at CORCO 2 plane.
24	POWER 3, Total power at CORCO 3 plane.
25	POWER U, Total power at upper tube sheet.
26	POWER L, Total power at lower tube sheet.
27	077777 (octal) stop word.

3.0 TEST CONDITIONS

3.1 Demonstration Test Criteria

Four parameters predict the performance of the acoustic leak detection system and define detection criteria:

a) The array processing algorithm.
b) Sodium/water reaction signal characteristics.
c) Background noise generation characteristics.
d) Signal transmission path characteristics (transfer function).

The effect of each of these parameters must be known to define an adequate demonstration test. Prior to the SCTI/Prototype program each of these parameters was examined to define the demonstration test.

3.2 Array Processing Algorithm

Four different algorithms were analyzed to define the best approach [13]. The technique for each approach is similar; the array is beam-steered sequentially through a series of locations. At each location a test is performed to check for the presence of a signal source in the background noise. The measured signal source is statistically examined to decide whether the local power significantly exceeds a threshold power. If the threshold is exceeded it is assumed to be due to a sodium/water reaction at that location.

The four approaches were analyzed to see if any one was significantly superior in detection capability. Each approach required a different level of knowledge of prior statistics of the signal source and the background noise. The linear array approach used by the GAAD system was determined to be the optimum for leak detection in a steam generator. Some increase in sensitivity could result from one of the more sophisticated algorithms, but this would be offset by increased potential for error due to using fallacious assumptions on the specific character of the signal source or background noise [13].

The detection of a localized signal noise source in broadband background noise is a simple statistical determination. To make the determination the following parameters must be defined:

a) Signal-to-noise ratio, [S/N].
b) Probability of finding a signal when none exists, i.e., false alarm [Q_0].
c) Probability of missing a signal when it exists; i.e., missed leak [Q_1].
d) Number of independent observations to make decision [N]; or detection time.
e) System cost, [$].

A typical curve describing the interrelationship between these parameters is shown in Figure 11. A direct correlation exists between numbers of observations of a sodium/water reaction and time to detect, governed by intrinsic properties of the reaction noise. [14]

When the detection system uses an array of transducers the detection time is reduced due to the array gain. The array gain is defined as:

$$\text{Array Gain} = \frac{\text{Power from Array}}{\text{Power from a reference Single Sensor}} \qquad \text{(A)}$$

When the accelerometers are installed in a double helix pattern the array gain becomes 6 to 9.5 dB. The reference sensor is considered to be on the circumference of the plane, with a leak at the central location when calculating signal-to-noise ratio.

When values of Q_0 and Q_1, the amount of money available and a minimum time of detection are defined, a practical system performance curve results. This was done in Part II of this report for the GAAD system

DETECTION TIME IS A FUNCTION OF

- SIGNAL LEVEL (LEAK RATE) (S) — $\frac{S}{N}$ RATIO
- BACKGROUND LEVEL (N)
- PROBABILITY OF FALSE ALARM (Q_o)
- PROBABILITY OF MISSING LEAK (Q_i)
- VESSEL SWEEP TIME (T)
- DATA ANALYSIS OVERHEAD TIME (E)
- COST OF GAAD SYSTEM ($)

SENSITIVITY CURVE

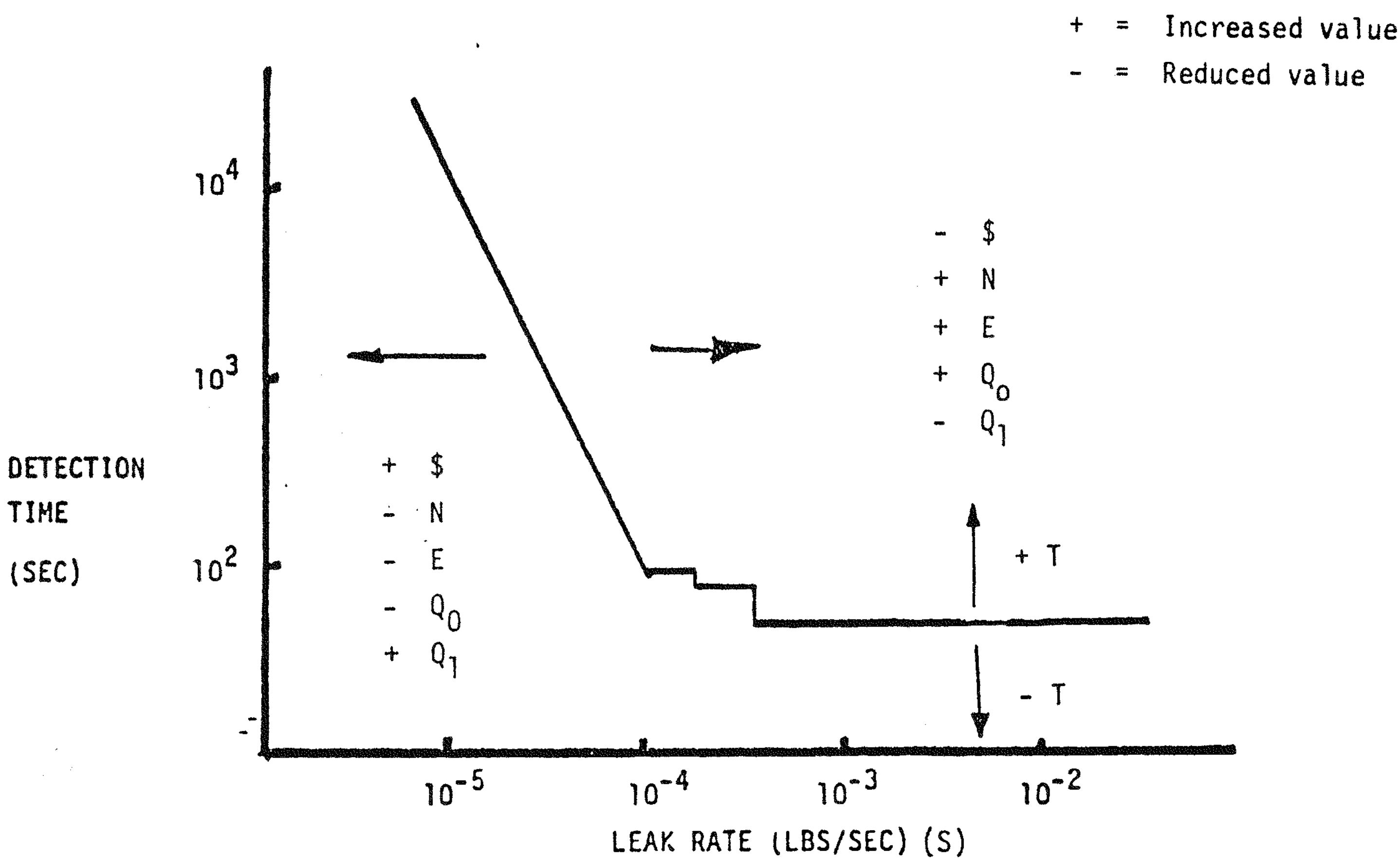


Figure 11. Parameters affecting system performance.

installed at SCTI. The result is a unique curve relating signal-to-noise ratio to GAAD system processing time. If the signal level is now defined together with the required detection time, then the background level must be limited so that the signal-to-noise ratio does not exceed the value implied by the system performance curve. For example, in Part II of this report the background noise amplitude limit was found to be approximately 300 microbar in order to meet detection requirements for small leaks.

3.3 Sodium/Water Reaction Signal Characterization

Examination of Figure 11 shows the detection capability of acoustic monitoring system is very sensitive to signal-to-noise ratio. Quite small decreases in signal amplitude result in a disproportionate increase in detection time.

A carefully designed and executed program was required to measure the acoustic pressure signals associated with sodium/water reactions [15]. Reverberation characteristics of the Sonic Amplitude Rig (SONAR) were first measured using several independent techniques. This allowed partition of the acoustic signal into direct and reverberant components. A wide range of water injection rates and rig operating conditions produced a general equation for water leakage into the steam generator [15].

$$\text{Signal Amplitude (microbar)} = 200 \times G^{0.5} \qquad \text{(B)}$$

where G is the water/steam injection rate in grams/second and the pressure is measured at 30 cms from the leak. This correlation is shown in Figure 12.

Experimental evidence, especially that obtained from the Large Leak Test Rig (LLTR) and the SONAR vessel, shows the sodium/water reaction noise

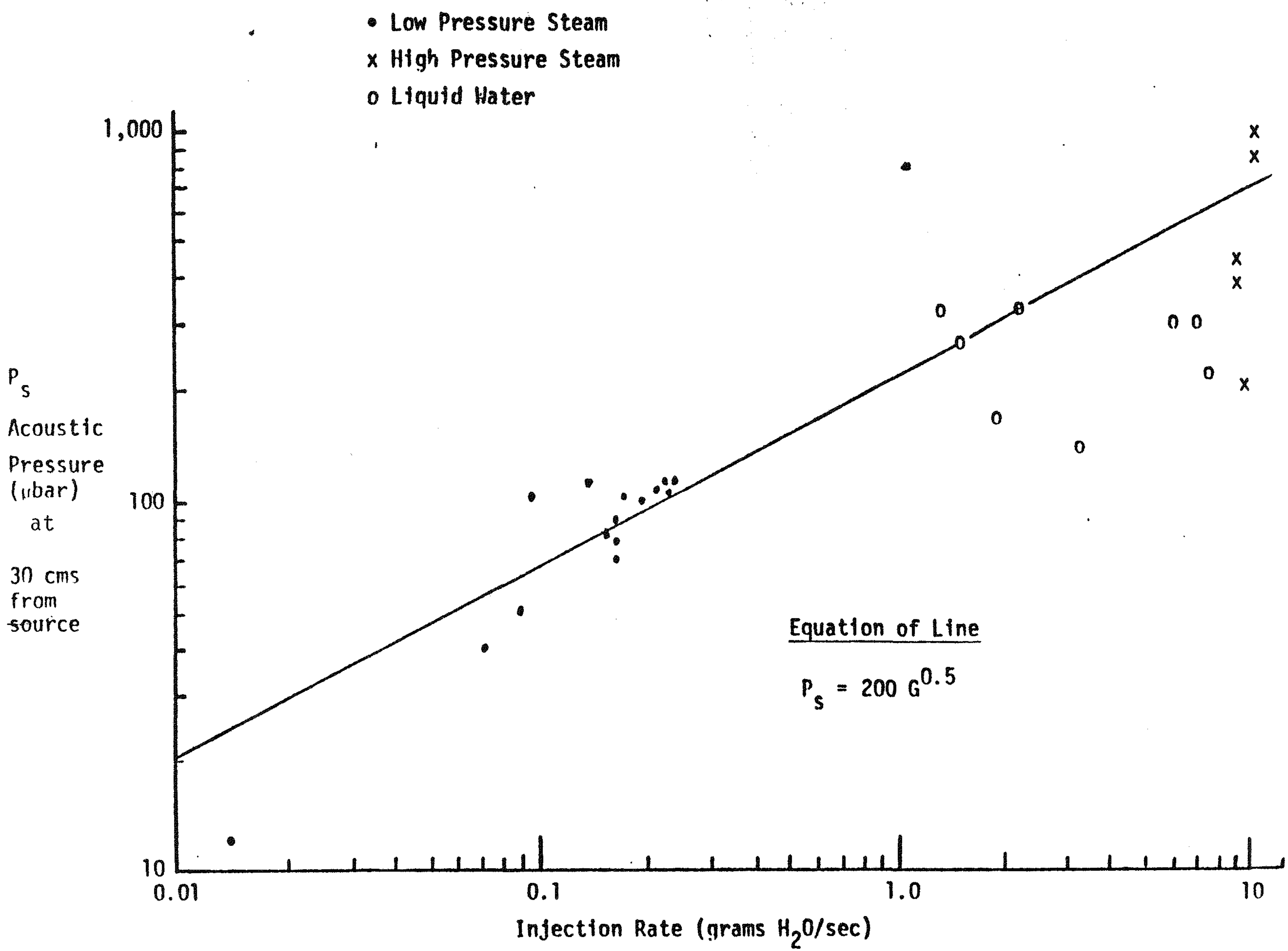


Figure 12. Sodium/water reaction noise generation data.

is proportional to the water injection rate. The correlation was used to satisfactorily predict injection noise up to approximately 32 grams H_2O/sec through a 1.37 mm (0.054-inch) diameter hole [14]. No signal saturation has been observed.

The experimental evidence also shows the capability of gas injections to simulate sodium/water reactions is limited. No quantitative correlation has been found between gas injection noise and sodium/water reaction noise. The acoustic width of a gas injection is much wider than that of a sodium/water reaction, as indicated by its narrower band width. The most important limitation is the saturation of the injection noise at relatively low gas flow rates. Only a fraction of the noise generated by a reaction can be produced by a gas injection. Limitations in simulating a sodium/water reaction by a gas injection are covered in detail in another report [11].

When an inert gas is injected into the steam generator it not only generates a local signal noise, but it also causes a significant increase in overall background noise in the vessel (see Section 4.1 for details). Increasing the injection rate becomes counter-productive since the signal level can actually decrease while the background noise increases.

High gas injection rates (greater than about 1 liter N_2/min) in the prototype SG fall into the counter-productive range and do not provide a satisfactory simulation of an intermediate leak condition. The maximum signal observed at the SCTI was at approximately 0.6 liter N_2/min injection rate.

3.4 Background Noise Generation Characterization

The background noise in a power plant becomes the key parameter for gaging the acoustic leak detection system sensitivity. Steam and sodium flow noise together with the noise generated by boiling were the principal background noise sources at SCTI. Additional contributions were measured due to control valves, mechanical pumps and other far field noise sources.

Typical values calculated prior to the SCTI test program suggested the background noise would range from 170 to 850 microbar. Actual values obtained are given later in Section 5.5. However, in the CRBRP superheater at LMFBR full power conditions, the steam noise will predominate and predicted background amplitudes reach 5,000 microbars [13].

3.5 Transfer Functions

The transfer of a signal from a source within the steam generator to the transducer array involves the following paths:

a) Through the bundle.
b) Across support structures.
c) Across the shroud.
d) Across support structures.
e) Transform from acoustic pressure in the liquid to wall acceleration.

The transfer of energy from the source along each of these paths has been examined analytically and the resulting correlations validated by experiment [13].

The liquid filled bundle and support structure were shown to transmit signals as if the internals of the steam generator is an isotropic homogeneous fluid. The transfer function is a simple power decay relationship through the fluid. The sound travels at an effective acoustic velocity calculated from an effective compressibility and density due to the presence of the internals.

The vessel wall, shroud and liquid filled shroud/wall annulus can be treated as an integral structure. The wall response to an impinging pressure wave can be calculated using a "lumped parameter" analytical model. This model has been validated for effective wall thicknesses from 1 cm to 13.7 cm (0.4 inches to 5.4 inches). [16]

The beamformer algorithm is based on the transfer function models described above. If these were in error the GAAD system could not correctly locate a noise source in a vessel. Noise sources have been correctly located in a foreshortened model of a hockey stick steam generator (MATOI). Location has been achieved in both the regular cylindrical section, in the bend region, across the anti-vibration suppressor, in a plane axially displaced 42 cms from a circumferential accelerometer array and across a 61 cm (2-ft) wide annulus [13].

3.6 Predicted Signal-to-Noise Ratio

An intermediate leak is defined as a water injection rate of approximately 45 g/sec. Using Equation B above, the predicted signal amplitude will be approximately 1400 microbars. Combining this with the expected background noise in a superheater at full power the signal-to-noise ratio is approximately 0.1 (-10 dB). In the evaporator, and most of the superheater, the ratio will be much higher as the background noise is lower.

The Test Plan [Appendix A] called for the best simulation of a leak equivalent to a signal-to-noise ratio of -10 dB. Limitations in correlating gas injections with sodium/water noise amplitude were known prior to the SCTI test program. For this reason the test plan defined a simulated signal-to-noise ratio, not a fixed gas injection rate.

The detection coefficient "CORCO" is equivalent to the local signal-to-noise ratio as defined and discussed in Part II of the report. Therefore, the requirement for best simulation is reached if a CORCO value of approximately 0.1 (i.e., -10 dB) is attained.

3.7 Gas Injection Conditions

An attempt was made to inject through the two protected orifices during the thermal/hydraulic tests with the prototype steam generator. No gas was injected through either orifice and no acoustic noise associated with rupturing of the disk was heard. The double-orifice injector had previously provided several gas injections, including a series of hydrogen injections to calibrate the facility chemical leak detection system. When an attempt was made to use the double-orifice injector in place of the plugged-protected orifices, it also was found to be plugged possibly due to hydroxides. Due to the expense of operating the facility under power transfer conditions, no attempt to open the injectors was made until the water side was empty and the rig was operating with only sodium flow.

A series of sodium side temperature and gas injection pressure tests were made in an attempt to unplug the orifices. These were unsuccessful. A piece of wire was then inserted into the small bore tubing feeding the double-orifice injector. After approximately four feet of wire was inserted a blockage was reached. The end of the wire was fashioned into a scoop to extract a sample from the blockage. The blockage appeared to be clean sodium. Heaters were then attached to the freeze tube containing the small bore tubing. The sodium was successfully blown down the small bore tube ($\sim$9 m) and into the vessel. Gas injections could then be made through the double-orifice injector.

Since the thermal/hydraulic test program had been completed injections could only be made into the steam generator with no water on the tube side, and sodium flow on the shell side.

Injections were made at approximately 10 liters N_2/min and then the injection rate was reduced until a maximum acoustic signal was observed. This was achieved at approximately 0.6 L N_2/min. Two separate injections were made with sodium flow rate at 1,000,000 lbs/hr and 500,000 lbs/hr. Data were taken by both the scanning and tubesheet systems. The scanning system was set to scan nine planes centered on the expected leak plane, while the tubesheet system scanned the three planes centered on the expected leak plane. At the same time, the output from eight selected accelerometers were recorded on the Sangamo Sabre III instrumentation recorder. Both the scanning and tubesheet systems transferred a data summary into the facility DAS at intervals of approximately two minutes.

4.0 TEST RESULTS

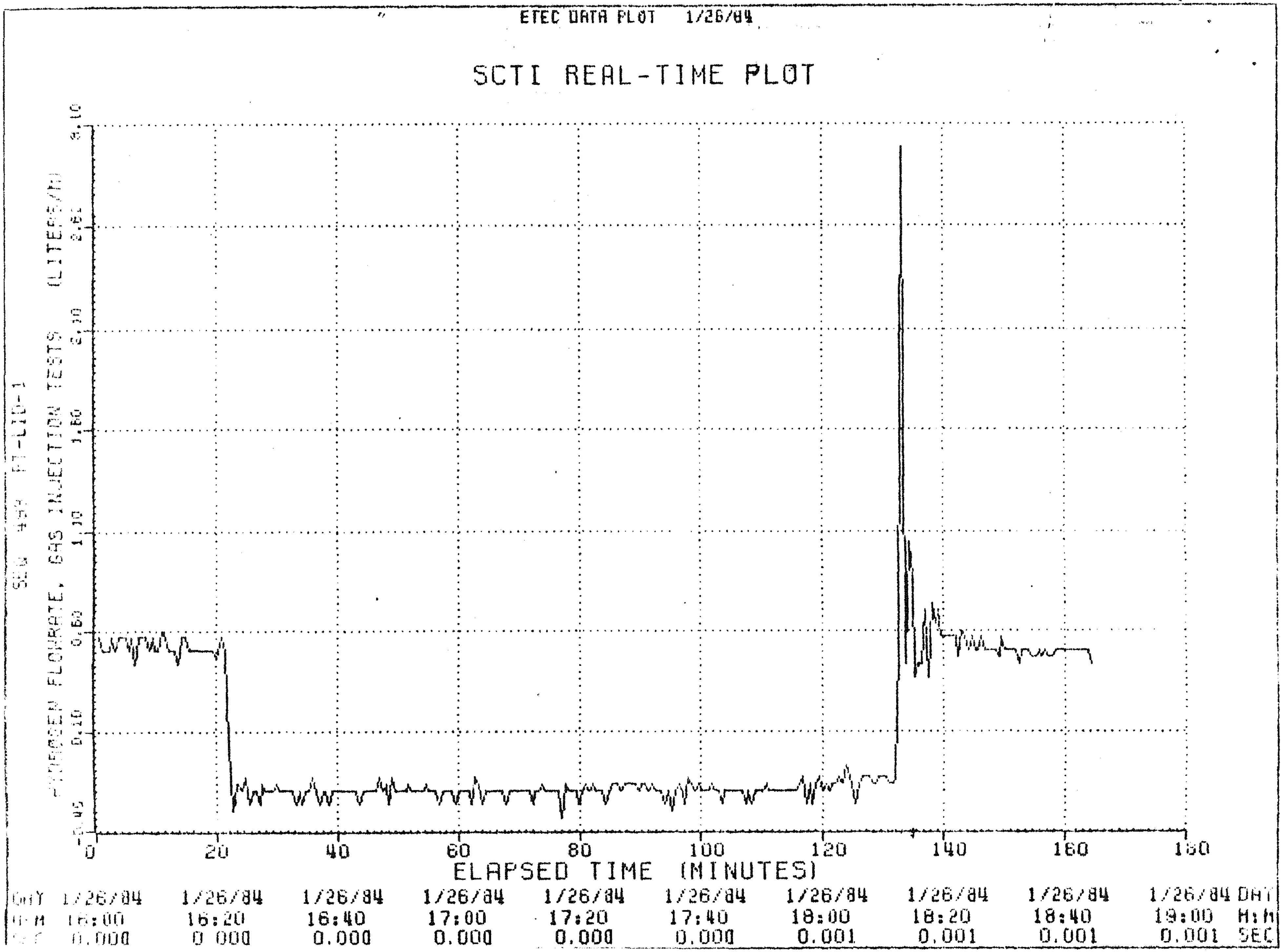
4.1 Data Recorded by Facility DAS (Test 1)

The tubesheet monitoring system (GE System #2) was restructured to monitor three planes at the level of the gas injection. At the time of the test the actual leak level was not known; therefore, the three planes monitored were at the best estimate of the axial location of the injector. The scanning system (GE System #1) was restructured to monitor an extended region covering nine planes centered about the best estimate. Data from the facility DAS are considered first since these are the data which would be directly available to the plant operator. (The GAAD system was in the control room, but required the operator to leave the control console to obtain detailed supporting information from the GAAD terminals.)

When the injection was initiated the operator took several minutes to stabilize the flow rate. During this setup time the actual flow rate could vary appreciably. An ETEC data plot of the flowmeter output is shown in Figure 13. The initial spike when the injection valve is opened is a characteristic of the flowmeter and does not necessarily represent a large injection. The flowmeter had a time-constant of about 30 seconds requiring careful manipulation of the gas injection pressure to produce the specified flow rate. During the 8 to 10 minutes of adjustment at the start, the flow could actually have been zero for several seconds since the meter cannot respond quickly; or alternatively a relatively high rate for the same reason.

A tabulation of data from the DAS disk is shown in Table 2 and plotted in Figure 14; this is data from GE system #2. Sodium flow rate was one million pounds per hour and the nitrogen gas injection was initiated at approximately 14:57 hours. The CORCO-3 values in the table and figure are the average of the previous 100 passes, i.e., the average of the current estimate and the ninety-nine prior estimates from the same location. Injection of gas was initiated just prior to pass #1605 and was stopped following pass #1732. Data for passes 1795 to 1732 therefore contain

Figure 13. Gas flow rate through leak injection device during demonstration tests.



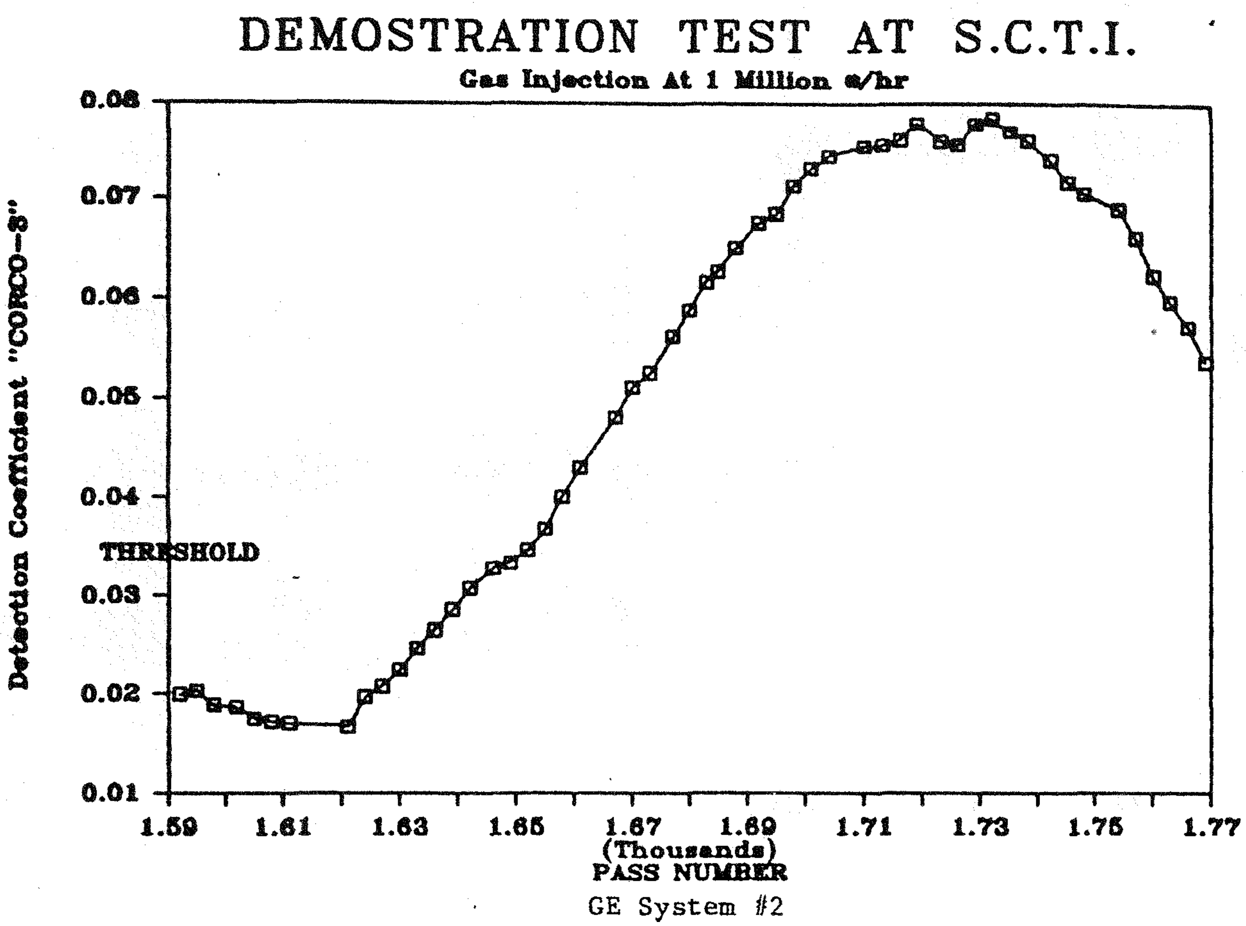


Figure 14. Plot of facility DAS data for demonstration test #1.

TABLE 2

GAAD System #2 Output to DAS as Recorded During Demonstration Test

DEMONSTRATION TEST SCTI. DOUBLE ORIFICE INJECTION
SODIUM FLOW 1 MILLION #/HR. N2 FLOW 0.6 LITERS/MIN
GE SYSTEM #2 DATA TRANSFERRED TO FACILITY D.A.S.

PASS #	TIME	PLANE #	BIN #	CORCO-3	ALARMS	NOISE
	14.50	1	71	0.0200		4
1595	14.52	1	71	0.0204		3
1598	14.54	1	71	0.0189		3
1602	14.56	1	71	0.0186		4
1605	14.57	1	71	0.0175		14
1608	15.00	1	59	0.0172		141
1611	15.02	1	20	0.0170		111
1621	15.08	3	20	0.0167		155
1624	15.10	3	20	0.0197		90
1627	15.12	3	20	0.0208		163
1630	15.14	3	20	0.0225		72
1633	15.16	3	20	0.0247		184
1636	15.18	3	20	0.0265		147
1639	15.20	3	20	0.0286		113
1642	15.22	3	20	0.0308		125
1646	15.24	3	20	0.0329		34
1649	15.26	3	20	0.0334		76
1652	15.28	3	20	0.0347		46
1655	15.30	3	20	0.0368	CORCO-2	55
1658	15.32	3	20	0.0401		37
1661	15.34	3	20	0.0431		71
1667	15.38	3	20	0.0481		49
1670	15.40	3	20	0.0512		53
1673	15.42	3	20	0.0526		37
1677	15.44	3	20	0.0563		48
1680	15.46	3	20	0.0589		71
1683	15.48	3	20	0.0617		41
1685	15.50	3	20	0.0628		46
1688	15.52	3	20	0.0651		53
1692	15.54	3	20	0.0676		47
1695	15.56	3	20	0.0685		62
1698	15.58	3	20	0.0713		43
1701	16.00	3	16	0.0731		35
1704	16.02	3	20	0.0744		34
1710	16.06	3	20	0.0754		55
1713	16.08	3	16	0.0755		67
1716	16.10	3	20	0.0761		37
1719	16.12	3	20	0.0778		52
1723	16.14	3	20	0.0759		48
1726	16.16	3	16	0.0755		42
1729	16.18	3	20	0.0777		46
1732	16.20	3	20	0.0783		36
1735	16.22	3	20	0.0770		5
1738	16.24	3	20	0.0760		3
1742	16.26	3	16	0.0739		3

information on the leak only, with no reduction in average value due to no-leak data from passes prior to #1605. The average signal-to-noise ratio at the leak site has increased to 0.078 from the usual (no leak) level of 0.020. Location was bin #20 on plane #3 (axial plane 75).

Note that when the injection was started an immediate increase in background noise level occurred. When the injection was stopped the background noise level fell back to the pre-injection level. The algorithm averages the signal-to-noise ratio measured at each location to form the CORCO-3 values; as a result the CORCO-3 values ramp from the background level towards the detection threshold. The CORCO-3 threshold at SCTI was set at 0.036 and was reached around pass #1655; however, Table 1 shows that within a few passes the correct location of the gas injector was indicated. When six successive values of signal-to-noise ratio from the same location exceed 0.070 the CORCO-2 threshold was reached. This is indicated in Table 2.

A similar set of data was transferred from the scanning system to the facility data acquisition system (Table 3 and Figure 15). This system monitored the nine planes (planes #73-81), and within the injection time only 65 passes were completed. As a result the CORCO-3 amplitude does not reach the value of 0.078, but approximately 0.05 before decaying back to the normal background level when the injection ceases. Once again CORCO-2 alarms were detected and the location of the injection indicated within a few passes as bin #23 on plane #4 (axial plane #76).

Since the local signal-to-noise ratio was 0.078 (Figure 14) and the objective was to attain a signal-to-noise ratio of 0.100, either the background noise must be decreased or the signal level increased. Increasing the injection rate would not increase the signal (see Ref. 11), so the background noise was decreased. Sodium flow through the vessel was reduced to 500,000 lbs/hour. It was expected that this would give a significant increase in sodium flow noise; however, this did not occur. When the injection was started the background level again increased by an order of

TABLE 3

GAAD system #1 output to DAS as recorded during demonstration test.

DEMONSTRATION TEST AT SCTI. DOUBLE ORIFICE INJECTION.
COVERS BOTH INJECTION PERIODS, WITH SODIUM FLOW AT 1 MILLION #/HR
FOR FIRST TEST, AND 0.5 MILLION FOR SECOND. N2 FLOW 0.6L/MIN.
GE SYSTEM #1, DATA TRANSFERRED INTO FACILITY D.A.S.

PASS #	TIME	PLANE #	BIN #	CORCO-3	ALARMS	NOISE	H20 LEAK RATE	
341	14.53	7	26	0.0197		4	1.39E-08	
343	14.55	2	39	0.0192		4	1.35E-08	
345	14.57	7	28	0.0191		3	7.58E-09	
347	14.59	7	28	0.0194		108	9.98E-06	
349	15.02	7	28	0.0201		55	2.68E-06	
351	15.04	7	28	0.0209		98	8.85E-06	Injection
353	15.07	7	28	0.0206		63	3.61E-06	initiated
355	15.09	7	28	0.0204		69	4.28E-06	
357	15.12	7	28	0.0204		59	3.13E-06	
359	15.14	7	28	0.0201		68	4.10E-06	
361	15.17	7	28	0.0206		51	2.36E-06	
362	15.18	7	28	0.0211		149	2.07E-05	
364	15.21	7	28	0.0212		82	6.29E-06	
366	15.23	7	28	0.0218		35	1.18E-06	
368	15.26	4	23	0.0218		33	1.05E-06	
370	15.28	4	23	0.0230		36	1.31E-06	
372	15.31	4	23	0.0240		25	6.61E-07	
373	15.32	4	23	0.0247		28	8.54E-07	
375	15.35	4	23	0.0259		44	2.21E-06	
376	15.36	4	23	0.0259		54	3.33E-06	
378	15.38	4	23	0.0277	CORCO-2	33	1.33E-06	
380	15.41	4	23	0.0291		35	1.57E-06	
382	15.44	4	23	0.0301		36	1.72E-06	
383	15.45	4	23	0.0302		38	1.92E-06	
385	15.48	4	23	0.0311		54	4.00E-06	
387	15.50	4	23	0.0329	CORCO-2	26	9.81E-07	
389	15.53	4	23	0.0348		33	1.67E-06	
390	15.54	4	23	0.0353		80	9.96E-06	
392	15.57	4	23	0.0370		118	2.27E-05	
393	15.58	4	23	0.0374		29	1.39E-06	
395	16.01	4	23	0.0395	CORCO-2	24	1.00E-06	
396	16.02	4	23	0.0402	CORCO-2	45	3.59E-06	
398	16.05	4	23	0.0412	CORCO-2	59	6.32E-06	
399	16.06	4	23	0.0421		29	1.56E-06	
401	16.09	4	23	0.0427		28	1.48E-06	
402	16.10	4	23	0.0436	CORCO-2	41	3.23E-06	
404	16.13	4	23	0.0449	CORCO-2	38	2.86E-06	
405	16.14	4	23	0.0456	CORCO-2	103	2.13E-05	
407	16.17	4	30	0.0474		34	2.42E-06	
409	16.19	4	30	0.0496	CORCO-2	31	2.10E-06	
411	16.22	4	30	0.0507	CORCO-2	31	2.15E-06	
413	16.24	4	30	0.0507		5	5.59E-08	Injection
414	16.25	4	30	0.0509		3	2.02E-08	stopped
416	16.27	4	30	0.0511		6	8.11E-08	
418	16.30	4	30	0.0510		11	2.72E-07	
419	16.31	4	30	0.0506		7	1.09E-07	
421	16.34	4	30	0.0497		12	3.16E-07	

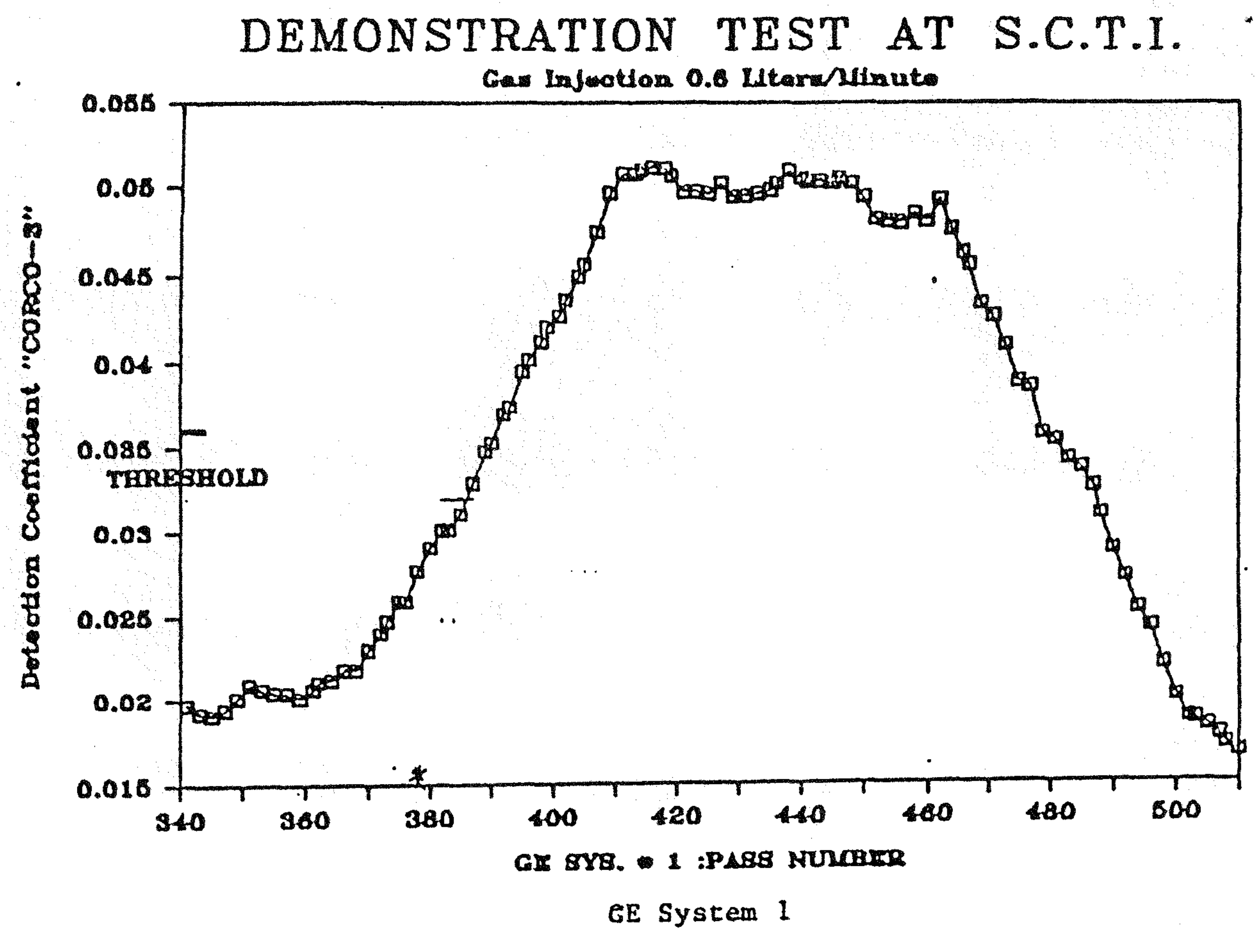


FIGURE 15. PLOT OF FACILITY DAS DATA FOR DEMONSTRATION TEST #1

magnitude. Background noise amplitude was controlled by the presence of bubbles, not the sodium velocity.

4.2 Inter-test Modifications to GE System #2

The tubesheet system (GE System #2) was restructured prior to the second demonstration test. Since the leak injection device was in a tube at the edge of the bundle the cross-sectional area of the beamformer grid was increased. This changes the bin number of the injection point compared to the one million pounds of sodium per hour test location. At the same time the planes scanned were changed from 73-75 to 74-76. This change resulted from leak location being indicated in plane #76 in GE System #1, and plane #75 in GE System 2. By moving the three plane scans higher on the vessel the possibility of missing the true location was reduced.

The number of focal points in the system scanning the nine planes was 49, corresponding to a grid size of 12 cms within the tube bundle. The system scanning the three planes used a grid size of only 9 cms, requiring 82 focal points to cover the extended area.

4.3 Data Recorded by the Facility DAS (Test 2)

A tabulation of data from the facility DAS records for GE System #2 is shown in Table 4 and plotted in Figure 16. Sodium flow rate was 500,000 lbs/hr and gas injection was initiated at 18:13:30 hours. The signal-to-noise ratio at the leak site reached 0.084, slightly above the value of Test 1. The threshold was transmitted to the DAS on pass #75; the printout is shown in Figure 17. Note that all the values in the CORCO-2 column substantially exceed 0.070. This figure can be compared with a similar printout (Figure 18) taken shortly before the start of the injection. Data from the DAS for GE System #1 are shown in Table 5 and plotted in Figure 19; injection was started about pass #507 and completed by pass #557. During this test GE System #1 indicated three CODE-1 alarms, the highest level alarm given when CORCO exceeds 0.200.

TABLE 4

GAAD System #2 Output to DAS Recorded during Second Demonstration Injection

DEMONSTRATION TEST AT S.C.T.I. DOUBLE ORIFICE
SODIUM FLOWRATE 0.5 MILLION #/HR N2 INJECTION 0.6 LITERS/MIN
GE SYSTEM #2 DATA TRANSFERRED TO FACILITY DAS

PASS #	TIME	PLANE #	BIN #	AVG CORCO	ALARMS	NOISE	H20 L/R
3	17.37	2	79	0.0527		7	1.14E-07
4	17.39	2	71	0.0431		5	4.75E-08
7	17.41	2	63	0.0321		21	6.24E-07
10	17.42	2	63	0.0267		13	1.99E-07
13	17.44	2	78	0.0304		8	8.58E-08
17	17.47	2	78	0.0261		7	5.64E-08
20	17.49	2	78	0.0233		3	9.25E-09
23	17.50	2	78	0.0214		7	4.62E-08
27	17.53	3	70	0.0213		4	1.50E-08
30	17.55	2	26	0.0189		6	3.00E-08
33	17.56	3	78	0.0184		8	5.19E-08
37	17.59	2	26	0.0181		5	2.00E-08
40	18.01	2	26	0.0182		4	1.28E-08
43	18.02	2	26	0.0178		5	1.96E-08
47	18.05	2	26	0.0176		6	2.79E-08
50	18.07	2	26	0.0186		4	1.31E-08
53	18.09	2	32	0.0182		9	6.50E-08
56	18.10	2	32	0.0189		3	7.50E-09
60	18.13	2	32	0.0189		119	1.18E-05
63	18.15	2	32	0.0185		59	2.84E-06
66	18.17	2	32	0.0179		113	1.01E-05
69	18.19	2	32	0.0198		94	7.71E-06
72	18.21	2	21	0.0221		43	1.80E-06
75	18.23	2	21	0.0248	CODE 2	56	3.43E-06
83	18.28	2	21	0.0291	CODE 2	51	3.34E-06
86	18.30	2	21	0.0310	CODE 2	42	2.41E-06
89	18.32	2	21	0.0322		60	5.11E-06
92	18.34	2	30	0.0333		84	1.04E-05
96	18.37	2	30	0.0350		89	1.22E-05
98	18.38	2	30	0.0351	CODE 2	47	3.42E-06
102	18.41	2	30	0.0375	CODE 2	43	3.06E-06
104	18.42	2	30	0.0391		40	2.76E-06
108	18.45	2	30	0.0426	CODE 2	48	4.33E-06
111	18.47	2	30	0.0438		44	3.74E-06
114	18.49	2	30	0.0465		53	5.76E-06
117	18.51	2	30	0.0493		83	1.50E-05
129	18.58	2	30	0.0588	CODE 2/3	55	7.84E-06
132	19.00	2	30	0.0612	CODE 2/3	31	2.59E-06
136	19.03	2	30	0.0659	CODE 2/3	56	9.11E-06
139	19.05	2	30	0.0684	CODE 2/3	45	6.11E-06
142	19.07	2	30	0.0707	CODE 2/3	46	6.60E-06
145	19.09	2	30	0.0732	CODE 2/3	55	9.76E-06
148	19.10	2	30	0.0751	CODE 3	46	7.01E-06
151	19.12	2	30	0.0773	CODE 2/3	64	1.40E-05
155	19.15	2	30	0.0796	CODE 2/3	60	1.26E-05

TABLE 4 (Cont'd)

GAAD System #2 Output to DAS Recorded during
Second Demonstration Injection

PASS #	TIME	PLANE #	BIN #	AVG CORCO	ALARMS	NOISE	H20 L/R
158	19.17	2	30	0.0821	CODE 3	53	1.02E-05
161	19.19	2	30	0.0836	CODE 3	43	6.82E-06
164	19.21	2	30	0.0840	CODE 3	5	9.26E-08
167	19.22	2	30	0.0812	CODE 3	3	3.22E-08
171	19.25	2	30	0.0778	CODE 3	3	3.09E-08
174	19.26	2	30	0.0758	CODE 3	4	5.35E-08
178	19.29	2	30	0.0720	CODE 3	3	2.86E-08
181	19.31	2	30	0.0705	CODE 3	5	7.77E-08
184	19.32	2	30	0.0688	CODE 3	3	2.73E-08
188	19.35	2	30	0.0653	CODE 3	5	7.20E-08
191	19.36	2	30	0.0638	CODE 3		0.00E+00
195	19.39	2	30	0.0617	CODE 3		0.00E+00
198	19.41	2	30	0.0603	CODE 3		0.00E+00
201	19.42	2	30	0.0584	CODE 3		0.00E+00
205	19.45	2	30	0.0546	CODE 3		0.00E+00
208	19.46	2	30	0.0518	CODE 3		0.00E+00
212	19.49	2	30	0.0506	CODE 3		0.00E+00
215	19.51	2	30	0.0481			0.00E+00
218	19.53	2	30	0.0443			0.00E+00
221	19.54	2	30	0.0407			0.00E+00
223	19.58	2	30	0.0392			0.00E+00
225	20.01	2	30	0.0376			0.00E+00
226	20.12	2	30	0.0373			0.00E+00

TABLE 5

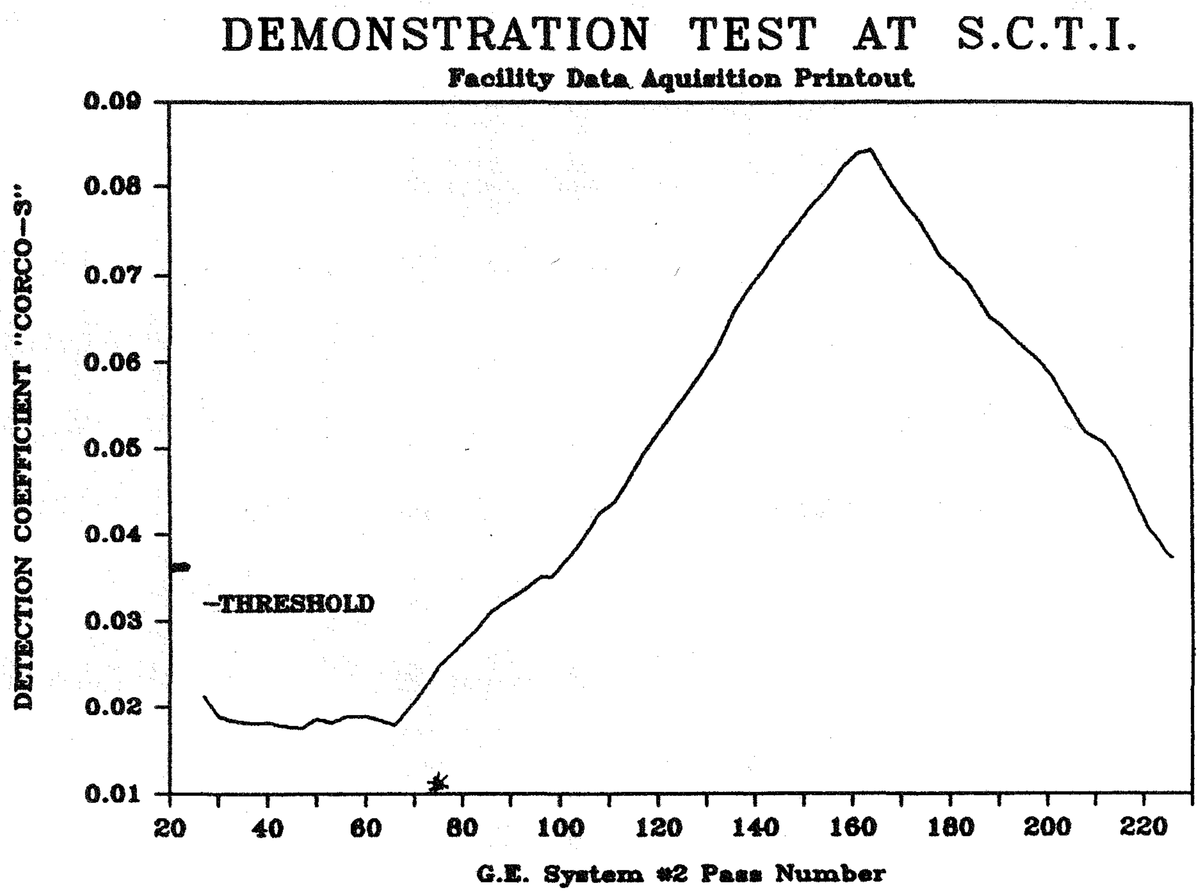
GAAD system #1 output to DAS recorded during second demonstration injection.

423	16.36	4	30	0.0497		12	3.16E-07	
425	16.38	4	30	0.0496		10	2.19E-07	
427	16.41	4	30	0.0502		20	8.85E-07	
429	16.44	4	30	0.0494		7	1.07E-07	
431	16.46	4	30	0.0495		8	1.40E-07	
433	16.49	4	30	0.0496		5	5.47E-08	
435	16.51	4	30	0.0498		4	3.51E-08	
436	16.52	4	30	0.0502		7	1.08E-07	
438	16.54	4	30	0.0509		11	2.72E-07	
440	16.57	4	30	0.0505		8	1.43E-07	
441	16.58	4	30	0.0503		14	4.35E-07	
443	17.00	4	30	0.0503		4	3.55E-08	
445	17.03	4	30	0.0502		7	1.08E-07	
446	17.04	4	30	0.0505		4	3.56E-08	
448	17.06	4	30	0.0502		4	3.54E-08	
450	17.09	4	30	0.0494		5	5.45E-08	
452	17.11	4	30	0.0482		5	5.31E-08	
454	17.13	4	30	0.0481		4	3.39E-08	
456	17.16	4	30	0.0480		6	7.62E-08	
458	17.18	4	30	0.0485		4	3.42E-08	
460	17.20	4	30	0.0481		3	1.91E-08	
462	17.23	4	30	0.0493		3	1.96E-08	
464	17.25	4	30	0.0476		4	3.36E-08	
466	17.27	4	30	0.0463		4	3.27E-08	Planes
467	17.28	4	30	0.0456		5	5.03E-08	
469	17.30	4	30	0.0434		5	4.78E-08	
471	17.33	4	30	0.0427		7	9.23E-08	
473	17.35	4	30	0.0410		6	6.51E-08	
475	17.37	4	30	0.0389		5	4.29E-08	
477	17.39	4	30	0.0386		5	4.25E-08	
479	17.42	4	30	0.0358		4	2.53E-08	
481	17.44	4	30	0.0354		21	6.88E-07	
483	17.46	4	30	0.0343		5	3.78E-08	
485	17.49	4	30	0.0338		13	2.52E-07	
487	17.51	4	30	0.0327		6	5.19E-08	
488	17.52	4	30	0.0311		7	6.72E-08	
490	17.54	4	30	0.0290		6	4.60E-08	
492	17.57	4	30	0.0273		4	1.93E-08	
494	17.59	4	30	0.0254		4	1.79E-08	
496	18.01	4	30	0.0243		3	9.64E-09	
498	18.03	4	30	0.0221		6	3.51E-08	
500	18.06	4	30	0.0201		3	7.98E-09	
502	18.08	3	22	0.0188		4	1.33E-08	← Location data lost; ready for next test.
503	18.09	3	34	0.0187		3	7.42E-09	
505	18.11	3	22	0.0183		2	3.23E-09	
507	18.14	3	34	0.0178		88	6.08E-06	← Injection @ 18:13:30
508	18.15	3	22	0.0173		61	2.84E-06	
510	18.18	3	22	0.0168		67	3.33E-06	
511	18.19	3	22	0.0166		54	2.13E-06	
513	18.22	3	9	0.0159		33	7.63E-07	
515	18.24	3	9	0.0164		71	3.65E-06	
517	18.27	8	49	0.0179		26	5.34E-07	
518	18.28	8	49	0.0179		25	4.93E-07	
520	18.31	8	49	0.0182		29	6.75E-07	
521	18.32	4	23	0.0186	CODE 1	123	1.24E-05	
523	18.35	4	24	0.0196	CODE 2	28	6.78E-07	

TABLE 5 (Cont'd.)

GAAD system #1 output to DAS recorded during second demonstration injection.

524	18.36	4	24	0.0199		34	1.01E-06
526	18.39	3	24	0.0221	CODE 1	30	8.77E-07
527	18.40	3	24	0.0231		64	4.17E-06
529	18.43	3	24	0.0248		26	7.39E-07
531	18.45	3	24	0.0261		42	2.03E-06
533	18.48	3	24	0.0279		35	1.51E-06
534	18.49	3	24	0.0285		25	7.85E-07
536	18.52	3	24	0.0313		31	1.33E-06
538	18.54	3	24	0.0333		27	1.07E-06
540	18.57	3	24	0.0339		41	2.51E-06
541	18.58	3	24	0.0346		27	1.11E-06
543	19.01	3	24	0.0357		32	1.61E-06
545	19.03	3	24	0.0372		43	3.03E-06
547	19.06	3	24	0.0394		24	1.00E-06
549	19.08	3	24	0.0402		26	1.20E-06
551	19.11	3	24	0.0415		99	1.79E-05
553	19.13	3	24	0.0428	CODE 1	50	4.72E-06
555	19.16	3	24	0.0447		28	1.55E-06
557	19.18	3	24	0.0465		55	6.20E-06
559	19.21	3	24	0.0484		3	1.92E-08
561	19.23	3	24	0.0484		3	1.92E-08
562	19.24	3	24	0.0481		5	5.30E-08
564	19.26	3	24	0.0479		3	1.90E-08
566	19.28	3	24	0.0477		4	3.37E-08
568	19.31	3	24	0.0476		3	1.89E-08
570	19.33	3	24	0.0469		3	1.86E-08
572	19.35	3	24	0.0469		4	3.31E-08
574	19.37	3	24	0.0473		3	1.88E-08
576	19.39	3	24	0.0470		3	1.87E-08
578	19.41	3	24	0.0466		3	1.85E-08
580	19.43	3	24	0.0469		4	3.31E-08
582	19.46	3	24	0.0470		3	1.87E-08
584	19.48	3	24	0.0479		4	3.38E-08
586	19.50	3	24	0.0483		4	3.41E-08
587	19.51	3	24	0.0486		4	3.43E-08
589	19.53	3	24	0.0491		3	1.95E-08
591	19.55	3	24	0.0499		3	1.98E-08
593	19.57	3	24	0.0500	CODE 3	3	1.98E-08
595	20.00	3	24	0.0495		6	7.86E-08
597	20.02	3	24	0.0495		4	3.49E-08
598	20.03	3	24	0.0495		7	1.07E-07
600	20.05	3	24	0.0496		4	3.50E-08
602	20.07	3	24	0.0493		4	3.48E-08
604	20.10	3	24	0.0485		7	1.05E-07
606	20.12	3	24	0.0483		7	1.04E-07
608	20.14	3	24	0.0482		6	7.65E-08
610	20.16	3	24	0.0474		4	3.34E-08
612	20.18	3	24	0.0470		7	1.02E-07
614	20.21	3	24	0.0456		6	7.24E-08
616	20.23	3	24	0.0435		3	1.73E-08
618	20.25	3	24	0.0427		3	1.69E-08
620	20.27	3	24	0.0418		3	1.66E-08
622	20.29	3	24	0.0381		4	2.69E-08
624	20.32	3	24	0.0371		16	4.19E-07
626	20.34	3	24	0.0350		3	1.39E-08
628	20.36	3	24	0.0334		3	1.33E-08



Sodium flow rate: 0.5 million pounds per hour

FIGURE 16. PLOT OF FACILITY DAS DATA FOR DEMONSTRATION TEST #2

GAAD ACOUSTIC DATA
SYSTEM NO. 2
PASS NO. 75

TIME: JANUARY 26,1984 18:23

CORCO 1	.13910	CORCO 2	.10520
PLANE NO.	2.	PLANE NO.	2.
BIN NO.	30.	BIN NO.	30.
CORCO 1A	.13910	CORCO 2A	.09920
CORCO 1B	.07070	CORCO 2B	.09720
CORCO 1C	.10350	CORCO 2C	.10650
CORCO 1D	.07040	CORCO 2D	.09970
CORCO 1E	.17260	CORCO 2E	.08250

CORCO 3	.02480
PLANE NO.	2.
BIN NO.	21.

POWER 1	56. UBAR
POWER 2	56. UBAR
POWER 3	56. UBAR
POWER D	36. UBAR
POWER E	52. UBAR

GAAD WATER LEAK RATE #1	1.92E-05 LBS/SEC
GAAD WATER LEAK RATE #2	1.45E-05 LBS/SEC
GAAD WATER LEAK RATE #3	3.43E-06 LBS/SEC

Figure 17. Facility DAS printout during injection - SCTI demonstration test #2.

GAAD ACOUSTIC DATA
SYSTEM NO. 2
PASS NO. 43

TIME: JANUARY 26,1984 16: 2

CORCO 1	.05820	CORCO 2	.04220
PLANE NO.	0.	PLANE NO.	1.
BIN NO.	46.	BIN NO.	24.
CORCO 1A	.05820	CORCO 2A	.03910
CORCO 1B	0.00000	CORCO 2B	.03670
CORCO 1C	.01430	CORCO 2C	.02460
CORCO 1D	.02780	CORCO 2D	.02030
CORCO 1E	0.00000	CORCO 2E	.01020

CORCO 3	.01780
PLANE NO.	2.
BIN NO.	26.
POWER 1	4. UBAR
POWER 2	4. UBAR
POWER 3	5. UBAR
POWER U	6. UBAR
POWER L	4. UBAR

GAAD WATER LEAK RATE #1 4.11E-08 LBS/SEC
GAAD WATER LEAK RATE #2 3.77E-08 LBS/SEC
GAAD WATER LEAK RATE #3 1.96E-08 LBS/SEC

Figure 18. Facility DAS printout prior to injection - SCTI demonstration test.

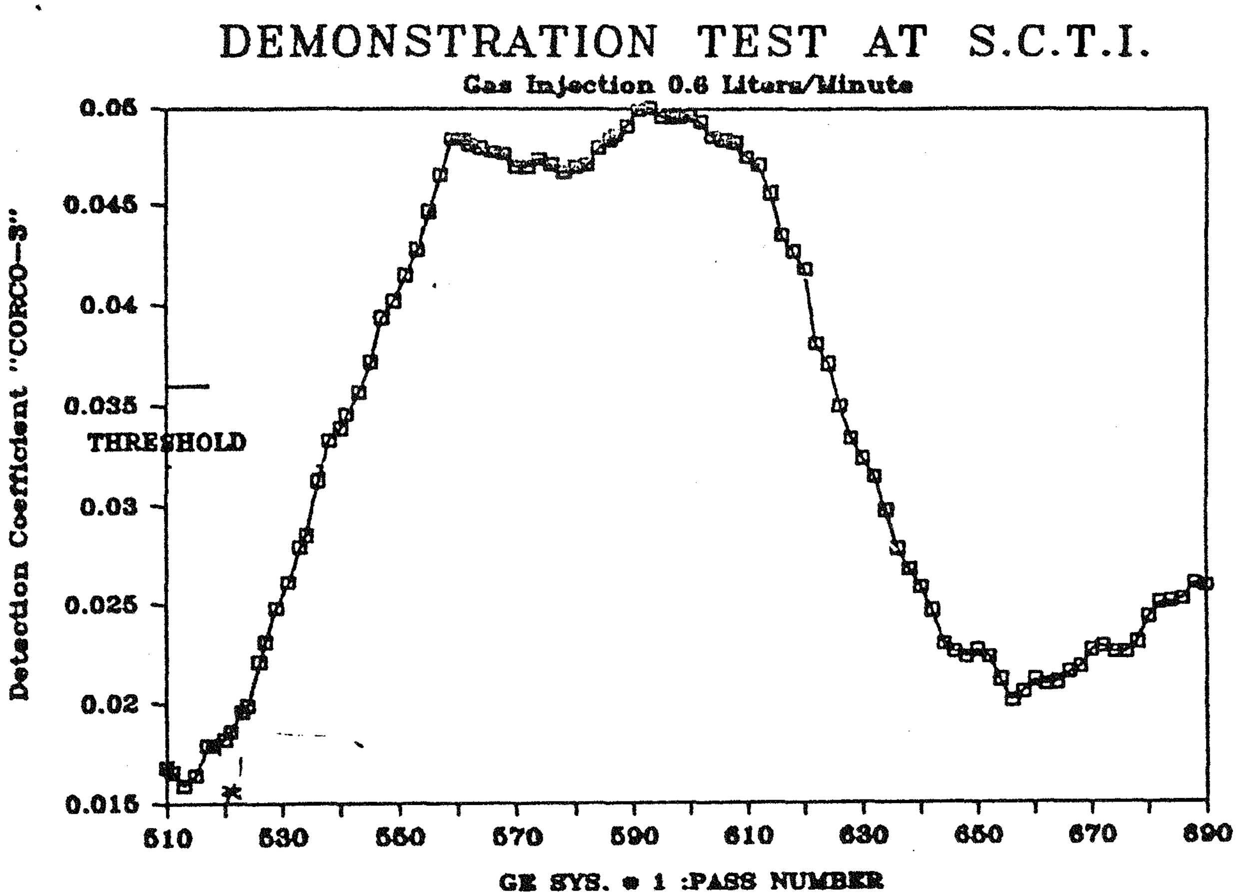


FIGURE 19. PLOT OF FACILITY DAS DATA FOR DEMONSTRATION TEST #2

The graphic display provided by the GAAD system is shown in Figure 20. Two modes of display are available; the one photographed provides a display at all times. The alternative display does not show the boxes until the CORCO value approaches the threshold levels. Note how the other boxes diminish in size as the leak site box strength increases, changing from a random display to a location diagram giving both axial and radial position of the injector.

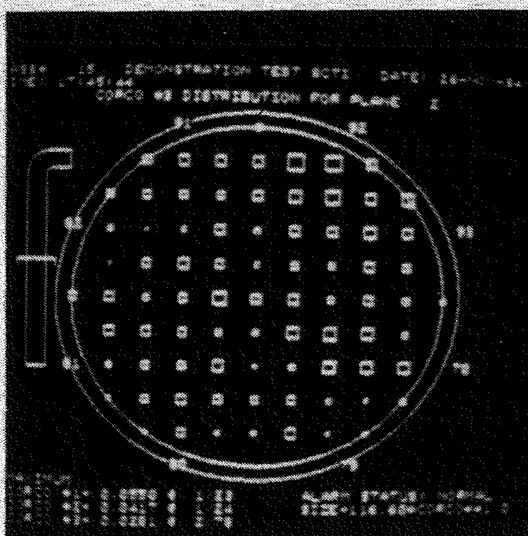
4.4 Data Recorded by GAAD System

Results presented so far are taken from the facility DAS records. These are only a portion of the information available from the GAAD system monitor terminal and graphics display. Data are also stored for later recall and diagnostic examination. This information is now presented.

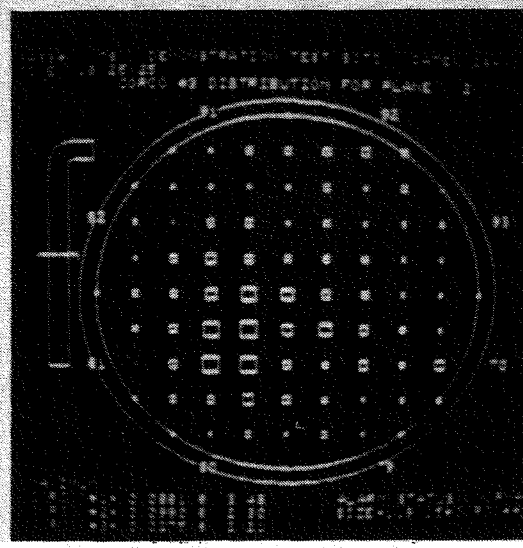
Local signal-to-noise ratios for each bin are stored in a file. Data from this file can be recalled during leak monitoring to give the history of any bin for the period prior to the request. An example is shown in Figure 21. This is the history of the injection site location (plane #2, bin #30). It presents the individual signal-to-noise ratio measured on each pass. Leak initiation and shutdown are clearly marked. When the same data are averaged over the previous six passes a smoother curve is produced (Figure 22). This is also an indicator of the likelihood for CODE-2 alarms. Once again, the gas injection period is obvious. When the same data are averaged over 100 passes a very smooth curve is obtained, but the gas injection is not defined as sharply (Figure 23). The operator specifies the bin and plane number for the plot; or can use the default setting which shares the location with the maximum CORCO; (either CORCO-1, -2 or -3, depending upon whether each value, the average of 6 values, or the average of 100 values is demanded).

The location diagram for the 0.6 L N_2/min into sodium flowing at 0.5 million lbs/hr is shown in Figure 24. Diagrams for the plane above (Figure 25) and for the plane below (Figure 26) show the degree of axial

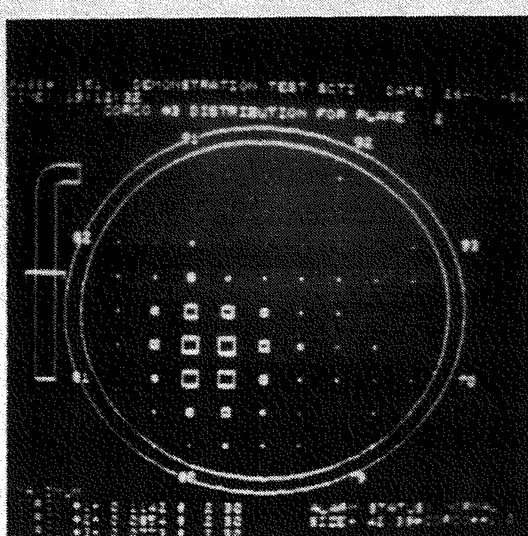
RESULT OF DEMONSTRATION TEST IN SCTI



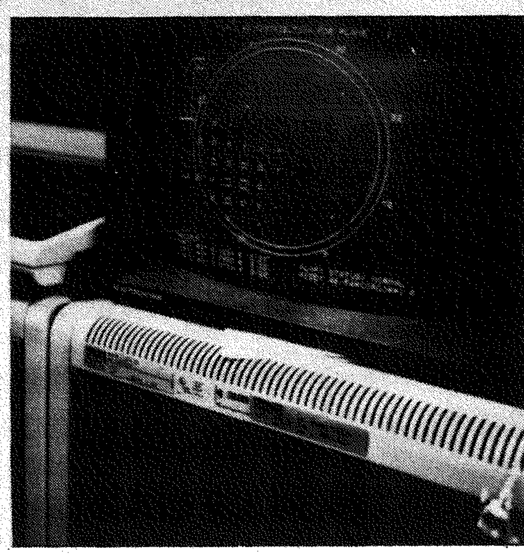
Before



Acquiring



Plane 2, Bin 30 is the leak site



Operator's graphic terminal

Figure 20. GAAD system operator's CRT presentation of leak detection/location during demonstration test.

FIGURE 21. CORCO HISTORY BASED UPON SINGLE PASS AVERAGING (CORCO-1).

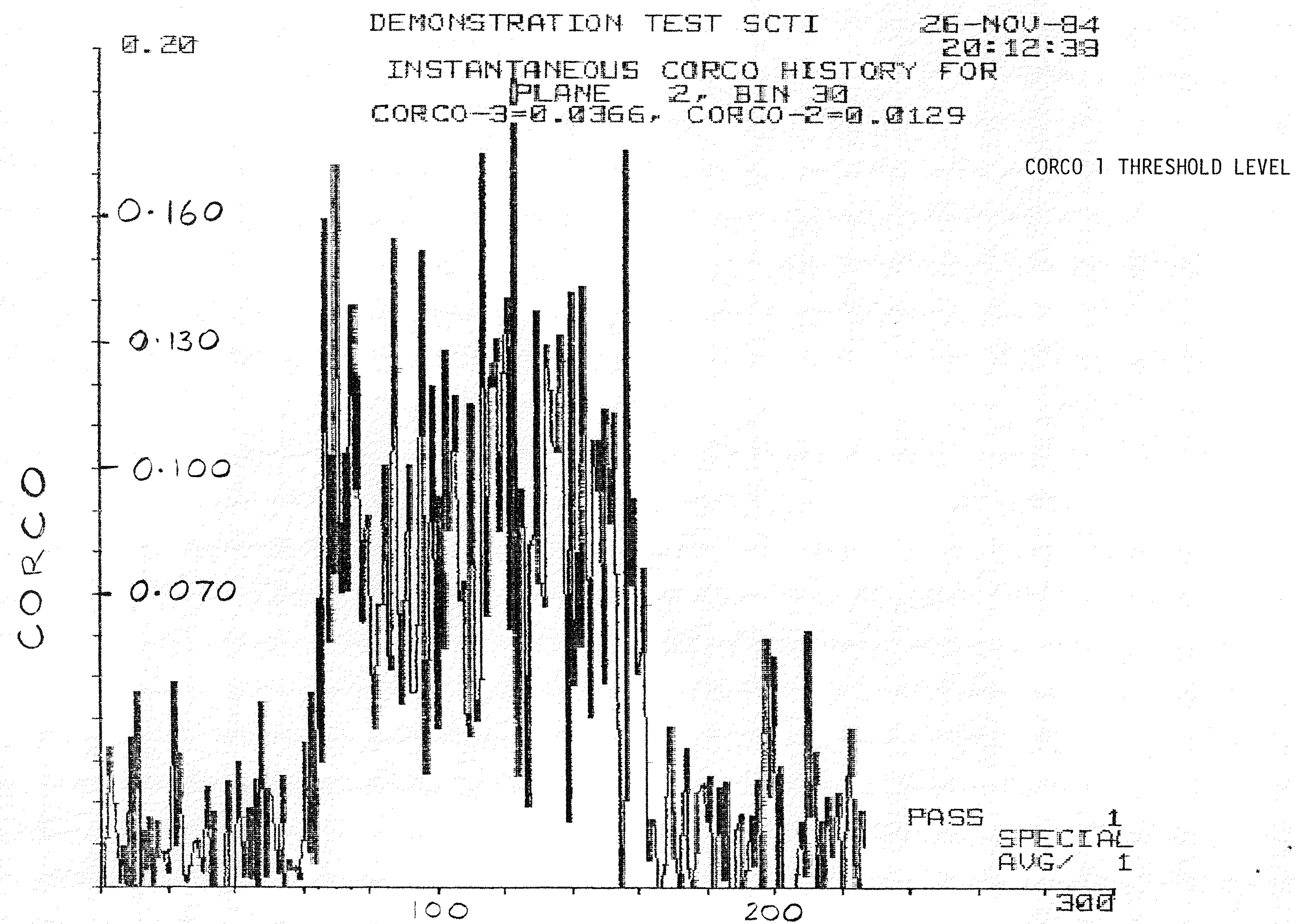


FIGURE 22. CORCO HISTORY BASED UPON AN AVERAGE OF SIX PASSES (CORCO-2)

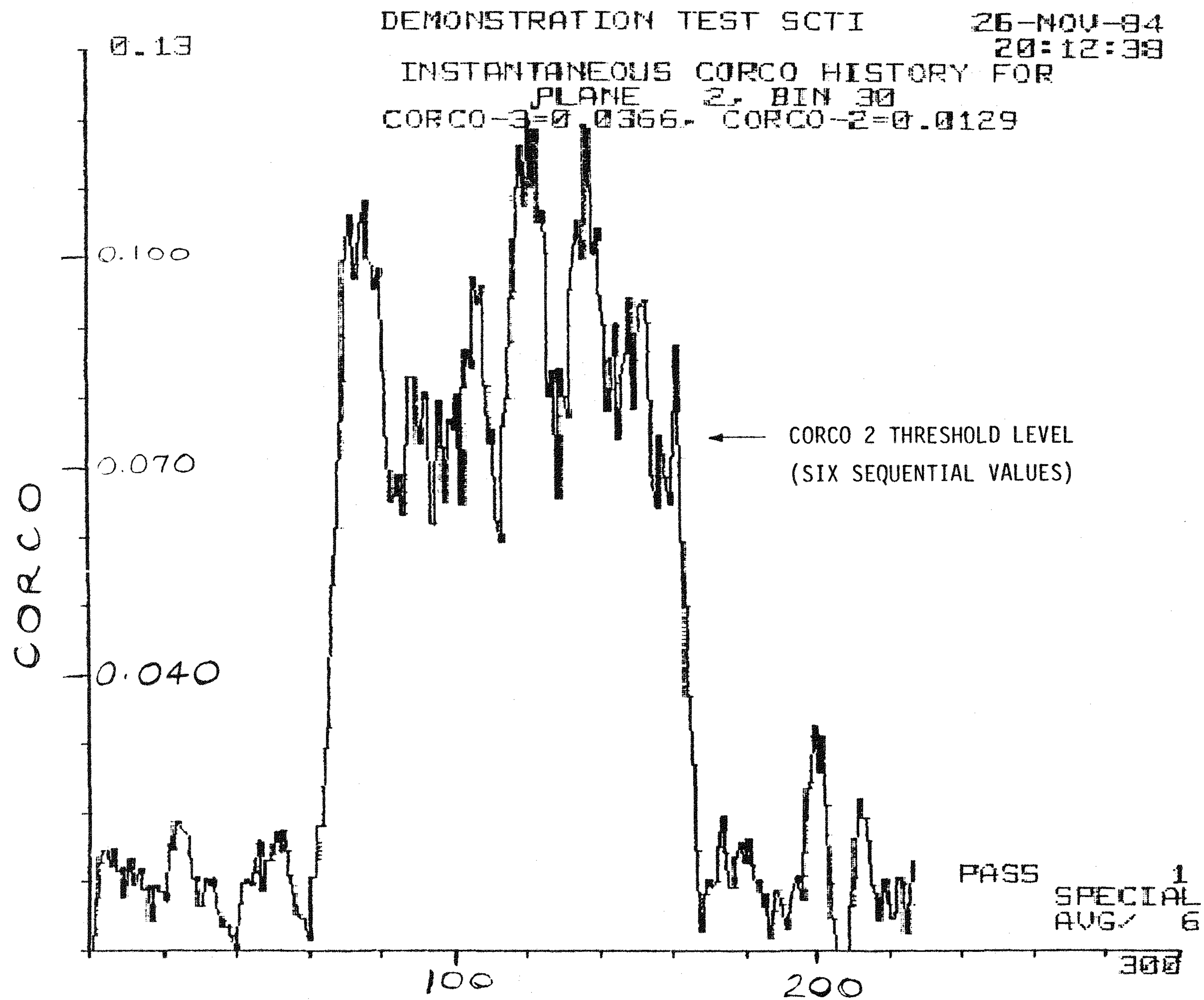


FIGURE 23. CORCO HISTORY BASED UPON AN AVERAGE OF 100 PASSES (CORCO-3)

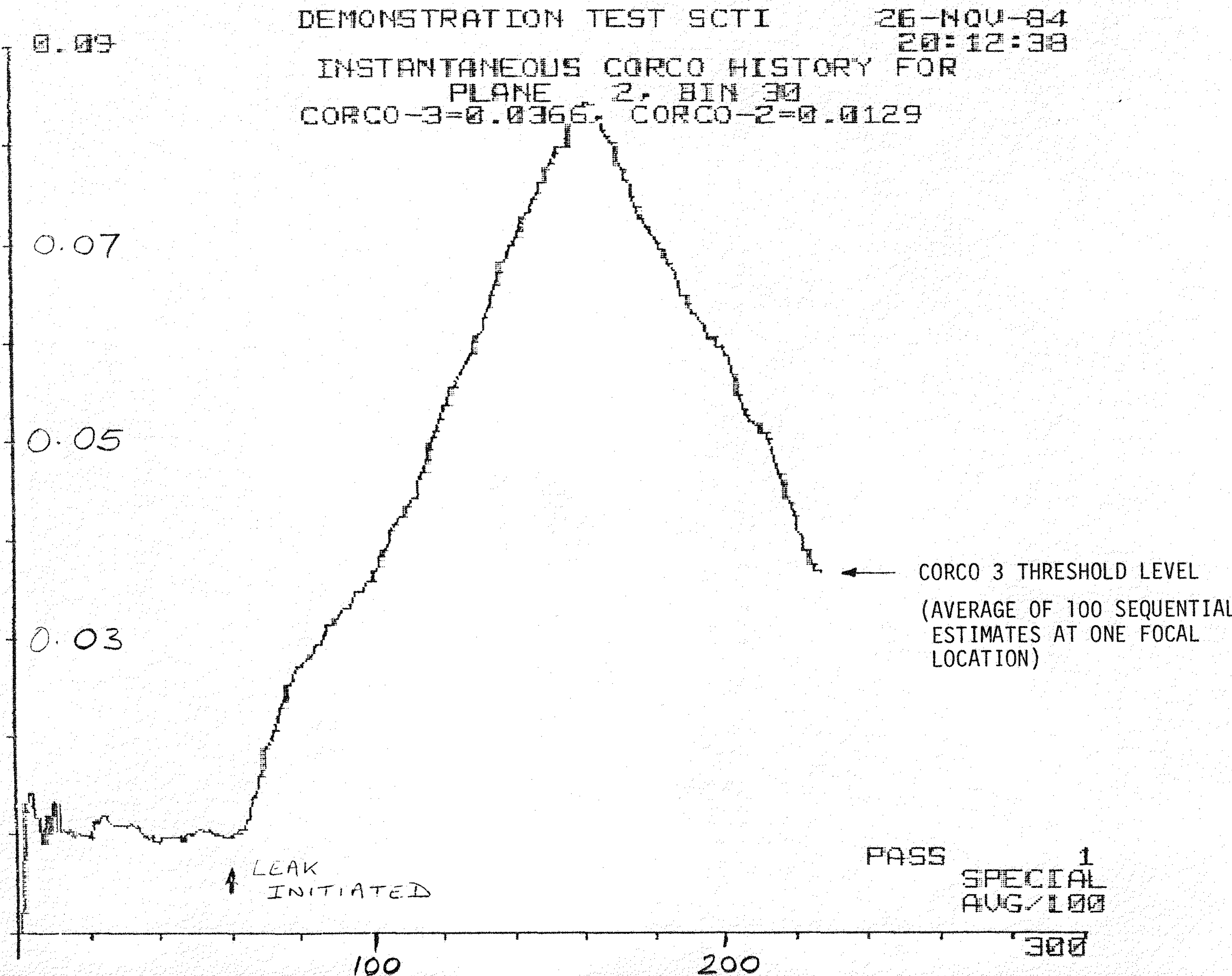


FIGURE 24. OPERATOR'S CRT PRESENTATION SHOWING INJECTION AT BIN #130 IN LEAK PLANE WITH A HIGH CORCO VALUE OF 0.0847

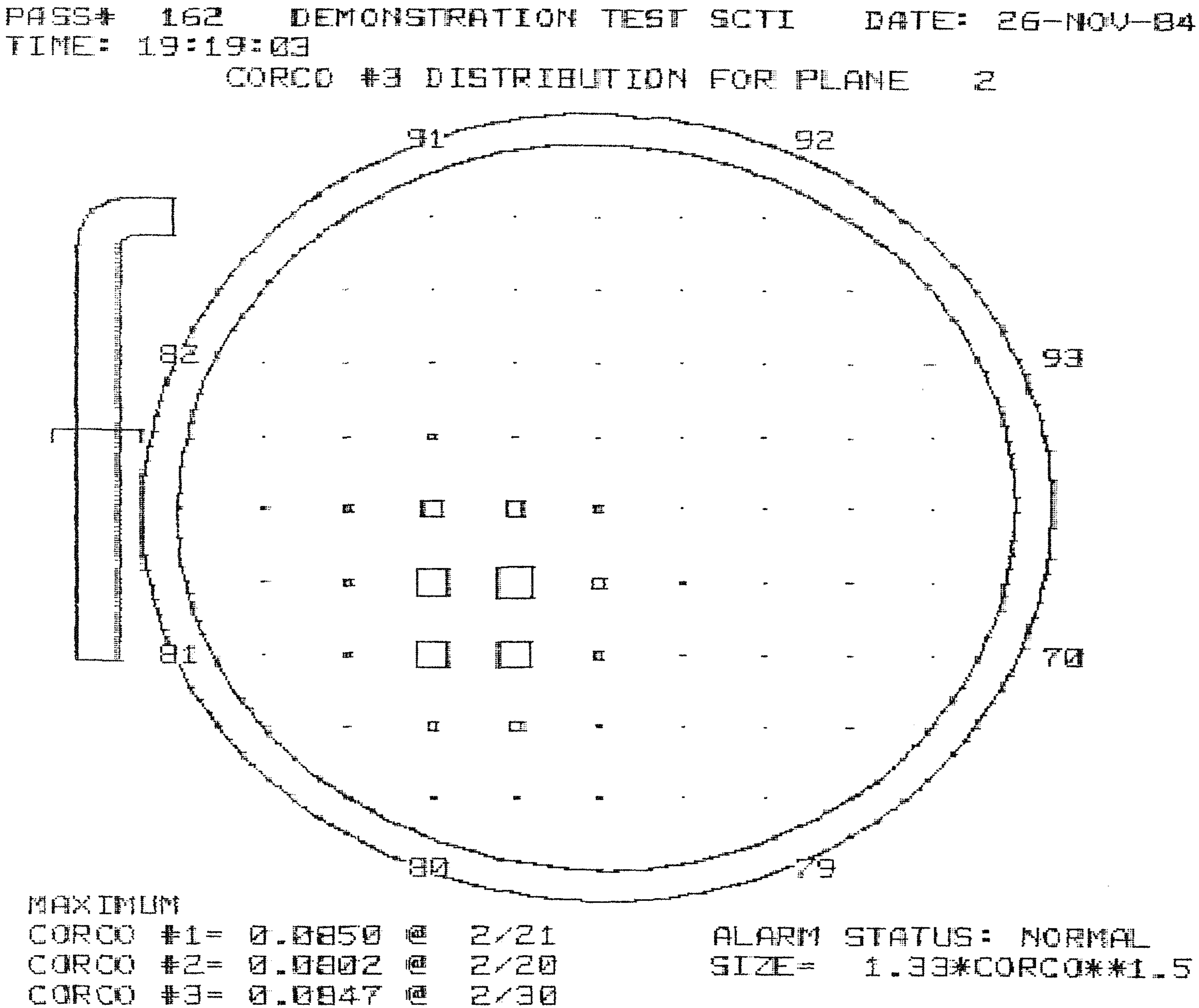


FIGURE 25. OPERATOR'S CRT PRESENTATION SHOWING ONE PLANE (12 cm) ABOVE THE LEAK SITE

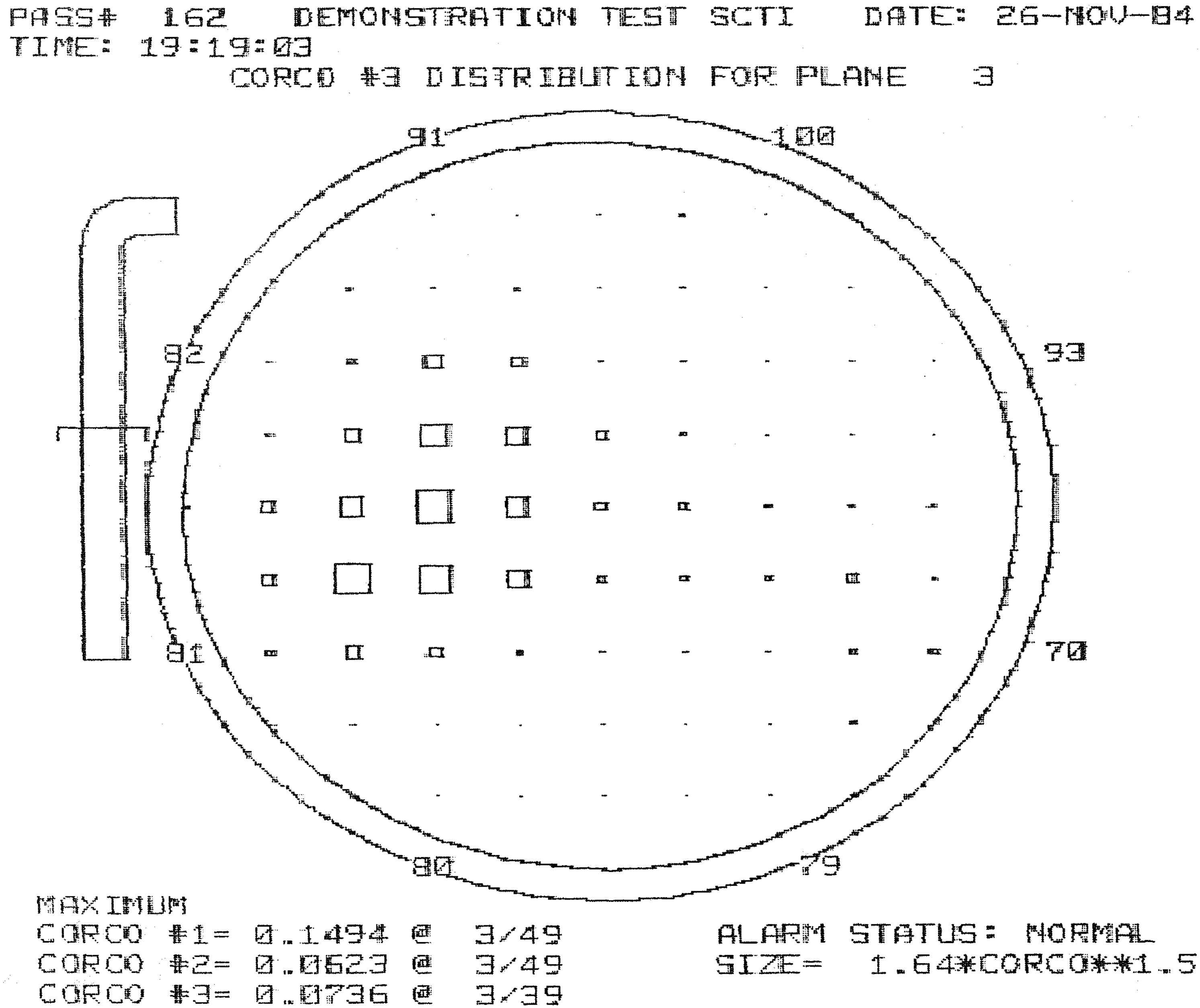
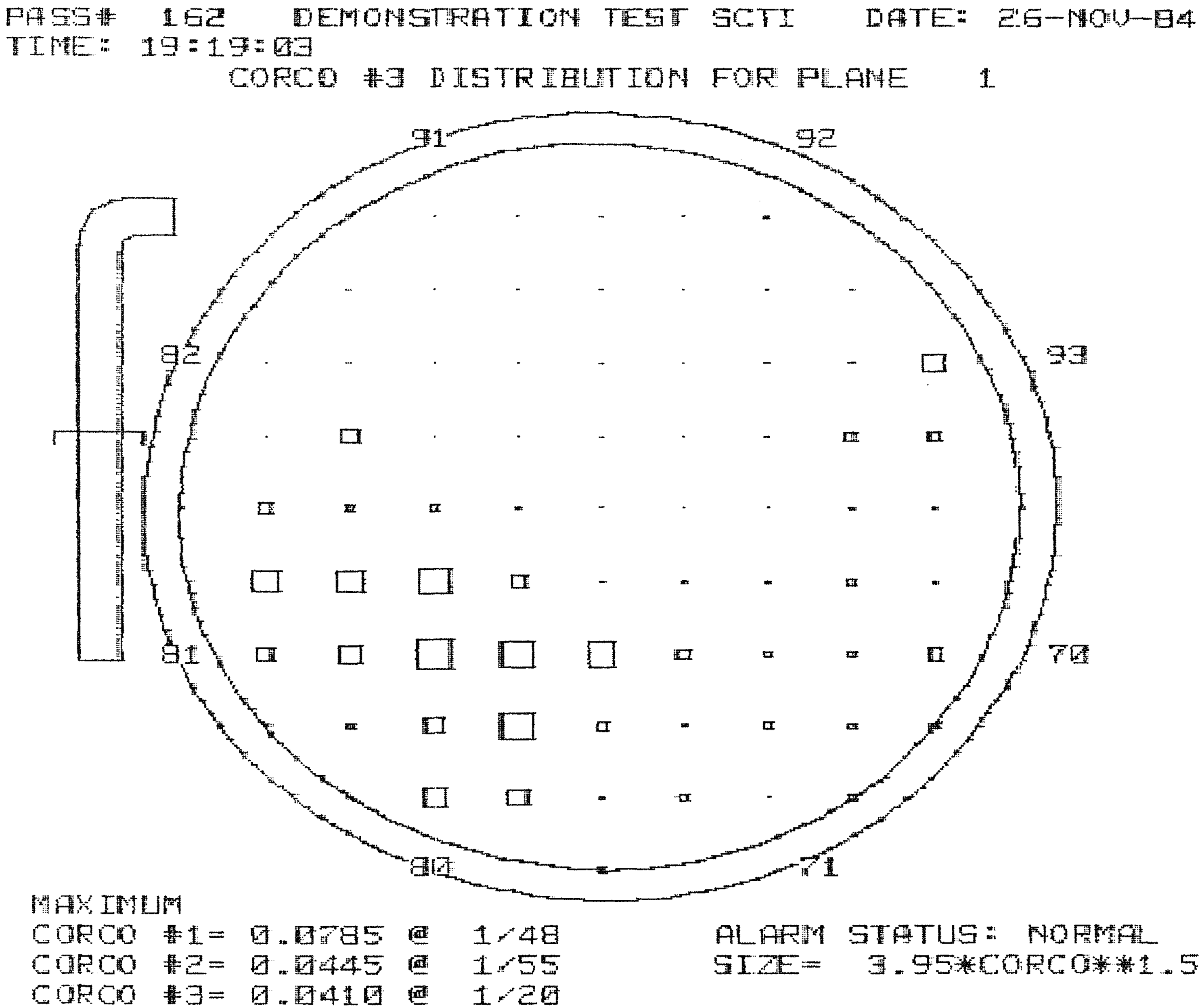


FIGURE 26. OPERATOR'S CRT PRESENTATION SHOWING ONE PLANE (12 cm) BELOW THE LEAK SITE



location. These diagrams use a default setting for the differentiation between the boxes. A more exact location can be obtained by using the "contrast" mode, with the result shown in Figure 27. The diagram with no injection of gas is shown in Figure 28.

FIGURE 27. OPERATOR'S CRT PRESENTATION SHOWING ABILITY TO ZOOM IN ON THE LEAK SITE, BIN #30 IN LEAK PLANE

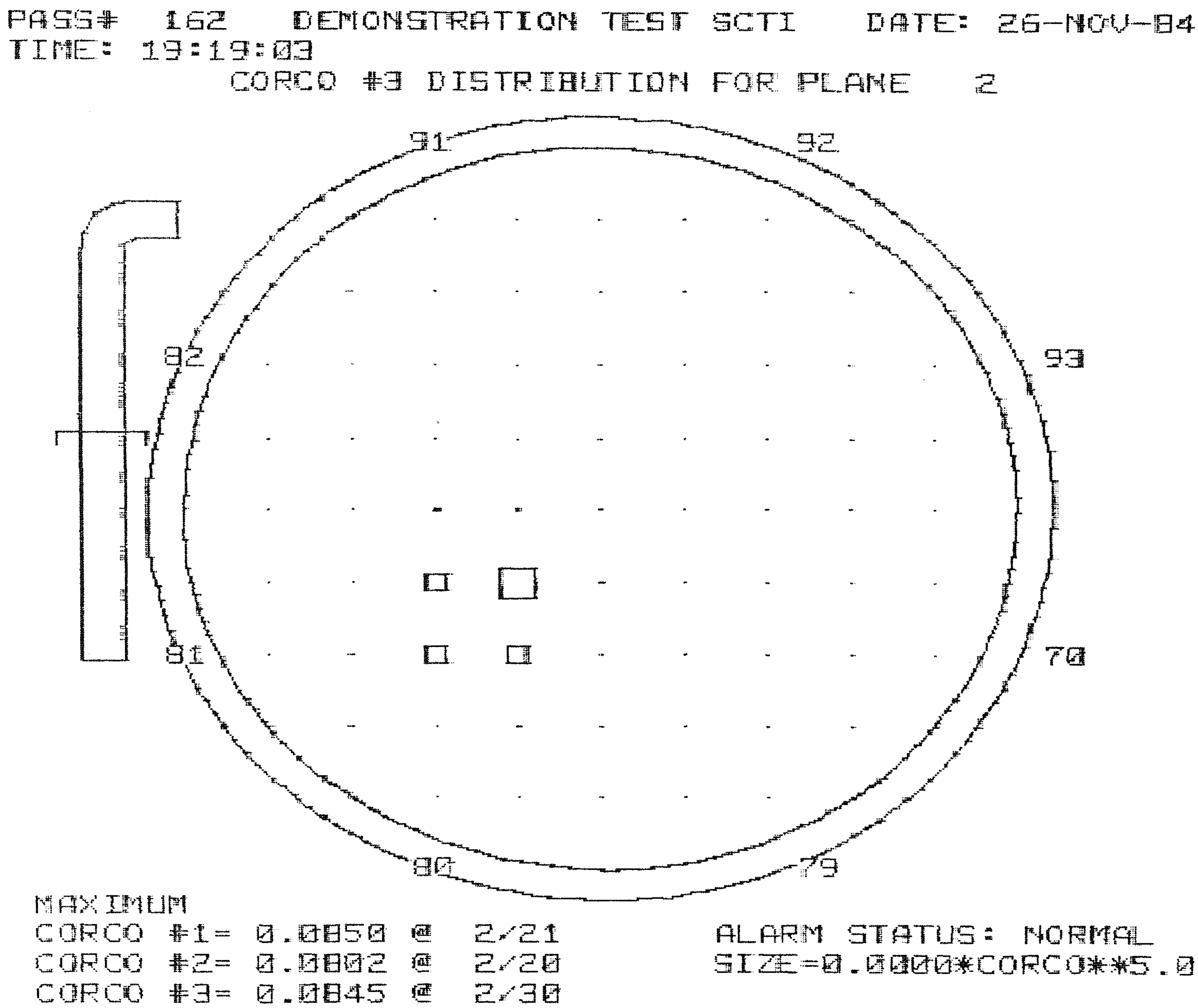
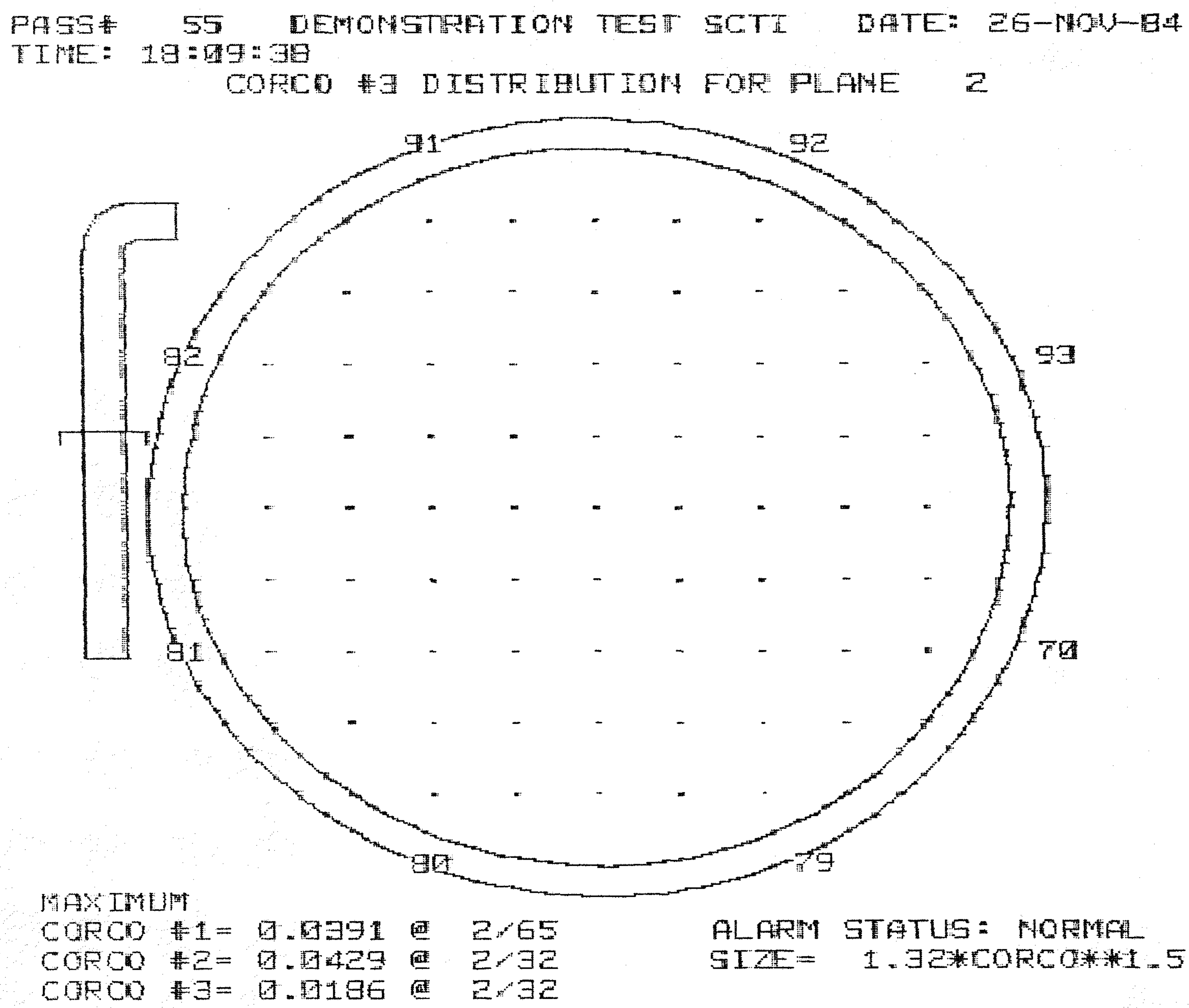


FIGURE 28. OPERATOR'S CRT PRESENTATION UNDER NORMAL CONDITIONS (i.e., NO LEAK)



5.0 DISCUSSION AND CONCLUSIONS

5.1 Leak Location

As discussed in the previous section, tests were made using a gas injection to simulate an intermediate sodium/water reaction. Two independent GAAD systems monitored the injections, and each quickly and correctly located the injection site to within a few inches. Post-test analysis using an intensifying technique to "contrast" the detection diagram showed the GAAD system has the potential for locating well within 9 cms. Gas injections tend to be acoustically larger than sodium/water reactions so the results obtained (Figure 27) are conservative.

No effort was made to optimize the GAAD systems to provide exact location of the injection point. Earlier tests in the LLTV showed location of a small leak can be precise [15].

5.2 Leak Detection

Both injections were quickly detected, and all levels of alarm threshold were activated. The local signal-to-noise ratio at the leak site was approximately 15% lower (0.085) than the predefined level of -10 dB (0.100). An ability to detect and locate these two injections demonstrated the GAAD system detection/location capabilities in a power plant environment when mounted on a prototypic steam generator.

Reference 11 discusses the limitations in simulating a sodium/water reaction by a gas injection. Despite these limitations the acoustic simulation of an intermediate leak condition was attained, and successful detection/location of the injections achieved.

5.3 Extrapolation of Performance to LMFBR Steam Generator

5.3.1 Detection Algorithm

The GAAD system algorithm is based on statistical processing of random acoustic pressures generated by the background noise sources. Prior to the SCTI test these statistics were predicted analytically. Changes to the predicted probability distribution at each focal point are examined. Deviation from the predicted statistics indicates the appearance of a sodium/water reaction or other signal source in the masking background noise. Inherent in this approach are assumptions on the character of the background and signal noise. Confirmation of these assumptions, using data from the prototype steam generator, validates the statistics for any other system.

One of the most important assumptions is that the mean of the pressure fluctuations approaches zero and the standard deviation(s) is given by the equation (developed in Part II of this report):

$$S = (1+CORCO)\sqrt{2/N} \qquad \text{(E)}$$

where N is the number of samples taken from the noise measurement. Implied in these assumptions is far-field noise, such as that from flow control valves or rotating machinery, does not produce a significant change in either mean or standard deviation of the measured fluctuations. If such changes had occurred they would be considered to be a signal source by the GAAD system and a false alarm produced.

A further assumption is that the leak produces changes to the mean value of the pressure fluctuations, when the beamformer is "focused" onto that location. When the beamformer is focused onto any other spatial location the statistics of pressure fluctuations remain essentially constant and are not affected by the appearance of a leak at some other location.

The SCTI/Prototype Steam Generator test was the first fully integrated test of the GAAD system in a power plant type environment. This particular test not only included the normal steam processing plant background noise, but during the program additional noise was introduced by:

a) Blasting activities to form chambers 13.1 m (43 feet) deep in the building bedrock foundation.
b) Drilling the bedrock with a four-foot diameter auger to provide piles for the new steam generator cell.
c) Testing of shuttle rocket engines at the nearby Rocketdyne facility for up to several minutes resulting in extensive vibration transmissions to the vessel.
d) Scram of the SCTI facility, normal and fast thermal/hydraulic transients, and control valve operation, etc.

During each of these far-field noise generation events no significant change in detection characteristics occurred, and no false alarms were generated.

Experience showed that external, or far-field, noise caused a general increase at all locations in the vessel. As a result the local signal-to-noise ratio actually decreases for the duration of the far-field noise; i.e., a slight decrease in the sensitivity of the GAAD system to detect a given size leak.

5.3.2 Detection Statistics

The standard deviation of the background noise pressure fluctuations was predicted to be about 0.042, with a mean value of 0.020. That is, the local signal-to-noise ratio (CORCO) has a one in six chance of lying outside the value of 0.062. (This assumes that data are collected for 10 milliseconds; increasing the N value in Equation C by 130 for each pass through the plane.) If the leak causes a change in the mean value, it is recognizable as a leak. The change in mean value considered significant is based on the data in Table 6. For example, if the alarm threshold is set to CORCO exceeding 0.229 there is only one chance in three million that a random measurement will occur; or one false alarm in three million estimates. Since there are 10,000 bins in the steam generator, a false alarm every 300 passes is possible. These figures are based on data collected for 10 milliseconds, or one pass through the plane. If a second data set is taken immediately following the high estimate there is only one chance in 10^9 passes that two successive readings will exceed 0.229. It is the low probability of successive estimates exceeding a threshold CORCO value that is the basis for the detection algorithm.

Table 6: Detection Criteria

Background Noise Mean Value	Signal Mean Value*	Number of Standard Deviation	Probability of Randomly Exceeding Value
0.02	0.062	1	1 in 6
0.02	0.109	2	1 in 43
0.02	0.145	3	1 in 740
0.02	0.187	4	1 in 32,000
0.02	0.229	5	1 in 3,000,000
0.02	0.270	6	1 in 10,000,000

* Measured by the beamformer when focused on leak.

In summary, the assumptions underlying the detection algorithm are:

a) The mean value of the measured local signal-to-noise ratio (CORCO) approaches zero as the number of estimates increases.

b) The standard deviation of these values is predictable.

c) The mean and standard deviation are independent of the background noise amplitude.

d) When an injection occurs, only the bin at that location has an increase in mean value; all other bins maintain their usual statistic.

e) Transient or continuous far-field noise generators do not increase mean or standard deviation.

f) Successive measurements of CORCO from an individual location reduce the chances of erroneous high measurements creating alarms.

Each of the assumptions is now discussed:

Mean Value: The mean of 1392 CORCO values was measured (Table 7) and the distribution plotted (Figure 29). These data were taken with only background noise during the demonstration test period. No gas was injected. Data were collected from each bin in three planes over six scans of each plane. The mean values for 100 estimates from the same bin is printed in Table 8 for Bins 70 and 30. In all instances the mean is close to zero, and reduces as the number of CORCO estimates increased.

Standard Deviation: Equation C predicts the standard deviation for background noise CORCO estimates as 0.042. The measured value is 0.028 (Table 7), 0.045 and 0.023 (Table 8). These values are close to or below the predicted deviation indicating Equation C might even be conservative.

Leak Site Statistics: CORCO values measured at the leak site (Bin #30) and at a randomly chosen location in the same plane (Bin #70) are tabulated in Table 8. A significant change in mean value and standard

TABLE 7. BACKGROUND NOISE CORCO DISTRIBUTION

STATISTICS

STD DEV	0.0277
MEAN	0.0055

CORCO	RANGE	DIST.	RANGE	DIST.
0.0152	0.0050	0	-0.1000	0
0.0251	0.0100	4	-0.0900	13
0.0282	0.0150	9	-0.0800	17
0.0261	0.0200	8	-0.0700	9
0.0117	0.0250	9	-0.0600	5
0.0189	0.0300	1	-0.0500	6
0.0227	0.0350	8	-0.0400	21
0.0246	0.0400	1	-0.0300	37
0.0195	0.0450	4	-0.0200	55
0.0206	0.0500	5	-0.0100	123
0.0261	0.0550	1	.0000	197
0.0195	0.0600	6	0.0100	304
0.0045	0.0650	15	0.0200	259
0.0207	0.0700	17	0.0300	171
0.0275	0.0750	21	0.0400	79
0.0175	0.0800	20	0.0500	46
0.0227	0.0850	34	0.0600	17
0.0158	0.0900	52	0.0700	13
0.0245	0.0950	72	0.0800	5
0.0235	0.1000	83	0.0900	9
0.0131	0.1050	117	0.1000	0
0.0233	0.1100	179	0	6
0.0145	0.1150	123	0	
0.0103	0.1200	130	0	
0.0106	0.1250	128	0	
0.0253	0.1300	93	0	
0.0150	0.1350	79	0	
0.0103	0.1400	45	0	
0.0148	0.1450	34	0	
0.0041	0.1500	28	0	
0.0108	0.1550	16	0	
0.0008	0.1600	12	0	
0.0040	0.1650	5	0	
0.0034	0.1700	6	0	
0.0012	0.1750	7	0	
0.0096	0.1800	3	0	
0.0198	0.1850	2	0	
0.0094	0.1900	4	0	
0.0251	0.1950	5	0	
0.0014	0.2000	0	0	
0.0081	0.2050	0	0	
0.0083	0.2100	1	0	
-0.0044	0.2150	0	0	
-0.0017	0.2200	2	0	
-0.0160	0.2250	1	0	
-0.0018	0.2300	1	0	

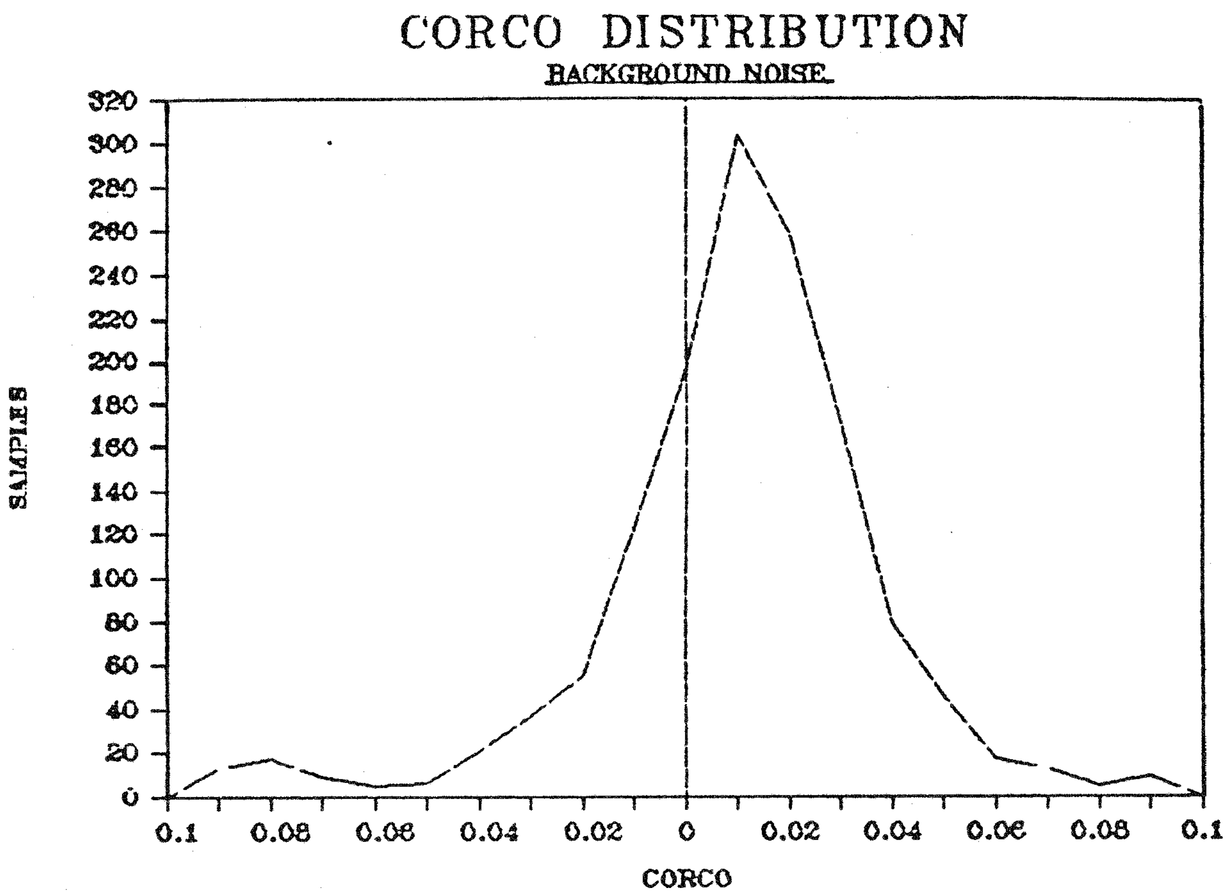


FIGURE 29. DISTRIBUTION OF CORCO VALUES WITH NO GAS INJECTION

TABLE 8 STATISTICS OF DATA TAKEN DURING INJECTION TEST DEMONSTRATION TEST AT SCTI

STATISTICS		
MEAN	0.0783	-0.0057
STD. DEV.	0.0448	0.0226
MAX	0.1935	0.0491
MIN	-0.0187	-0.0536
LOCATION	LEAK BIN	REF. BIN

DATA		LEAK PERIOD DISTRIBUTIONS			
REF. BIN 70	LEAK BIN 30	RANGE	BIN 30	RANGE	BIN 70
0.0215	0.0031	-0.1000	0	-0.1000	0
0.0301	0.0265	-0.0900	0	-0.0900	0
0.017	-0.0187	-0.0800	0	-0.0800	0
0.0222	0.0064	-0.0700	0	-0.0700	0
0.0151	0.0039	-0.0600	0	-0.0600	0
0.042	0.0049	-0.0500	0	-0.0500	3
-0.0105	0.0016	-0.0400	0	-0.0400	2
-0.0145	0.0109	-0.0300	0	-0.0300	9
0.0328	0.0347	-0.0200	0	-0.0200	17
0.005	0.0081	-0.0100	1	-0.0100	18
-0.0258	0.0466	.0000	0	.0000	12
0.0239	0.0053	0.0100	8	0.0100	10
0.0187	0.0693	0.0200	3	0.0200	13
-0.0075	0.0003	0.0300	3	0.0300	11
0.0252	0.1594	0.0400	5	0.0400	4
-0.0128	0.0584	0.0500	9	0.0500	2
0.0185	0.1033	0.0600	7	0.0600	0
0.0126	0.0749	0.0700	11	0.0700	0
-0.0106	0.1726	0.0800	6	0.0800	0
-0.0205	0.0704	0.0900	9	0.0900	0
-0.0377	0.1035	0.1000	4	0.1000	0
0.0209	0.0707	0.1100	9	0.1100	0
-0.0092	0.1391	0.1200	7	0.1200	0
-0.0319	0.0954	0.1300	6	0.1300	0
0.0491	0.1222	0.1400	4	0.1400	0
-0.0213	0.0632	0.1500	3	0.1500	0
-0.0029	0.0827	0.1600	3	0.1600	0
-0.0246	0.089	0.1700	0	0.1700	0
-0.019	0.0507	0.1800	2	0.1800	0
0.0005	0.0376	0.1900	0	0.1900	0
-0.0009	0.0675	0.2000	1	0.2000	0
0.0205	0.0677				0
-0.0289	0.1008				
-0.0286	0.0551				
-0.0479	0.052				
-0.007	0.1551				
0.0108	0.0654				
-0.0068	0.0439				
0.0159	0.0687				
0.0138	0.101				
-0.0218	0.0464				
0.0306	0.0469				

deviation occurs at the leak site, but no significant change in the reference bin #70 statistic were measured (Figure 30). Prior to initiating the injection both the reference and leak locations had similar characteristics (Figure 31). Immediately following the test the statistics for the leak site are similar to those prior to the test (Figure 32).

Background Noise: During the injection of gas, the background noise measured throughout the vessel increased by an order of magnitude. Despite this increase in background noise amplitude and the presence of the injector in the same plane, no significant change in the reference location (Bin #70) statistics were measured (Figure 33).

Far-Field Noise: As noted in Section 5.3.1 above, significant transient phenomena and external noise sources were experienced. The only event causing "false alarm" signals was a steam leak from the water/steam outlet flange. In general, most of these alarms were from data taken by accelerometers actually on the tubesheet mass. Accelerometers a few inches away from the tubesheet did not have a strong coherent component due to the flange leak.

Although it was possible to reconfigure the GAAD system to avoid sensitivity to a steam flange leak, no changes were made. A unique location diagram resulted when the steam flange leaked. The SCTI operators used this as an early indication of a flange leak and could adjust operating parameters to correct the situation causing the leakage. The GAAD system detected the steam-to-air leakage approximately twenty-four hours prior to detectable quantities of water leaking into the insulation.

Detection Criteria: The use of successive CORCO estimates as a detection threshold was used at the SCTI. If the normal background CORCO values are less than 0.02, typical of the values measured in the SCTI, then the probability of a random value exceeding 0.200 is one estimate in 5×10^5 estimates (Table 6). This equivalent to one false alarm in approximately twenty years. If a second estimate is made immediately, the probability of two successive estimates is longer than the expected plant life. The GAAD

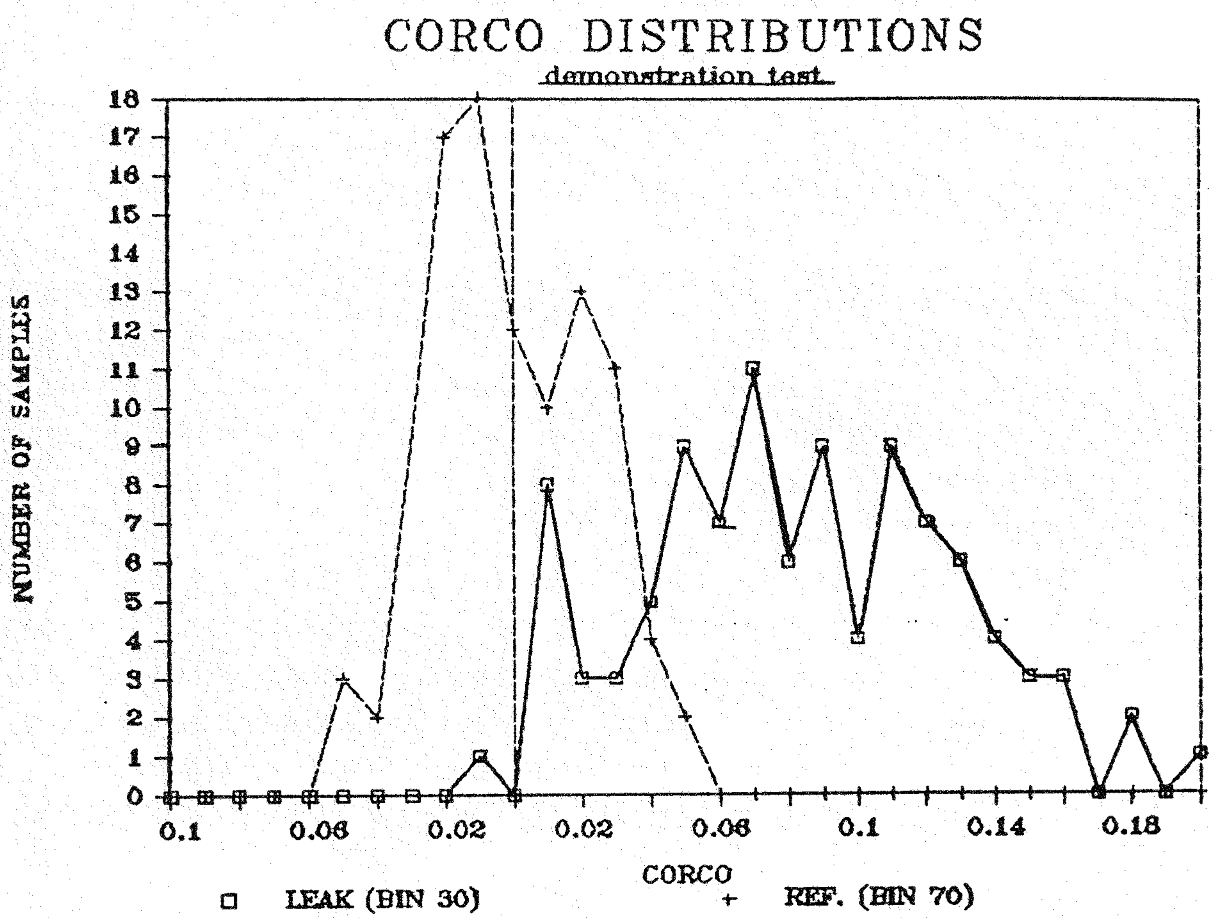


FIGURE 30. CHANGE IN CORCO DISTRIBUTION DUE TO INJECTION AT LEAK SITE

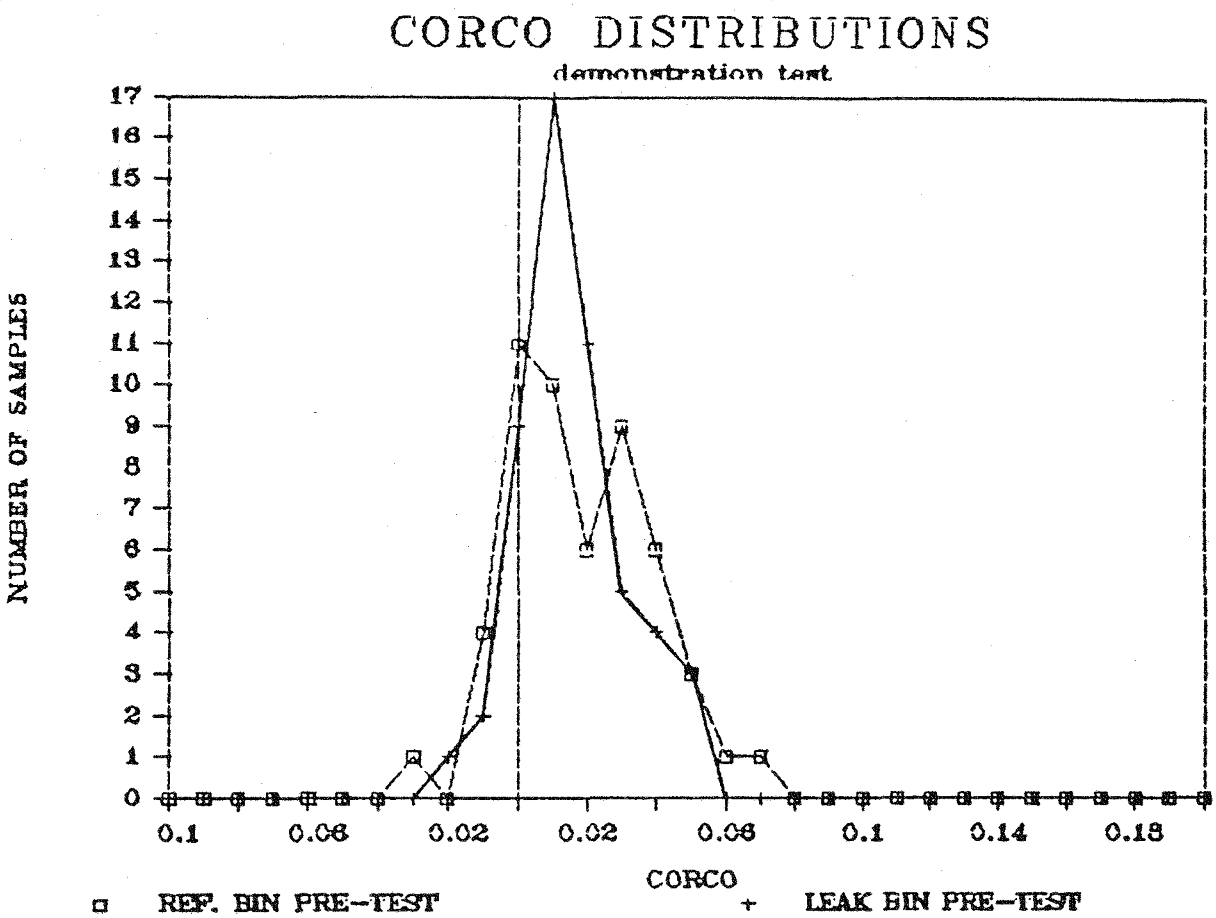


FIGURE 31. PRE-TEST CORCO DISTRIBUTION FOR LEAK AND REFERENCE SITES

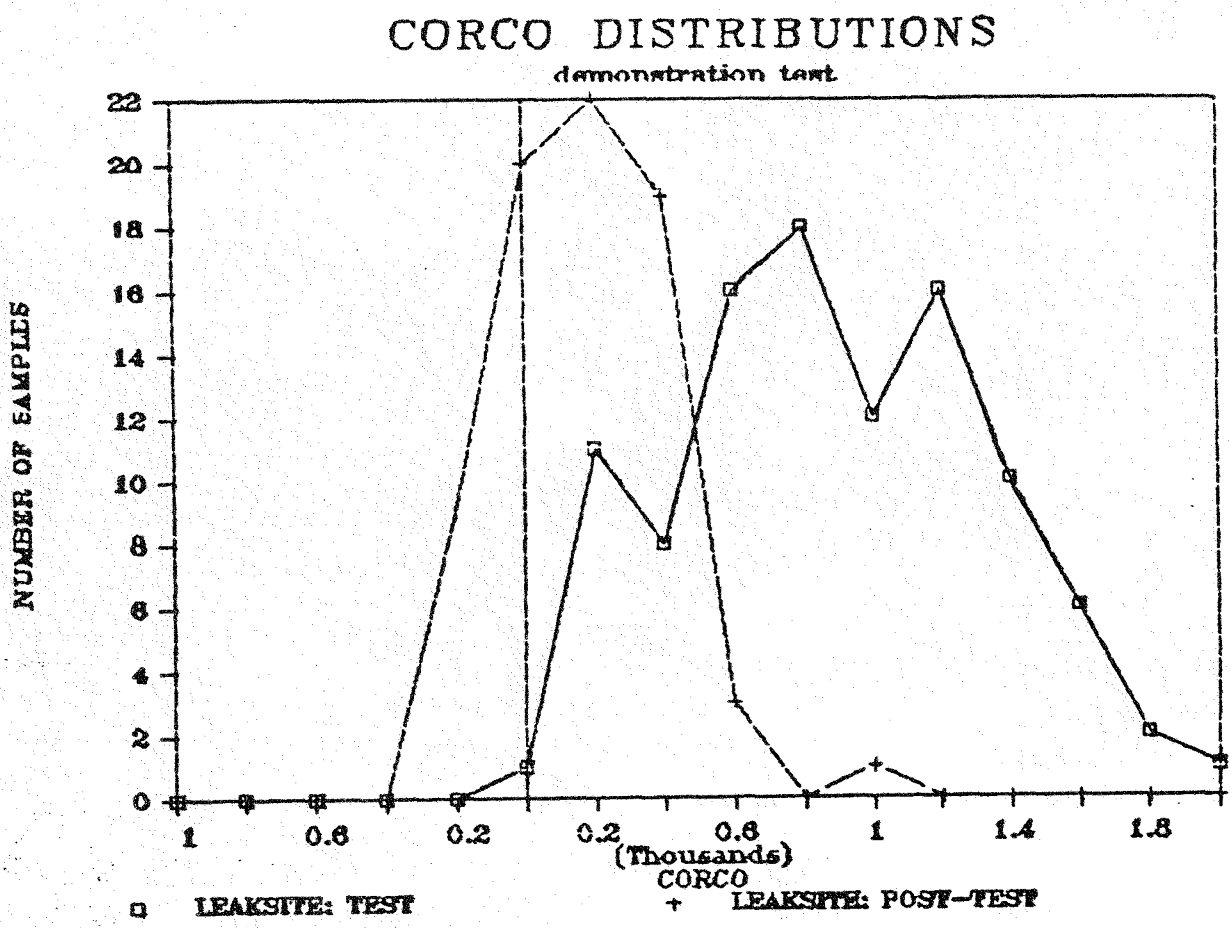


FIGURE 32. CHANGE IN CORCO DISTRIBUTION FOR LEAK SITE DURING AND AFTER INJECTION

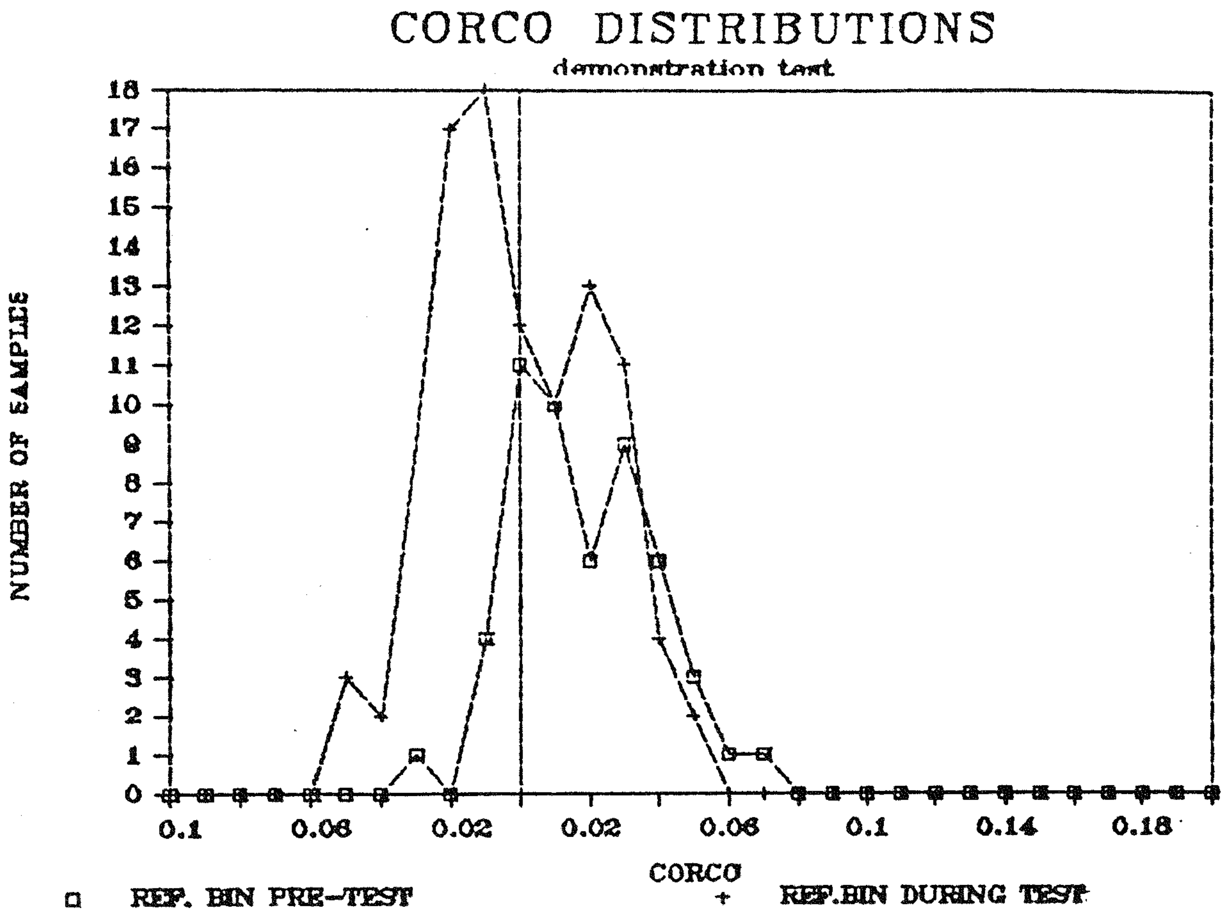


FIGURE 33. REFERENCE SITE BEFORE AND DURING INJECTION

system used this approach of immediately re-checking the same plane and bin. Only if the same bin exceeded 0.200 was an alarm generated. The CODE-1 alarm was activated if two successive values exceeded 0.200.

If the local signal-to-noise ratio is 0.020 then the probability of a random value exceeding 0.07 is one estimate in 74 estimates. For six successive estimates to exceed 0.07 the probability also exceeds the plant life (but is slightly more possible than two successive values of 0.200). The CODE-2 alarm was activated if six successive values exceeded 0.070.

Other than the alarms documented above (Far-Field Noise) no other false alarms were generated, validating the use of successive values as a detection criteria. The only caveat to this conclusion is to the length of time required between successive estimates. At the SCTI this time was of the order of two seconds; in a hardwired, real-time system the time could be up to hundreds of times shorter ($\sim$50 milliseconds). The detection algorithm can be written to include a delay between successive estimates. This would avoid any possibility of making two or more measurements on a short, transient, local noise.

The discussion on the SCTI/GAAD system data given in Section 5.3 indicated the basic detection algorithm was validated. All of the assumptions tabulated in Section 5.3 were validated by SCTI/Prototype data. Any predictions of GAAD system performance in a different steam generator will have a high degree of confidence. In the next subsection the requirement for detecting an intermediate leak within 20 seconds will be discussed.

5.4 Conclusions for Intermediate Leak Detection

Operating experience and test data from the GAAD system at the SCTI showed the probabilistic approach was valid, and independent of background noise, far-field noise and transient steam generator operating conditions. The gas injection produced a signal-to-noise ratio of the magnitude expected from an intermediate sized water-into-sodium leak. The injection was definitively detected and located by two independent GAAD systems. Characteristics of the background noise and the background-plus-signal noise were measured. The data confirmed the statistical model used in the detection algorithm. Operating experience as a leak detection system confirms the detection criteria model, since no unexplainable false alarms were generated once the model was implemented in October 1983.

The demonstration tests confirmed rapid detection of a gas injection, which provided the best acoustic simulation of a leak equivalent to a signal-to-noise ratio of -10 dB. A sodium/water reaction has a broader spectral content than a gas injection, and experience in the SONAR vessel suggests that detection and location is better than for a gas injection [32].

Time to detect a leak of this magnitude is dependent upon the detection algorithm and upon the detection criteria model. Both of these were validated by operation of the GAAD system on the prototype steam generator installed at the SCTI, and by the data obtained during demonstration tests. The detection algorithm and detection criteria model are independent of the steam generator. Using successive measurements of local signal-to-noise ratio allows a single scanning processor to detect an intermediate leak within about 7.5 seconds. This assumes the acoustic system uses a dedicated hardware/firmware implementation of the detection algorithm (Integrated General Electric Advanced Acoustic Detection, or IGAAD system). Based on the results from the SCTI a significant decrease in time, or alternatively, a significant system cost reduction becomes feasible.

The time to detect a leak producing a -10 dB signal-to-noise ratio in a typical design of a steam generator is about 7.5 seconds with the IGAAD system. If the data length covers 50 milliseconds, the standard deviation becomes 0.02. Requiring five successive readings to exceed 0.06 will give one false alarm in about 50 years. It is concluded an IGAAD system will provide effective detection of intermediate sized water-into-sodium leaks.

5.5 Signal-to-Noise Ratio Extrapolation

The test objective was to detect a leak producing a signal-to-noise ratio of 0.100. This value was based on measurements of a signal level from a sodium/water reaction, and prediction of background noise amplitudes from tests in test rigs and steam generators. Prior to the SCTI test program background noise level predictions were published. Initial examination of the SCTI data indicates pretest background noise predictions were valid (Table 9). The predicted value for signal-to-noise ratio for an intermediate leak appears to be realistic for steam generators, based on the test data from the Prototype steam generator program at SCTI.

Table 9: Background Noise Predictions

	Predicted				Measured at the SCTI		
	Noise Contributors			Totals		Totals	
Test #	Boiling	Steam	Flow	Bundle/Tubesheet	LTS	Bundle	UTS
2.2	845.5	97.5	36.8	851.9/104.9	154	830	116
2.10	845.5	55.3	36.8	848.1/ 66.4	121	764	121
2.11	845.5	51.9	36.8	847.9/ 63.6	73	853	231
2.12	845.5	49.6	36.8	847.8/ 61.8	100	625	86

*Microbars.

5.6 Performance as Leak Detection System at SCTI

In March 1983, the GAAD system was incorporated into the facility leak protection system. Following an initial shakedown period it operated successfully, culminating in detection of the gas injections during the demonstration test. The acoustic leak detection system program at the SCTI was originally conceived as a developmental experience. The GAAD system was designed and programmed to rapidly monitor the steam generator and obtain data on background noise during the thermal/hydraulic program. Predicted test time was a few weeks with about ten minutes hold time at each test point.

During initial rise-to-power tests in November 1982, a hydrogen excursion was detected [6]. A subsequent review concluded this was not due to a water-to-sodium leak, but the concerns raised at that time caused the status of the acoustic system to change. It was incorporated into the facility leak detection system to complement the chemical monitors. ETEC configuration control procedures were imposed on the system. This change in status required ETEC control of the GAAD system modifications and operation, and limited flexibility in conducting software and hardware tests during the remainder of the program. An interface between the GAAD system and the facility DAS system was designed and installed.

Significant software development was driven by the need to provide leak protection. Although the change in program direction created its own problems, the goal-driven requirements were beneficial in initiating a change from a developmental system to an operational leak detector/location system. In particular long term data storage and off-site monitoring aspects were advanced to an operational level, and detection criteria models reduced to practice by operating as a facility leak detection system.

An early change in detection criteria was mandated by alarms at sodium-only flow conditions in the steam generator. It was discovered that at very low background noise levels the noise signals could be highly coherent. Although the CORCO values were high, the calculated water injection rate would be far below a level that could exist (e.g., 10^{-8} lbs H_2O/sec) or create damage conditions. The detection criteria was modified to include a lower limit of predicted water injection. Special attention to stray grounding troubles also helped resolve this problem.

After this initial shakedown period of co-current development and leak detection the acoustic detection system operated without false alarm. Alarms generated by the steam flange leak are not considered to be false alarms. (See Section 5.3.)

Since all alarm codes were automatically recorded by the D.A.S. the history can be independently recalled [6]. A summary from the reference is shown in Table 10. Each alarm was investigated as it occurred to find the cause. Note all alarms were due to real steam flange leaks. During the same period 11 false alarms were received from the chemical leak detection system [6].

Table 10: Alarms Transmitted to Facility DAS
(Steam leaking from flange)

No.	Date	Type	Number of Alarms	Cause
Up to 06/04/83 - Interface development and detection criteria update.				
1.	09/03/83	Code-2	13	Steam flange leak
	09/03/83	Code-1	1	"
2.	09/06/83	Code-2	2	"
3.	09/21/83	Code-2	4	"
4.	09/24/83	Code-1	4	"
5.	09/26/83	Code-1	1	"
6.	10/02/83	Code-2	2	"
7.	10/17/83	Code-1	2	"
8.	10/22/83	Code-1	2	"
9.	10/27/83	Code-1	2	"
10.	11/07/83	Code-1	6	"
11.	12/09/83	Code-1	11	"
	to 12/16/83	Code-2	19	"
		Code-3	1	"
	01/26/84	Demonstration Test		

6.0 AUTOMATIC LEAK DETECTION SYSTEMS

6.1 Introduction

The successful demonstration test of the GAAD system is part of an integrated US-DOE program on sodium-water reaction phenomena. Development of systems to detect sodium water reactions within an LMFBR steam generator before damage propagation is one of the program's primary objectives. In the next two subsections pertinent data from the sodium-water reaction damage programs are presented (6.2, 6.3). This data shows that any through-wall hole in the steam generator heat transfer tube can cause severe damage to the unit, unless corrective actions are taken. Experimental data indicates this corrective action must be initiated within 40 seconds. Data from the sodium water reaction programs were used to set the objectives for the demonstration test (Appendix A).

Design of any monitoring system is a judicious choice between sensitivity and false indications. The cost of the monitoring system is also a balance between the potential frequency of an indication (or false alarm), and the potential for economic impact in not initiating corrective actions. Operating experience with operating plants and large test facilities is examined in the following subsection. The severe economic and programmatic impact of leaks (6.4) in a steam generator, and the need for rapid corrective action suggests an automatic leak detection system is a valid option for an LMFBR. The potential for real and false alarms, and the consequences, are documented.

To reduce the potential for false alarms two simultaneous, independent alarm indications are recommended, and probably a two-out-of-three system is economically justified. The candidate systems for use in an automatic leak protection system are reviewed in the following subsections (6.5-6.7).

The importance of the successful demonstration test to the overall US-DOE program on automatic leak protection systems for LMFBR steam generators is covered in the final subsection. (6.8)

6.2 Self-Wastage Program Data

A comprehensive study of self-wastage of small defects in heat transfer tubes provided an explanation of the damage phenomena [5,19]. Small leak protection criteria curves were developed; and used in Part II of this report for SCTI/Prototype Steam Generator leak protection criteria and requirements. A recent investigation showed self-wastage growth caused water injection rates to increase orders of magnitude within 30 seconds. [20] Prior to growing to an intermediate leak rate the defect remained plugged, sometimes for months. Analysis of the detection requirements from both impingement and self-wastage indicated chemical leak detection systems provide ineffective protection if used without complementary acoustic systems. [9,20]

6.3 Intermediate Leak Damage Potential

An intermediate leak is defined as greater than approximately 5 gm/sec (0.01 lbs H_2O/second), and less than approximately 900 gm/sec (2 lbs H_2O/second). The higher limit corresponds to an injection rate which drives sodium away from the leak site. It is dependent upon the specific steam generator design. Of more importance to leak detection are those leaks which produce a destructive sodium-water reaction flame [19]. For the flame to remain stable, a continuous supply of sodium is required. If the hydrogen gas lifts the sodium away from the injection site the potential for multiple tube failure is reduced [8]. Leaks below the lower limit (5 gm/sec) can exist for an appreciable length of time prior to initiating damage propagation.

The lower leak rate (5 gm H_2O/sec) corresponds to an injection which causes optimum penetration damage to an adjacent tube. It is dependent upon the steam generator design and materials, and upon the sodium temperature [19]. The value given is typical of the injection rate for a steam generator design similar to that for the prototype tested at SCTI/ETEC [10].

Such leaks can cause damage propagation within approximately twenty seconds [8]. Detection at this level of injection is borderline at full power conditions in a superheater, but the injection from the damaged tube will probably be in the range of 50 gm H_2O/second. Similarly, injections associated with self-wastage are unlikely to be detectable before growth of the injecting orifice. The resulting injection rate after growth again reaches approximately 50 gm/second (approximately 0.1 cm dia hole). Tests in which damage propagation occurred show secondary injections produced wastage on tertiary tubes at close to the optimum penetration rates. Tertiary failure is likely within a further twenty seconds.

A series of damage propagation tests, initiated by a leak of approximately 50 gm/second was completed in the Large Leak Test Rig, (Series II) [8]. The major objective of thie test program was defining the potential for multi-tube failure in a large steam generator. The results from the Series II program indicated severe damage results to the tube bundle if leak propagation is allowed beyond a secondary tube failure. It was also demonstrated that leak propagation beyond a single secondary failure can be avoided if leak detection and corrective action is taken within approximately 40 seconds. [8,9,10]

This requirement can only be satisfied by an automatic shutdown system for the steam generator [9]. Timescales for leak propagation are too short; they do not allow intervention by an operator in response to a detection indication. Since the cost of an automatic shutdown system is higher than the current approach of using chemical detection systems, one must consider whether its use in a plant is justified. If the probability of a leak is small the economic risk in not installing an automatic system is also small. Conversely, if the probability is high then the economic risk will be high if an automatic system is not used.

6.4 Operational Experience with LMFBR Steam Generators

Operating experiences with Liquid Metal Fast Breeder Reactor power plants show the steam generator is the primary component having potential to reduce plant availability. The United Kingdom's Prototype Fast Reactor (PFR) steam generators have been plagued by small water-into-sodium leaks. As a result, the PFR after a decade of operation is still unable to maintain full power operation [1]. A large sodium-water reaction occurred in the Russian reactor (BN-350) steam generators, and subsequently a steam generator and parts of the secondary loop were replaced [2]. The KNK reactor in Germany had a leak in a steam generator, causing extensive downtime before power operation was resumed. [3] The availability of the French demonstration reactor, Phenix, was reduced to 33% during 1983 as a result of small leaks in steam generators. [4]

Schedule and cost of development programs associated with prototype steam generators in large test facilities have been significantly increased by both real leaks and also false alarms. A small leak was found in a few tube, helical coil steam generator installed in the General Electric Steam Generator Test Rig (GE-SGTR). Extensive supplementary programs were unable to locate the defect [5]. Alarms during tests of prototype steam generators in the U.S. Energy Technology Engineering Centre (ETEC) [6], and at the Dutch Hengelo test site caused extensive program delays. Eventually the hydrogen indications were found to be false alarms. [6,7].

Practical experience obtained over the last decade shows that the probability of a leak occurring in the steam generator is high. Each of these plant units were "demonstration quality." It must be concluded that units produced under normal commercial/industry conditions will probably have even greater potential for defective welds and tubes.

Even if the probability for defects is low, economic losses can result from false alarm indications. Operating experience with current detection systems shows that false alarms are possible, and have resulted in severe economic impact. An automatic leak protection system must meet a false alarm criterium, as well as detection and cost criteria.

6.5 Chemical Leak Detection Experience

The Hydrogen Diffusion Tube Detector (HDTD) is the reference monitor for small leak protection on LMFBR steam generator. It attained this position by default, not because it provides full protection. Despite almost twenty years of development and test it cannot be considered a reliable instrument; the output drifts, it requires repeated calibration and specialist attention, and specialist interpretation for effective leak detection. [6,21,22]

General Electric developed a version of the HDTD for industrial use in conjunction with Argonne National Laboratories [22]. Sodium is sampled from the outlet of the steam generator, and flows to the sensing cell containing a pure nickel tube. Hydrogen diffuses across the nickel membrane into an evacuated space, where it is measured by a VAC-ION pump. The hydrogen monitoring system now forms part of the sodium boundary, and the GE version was designed to meet the appropriate design and fabrication codes. In particular the creep and failure characteristics of several designs of nickel tubes was obtained. Instrumentation was included for control and operation of the module, including trace heating of the sample lines and HDTD. An ability to calibrate the hydrogen monitor was included; either diffusion of hydrogen into the sodium stream, or sodium-hydroxide injections [23].

Data signals from the module were sent to the facility data acquisition system. A very simple algorithm was used to analyze the analog signal from the voltmeter. No requirement for low false alarm rates was included in the data analysis. Many recommendations for modifying the data analysis and control signals were included in the final report on the module test at EBRII. [24] A recommendation for chemical detection algorithm development and test was included in the report on leak detection at SCTI. [6]

Oxygen and hydrogen concentration can be monitored by electrochemical cells. [25,29,30] However, commercial development of these meters is questionable. Neither Westinghouse or General Electric now offer the cells. Even if they were available, operational experience is not very good [26,27,6]. Reliable operation for long periods in a plant environment will require extensive development [25,6].

The General Electric leak detection module contained both HDTD and oxygen electro-chemical cell monitors. Producing an industrial quality chemical detection system did not overcome the inherent problems of the chemical monitors:

a) Variable operating characteristics of both monitors
b) Poor reliability of the oxygen monitor
c) Lack of proven data analysis algorithms; and need to include a low false alarm probability criterion in the algorithm.

To these must be added a serious limitation when considering chemical detection of intermediate leaks: response time. Since both hydrogen and oxygen monitors rely on transport of the impurity from the leak site to the measuring cell, the response time cannot be less than the transit time. Even at full sodium flow conditions this is typically twenty to thirty seconds. At low flow rates the time can be many minutes. [26,27,28]

Tests were performed in the Prototype steam generator to measure the transit time and hydrogen "hide-out". [26,6] Small hydrogen gas injections were made at various locations within the vessel. The change in hydrogen-in-sodium concentration with time was measured on the facility HDTD monitors. The initial response time of the main stream monitor corresponded to the sodium transport time from the injection site to the monitor cell. However, the time taken for the vent line monitor signal to reach 63% of the final level was about five minutes independent of sodium flow through the vessel. Test data also showed that only 28% to 50% of the injected hydrogen was ever seen by the in-sodium hydrogen meters. Hydrogen hide-out can obviously have a strong impact when making leak-rate predictions from changes in hydrogen concentration.

It must be concluded chemical leak detection monitors of the current designs are unsuited as the primary system in an automatic shutdown system to protect against intermediate leaks.

6.6 Acoustic Leak Detection System Experience

6.6.1 General Electric Advanced Acoustic Detection System

The General Electric acoustic detection program at SCTI met the primary objective of the Test Plan. The capability of the General Electric Advanced Acoustic Detection (GAAD) system to meet automatic shutdown criteria was demonstrated.

Two tests were completed which provided acoustic simulation of a leak equivalent to a signal-to-noise ratio of approximately -10 dB (i.e., equivalent to 5 gms H_2O/sec (0.01 lbs H_2O/sec) with worst case plant operating conditions). Data from these tests confirmed:

a) The correct performance of the detection algorithm by rapidly detecting both injections and activating all three alarm codes.

b) The validity of the leak detection criteria model; and its independence from background noise amplitude, far-field noises and transient steam generator operating conditions, including scrams.

Confirmation of the detection algorithm and the leak detection criteria model allows the SCTI/Prototype Steam Generator data to be extrapolated to any Liquid Metal Fast Breeder steam generator.

If the data obtained from this test program are applied to the steam generator design and operating conditions predicted for the Clinch River

Breeder Reactor Plant, an intermediate leak would be detected within 7.5 seconds. This assumes a GAAD system is used which has the detection algorithm implemented in dedicated hardware/firmware (i.e., the IGAAD System).

Significant acoustic system development resulted from incorporation of the GAAD system into the SCTI facility small leak protection system. In particular long term data storage and off-site monitoring techniques were developed. Detection criteria and facility requirements were reduced to practice. As a result, the GAAD system developed from a developmental system into an operational leak monitor over the SCTI program.

Following an initial shake-down period no false alarms were generated by the GAAD system. No alarms were generated due to far field noise such as blasting and drilling of the bedrock to form a new steam generator cell, or testing of rocket engines.

The GAAD system incorporated into the SCTI facility small leak protection system had one major limitation. Early in the development of the GAAD system a decision was taken to simulate the detection algorithm in software codes. The detection algorithm codes were then run in a general purpose computer, and operate at data computation speeds which are orders of magnitude below that currently attainable with dedicated data analysis hardware/firmware systems. As a result of the computer simulation the GAAD system did not operate in real time. Analog signal manipulation and conversion was performed at prototypic speed. Alarm system algorithms and operator interface software are almost independent of the computational speed of the detection algorithm. As a result, this hardware and software was validated by the program at SCTI.

The detection algorithm implementation is only a small, but obviously very important part of the total GAAD system. The detection algorithm can be implemented in current hardware/firmware. The transfer from computer simulation to dedicated processing is mechanistic, no change in logic from that tested in the current program is needed. [31]

6.6.2 High Frequency Acoustic Detection Systems

An acoustic detection system which measures the change in amplitude of the high frequency (i.e., greater than 100 kHz) components of steam generator noise was also tested on the prototype steam generator at SCTI. While the high frequency system shows promise, early claims of simple hardware and data analysis have not been substantiated [6,32,33,38]. It is shown in Appendix C that at least 50 transducers will be required on a steam generator vessel, plus some further quantity to monitor plant component noises. Data analysis requirements changed from a simple amplitude threshold level to a dynamic threshold level that required input from plant instruments monitoring system parameters for the system used on the prototype steam generator at SCTI. A significant number of false alarms were generated by the SCTI/HALD system. It was sensitive not only to external plant noises, and also to acoustic emission initiated by changes in plant operating conditions [38]. Resulting from SCTI/HALD experience, a refined approach was developed which does not require the plant parameter input and is expected to be relatively insensitive to transient plant noises. This should reduce the false alarm rate.

A passive beamformer data analysis approach is being developed for a high frequency detection system by ANL. This makes the detection algorithm almost identical to that used in the GAAD system [34,35]. The high frequency signal is demodulated, and the data manipulation is made on the modulation envelope. The bandwidth is 10 KHz, identical to that for the GAAD system. If the modulation envelope has an improved signal-to-noise ratio over that for the low frequency system a reduction in detection time could result.

The majority of tests in which the high-frequency system was exercised used gas injections to simulate sodium-water reactions. It was assumed that the gas injection provided a good simulation of a Na/H_2O reaction. The high frequency system monitored the sodium-water reaction from a small water injection made prior to test A-3 in the LLTR Series II program. The output of the transducer increased, even though the water injection rate decreased. The highest signal was indicated just prior to the leak plugging. In test A-8 of the same series the acoustic signal tends to decrease, although the water injection rate tends to increase [36]. This leads to the conclusion that similarity assumed between gas injections and sodium-water reactions. Further work is also required to define the signal path from a small sodium-water reaction that is transmitted to the high frequency detector mounted external to a large vessel (e.g., helical tube steam generator).

6.7 Alternative Intermediate Leak Detection Systems

In a companion report [11] the impact of gas bubbles homogeneously distributed through a liquid is discussed. A significant change in acoustic wave propagation velocity results when the void fraction (i.e., bubble volume/vessel volume) exceeds a value of approximately 10^{-4}. An intermediate leak detection system is being developed by ANL which detects the presence of hydrogen bubbles from the sodium water reaction. It is an active system, ultrasonic energy is transmitted along the axis of the vessel and detected at the opposite end. Early results using gas injection into EBR-II steam generators and at SCTI are promising. [37]. Its validity for sodium-water reaction detection under prototypic operating conditions has not been confirmed. Rapid dissolution of hydrogen into the hot sodium may severely reduce its efficiency as a detector particularly for small leaks [6], particularly for small leaks.

6.8 Automatic Leak Protection System

Power plant, large test facility, and laboratory experience with sodium-water reactions indicate severe damage propagation can occur within approximately forty seconds unless corrective action has been initiated. This timescale is too short to depend upon operator response to an alarm. Corrective action should be initiated automatically upon receipt of a validated signal from a steam generator intermediate leak protection system. Experience indicates that an indication (or actual occurrence) of a sodium water reaction is not a low probability event. The economic penalties associated with a leak, or even a false alarm are severe enough to warrant installing a complex monitoring system. To provide effective full-time coverage, and very low false alarm rates two simultaneous indications from three independent monitors is recommended.

The GAAD system meets the criteria for installation into an automatic protection system. It requires a final design phase in which dedicated hardware/firmware is used to provide the correct data manipulation rates, and provide real-time monitoring. The test at SCTI demonstrated the detection/location algorithm is correct, a low false alarm probability is feasible, and the operator/machine interface is effective. In contrast, the reaction product monitors (oxygen and hydrogen meters) have rudimentary data analysis algorithms and suspect reliability.

The final development to the Integrated General Electric Advanced Acoustic Leak Detection (IGAAD) system is hardware intensive. Rapid evolution of hardware suitable for real-time data manipulation is underway. It is driven by the current industry and military needs, and will continue to evolve without DOE intervention. Unless a real-time monitor is needed for a test facility further development should be postponed until the need-date for an IGAAD system is established. One or two years of final design activity will be required, prior to test and operational use. A report is in preparation providing a reference design of the IGAAD real-time acoustic leak detection/location system.

PART II

SCTI/PROTOTYPE STEAM GENERATOR WATER LEAK DETECTION CRITERIA AND ALARM LEVELS

1.0 INTRODUCTION

1.1 Background

During November 1982 transient increases in both hydrogen and oxygen were monitored in the SCTI facility. [6] On both occasions the power was being increased. The change in concentration was equivalent to that expected from an injection of 1 lb. of water. At that time the GAAD system was an ancillary experiment. As a precaution, the Test Requestor requested 24 hour on-site coverage by the GAAD system during the period prior to a shutdown for in-service inspection of the steam generator a few days later. Subsequently, one of the authors (D. A. Greene) reviewed all existing sodium-water reaction phenomena. Based on this review leak detection criteria were provided for both acoustic and chemical monitors. The decision was made to include the GAAD system as an integral part of the facility small leak protection system. In March 1983 ETEC approved the integration approach, and GAAD system output was transferred into the facility Data Acquisition System (DAS).

The GAAD system complemented the chemical leak detection system; operator corrective action was required if both systems indicated a leak. Because of longer experience with chemical monitors, the operator still responded to a strong signal from the hydrogen monitor even if no acoustic indication was received.

The objectives in defining detection thresholds for the GAAD system were:

a) Provide acoustic leak protection against leaks in the tube-to-tubesheet region that might cause rapid damage propagation
b) Provide acoustic leak protection against small water-into-sodium leaks anywhere in the tube bundle.

In order to reduce operator training and operator acceptance the GAAD system was structured to be similar to the chemical monitor. The similarity criteria are shown in Table 1, together with the way in which the criteria were met.

The GAAD system incorporated into the facility leak protection system used two monitoring systems. The first scanned both tubesheets within about 90 seconds, the other scanned the total internal volume of the steam generator. During critical parts of the prototype steam generator program on-site support was provided, at other times off-site coverage was provided by the Pager system described in Part I, Section 2.6.

1.2 Structure of Part II

A review of sodium water reaction, damage and setting of facility leak protection system detection requirements is given in Section 2. This is followed by a section developing the acoustic system criteria to be responsive to the detection requirements, including a requirement for a very low false alarm rate added by the facility operator. Acoustic detection criteria developed in Section 3 are then applied to the Prototype Steam Generator test program in the SCTI facility in Section 4.

TABLE 1.

SIMILARITY CRITERIA FOR ACOUSTIC DETECTION SYSTEM

LEAK DETECTION CRITERIA:

* Both systems respond to the same criteria.
* Both systems require identical operator action.

OPERATOR INTERFACE CRITERIA:

* Ability to check accuracy of indication, requires simple diagnostic checks.
* Ability to quickly check signal history, requires immediate recall of recent output.
* Diagnostic recall of long-term history, especially detailed output before and after alarm indication.
* Minimize training requirements by mimicking chemical system data acquisition and response.

GAAD SYSTEM RESPONSIVE TO CRITERIA:

* Met detection criteria.
* Complete diagnostic package included.
* Operator can recall immediate history, any bin.
* Long-term history from D.A.S.
* Data prior to, and following alarm "frozen".
* Minimal operator training required.

2.0 DETECTION REQUIREMENTS

2.1 Wastage Damage Rate Criteria

The damage potential of small leaks has been comprehensively examined and reported. [5,17,18,19] From this data base the wastage damage rates were derived for the prototype steam generator (Figure 1). The left-hand portion of the curve shows the response time requirements to protect against self-wastage phenomena; the right-hand portion for protection against damage due to impingement wastage. Line "B" is the recommended curve for defining leak detection and alarm criteria. Although curve "A" is more applicable to the tubesheet region, the assumption must be made that a defect might occur at the sodium inlet region (curve "B"). It was unlikely that conditions for curve "C" would be reached during the test program at SCTI.

Impingement wastage is a function of the effective diameter of the defect in the heat transfer tube. Since leak detectors monitor H_2O injection rate, Figure 1 gives damage rates as a function of leak rate. The leak rate was calculated assuming superheated/saturated steam properties. If liquid is injected the rate increases by a factor of four. The damage rate is also a function of the local geometry, especially the impingement angle of the Na/H_2O reaction flame. The curves in Figure 1 assume normal impingement onto the closest target tube. Curve "B" is therefore conservative and expected to cover the majority of SCTI operating conditions. The conservatism of curve "B" is summarized in Table 2.

2.2 Recommended Detection Criteria for Prototype Steam Generator

The following criteria, based on Figure 1 and the experience from experimental Na/H_2O reaction programs, were recommended for preparing SCTI corrective action procedures.

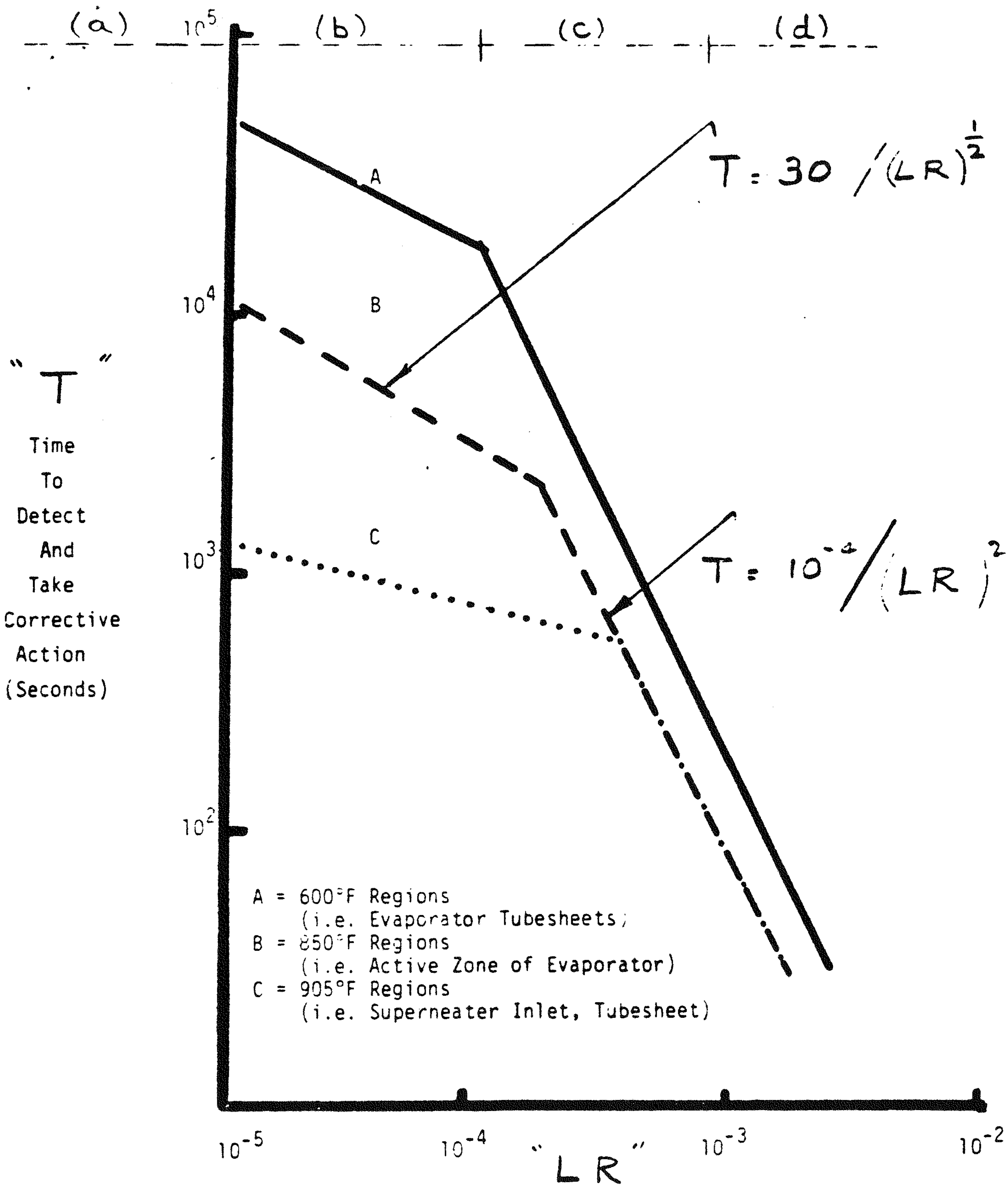


FIGURE 1.

WASTAGE LIMITS FOR ACOUSTIC LEAK DETECTION SYSTEM

Table 2: Conservatism of Curve "B"

RECOMMEND LINE "B"

- Curve A is low temperature (tubesheets @ power).
- Curve C is once-through operation.

TEMPERATURE EFFECT

- Impingement has a factor 2½x conservatism.
- Self-wastage has approximate order of magnitude conservatism.

WATER PHASE

- Wastage is controlled by orifice diameter and is independent of water phase and pressure.
- Curve assumes steam injection.
- Liquid injection increases water injection rate by a factor approximately 4x

LOCAL GEOMETRY

- Assumes normal impingement of jet.
- Assumes impingement on nearest tube.

a) Leak rates < 1×10^{-5} lbs H_2O/sec:

Defects of this size tend to plug with intermittent injection periods during self-wastage of the tube wall. Such defects are almost impossible to detect and locate because of the self-plugging tendency [64]. It is recommended that no operator action be initiated for leakage rates of this magnitude.

b) Leak rates 1×10^{-5} to 1×10^{-4} lbs H_2O/sec:

Once the defect reaches a size to give injections in this range, it tends to remain open at operating conditions. Almost invariably it plugs if the system is shut down. Self-wastage is the primary damage mode, with possible rapid leak growth at the end of the time suggested by curve "B" (Figure 1). The operator has 30 minutes to 3 hours to detect and take action, and potentially much longer due to the conservatism inherent in the wastage curves. It is recommended that (a) the DAS provides an operator "ALERT" signal, (b) operation of the system continues, and (c) a pre-planned diagnostic/location program be initiated.

c) Leak rates 1×10^{-4} to 5×10^{-4} lbs H_2O/sec:

The probable damage mode for injections in this range is impingement damage of an adjacent tube. The target tube will be penetrated in a minimum of 2 minutes for the higher rates, but up to 30 minutes at the lower rates. Should damage propagation occur, significant damage to the unit could take place within a relatively few minutes.

d) Leak rates > 5×10^{-4} lbs H_2O/sec:

This level of leak rate is probably the result of rapid enlargement from self-wastage of a small defect or, alternatively, initiation of impingement damage propagation. It can have potentially rapid growth due to multiple, sequential failure of other tubes. It is recommended that the DAS provides a "SCRAM" signal to the operator who then initiates a plant trip and steam generator blowdown.

The above damage rate criteria are summarized in Table 3.

Table 3: Wastage Damage Rate Criteria

10^{-8} lbs/sec $<$ LEAK RATE $<$ 10^{-5} lbs/sec

- Self-plug.
- Difficult detection and location.
- Recommend no operator action; inform supervision.

10^{-5} lbs/sec $<$ LEAK RATE $<$ 2×10^{-4} lbs/sec

- Continuous injection.
- Self-wastage is primary damage mode.
- Time: 30 minutes to 3 hours.
- Recommend operator ALERT, diagnostic mode.

1×10^{-4} $<$ LEAK RATE $<$ 5×10^{-4} lbs/sec

- Impingement wastage is primary damage mode.
- Time: 2 minutes to 30 minutes.
- Recommend operator ALARM.
- Controlled shutdown to hot, dry layup condition.

5×10^{-4} $<$ LEAK RATE

- Impingement with potential for failure propagation.
- Time: 20 seconds to few minutes.
- Recommend operator SCRAM.

It should be remembered that it is highly improbable that damage propagation beyond the rig confines will occur. An automatic system scram will be initiated by bursting of the rupture disk and actuation of the sodium/water reaction vent system if loop pressures become excessive. The above criteria are based on a conservative response time curve, and it is unlikely that an uncontrolled scram will result if the recommended operator actions are taken.

These criteria apply to any detection system, chemical or acoustic. The remainder of this part of the report applies these detection requirements to the General Electric Advanced Acoustic Detection (GAAD) system.

3.0 ACOUSTIC LEAK DETECTION CRITERIA

3.1 Introduction

The internal volume of the steam generator vessel is sequentially scanned. At each of approximately 170 planes the array of accelerometers is focused onto a grid of approximately 80 locations. At each of these locations the noise concentration (CORCO) is measured. Coincidentally, the average background noise (POWER) is measured.

CORCO: This is the signal-to-noise ratio at the array focal point. It is directly analogous to the hydrogen concentration measured by the chemical leak detector.

POWER: This is the noise amplitude at the reference plane. It is a function of the operating parameters of the system such as intensity of boiling, fluid velocities, etc. It is directly analogous to the influence of sodium flowrate/volume on the chemical leak detection system.

BIN: This is the location at which the maximum value of CORCO is found. There is no comparison between this parameter and measurements made with the non-specific chemical leak detection system. For the chemical system to provide this parameter, a large number of sampling points would be required within the steam generator.

Each of the above parameters were transferred from the GAAD system to the facility data acquisition system (DAS) at regular intervals.

3.2 Statistical Processing of Data

The GAAD system uses statistical analysis of the accelerometer data to assess the probability that a leak exists in a particular bin. If the data sample is small the ability to make a prediction is limited. Further, there is the possibility of giving a false alarm if the decision point (alarm level) is too low, or of missing a leak if the decision point is too high. As the data sample size is increased predictions can be made with greater confidence. The GAAD system algorithms must chart a middle path between a large data sample and prediction certainty, and the need to detect the occurrence of a leak within stated time restraints.

The data collection rate is limited by the bandwidth of the leak noise to 20,000 samples per second per accelerometer [32]. It is assumed the data have a normal distribution, and since we are concerned about the difference in distributions with and without a leak, a "Chi-squared" test is appropriate. A measure of the variability of the data is the "standard deviation" (S), and the data frequency plot is a normal curve described in terms of S. It can be shown that the standard deviation of CORCO is

$$S = (1 + \text{CORCO}) \sqrt{2/N} \tag{1}$$

where N is the number of samples of data (degrees of freedom). For example, the present computer-driven GAAD system collects an equivalent of approximately 130 samples in 10 milliseconds. Data from each plane were analyzed for five seconds providing current estimates of CORCO for each focal point (BIN) from the 10 msec of data.

These CORCO values are expected to have a normal distribution with a standard deviation of "S" (Figure 2). Should a leak be present the CORCO distribution will shift to higher values with slightly higher standard deviation. In a practical situation these two distributions overlap as shown in Figure 2. If a measured CORCO value falls in the overlap region

CORCO DISTRIBUTION

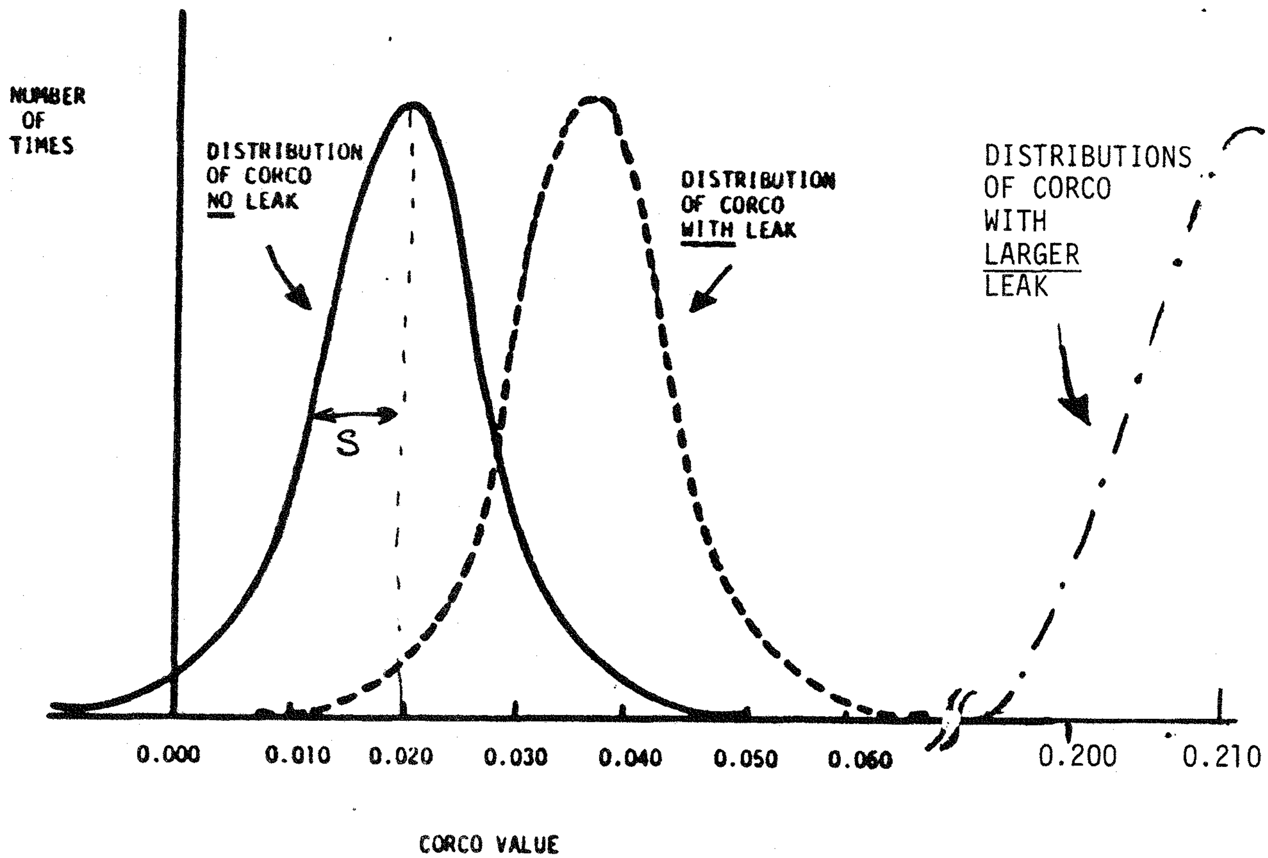


FIGURE 2.

DISTRIBUTIONS OF "CORCO" VALUES

there exists the potential for a false alarm. The potential for a false alarm can be reduced in one of two ways:

a) Move the decision/threshold point to a higher level with reduced detection sensitivity. (In Figure 2, the threshold point is set at 10x the mean value of CORCO.)

b) Increase the number of data which has the effect of reducing the standard deviation (variance) of the distribution. This requires longer sampling times. In Figure 3, the threshold level is reduced from 10x to 2x with more data collected.

CORCO DISTRIBUTION

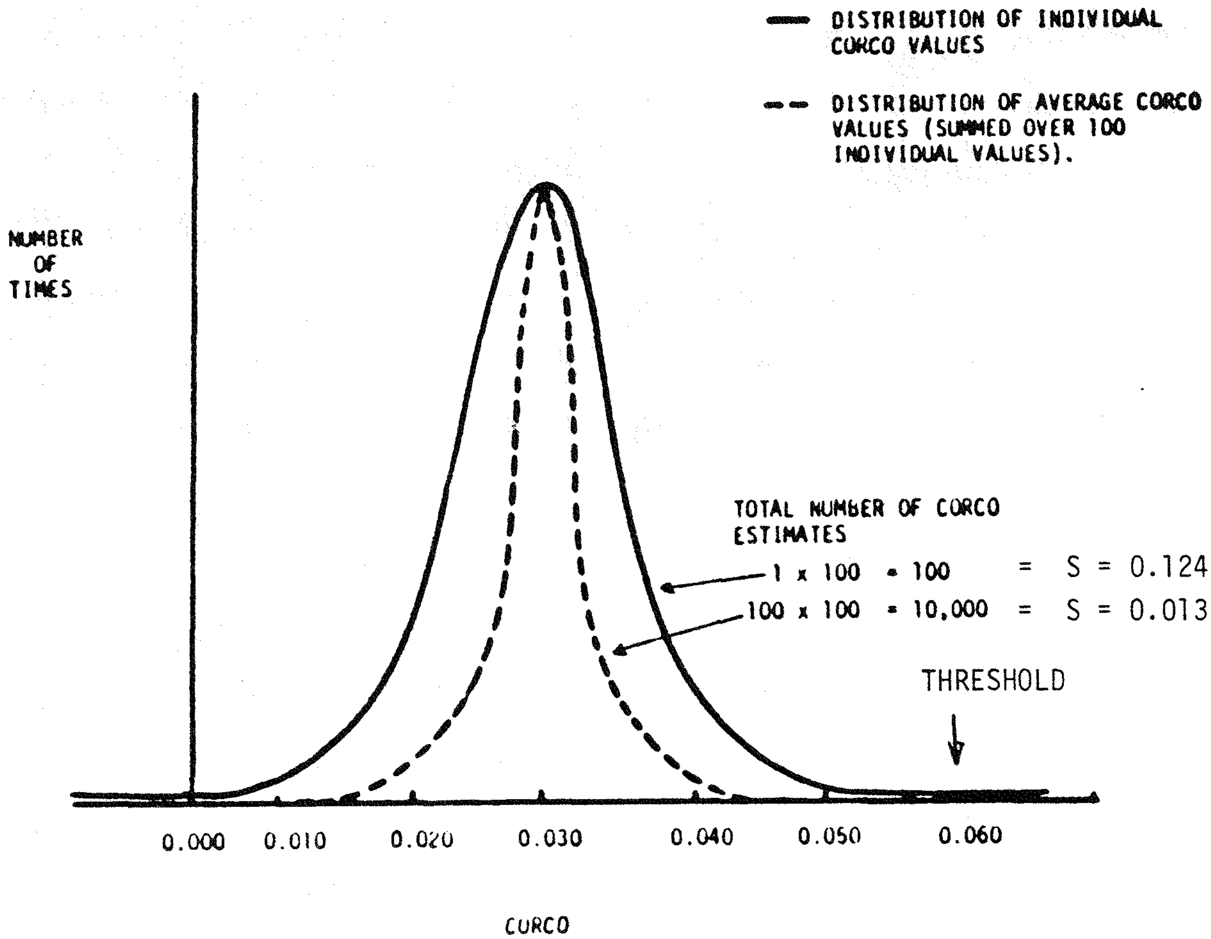


FIGURE 3.

CORCO DISTRIBUTION FOR SINGLE AND AVERAGED NUMBER OF ESTIMATES

Both of these examples assumed a constant detection threshold criteria of two standard deviations above the mean CORCO level.

3.3 Expected Values of CORCO

The hydrogen concentration in the sodium will generally be reduced to some appropriate level (∿100 ppb H in Na) and will tend to maintain this level as thermal/hydraulic operating conditions in the facility change. A similar phenomena has been observed with the magnitude of CORCO when no leak is present. It tends to have a relatively constant value of 0.02 (or lower) independent of operating condition. This is based on test data from the 50 MW test facility at Hengelo [38,39]. Experimental data from the prototype steam generator test indicated CORCO had a similar and approximately constant value at SCTI.

Using the expected mean value of CORCO (0.020) and N = 100 in Equation 1, the probability of the data point exceeding a specified mean CORCO level was calculated. The results are shown in Columns 1 and 5 of Table 4.

3.4 Application to Acoustic Leak Detection at SCTI

Measurements of POWER were made on the prototype steam generator for sodium only flowrates. Typically, the background noise is less than 300 μbar, and could be as low as 60 μbar in the tubesheet region for flowrates up to 700 gpm Na. Water leaks generate signal amplitudes given by [15]:

$$\text{Signal Amplitude } (\mu\text{bar}) = 200\ (\text{LEAK RATE, } H_2O \text{ gms/sec})^{0.5} \qquad (2)$$

The values given in Columns 3 and 4 of Table 3 were calculated from Equation 2 assuming the appropriate background noise level and CORCO value. (CORCO value is the ratio of signal power to background noise power).

TABLE 4.

PROBABILITIES FOR SINGLE ITERATION

		H_2O Leak Rate (lb/sec)		
CORCO Value Beamformed	Number of Standard Deviations	Background Noise Level 30 microbar	Background Noise Level 60 microbar	Probability of Randomly Exceeding CORCO Value
0.062	1	3.1×10^{-4}	1.23×10^{-5}	1 in 6
0.109	2	5.4×10^{-4}	2.16×10^{-5}	1 in 4.3x10
0.145	3	7.2×10^{-4}	2.87×10^{-5}	1 in 7.4×10^{2}
0.187	4	9.3×10^{-4}	3.7×10^{-5}	1 in 3.2×10^{4}
0.229	5	1.13×10^{-3}	4.5×10^{-5}	1 in 3.4×10^{6}
0.270	6	1.34×10^{-3}	5.4×10^{-5}	1 in 1×10^{7}

* Assumes:

Mean CORCO (no leak present) = 0.020 (beamformed)

Array gain = +5 dB

Number of samples/iteration (N) = 130

Standard deviation [$s = (1+CORCO)\sqrt{2/n}$] = 0.044 (prior to beamforming)

The detection equation indicates that the ability to detect a leak is a strong function of signal-to-noise ratio. [13] This equation is based on the signal and background noise measured by one sensor. When detection is made from data collected by an array of sensors the number of independent samples required is reduced because of the array gain. The array gain is defined as

$$\text{Array Gain} = \frac{\text{Power from array}}{\text{Power from reference sensor}}$$

If the sensors are placed in a double helical pattern around a vessel, it is calculated that the array gain will be 6 to 9.5 dB above that for one reference sensor. [13] The reference sensor case assumes that the leak is located on the vessel centerline in the same plane as the sensor on the wall. A double helical pattern of sensors is chosen because it gives the most regular array gain as the leak location is moved within the reference plane. The array gain was calculated using the SAD Code [13] and a conservative value of +5 dB is used to calculate the quantities shown in Table 4.

3.5 Acoustic Detection Leaks > 5×10^{-4} lbs H_2O/sec

Section 2.1 of this document presents timescales for corrective action at various leak rates. If the leak rate is greater than 5×10^{-4} lbs/sec, action is required within two minutes. If the GAAD system is limited to monitoring about two dozen planes (i.e., both tubesheet regions), an estimate of current CORCO values will be made at each plane within the specified time limit. It is assumed that the SCTI will operate for three months and about 5×10^{-5} estimates of CORCO will be made. An injection rate of 1×10^{-3} lbs H_2O/sec during sodium-only flow (300 μbar background noise) will increase the CORCO from the expected 0.020 to about 0.200. At this level the probability of this being a random occurrence with no leak actually being present is 3×10^{-5} (Table 3, Line 5). This is equivalent to one false alarm in three months of operation.

A second estimate is taken immediately by the same GAAD system at the suspect plane. The chance of two simultaneous values exceeding CORCO of 0.2 is equivalent to one false alarm in three months x 5×10^{-5}, or an extremely unlikely event. If the background noise is lower than 300 μbar the detection reliability is further increased.

4.0 DETECTION THRESHOLDS

4.1 CORCO-1 Threshold (Code 1 Alarm)

It was shown in the previous section that if any CORCO value exceeds 0.200 on two successive passes for the same location, there is a high probability that a leak is present. The leak rate associated with this CORCO value can be calculated (see Appendix B). The GAAD system detection algorithm calculates the water injection rate and uses the value to determine if an alarm signal should be sent to the operator. According to Figure 1, leaks above $5\text{x}10^{-4}$ lbs/sec require two or more minutes to initiate damage propagation using conservative assumptions. The tubesheet's monitor will provide an indication within 1½ minutes.

4.1.1 Criteria for Code 1 Alarm (CORCO-1)

Alarm transferred if CORCO value exceeds 0.200 AND THE CALCULATED WATER INJECTION RATE ASSOCIATED WITH THIS CORCO VALUE EXCEEDS $5\text{x}10^{-4}$ H_2O LBS/SEC. NO RESTRICTIONS ON BACKGROUND NOISE LEVEL (POWER) ARE APPLIED. Alarm transferred to operator's console.

- Rationale

a) If the background noise levels are very low, such as during sodium-only operation at low flow, electronic noise can be relatively coherent producing high CORCO values. However, the predicted H_2O injection rate would be extremely low and far below the alarm rate of $5\text{x}10^{-4}$ lbs/sec. No alarms are justified for this condition.

b) If the steam generator operates with a background noise of 300 microbar, a CORCO value of 0.200 corresponds to $5\text{x}10^{-4}$ H_2O lbs/sec. If operated with a lower background level, say 100 microbar, a CORCO value of 0.2 corresponds to a lower injection rate, e.g., $0.4\text{x}10^{-4}$ H_2O lbs/sec for 100 microbar. With the current criteria a Code 1 alarm would be generated at predicted injection rates lower than the limit proposed ($5x10^{-4}$ H_2O lbs/sec). If the background noise is higher than 300 microbar a value of CORCO greater than 0.200 corresponds to a leak rate in excess of the alarm limit. Experience at SCTI during the current test program indicated that normal CORCO values, with no leak noise, are far below the 0.200 level.

4.2 CORCO-2 Threshold (Code 2 Alarm)

Up to six separate estimates of CORCO for each plane will be available within nine minutes with the tubesheet scanner. There is only one chance in 46,000 estimates (6^6) that all six values would be above a CORCO value of 0.070. This is again equivalent to about one false alarm in three months. Further sequential values above the 0.070 level significantly decrease the risk of false alarms. Once again, the water injection rate equivalent to the CORCO value is calculated and compared to the detection requirement ($5x10^{-4}$ lbs/sec to $2x10^{-4}$ lbs/sec). According to Figure 1, such leak rates will exist for at least 10 to 30 minute prior to propagation, using very conservative criteria.

4.2.1 Criteria for Code 2 Alarm (Code 2)

Alert transferred to Operations Engineer's console, but not to the operator if six successive values of CORCO from a single location exceed 0.070, AND IF THE CALCULATED WATER INJECTION RATE ASSOCIATED WITH THIS CORCO VALUE EXCEEDS $1x10^{-4}$ LBS H_2O/SEC, and if the background noise level is less than 300 microbar.

- Rationale

a) If the background noise levels are very low, such as during sodium-only operation at low flow, electronic noise can be relatively coherent producing high CORCO values. However, the predicted injection rate would be extremely low, and far below the alarm rate of $1x10^{-4}$ lbs H_2O/sec. No alarms are justified under these conditions.

b) If the steam generator operates with a background noise of 300 microbar, a CORCO value of 0.070 corresponds to approximately $1x10^{-4}$ lbs H_2O/sec. At lower levels of background noise, say 100 microbar, the corresponding injection rate would be $0.1x10^{-4}$ lbs H_2O/sec. A Code 2 alarm would be generated at predicted injection rates below the proposed limit ($1x10^{-4}$ lbs H_2O/sec) if just a CORCO-2 amplitude was used.

c) A 300 microbar restriction was used. This Code 2 alarm level corresponds to injection rates which allow a relatively long time period before wastage damage propagation occurs. The acoustic system is most effective when the background noise level is low, usually corresponding to low sodium flow rate. At high background noise and high sodium flow rate, the chemical detector is effective and the acoustic system complements the chemical response.

The chemical response time under high flow conditions is approximately two minutes, whereas at low flow conditions or in stagnant sodium (such as vessel fill) the time can exceed 30 minutes.

4.3 CORCO-3 Threshold (Code 3 Alarm)

The value of CORCO is integrated for 100 passes for each BIN in each plane. For this number of samples, the pre-array gain CORCO distribution's standard deviation becomes

$$S_1 = (1+0.063)\ \sqrt{2/13000} = 0.0132$$

This standard deviation is used to prepare Table 5. This table assumes the data from the previous 100 iterations have been used to calculate CORCO.

TABLE 5.

PROBABILITIES FOR 100 ITERATIONS

CORCO Value* After Beamforming	Number of Standard Deviations	H_2O Leak Rate (300μ bar) lbs/sec	(60μ bar) lbs/sec	Probability of Randomly Exceeding CORCO Value
0.024 1	1.18×10^{-4}	6×10^{-6}		1 in 6
0.028 2	1.4×10^{-4}	5.6×10^{-6}		1 in 4.3x10
0.032 3	1.6×10^{-4}	6.4×10^{-6}		1 in 7.4×10^{2}
0.036 4	1.8×10^{-4}	7.1×10^{-6}		1 in 3.2×10^{4}
0.040 5	2.0×10^{-4}	8.0×10^{-6}		1 in 3.4×10^{6}
0.045 6	2.2×10^{-4}	8.8×10^{-6}		1 in 1.0×10^{7}

* Assumes:

Mean CORCO (no leak present)	= 0.020
Array gain	= +5 dB
Number of samples taken (N)	= 13,000
Standard deviation $[S=(1+CORCO)\ \sqrt{2/N}]$	= 0.013

If the CORCO limit is set to 0.036; about 1 value in 32,000 will randomly reach this level. This is equivalent to about one false alarm in six months operating time. The GAAD system will integrate and provide the CORCO value for the previous 100 iterations.

Examination of Figure 1 indicates up to three hours (180 minutes) is available to monitor the tubesheet regions for leaks in this range (leaks 10^{-5} to $2x10^{-4}$ lbs H_2O/sec). The CORCO value is again transformed into water injection rate and compared to the detection requirement. The tubesheets monitor obtains 100 passes in approximately 150 minutes, ample time for a cautionary message to be transmitted and operator action initiated before damage propagation.

4.3.1 Criteria for Code 3 Alarm (CORCO-3)

Alert transferred to Operations Engineer's console, but not to the operator's console, if the average of 100 values of CORCO at any location exceeds 0.036 and the background noise is less than 300 microbar, AND IF THE CALCULATED WATER INJECTION RATE ASSOCIATED WITH THIS VALUE EXCEEDS $1x10^{-5}$ LBS H_2O/SEC.

- Rationale

a) If the background noise levels are very low, such as sodium-only operation at low flow, electronic noise can be relatively coherent producing high CORCO values. However, the predicted injection rate would be extremely low and far below the alarm rate of $1x10^{-5}$ lbs H_2O/sec. No alarms are justified under such conditions.

b) If the steam generator operates with a background noise of 300 microbar, a CORCO value of 0.050 corresponds to approximately $1x10^{-5}$ lbs/sec. At lower levels of background noise, say 100 microbar, the injection rate would be $0.1x10^{-5}$ lbs/sec. With the current criteria a Code 3 alarm would be generated at predicted injection rates below the proposed limit ($1x10^{-5}$ lbs H_2O/sec).

c) A 300 microbar restriction is proposed. This alarm level corresponds to injection rates which allow a relatively long time period before wastage damage propagation occurs. The acoustic system is most effective when the background levels are low, usually corresponding to low sodium flow rate. At high background noise and high sodium flow rates, the chemical detector is effective and the acoustic system complements the chemical response.

4.4 Alarm Transmission Technique

The tubesheet GAAD system monitored the two tubesheet regions. It required approximately 1½ minutes to scan an axial region of 40 cms length at each end of the vessel. If any of the three detection thresholds was exceeded an immediate interrupt of the DAS was sent. Information on the cause for the interrupt was transmitted.

4.4.1 Code 1 (CORCO-1)

A value of CORCO has exceeded the detection level of 0.200. The value has been rechecked and confirmed. Scanning is halted to allow immediate transfer of the alarm condition and then continues. The information transferred at the end of the pass contains CORCO-1; therefore, no extra information is required. Only one alarm interrupt is given, even if CORCO-1 remains above the threshold of 0.200 for several passes. If the value remains above 0.200 for a long period of time, the alarm interrupt will again be given after 10 minutes. This alarm level was provided directly to the plant operator.

- Code 2 (CORCO-2)

A sequence of six CORCO values at one location has exceeded the detection limit. A similar procedure to that for CORCO-1 is followed, except the signal is repeated at 20 minute intervals. This alarm level was output on to a dedicated console, and an alarm annunciation at the terminal attracts the attention of the Operational Engineer.

- Code 3 (CORCO-2)

The integrated CORCO value (100 iterations) has exceeded the threshold. A similar procedure to that for CORCO-1 will be followed, except the warning signal is repeated at hourly intervals. This alarm level was output on to a dedicated console, and an alarm annunciation at the terminal attracts the attention of the Operational Engineer.

The data provided to the DAS was in CORCO values. Within the DAS this information was converted to equivalent water injection rate using the formula provided in Appendix B. Both CORCO and water injection rates were provided to the facility personnel.

Any alarm CODE was also transmitted via the automatic paging system (Part I, Section 2.6). This signal provided information on the alarm code level, and the exact location of the suspected leak. Paging was available in both the Los Angeles and San Francisco Bay areas, and allowed a specialist on the GAAD system to telephone from either region to provide real-time consultation service to the facility personnel.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support and encouragement in completing this demonstration test of the personnel and management of the Sodium Components Test Installation at the Energy Technology Engineering Center, Santa Susana, California. Similar acknowledgements are made to T. Claytor (ANL), R. Randall (RI), and P. M. Magee and other colleagues at General Electric who participated in the GAAD system program either directly or indirectly.

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REFERENCES

1. ________ "PFR Achieves Record Operation." Atom, No. 337, p. 13, November 1984.

2. Lukasevich, B. I., et al., "Pre-operational Tests and Start-up of the BN-350 Steam Generators." ERDA-32 Proceedings of the US/USSR Seminar on the Development of Sodium-Cooled Fast Breeder Reactor Steam Generators. Los Angeles. December 1974.

3. Goldman, K., "Minutes of Specialists Meeting on Sodium-Water Reactions." UNC-SPLM-1059. October 1969.

4. Ferry, R., "Phenix," Plenary Session on Reactor Operating Experience, Liquid Metal Engineering and Technology. Oxford. April 1984.

5. Greene, D. A., "Self-wastage Phenomena, Data Review and Evaluation." General Electric Company, GEFR-00051, V.I, V.II, and V.III. September 1977.

6. Burns, W. E., and R. M. Jassak, "Water-to-Sodium Leak Detection System Performance during CRBR Prototype Steam Generator Testing." ETEC-TDR-84-9. April 1984.

7. Personal Communication with Hengelo 50 MW Test Facility Manager. Details of the diagnostic programs may be found in documents from the ETEC-SCTI/TNO-HENGELO Technology Transfer Program.

8. Whipple, J. C., et al., "Test Results and Evaluation of LCTR Leak Propagation Tests and Supporting Small Leak Tests." Second Joint US/Japan Steam Generator Seminar. Sunnyvale, CA. January 1981.

9. Magee, P. M., "Intermediate Leak Detection and Automatic Shutdown to Minimize LMFBR Steam Generator Damage Propagation." General Electric Company Report GEFR-00559. April 1981.

10. Fox, C. H., et al., "CRBRP Steam Generator Testing Experience." Liquid Metal Engineering and Technology, V.2. Proceedings of Third International Conference, Oxford, England. April 1984.

11. Greene, D. A., "Limitations in Simulating Sodium-Water Reaction Noise by Gas Injections." General Electric Company Report GEFR-00737. April 1985.

REFERENCES (Continued)

12. Greene, D. A., and F. F. Ahlgren, "An Acoustic Protection System for Liquid Metal Heated Steam Generators." Fluid Transients and Acoustics in the Power Industry. ASME, San Francisco. December 1979.

13. Greene, D. A., et al., "Acoustic Leak Detection/Location System Reference Design: Supporting Tests, Analysis, and Data." General Electric Company Report GEFR-00478. September 1980.

14. Greene, D. A., et al., "Reference Design of 'GAAD' Acoustic Leak Detection/Location System for Steam Generators." General Electric Company Report GEFR-00591. December 1981.

15. Greene, D. A., et al., "Acoustic Leak Detection/Location System Progress Report on Support Tests and Analyses." General Electric Company Report GEFR-00540. September 1980.

16. Greene, D. A., et al., "Tests and Analysis in Support of An Acoustic Leak Detection/Location System (Progress Report)." General Electric Company Report GEFR-00384. September 1978.

17. Greene, D. A., et al., "Experimental Investigation of the Wastage of Steam Generator Material by Sodium/Water Reactions." General Electric Company Report GEAP-14094, V.I and V.II. January 1976.

18. Greene, D. A., "SONAR Rig Wastage Tests in Support of LLTR, Series II, Test A-3." General Electric Company Report GEFR-00525. July 1980.

19. Greene, D. A., "Sodium-Water Reaction Phenomena Associated with Small Leaks in LMFBR Steam Generators." Liquid Metal Engr. & Tech., V.1, pp. 13-22. Proceedings of Third Intl. Conf. held in Oxford, England. April 1984.

20. Greene, D. A., and J. W. Malovrh, "Interim Report: Effect of Temperature in Self-Wastage and Its Implications for Steam Generator Leak Protection and Design." General Electric Company Report GEFR-00734. April 1985.

21. McKee, J. M., and S. B. Skladzien, "Evaluation of Steam-to-Sodium Leak Detectors on the SCTI, Phase II." ANL-CT-73-27. December 1973.

22. Magee, P. M., et al., "Development of LMFBR Steam Generator Leak Protection Systems." 77-WA/NE-12. ASME, Winter Meeting, Atlanta, GA. November 1977.

23. McKee, J. M., et al., "Use of Steam Leak Simulator in EBR-II," Liquid Metal Engr. & Tech., V.1, p. 115. Oxford. April 1984.

REFERENCES (Continued)

24. Lunsford, D. W., et al., "Evaluation of the MK-II Chemical Leak Detection System Operational Performance at EBR-II." General Electric Company Report GEFR-00665. March 1983.

25. Epstein, L. F., and J. M. McKee, "Electrochemical Oxygen Meter," ANL-CT-77-3. March 1977.

26. Greene, D. A., et al., "Chemical Leak Detection Tests on the CRBRP Prototype Steam Generator." General Electric Company Report GEFR-00709. March 1984.

27. Mason, L., et al., "The Monitoring of Oxygen Hydrogen and Carbon in the Sodium Circuits of PFR." Liquid Metal Engineering and Technology, V.1, p. 53. Oxford, England. April 1984.

28. Davies, R. A., et al., "Performance of PFR Hydrogen Leak Detection System Based on Water and Hydrogen Injection into the Steam Generation Units." CONF-760503-P2. International Conference on Liquid Metal Tech. in Energy Production. Champion, PA. May 1976.

29. Rettig, D., et al., "Application of Electrochemical Cell to Hydrogen Detection in Cover Gas and to Carbon Activity in Sodium." Liquid Metal Engineering and Technology, V.1, p. 67. Oxford, England. April 1980.

30. Bouchacourt, M., et al., "EdF Experience on Analysis of Non-Metallic Impurities in Sodium Liquid Metal Engineering and Technology." V.1, p. 45. Oxford, England. April 1984.

31. General Electric Company Specification 23A3104, "IGAAD Frequency Domain Beamformer." September 6, 1984.

32. Greene, D. A., et al., "Acoustic Leak Detection Development in the United States." CONF-810615, Rev. 1, V. 1. Second Joint US/Japan LMFBR Steam Generator Seminar. June 1981.

33. Randall, R. L., and T. N. Claytor, "High-Frequency Acoustic Leak Detection System Performance During Testing of the CRBRP Prototype Steam Generator." ESG-DOE-13430. December 1984.

34. Claytor, T. N., et al., "Development of a Passive Acoustic Imaging System." ANL-CT-83-102. November 1983.

35. Claytor, T. N., et al., "Passive Acoustic Imaging: Steam Generator Test Results." ANL-84-26. January 1985.

REFERENCES (Continued)

36. Amos, J. C., and P. M. Magee, "LLTR Series II Test Program Intermediate Leak Tests Final Report." General Electric Company Report GEFR-00663. September 1983.

37. Claytor, T. N., "Void Particulate Monitor Tests at EBR-II." ANL-82-60. October 1982.

38. Claytor, T. N., et al., "EBRII Steam Generator Leak Detection Monitoring Performance: Interim Report, ANL-82-52. July 1983.

GAAD SYSTEM
DEMONSTRATION OF RAPID ACOUSTIC DETECTION OF SIMULATED INTERMEDIATE WATER LEAK IN PROTOTYPE STEAM GENERATOR

ABSTRACT

Leakage of water into sodium in a Liquid Metal Fast Breeder Reactor (LMFBR) steam generator can rapidly lead to multi-tube failures, with serious economic losses, unless early correct actions are taken. The General Electric Advanced Acoustic Detection (GAAD) system was developed to provide this early warning of leakage. It also provides location of the leak. This report is presented in two parts.

Part I describes a successful demonstration test in the Prototype Steam Generator installed in the Sodium Components Test Installation (SCTI) at the Energy Technology Engineering Center. The demonstration test proved the General Electric Advanced Acoustic Detection (GAAD) system will detect and locate intermediate size, water-into-sodium leaks. This will be achieved within 7.5 seconds with only one false alarm in thirty years when the detection algorithm is transferred from the computer to dedicated hardware/firmware. This performance satisfactorily meets criteria for a Liquid Metal Fast Breeder Reactor (LMFBR) automatic shutdown system.

Two GAAD systems provided manual protection against leaks up to 1 gm/sec for the Prototype Steam Generator as part of the SCTI sodium/water detection system.

Part II describes leak detection and alarm requirements for both chemical and acoustic monitors monitoring the prototype steam generator installed in the SCTI. Acoustic detection criteria to meet these requirements were programmed into the GAAD system, with the added requirement of a very low false alarm rate.

GAAD SYSTEM
DEMONSTRATION OF RAPID ACOUSTIC DETECTION OF SIMULATED INTERMEDIATE WATER LEAK IN PROTOTYPE STEAM GENERATOR

APPENDIX A

ACOUSTIC PROGRAM TEST PLAN

ENERGY SYSTEMS AND TECHNOLOGY DIVISION

ADVANCED REACTOR SYSTEMS DEPARTMENT

GENERAL ELECTRIC COMPANY . . . 310 DEGUIGNE DRIVE, P.O. BOX 508
SUNNYVALE, CALIFORNIA 94086

XL-791-10141

October 22, 1981

Mr. J. Winters
Westinghouse Electric Corporation
Advanced Reactors Division
P. O. Box 158
Madison, Pennsylvania 15663

SUBJECT: DOE Contract No. DE-AT03-76SF70030, Work Package No. 40 10.1
LMFBR Steam Generator System Development, WPT No. SG027

Transmittal of Acoustic Program Test Plan for Prototype Steam Generator Test at SCTI/ETEC

Dear Mr. Winters:

The attached Acoustic Program Test Plan is provided for use as an Appendix to the Test Request. This document was produced in cooperation with Rockwell International and Argonne National Laboratory. It has been reviewed by ETEC and DOE-RRT, and their comments have been incorporated.

D. A. Greene may be contacted regarding this transmittal.

Very truly yours,

W. V. Leeburn, Manager
Steam Generator Projects

Attachment

WVL/DAG/mj

PROTOTYPE STEAM GENERATOR TEST AT SCTI/ETEC

ACOUSTIC PROGRAM TEST PLAN

D. A. Greene GE-ARSD
A. Thiele RI
T. N. Claytor ANL

October 1981

An integrated test plan covering programs at General Electric (ARSD), Argonne National Laboratory, and Rockwell International (AI).

Review completed by D.O.E. and ETEC

CONTENTS

CONTENTS (continued)

PROTOTYPE STEAM GENERATOR TEST AT SCTI/ETEC

ACOUSTIC PROGRAM TEST PLAN

1. INTRODUCTION

This plan provides an overview of the acoustic detection test program which will be completed in conjunction with the prototype LMFBR steam generator test at the Energy Technology Engineering Laboratory (ETEC). The steam generator will be installed in the Sodium Components Test Installation (SCTI). Two acoustic detection systems are under development in the U.S.A. The GE-ARSD Acoustic Detection (GAAD) System maps the acoustic pressure field inside the steam generator volume. A local acoustic pressure anomaly is taken as an indication of a leak. The Atomics International High Frequency Acoustic Leak Detection (HALD) System detects the high frequency (∿300 KHz) acoustic emissions generated by the leak. High frequency noise is transmitted from the leak site along the tubes to monitors on the tubesheets, supplemented by accelerometers on the steam generator all for direct detection of signals transmitted through the tube bundle. Argonne National Laboratory is cooperating in the development of the high frequency system, particularly noise analysis methods. Three separate injection devices were installed during fabrication of the steam generator. These injectors will be activated during the steam generator test program to provide simulated leak conditions during operation.

2.0 OBJECTIVES

2.1 DEMONSTRATION

The capability of both acoustic detection systems to meet an LMFBR automatic shutdown criteria by detecting an injection under specified SCTI thermal-hydraulic operating conditions. Such conditions will be specified to:

2.1.1 • permit demonstrations of acoustic systems performance with simulated leaks

2.1.2 • provide best acoustic simulation of a leak equivalent to S/N of ∿-10dB (i.e., equivalent to ∿0.01 lb H_2O/sec with acoustic worst case plant operating conditions)

2.1.3 • allow extrapolation of performance to Clinch River Breeder Reactor Plant (CRBRP) "worst case" operating conditions for acoustic detection

2.1.4 • detect this "fast shutdown" leak within an equivalent of 20 seconds of real-time data

2.2 BACKGROUND NOISE MEASUREMENT

The acoustic detection systems will measure the background noise generated in the steam generator as a function of thermal-hydraulic conditions. These data will be used to generate the following information:

2.2.1 • Correlating absolute noise levels with thermal hydraulic data, and developing empirical background noise models to compare with analytical models.

2.2.2 • Determine magnitude of the coherent noise generation power as a function of thermal hydraulic conditions. Develop leak detection minimum alarm thresholds from these magnitudes.

2.2.3 • Determine if localized noise anomalies exist which may be able to generate false alarms.

2.2.4 • Determine susceptibility of background noise levels to extraneous far-field events which generate false alarms.

3.0 BACKGROUND

A prototype steam generator has been fabricated and will be tested in the Sodium Components Test Installation at the Energy Technology Engineering Center. The SCTI operates at power transfers up to ∿70MW. Due to the expenses of rig operation the test operation is expected to be limited to a time period of four to six weeks.

Tests have shown that a leak of water into sodium can rapidly lead to multi-tube failure within a steam generator, with potentially sizeable economic losses to a power generation facility. Early leak detection and automatic shutdown of a steam generator vessel will reduce the damage potential. Such corrective actions can lead to a prompt return to generation service. Intermediate leak tests in the Larqe Leak Test Riq demonstrated that if leak detection and corrective action occur within approximately 40 seconds leak propagation can be avoided. This requires the leak detection system capability of detecting leaks of 0.01 lbs H_2O/sec or less within a 20 second period.

During the test of the prototype steam generator a sodium/water reaction inside the vessel will be simulated by a gas injection. The steam generator will also be tested under a wide range of thermal hydraulic conditions. Earlier base technology programs have resulted in background noise generation predictive models. Noise levels in the steam generator can be predicted from these models, and compared to and modified by data collected during the thermal-hydraulic test program. The SCTI tests will provide the first integrated tests of the acoustic systems, and the sodium/water detection and background noise models and design bases. It will also provide experience on an operating steam generator that is an order of magnitude higher power than the EBR-II steam generators. It should be noted that the acoustic detection systems will be tested on a non-interference basis with the thermal/hydraulic tests, and will not extend the total test time.

4.0 SCOPE

The scope of the acoustic detection program extends beyond the actual measurements and data acquisition during test operation at SCTI. It can be characterized by the following regimes:

4.1 Pretest analysis and experimental investigations.

4.2 Test condition definition: Define the test conditions most nearlv meeting the objectives (section 2.1) for each of the leak detection systems. The chosen test condition will be based upon pretest analysis.

4.3 Check out system operation. Acquire background noise generation data during the planned SCTI thermal-hydraulic test program.

4.4 Leak test: Operate leak injection systems during conditions defined in section 4.2.

4.5 Define optimized leak test: Analyze leak injection data immediately and select final leak injection test conditions.

4.6 Operate final leak injection test.

4.7 Post-test data analysis to validate leak detection system performance and provide improved noise generation models.

4.8 LMFBR performance predictions: Develop performance predictions for the leak detection system in an operating plant. The data may also lead to design improvements in the acoustic detection systems. Summarize in a final report.

5.0 TEST EQUIPMENT

5.1 GAAD System (Low Frequency System).

GE-ARSD Acoustic Detection (GAAD) system is designed to detect and locate water leaking into sodium in the steam generator. Some 200 accelerometers attached to the steam generator wall respond to motions resulting from internal acoustic pressure fluctuations. Sub-assemblies of eight accelerometer outputs are beamformed to sequentially measure the acoustic power at selected focal points in a reference plane. By suitable choice of accelerometer outputs the acoustic pressure field inside the steam generator volume is mapped sequentially. A local acoustic pressure anomaly is taken as an indication of a leak.

The GAAD system has several sub-systems including analog signal conditioning, multiplexing to provide sub-assemblies of accelerometers, digitizing of the analog signals, beamforming and acoustic power measurement, and alarms and operator interfacing. Eventually these functions will be performed in firmware operating at clock frequencies which allow real-time data analysis. Firmware design would rapidly become obsolete due to the rapid evolution of digital electronics. Therefore, the beamforming and acoustic power measurement, and the leak detection/location algorithms have been simulated by software programs. The disadvantage of this approach is the time overhead required for computation, which does not allow real time data analysis. This disadvantage is outweighed by the flexibility in design and operation inherent in the software simulation.

A diagram of the GAAD system is shown in Figure 1. The analog system, containing amplifiers, channel selection multiplexers, and controlled gain amplifiers is located in the steam generator cell. Cables connect the analog sub-system to the digital sub-system in the control room. The filtered analog signals are digitized and analyzed in a minicomputer. Attached to the digital sub-system are peripheral devices for data storage and data presentation. Three channels of data are processed. Two are associated with leak detection and mapping of local acoustic pressures (ALARM and SCAN). These data channels are automatically connected to $\sim$24 accelerometers from any designated section of the steam generator. The remaining data channel (DATA) monitors the total complement of accelerometers to obtain background noise characteristics along the total vessel length.

5.2 HALD System (High Frequency System)

The HALD system monitors the steam generator with thirteen high frequency transducers. These transducers consist of an integral assemlby with a PZT element and a pre-amplifier providing an amplification of 50dB. The transducer is mounted on an acoustic waveguide attached to the vessel wall. The waveguide supports the transducer so that it is outside of the insulation and at the ambient temperature (Figure 3). Both tubesheets have three transducers, there are another three in the same plane as the injection devices, and another four transducers mounted between the tubesheets and leak plane to monitor the axial signal attenuation.

The performance of the high frequency transducers can be checked by mounting a pulser on a waveguide, and measuring the accelerometer response to a pulser generated vibration. Up to five calibrating pulse waveguides are attached to the vessel surface, approximately two inches away from accelerometers on the tubesheets and along the vessel axis.

ȷure 1

ACOUSTIC DETECTION SYSTEM FOR SCTI

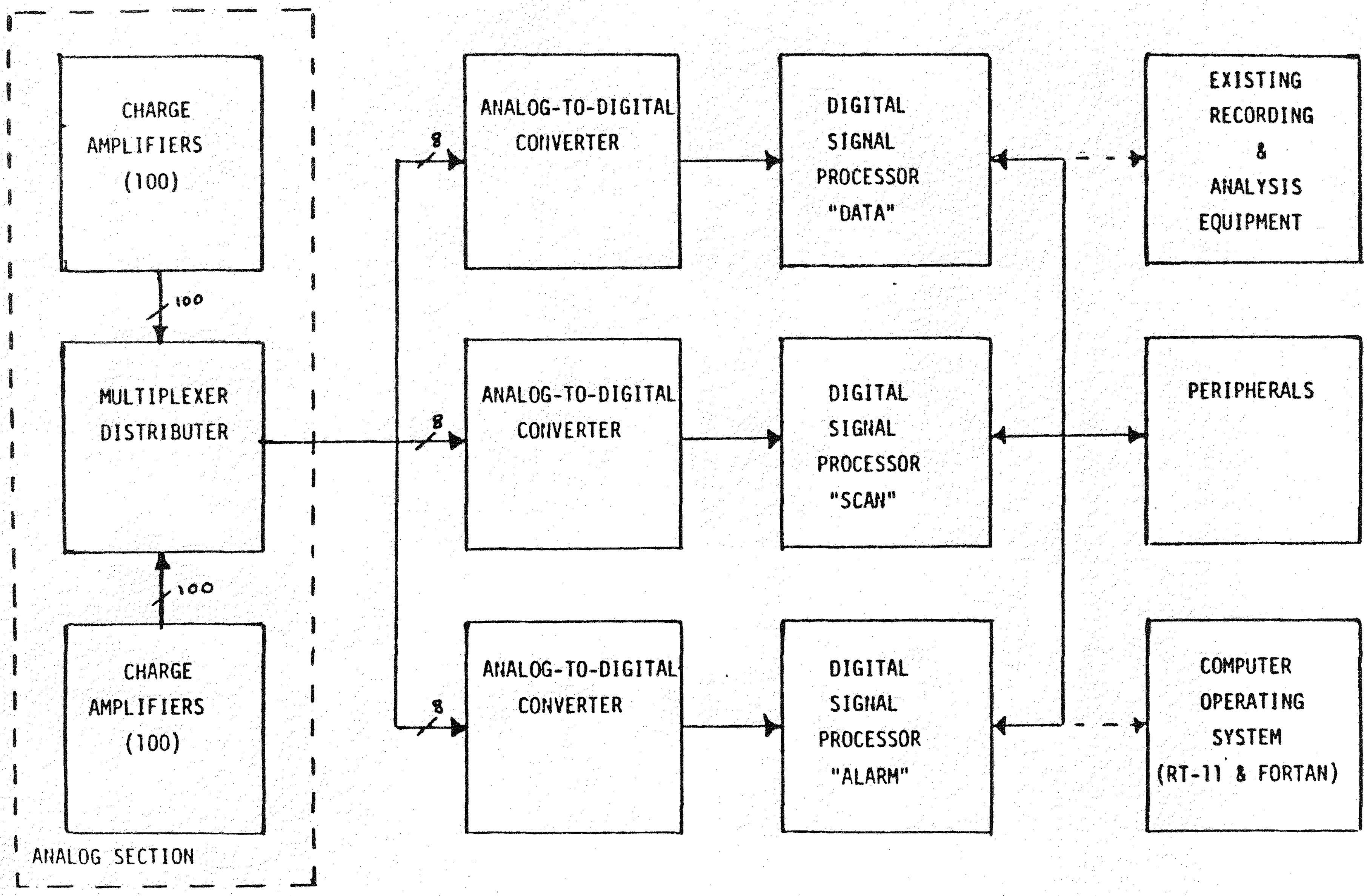
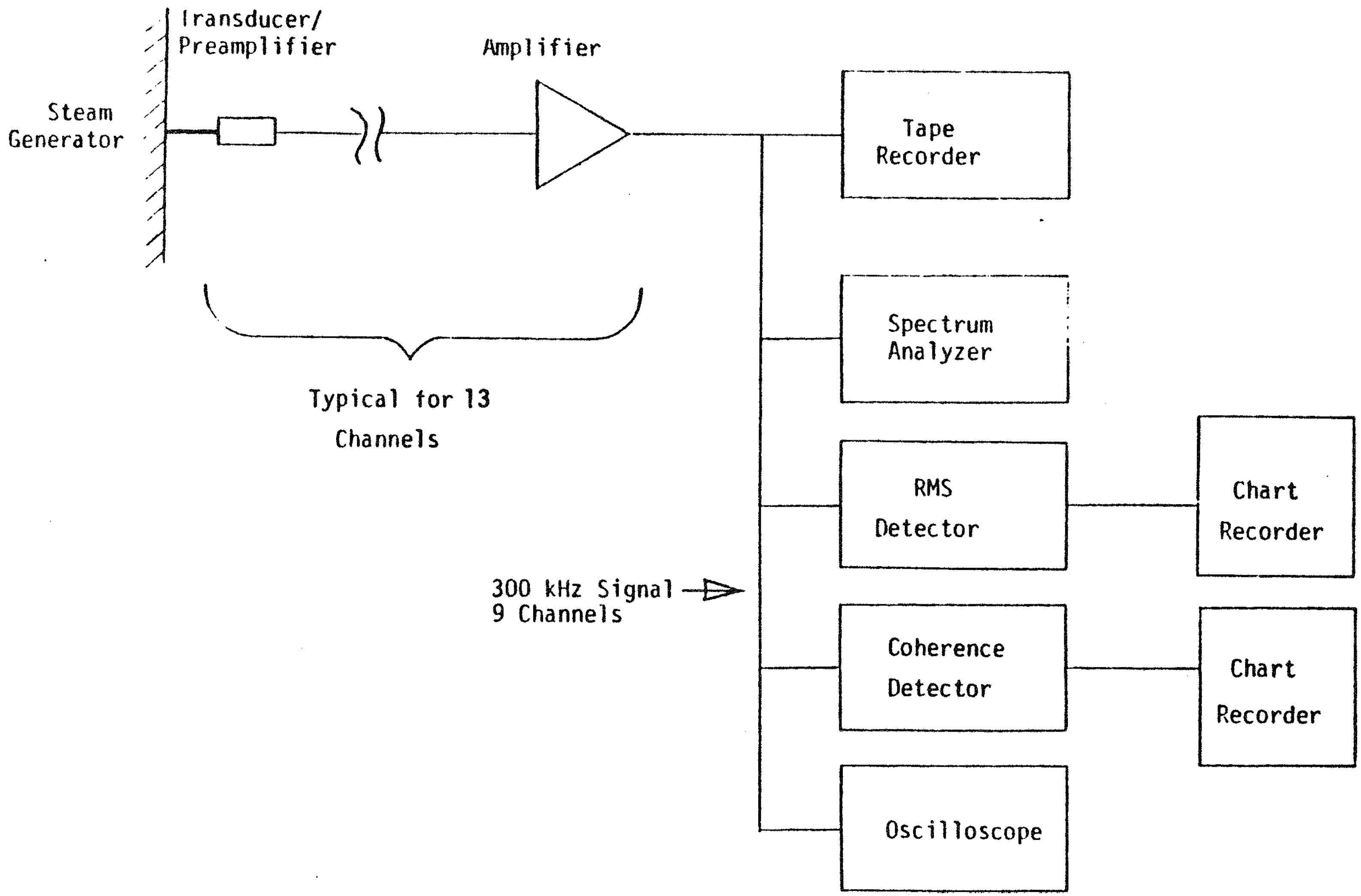


Figure 2

High Frequency Acoustic

Leak Detection System



5.3 Injection Devices

Leak source assemblies are installed in two tubes of the CRBR prototype steam generator. Two different designs are used to give a redundant, as well as diverse, source. The first design utilizes small orifices covered by rupture discs. Three such orifices are welded into a tubular assembly that replaces a section of an instrumentation tube in the steam generator. The three orifices are on 2.62-in. centers with the No. 1 leak 333.875 in. from the centerline of the tube's short leg. (Each leak orifice is 0.006 in. in diameter.) The rupture leak assembly is installed into instrumentation tube 4071 that is located on the outside radius of the tube bundle. Pressure tubes are used to rupture the discs and to supply the leak with the leak fluid. These tubes are tagged for identification and routed along with other instrumentation leads. The pressure tubes are sealed on the exposed ends to prevent damage from moisture or contamination (Figure 3).

During installation of the injectors in 4071, leak No. 1 was damaged and cannot be used. Leaks No. 2 and 3 are available for use during the test. The second leak design, described below, provides a third leak for use during the test. Although the second leak design has two holes it is expected that gas will be injected only through one hole during operation.

The second leak source design that is installed in the prototype steam generator utilizes an open orifice concept. This assembly consists of two leak orifices, 0.008 in. in diameter, that are connected by a common internal cavity which is supplied by a pressure tube. The design is intended to facilitate flushing out the leak with sodium so that any plugging may be cleared. The open orifice assembly is installed with the No. 1 leak 331.62 in. from the short leg centerline of tube 3058. These differences are the major deviations between the two designs. The open orifice leak source is treated the same as the rupture disk in all other regards. The leak locations are shown in Figure 4, and a schematic of the injection system in Figure 5.

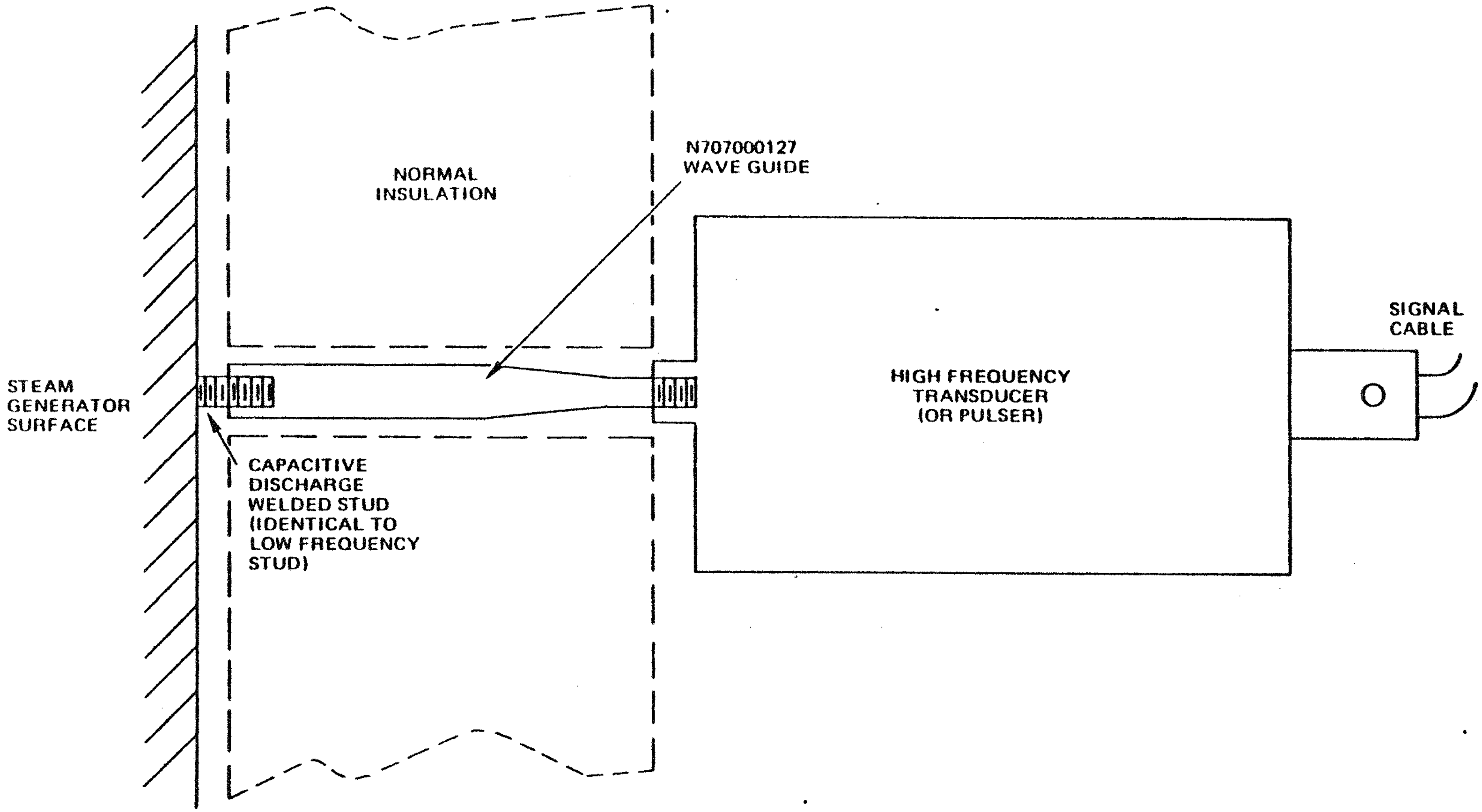
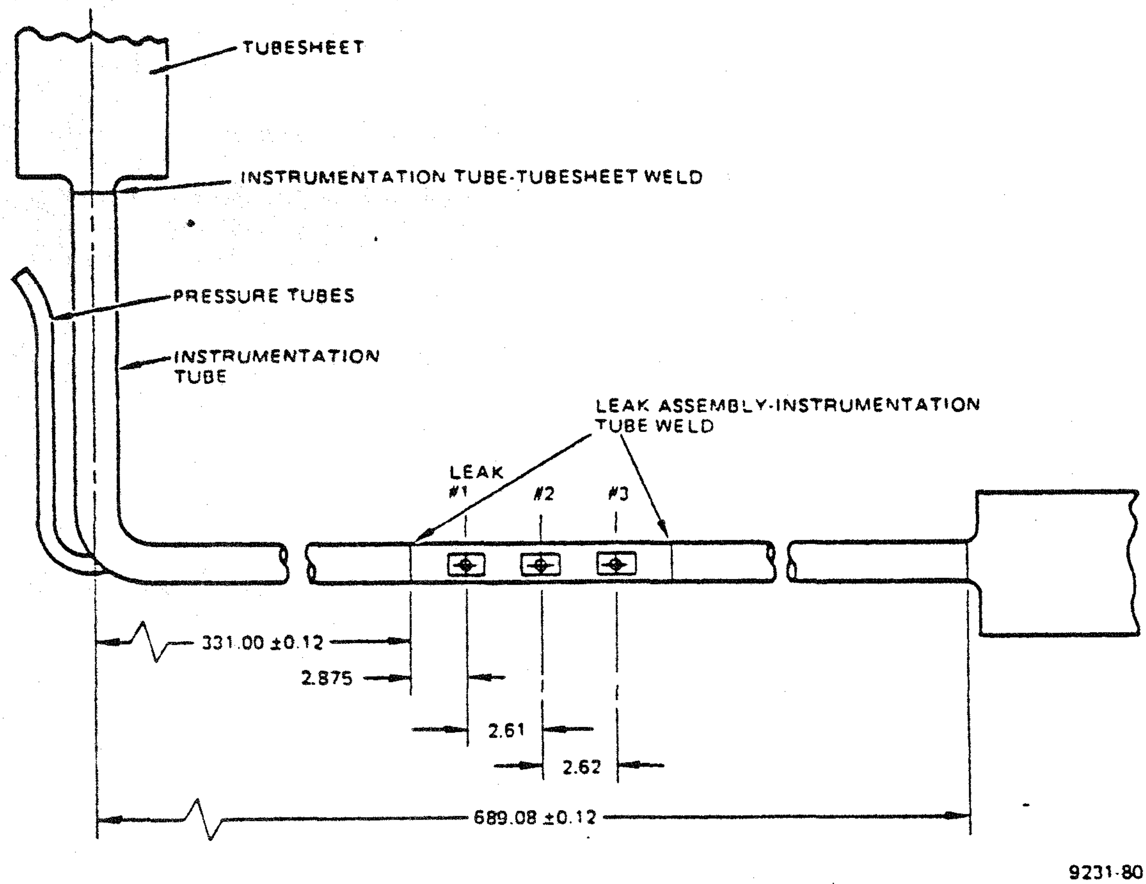


Figure 3. Transducer Installation High Frequency Acoustic System

Figure 4

CRBRP Prototype Steam Generator

Location of Leak Devices



NOTES:

a) Leak #1 was damaged during installation and cannot be used.

b) Leak #4 is a double orifice injector installed at 331.62 inch location.

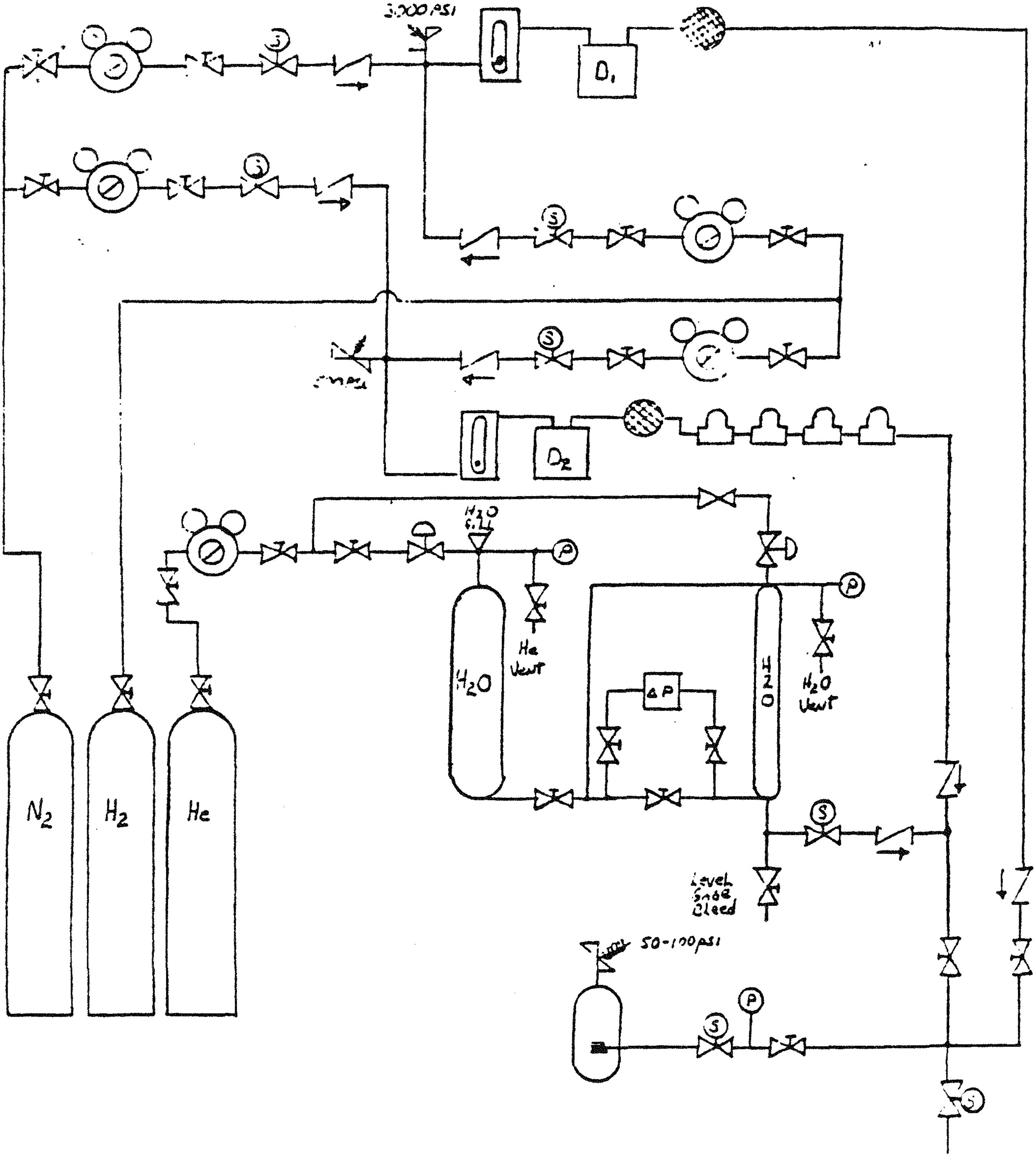


Figure 5. GE-ARSD Leak Injection Module

6. PRE-TEST PREDICTION, ANALYSIS, AND SUPPORTING EXPERIMENTS

6.1 Low Frequency Acoustic System (GAAD)

6.1.1 Preparations for SCTI (Analysis)

The GE computer-model STMGEN provides a description of flow, boiling and heat transfer along each section of the vessel. Utilizing these results in conjunction with flow-noise correlations established earlier (c.f. GEFR-00355) a preliminary estimate of the composite acoustic background noise can be made.

This background noise value becomes a key parameter for gauging system sensitivity. With an accurate S/N ratio established for each test point; required data collection times and system performance can be predicted.

With a complete T/H description of the vessel, accelerometer arrays can be dynamically configured for each test to monitor active regions most applicable for the validation of noise generation models.

Examination of all test conditions will be made to select those tests, the comparisons of which isolate potential noise generating sources: water-boiling, sodium flow, steam flow noise, electrical noise, etc.

Steam generation rate, sodium flow and steam flow are expected to be the principle parameters which impact the acoustic system. However, other physical factors and combinations of factors likely to impact the data acquisition will be systematically considered. The signal strength from gas injections will be predicted from experiments completed in the SONAR test rig (section 6.3).

6.2 High Frequency Acoustic System (HALD)

The signal strength will be predicted from equations that have been developed during an extensive testing program. These calculations will include both the leak itself and the attenuation between the leak source and the transducer location. The background signal levels will be estimated from correlations developed in testing at EBR-II. These data will be used to predict the background signal level and the signal to noise ratio under the various operating conditions of the SCTI test matrix. The following calculations will be made:

Pre-test Analysis

1. Predict signal strength at leak for
   a) Rupture Disc Leak
   b) Open Orifice Leak
2. Predict attenuation between leak source and transducer location.
3. Predict the background noise in the steam generator as a function of steam flow, sodium flow, and boiling conditions.
4. Select the steam generator operating conditions to be used in conducting performance tests of the monitoring system.

6.3 Preparations for SCTI (Experimental)

6.3.1 Each acoustic detection system and related devices will be checked out and demonstrated to be fully operational prior to shipment to ETEC.

[HOLD] HALD System: A pre-test program will be completed using this system and the ACTOR heat exchanger at Argonne National Laboratory, and also on the steam generators attached to the EBR-II reactor.

GAAD System: The GAAD system will be delivered to and set up in the Acoustics Laboratory in San Jose. Both the leak detection and data acquisition computer systems will be checked using the test rigs and facilities in the Acoustics Laboratory.

6.3.2 A proof test of the SCTI leak injection systems will be completed in the SONAR test rig in the Acoustics Laboratory in San Jose. This test series will provide the data required to generate procedures which optimize the performance of the injectors, especially in terms of operational life and recovery if the leak plugs. It is further expected that the test program will:

a) fully define the leak detection system prior to the SCTI test and verify the system adequacy.
b) provide assurance that there is a high probability that the leak detection tests can be performed, by optimizing injection system design and operation.
c) measure absolute noise levels at low and high frequencies as a junction of operating parameters.

7.0 TEST MATRIX

The test matrix is summarized in Table 7.1. Each of the main sections of the matrix are considered in more detail below.

7.1 Instrumentation Checkout and Calibration

i Objective: Check that all instrumentation and transducers are correctly installed and connected. Provide datum noise level for system performance

ii Approach: Use usual instrumentation checkout and calibration techniques

iii Expected Results: Acoustic detection system functioning correctly.

7.2 Pretest Shakedown and Calibration of Acoustic Systems

i Objective: Measure far-field noises generated outside vessel envelope (e.g., compressors, valve actuators, etc).

ii Approach: Monitor all or selection of accelerometers to define the response of the acoustic systems to normal SCTI facility component operation. Attempt to characterize the signature of components which generate noise intruding into the vessel. These tests will be made with vessel

a) cold and empty

b) heated and empty

c) sodium filled

d) with sodium flow

iii Expected results: Identification and characterization of potential noise generators associated with SCTI facility and its operation before, during and after test operation. If the acoustic detection system is delivered late, no data will be obtained with the vessel empty.

7.3 Pre-Operation Tests (High Frequency System - HALD)

i Objective: Measure attenuation of signal along tubes when vessel is empty (dry attenuation test), check leak signal amplitude as a function of gas flowrate, and perform location tests.

ii Approach: Known gas flowrates and types (Ar, He, N_2, etc.) will be injected through the twin orifice leak. The signal amplitude and character will be monitored at various transducer locations. Additional tests will be made to characterize the attenuation between potential leak sites and the transducers, and from one transducer location to another.

iii Expected Results: High frequency leak characteristics, and transfer functions between potential leak sites and transducer locations.

7.4 Pre-Power Generation Tests

i Objectives: To measure the effect of sodium wetting the tubes on transfer function (HALD system). Measure noise generated by sodium flow only. Preliminary leak detection and location experiments if twin hole leak is operated. Measure facility far-field noise effects.

ii Approach: During a portion of pre-power operation the steam generator will be filled with sodium, the water-side empty. Data will be collected as sodium is circulated, and at various temperature levels as the clean-up phase is accomplished.

iii Expected Results: Correlation of sodium flow noise as a function of vessel axial length. Effect of sodium temperature on these correlations. Characterization of far-field noise.

7.5 SCTI: Steam Generator Thermal-Hydraulic Performance Matrix

i Objective: Collect data to confirm the pre-test predictions (section 6), and meet the overall program objectives (section 2.2).

ii Approach: Record data at all planned thermal-hydraulic test conditions. Perform sufficient data analysis during the operating period to confirm data acquisition is satisfactory. Make preliminary comparison of reduced data with pre-test predictions.

iii Expected Results: Data which can be used to validate or provide correlations for acoustic background noise. These correlations will be used to predict LMFBR steam generator conditions. Preliminary data analysis will provide test conditions for leak detection tests.

7.6 Leak Detection Test

i Objective: Demonstrate the capacity of both detection systems to meet an LMFBR automatic shutdown criteria (section 2.1).

ii Approach: This acoustic leak detection program is based on the expectation of at least one injection from each acoustic injector installed in the prototype steam generator, or a minimum of three controlled injections. Based on pretest analysis an optimal test will be chosen from the current thermal-hydraulic test matrix. Two leak detection tests will be recorded at these operating conditions:

a) injection at conditions meeting section 2.1 objectives as they apply to the GAAD system.

b) injections at conditions meeting section 2.1 objectives as they apply to the HALD system.

At the completion of the thermal-hydraulic test matrix one of the test conditions previously achieved will be repeated. This condition will be chosen based primarily on the results from on-line data analysis, modified by preliminary results from the two tests described above. (If necessary priority may be given to one of the detection systems in defining this test condition).

8.0 This test program is expected to provide sufficient characterization of background noise generation by sodium flow in the shellside, and water boiling in the tubeside to predict acoustic conditions in future LMFBR steam generators. It will not provide further information on noise generation due to steam flow (superheater conditions). The ability of both acoustic systems to detect a leak will be demonstrated. The information gained during this program will be reported in one or more comprehensive reports within twelve months of completing the test program. Interim reports may be issued prior, during, or immediately following the test if any significant events or findings occur as the program is followed.

TABLE 7.1 TEST MATRIX SUMMARY

7.1 Instrument checkout and calibration

a) Checkout all instrumentation and connections

b) Measure quiescent background noise character of equipment

7.2 Pretest shakedown and calibration

a) Measure far-field noise effects

b) Measure quiescent background noise character of SCTI and steam generator

7.3 Pre-Operation Tests (HALD)

a) Leak checkout and calibration

b) Dry attenuation tests

c) Leak to transducer, and transducer to transducer transfer function

d) Location tests

7.4 Operation Tests - Pre-power Generation

a) Sodium wetting test

b) Sodium flow test - no water side

c) Facility noise effects

d) Open orifice injection tests.

7.5 SCTI Test Matrix

Monitor the acoustic characteristics of the steam generator as operating parameters are changed

a) Simulated plant operation

b) Waterflow rate change

c) Sodium flow rate change

d) Sodium inlet temperature change

e) Power change

7.6 Leak Operation Test

a) Two leak detection tests at conditions selected during pretest analysis.

b) Leak detection test at conditions selected based on-line analysis of SCTI test matrix

SUMMARY

This document is an integrated test plan covering programs at General Electric (ARSD), Rockwell International (RI) and Argonne National Laboratory (CT). It provides an overview of the acoustic leak detection test program which will be completed in conjunction with the prototype LMFBR steam generator at the Energy Technology Engineering Laboratory. The steam generator is installed in the Sodium Components Test Installation (SCTI). Two acoustic detection systems will be used during the test program, a low frequency system developed by GE-ARSD (GAAD system) and a high frequency system developed by RI-AI (HALD system). These systems will be used to acquire data on background noise during the thermal-hydraulic test program.

Injection devices were installed during fabrication of the prototype steam generator to provide localized noise sources in the active region of the tube bundle. These injectors will be operated during the steam generator test program, and it will be shown that they are detected by the acoustic systems.

GAAD SYSTEM
DEMONSTRATION OF RAPID ACOUSTIC DETECTION OF SIMULATED
INTERMEDIATE WATER LEAK IN PROTOTYPE STEAM GENERATOR

APPENDIX B

CALCULATION OF WATER INJECTION RATE

FROM 'CORCO' VALUE

APPENDIX B

CALCULATION OF WATER INJECTION RATE FROM 'CORCO' VALUE

$$CORCO = \left(\frac{SIGNAL\ (\ bar)}{BACKGROUND\ NOISE\ (\mu BAR)}\right)^2$$

$$SIGNAL = (QH_2O)^{0.5} * 200 \quad \text{(from SONAR Experimental Results)}$$

$$\therefore\ CORCO = \frac{((QH_2O)^{0.5} * 200)^2}{NOISE^2}$$

$$\therefore\ QH_2O = CORCO * NOISE^2 \div 200^2$$

QH_2O is in gms/sec -- convert to lbs/sec.

CORCO is transferred to DAS at an integer value. In order to do this, it is multiplied by 10^4 (e.g., CORCO of 0.200 is transferred as 2000).

$$QH_2O = \frac{CORCO * NOISE^2}{200^2 * 454}$$

Convert CORCO from beamformer value and adjust for 10^4 multiplication.

H_2O Injection Rate = $CORCO * NOISE^2/2.27*10^{11}$

APPENDIX C

TEST OF THE HIGH FREQUENCY ACOUSTIC DETECTION SYSTEM (HALD) AT SCTI

An acoustic detection system which measures the change in amplitude of the high frequency (i.e., greater than 100 KHz) components of steam generator noise was also tested on the prototype steam generator at SCTI. It was originally conceived as a simple detection system which responded to high frequency acoustic energy propagation from the leak site through the solid metal parts of the steam generator to detectors on the massive tubesheets. Three high frequency piezo-electric transducers with an integral pre-amplifier on each tubesheet provided full coverage for leaks at any location. [32] A further ring of high frequency accelerometers was placed at the double orifice injector plane, and at several axial location (13 total on vessel) for the prototype steam generator test at SCTI. The selection of a high frequency approach was based on expectations that a positive signal-to-noise ratio would be produced by a small sodium-water reaction, since the background noise at high frequencies is relatively low. [32]

Following the test program at SCTI reports have been issued giving data on the high frequency system. [6,33] While the high frequency approach shows promise, early claims of simple hardware and data analysis have not been substantiated by the test program at SCTI.

Using attenuation data based on SCTI results published in this report [33] it is possible to predict the number of high frequency sensors required on the CRBRP steam generator to meet sensitivity requirements. A conservative estimate is 50 transducers on the vessel, plus those required to monitor external plant components. With this complement of transducers a maximum attenuation of 3 dB will be measured by a transducer. This is compared to a transducer in the plane of the leak, the leak appearing on the vessel centerline.

Using the data on estimated signal-to-noise ratios in the CRBRP superheater (Table 1, [33]), and the evaporator (Table 2, [33]) and the 50 detector array it is found that:

- The design-basis-leak will not be detected above approximately 70% power in the superheater vessel.
- The design-basis-leak will not be detected below the sodium inlet region above approximately 40% power in the evaporator
- The design-basis-leak will be detected at all powers in the evaporator above the sodium inlet region.

GAAD SYSTEM
DEMONSTRATION OF RAPID ACOUSTIC DETECTION OF SIMULATED
INTERMEDIATE WATER LEAK IN PROTOTYPE STEAM GENERATOR

APPENDIX C

TEST OF THE HIGH FREQUENCY ACOUSTIC DETECTION SYSTEM (HALD) AT SCTI

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