STATUS OF U.S. EVALUATIONS OF ACOUSTIC DETECTION OF IN-SODIUM WATER LEAKS

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Prepared from Information Developed Under
U.S. Department of Engergy Programs

For Presentation

At

IAEA Working Group on Fast Reactors Specialists' Meeting on
"Acoustic/Ultrasonic Detection of In-Sodium Water Leaks" (SM-2)

Aix-En-Provence, France

October 1 - 3, 1990

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Abstract

An overview of the United States testing program to evaluate acoustic leak detection and location systems on simulated water leaks in functional liquid sodium steam generators is provided. Testing was conducted on the modular hockey stick steam generator during the large leak test program in the LLTR, on the CRBR prototype hockey stick steam generator in SCTI, on a double wall tube steam generator installed in EBR-II and on the helical coil steam generator tested in SCTI. These test programs have demonstrated the acoustic leak detection system potential, however, additional development is required before the system can perform to its effective and required potential.

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Introduction

During sodium-water reaction tests conducted as a result of the Enrico Fermi No. 1 steam generator failure, it was discovered that the time required to produce secondary tube leakage might be shorter than the transport time for many chemical leak detection systems. Therefore, interest in faster responding steam/water leak detection systems was revived. During water-reaction testing, Atomic Power Development Associates, Inc. (APDA) evaluated acoustic signals as possible leak detector candidates. An acoustic system has the potential to provide adequate leak detection response and also offers the possibility of locating the leak location within the steam generator. From these early beginnings, two U.S. companies and one national laboratory have pursued the development of the concept. Both companies have made significant progress towards developing a viable system. It appears that the shortcomings in both systems, the amount of data that can be handled and the number of computations needed on the data, will soon be resolved by the rapid improvement in digital data processing equipment.

APDA Acoustic Feasibility Study

During sodium-water reaction tests conducted by APDA to study secondary tube material wastage produced by a water leak from an adjacent tube, the observed wastage rates were sufficiently large to question the adequacy of chemical leak detection methods because of the nominally long transport times required to get the hydrogen or oxygen to the detectors. As a result, APDA initiated a study on the acoustical characteristics of sodium-water reactions. A series of recordings were made on approximately 20 sodium-water reaction tests conducted from January 1968 to December 1969. An increase in the amplitude of the acoustical spectra was detected in every test, predominantly in the 2 KHZ range. Since there is evidence that the acoustic spectra should resemble "white noise", the experimenters concluded that the system, including the mounting of the transducers, the vessel dimensions, the internals, the transducers, and the signal transmission, conditioning and recording equipment were contributing to the predominantly 2 KHZ signal being measured. The acoustic signals were recorded on wastage tests conducted in two different test tanks. One tank was 3 feet in diameter, 5/8-inch thick and 16 1/2 feet long, and manufactured from carbon steel. The second vessel was 3/8-inch thick, 12-inch in diameter and 48-inch long. The acoustic transducer locations on the larger vessel are shown on Figure 1.

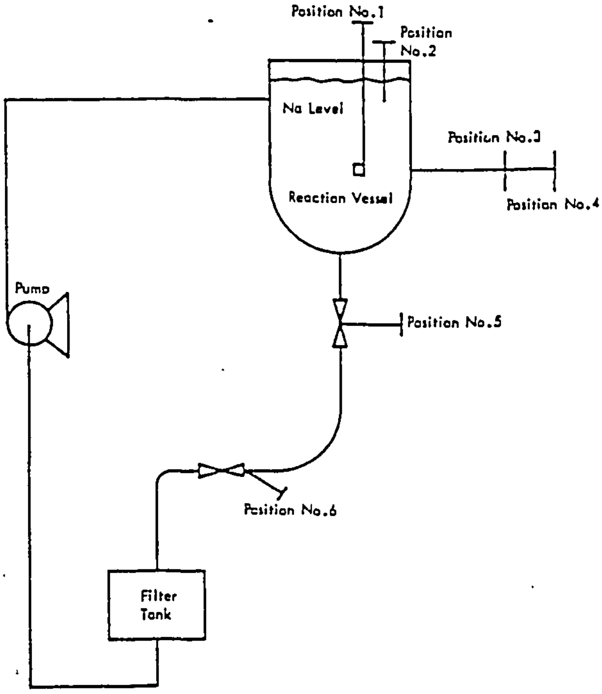


Figure 1. APDA Accelerometer Location

The transducer at position 2 was mounted on a 1 1/2-inch diameter rod inserted vertically into the tank to a depth of 1-foot below the sodium surface. The transducer at position 3 was mounted on a 1-inch diameter rod 12-inch long welded to the outside of the vessel. The transducer at position 4 was mounted on a 1/2-inch diameter rod 15-inch long welded to the tank at the same elevation as Position 3 but rotated a few degrees. The transducer at position 5 was mounted on a 1 1/2-inch diameter rod, 10-inch long, welded to a flat plate which was bolted to a valve flange. This valve was located at the exit of the test vessel. The transducer at position 6 was mounted on a 1 1/2-inch diameter rod, 6-inch long welded to a plate which was bolted to a valve flange. The valve was located 20-foot downstream from the test vessel. Endevco Model 2217E accelerometers were utilized for detecting the generated acoustic signals. Early tests indicated that Position 1 and Position 6 were not as useful as Position 2, 3, 4 and 5 and these locations were abandoned.

Several methods of data analysis were experimented with by APDA. RMS amplitude of the signal observed from each accelerometer was recorded and shown in Figure 2. Spectral Analysis and statistical averaging were attempted. Subtraction of the pretest background spectrum from the spectrum measured during the leak test was evaluated. The data indicated that the predominant acoustic signals being measured due to the water reaction were in the 500 to 2500 Hertz range.

The basic conclusions reached in this study were:

1. Acoustic spectra are always generated by sodium-water reactions.
2. The acoustic system response is extremely fast - almost instantaneous.
3. Additional work is required to separate the sodium-water reaction acoustic spectra from the acoustic spectra generated by normal fluidic and mechanical plant processes.

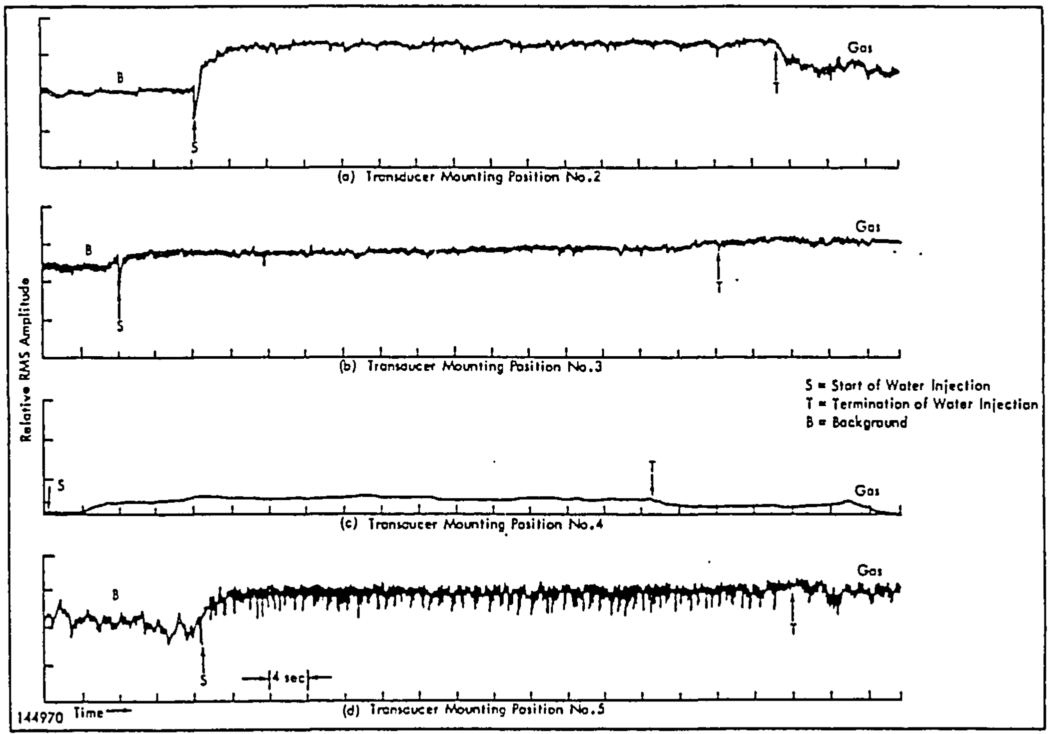


Figure 2. Typical Accelerometer Measurements During a Leak Test

General Electric GAAD Acoustic Leak Detection System

The General Electric Advanced Acoustic Leak Detection (GAAD) system is based upon analyzing acoustical signals taken from an array of approximately 200 accelerometers mounted on the external surface of the steam generator. The spectral frequency range analyzed on these transducers is from 1 to 10 Khz. The signal path is assumed to radiate from the leak site through the tube bundle and sodium to the accelerometer. The accelerometers are coupled to the steam generator wall through a ceramic thermal insulator and retained in place by a mounting plate bolted to the generator wall with capacitive welded studs. The accelerometers are arranged on the shell in a helical pattern. Eight accelerometers are installed for each 360-degree revolution around the steam generator. Figure 3 shows the general installation arrangement. Typically, each accelerometer is located 12-cm (4.72 inches) apart axially on the steam generator. Eight adjacent accelerometers are selected to form an array which examines an axial reference plane at the center of the array. After that plane is examined, an accelerometer is dropped from one end of the array and the next adjacent accelerometer at the other end of the array is added. Thus axial reference planes, 12-cm apart, from the bottom of the steam generator to the top are sequentially analyzed. Within each plane the signal from each accelerometer is time shifted to account for the transport time from a predetermined common point on the plane to each transducer, Figures 3 and 4. The signal levels are correlated. Random noise should have zero or statistically insignificant correlation. A suitable selection of points on the plane allows the internal volume of the steam generator to be sequentially scanned. A small sodium-water reaction creates an additional, fixed location noise source and shows up as a statistically significant increase in the correlation coefficient in this volume of the steam generator. Because of the number of signal detection points, the signal-to-noise ratio, the signal frequency, the number of correlations which must be performed and the short time predicted from critical leak enlargement until damage propagation from tube-to-tube begins, the signal handling and processing from the accelerometers to the final display must be precisely controlled using the best available technology.

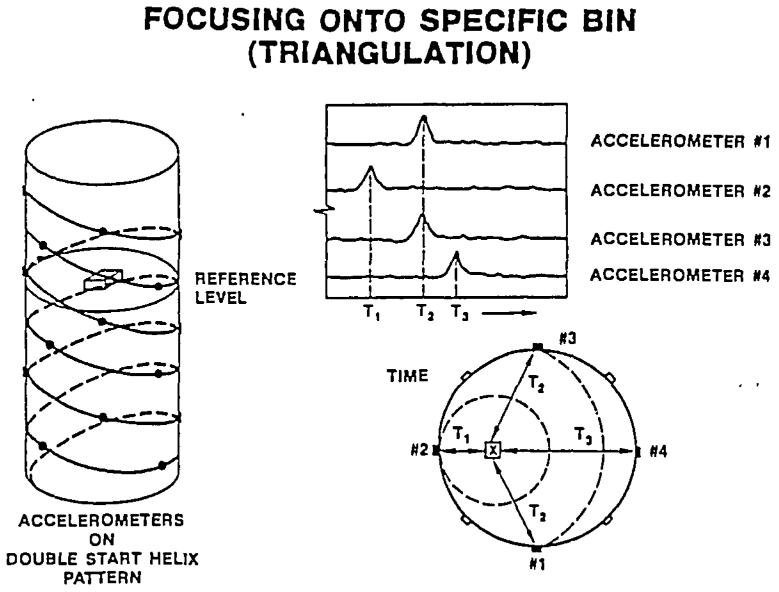

FOCUSING ONTO SPECIFIC BIN (TRIANGULATION)

Figure 3. GAAD Accerometer Location and Beamforming

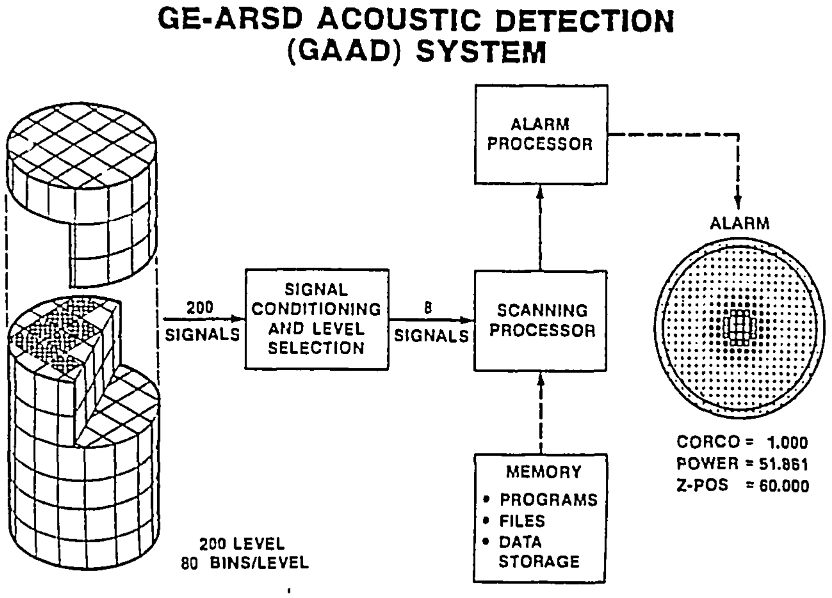


Figure 4. GE Advanced Acoustic Leak Detection System

The most important parameter in predicting the reliability of an acoustic detection system is signal-to-noise ratio. Absolute measurements made of the sodium-water generated noise in simulated tests indicate the following:

1. Sodium temperature has a negligible effect on both frequency and signal level when injecting steam into sodium.
2. Increasing sodium cover gas pressure increases the noise signal level and slightly increases the frequency band width.
3. Noise signal level increases with steam injection rate. Signal saturation level has not been determined.
4. Noise signal band width is lower for water than steam injection but no observable change in amplitude has been observed.

Development of the GAAD acoustic leak detection system was carried out over a period of several years. The effort expended resulted in a complete GAAD system being installed and tested on the Clinch River Breeder Reactor prototype steam generator while it was being tested at ETEC. This system was initially installed on the steam generator as an ancillary test, however, it was incorporated into the facility small leak detection and protection system soon after the start of steam generator testing. When it was incorporated into the facility protection system, it was reconfigured to provide increased emphasis on surveillance for small leaks within one meter of both the upper and lower tube sheets. This resulted in reduced significance on surveillance for the rest of the steam generator, and the detection time was increased to 20 minutes for the area of the steam generator over one meter from the tube sheets. The GAAD system was interfaced with the Sodium Component Test Installation (SCTI) Facility Data Acquisition System to allow collection of long term system performance and to provide an operator interface. The alarm limits established for the GAAD system during the CRBR prototype steam generator were as follows:

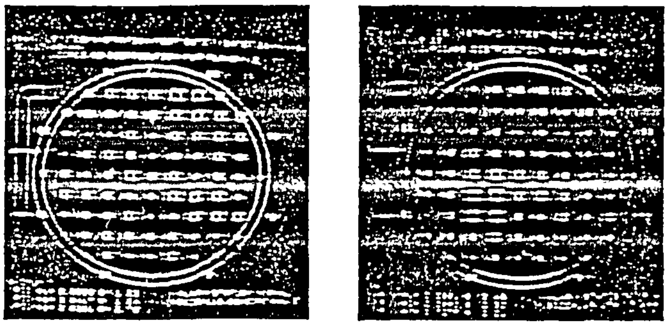
EQUIVALENT WATER LEAK RATE	ALARM CRITERIA
1 X 10^{-5} lbs/sec	Level 3 alarm in less than 2 hours
1 X 10^{-4} lbs/sec	Level 2 alarm in less than 15 minutes
5 X 10^{-4} lbs/sec	Level 1 alarm in less than 2 minutes

The GAAD system showed considerable promise as a viable leak detection system. The system is tolerant of most externally generated noise sources. In addition, the system has demonstrated that it can localize a fixed noise source if the noise level is sufficiently larger than the background and the system has sufficient time to statistically analyze the data. This was demonstrated by a simulated steam leak of 10 liters/minute of nitrogen through a steam generator mid-plane orifice with the steam generator sodium flow rate at 2 X 10^6 lbs/hour with a sodium temperature of 675 F. The GAAD system locked on to the noise source and displayed both the axial and diametrical location of the source, as shown in Figure 5. Some additional development in the system could significantly enhance its effectiveness. Approximately 10% of the accelerometers required some maintenance during the test program. The majority of these were caused by 16 failed stud welds. Eleven ceramic insulators required replacement. Neither of these problems should be difficult to resolve. A larger, more significant improvement, could be made in the signal processing area. The GAAD system tested utilized signal processing equipment available in the early 1970's. Many improvements in hardware and software have been made in the intervening years, particularly in operational speed. Utilization of this new equipment would greatly improve the GAAD system's capability.

Atomics International HALD System

The Atomics International (AI) High Frequency Acoustic Leak Detection (HALD) system is based upon analyzing acoustical signals in the range of 180 ± 60 Khz. An array of accelerometers was coupled to the steam generator walls by the use of small diameter wave guides. The wave guides were internally threaded into a stud which was capacitively welded to the

RESULT OF DEMONSTRATION TEST IN SCTI



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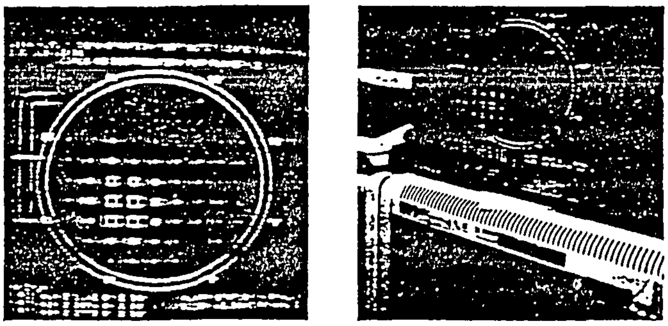
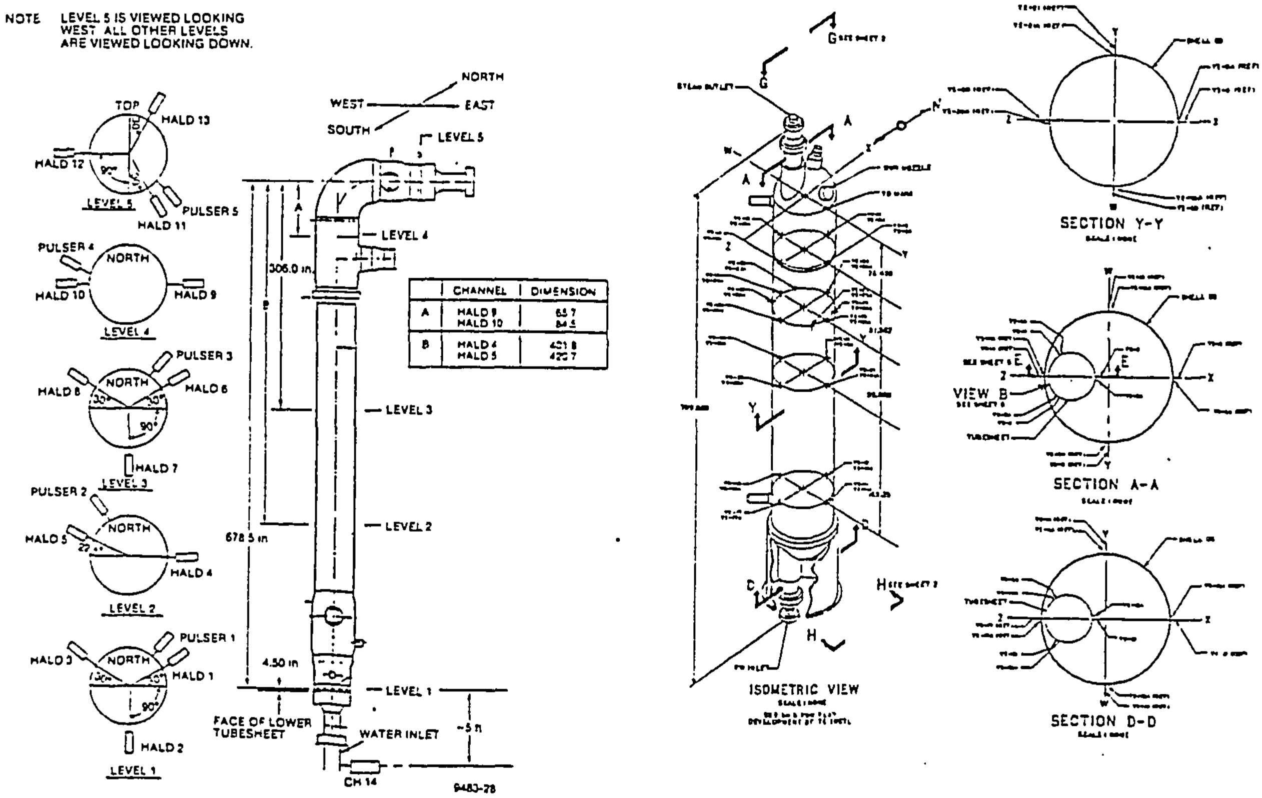


Plane 2, Bin 30 is the leak site

Operator's graphic terminal

Figure 5. GAAD Response to a Simulated Leak

generator wall. The high frequency accelerometer included an internal preamplifier, band pass filter and output driver. The output of the driver feeds an automatic gain control (AGC) amplifier. The HALD system tested at ETEC during the CRBR prototype steam generator test utilized the SCTI data acquisition system (DAS) to process the accelerometer data. The AGC amplifier gain, effectively the RMS signal level, for each accelerometer was patched to the DAS. Background measurements of signal levels with different sodium and water flowrates and temperatures were performed. From these measurements, AI developed a series of correlation equations which were then programmed into the facility DAS. During testing, the DAS was effectively subtracting the predetermined background from the measured signal and then attempting to calculate a leak rate based upon the remainder. This method was soon proven to be unworkable. The SCTI facility was designed with multiple flow paths to allow testing steam generators to their design limits. Changing flow paths was found to have a significant influence on the acoustical background level measured at the steam generator surface. In addition, the system was vulnerable to extraneous maintenance work and valve operation; these generated acoustic signals which found their way back to the sensor attached to the steam generator. The HALD detectors, however, did respond to every simulated leak injection accomplished during the test program.



CRBR Protoytpe Generator Helical Coil Generator

Figure 6. HALD Accelerometer Location on Steam Generators

This again demonstrated the validity of the basic concept but reinforced the necessity to provide more sophisticated data analysis techniques to separate the leak acoustic signals from the plant and process background signals. AI reassessed their design and working in conjunction with the Argonne National Laboratory (ANL) decided to modify their system to employ a triangulation techniques to detect and locate an internal steam generator steam leak. A system was then assembled for checkout during the Helical Coil Steam Generator (HCSG) testing in SCTI.

The HALD system designed for the HCSG consists of thirty seven (37) acoustic sensors. The cylindrical portion of the vessel was monitored with 20 sensors, four sensors 90 degrees apart at each of five levels. The levels were approximately symmetrical with respect to the center of the vessel. Three additional sensors were installed at each tube sheet which are external to the cylindrical portion of the vessel. Seven external acoustic sensors were installed on the sodium inlet and outlet, water inlet, steam outlet, sodium vent line, sodium drain lines and sodium vapor trap.

The acoustic sensor design was not changed from the CRBR prototype steam generator test. The sensor signals were again connected to AGC amplifiers. The digital gain outputs from the AGC amplifiers were directly monitored by a ETEC supplied Hewlett Packard (HP) CPU via an IEEE-488 interface. The broad-band output from the AGC amplifier was connected to a four-channel RMS detector module. The RMS detector output was proportional to the modulation of the energy in the signal from the sensor. The RMS detector also contains a zero crossing detector with a binary output. The RMS detector binary outputs are fed to a multichannel correlator system. The output of the multichannel correlator system includes 15-bit estimates of average peak correlations and time delays for selected measurement combinations. This information was also fed to the HP CPU via the IEEE-488 interface. Leak location/detection analysis was performed by the HP CPU utilizing the data received via the IEEE-488 interface and preprogrammed algorithms. The primary objective was to locate the noise source within the steam generator, distinguish an actual leak from background noise and estimate the leak rate. If the leak rate was estimated to be larger than 10^{-2} lbs/sec, the system was to provide a signal which could be used to automatically initiate a steam generator blowdown. The system operates by first locating a leak, determining that the location is within the steam generator, and then examining the size of the leak. If the system determines, thru cross correlation of the acoustic signals, a stationary noise source exists within the steam generator, the coordinates of the leak site and its estimated leak rate are displayed.

Initial tests were performed on the redesigned system on an operating steam generator in the EBR-II facility at the Idaho Nuclear Engineering Laboratory (INEL). The prototype system was successful in recording signal amplitude from each installed sensor and performing correlation measurements and time delays relating 32 combinations of sensor during various modes of steam generator operation including start-up, full power and shut down with various types and locations of acoustically simulated leaks. The data revealed that the calibration of the RMS detector had a significant effect on the accuracy of the time delay measurement. When the RMS detectors were set for operation near the center of their linear range, the acoustically simulated leak locations were typically located to within one inch.

The prototype was designed with two sets of RMS detectors. The AGC amplifiers operate with a band pass of 180 ± 60 Khz. The RMS detectors in the correlator system operated at a center frequency of 500 Khz. Either could be connected to the correlators. The EBR data review indicated that the 500 Khz correlation measurements had a better precision than the 180 Khz correlation measurements. As a result correlation measurements were taken from the 500 KHz RMS detector modules signals on subsequent testing.

The upgraded HALD system was completed, delivered to ETEC and installed on the HCSG. The HALD system was calibrated and maintained in running condition throughout the first phase of testing on the HCSG. No false alarms were detected during the full operational period. Because of priority items no simulated acoustical leak tests were run during this period. During the second phase of the HCSG test program, the HALD system was not put on line until near the end of the testing program. The HALD system was activated and calibrated and helium simulation tests were attempted on several Leak Injection Devices (LID). Unfortunately, helium flow could not be established through most of the LID's, however, ETEC was successful in obtaining a small leak rate on some LID's. The HALD system accelerometers responded to all successful simulated leaks. However, the HALD system could not converge on the leak location using the acoustic signal generated by the helium injection simulated leak. The cause of this problem was not resolved. The HCSG tests were terminated at this point and no further testing was accomplished on the HALD system.

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