Acoustic Emission Techniques for Locating Internal Leakage of Redundant Components

H. Wichmann* and D. Phillips†
The Marquardt Company, Van Nuys, California

Acoustic emission techniques have been used for over a decade to locate leaks in petrochemical operations. This approach was refined for locating low-level leaks in spacecraft liquid rocket propellant and pressurant feed systems. This paper presents the principles of acoustic emission leak detection, describes the sensors and signal conditioning, discusses acoustic signal transmission and isolation techniques, as well as experimental data, and shows how these data can be applied to identify internally leaking parallel redundant components in all-welded feed systems.

Introduction

A PROGRAM was performed for locating leakage sources in typical liquid rocket propellant and pressurant spacecraft feed systems. The leak detection method investigated involved the use of acoustic emission sensors in combination with various signal-to-noise enhancement techniques to listen to the acoustic waves emitted by the leaks. Of particular interest was the determination of minimum leakage levels that could be detected. Several media and types of leaks were explored and it was demonstrated that leakage rates as low as 0.1 lb/h of water and 3 scc/h of helium could be detected.

The acoustic leak emission detection investigation demonstrated that this method of leak detection has the potential to identify internally leaking fluid system components in all-welded propulsion systems without the need to break into these systems. This paper presents the principles of acoustic emission leak detection, describes the sensors and signal conditioning, discusses acoustic signal transmission and isolation techniques as well as experimental leakage data, and shows how internally leaking parallel redundant components in all-welded feed systems can be identified.

Principle of Acoustic Emission Leak Detection

The acoustic leak detector senses a leak by the "noise" developed in the small crack or flow passage that is the leak path. The noise is generated by the boundary-layer pressure fluctuations produced by vortices in the high shear boundary layer. Factors affecting the amplitude of the noise generated are mass flow rate, fluid density, leak path configuration, and viscosity or friction coefficient.

Analytical and experimental studies of noise generated in boundary layers have been conducted which provide some basis for analytical predictions. However, little data have been found which relate the effectiveness of the conversion from the fluid pressure fluctuations to stress waves (acoustic waves) in the metallic tubes and fitting of propellant lines. The effectiveness of this coupling is important since the noise is detected by a transducer which senses the acoustic waves in the metallic propellant lines and which is located some distance away from the leak. In fact, the size and configuration of the lines greatly affect the acoustic losses (transmission efficiency) in the lines between the leak source and the sensor.

The noise generated in the boundary layer is broadband noise (random) which has energy distributed over a wide range of frequencies. Analytical and experimental data indicate that the noise spectrum peaks at a characteristic frequency and that this frequency is related to boundary-layer thickness. Thus, to be able to measure relatively small leaks emitting very little noise, it is important to have knowledge of the peak frequency at which these acoustic waves occur and to have optimized the sensor and signal conditioning for this peak frequency. Some understanding of the variation in peak noise frequency as a function of the characteristic leak dimension and various fluids may be obtained by examining Table 1.

Table 1 lists the peak frequencies for a feed system at 250 psia pressure when the leak exhausts to vacuum. Data is presented for water, helium, and nitrogen with characteristic leak dimensions ranging from 0.03 to 0.001 in. In the case of the gases, it is assumed that they are flowing at sonic velocity. Table 1 also shows large variations of the characteristic frequency as a function of leak dimension and fluid properties. For small leak dimensions the noise is predicted to peak at ultrasonic frequencies. For helium this frequency is very high.

To achieve a highly sensitive acoustic emission leak detection system it was necessary to minimize acoustic losses between the leak source and the sensor and this, in turn, required an understanding of various acoustic wave modes that exist in the transmission of the source signal. Since the wave mode characteristics can vary between similar structures, it was important to perform intrastructure comparisons to verify the general applicability of detailed test data taken on one structure for applicability to another structure.

Structural Wave Modes

General types of acoustic stress wave modes often seen in structures are: bulk longitudinal, shear, Raleigh, plate longitudinal, and Lamb waves. Of these, only Lamb and plate longitudinal waves are common in typical rocket propulsion thin-wall tubing. These waves can be symmetrical, in other words dilational, in which case a periodic thickening and thinning of the plates is observed as the wave passes a given point or they are asymmetrical, in which case the wave propagates as a full thickness ripple along the tubing. The velocity of Lamb waves is a complex function of plate thickness, wave frequency, and the elastic constraints.

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*Manager, Rocket System Components. Fellow AIAA.
†Project Engineer.

Table 1 Peak noise frequency

Characteristic leak dimensions, in.	Liquid water velocity 192 ft/s, kHz	Gas helium velocity 3275 ft/s, kHz	Gas nitrogen velocity 1136 ft/s, kHz
0.03	8	131	45
0.01	23	393	136
0.003	77	1310	454
0.001	230	3930	1363

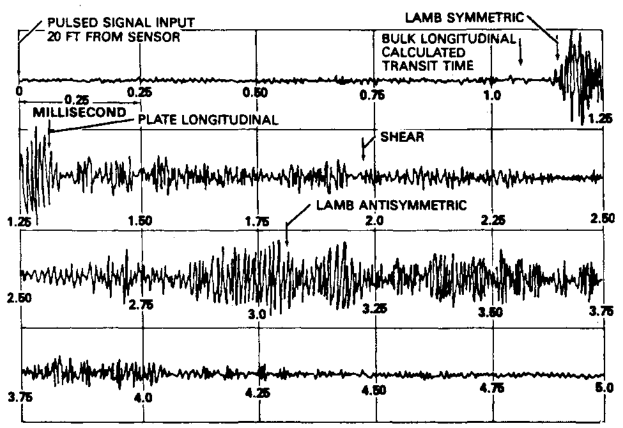

Fig. 1 Wavemode transit times.

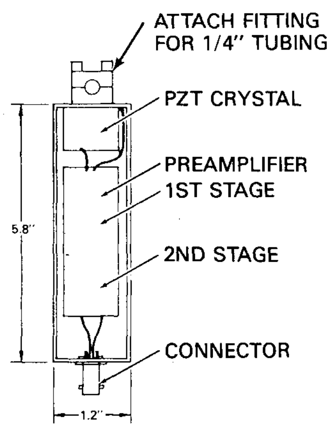

Fig. 2 Schematic of electronic sensor.

To investigate the presence of various wave modes, a broadband (20-250 kHz) acoustic pulse was introduced into a ¼-in.-diam tube at a spacing of 20 ft from the detection sensor. The approximately 4 μs duration pulse used to actuate the pulser also was used to trigger the oscilloscope camera. Figure 1 shows the expanded wave form as seen by the sensor spacing and compares the arrival time of various wave mode groups to the calculated arrival times.

It is seen that the symmetrical Lamb mode is the first to arrive and the longitudinal plate mode is close behind. The bulk longitudinal and the shear modes are not present, as expected, since the tube thickness is small. Several groups of antisymmetric wave mode signals arrive later in the sequence with perhaps some other weaker unidentified wave modes and/or reflections mixed in. Similar test data were obtained for ⅛- and ½-in.-diam tubing.

Acoustic Emission Sensors and Signal Conditioning

Piezoelectric sensors were used to pick up the acoustic energy emitted by a leak and transmitted along feed system tubing. A schematic of this type of sensor is shown in Fig. 2.

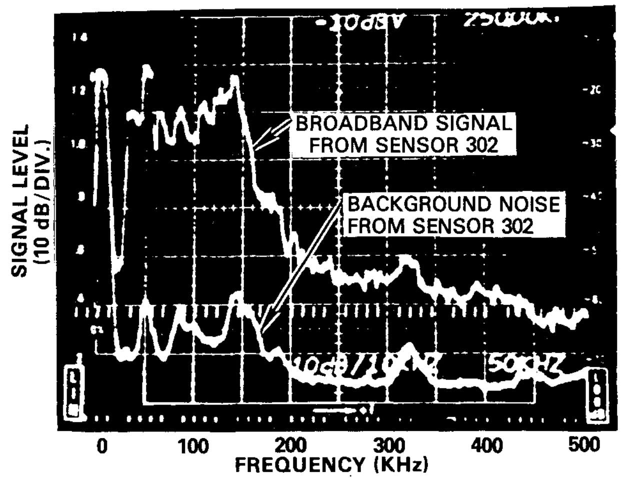

Fig. 3 Sensor output.

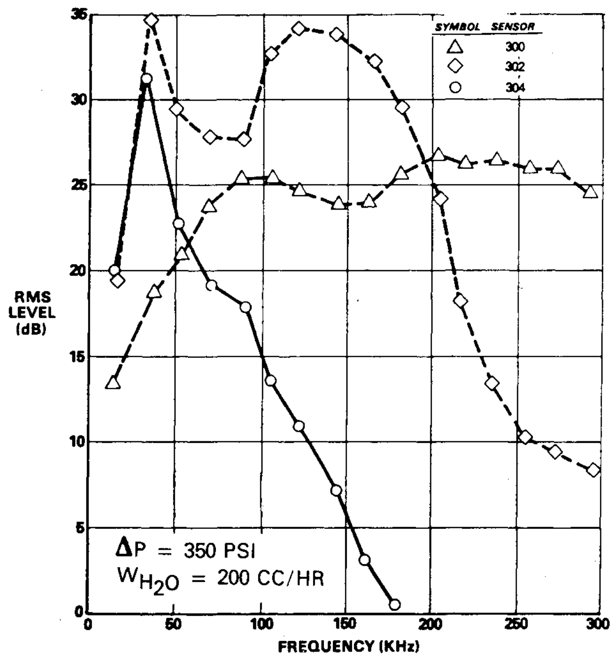

Fig. 4 Frequency sensitivity of three sensors.

The sensor consists of a piezoelectric detector which is a highly sensitive lead-zirconate-titanate (PZT) crystal that detects the high-frequency acoustic noise generated by the leak. The signal picked up by this crystal is amplified through a two-stage amplifier located within the transducer casing. A connector on the transducer allows for transmission of the signal via coaxial cable to a signal conditioning unit. Also shown in Fig. 2 is the attachment fitting that was used for mounting the transducer on the ¼ in. tubing. Figure 3 shows the output at one of the sensors as seen on a spectral analyzer. The double exposure of this photo shows both the broadband and background noise for a particular test setup.

To maximize the signal output from low-level leaks several sensors were evaluated during the performance of the leak detection program. These sensors differed from one another by the size and shape of the piezoelectric crystals used to pick up the acoustic energy. Figure 4 shows the frequency sensitivity of the three principal sensors evaluated.

In this figure the output for the three sensors is shown when monitoring a water leak of 200 cc/h. It is apparent that the frequency response of the type 304 sensor is excellent at approximately 35 kHz, but rapidly decreases at frequencies above 250 kHz. The type 302 sensor features the highest

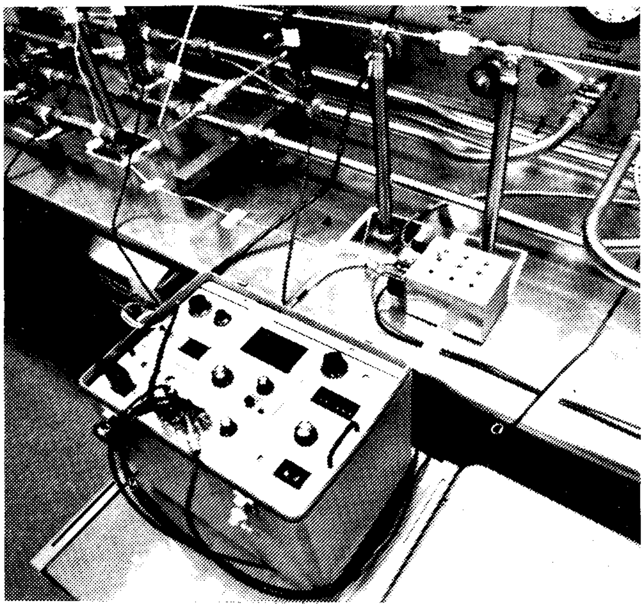

Fig. 5 Leak monitoring unit and sensors.

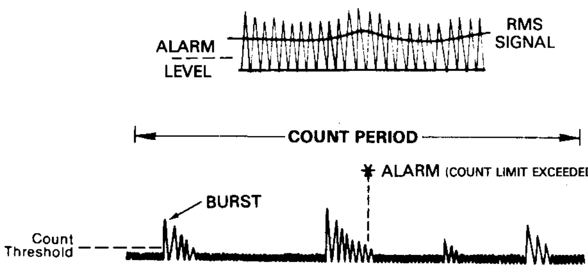

Fig. 6 Leakage monitoring using rms or counts mode.

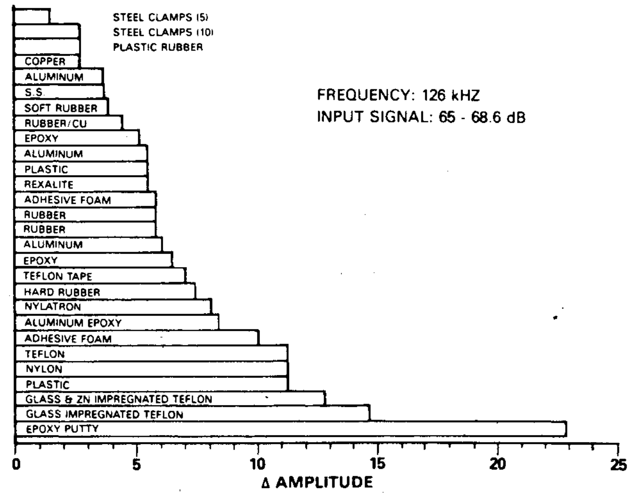

Fig. 7 Acoustic isolation test results.

frequency response from 35 to 190 kHz, but rapidly becomes poor at higher frequencies. The type 300 sensor has a fair frequency response over a broad range of frequencies from approximately 75 to the highest frequency measured, namely 300 kHz. Knowledge of the frequency response characteristics of the sensors is important in selecting the best sensor for a particular application.

Signal processing and display of output from several sensors was accomplished with a leak monitoring unit, shown in Fig. 5 with several installed acoustic emission sensors in a typical test system.

The unit can receive inputs from up to six sensor channels and each can be monitored by manual switch selection. Each sensor channel can be monitored over 16 different frequency bands. These bands are sensitive to a range of frequency about the center point. For example, one band is centered on 180 kHz and is sensitive to frequencies between 171 and 234 kHz. The advantage of monitoring only specific frequency bands and in filtering out frequencies outside of these bands is the ability to monitor only those frequencies where a high signal-to-noise ratio exists and thereby to maximize leakage monitoring sensitivity.

The unit also includes a feature wherein the continuous signal from the sensor can be processed in two ways. One is to give the average root mean square (rms) and the other counts the number of noise spikes over threshold. The second mode is particularly useful for intermittent leaks, where the rms signal is too small. The difference in signal monitoring approach can be seen in Fig. 6. The counts mode can be selected to count over a specific time interval, such as a 10 s period. The rms mode and the counts mode of operation each has an adjustable alarm level, and both the rms level and counts value are displayed on a digital panel meter. For leakage monitoring, the alarm levels are set so that they are above the background noise level—typically 2 dB higher for the rms level and 1000 counts more for the counts mode.

To maximize acoustic transmissibility a large number of system variables were explored. These included five different transducer attachments, five experimental leak configurations plus three valves (two of which permitted leakage adjustments), three sizes of tubing, tubing line lengths ranging from 3 to 20 ft, six different tube fittings or joints, and four test fluids. In addition, acoustic isolation was also explored.

Acoustic isolation is extremely important when trying to locate a leak in a complex feed system using multiple sensors. The objective here is to provide isolation such that leakage occurring in one line section would be identified only by the transducer monitoring that particular line section and not by any of the other transducers in the system. For this purpose a large number of materials were evaluated as acoustic isolators. Figure 7 presents a summary of the test data obtained.

To obtain the relative acoustic energy absorption characteristics of the materials, samples of 2 in. lengths of each of the materials were applied to the ¼-in. tubing, and an acoustic signal of 65-68 dB at a frequency of 126 kHz (without any damping) was generated. The relative damping obtained with the various materials is presented in Fig. 7. As shown, epoxy putty and glass impregnated teflon proved to be the best isolators.

Leakage Data

During the performance of the acoustic emission leak detection program hundreds of tests were performed to evaluate the effects of system configuration and sensor configuration on the ability to measure very low leakage flow rates. The majority of tests were performed with water as the operating fluid; however, some testing was also done with freon and gaseous nitrogen. These data are reported in Ref. 1 and are too voluminous to be repeated in this paper. Subsequent to the program described in Ref. 1, additional tests with gaseous nitrogen and helium were performed to further explore the sensitivity limits of the leakage measurements with these gases.

As discussed previously, leakage measurements were accomplished using either the rms or counts mode. An understanding of the rms levels that were measured for various fluids and at various leakage rates may be gained by examining Fig. 8.

SYM	FLUID	P (PSI)	W (LB/HR)	Q_{LIQ} (CC/HR)	Q_{GAS} (SCC/HR)
LEAK (.004″ × .0014″)					
○	H_2O	100	.33	150	–
△	H_2O	200	.51	230	–
□	H_2O	350	.69	310	–
◇	GN_2	54	.011	–	4,200
▷	GN_2	100	.020	–	7,600
⌬	GN_2	200	.038	–	14,600
⬡	FREON	72	.17	59	15,400
LEAK (.007″ × .0006″)					
►	GN_2	83	.0006	–	230
●	FREON	83	.01	3.4	890
NUPRO METERING VALVE					
✸	H_2O	200	.10	46	–

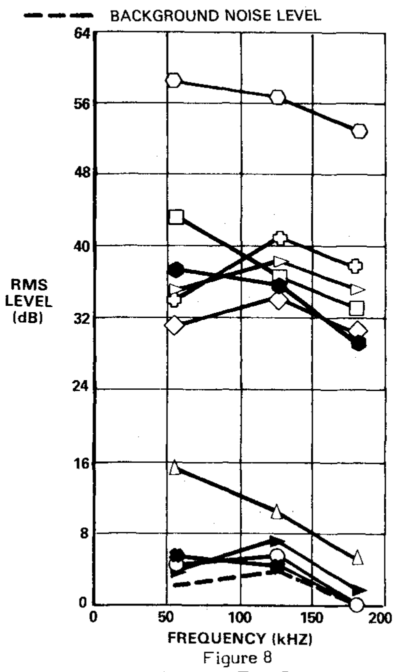

Fig. 8 Leakage test data.

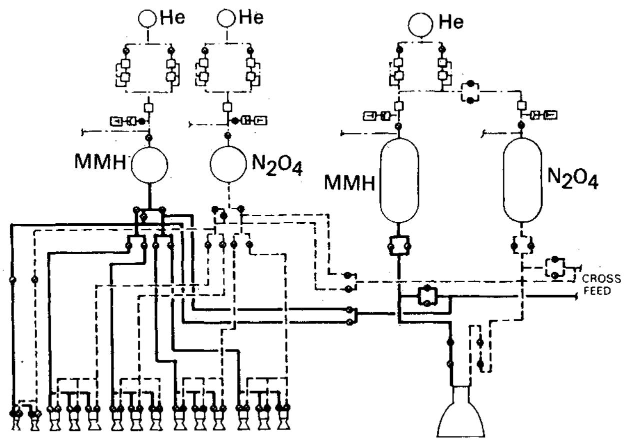

Fig. 9 Space Shuttle auxiliary propulsion system simplified schematic.

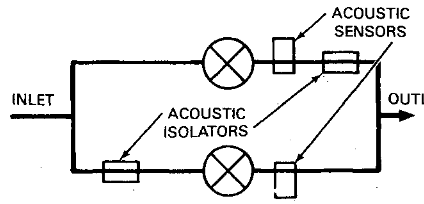

Fig. 10 Schematic of redundant valves with leakage detection components.

Table 2 Counts mode leakage data

Fluid	Pressure drop, psi	Leakage rate, scc/h	No. of times measured	Range of counts, thousands/10 s
Helium	100	2	7	2-40
Helium	100	3	7	20-40
Nitrogen	400	20	5	4-33
Nitrogen	50	6	7	100-286
Helium	200	6	9	21-56

As shown in this figure, the background noise level ranged from about 3 dB at 54 kHz to 4 dB at 126 kHz and was 0 above 180 kHz. The test results show that the liquid freon generated much more noise than the water. In fact, 0.01 lb/h of freon generated almost as much noise as 0.69 lb/h of water. This was expected since the vapor pressure of freon at ambient conditions is less than atmospheric pressure, so that the freon is actually boiling as it comes out of the leakage path. The boiling causes additional acoustic energy to be generated. The results also indicate that for the same mass flow, the freon generated more noise than the gaseous nitrogen. Gaseous nitrogen generates considerably more noise than water for a given displacement under the same tank pressure conditions.

Experience with the acoustic emission leak detection system showed that the counts mode actually has the ability to measure lower leakage rates than the rms mode. One disadvantage with the counts mode, however, is that a certain period is required during which counts are accumulated, whereas the rms mode is essentially an instantaneous measurement. During the experimental program numerous data points were obtained using the counts mode, and the counting period was generally set for 10 s. To demonstrate the ability to measure very low gaseous leakage rates the data in Table 2 were obtained.

All of these data were obtained with a Nupro valve, which was adjusted to achieve various leakage rates, and with the type 302 sensor, which was considered optimum for the water tests. It is believed that the use of the type 300 sensor, which is more sensitive at the higher peak frequencies inherent in gaseous leaks, would have provided even higher readings for the particular leakage rates. It also should be pointed out that the triggering level for the counts mode for the data in Table 2 was set such that the background noise did not accumulate more than 1000 counts. The data in Table 2 show that leakage flows of a magnitude of several scc per hour of either gaseous helium or nitrogen can be detected using the acoustic emission leak detection system.

Leakage Source Identification for Redundant Components

To achieve high reliability in spacecraft liquid rocket propulsion systems these systems frequently employ parallel or series redundant components. To illustrate this point, Fig. 9 shows a simplified propulsion system schematic of the auxiliary propulsion system located in the left pod of the Space Shuttle.

This propulsion system consists of two sets of propellant tanks, three pressurization systems, various tank valves to allow crossfeed between the propellant tanks and to feed the 14 reaction control thrusters and the one orbital maneuvering engine. Both series and parallel redundancy are evident in the arrangement of the pressure regulators, series redundancy is provided in the orbital maneuvering engine shutoff valve, and many tank valves are included to achieve both series and parallel redundancy.

For ground testing of series redundant components there are generally ways of identifying which of two components is leaking. In the case of valves, this is accomplished by alternately opening one or the other of the two series redundant valves and thereby measuring leakage flow through one valve at a time. In the case of series pressure regulators, the differences in set points may be used to identify which of the two regulators is leaking. However, when it comes to identifying which of two parallel redundant components in an all-welded system is leaking, no convenient approach is presently available. The system builder is therefore generally faced with removing both of the candidate leaking components from the system to be able to test them on an individual basis. The acoustic emission leak detection approach makes possible the measurement of which of two parallel redundant components is leaking without disturbing the system and thereby eliminates the need for removing the second component.

Figure 10 schematically shows two parallel redundant components and the acoustic emission leak sensors and isolators required to permit identification of which of the two components is leaking. To permit identification of the leakage source two requirements must be satisfied. One is that the leakage sensor is sensitive enough to measure the particular leakage rate emanating from the leakage source. This test program has demonstrated the feasibility of this approach. The other is that the leakage detection system must be able to distinguish where the acoustic noise from the leakage source is coming from. To accomplish the latter, two sensors and two acoustic isolators are required. As shown in Fig. 10, one acoustic emission sensor is clamped to the downstream side of each component and one acoustic isolator is clamped to the upstream side of either component with the other acoustic isolator being clamped to the downstream side of either sensor. The acoustic isolators thereby assure that each sensor is listening primarily to the leakage noise generated in one component only.

In operation this redundant component leakage identification system can be used to measure the background noise first, prior to the pressurization of the components. The components then can be pressurized and the acoustic emission sensor outputs compared. The sensor with the greater output identifies the leaking component and will therefore permit the removal of only that component from the system. This results in a substantial cost and schedule savings.

Conclusions

A leakage isolation program using an acoustic emission leakage detection approach was performed and the feasibility of this approach for liquid rocket propulsion systems was evaluated. A large number and range of variables were explored, and it was demonstrated that the measurement of leakage rates as low as 0.1 lb/h of water or 3 scc/h of gaseous helium is feasible. The acoustic emission leak detection system approach is nonintrusive to the propulsion feed systems, and therefore does not degrade reliability or operation of the system. The feasibility demonstration of this leak detection approach offers a number of promising applications. These range from automatic leak detection in space to the identification of leakage sources of spacecraft systems during ground checkout and are particularly advantageous for identifying leakage sources in redundant components.

Acknowledgments

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References

[1] Phillips, D.G., Minton, S.J., and Wichmann, H., "Automatic Leak Detection System," AFRPL-TR-81-93, Nov. 1981.

[2] Anglim, D.D., "Space Shuttle AFT Propulsion Subsystem," AIAA Paper 81-1511, July 1981.