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Validation of Valve Leak Quantification with Non-Intrusive Acoustic Emission Technology

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Abstract

In the late 1980s and early 90s several companies tested a range of acoustic devices for monitoring valve leakage during the check valve diagnostic system research performed at the Utah State Water Research Laboratory as part of two separate nuclear industry sponsored initiatives. The acoustic sensor technology and analysis techniques evaluated were found helpful but no progress was made non-intrusively quantifying the leak rate through the valves tested during these programs. Around that same time oil & gas companies in the UK were experimenting with detection and quantification of valve leakage using acoustic emission (AE) technology. The AE sensors and signal processing technology selected for the UK oil & gas effort responded to much higher frequencies compared to the sensors and systems used during the nuclear utility initiative in the U.S. This research led to new products for detection and quantification of valve leakage in oil & gas applications.

Because of minimum leak threshold and accuracy concerns, non-intrusive acoustic valve leak measurement has remained an elusive goal for commercial nuclear power. Various general purpose acoustic tools have been trialed to detect leakage with mixed results due to complications caused by plant and system acoustic characteristics. Several of today’s moderately successful check valve diagnostic systems employ acoustic sensors and can detect the most likely event representing flow cut-off when a check valve disc fully closes but leak rate quantification with any of these systems is not possible. Correlation methods and other AE analysis techniques that have been developed to quantify leakage in steam systems have been generalized as small, medium and large leakage classifications with no clear criteria for these levels.

During the last couple of years nuclear plant engineers responsible for 10CFR50 Appendix J programs have made extensive use of a new acoustic valve leak detection system known as MIDAS Meter®. Appendix J valve testing (also known as Type C testing) requires that sections of nuclear plant piping be isolated by closing a number of valves thereby creating a confined pressure boundary. The isolated piping within the boundary is pressurized with approximately 50 PSI of air and the leak tightness of the boundary is evaluated. When the isolated piping exhibits excess leakage or cannot maintain the test pressure, the valves creating the boundary are evaluated one-by-one to find the culprit leaker. The process of finding and correcting the problem valve can take from hours to several days and may become an outage critical path activity. Appendix J engineers have enjoyed considerable success with their new found ability to quickly and confidently identify the leaking valves with MIDAS Meter® and remove their test programs from critical path.

MIDAS Meter$^{\circledR}$ is a high frequency acoustic emission based system which includes algorithms that convert the acoustic emission signal to leak rate. The basic algorithms were first developed from the field results obtained during the early development work for UK oil & gas operators and refined over the next 20 years. Though not originally validated under a 10CFR50 type QA program, nuclear plants that own MIDAS Meter$^{\circledR}$ have been eager to go beyond simple troubleshooting and use the leak quantification results for nuclear applications including safety-related decision making. In order to support owners and avoid improper application of this very successful new tool, Score Atlanta embarked on an extensive validation program consistent with 10CFR50 requirements. A purpose built leak test flow loop and valve simulator apparatus were constructed in the Atlanta facility and testing began in early 2013. To support Appendix J users the air testing was performed first and completed in July 2013. The water testing followed and should be completed in early 2014. Numerous combinations of leak path, leak path geometry and differential pressure were created and evaluated during the air phase of the program. Pressure was limited to 150 PSI for air testing. The water testing includes pressures up to 1250 PSI and a similar number of varying leak paths and pressure test points. This paper discusses the preliminary results of the test program, including any special limitations required for use of AE-derived valve leak results in nuclear safety related applications. The full results of the test program and guidance for nuclear safety-related use of the technology are expected to be available ahead of the 2014 ASME-NRC Valve Symposium.

Figure 1
MIDAS Meter$^{\circledR}$ Handset and PDA

Background

The historical methods used to test a closed valve for leakage have not changed much over time. Once a valve is installed in the plant or process system there are a few basic leak testing options such as: pressurizing the piping on one side of a closed valve and monitoring the stability of that pressure including what is required to make-up any observed loss, or monitoring changes in the pressure of the test volume over time. Since nuclear plant systems are often complex with a number of valves and other components in the test boundary there is always some question as to whether the pressure may be escaping through a different valve or leak path. Boundary leakage can be difficult to quantify and improving the insitu valve leak rate measurement process has remained an attractive but elusive goal.

In the late 80s and early 90s various nuclear utilities and a handful of vendors evaluated nonintrusive check valve testing methods at the Utah State University Water Research Laboratory. The evaluation included how well the diagnostic systems could track movement of the check valve disc, evaluate internal mechanical noises such as backseat and seat impacts and detect back leakage when the check valve was closed. Several of the check valve diagnostic systems evaluated included some form of acoustic sensor and related data acquisition and several hand-held acoustic instruments were tested by participating utilities.

The Utah State testing proved that acoustic devices could be used to identify the point where the valve disk impacted the seat or backseat and changes in the noise level being recorded were helpful for identifying the absence of flow when the valve closed. All of the sensors used at that time responded to frequencies less than 40 kHz and though flow noise can be detected at these low frequencies small leaks at high differential pressure are generally detected at much higher frequency. No correlation between leakage rate and acoustic measurements was found.

Technology Evolution

At about the same time that nuclear industry groups were looking at check valve diagnostic systems and acoustic testing methods, UK oil & gas operators were investigating sensors and systems to detect leakage through closed valves. BP led one initiative that evaluated sensors and equipment pioneered by Hal Dunegan of Dunegan Research Company (which later became Physical Acoustics). The sensors selected by Dunegan responded to much higher frequencies than those used in the US nuclear research. Commonly known as Acoustic Emission (AE) sensors these sensors respond to frequency events ranging from around 60 kHz to several megahertz. This particular AE-based leak detection technology was used extensively by various Score Group companies for many years and included ongoing refinement of the leak correlation algorithms based on field experience gained in oil & gas facilities worldwide and a limited amount of laboratory testing.

High frequency AE sensors and related technology have long been used for structural fatigue monitoring of pressure vessels, bridges and other steel structures. The normal process involves recording the short duration burst-like events that emanate from the fatigued metal. A trigger level is set and events above a certain threshold are counted and the number of counts used to approximate deterioration of the structure. Leak detection requires that AE sensors be used in a completely different manner.

The turbulence of a fluid or gas leaking through a small opening excites the metal at the leak location and creates additional turbulence in the pipework downstream of the leak. The leak event is not a single burst event but rather a continuous noise that is actually broadband and closely resembling white noise. Depending on the pressure and size of the leak path, the frequency of the noise generated by the leak spans from the audible range which can be detected by human senses, up to several hundred kilohertz which is only detected by sensitive sensors. There are many different sensors that can be used to detect leakage noise and many leak detection products that employ some of these sensors have been commercially available for up to 30 years.

As an initial step in the long term plan to evolve the state-of-the-art in valve leak testing using AE sensors and signal processing technology, Score Atlanta purchased the acoustic emission products business and related intellectual property of Dunegan Engineering Corporation, Inc. (DECI) in 2009. This included a wide range of acoustic sensor designs some of which are only suited for structural fatigue monitoring but also others that are very well suited for detecting the weak broadband signals that emanate from very low level leak sources. As a leading supplier of AE sensors and related products combined with a unique valve diagnostic orientation and knowledgebase, Score Atlanta was afforded a broad base of technology and know-how that provided many options when it came to selecting, further developing and deploying AE technology for through-valve leak testing. When a custom sensor was required for any of a range of experiments, Score Atlanta engineers simply went to the sensor lab and made one that met the required specifications.

The active element of an acoustic emission sensor is a small piece of piezoelectric ceramic that is cut to prescribed dimensions based on desired response characteristics. Because there is a tolerance associated with the cut and some variation in the properties of the piezoceramic element and assembly process, one early challenge was establishing adequate manufacturing repeatability for the sensor. Before this point in time, close tolerance between AE sensors was not a critical requirement. However, for use in systems where the correlations will be developed with one or several systems and field use will involve completely different sets of sensors and systems, the manufacturing tolerances become very critical. Differences in output among sensors would unnecessarily contribute to inaccuracy of the overall process so for any given acoustic input each sensor must produce a repeatable output within a tight band.

Score Atlanta began sensor manufacturing runs in 2009 in order to determine the sensitivities and refine the process. After several runs and consultation with the piezoceramic manufacturer, acceptance parameters were developed for sensor manufacturing and calibration. Score Atlanta, in collaboration with Score Diagnostics, Limited (UK-based sister company) and a subcontracted electronics design house, developed early prototypes of a new AE-based leak detection tool for valves. After a lengthy product development program the first MIDAS Meter® valve leak detection systems were delivered to US nuclear plants in July 2011.

Early Nuclear Plant Experience

MIDAS Meter® was first employed in commercial nuclear power plants as a troubleshooting tool to find leaking valves during Appendix J Type C leak rate testing. Appendix J engineers create an isolated pressure boundary within system piping by closing many valves. The isolated section of process pipework is then pressurized and the isolated section within the boundary is monitored to ensure leakage does not exceed established criteria. Occasionally the isolated section of piping exhibits excessive leakage or does not maintain the test pressure and all boundary valves must then be evaluated. This requires systematically troubleshooting the test volume to identify the leak path(s). This troubleshooting can be as simple as placing a rubber glove over a vent valve outside the test boundary (i.e. if the glove blows up when the vent is opened the leakage is through the associated boundary valve. If not, the next boundary valve is tested in a similar fashion). There is no guarantee that a valve found to be leaking during this test is the only valve leaking or whether the leakage detected is the largest contributor to the failed test. It is a problematic process but it has been an accepted troubleshooting technique for many years.

Figure 2 above is an actual system line-up for an Appendix J leak rate test in a BWR. In prior years this particular 11 valve boundary was a leak problem and many hours were spent finding and working the valves that contributed to leak test failures. MIDAS Meter® quickly identified the leaking control valve, circled in red and the Appendix J testing was completed quickly and had a less significant impact on the outage.

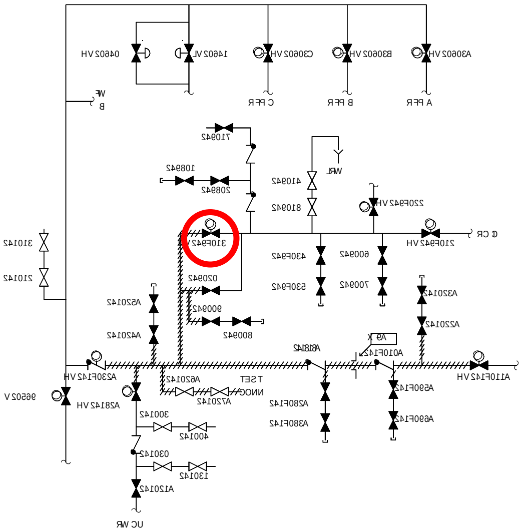


Figure 2
Actual Appendix J Test Boundary at a BWR

There are many similar success stories several of which have been discussed in papers and articles presented at various industry meetings. An engineer at one plant has been nominated for an award based on performance improvements gained through the MIDAS Meter® testing initiative while others claim direct financial savings totaling hundreds of thousands of dollars each time they quickly and definitively identify the correct leaking valve. These Appendix J user testimonials quickly captured the attention of maintenance and engineering colleagues associated with post maintenance local leak rate testing activities.

Within a few short months of the initial systems being delivered inquiries began arriving regarding use of MIDAS Meter® to quantify leakage during post maintenance leak rate testing thereby avoiding traditional time consuming methods. The key questions were related to accuracy and while extensive field data exists all of the parameters necessary to quote a specific range consistent with nuclear requirements were not well documented. In these few cases, the question was asked and proper guidance was received. The growing concern became what if someone does not ask and takes the leak rate results at face value.

Several documents prescribe leak rate testing rules for nuclear power plant valves including the ASME OM Code. ISTC *Inservice Testing of Valves* and specifically ISTC-3600 defines leak rate testing requirements. Containment isolation valves are referred to the owners Appendix J program and tested as previously described. Valves requiring LLRTs other than containment isolation valves are tested per ISTC -3630 (c) and the options include as follows:

> *(1) measuring leakage through a downstream tell-tale connection while maintaining test pressure on one side of the valve*
>
> *(2) measuring the feed rate required to maintain test pressure in the test volume or between two seats of a gate valve, provided the total apparent leakage rate is charged to the valve or valve combination or gate valve seat being tested and the conditions required by subpara. ISTC-3630 (b) are satisfied.*
>
> *(3) determining leakage by measuring pressure decay in the test volume, provided the apparent leakage rate is charged to the valve or valve combination or gate valve seat being tested and the conditions required by subpara. ISTC-3630 (b) are satisfied.*

Unfortunately there is no provision for alternate leak rate measurement methods such as acoustic emission in this part of ISTC. There could be many reasons for this including past industry program experience discussed above and questions regarding potential accuracy or the availability of validated AE methods. It is important to note that options (2) and (3) are likely to produce very conservative results because of the potential for more than one valve to leak during the test.

In order to evaluate accuracy requirements for leak rate testing under ISTC the leak rate acceptance criteria becomes an important variable. ISTC-3630 (e) requires that maximum permissible leak rates for a specific valve or valve combination be established by the owners program. However, in the absence of owner defined acceptance criteria for any particular valve the following leak rates shall be permissible:

> *(1) for water, 0.5D gal/min (12.4d ml/s) or 5 gal/min (325 ml/s), whichever is less at function pressure differential*
>
> *(2) for air, at function pressure differential, 7.5D standard ft^3/day (58d std.cc/min)*
>
> *Where*
> *D=nominal valve size, in.*
> *d=nominal valve size, cm*

The guidance provided in ISTC suggests that the maximum leak rate allowed will be 5 gallons per minute when the test media is water. As a consequence valves with a larger diameter than 10 inches are still restricted to 5 gallons per minute. There is no definition of *function pressure differential*. Recognizing that owner defined limits for plant and system specific valves may be larger or smaller it would be prudent to assume that leak rates from 1 to 4 times the guidance of ISTC would be an appropriate window to evaluate and validate leak rate calculations based on any type of measurement including the AE methods discussed herein. Assuming the smallest valve to be 1 inch and a maximum leak rate of 4 X 5 gallons per minute for larger valves, the range would be .5 to 20 gallons per minute for water.

Similarly, the expected range for air would be .3 to 25 SCFH for a range that covers 1 inch to 20 inch valves. No maximum was provided for air so the larger the valve the larger the allowable leakage. These ranges will become important when evaluating how well MIDAS Meter® will perform for this particular application.

Additional Laboratory Research & Testing

Because much of the early AE data from the oil & gas research was taken from valves in the field, controls were not in place to ensure data quality and as a consequence the resulting accuracy of the original algorithms is not sufficiently documented for valves that require a high level of precision in the leakage measurement such as critical isolation valves in nuclear plant systems. This does not detract from the success of the AE-based testing approach at finding leaking valves as a troubleshooting tool but it has prevented the approach and resulting test data from being used as the sole source of information on whether a safety-related valve may be leaking beyond allowable limits.

Review of the early data (1990's origin) suggested that tighter controls on reference measurements, system conditions, operator practices and analysis techniques could reduce the overall uncertainty of the test approach in general. For example, actual leak rates calculated in the field included uncertainties inherent in the process when extensive sections of pipe are pressurized by a potential leak path and the leak rate calculated from the pressure decay upstream or build-up downstream over time (i.e. similar to the typical plant LLRT testing process as discussed above). Since this method is only as accurate as the calculation of the test volume under pressure, calibrated flow meters and other precision measuring devices could significantly improve the leakage measurement algorithm and reduce uncertainty. The differential pressure across the valves in the field also included uncertainties when pressure transducers were not installed near the valve. Upstream and downstream pressure transducers close to the valve would eliminate much of this uncertainty. Many different technicians were also involved in the original field testing each with their own techniques for application of the equipment. The acoustic couplants and application process were not documented and calibration of the equipment including manufacturing tolerances of sensors was not well controlled. Several of these uncertainties can be reduced by fixing the sensor to the valve and using an acoustic emitter to test the effectiveness of the coupling before each test. Improvement in the overall method, including correlation accuracy is expected to be high when these variables are tightly controlled.

In order to fully develop the algorithms and analysis process for nuclear use, Score Atlanta modified its existing ISO9001 QA program to account for additional nuclear requirements and repeated much of the development related testing and analysis. This required a special purpose built test loop, valve simulator, instrumentation and systems necessary to evaluate all aspects of the process in a tightly controlled setting. The flow loop (see **Figure 3**) was constructed from stainless steel pipe and the pressure driven by 3 large accumulators such that tests on air and water are possible. Pressure transducers were installed upstream and downstream of the valve simulator. Calibrated flow meters were installed downstream of the valve simulator and leak location.

Figure 3
Flow Loop and Instrumentation

The stainless steel valve simulator (see **Figure 4**) was designed such that leaks of the desired sizes and shapes could be precisely controlled. The valve simulator houses a disc similar to a valve disk except with adjustable leak path sizes and shapes. The smallest leak path tested, which falls within the average size range of a human hair was a single 0.0314 mm^2 leak path installed at the seat location on the simulator disc. The leak sizes were increased in increments up to a single leak path of 78.54 mm^2. This was followed by multiple leak paths around the seat circumference using some combination of the leak paths discussed above at up to 8 locations. Combinations of multiple leak paths of smaller sizes were compared to single leak paths of the same area. Various leak path shapes of known area were compared to other leak shapes of the same effective area including concave and convex internal shapes.

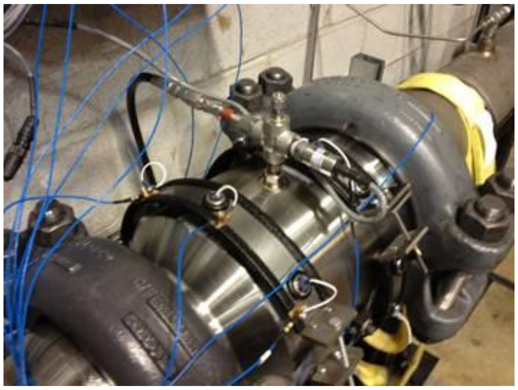


Figure 4
Valve Simulator

Of course the leak rate is a function of the leak path size and the differential pressure that provides the energy to drive the leak. **Figure 5** illustrates the air leak rates achieved with various leak paths up to 150 psig. Each dataset or line represents a single fixed leak path of the area specified and reflects how leak rate increases with differential pressure when the leak path area is fixed. In order to ensure the accuracy of the various flow transducers and the resulting leak rate, several different methods were used to evaluate leak volume. As a sanity check the expected flow through the controlled leak paths was calculated and charts developed to compare the expected flows (leakage) to the measured values. An additional check during the water tests involved capturing and measuring the volume discharged downstream of the flow meters in graduated beakers.

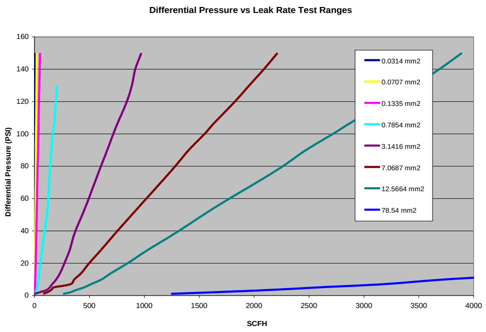


Figure 5
Differential Pressure vs Leak Rate

Based on the allowable leak rates discussed in ISTC 3630 (e) (2) and the 25 SCFH maximum range for air discussed above, the leak range requiring validation is limited to the far left of this chart. That does not mean the leak calculations cannot be used for large leaks, especially in nonsafety-related applications but use beyond the limit where the LLRT is considered “failed” does not have safety-related implications. The applicable range of calculated leak rates for air is represented by the area within the box in **Figure 6**.

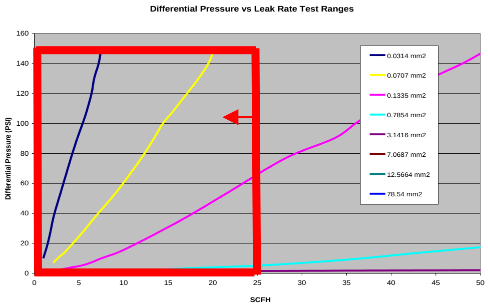


Figure 6
Range of Interest per ISTC Leak Limits

Since it is impractical to have a number of technicians hold MIDAS Meter® handsets around the simulator during the various tests, a special configuration was manufactured whereby the sensor could be separated from the electronics and mounted directly to the valve. A sensor band was fabricated to hold up to 8 sensors properly attached and acoustically coupled around the circumference of the simulator. The MIDAS Meter® electronics were housed in special enclosures and mounted near the valve simulator. This configuration was calibrated and verified to be identical to a normally assembled MIDAS Meter® handset. A high frequency signal generator and acoustic emitters were used to insert an artificial leak noise into the valve simulator and pipe work before and after each test run to ensure each sensor was properly coupled. The output of the 8 MIDAS Meter® units was routed to a multichannel data acquisition system and recorded along with the output of the various pressure transducers and flow meters.

All instruments such as the flow meters, pressure transducers and all AE related equipment were calibrated under the Score Atlanta QA program or by vendors that supply calibration services under a 10CFR50 acceptable program and are approved under the Score Atlanta program.

The MIDAS Meter® onboard data acquisition computer records the AE sensor signal at 1.2 MHz, processes the spectral data and displays or transmits the results on a dB scale. The user does not interact with the raw AE data. However, because this is an internal automated Midas Meter® process it was also important to capture raw AE signals in a parallel high speed recording system in order to visualize, analyze and further confirm what MIDAS Meter® is accomplishing internally. A second sensor band was installed on the simulator with similar AE sensors and routed to the high speed data acquisition and recording system and all of the MIDAS Meter® tests were monitored in parallel. The data was stored and processed at the same time and spectral graphs were created for the high speed data. In effect, the high speed system provided a second independent verification of MIDAS Meter® results and was helpful when questions emerged surrounding an individual or group of data points.

Test Program Results

The acoustic emission analysis challenge is to extract meaningful content from the noise signal generated by the leak and detected by the AE sensor. There are several ways to do this including simple measurement of the time domain sensor signal itself. At a very basic level it is clear that the AE sensor output increases with broadband leakage noise as shown in **Figure 7**. In this example the very thin center line shown in red is the raw AE sensor output recorded by the high speed system when the simulator was leak tight. In this case the MIDAS Meter® would read, calculate and transmit a signal at 20dB which is derived from the amplitude and frequency content of this low level (background) noise signal.

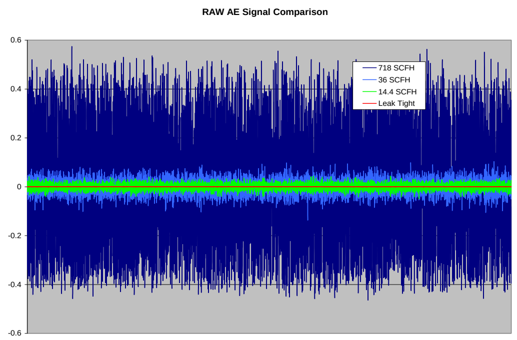


Figure 7
Raw Acoustic Sensor Signals Change as Leak Size Increases

The green data set which looks like an increase in noise level is simply that, an increase in noise level caused by a leak of 14.4 standard cubic feet per hour (SCFH). The MIDAS Meter® reading at this level has jumped to 40 dB illustrating sensitivity to this low level leak. The next leakage level shown in light blue is 36 SCFH and the MIDAS Meter® reading has increased to 47 dB which is well above the maximum target leak rate of 25 SCFH discussed above. The largest dark blue data set is 718 SCFH and 66 dB. All of these leak tests were performed at 100 psi and the only change was the size of the leak path. An analysis tool typically employed when evaluating noise signals such as above is to calculate the RMS value of the series. However, MIDAS Meter® takes it one more level.

Another acoustic emission analysis technique involves converting the time domain signal to frequency domain using Fourier analysis tools to evaluate the spectral content and density of the signal components. This approach requires some understanding of the target frequency ranges of the measurement as the sample rate of the data acquisition system must be twice the top-end of the frequency range of interest. As discussed earlier valve leakage frequencies are broadband extending from audible to several hundred kilohertz which requires a sensor that spans the desired range with as flat a response as possible. Many of the sensors used in early nuclear industry research efforts were 40 kHz or 60 kHz resonant sensors that have a pronounced peak output at those specific frequencies and quickly drop off as the signal leaves the resonant peak. Most AE sensors have some natural resonant frequency as well but generally at much higher frequency. Keep in mind that leak signals are broadband spanning from the audible range to several hundred kilohertz. A low frequency sensor of 60 kHz or less misses much of this signal.

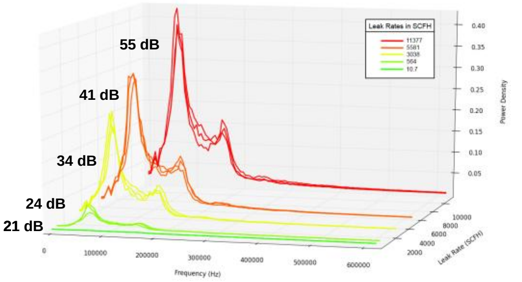
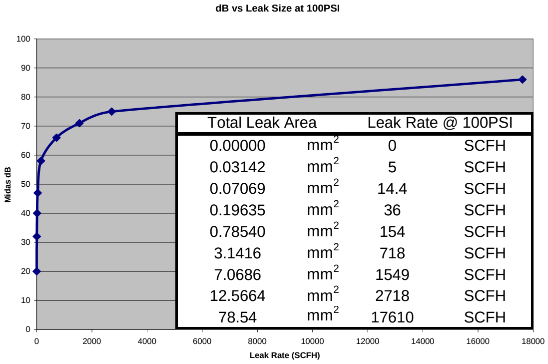


Figure 8
AE Spectral Plots Reflecting Growing Leak Rate at Constant Pressure

Spectral plots of the frequency characteristics of a typical set of leak data are shown in **Figure 8**. Each spectral plot represents a different leak area and leak rate at a common differential pressure. The frequency content of the leak signal tends to shift up and down with differential pressure and better predictability is achieved by understanding how this occurs. The numerical values provided at the left are representative MIDAS Meter® dB values similar to what the user sees in the field. A Midas Meter® user does not interact with the spectral data during field testing. Clearly, it is much easier for the user in the field to respond to the numerical dB values versus interpreting spectral charts similar to those shown in **Figure 8.**

In the field, system operating pressures and test pressures are typically fixed by plant operating characteristics and the variable is the changing size of the leak path over time. This research highlighted that a strong correlation exists between changing leak size and AE measurements when the differential pressure is known or fixed as shown in **Figure 9**. The shape is logarithmic consistent with the dB scale used to represent the changing acoustic level.



Total Leak Area		Leak Rate @ 100PSI	
0.00000	mm^2	0	SCFH
0.03142	mm^2	5	SCFH
0.07069	mm^2	14.4	SCFH
0.19635	mm^2	36	SCFH
0.78540	mm^2	154	SCFH
3.1416	mm^2	718	SCFH
7.0686	mm^2	1549	SCFH
12.5664	mm^2	2718	SCFH
78.54	mm^2	17610	SCFH

Figure 9
Relationship between MIDAS Meter AE dB Readings as Leak Size Grows

Unfortunately, we cannot assume a single leak path in the field environment. More likely the valve will leak at several locations around the seat and prior to this research it was not clear how multiple leak paths would affect the AE measurements. Therefore, the valve simulator was designed such that multiple controlled leak paths could be created and evaluated. **Figure 10** below includes a sample of the multiple leak path and alternate leak path shape data on top of the single leak path data. Except for minor variations as would be expected, the logarithmic curve fit and R^2 values are essentially the same for **Figures 9 & 10** data sets.

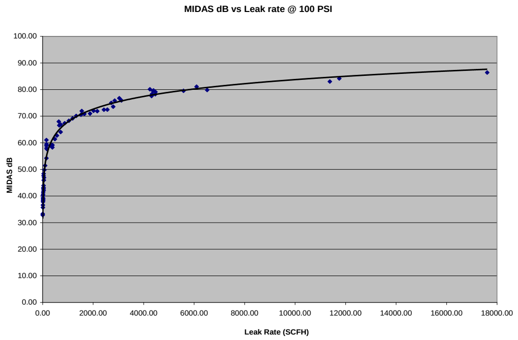


Figure 10
Combination Single, Multiple and Mixed Leak Path Shape data at a Common Pressure

Algorithm Refinement and Accuracy

First and foremost MIDAS Meter® is not a flow meter. It could be in certain instances but a hand held instrument designed to test a wide range of valve sizes that operate in a wide range of pressurized systems faces unique challenges. Mechanical flow meters for example require that the system process medium be routed through the section of the meter used to mechanically respond to the flow which is not possible for a nonintrusive field instrument such as MIDAS Meter®. Pressure drop based flow meters require precise knowledge of the pressure, require a controlled orifice and there are almost as many flow ranges as there are conceivable flow rates with each calibrated to be most accurate across a specific range. **Figure 11** below reflects the MIDAS Meter® readings as differential pressure is increased across a leak path of known size. The linear relationship suggests that a calibration algorithm or correlation would convert this AE response signal into a useful flow measurement parameter for this particular low level leak size.

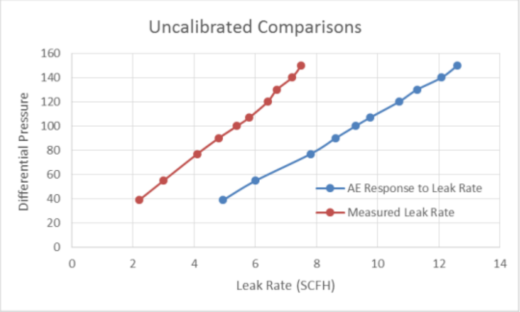


Figure 11
Comparison of Pressure Transducer and Uncalibrated AE Response

The calibration correction needed to move the AE response to the measured response is not exactly the same for a different leak path size. The relationship is complicated by the change in the leak path size and shape and is similar to inaccuracies induced in the orifice-based flow meters discussed above when the orifice size is changed.

Figure 12 identifies how the measured leak rate and AE response shifts farther to the right when the leak path size is increased. This is the target condition or change that must be detected in the field with AE-based measurements. The only difference between measured leak rates 1, 2 and 3 is the size of the leak path. Seventy-two (72) different leak configurations of varying leak path size, shape and numbers were tested during the air phase of this program. The challenge is to find the algorithm that moves the AE response closest to the measured leak rates for all leak path sizes and combinations.

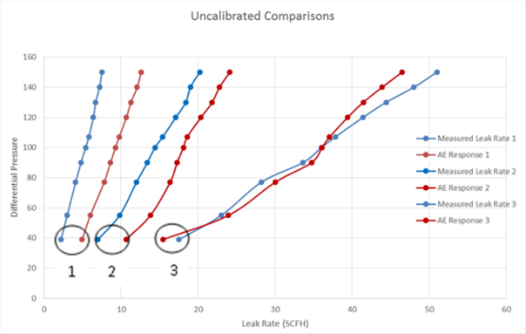


Figure 12
Comparison of Pressure Transducer and AE Response as Leak Size Increases

One very important consideration that drives the best fit algorithm and resulting accuracy is the desired range of the leakage measurement. Leaks were generated and measured from less than 2 SCFH to as large as 18,000 SCFH during the air phase of this program. Five (5) different calibrated flow meters were required to measure the actual leakage across the entire range. A user in the field will only have one MIDAS Meter® when facing this potential range.

As suggested in **Figure 12** above and shown in **Figure 5** the larger the leak path size the shallower the relationship between differential pressure and leak rate at the pressures tested due to the logarithmic nature of ASL. This complicates analysis and algorithm development since the correlation between leak size and differential pressure changes as the leak size increases. To negate this problem the analysis must assume a fixed differential pressure and changing leak path size. To construct this type of chart the individual data points at each pressure must be extracted and new datasets assembled such as shown in **Figures 9 & 10** above. As a consequence the broader the desired range of applicability the larger the potential error. Considering these and other analysis complications the range of applicability for nuclear validation shall be consistent with the guidance extracted from ISTC. The field accuracy of the model shall be validated up to 25 SCFH (approximately 12 liters per minute) for air and 20 gallons per minute for water. These are minimum targets and use of the system and model beyond these ranges is likely as further analyses are completed.

Based on these targets **Figure 13** was developed to chart and evaluate a model specifically for the ISTC range. This chart is only applicable for air and a similar approach shall be used for water up to 1250 PSI. The minimum differential pressure for the air model shall be 39 PSI since pressures below 39 PSI create a different relationship for some leak sizes. It is important to note that the results shown below are from an algorithm that simply converts the MIDAS Meter® dB reading to leak rate with no consideration of differential pressure as long as the pressure is between 39 PSI and 150 PSI. The preliminary prediction intervals at these conditions are X(2.0) for the upper limit and X(.50) for the lower limit in order to ensure 95% confidence in the predicted results. Improvement over these results is expected as provision for differential pressure is added.

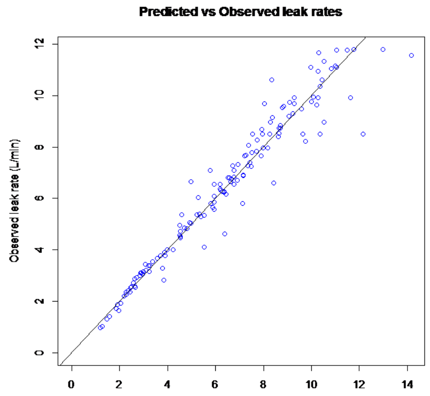


Figure 13
Limited Range Predictions for LLRT Applications

Implementation and Accuracy Considerations

Many steps were taken to ensure the flow loop testing was as close to real world test conditions as possible albeit there was no flow noise or other vibrations that would work against the sensor and potentially overwhelm the leak signals. There was no heat as would be present during nuclear plant operation and the valve was a simulator with fixed wall thickness. In real life implementation there will be interfering vibrations, heat and a range of valve dimensions encountered. Sensor design features and filtering have been employed to minimize the effects of plant noise and special wave guides are provided to keep heat away from the sensor. Provided the hot water is not flashing to steam at the leak location the water algorithm is not expected to change due to temperature. Flashing introduces a different acoustic behavior and the algorithm has not been evaluated for this condition.

The leak simulator included features in the design that allowed the distances between the leak location and the outer valve body wall to be varied thereby changing the amount of steel between the 2 locations. The purpose of this design feature was to simulate attenuation of the AE signal due to different valve wall thicknesses.

The differential pressure sensors used during the test program provide an exact measurement of differential pressure across the valve and are a key component in the accuracy of the algorithm. In the field environment it may not always be possible to know the differential pressure across the valve with such precision which has a direct effect on the accuracy of the calculated results.

Sophisticated high frequency acoustic emitters were used to insert a simulated leakage noise into the pipe in order to ensure proper acoustic coupling of the MIDAS Meter® sensors before each test. These devices will not likely be used in the field so it is imperative that the user is trained on how to achieve a proper coupling of the sensor to the pipe or valve. This should be controlled by the field test procedure.

The preliminary prediction intervals for 95% confidence mean that the calculated results must be multiplied by 2 to establish the worst case leak rate and by .5 to establish the minimum leak rate. Exact differential pressure is not important as long as it is verified to fall between 39 PSI and 150 PSI. This may seem like a large error compared to typical flow and pressure instruments but is quite remarkable considering the application. And, a large error on a very small leak is still a very small leak. It is also likely that this measurement and prediction interval produces better results than per ISTC -3630 (c) options (2) and (3) when the entire measured leakage must be assigned to one valve. Even better accuracy may be obtained when a differential pressure component is added.

Conclusions

Nuclear plant users discuss large financial savings associated with MIDAS Meter® and Appendix J engineers in particular describe the benefits associated with knowing exactly and immediately which valve or valves are leaking in their test line-up or boundary. As a direct result of their new MIDAS Meter® program an engineer at one U.S. nuclear power plant has been nominated for a company award related to plant performance improvements attributed to deployment of this technology.

The process of troubleshooting leak boundaries as part of Appendix J testing does not necessarily require a calculated leak rate through each valve since the leak rate is already quantified by the approved plant test equipment. However, the sensitivity of the AE signal identifies not only which valve may be leaking but whether there are several leakers and which valves are leaking the most. All of this is accomplished without the leak quantification capability of the technology.

This research also demonstrates that a strong correlation exists between acoustic emission and the through valve leak rate. The leakage noise is broadband and many different sensors can be used to measure this noise. Sensors that operate at lower frequencies (</=60 kHz) suffer interference from other plant and process noises such as flow noise, pumps and other rotating equipment. This noise often overwhelms the low level leakage signal in these frequency ranges. Conversely, higher frequency AE sensors and filtering neutralizes the effects of plant noise. The high frequency spectral analysis and signal processing helped set up the correct filters and frequency window for each sensor thereby protecting the signals from pollution by plant noise. Correlation algorithms are as a consequence, sensor and system specific. In effect, the algorithms developed for the AE sensors employed by MIDAS Meter® do not provide the same correlation when used with any other sensor. Filtering and sensor output amplification levels also complicate use of MIDAS Meter® algorithms with any other sensor.

At the time of this writing, approximately 54 gigabytes of test data contained in 90,000 data files were still being sorted and analyzed. Analysis of the air data is still underway and water testing was approximately 60% complete. At the conclusion of the program new algorithms will be implemented in the MIDAS Meter® leak correlation software. It is important to note that the existing software does not yet contain these new models. The software that implements the new models must go through a software verification and validation process to ensure the model is implemented correctly. At that time, MIDAS Meter® will be appropriately validated for nuclear safety-related use. In the weeks leading up to the valve symposium eligible MIDAS Meter owners will begin receiving software upgrades that implement the new leak calculation models. The new models for air will be released first followed shortly after by new water models. After the water models are completed a single software V&V test program will begin that leads to the new formally controlled software revision. These new models and software upgrades do not require any type of change to existing MIDAS Meter hardware.

After many years of research, trial and error, it is clear from these results and more sophisticated spectral analysis that the elusive goal of non-intrusive through-valve leakage measurement is well within our grasp.

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Disclaimer

This paper discusses the preliminary results of an extensive development and validation program that is not complete at the time of this writing. Conclusions, recommendations field procedures and software programs that implement the methods described herein may change over time.