Acoustic Emission data analysis to evaluate damage mechanisms in pipeline carbon steels

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Abstract
The Acoustic Emission (AE) technique allows detection of damage as it proceeds in mechanical components, monitoring the initiation and propagation of the defects, submitted to variable stresses and aggressive environmental exposure. To monitor significant sections of large diameter gas transmission pipes a specific study was carried out aimed at investigating AE features and their applicability. Steels pipe widely used in the Oil&Gas industry for conventional and modern gas pipelines were selected. On these materials fracture mechanics tests were carried out to monitor the crack initiation and propagation. Different fracture modes were investigated, that is ductile, brittle and stress corrosion fracture mechanisms, in order to ascertain the capability of AE system to identify crack growth as well as discriminate the different mechanisms. AE data were submitted to a post analysis which revealed that acoustic emission energy is a suitable parameter to discriminate the failure mechanisms.

Keywords: Acoustic Emission, AE energy, pipe steels, monitoring, fracture mechanics, crack growth, stress corrosion cracking

1. Introduction
Structural health monitoring (SHM) is required to improve the safety of critical structures used after a long service life subjected to severe loads as well as to aggressive environmental conditions. The Acoustic Emission (AE) technique is generally applied concerning the non-destructive inspection of structures used with extended operating life. In fact, components that include mechanical discontinuities could develop stresses above the yield limit as a result of stress concentration. In this situation, the stable propagation of defects or discontinuities becomes active as an acoustic emission signal source. The advantage offered by AE technique, compared to other NDT methods, is related to its capability to detect the elastic waves generated by crack initiation and the growth is revealed by acoustic emission bursts. This signal can be detected by a remote measuring system and therefore allows continuous monitoring of damage progress. This gives a cost saving of maintenance since human intervention is reduced.
A complexity of AE technique is related to selective identification of acoustic signals and the separation from surrounding noise. This added complexity requires a full description of both the burst physical characteristics and the material behaviour by which the AE burst has been generated. The features of AE signal detected by the sensor can be identified by “Conventional Parameters” or by “Other Parameters” related to the features of the AE burst and pure “Frequency Parameters” [1, 2] Anyway, the main aim is to identify the fracture mechanisms and to distinguish the fracture emission from noise.
Identifying electrical signals by conventional parameters means to determine the parameters such as: Hits, Counts, Amplitude, Rise Time, Duration and Energy of AE signal detected by the sensor. Other parameters are related to other physical characteristics of the burst such as: “Average Frequency”, “Initial Frequency”, “Reverberation frequency”, “RA” value parameter evaluated by “Rise time divided” by “Amplitude”. The improved AE system can storage all detected AE bursts after their digitalization, allowing easy and quick evaluation of “Frequency Parameters” restoring and analysing a single AE waveform [3].
Frequency-domain features seem to discriminate more easily the AE source mechanisms. In this case the usefully parameters for AE analysis are: “Frequency Centroid” which results from a sum of the magnitude times frequency divided by a sum of magnitude and “Peak Frequency”. This
last term concerns the frequency feature reported in kilohertz. It is defined as the point in the power spectrum at which the peak magnitude is observed [4].

To establish relationships between AE signals and damage, the acoustic parameters (classic-based, other-based and frequency-based), are usually evaluated cumulatively. Moreover an interesting tendency is the statistical evolution. This approach allows determination of the probability than an AE signal, or better a selected specific AE parameter, can be associated to the damage phenomenon. In any case conventional/classic parameters have a good capacity to reveal fracture phenomena.

Materials tested are API 5L grade X65, X80 and X100, which are used to manufacture large diameter pipes for gas transport. Quasi-Static and Stress Corrosion Cracking tests have been carried out. The relationship between the Acoustic Emission Energy (AEE) parameter and the damage occurring during fracture mechanics tests has been investigated. The results obtained provide confidence to use the acoustic emission technique for Pipeline Health Integrity Monitoring (PHIM).

2. Experimental activities

2.1 Materials and specimens

For the investigation, 3 micro-alloyed steels were selected: API 5L grades X65, X80 and L690M or X100M, according to ISO3183. Micro-alloyed steel plates are obtained by means of a suitable combination of chemical composition and thermo-mechanical treatment in order to obtain the strength, toughness and weldability requirements. From the plates, the pipes are manufactured by the UOE\(^1\) process. The differences between the selected steels are presented in Table 1:

\[\text{Table 1. Material features}\]

<table>
<thead>
<tr>
<th>Steel API 5L grade</th>
<th>Yield strength (MPa)</th>
<th>Microstructural phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade X65</td>
<td>450 ÷ 600</td>
<td>polygonal ferrite and pearlite</td>
</tr>
<tr>
<td>Grade X80</td>
<td>555 ÷ 705</td>
<td>acicular ferrite low content of both polygonal ferrite and martensite</td>
</tr>
<tr>
<td>Grade X100</td>
<td>690 ÷ 840</td>
<td>acicular ferrite, bainite, low content of martensite</td>
</tr>
</tbody>
</table>

API 5L grade X65 represents a conventional choice in manufacturing pipelines. In fact, most of the gas network line over the world is still designed by X65 steel grade. New generations of gas transmission pipelines are currently designed by using X80, while X100 steel can be a good candidate for future gas pipelines operated at high pressure.

In order to investigate AE activity generated by different cracking mechanisms 40 fracture mechanic specimens have been machined, both to be submitted to quasi-static tests and to stress cracking corrosion tests. All tests were prepared and carried out according to ASTM standard\([5]\), Single Edge Bend (SE(B)) and Compact Tension (CT) specimens were extracted and machined from the wall of a large diameter pipe used for high pressure gas line transport. All CT and SEB samples were fatigue pre-cracked before mechanical tests.

2.2 Quasi-Static tests

A first step of the experimental activity was oriented to short term tests. Ductile behaviour is the typical fracture mechanism of these steels at room temperature (R.T.). Instead a brittle fracture

\(^1\) UOE - The pipes are manufactured from plate by mechanical processes: the first step is to bend the plate in a U shape, shape O is made by longitudinal welding and the final diameter internal size is reached by hydraulic expansion E.
mechanism was activated during the tests, until complete crack opening, at cryogenic temperatures up to -70°C. Moreover choosing 3 crack opening rates equal to: \( V_1 = 0.04 \), \( V_2 = 0.01 \) and \( V_3 = 0.002 \) mm/sec were selected.

Figure 1 and the Figure 2 show the images of SE(B) and CT specimens during the tests. The bending and tensile tests were carried out by a servo-mechanical testing machine. This system was selected, respect to a servo-hydraulic machine, because the actuator, which applies load to the specimen under test, is much less noisy compared to the high level noise generated by the dither frequency of the hydraulic servo valve used to preserve the cleaning of the feedback wire.

Figure 1. SEB specimen under three point bending test with clip gauge (mechanical transducer) to measure crack-mouth opening displacement and AE sensor with resonance frequency equal to 90 kHz.

Figure 2. CT specimen under tensile test with 2 AE sensors with resonance frequency equal to 90 and 150 kHz.

2.3 Stress Corrosion Cracking tests

The second step of the experimental activity was oriented to long term tests. In order to activate the crack corrosion phenomenon each CT specimen was preloaded by a wedge inserted in the crack mouth, as shown in Figure 3. The thickness ‘t’ of wedges were designed in order to apply 5 different start values of stress intensity factor \( K_I \) identified as: E(\( t=3.07\)mm), F(\( t=2.9\)mm), G(\( t=2.8\)mm), H(\( t=2.74\)mm), I(\( t=2.67\)mm). The range of \( K_I \) applied was from 99 to 40 MPa√m. The specimens were immersed in saline solution applying cathodic protection and the environmental exposure was continued for 1300 hours. Afterwards, specimens were dismounted, fully opened and submitted to fracture analysis.

Figure 3. CT specimen after corrosion test. In evidence the wedge at the mouth notch and AE sensors.
2.4 Acoustic Emission apparatus

Acoustic Emission apparatus (Vigilant) was manufactured by Ultra Electronics (UK) and was designed by piezoelectric sensor connected to preamplifier device with 40 dB gain value. The Data Acquisition Unit (DAU) consists of 24 acoustic and 12 non-acoustic channels. Data processing is performed in real-time as the structural events occur. This is achieved through Digital Signal Processing (DSP) technology which allows the sensor signals to be evaluated rapidly. Advanced algorithms provide intelligent filtering which substantially reduces data storage requirements. This approach offers significant benefits over traditional systems which employ minimal processing and record large datasets for offline analysis.

The database is downloadable from the Vigilant to the PC using Ethernet port. The database is stored in ASCII characters, so the data can be imported easily to the spreadsheet. Each valid hit, or rather when the amplitude is over the threshold level, is analysed in real time and the derived conventional parameters are stored into a single record. The data record has the following field structure:

- Date and time - ID arrays, ID sensors, Delta time, Amplitude, Pulse Rise time, Pulse Duration, Average signal level, Cluster threshold and Non AE parameters.

The data, available by the DAU, makes the Vigilant an advanced system, useful both for AE laboratory analysis and for long time Structural Health Monitoring (SHM) apparatus.

To investigate the effectiveness of AE sensors, two different resonance frequencies were selected: \( f = 90 \text{ kHz} \) and \( f = 150 \text{ kHz} \). AE activity of CT specimens was monitored simultaneously by two sensors, while SE(B) specimens were tested using just one sensor with resonance frequency \( f = 90 \text{ kHz} \). The AE sensor with a lower resonance frequency \( f = 90 \text{ kHz} \), respect to the higher value \( f = 150 \text{ kHz} \), allows to detect more favourable acoustic waves generated from a defect localised at long distance. The inter-distance and the positioning of the sensors are fundamental to detect all acoustic signals, which are generated by defects on the pipeline at a distance \( D \) from the sensors. In fact, it is well known the attenuation of elastic waves is quantitatively represented by the parameter \( Q \) calculated from the relationship [4]:

\[
Q = \frac{2\pi E}{\Delta E}
\]  

(1)

A larger \( Q \) value means lower attenuation. \( Q \) is larger than 1000 for typical metals. When AE waves propagate for a distance \( D \), the amplitude \( U(f) \) of frequency components \( f \) attenuates from \( U_0 \) to \( U(f) \) or rather, to the position of the sensor. Then, the wave amplitude which hit the sensor is described by:

\[
U(f) = U_0 \exp\left(-\frac{\pi f D}{\nu Q}\right)
\]

(2)

Where: \( f = \text{frequency (90 or 150 kHz)} \), \( \nu = \text{wave speed} = 3000 \text{ m/sec} \), \( Q = 1000 \), and the distance \( D \) is taken equal to the unit: \( D = 1 \text{ meter} \). Using PZT sensor with resonance frequency equal to \( f = 90 \text{ kHz} \), the AE wave results attenuated, from the source to the sensor, equal to:

\[
\frac{U(f)}{U_0} = -7dB/m
\]

(3)

For AE sensor of resonance frequency equal to \( f = 150 \text{ kHz} \), the attenuation is higher, equal to:
\[
\frac{U(f)}{U_0} = -11.7 \text{dB/m} \quad (4)
\]

Before each test, AE chain hardware and the data acquisition was calibrated by an artificial AE source: “Hsu-Nielsen source”. This is a procedure according to ASTM to break pencil leads.

In the following sections, test results and discussion are given, focusing only on quasi-static tests of the AE data collected during SE(B) tests, as CT specimens was tested at the beginning of the experimental activity to define the set-up of the tests system.

3. Results

3.1 Quasi-Static Tests

3.1.1 Effect of resonance frequency

The most significant difference in term of acquired hits, was found during the tensile tests on X65 CT specimens carried out at room temperature (RT), and at higher crack opening rate: \( V_1 = 0.04 \) mm/sec, Figure 4 and Figure 5. In particular, for the X65A specimen, total hits acquired from the PZT sensors, \( f = 90 \) kHz and \( f = 150 \) kHz, were equal to 486 and 126 hits respectively. This effect was confirmed for all specimens and steel tested. This difference is also attributed to the strict band-width of the pre-amplifier connected to the PZT sensor.

Figure 4. X65A. AE hits recorded during CT tests carried out at room temperature (R.T.) (\( f = 90 \)kHz).

Figure 5. X65A. AE hits recorded during CT tests carried out at room temperature (R.T.) (\( f = 150 \)kHz).

3.1.2 Effect of crack opening rate and steel grade/microstructure

The Acoustic Emission activity, recorded during tensile tests carried out at room temperature of CT specimens, is reported in term of total hits and summarised in the histogram of Figure 6.

A greater number of hits was recorded during the tensile test of CT X65A, carried out set-upping the higher crack opening rate \( V=0.04 \) mm/sec. The same trend was found for X80 steel grade.
The X100 grade showed, only for rate A or rather V = 0.04mm/sec, a lower acoustic emission activity respect to the other lower steel grade. Anyway, for rate B or rather V=0.01 mm/sec, the total number of hits were similar for all three considered steels.

SE(B) specimens were tested just at the bending rate V = 0.01mm/sec as the higher value, selected during the set-up of CT specimens, was considered less representative of damage evolution in service. Besides the reproducibility of the tests, CT vs SE(B), was confirmed by the same trend of AE activity as verified for rate B, Figure 6 and Figure 7.

Also for SE(B) tests, the acoustic emission was found higher for X65 steel Figure 7. This result further confirms the good reproducibility of the AE measures.

3.2 Stress Corrosion Cracking Tests

The approach was to test each steel grade by 2 CT specimens pre-loaded with the same higher wedge thick equal to t = 3.07mm, which corresponds, for initial crack length a ~ 30mm, the stress intensity factor KI ~ 130MPa√m. In this way, at the end of corrosion exposure time, the comparison of the AE results, got from these specimens carried out in the same test conditions, was performed. At the end of corrosion tests, CT specimens were opened by a testing machine recording the load value to pull-out the wedge from the mouth notch. Then the specimens were opened...

\[2\text{ In the Figure 7 Total Hits axis is magnified.}\]
fully opened in liquid nitrogen. Once the specimens were opened any optical observations were carried out to evaluate the total crack length.

The stress intensity factors found were: $K_{ISCC} = 94$ and 105 MPa√m, $K_{ISCC} = 129$ and 89 MPa√m, $K_{ISCC} = 129$ and 128 MPa√m for X65, X80 and X100 steel grade respectively. The most interesting situation was found for X80 steel where a difference of $K_{ISCC} = 40$ MPa was found for the CT specimens tested with the same nominal initial stress condition. AE data collected during the corrosive cracking tests, detailed in terms of cumulative counts, are reported in Figure 8, Figure 9 and Figure 10, for X65, X80 and X100 CT specimens respectively.

The activity of acoustic emission recorded during the stress corrosion cracking was found to be significant. In fact, cumulative counts recorded from all CT specimens were found to be over $10^5$ counts. Most of counts were ascribed to the noise generated by the protective cathodic voltage as the amplitude threshold was selected equal to 50dB, i.e. selected intentionally low to collect all AE data. AE trends of some specimens, X65D, X65H, X80G, X100E and X100G were different with respect to all others. In fact, considering the lower/common trend only ascribed to the noise, these differences shall be ascribed to the damage.

Figure 8. X65 Steel grade. CT Specimen X65D and X65H with higher counts shown during no stop recording during stress cracking corrosion (SCC) tests.

Figure 9. X80 Steel grade. CT Specimen X80G with significant higher AE activity in SCC tests.

Figure 10. X100 Steel grade. CT Specimen X100G with significant higher AE activity in SCC tests.

4. Discussion

Further data analysis was performed in order to initially evaluate how and when acoustic emission is able to reveal the damage evolution in the steel structures submitted to stress, as well as to the aggressive environment. A tailored software, developed by CSM in MS-Access, was used to import the data sets into a database appropriate for quick filtering, querying and data analysis.
4.1 Quasi-static tests

For the specimen X65 the damage is characterized by a large extension. Typical behaviour of AE data is represented by X65B SEB test in Figure 11. The plot reports load vs clip gauge recorded during all test duration and the correspondent AE hits activity. The unload steps were programmed for further crack length evaluation. The red arrow point shows a quick drop of load. This effect was generated by the brittle crack initiation and is known as a “pop-in”. Highest AE events connected to the pop-in come after AE events with lower amplitude of about 80dB. In fact, it was detected, in real time, both by the pop-in in the graph of Figure 11 and also by the ear.

![Figure 11. X65B Load vs clip-gauge opening mouth and acoustic emission hits (total hits recorded 449, A_{threshold} ≥50dB).](image)

This damage is ascribed to the initiation of the separation. This defect is traceable by a brittle fracture localised at the middle thickness of the specimen, with the propagation perpendicular to the main crack path surface. The separation is indicated by the yellow arrows in the specimen fracture surfaces of Figure 12. The analysis of the fracture morphology reveals also the presence of ductile crack propagation. These cracks are characterised by the path parallel to the main crack surface and are surrounded by red dotted circle in the Figure 12. This complex surface fracture aspect, with the presence of damage generated by brittle and ductile fracture mechanisms as described for the specimen X65 B, was found for all specimens machined from all 3 pipe steels: Figure 13 and Figure 14. These effects are ascribed to the hot rolled and accelerated quenching of the manufacturing process of the original plates. To classify the type of failure from the AE reference can be made to suitable literature like ASTM Standard [6]. Moreover another ASTM Standard [7] enlarges this concept strictly to the acoustic emission event parameter considering the analysis of the burst as Classic Parameters like: “energy per event, average emission count per hit, or average amplitude per hit”.

![Figure 12. X65B specimens: optical image of the fracture surfaces.](image)

![Figure 13. X80E specimens: optical image of the fracture surfaces.](image)

![Figure 14. X100D specimens: optical image of fracture surfaces.](image)
Lloyds Register [8] gives the fundamental of the acoustic emission effect associated to the damage mechanisms as fatigue, stress corrosion cracking related to the brittle and ductile fracture mechanism. Nevertheless these mechanisms are related to the hits/counts acoustic emission parameter.

Figure 15. X65B. Frequency distribution evaluated for hit amplitude class of 10dB.

Based on the above references it was decided to plot the data collected during the tests were elaborated in term of frequency distribution of hits. The plot of Figure 15 shows the statistical distribution, evaluated in the class amplitude ranges equal to 10dB. For X65B sample the most hits are in the class 50-60dB that can be associated to noise. Then the occurrences decrease from the class 60-70 up to 90-100dB. In the classes at higher amplitudes lies the key to discover the relationship between AE hits and the source of the damage. Based on previous experience at CSM [6] the approach to evaluate acoustic emission energy was undertaken. Acoustic emission energy parameter and applied load vs time is reported in Figure 16 for the X65B test. Analysing the trend in detail, AE activity reveals different rates during the test. This aspect was evaluated further via the energy rate \( \dot{E}_{AE} = \frac{\Delta E_{AE}}{\Delta t} \), taking the base of time equal to \( \Delta t=10\text{sec} \).

The energy rate is reported in Figure 17. It is evident the crack pop-in is detected by a very high acoustic emission energy which corresponds to relevant peak of the energy rate \( \dot{E}_{AE} \). Further severe damage is highlighted, by \( \dot{E}_{AE} \) peaks, in the time test interval between 1800-2000 seconds. In order to attempt to discriminate the energy rate, due to ductile fracture respect to brittle fracture, a threshold of \( \dot{E}_{AE} \) has been defined equal to \( \dot{E}_{AE}=300 \text{ (dB/μsec))/(10sec)} \).

Figure 16. X65B. Acoustic emission energy and load vs time.
In the plot a green line has been drawn as a boundary between the energy rate value representative of brittle and ductile fracture, Figure 17. Evidence of the threshold level of $E_{Ac} = 300 \text{dB/\mu sec}/10\text{sec}$ was also found for both tests carried out at low temperature ($T=-22^\circ\text{C}$) for X65 and for higher steel grade X80, see Figure 18 and Figure 19, respectively. In particular, the test X65 was carried out in order to promote the damage with a brittle fracture mechanism. In this case, Figure 18, no remarkable crack pops were found, but relatively high $E_{Ac}$ peaks clearly indicate the point of stable brittle crack propagation, as was later verified on the fracture surface. As reported above, the higher steel grades are characterized by lower AE activity. This behaviour is associated both with the different microstructure and the lower inclusion contents of X80 and X100 API 5L steel grade, respect to the older steel X65. Anyhow in tests X80, though AE activity was lower, the brittle damage is in evidence by the $E_{Ac}$ parameter, Figure 19. In this tests brittle cracking started at the beginning, whereas during the tests, the stable crack propagated by a ductile mechanism, (for a total stable ductile crack propagation $\Delta a=1.04\text{mm}$), according to the acoustic emission activity recorded.

The approach based on a threshold level to discriminate the damage mechanism by acoustic emission parameters was investigated previously by Mirabile [6], considering low acoustic emission activity due to plastic deformation, and in particular to the size of the plastic ratio at the crack tip. In fact, from the tests carried out by similar steel pipes, a dependence of acoustic emission energy $E_{AE}$ to the four order power of the plastic zone size: $E_{AE} = r_p^n$, with exponent $n=4$, was found. AE activity level, even though it was significant, was very low respect to AE produced by fracture phenomenon.

Low intensity AE activity can be also ascribed to “micro-fracture event” [6]. The magnitude of an event is dependent on the fracture area according to the relationship: $M_{AE} = \log_{10} \Delta a$.

Scruby [10] described the approach to evaluate wave displacement amplitude originating from micro-fracture events. For transverse (shear) waves at position $r$, $\Theta$ respect to the AE source, the amplitude $u_r$ is give by:

$$u_r = [\sin 2\Theta] \frac{b \, da}{4 \pi c_t} \delta (t-r/c_t)$$  \hspace{1cm} (5)$$

where $\delta(t-r/c_t)$ represents the point disturbance at the origin with the transverse wave velocity ‘$c_t$’, and $b \, da$ the crack volume, that is the volume of space left by the increment of crack growth. The approach cannot take into account the specific fracture mechanism i.e. ductile or brittle.
4.2 Stress Corrosion Cracking Tests

AE trend recorded during of SSC tests and reported in the Figure 8, Figure 9 and Figure 10, is interpretable by the schematic representation of the three different source types indicated in ASTM E 569-02 [7]. Specimens X65D, X65H, X80G, X100E and X100G can be classified as ‘Source 2’ as ACTIVE, AE trends of above mentioned specimen is not with constant growing as ASTM schematic representation. From the point of view of AE, the activity is characterized by source acoustic mechanisms which fall into two categories:

- Primary events: associated to the initiation of micro-cracks or their coalescence generating a sequence of AE bursts.
- Secondary events: due to ‘intrinsic noise’ generated by the corrosion products at the surface crack tip or, in the case of fatigue, to the friction between the same fracture surfaces. AE activity is rather constant in time.

In order to validate the AE trend of the selected specimens classified as ‘Source 2’, the fracture surfaces of the CT specimens were observed using standard optical microscope and none SCC damage evidence was revealed. Subsequently scanning electronic analysis was also performed and SC cracks were discovered. Their morphological aspect is inter-granular crack and the size is about 100 μm, as reported in the figures from 20 to 22 (X65, X80 and X100 specimens). In the figures, the fatigue pre-crack tip is indicated by the red arrows. The features of stress corrosion cracks are indicated by yellow arrows and by red dotted areas.
5. Conclusions

Experimental fracture mechanics tests were performed on specimens extracted from 3 different steel grades API 5L X65, X80 and X100, and monitored by acoustic emission technique. The research was oriented to correlate acoustic emission activity with fracture mechanisms operating during the failure process. The obtained results led to the following conclusions:

- PZT sensor resonance frequency of $f = 90$ kHz revealed a greater efficiency than a higher frequency $f = 150$ kHz to collect acoustic emission bursts generated by sample steels. A lower resonance frequency is also more suitable for long distance AE monitoring.

- Considered steels, designed with different strength levels and microstructures, revealed different acoustic emission activities during the fracture processes. X65 steel, with ferrite pearlite microstructure, gave acoustic signals which were stronger and therefore easier to interpret than the other steels.

- A higher crack opening rate produces a more brittle failure mechanism, leading to higher acoustic emission hits density.

- Conventional/classic acoustic emission parameters were investigated in order to establish the best parameter useful to be related to ductile/brittle fracture mechanisms and acoustic emission activity. Acoustic emission energy and energy rate parameters were found suitable to distinguish between different fracture mechanisms. In particular a threshold
level, which corresponds to the boundary between ductile and brittle fracture mechanisms, was found in terms of energy rate and equal to $\dot{E}_{ac} = 300 \cdot (\text{dB}/\mu\text{sec})/10\text{sec}$.

- Acoustic emission is well adapted to monitor stress corrosion cracking phenomena. Fracture process was revealed by cumulative total hits. The assessment was done following the standard procedure.

These essential conclusions will strongly aid future development of a Pipeline Health Integrity Monitoring (PHIM) system based on the Acoustic Emission technique. In addition acoustic parameters will help to define criteria for safety of high pressure gas pipelines in service.

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