

CHAPTER 6 UNIFORM CORROSION MONITORING

This chapter presents the experiment procedures, results and discussions of uniform corrosion monitoring on a storage tank in the laboratory. The home-built AE sensor made from chapter 4 is also applied to the uniform corrosion monitoring. A system calibration is applied, using an air jet as the artificial AE source. The effects of the wave propagation path are explained, and an equation is constructed to explain the effects of the wave propagation path between the output (AE signal from data acquisition device) and input (electrical energy from potentiostat control). The prediction of the acoustic energy at uniform corrosion is presented. A model formulation created from chapter 3 (section 3.7) and a method for transferring information between different AE sensors are also proposed.

6.1 Introduction of Uniform Corrosion Monitoring

The uniform corrosion monitoring is one of the applying of AE testing system. In this subsection, the uniform corrosion monitoring using AE testing is described.

Uniform corrosion is one of the main causes of failures in various applications, such as in the bottom floors of storage tanks in the oil and petroleum industries. The corrosion mechanism generates discrete micro-seismic AE signals. AE can be used to detect and monitor corrosion processes (Weng et al., 1982; Dunn et al., 1984; Ferrer et al., 2000), to classify the level of severity of the corrosion (Jones et al., 1991; Saenkhum et al., 2003; Pratepasen et al., 2006) and to locate the corrosion source. In this section, the uniform corrosion monitoring using AE was studied. The details are shown as follow.

6.1.1 Uniform Corrosion and Polarization Curve

1. Introduction of Uniform Corrosion

Uniform corrosion refers to corrosion dominated by a uniform thinning of materials that proceeds without an appreciable localized attack. Carbon steels and copper alloys are good examples of materials that typically exhibit generalized corrosive attacks, whereas passive materials, such as stainless steels or nickel-chromium alloys, are generally subject to localized corrosive attack. Under specific conditions, however, each material may be subject to each form of corrosion.

Carbon steel usually has a very low corrosion rate. However, a liquid may contain elements of sulfur and soil that may support a relatively high corrosion rate, which may lead to the presence of aerobic bacteria. Aerobic bacteria that are present in the soil and use oxygen to grow are known as sulfur oxidizing bacteria. This type of bacteria can oxidize sulfur (S) or thiosulphate ($S_2O_3^{2-}$) to sulfuric acid (H_2SO_4). The electrochemical reaction for the uniform corrosion caused by sulfuric acid on carbon steel starts with a release of electrons at the anodic surface: $Fe \rightarrow Fe^{2+} + 2e$. Then, the acceptance of electrons is coupled by hydrogen ions at the cathodic surface: $2e + 2H^+ \rightarrow 2H$. Previous reactions are followed by the aerobic corrosion involved with H_2SO_4 . The mechanism of aerobic corrosion in an H_2SO_4 concentrated solution concludes the reaction as $4Fe + H_2SO_4 + 2H_2O \rightarrow FeS + 3Fe(OH)_2$. Ferrous sulfide (FeS) and ferrous hydroxide ($Fe(OH)_2$) are the corrosion products from this process (Jones, 1997; Ferrer et al., 2002). This corrosion process is considered to be a uniform corrosion.

2. The Polarization Curve and Uniform Corrosion Rate

The measurement of the current density (I_{corr}) to compute a uniform corrosion rate can be measured from a polarization curve (the degree of potential change as a function of the amount of current applied). When the potential of the metal surface is polarized by the application of the current in a positive direction, it is said to be anodically polarized; when the current is polarized in a negative direction, it is cathodically polarized. The degree of polarization is a measure of how the rate of the anodic and the cathodic reactions are related by various environmental and/or surface process factors. The former is called the concentration polarization, and the latter is called the activation polarization. The variation of the potential as a function of the current (a polarization curve) makes it possible to study the concentration effects and activation processes on the rate at which anodic or cathodic reactions can give up or accept electrons. Hence, polarization measurements can thereby determine the rate of the reactions that are involved in the corrosion process--the corrosion rate (Mansfeld, 2005; Flitt and Schweinsberg, 2010).

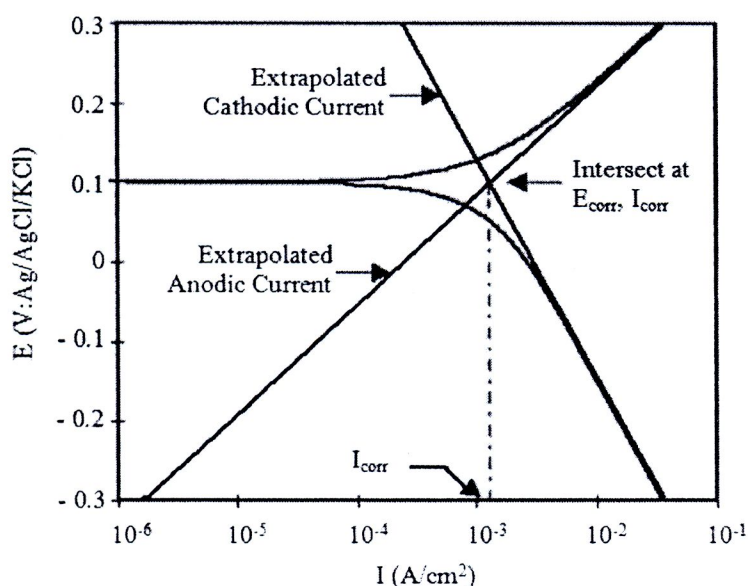


Figure 6.1 The polarization curve of classic Tafel analysis

In figure 6.1, the polarization curves are typically plotted as potential (E) versus log current density (absolute current). The potentiostat was used to control the electrochemical potential of the corrosion process at the static corrosive potential (E_{corr}). This potential value of each corrosive condition is different. The values of these characteristic constants in the Tafel method depend on the metal and the environment under consideration. It is possible to extrapolate the anodic and cathodic linear (Tafel lines) portions of the polarization curves to their corrosive potentials: under ideal conditions, these two portions should intersect. The value of the current at their intersection will be the rate of corrosion, expressed in terms of the current density. The values of the exchange current densities for the cathodic and anodic reactions have a profound effect on the corrosion rate.

The corrosion rate of uniform corrosion in millimeters of penetration per year may be calculated from (Prateepasen et al., 2006):

$$\text{Corrosion Rate (mm/y)} = \frac{87.6W}{DAT} \quad (6.1)$$

where W is the weight loss in milligrams, D is the density in grams per cubic centimeter, A is the area in square centimeters, and T is the time in hours.

Based on Ohm's law, the electrical energy of uniform corrosion from the potentiostat control can be defined as

$$P_{corr} = I_{corr} E_{corr} \quad (6.2)$$

where P_{corr} is the electrical power from the uniform corrosion, I_{corr} is the current from the uniform corrosion, and E_{corr} is the voltage from the uniform corrosion.

6.1.2 System for Uniform Corrosion Monitoring Using AE

Metallic corrosion involves some chemical reactions that result in a redistribution of energy. Any corrosion process is thus a potential source of AE. The initiation and growth of corrosion cracks produce a variety of distinct and discernible signals, such as electrochemical noise, electrochemical current transients, AE and load drops. The early detection of initial corrosion damage would improve safety, while flaw location could reduce effective downtime during maintenance. Of the signals emanating from corrosion sources, only AE can be remotely detected without prior knowledge of the source. Corrosion initiation and cracking can be localized with AE by the use of detector arrays and time of arrival analysis.

The acoustic energy (acoustic stress wave) generated from the uniform corrosion process can be dispersed in any direction. The AE signals released from corrosion propagate through liquid medium (longitudinal wave), coupling and AE sensor, respectively. A diagram of wave propagation path in the uniform corrosion monitoring is shown in figure 6.2.

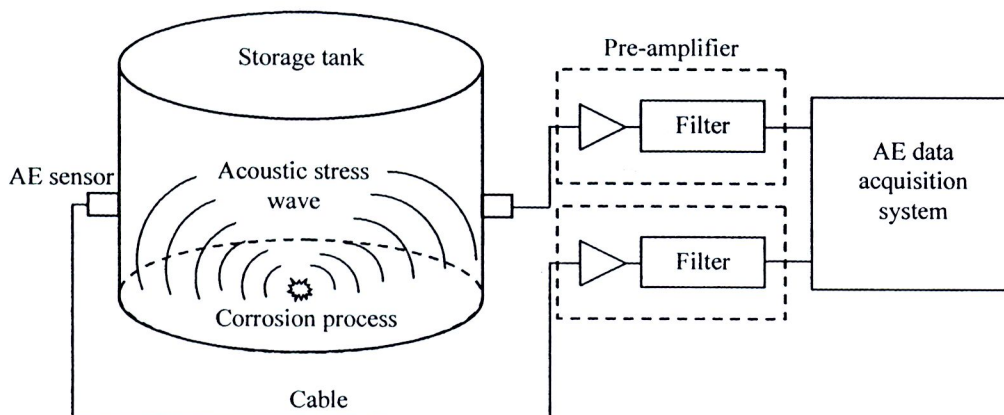


Figure 6.2 System of AE testing for uniform corrosion monitoring

AE activities (hits or events, individual signal bursts produced by corrosion, and peak amplitude) and AE parameters, such as energy (definitions vary across AE system suppliers), have been studied to forecast the rate or severity of corrosion (Prateepasen et al., 2006; Jirarungsatean and Prateepasen, 2010).

It is clear from previous research that AE parameters can be used to analyze and forecast the rate or severity of corrosion. The intensity of the AE energy level and hits are generally used to grade the severity level of corrosion. However, effects of the wave propagation path, including different conditions such as the size of the tank, the type of AE sensor or the liquid medium, may cause different AE signal intensities when obtained from an identical corrosion source

6.1.3 AE Source and Wave Propagation

1. AE Source from Corrosion Process

AE sources in corrosion processes can help evaluate metal damage. It is necessary to properly apply signal conditioning. AE sources emitted from the corrosion process have been studied in the past decade. Corroded metal (Arora, 1984), bubble activities (formation and collapse) (Arora, 1984; Darowicki et al., 2003; Jirarungsatean and Prateepasen, 2010), passive film rupture (Jones and Friesel, 1992; Darowicki et al., 2003; Jirarungsatean and Prateepasen, 2010), mechanical cracking (Yonezu et al., 2006; Zhang et al., 2008; Alvarez et al., 2008) and the movement of corrosion products (Arora, 1984; Kasai et al., 2009) have been suggested as AE sources. Most AE sources reveal information about the mechanism of corrosion and environmental action. Uniform corrosion is similar in the case of the gas bubbles generating AE signals due to their movement and oscillation. Acoustic bubble signals can instantaneously drown the emitted metal damage signals. These are filtered out by signal conditioning hardware. In addition, the AE source from passive film rupture is only identified at the start of corrosion, except in the case of corrosion on film - based materials such as stainless steel and certain alloys. In previous research, it is shown that AE sources are the breakage of bubble and the fracture of corrosion product.

2. Wave Propagation Path in Uniform Corrosion Monitoring

In figure 6.2, before AE sensors capture the acoustic stress waves, however, they are attenuated based on the distance they travel in the liquid medium ($A_\alpha(\omega)$), the effect of the incident angle (A_{angle}) between the liquid and the surface of the storage tank (which determines reflection and refraction) and the effect of the AE sensor coupling loss (L_c) between the surface of the storage tank and the wear plate of the AE sensor. A block diagram of the wave propagation path is shown in figure 6.3.

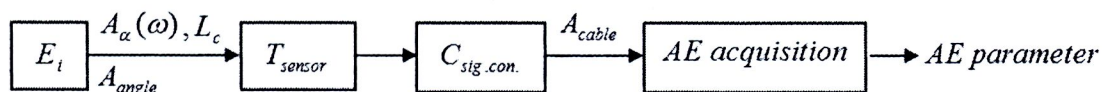


Figure 6.3 A block diagram of the wave propagation path

When the AE sensors capture an acoustic stress wave, the sensitivity or the ability of AE sensors (T_{sensor}) (to convert mechanical energy into electrical energy) determines the

effect on amplitude signal. Then, the amplitude signal or electrical energy is quickly amplified ($C_{sig.con.}$) by a preamplifier and filtered (mechanical and electrical noise). Next, the amplitude signal or the AE signal is attenuated due to the cable length (A_{cable}). Lastly, the AE signal is then sent to an AE data acquisition system to extract the AE parameters.

Attenuation of the Acoustic Energy in Medium (Liquid)

In this case, the total acoustic energy (I_e) received from the uniform corrosion source is composed of two parts: the kinetic energy (KE), which is associated with the motion of the vibrating liquid, and the potential energy (PE), which is associated with energy stored through the compression of a liquid (Kino, 1987; Barron, 2003). The total acoustic energy can be written as

$$I_e = KE + PE \quad (6.3)$$

thus,

$$KE = \frac{1}{\lambda} \int_0^\lambda \frac{1}{2} \rho u^2(x,t) dx = \frac{1}{2\pi} \int_0^{2\pi} \frac{1}{2} \rho u^2(\zeta, \theta) d\zeta \quad (6.4)$$

$$\zeta = kx$$

and

$$PE = \frac{1}{\lambda} \int_0^\lambda \frac{p^2(x,t)}{2\rho c^2} dx = \frac{1}{2\pi} \int_0^{2\pi} \frac{p^2(\theta, \zeta)}{2\rho c^2} d\zeta \quad (6.5)$$

where λ is the wavelength (m), ρ is the density (kg/m^3), u is the viscosity (Pa-s), x is the distance (m), ζ is the damping ratio, θ is the angular coordinate, k is the wave number (m^{-1}), p is the instantaneous acoustic pressure (Pa), and c is the velocity of sound (m/s).

$A_\alpha(\omega)$ is the attenuation by the wave propagation path (acoustic energy) in liquid. The attenuation of acoustic energy is dependent on the wave frequency, distance and wave number. The acoustic energy attenuation can be written as (Kino, 1987; Barron, 2003)

$$I_e(x) = I_{e0} e^{-2\alpha x} e^{jkx} \quad (6.6)$$

where I_{e0} is the acoustic energy at the uniform corrosion source, α is the attenuation coefficient, x is the distance (m), k is the wave number (m^{-1}), and $j = \sqrt{-1}$.

The attenuation coefficient (α) and wave number (k) can be expressed as

$$\alpha = \frac{\omega}{c} \sqrt{\frac{(1 + \omega^2 \tau^2)^{1/2} - 1}{2(1 + \omega^2 \tau^2)}} \quad (6.7)$$

and

$$k = \frac{\omega}{c} \sqrt{\frac{(1 + \omega^2 \tau^2)^{1/2} + 1}{2(1 + \omega^2 \tau^2)}} \quad (6.8)$$

where ω is the angular frequency (rad/s), and τ is the relaxation time (s).

Effect of the Incident Angle

In figure 6.3, A_{angle} is the incident angle loss. In this case, we find that sound waves may strike a surface at various angles of incidence. Let us now consider the case of a sound wave that strikes the interface between two materials at an angle of incidence (θ_i). The sound power transmission coefficient (E_T) for oblique incidence can be defined as (Kino, 1987; Barron, 2003)

$$E_T = \frac{4Z_1 Z_2 \cos \theta_i \cos \theta_t}{(Z_1 \cos \theta_i + Z_2 \cos \theta_t)^2} E_i; \quad 0 \leq \theta_i \leq \theta_{cr1}, \theta_{cr1} = 30^\circ \quad (6.9)$$

where Z_1 is the acoustic impedance of liquid (10^6 kg/m²s); in this work, Z_2 is the acoustic impedance of carbon steel, θ_t is the transmission angle, E_i is the sound power of the incidence, and θ_{cr1} is the first critical angle based on Snell's law.

Effect of the AE Sensor Coupling

Given the above parameters, L_c is the AE sensor coupling loss. When the sound power moving through carbon steel into AE sensor, a portion of the sound power is reflected, and a portion is transmitted into the AE sensor. Let us consider the case of transmission from carbon steel into an AE sensor. The AE sensor coupling loss may be written as (Kino, 1987; Barron, 2003)

$$E_T = \frac{4Z_2 Z_3}{(Z_2 + Z_3)^2} E_i \quad (6.10)$$

where Z_3 is the acoustic impedance of the wear plate (AE sensor).

Effect of AE Sensor Sensitivity, Cable Length and Amplified Signals

Lastly, T_{sensor} is the AE sensor sensitivity (mV/kPa). The output voltage of the AE sensor is proportional to the acoustic power or acoustic pressure (see section 3.5). The AE sensor sensitivity can be calibrated by air jet. A_{cable} is the signal loss (attenuation) due to cable length (mV/m), and $C_{sig.con.}$ is the amplified signal (dB) obtained from pre-amplifiers. The amplified signal depends on the amplitude reference ($1\mu V$) and the signal amplitude from the AE sensor (V_s). It can be defined as (McIntire, P., 1987)

$$dB = 20 \log \frac{V_s}{1\mu V} \quad (6.11)$$

6.2 Uniform Corrosion Monitoring on Carbon Steel Storage Tank

Before home-built AE sensor and system calibration are applied to uniform corrosion monitoring on carbon steel storage tank to forecast the uniform corrosion energy, however, the equation to forecast the uniform corrosion energy is required. The equation in this study is created based on theoretical methods to explain the effect of wave propagation path in uniform corrosion monitoring. The detail of equation to forecast the uniform corrosion energy is shown as follow.

6.2.1 Modeling the Equation to Monitor the Uniform Corrosion Process

1. Relationship between electrical energy and mechanical energy

The AE sources (mechanical energy) of uniform corrosion are bubble and fracture of corrosion product. However, it is very difficult to measure the mechanical energy of uniform corrosion process directly. From the polarization curve of classic Tafel analysis, the electrical energy from anodic dissolution is correlated with corrosion rate and the main objective of this study is to explain the effect of the AE wave propagation paths and system calibration when using various AE monitoring conditions. Hence, we analogize the electrical energy to mechanical energy. In this way, the equation 6.13 can be explained easier.

From assumption, the uniform corrosion energy from the potentiostat control can be analyzed using Ohm's law. Ohm's law can be defined as (Merhaut, 1981)

$$P = IE \quad (6.12)$$

where P is the electrical power (watts), I is the current (amperes), and E is the voltage (volts).

An analogue of Ohm's law in mechanical systems is analyzed. There is an analogy between the mechanical systems with force; F (N) plays the same role as the voltage, and the velocity v (m/s) plays the same role as the current. In a mechanical system, the power P_m (N-m/s) is given by

$$P_m = \frac{1}{T} \int_0^T Fv dt$$

where T is the integration time and t is the initial time.

This expression gives a formula analogous to that in electrical circuit theory.

$$P = F_{ef} v_{ef} \cos \varphi$$

where φ is the phase difference between the force and the velocity.

From the acoustic parameters, the acoustic energy (E_{AE}) and average energy of AE signal (AE_{rms}) are selected for this study. The acoustic energy can be computed using

$$E_{AE} = \frac{1}{R} \int_0^T V^2(t) dt$$

and

$$AE_{rms} = \sqrt{\frac{1}{T} \int_0^T V^2(t) dt};$$

thus,

$$P(\text{watt}) \approx P_{corr} \approx (AE_{rms})^2 \approx P_m \approx U$$

and

$$AE_{rms} \approx \sqrt{|P_{corr}|},$$

where V is the voltage of AE sensor, and R is the electrical resistance of the measuring circuit.

2. Validation of effects of wave propagation path and the equation

Essentially, the electrical energy produced from the polarization curve is correlated to the corrosion rate. In this study, the mechanical energy generated from uniform corrosion is assumed to be related to the electrical energy. Thus, the electrical energy will be used to represent the energy released from the uniform corrosion and will thus be employed to forecast the corrosion severity.

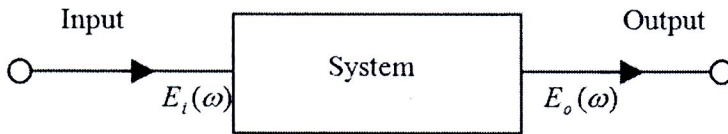


Figure 6.4 A block diagram of a scalar system

The scalar system of the equation is shown in figure 6.4. The input is the AE energy generated from the uniform corrosion source ($E_i(\omega)$). The system composes of each item of the wave propagation path. Its effect can be calculated from the equations in subsection 6.1.3. The output ($E_o(\omega)$) is the AE energy detected by an AE acquisition device. The equation can be described by

$$\frac{E_o(\omega)}{E_i(\omega)} = [A_\alpha(\omega)] \cdot [A_{angle}] \cdot [L_c] \cdot [T_{sensor}] \cdot [C_{sig.con.}] \cdot [A_{cable}] \cdot [K] \quad (6.13)$$

where K is the average of the uniform corrosion correction factor.

To compute the correction factor, the energy of the uniform corrosion (from electrical energy: P_{corr}) and the AE energy from the AE acquisition device (subsection 6.3.2) are determined using equation 6.13. The transfer function to compensate for the difference in sensitivities among AE sensors can be found by using an air jet (subsection 6.3.3).

Equation 6.13 can be employed to forecast the energy of the uniform corrosion. However, when the conditions, such as the size of the tank, the type of AE sensor or the liquid medium are different, equation 6.13 can still be used. Under these conditions, recalibrating the AE sensor by finding out the term T_{sensor} and recalculating a new constant for each wave propagation item is required.

6.2.2 Using the Potentiostat to Control the Electrochemical of Uniform Corrosion Process to Find Out the Parameters of Equation

The test specimens are prepared from carbon steel type ASTM A36 bars. The exposed surface is mechanically ground and then cleaned with distilled water, dried in a stream of warm air, and stored overnight in desiccators. The experimental system is constructed as illustrated in figure 6.5.

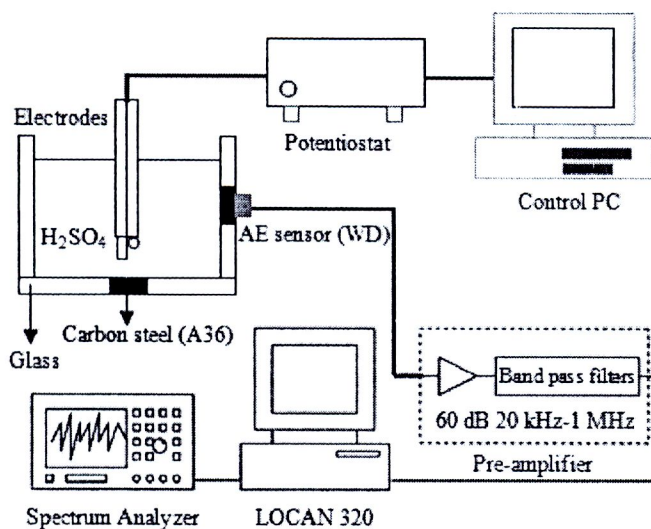


Figure 6.5 A diagram of the experiment system for potentiostat control

For the experiment, a 3-mm-thick, exposed surface area of ASTM A36 sample is 6.25 cm^2 ; using H_2SO_4 , the pH values in the solution are adjusted to be 4.5, 5.0, 5.5 and 6.0, respectively. This pH range refers to the values in the crude oil (Prateepasen et al., 2006). The potentiostat is used to control the electrochemistry of the uniform corrosion process at the static corrosive potential (E_{corr}). This potential value of each corrosive condition is different. Thus, the E_{corr} values for each pH adjustment are obtained from the polarization curve using potentiodynamic tests.

The WD sensor is mounted on the carbon steel to detect the acoustic signals. To minimize the energy loss at the interface of the carbon steel and the sensors, an appropriate couplant is selected, and its mounting performance is carefully checked.

The signals are amplified by 60 dB using pre-amplifiers that had been fitted with a 20 kHz – 1 MHz band-pass filter. Output signals from the pre-amplifier are fed into the amplifier. Data are recorded by a LOCAN 320, set at a gain of 32 dB, and a real-time signal analyzer HP 89410A (with a sampling rate of 10 MHz). The experiment is set up to monitor and collect AE signals for 24 hours. For each detected AE signal, the amplitude and energy (acoustic parameters) are studied. These AE parameters are then analyzed, corresponding to the corrosion behavior for each corrosive condition tested.

6.2.3 Using the Air Jet to Calibration the Sensitivity of AE Sensors and System Transferable

Each AE sensor presents a different sensitivity due to its frequency bandwidth response. Consequently, different AE sensors may receive different levels of AE energy from the identical AE source. To minimize this problem, the AE sensors must be calibrated by using the air jet to make the AE energy obtained from the different AE sensors compatible.

To calibration the sensitivity of AE sensors, an air jet is used. The air supply system for the air jet calibration rig is shown in figure 4.3. nozzle with a 0.5-mm diameter bore is placed even with the bottom of the storage tank at a fixed distance of 5 mm (according to the ASTM E976) The air pressure is varied from 300 to 500 kPa in increments of 50 kPa.

The WD and AE3 sensor are mounted on the outer shell of a storage tank at 15 cm above the tank bottom. A couplant of the same type is applied at the interface of the bottom of storage tank and the sensors. The sensor mounting condition and signal setup are the same as described in subsection 6.2.2. For the transferable system of each AE sensors is shown in subsection 3.6.4.

6.2.4 Applying the Equation to Monitor the Uniform Corrosion Process in the Laboratory

To validate that the equation can be used in another condition, a test is performed in a laboratory setting. A set of experiments are designed using a 1-m diameter storage tank. The liquid mediums are a concentrated H_2SO_4 solution set to pH 4.5 and water. The AE sensors (WD and AE3) are mounted on the outer shell of a storage tank at 15 cm above the tank bottom. The AE spectrum is recorded using the same equipment and under the same conditions as those that are used in subsection 6.2.2 (including the specimen preparation). After that the recording, the acoustic signals obtained from the WD and AE3 sensors are calculated and converted to read as the corrosion energy at the source. The experimental system is constructed as illustrated in figure 6.6.

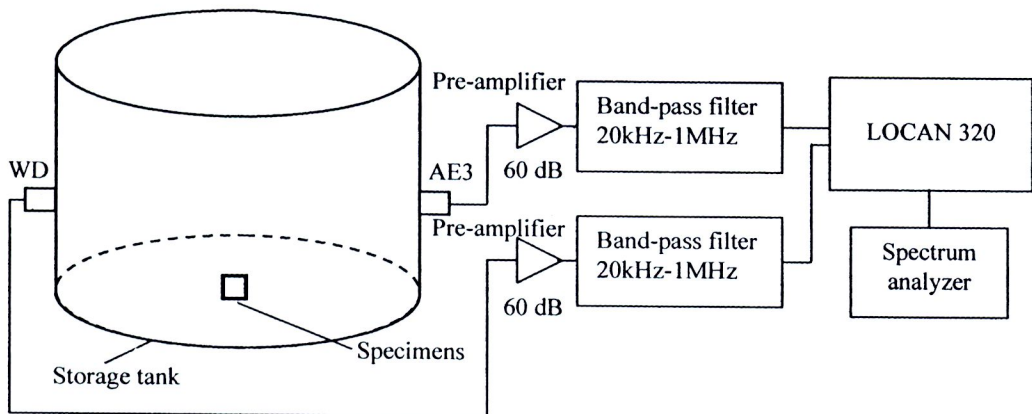


Figure 6.6 A diagram of the experiment set-up for uniform corrosion monitoring

6.3 Experimental Results of Uniform Corrosion Monitoring on Carbon Steel Storage Tank

In this study, the results are divided into two main parts. The first main part is to describe the effects of wave propagation path and system calibration (subsections 6.3.1-6.3.4). The second part is to validate the model formulation (subsections 6.3.5).

6.3.1 The Equation to Monitor the Uniform Corrosion Process

The energy of uniform corrosion can be forecasted by substituting the value of the effect of the wave propagation path. The equation for forecast the energy of uniform corrosion process is modeled (presented in section 6.2.1). The electrical energy of uniform corrosion from the potentiostat controlled electrochemical potential is first computed to create the equation. Then the AE sensors are calibrated by the air jet. Consequently, the average uniform corrosion correction factor (K) could be computed. Finally the equation for the effect of the wave propagation path is used to forecast the energy of uniform corrosion on a storage tank.

6.3.2 The Potentiostat Control of the Electrochemical of Uniform Corrosion Process

In this study, the E_{corr} is determined from the polarization curve. The polarization curves of each pH level between 4.5 and 6 pH have similar shapes. The typical polarization curve of pH 4.5 is shown in figure 6.7.

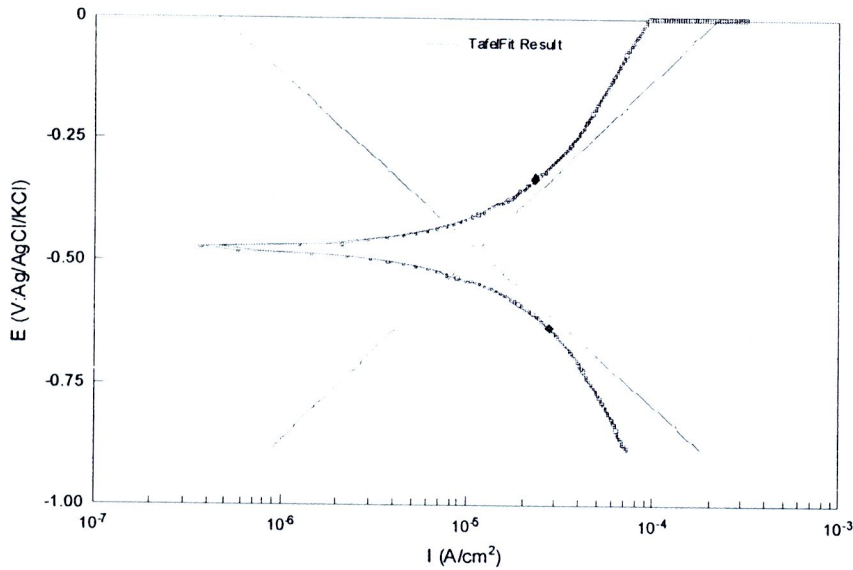


Figure 6.7 The polarization curve of the ASTM A36 steel uniform corrosion test in H_2SO_4 solution, pH 4.5

Then, the corrosion rate and P_{corr} are computed by equation 6.1 and 6.2, respectively. The result is shown in table 6.1.

Table 6.1 Corrosion potential, Current density, Corrosion rate and Electrical energy from uniform corrosion of ASTM A36 in H_2SO_4 solution

pH	E_{corr} (Volts)	I_{corr} (A/cm^2)	Corrosion rate (mm / y)	P_{corr} (watt)*
4.5	-0.47577	1.1407×10^{-5}	0.0625	-3.3920×10^{-5}
5.0	-0.43673	8.6600×10^{-6}	0.0504	-2.3640×10^{-5}
5.5	-0.47081	1.8800×10^{-6}	0.0432	-5.5310×10^{-6}
6.0	-0.48579	1.2700×10^{-6}	0.0292	-3.8500×10^{-6}

*A negative symbol means a needing power for one corrosion reaction.

The results of AE_{rms} (energy) from the WD sensor at various pH concentrations (corrosion rates) are shown in figure 6.8. The AE signal is the amplitude of the acoustic waveform in the time domain recorded by the real-time signal analyzer HP 89410 A. The results show that the AE energy is increasing with the corrosion rate. For this reason, the AE energy can be used to predict the uniform corrosion rate.

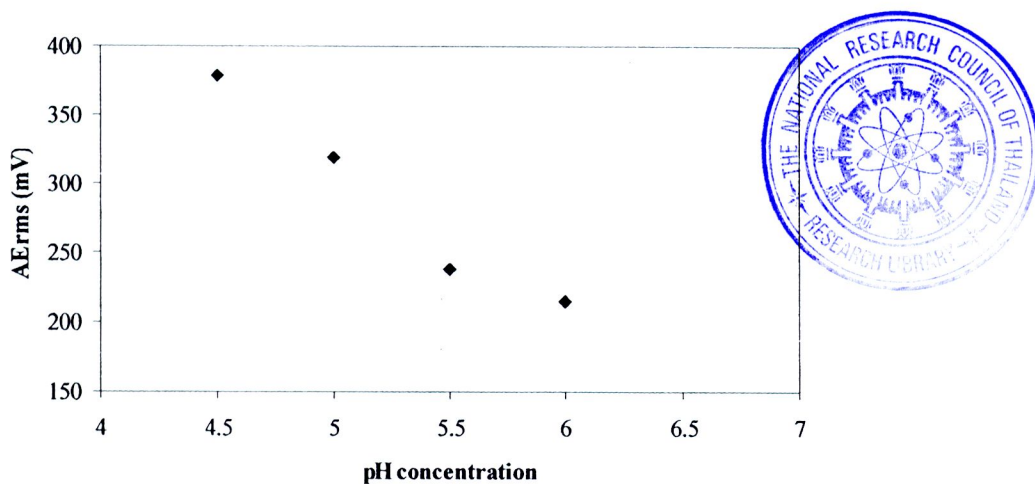


Figure 6.8 The relationship of each pH value for the H_2SO_4 solution to AE_{rms}

6.3.3 The Sensitivity of AE Sensors and the Average of the Uniform Corrosion Correction Factor

The home-built AE sensor (AE3) and WD sensor are calibrated by air jet to make the AE energy obtained from the different AE sensors compatible.

1. The Sensitivity of AE Sensors

The WD and AE3 sensors are calibrated using an air jet at pressure levels between 300 and 500 kPa. The calibration results from the WD and AE3 sensors are plotted in figure 6.9. It can be seen that the AE_{rms} and air pressure are linearly related, and the gradients for the WD and AE3 sensors are 0.31 and 0.11 mV/kPa, respectively. The R^2 are 0.99 and 0.98 for the WD and AE3 sensors, respectively. These values represent the sensitivity of the two sensors.

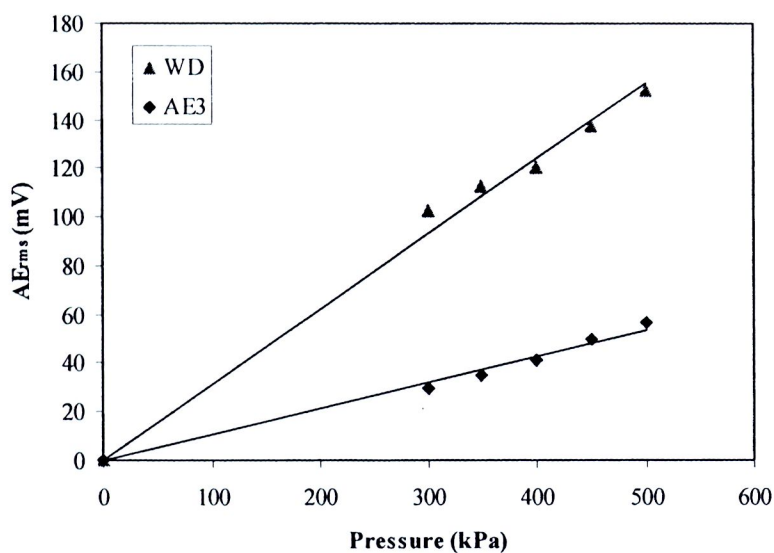


Figure 6.9 The relationship between AE_{rms} and air jet pressure for each sensor

2. The Average of the Uniform Corrosion Correction Factor

The average uniform corrosion correction factor can be calculated by equation 6.13. The value of the energy released from the uniform corrosion (P_{corr}) is shown in table 6.1. The AE energy $E_o(\omega)$ can be computed using AE acquisition device (AE_{rms}). The ratio of AE_{rms} from both sensors can be found using the slope as shown in figure 6.9. The effect of the distance, the incident angle loss and the coupling loss (i.e., the acoustic energy attenuation) are computed by equations 6.6, 6.9 and 6.10, respectively. The parameters for computation, $\alpha = 0.0005$, $x = 0.16$ m, $\theta_i = 26^\circ$, $Z_1 = 1.5$, $Z_2 = 45$ and $Z_3 = 32$ (10^6 kg/m²s), and equation 6.11 are used to find $C_{sig.con.}$. The signals are amplified to 60 dB, and coax cable losses are 0.034 mV/m (10 meters length). Consequently, the average correction factor of the uniform corrosion is computed and is shown in table 6.2.

Table 6.2 Parameter used in the computation of the uniform corrosion correction factor

pH	$A_\alpha(\omega)$	A_{angle}	L_c	T_{sensor}	$C_{sig.con.}$	A_{cable}	K (average)
4.5	1.0001	1.1875	1.0293	0.31	0.001	1.0009	22.4602×10^4
5.0							
5.5							
6.0							

6.3.4 Applying the Equation to Monitor the Uniform Corrosion Process in the Laboratory

To validate the equation to forecast the uniform corrosion energy, the AE signal received from uniform corrosion process on carbon steel based on the WD and AE3 sensors are computed by equation 6.13. Because the conditions are different, such as the size of the tank (distance), the effect of the incident angle loss and the sensitivity of the AE sensor (AE3), the parameters for computing the energy of uniform corrosion, $x = 0.52$ m and $\theta_i = 17^\circ$, are shown in table 6.3.

Table 6.3 Parameters used in computing the energy of uniform corrosion

Sensors	$A_\alpha(\omega)$	A_{angle}	L_c	T_{sensor}	$C_{sig.con.}$	A_{cable}	K (average)
WD	1.0005	1.0659	1.0293	0.31	0.001	1.0009	22.4602×10^4
AE3				0.11			

In table 6.4, the results from the H₂SO₄ solution that had been set to pH 4.5 show that the error of the energy calculated from the equation is less than 5 % in both sensors and that equation 6.13 can be used to forecast the energy of the uniform corrosion source. The performance can be applied in the real applications and minimize the error in grading the corrosion severity.

Table 6.4 Energy of the uniform corrosion source calculated from the equation 6.13, pH 4.5

Sensors	P_{corr} (watt)	Energy from the equation (watt)	Error (%)
WD	3.392×10^{-5}	3.3472×10^{-5}	1.32
AE3		3.2403×10^{-5}	4.47

From these results, the effect parameters in the wave propagation path shown in table 6.3 exhibit small effects on the variation of energy released from the uniform corrosion source, except for the sensitivity of AE sensor, the signal condition (preamplifier) and the corrosion rate (see figure 6.8 and table 6.1).

Table 6.4 illustrates how the air jet calibration system can be used to calibrate the sensitivity of AE sensors (WD and AE3) to calculate, using this equation, the uniform corrosion energy source. In addition, each sensor exhibits similar results with a small error.

6.4 Verification the Model Formulation

In the following subsections of this part, as an exemplar of in situ calibration, an air jet generated AE energy source is employed to calibrate in situ AE sensors on the uniform corrosion monitoring for verification the model formulation (created in section 3.7).

6.4.1 Verification the Model Formulation Using Air Jet System Calibration

The air jet system calibration on the bottom of storage tank is a source where the stress wave energy produced from the impact force can be calculated by equation 3.78. This system is practical for in-situ calibrations. The energy calibration of the WD and AE3 sensor is shown in figure 6.10.

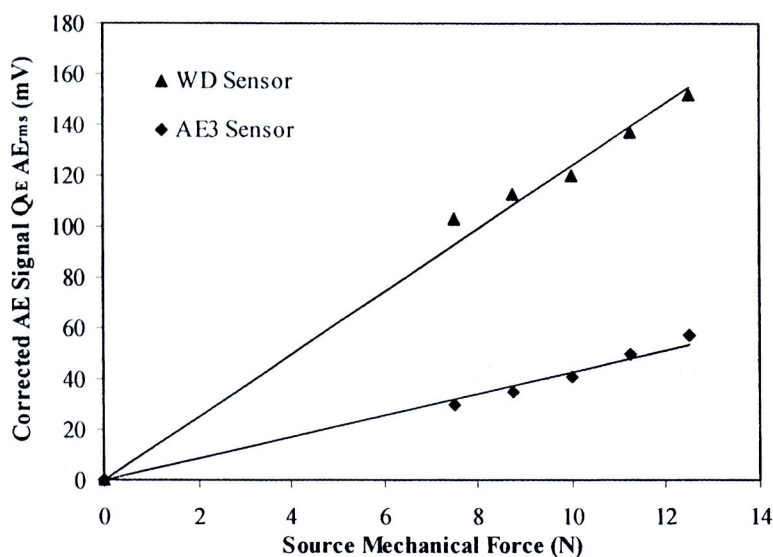


Figure 6.10 The relation between AE_{rms} and mechanical force from air jet pressure for AE sensors in situ on the bottom of storage tank

The linearity between the measured energy in an AE signal and the mechanical source energy is generally assumed in the energy considerations of AE. However, a theoretical physical model developed by Clough (1987) shows that the energy flow in an AE detection process is linear even though there are losses due to material absorption and leakage to the surroundings. The existence of a basic linear relationship between the measured energy in an AE signal and the mechanical source energy is important, otherwise the artificial AE sources used for calibration would need to have similar intensities to those of the in situ AE sources which may vary significantly in different applications.

For the energy measurement coefficient due to the system-source frequency bandwidth effect, the effective measurement bandwidths of both sensor systems are determined by the overlap frequency bandwidths of the AE sensors, band-pass filters and AE calibration source. The frequency bandwidth of air jet source from previous research is more than 1 MHz (Green, 1978) while the frequency bandwidth of the AE signal associated with uniform corrosion is below 125 kHz (Prateepasen et al., 2006). In this case, the energy measurement coefficients are 1 for both AE sensors.

The average of constant (C_{system}) from mechanical source energy calibration system using formulation (equation 3.82) in case of AE3 and WD sensor are 0.2389 and 0.0796 respectively. To validate the model formulation, the mechanical sources are calculated by equation 3.82. The results of calculated mechanical sources and error are shown in table 6.5.

Table 6.5 Calculated force using the model formulation

Theoretical force (N)	Calculated force (N)		Error (%)	
	WD	AE3	WD	AE3
7.50	8.17	7.08	8.93	5.60
8.75	8.96	8.34	2.40	4.68
10.00	9.59	9.74	4.10	2.60
11.25	10.92	11.88	2.93	5.60
12.50	12.10	13.62	3.20	8.96

To validate the model formulation, the AE signal received from uniform corrosion process on carbon steel based on the WD and AE3 sensors are computed. The results from the H₂SO₄ solution that had been set to pH 4.5 (0.0625 mm/y) and water solution (0.0212 mm/y) are shown in figure 6.11 (uncalibrated AE sensors).

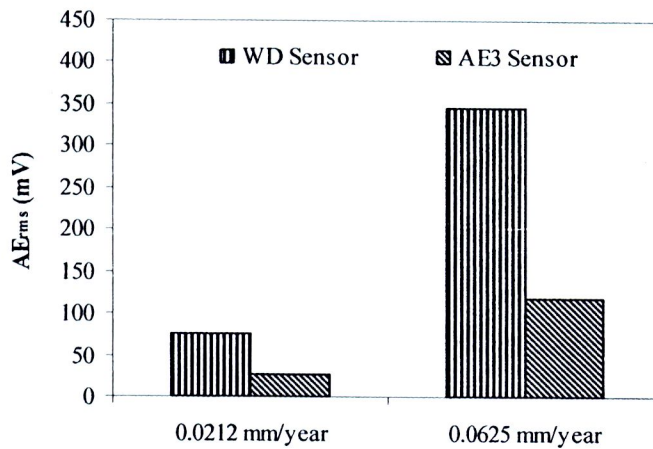


Figure 6.11 Uncalibrated AE signal energy detected by WD and AE3 sensor

After calibrated AE sensors by air jet and converted the AE signal using model formulation, the results are shown in figure 6.12.

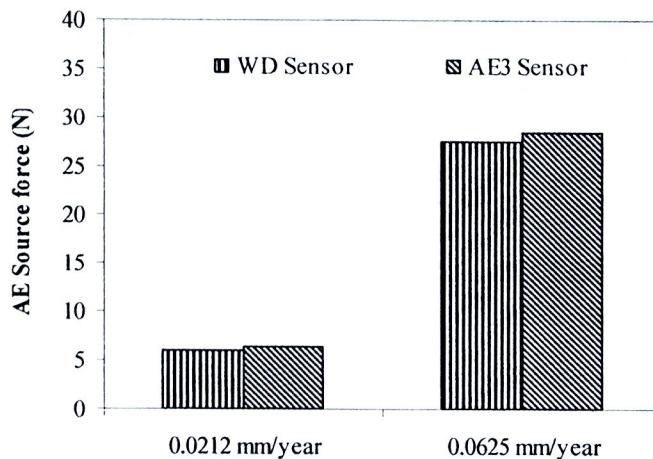


Figure 6.12 Calibrated AE source energy

The figure 6.12 shows the estimated AE source energy for the uniform corrosion monitoring from both sensors. The result shows good agreement that the variations between AE3 and WD sensor are 4.20 and 2.98 % for the 0.0212 mm/year and 0.0625 mm/year of corrosion rate, respectively.

6.4.2 Transferring Information (AE Signal) between Different AE Sensors

From the transferable system (subsection 3.6.4), the average of the scalar ratio from air jet system calibration in case of AE3 and WD is computed by equation 3.77. The average of the scalar ratio is 3.0118 (from 7.5-12.5 N of force). The AE data (AE_{rms}) between both sensors is transferred. The result is shown in figure 6.13.

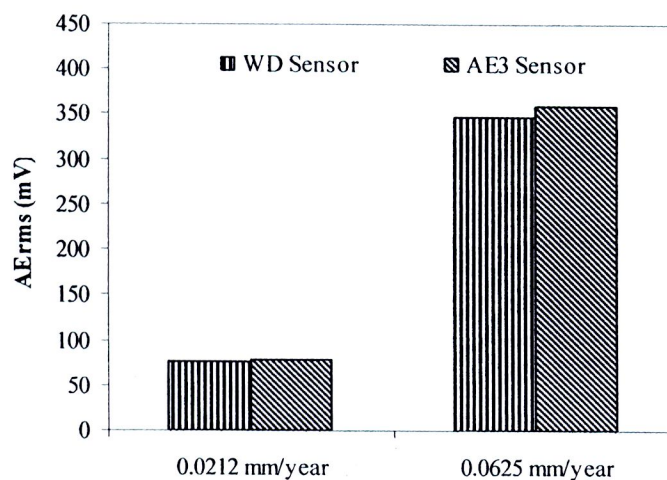


Figure 6.13 Transferred AE signal using the scalar ratio from air jet system Calibration

In figure 6.13, the result shows good agreement that the variations between AE3 and WD sensor are 4.84 and 3.51 % for the 0.0212 mm/year and 0.0625 mm/year of corrosion rate, respectively.

6.4.3 Application of the Equation and Model Formulation

The equation 6.13 and model formulation in this study are created based on theoretical and empirical methods. This equation and model formulation can be applied to monitor uniform corrosion at the bottom floor of a storage tank. When the conditions are different, such as when sensitivities of AE sensors vary, the size of the tank or the signal condition (amplifier), this equation only requires the recalibrated sensitivity of the AE sensor and recalculated values for the constants.

The acoustic energy received from a uniform corrosion process can be used to forecast the corrosion rate by analysis, combined with the hit or even measures. First, a database of the uniform corrosion rate in our laboratory is used to forecast the corrosion rate. In the next step, the data of uniform corrosion in the field were quickly collected using this equation (analysis effects of wave propagation path and system calibration). The benefit of this database is an increased ability to accurately forecast uniform corrosion rates.

6.5 Summary

In this chapter the effects of the AE wave propagation paths, including the liquid medium, the AE sensor, the connection cable and the amplified signals, on the AE signal received from a uniform corrosion process on carbon steel, are investigated and modeled by theoretical and empirical equations. In addition, to verify the proposed model for various types of AE sensors, the air jet implemented is demonstrated to convert AE energy from different AE sensors. Finally, the equation (6.13) and model formulation (section 3.7) are proposed to estimate the AE energy for different wave propagation paths. Experimental tests were performed to validate the proposed equation and model formulation. From the experimental results, the error of prediction of the uniform corrosion energy is less than 5%. For model formulation, the estimated AE

source energy for the uniform corrosion monitoring from both AE sensors shows good agreement. For home-built AE sensor, it can be used to monitor the uniform corrosion process on carbon steel storage tank. The benefit of this study is outline to forecast the grade of the severity of uniform corrosion quantitatively when using various AE monitoring conditions.