Reliable Monitoring of Leak in Gas Pipelines Using Acoustic Emission Method

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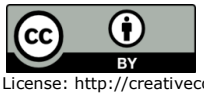
Abstract. The leak detection in gas pipelines using a continuous monitoring system can be used as an early diagnostic tool to prevent catastrophic failures. Among other Structural Health Monitoring systems, the Acoustic Emission (AE) method has advantages through detecting leaks in real time with long range sensors as well as locating leak positions at multi-dimensional space while the sensor selection and spacing are two key issues to detect the target leak rate reliably. In this study, the detectability of the leak in gas pipelines at various operational conditions using the AE method is studied. A 152 cm long, 11.43 cm diameter steel pipeline is built in the laboratory to be tested for leak generation at different operational conditions including the internal pressure level (68.95 kPa to 344.74 kPa with 68.95 kPa increments) and the presence of earth pressure (unburied, partially buried and fully buried cases). The leak rate at a particular condition is varied through changing the diameter of the orifice introduced to the pipeline wall. It is identified that the leak emission amplitude increases with the pressure level while it decreases with the presence of the earth pressure. The AE amplitudes for three orifices under different operational conditions that cause different leak rates are identified. The experimental results are linked with the numerical models which enable understanding the attenuation characteristics of the extended pipeline geometry for a particular frequency. The attenuation curves acquired numerically for vertical wave motions are combined with the AE amplitudes obtained in the laboratory to define the maximum sensor spacing to detect and locate the leak reliably.

Introduction

Acoustic Emission (AE) is a passive non-destructive testing method that relies on the propagating elastic waves released from active sources. Examples of sources that generate the AE activities include crack growth, mechanical friction and leak, and have two characteristic waveform signatures as burst type and continuous type. The leak source causes continuous emission which is defined by ASTM E 1316 [1] as “a qualitative description of the sustained signal level produced by rapidly occurring acoustic emission sources”. The detection approach and data processing of continuous emissions are different from burst emissions because of indefinite arrival time and end time of elastic waves.

In addition to typical pipeline integrity management approaches such as mass-balance method, pressure drop method [2], the AE has been studied by several researchers since 1980s. As compared to acoustic noise based approach [3] through monitoring frequencies less than 400 Hz, a typical application of the AE method relies on propagating elastic waves through pipe structure in the frequency range of 1 kHz – 60 kHz. Kupperman et al. [4] demonstrated that the leak detection in reactor components with acoustic emission with the minimum leak rate as 0.23 litter/hour in laboratory environment; however, the threshold to detect the leak rate depends on pipe geometry, material, internal pressure and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measurement system selected. Miller et al. [5] designed a reference standard pipe to evaluate the AE equipment for leak detection. The fundamental advantage of the AE method is the capability to pinpoint the leak location in real time. Grabec [6] developed leak localization using cross correlation technique, which has limited success due to the influence of reflected waves and multiple wave modes. There are many studies since then to improve the location accuracy of continuous emissions. For instance, Hessel et al. [7] applied neural network approach to improve the leak detection with airborne sensors while the approach may not be applicable to different pipeline configurations. Grabec et al. [8] applied the neural network through using prototype waveform signatures on contact transducers to overcome the limitations of cross correlation function. The same research group improved the arrival time determination with applying a certain digital filter to AE waveforms before cross correlation function [9]. Gao et al. [10] also studied the effect of filtering on leak detection in plastic water pipelines. Fukuda and Mitsuoka [11] applied prewhitening filter to AE waveforms to improve the leak detection and location through identifying a definite peak in the result of cross correlation of two waveforms. Wavelet transformation is implemented to analyze complex leak signatures [12]. Jiao et al. [13] used the dispersion curves of pipelines to identify the leak location with single sensor while the waveform can be influenced with reflections and multiple-sources in a realistic test.

However, for any leak localization method, the dispersion (wave mode and frequency dependent velocity) and attenuation limit the minimum detectable leak rate and the maximum sensor spacing [14]. Muggleton et al. [15] studied wave attenuation in plastic water pipes for frequencies less than 1 kHz. The attenuation factor depends on pipe material and geometry, surrounding medium and internal medium. The leak detection and location in gas pipelines are more challenging than water pipelines because of smaller particle size of gas as compared to water that is the main source of AE through creating turbulence event at the leak location. Leak detection and location becomes more challenging for soil-buried pipelines as compared to on-ground pipelines or submerged pipelines [16]. The reliable leak detection using the AE method requires understanding leak waveform characteristics as a function of pipe operational conditions and estimating the signal attenuation to define the discrete sensor spacing for pinpointing leak position spatially. In this study, a pipeline geometry used in gas distribution networks is built in laboratory, and the pipeline conditions including internal pressure, leak size and surrounding earth pressure are varied in order to identify the AE leak characteristics. A longer pipeline model is built numerically under dynamic loading in order to identify the attenuation characteristics of particular geometry and frequency (60 kHz selected). Based on experimental AE amplitude and numerical attenuation curve, the sensor spacing for reliable leak detection and location is identified.

1. Experimental Design and Results

A 152 cm long, 11.43 cm diameter steel pipeline is built in the laboratory to be tested for leak generation at different operational conditions including the internal pressure level created through air (68.95 kPa to 344.74 kPa with 68.95 kPa increments) and the presence of earth pressure (unburied, partially buried and fully buried cases). The leak hole is varied through three different orifice diameters as 0.41 mm, 0.64 mm and 1.3 mm. The orifice is mounted through the pipe thickness through threaded bolts, similar to the design of Miller et al. [5]. Figure 1 shows the condition of only orifice location buried inside the soil. Two AE sensors are placed at two ends of the pipe. The sensors are R6 sensors with 60 kHz resonant frequency. For the fully buried case, the AE sensor 1 is also buried into the soil to

understand the effect of earth pressure on the sensor response.

Table 1 summarizes the experimental variables, ranges and their effects on AE leak characteristics. The details of the effects of three variables on leak characteristics are discussed in detail below. In summary, the most challenging case for leak detection is the minimum internal pressure and orifice size with the fully buried condition. Based on the operational condition of pipe and the acceptable leak size, the reliable leak detection using AE method with the selected sensor spacing can be identified.

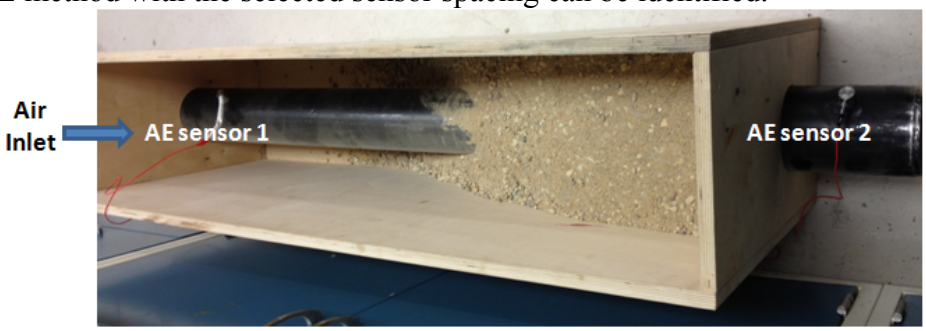


Figure 1. A photograph of the pipeline with partially buried condition

Table 1. Variables affecting leak AE characteristics

Variable	Value Range	Effect on Leak Characteristics
Pipe internal pressure	$P_{initial}$ = 68.95 kPa P_{end} =344.74 kPa ΔP =68.95 kPa	Increase in chaotic turbulence flow around the leak location
Orifice size	0.41 mm 0.64 mm 1.3 mm	Increase in amplitude and decrease in frequency content with the increase of orifice diameter
Earth pressure	Unburied Partially buried Fully buried	Decrease in propagating wave amplitude due to additional boundary constraint caused by the earth pressure

1.1 Leak Emission Waveform Signatures

Continuous emissions do not have a well defined signal arrival as shown in Figure 2. Therefore, conventional threshold based approach to detect the initiation of leak waveforms may cause incorrect channel sequence for localization. In this study, the AE sensors are synchronized; in other words, if one channel is triggered, the data acquisition system records AE signals from all active channels. With this setup, it is ensured that the closest sensor to the leak source triggers all the active AE channels.

Figure 2a and Figure 2b show the waveforms detected for three conditions as unburied, partially buried and fully buried conditions for channels 1 and 2, respectively. The orifice diameter and internal pressure are 0.41 mm and 206.84 kPa. The presence of earth pressure around the orifice or the leak location causes significant loss of amplitude as the soil reduces the impact energy that the leak turbulence causes. For the fully buried case, channel 1 is also buried and there is no influence of earth pressure on the sensor response. For this orifice size, there is no significant effect of fully pipe buried case as compared to partially buried case. However, when the orifice size increases, the effect becomes apparent as discussed in the next section.

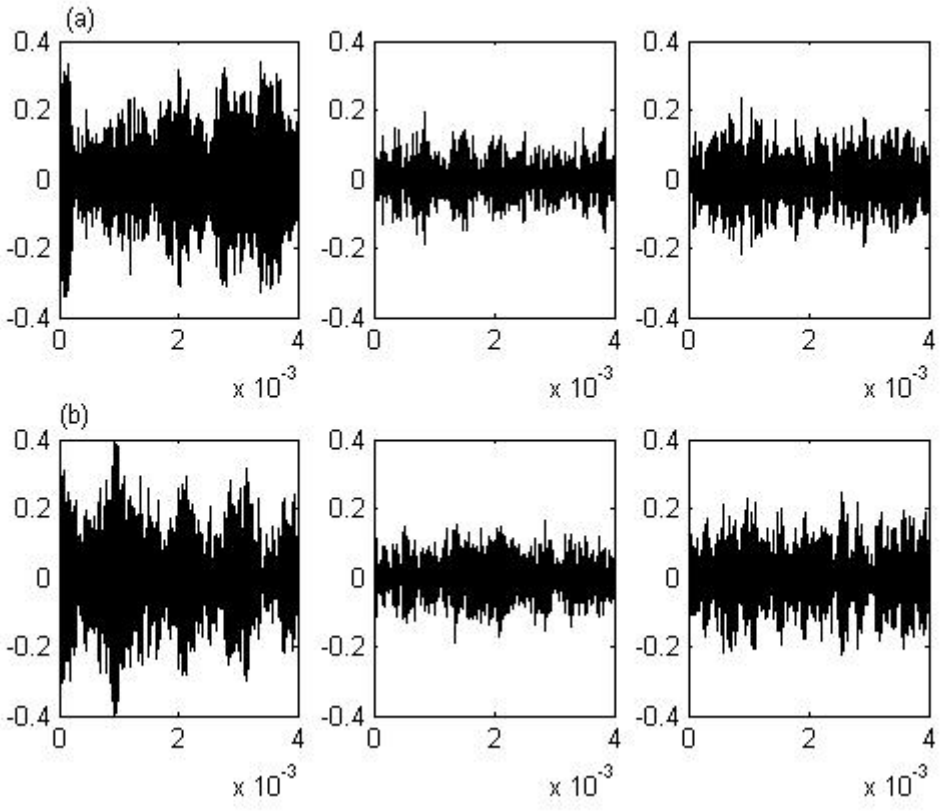


Figure 2. Leak waveform signatures (time versus voltage) for unburied, partially buried and fully buried cases (left to right) of (a) channel 1, (b) channel 2

1.2 AE Amplitudes per Variable

The AE amplitudes for different leak conditions are presented in Figure 3. The AE amplitude increases when the pressure increases. For the unburied case, the amplitude does not vary much after 200 kPa as the AE system reaches the maximum dynamic range. There is a slight difference in the responses of two sensors as there is about 3 dB difference in sensitivity that reflects into the output signal. When the leak size or the orifice size increases, the AE amplitude increases as well. When the pressure increases, the turbulence at the leak location increases and causes more chaotic behaviour and higher impacts, as a consequence, higher amplitude elastic waves, which agrees with the result of Yang et al.[17]. There is an exception for the fully buried case that the AE amplitudes of orifices 2 and 3 indicate similar trends with the pressure change.

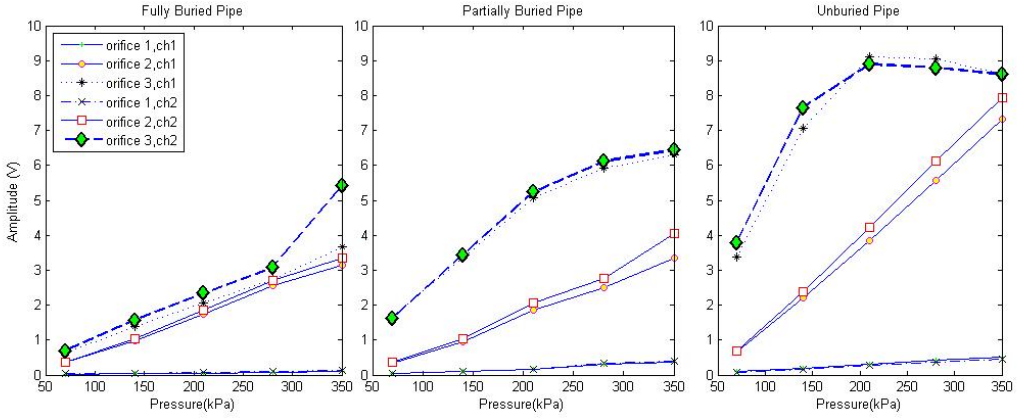


Figure 3. Leak waveform signatures (time versus voltage) for unburied, partially buried and fully buried

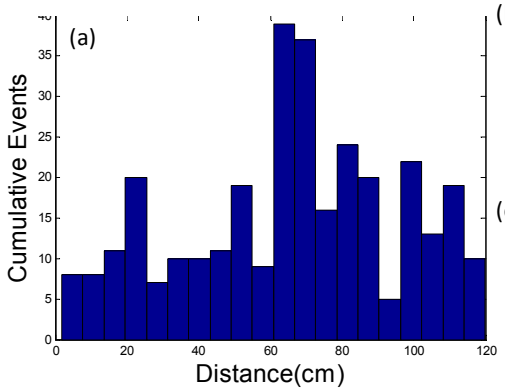
Understanding the change in AE response with pipe condition is critical to estimate the sensor spacing and the threshold for detectable leak size. Assuming that the attenuations due to spreading and absorption in the laboratory pipe are negligible for the selected source-sensor distance, Figure 3 can be used as a guide to define the discrete sensor spacing if the attenuation coefficient of a pipe is known. The attenuation coefficient can be obtained numerically or experimentally using a simulated signal (e.g. ultrasonic wave generated with a transmitter) on the pipe. The leak AE amplitudes are driven for specific pipe geometry and leak simulator design. It is important to note that the amplitudes may show some variations depending on pipe thickness and geometry of leak hole [18].

1.3 Leak Location Accuracy

The arrival time difference is the most critical input to the leak location algorithm as there is no well defined arrival time of continuous emissions. The cross correlation function is typically used to determine the arrival time difference while this approach has limited success if the waveform includes reflected waves as in the case of this study as discussed in the introduction section . However, the AE method is a statistical method; therefore, an accumulation of an event cluster would be sufficient to pinpoint the leak location.
The cross correlation function for discrete and finite duration signals is defined as

$$R_{y_1y_2}(\tau) = \sum_{t=1}^{N} y_1(t) y_2(t+\tau)$$

where $R_{y_1y_2}(\tau)$ is the cross correlation coefficient of two signals, y_1 and y_2, as a function of a time delay τ , N is the lengths of signals. The time delay becomes the input to the equation for linear localization as $x = \frac{\tau V(f,h) + L}{2}$, where L is the distance between the sensors and V is the wave velocity which depends on the frequency and the pipe thickness. The equation is valid if the source to sensor path is straight. Ozevin and Harding [19] showed that the leak can be localized in multi-dimensional space using the linear localization equation and the geometric connectivity of the pipeline networks, which eliminates the limitation of source-sensor direct path need. Using the equations above, the leak location in the model pipeline is identified. Figure 4a shows the event histogram for 68.95 kPa pressure, 0.41 mm leak diameter and unburied case together with the average leak position and standard deviations for the range of orifice sizes and pressure values. The actual leak position is 76.2 cm. The average errors for unburied and buried pipes are 22% and 28%, respectively. The localization can be improved further using filtered waveforms and considering reflected waves through boundaries.



(b)

Pressure	Orifice size		
	1	2	3
68.95	66.13±29.83	57.88±30.77	58.76±30.4
137.90	66.04±28.38	55.86±31.37	58.4±30.96
206.85	57.77±27.91	57.99±32.62	55.62±33.01
275.80	65.88±27.3	57.87±32.17	58.11±32.44
344.75	62.89±25.9	57.65±33.90	59.34±32.95

(c)

Pressure	Orifice size		
	1	2	3
68.95	51.93±28.49	61.17±34.48	45.65±32.08
137.90	42.95±29.86	61.66±34.12	50.23±37.48
206.85	46.83±31.36	63.01±33.29	54.21±37.57
275.80	48.39±30.53	62.76±34.42	59.46±36.47
344.75	48.98±29.48	56.14±36.08	66.27±25.48

Figure 4. (a) Event distribution for 68.95 kPa pressure, 0.41 mm leak diameter and unburied case, (b) mean and standard deviations for unburied pipe, (c) mean and standard deviations for buried pipe

2. Numerical Model of the Pipeline Geometry

2.1 Characteristics of Numerical Model

The numerical models provide the flexibility to study the wave propagation behaviours in various pipeline geometries. The solution of wave equation using numerical methods requires a delicate selection of mesh size and time step in order to prevent dispersion pollution, in other words incorrect mesh velocity. As a rule of thumb, 1/20th of wavelength and inverse of maximum frequency are selected for mesh size Δx and time step Δt, which provides $V = \Delta x / \Delta t$ where V is wave velocity. Because of non-axisymmetric loading, the geometry is modelled in three dimensions using the symmetry to decrease the number of degrees of freedom. Quadratic polynomial and tetrahedral elements are selected for meshing. The numerical simulations are conducted using COMSOL Multiphysics Software.

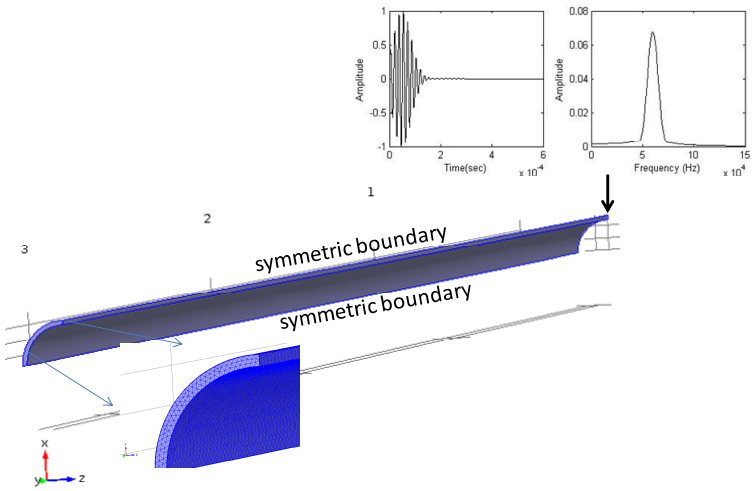


Figure 5. Finite element model showing the mesh density and the loading function

Figure 5 shows the symmetric boundaries and the density of meshing. The pipe diameter and thickness are the same as the laboratory model. The length is 3.35 m to understand the wave attenuation profile. The mesh size and time step are set as 3.33 mm and 1.11 μsec, respectively. The loading function is defined by $F(t) = \sin(\omega t) e^{-(t-\tau)^2/\tau^2}$ where ω is circular frequency; τ is the period of modulated signal taken as the period of the peak frequency. The frequency is 60 kHz with six cycles to reach a narrowband frequency response which enables the attenuation profile of a specific frequency. The coating material and other damping sources such as connections can be included into the model to obtain the attenuation curves.

2.2 Waveform Signatures and Attenuation Curve

Figure 6 shows two displacement histories in the direction of loading at 0.8 m and 1.1 m away from the source. Based on the first arrival of waves at 0.8 m location, the wave velocity is calculated approximately as 2600 m/sec which agrees with the expected value. The load function applied at the end of pipe is in radial direction; however, due to asymmetric nature, it causes displacements in all directions. Therefore, a complex waveform signature is obtained. At some locations, the wave is distorted because of overlapping of various wave mode arrivals.

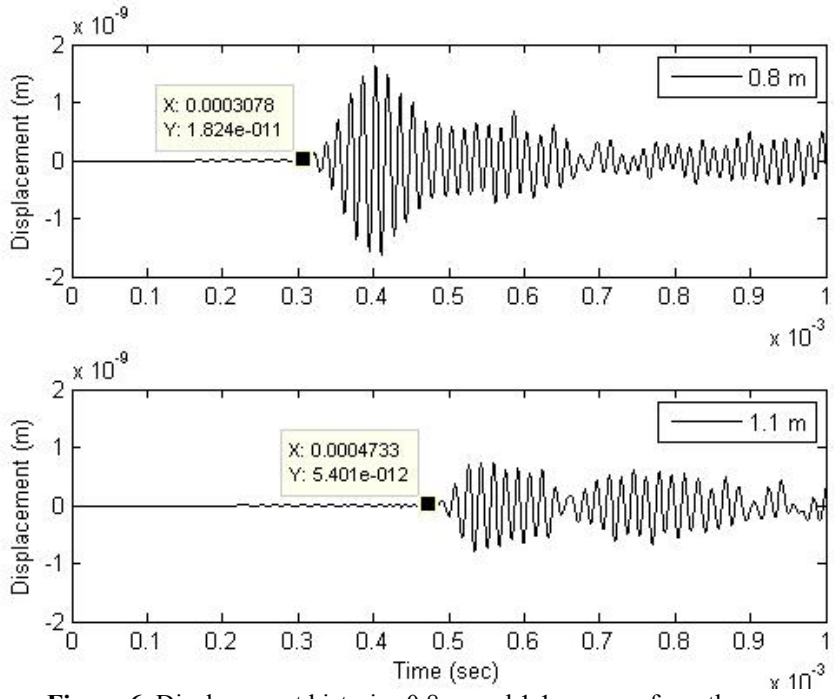


Figure 6. Displacement histories 0.8 m and 1.1 m away from the source

Figure 7 shows the maximum displacement values at every 0.1 m away from the source and the exponential curve fit with the equation as $A(m) = 1.29E - 10e^{-0.1929x}$. The attenuation coefficient $\beta(60kHz)$ as -0.1929 causes dB loss as 1.68 dB/m using the equation $dB = 20\log(\beta(60kHz)x)$. As an example, for the unburied pipe and orifice 1 with 68.95 kPa internal pressure, the amplitude is 58 dB. Assuming the minimum threshold as 35 dB, the required sensor spacing is about 14 m.

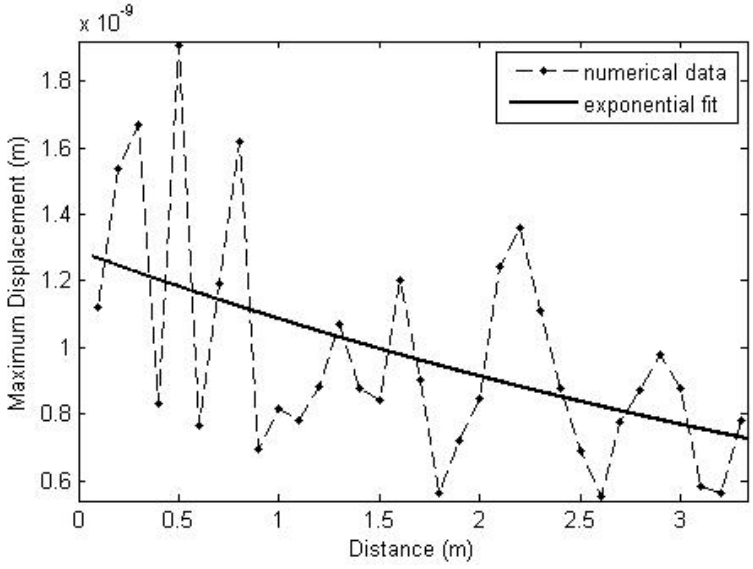


Figure 7. Maximum amplitude values and exponential curve fit

3. Discussion and Conclusion

The identification of sensor spacing for leak localization is studied using experimental and numerical data. The experiments on a small scale pipe provide the AE amplitudes at different leak rates and pipeline conditions; the numerical method allows attenuation coefficient for the particular geometry and frequency. For different sensors, the AE leak

amplitude at near field can be estimated through comparing the sensor sensitivities. For different frequencies, the numerical study can be repeated for obtaining the attenuation coefficient and identifying the sensor spacing

Acknowledgement

This research is supported by National Science Foundation, Grant ECCS 1125114. The authors would like to thank Waltz Tsang and Aerielle Karr for their help during testing.

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