CEPA STUDY ON CHARACTERIZATION OF PIPELINE PRESSURE FLUCTUATIONS IN TERMS RELEVANT TO STRESS CORROSION CRACKING

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ABSTRACT

Neutral-pH stress corrosion cracking (SCC) is a topic of significant interest to pipeline operators in the Canadian Energy Pipeline Association (CEPA). In recent years there has been a shift in laboratory SCC research toward investigating cracking phenomena under more realistic environmental and physical loading conditions. To support this move, CEPA has been active in collecting pressure-time data from its varied membership of liquid and gas pipeline companies. Histories of pressure fluctuations in operating systems have been characterized in terms of loading cycles, R-values (the ratio of minimum to maximum stress) and strain rates. These parameters are relevant to the design of laboratory experiments for the investigation of SCC. An overview of the data is presented for both liquid and gas pipelines in various service applications.

INTRODUCTION

Neutral pH stress corrosion cracking (SCC) is a topic of significant interest to pipeline operators in the Canadian Energy Pipeline Association. As the name implies, SCC requires that stress be applied to susceptible material in a conducive environment. Despite the fundamental importance of stress, the connection between the cyclic pressure fluctuations experienced in an operating pipeline and the probability of a near neutral-pH SCC failure is not yet well described.

With the exception of full scale pipe tests done at CANMET, NRCan[1,2,3,4,5], relatively little work has been reported in the open literature on characterization of actual stress regimes nor on results of tests to determine their impact on SCC in line pipe. Notable exceptions are studies conducted by Parkins[6] and by NOVA Gas Transmission[7]. NOVA Research & Technology Corporation (NRTC) has shown that the extent of growth seen for early stage SCC clusters in a realistic environment does not depend on hoop stress in the range 40 to 100% SMYS where fluctuations in stress were limited to <2%[8].

The objective of this study was to compile and study operating pressure information for a wide range of pipeline systems with the aim of enabling researchers to design relevant laboratory SCC programs. It is hoped that the research results obtained will ultimately enable pipeline operators to evaluate the role of operating pressure in the development of SCC on specific pipelines.

ANALYTICAL METHODS

Characterizing cyclic stress has been performed for many years in terms of testing for fatigue of structures. In that regard parameters of significance relate to the magnitude of the stress, the amplitude of pressure fluctuations, and the frequency of loading, important inasmuch as the rate of fatigue damage accumulation is proportional to it. A number of techniques have been developed over the years to quantify the components of the cyclic stress profile for fatigue testing and life prediction; a number of these methods are described in ASTM Standard E1049-85[9] (Level Crossing Counting, Peak Counting, Simple Range Counting and Rainflow Counting).

Pipeline SCC, in contrast to pure fatigue, involves environmental degradation and a greater emphasis on loading rates. In the case of high-pH SCC the cracking rate is believed to be limited by a film rupture and dissolution step; arguably the competing reactions responsible for film formation and rupture elevates the significance of the strain rate[10]. Similarly, in the case of near-neutral pH SCC, slow strain rate tests suggest a role of hydrogen in the cracking mechanism[11]. To determine loading rates from operating pressure histories an alternate proprietary technique[12], similar in some respects to Simple-Range Counting, was developed to characterize the operating pressure spectra of pipelines in terms of:

- R-value: a measure of amplitude given as the ratio of minimum to maximum pressure or hoop stress;
- maximum stress and local stress maxima
- strain rate

The program analyses the pressure time data in the time domain and determines local maxima and minima for pressures. Figure 1 depicts the logic used in the calculation of R-values and strain rates[12]. In this figure points A, C, E, G, I and K represent pressure minima. Points B, D, F, H, J and L represent pressure maxima. As long as the general pressure time transient is increasing R-values are calculated from a fixed point. For example, starting with A as the first minimum point, R ratios are calculated for the series:

A ---------------> B
B ---------------> C
C ---------------> D
D ---------------> E
E ---------------> F

At the point F the general pressure transient starts to decrease and R-values are then calculated from the next minimum value which in this case is point I. Hoop stress values were calculated using the Barlow Equation. The hoop strain rate was calculated as the derivative of the calculated strain and the loading rate.

Fast Fourier Transform Analysis of the pressure data submitted to this study failed to identify unique frequencies corresponding to cycles of stress induced by identifiable mechanisms in pipeline operation.

DATA

For the purpose of this work the input data was the time-based record of compressor or pump discharge or suction pressure as routinely measured for system control. In some cases, readings used in the study were being collected at relatively high sampling rates for other reasons. In no case was special equipment installed to collect the data.

Data was collected from both liquid hydrocarbon as well as natural gas pipelines through the cooperation of member companies in CEPA. Time periods analyzed in detail varied from several days to several weeks depending on the number of measurements available and the continuity of the data. Sampling frequencies varied from 1.4 measurements per minute to 4.5 per hour (0.023 - 0.00125 HZ) for the liquid pipeline data, and 0.7 per minute to 2.5 per hour (0.012 - 0.00069 Hz) for gas, with data from one gas line at the high frequency of 6 per minute (0.1 Hz).

Pressure histories were received for pipelines with diameters ranging from NPS10 to NPS42. Operations included storage facilities, pure transmission lines, and lines feeding distribution systems.

RESULTS

Pressure Records

Figures 2A and 2B summarize operating pressure data for natural gas and liquid hydrocarbon pipelines respectively.

Five of the six gas pipeline data sets are from lines with a design factor of 0.72; a sixth, G2, has a design factor of 0.80, Figure 2A. Actual pressures in the case of the former range from 45% SMYS up to the MOP. In the case of one line (G1) there are periodic pressure reductions of approximately 12% SMYS for unknown reasons related to system operation.

In the case of the three liquid pipeline data sets the pressures range from approximately 10% to 50% of SMYS, Figure 2B. All three data sets display large and, compared to gas, frequent pressure swings; two of the three display well-defined and abrupt pressure reductions, which last from one half day to two days.

R-Values

The ratio of minimum to maximum pressure or R-value is used to characterize swings in operating pressure. These swings in pressure at a given level of maximum stress can impact crack growth especially in later stages of near neutral-pH SCC where mechanical factors will tend to dominate the cracking process.

Figure 3 presents a cumulative distribution of R-values for the natural gas and liquid hydrocarbon pipeline data. The three data sets with consistently lower R-values are the liquid lines. The tenth percentile in the cumulative distributions is below R = 0.7 for liquid lines whereas gas line data sets have their tenth percentile consistently above 0.9.

Strain Rates

The strain rate reported reflects the rate of change in pressure or hoop stress. In all cases no systematic or significant difference is seen in the strain rate during loading (increasing pressure and stress) and unloading (decreasing pressure and stress).

Figure 4 shows a typical pattern of strain rates over time. In general, the strain rate is relatively constant. Only a few changes occur at a strain rate more than an order of magnitude greater than the mean. In some cases, high strain rate excursions seemed to be focused in time suggesting that these excursions may be related to specific operating events.

The distribution of average strain rates is shown in Figure 5. Twenty of twenty-three pressure histories examined showed average strain rates less than 10^{-8} s^{-1}.

DISCUSSION

Discharge pressures from pumping or compressor stations recorded at different frequencies have been analyzed for oil and gas pipelines from NPS10 to NPS42 operating in different situations. Analysis of the data allows a number of insights and comparisons.

Frequency of Data Collection

An apparent operating pressure history can be obtained from on line pressure measurements in various ways. In simple recording systems, a set sampling frequency is used to collect the data. Sampling frequencies are selected to collect a manageable amount of data. Data reduction is achieved in other systems by averaging frequent readings over set periods of time or by recording measurements only when significant change occurs.

This sampling frequency can influence the final result. Figure 6 shows one possible consequence of setting the sampling frequency too low. The slower sampling frequency (in this case one quarter the rate of the faster one) results in a representation of the operating pressure history in which the number of pressure cycles is reduced as are the extremes of pressure evident in the more frequent sampling pattern.

In an attempt to evaluate appropriate sampling frequencies, operating pressure histories were examined to determine the largest change seen for successive pressure measurements. For gas pipeline data, an 8% pressure change (R=0.92) occurred between two successive data points collected two minutes apart. For liquid pipelines a 32% pressure change (R=0.68) was seen in a sampling interval of 45 seconds. It is thus conceivable that significant pressure changes can occur in quite short intervals especially in liquid lines. From the perspective of the Nyquist sampling theorem, to derive an accurate pressure history the sampling interval may, depending on the variability of the pressure, have to be as short as a few tens of seconds. Such a high sampling rate is not always warranted. In cases such as line G2 in Figure 2A, data was collected every six seconds but significant pressure changes occurred very slowly. In this case the high sampling frequency appears to offer little benefit. In other cases, slower sampling frequencies may be distorting the actual operating pressure history by under-representing the number and size of pressure cycles.

Pressure Data and R-Values

As Figures 2 and 3 illustrate gas lines operate at consistently higher mean stresses and R-values than the liquid lines for similar modes of operation. This is related to the viscosities and pressure drops of the fluids being transported. Furthermore, particular data sets display groupings of R-values that appear to reflect different operating modes.

The biggest factor influencing the mean R-value is the consistency of the mode in which a pipeline is operated. Transmission lines kept in consistent operation show very high mean R-values > 0.95, Figure 3. In contrast, low mean R-values are associated with operations that see shifting modes of operation. A striking example of the effect of changing the operating mode is seen for some gas pipelines feeding distributions systems where the line is packed during one phase then drawn down in the next phase, or lines used for injection and withdrawal of gas from storage facilities. In one case studied, approximately 40% of the pressure readings occurred in a charging mode where pressure climbed from 4800 kPa to 10,300 kPa while the balance of the measurements come from a discrete low pressure operating mode with pressures of 700 kPa or less. The mean R-value for such a disparate operation was understandably low (0.53) as every flow reversal passed through a pressure minimum of zero. In the case of batched liquid pipelines studied, mean R-values ranged from 0.4 to 0.9.

The data set from other operations included time periods when the pipeline experienced changes in the operating mode for unspecified reasons. A large transmission line for example showed two modes of operation in which pressure readings fell by 80% from routine operating levels for 10% of the time history provided. This resulted in a reduction of the mean R-value to 0.93. Similarly, facilities showing three distinct operating modes in the time history provided (*ca*. 1725 kPa 40% of the time, 3450 to 5500 kPa 20% of the time and >5500 kPa for the balance of the time) had mean R-values in the range 0.84-0.86.

Influence of Mean Operating Pressure

A crude correlation exists between the mean operating pressure and the mean R-value for both gas and liquids pipelines. This suggests that for whatever reason the absolute change seen in pressure fluctuations in pipeline operations tends to be of a similar absolute magnitude regardless of the mean operating pressure in the system. Therefore as the mean operating pressure drops, the average R-value tends to decrease. One outcome of this general observation is that the mean R-value will decrease along a section of pipeline where a significant pressure drop occurs.

Strain Rate

In general, average strain rates were in the range of 10^{-9} sec^{-1} or less with only the occasional significant excursion from this mean . A few facilities showed more variation with extreme values being clustered in time presumably around specific changes in operations but the nature of these changes has yet to be identified. It is possible that specific operating practices may result in very rapid and potentially more damaging changes in hoop stress. No correlation was observed between the strain rate and the fluid type.

A strain rate of 10^{-6} sec^{-1} would appear to represent an exceptional value.

Relation to Cracking

Other methods of characterizing pressure data have been described previously[10]. These include; Level Crossing Counting, Peak Counting, Simple Range Counting and Rainflow Counting. All of these methods are used to characterize irregular loading patterns over time in terms of a number of cycles of various sizes. Use of this information is based on the assumption that a fatigue model is applicable to crack growth.

Variations in hoop stress contribute to the growth of environmentally assisted cracking in line pipe; however, further research is required to understand the role of individual parameters such as hoop stress, R-value and strain rate in the mechanism of near neutral-pH SCC. The development of SCC proceeds through stages from initiation of cracks to final failure. The early stages are likely to be influenced by environmental factors that become less important as the process proceeds to final failure. In the final stages, crack growth is almost certainly mechanically driven through a fatigue process that depends on the cycles of stress experienced rather than the elapsed time of exposure to the cracking environment. As models become available to relate crack growth to mechanical factors in the mid to late stages of SCC development, it may be possible to rank pipelines in terms of their susceptibility to SCC failure based on operating pressure information. This may assist in the prioritizing maintenance actions on lines suspected to suffer from SCC or even enable a reduction in risk through more knowledgeable management of pipeline operating pressures.

CONCLUSIONS

The results obtained here using the NOVA Transient Pipe Stress Analysis Program[13] characterized the stress cycles, R-values and strain rates associated with individual swings in pressure within discrete time domains in operating pressure histories taken from a wide variety of pipelines. Summary information is being provided by CEPA to researchers interested in constructing relevant mechanical testing programs for laboratory work on SCC. Information on specific pipelines may also be of use in the future to pipeline operators to interpret the implications of research findings for their facilities.

In summary

1. This study gives an overview of the nature of pressure changes in a wide range of operating pipeline systems.
2. For pipelines subject to highly variable operating pressures, determination of the actual pressure pattern may require data collection at higher frequencies than presently used.
3. 90% of operating pressure variations recorded for gas transmission lines were at an R-value of 0.9 or higher. Liquid pipeline data displayed greater variation. In all

cases 10% of fluctuations were at or below R=0.7 for liquid lines.

4. For pipelines having mixed operating modes, the R-value varies more widely and the mean R-value is reduced. Average values as low as 0.83 with individual values < 0.25 were seen for discharge pressure data.
5. The amplitude of pressure swings in an operating pipeline appears to be somewhat independent of the operating pressure. This results in the reduction of R-values along sections of line showing a significant pressure drop.
6. Strain rates varied in magnitude and constancy. Average values were typically 10^{-9} sec^{-1} or less; however, a few facilities showed strain rates in the vicinity of 10^{-6} sec^{-1}. In most facilities, the strain rate was relatively constant with only occasional excursions to 10^{-8} sec^{-1}; however, a few facilities showed more variation and extreme values clustered around specific points in the time record.
7. Available methods of analysis are sufficient to construct relevant stress regimes for realistic mechanical testing tasks in laboratory investigation of the development of SCC.

RECOMMENDATIONS

- Future SCC laboratory studies should make use of realistic mechanical testing parameters relevant to actual field operations.
- Researchers and pipeline operators should develop the capability to interpret SCC laboratory results in terms of the SCC susceptibility of operating pipelines based on available operating pressure data.
- In some cases extreme values of strain rate were observed to cluster in specific time periods. Investigation of relevant operating histories could identify specific operating practices that lead to high strain rates.

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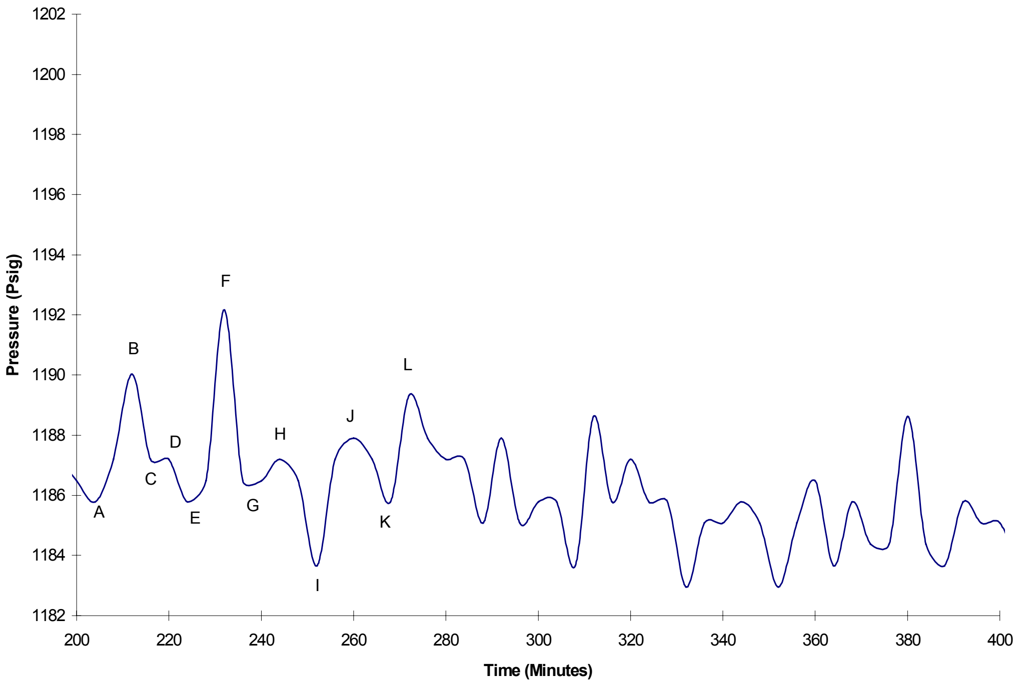

Figure 1: Schematic illustration of a pressure record showing maximum and minimum pressures, A to L.

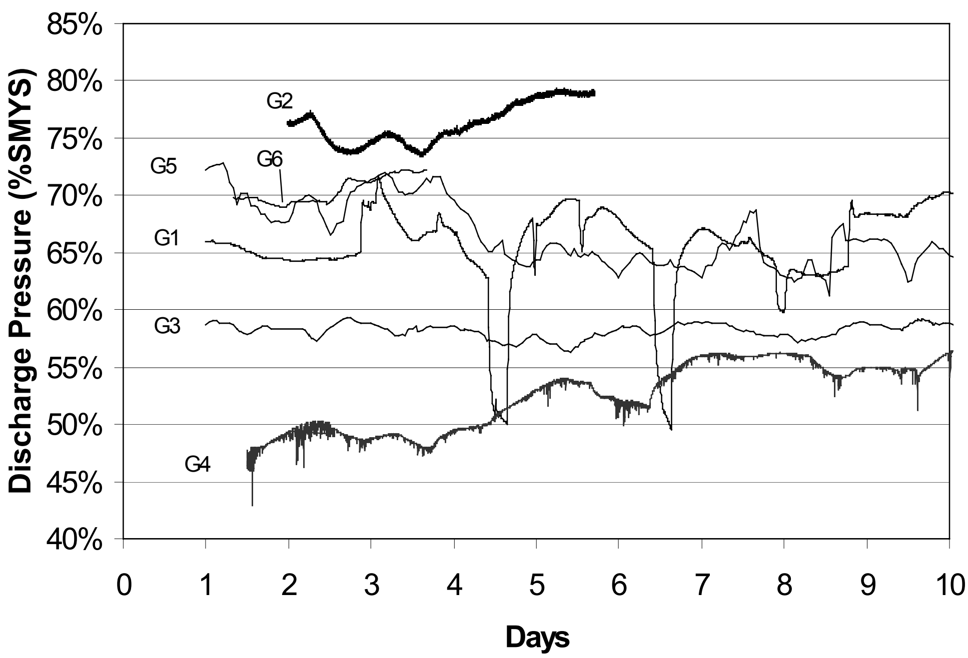

Figure 2A: Operating pressure histories for six gas transmission pipelines.

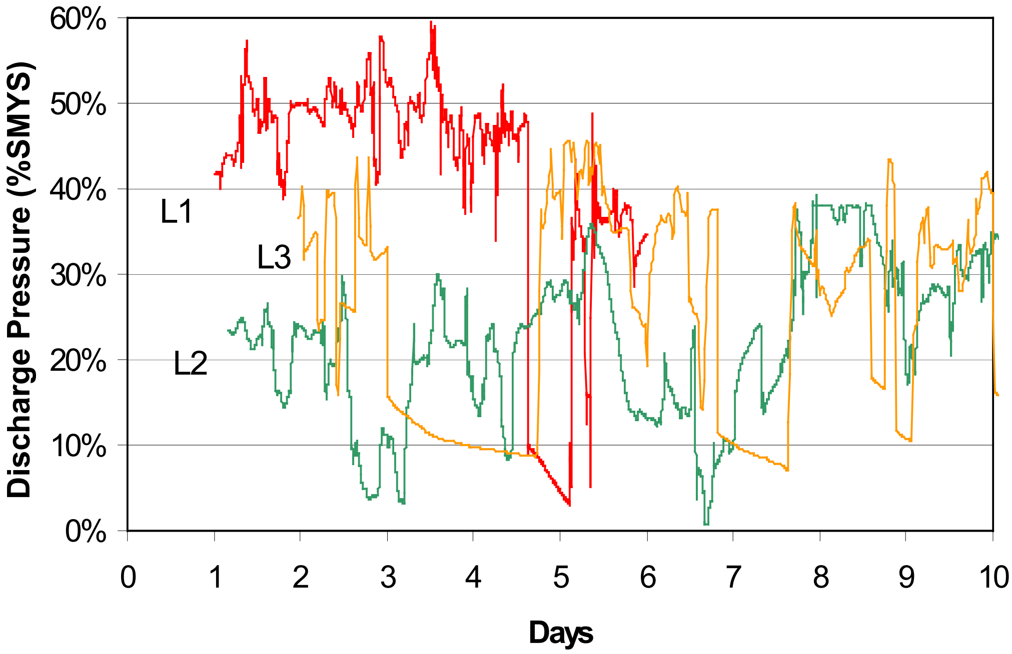

Figure 2B: Operating pressures for three liquid hydrocarbon pipelines.

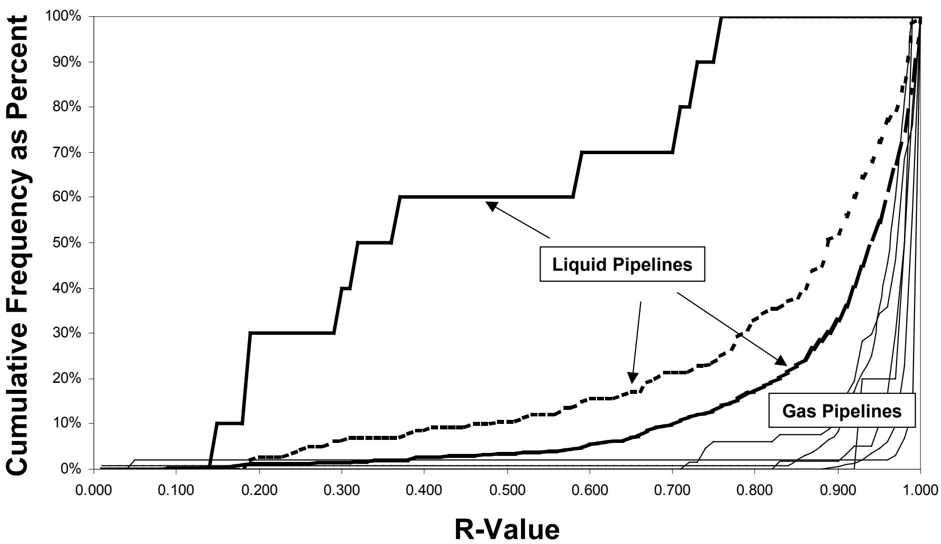

Figure 3: Distribution of R-values for operating pressure cycles showing liquid hydrocarbon pipelines have generally lower R-values than gas transmission pipelines.

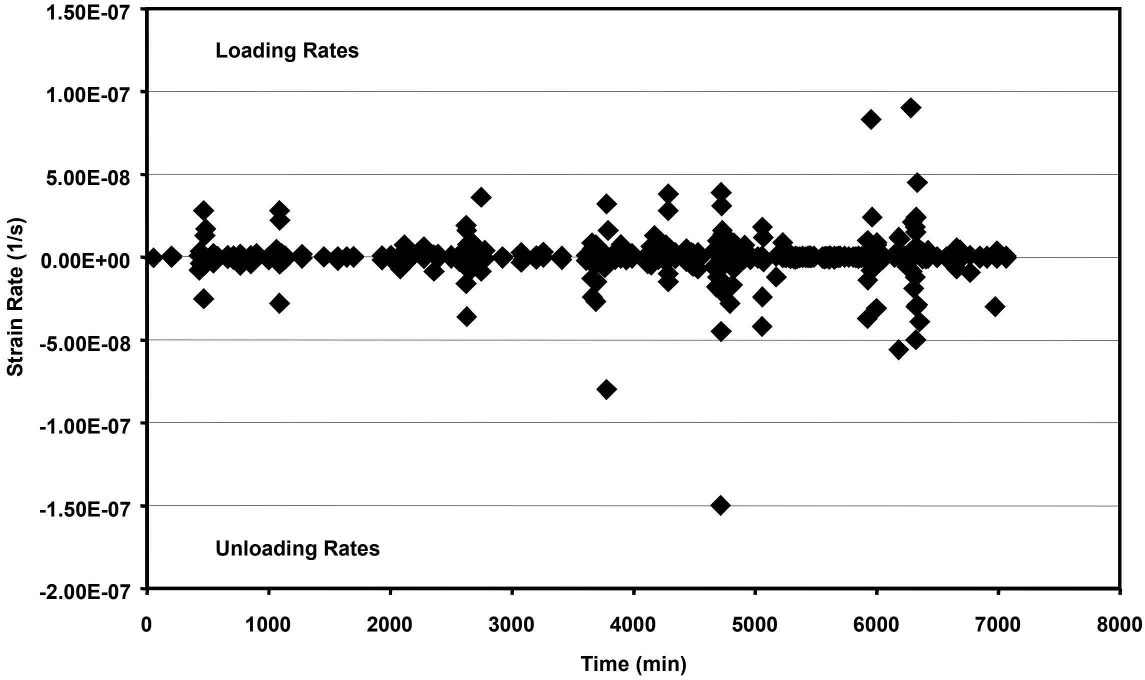

Figure 4: Hoop strain rates calculated for pressure fluctuations measured over time on an operating pipeline.

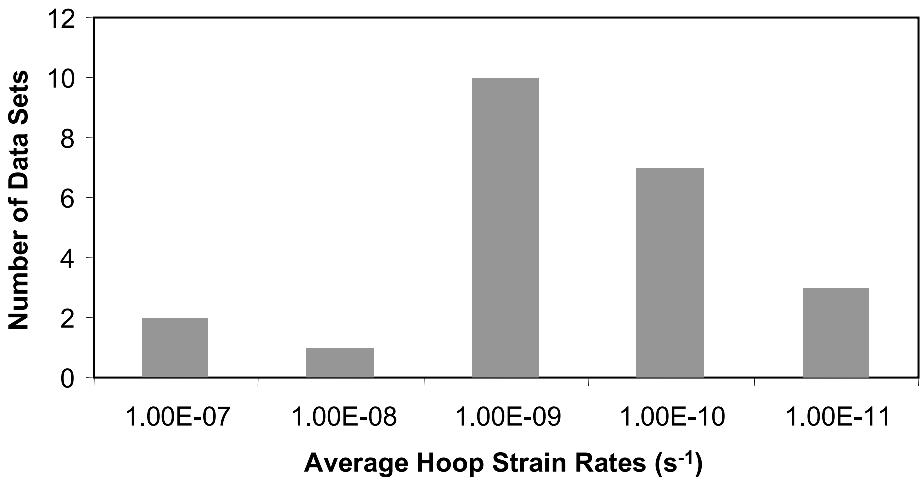

Figure 5: Distribution of average hoop strain rates for twenty-three operating pressure histories taken from various oil and gas pipelines.

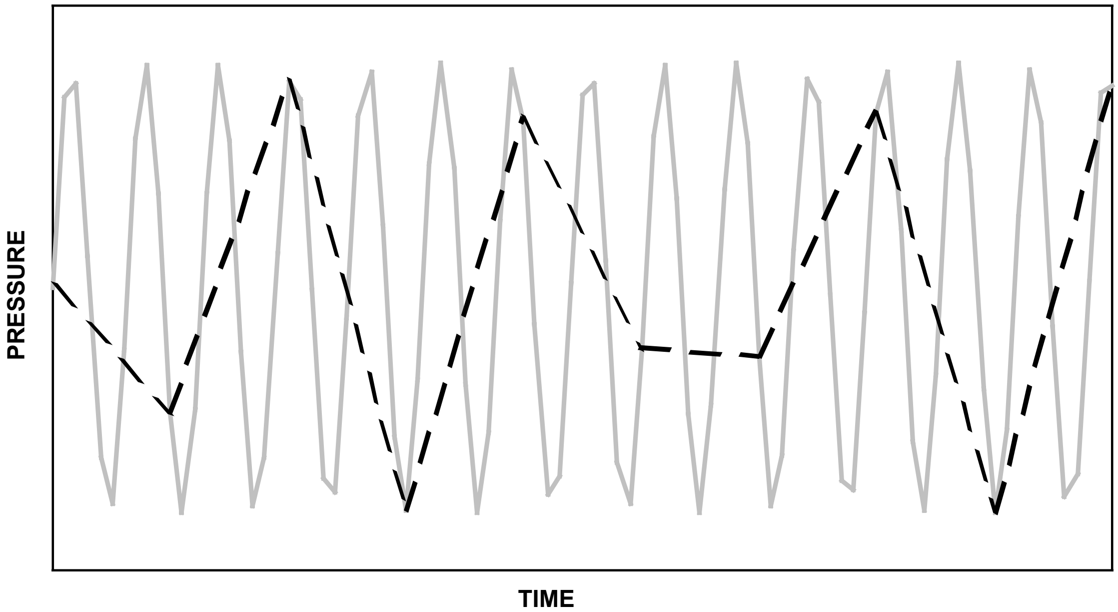

Figure 6: Schematic of waveform 'aliasing' caused by sampling at too low a frequency.