PERIODIC HYDROSTATIC TESTING OR IN-LINE INSPECTION TO PREVENT FAILURES FROM PRESSURE-CYCLE-INDUCED FATIGUE

by

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INTRODUCTION

The public record[1] reveals that liquid pipeline service failures have occurred because of pressure-cycle-induced fatigue crack growth of defects. Our own familiarity with this phenomenon suggests that it may be more common than the public record reveals. However, we are also well aware that such failures have been prevented by preemptive responses on the part of pipeline operators worldwide. In this paper we reveal a technique that we have used to assist operators in addressing and controlling this phenomenon. We are reasonably certain that similar techniques applied by others have also been successful in preventing failures.

CRACK GROWTH FROM AN INITIAL IMPERFECTION

Pipelines, as constructed, may contain defects or imperfections arising from the pipe-manufacturing process from transit fatigue or from construction flaws. If these defects are severe, they will not survive the initial preservice hydrostatic test and will be eliminated. If they are not severe enough to fail in the test, they will remain in the pipeline, and they may become enlarged by pressure-cycle-induced fatigue. This situation is illustrated schematically in Figure 1a by the failure-pressure-versus-crack-size relationship. Figure 1a shows that no flaw larger than a_T can survive the initial test. The test establishes an initial safety margin because flaws must be larger than a_T (as large as a_S) to fail at the maximum operating pressure (MOP). If a mechanism exists for flaws to grow in service, the margin will be eroded and, as shown in Figure 1b, after a time t_1 an existing flaw of size a_T may grow to a size a_S. At that point, a service failure at the MOP becomes possible. However, if this situation is anticipated and if the rate of crack growth is predictable, a pipeline operator can make a timely intervention before the size a_S is reached. By conducting a current hydrostatic test, the operator can either remove those flaws that now have sizes larger than a_T or at least prove that they do not exist. The maximum remaining defect size is then reset to a_T.

SERVICE PRESSURE CYCLES AND THEIR EFFECT

A typical 15-month service pressure spectrum for a liquid pipeline is shown in Figure 2. Literally hundreds of large variations in pressure are experienced as various pumping schemes are used to meet shippers' requirements and to take advantage of varying electric-power rates between daytime and nighttime. Variations in pressure cause variations in hoop stress, and if a longitudinally oriented crack is present, the variation in stress can cause the crack to grow. Figure 3 presents the mathematically defined term "stress-intensity factor". The latter is the crack-driving force. As "K" is proportional to S, ΔK is proportional to ΔS. In other words, fluctuating stress causes K to fluctuate, and a fluctuating K represents the factor that will cause a crack to grow. Notice that K is a function of crack size "a" as well as a function of S. In fact, the log of the rate of crack growth, da/dN, has been shown to be proportional to the log ΔK as shown in Figure 4. This results in an equation for da/dN. By solving for dN and integrating one can predict the number of cycles that are required to grow the crack from an initial size a_T established by a test to the size a_S that will fail at the MOP. This relationship is often called the "Paris" law after the person who first proposed it. It is a form of linear-elastic fracture mechanics.

Description of the Model

Crack-growth models can be used to evaluate the effect of pressure-cycle-induced growth on the possibly remaining flaws in a pipeline. One such model, referred to as RETEST and described in detail in Reference 2, is based on linear-elastic fracture-mechanics (LEFM) principles and assumes that a family of "initial" defects is present in the pipe.

As a first step in a RETEST analysis, the user establishes the sizes of both the initial and the final defects. The initial defects (or cracks) are assumed to be the largest sizes that could barely survive at the hydrostatic test pressure. The final defects (or cracks) are assumed to be those that would fail at the maximum operating pressure (MOP). The hydrostatic test pressure level, the pipe geometry (diameter and wall thickness) and the material properties, flow stress and fracture toughness, are important parameters in this assessment. They determine the initial crack sizes that could survive the hydrostatic test and the final crack sizes that will fail at the MOP. Since the number of defects of all possible sizes (length-and-depth combinations) that could survive the hydrostatic test is infinite, the analysis utilizes nine defect depths ranging from 10 percent to 90 percent through-the-wall thickness (in 10-percent increments). The corresponding length for each of these nine defects is determined based on its depth, the hydrostatic test pressure, and the Charpy V-notch impact energy and flow stress. A mathematical model is used to calculate these sizes. It is explained in detail in Reference 3.

The pressure-cycle data are used as the mechanism for fatigue crack growth. The actual pressure data are rainflow-cycle counted[(4)]. This procedure appropriately matches pressure pairs (peaks and valleys) for the pressure-cycle spectrum. The pressure-cycle data (ΔPs) are applied to each of the nine defects defined above until the defect reaches the final size (calculated as explained above) that will fail in service. A linear-elastic model[(5)] is used to calculate the applied stress-intensity-factor ranges (ΔKs) that cause the cracks to grow in response to the pressure cycles (ΔPs). This approach is suitable because the cracks grow in microscopic steps in an essentially elastic-strain regime in response to the cycles of pressure. The length of time (in years) to failure is then determined based on the representative time period of the pressure-cycle data. For example, if the pressure-cycle data represent 1 month of operations and the analysis applies these same pressure data 18 times before the defect reaches a critical size, the fatigue life of the defect is 1.5 years (18 months).

The rate of crack growth induced by the pressure-cycle spectrum is modeled using the Paris Law equation:[6]

$$\frac{da}{dN} = C\,(\Delta K)^n$$

where "a" is the crack depth, "N" is the number of pressure cycles, "$\frac{da}{dN}$" is the amount of crack growth (da) per cycle, and ΔK is the stress-intensity factor for a given pressure cycle. The constant "C" and the exponent "n" characterize the rate of fatigue crack growth applicable to the particular material and environment of interest.

Material Properties

Properties Used in the Analysis. The material properties, C and n, appropriate for the analysis are typically established on the basis of an actual fatigue-related leak in a pipeline. The constants are determined based on the apparent dimensions of the initial defect, which has been observed to grow to failure after a certain number of years in service.

The yield strength (YS) of the pipe material is used in the analysis to define a "flow stress". The flow stress (FS) of the pipe material is taken to be the YS plus 10,000 psi.

The fracture toughness of the material is approximated by an equivalent full-size Charpy V-notch impact energy. This value of toughness is based on the defect size and failure pressure level determined during the examination of the leak, and it is based on the apparent size of the flaw that caused the failure.

Operating-Pressure Cycles

For the typical pipeline to be analyzed, pressure data can be supplied in digital format for relevant pump stations. These pressure data can be acquired simultaneously at 15-minute intervals for representative operating periods.

To calculate pressures at intermediate points between each of the stations we typically use a gradient factor of K= sp. gr. of product * 0.433 to represent head loss. An average of the specific gravities of all products can be used. Accordingly, the pressure, P_X, at any point between stations under flowing conditions is

$$P_X = (P_1 + K h_1 - P_2 - K h_2)\left(\frac{L_2 - L_X}{L_2 - L_1}\right) - K\,(h_X - h_2) + P_2 \quad ,$$

where

P_1 = Pressure developed at upstream station during operation, psig
P_2 = Suction pressure at downstream station during operation, psig
K = psi/foot of head

L_1 = Mile Post upstream, miles
L_2 = Mile Post downstream, miles
L_X = Mile Post of Location X , miles
h_1 = Elevation of upstream, feet
h_2 = Elevation of downstream, feet
h_X = Elevation of Location X, feet.

This method is used to determine the pressure cycles for all of the chosen locations between pump stations.

TYPICAL RESULTS

Typical partial results of RETEST-1 analyses are shown in Table 1. Table 1 presents years to failure for six locations on a particular pipeline. Each line in Table 1 represents one analysis case. Numerous cases may have to be run for a given pipeline because of changes in features, hydrostatic test pressures, and operating circumstances along a pipeline. In Table 1 several cases are shown for illustrative purposes, but only four of the nine initial flaw depths are shown to simplify the table. Only growth in depth, not growth in length is considered, because experience shows that flaw length changes very little with pressure cycles, an amount that can be ignored for analysis purposes. This is not to say that length is not important. It is important because it affects the failure pressure and the crack-driving force significantly.

While one would suspect that the most fatigue-prone regions of a pipeline would be the regions immediately downstream from the pump stations, this is not always the case. For example, one critical case in Table 1 is Case 6. It has about the same time to failure as Case 1. While its location is 30 miles from the pump station, thus making it subject to a smaller range of pressure per cycle, it happens to be a point where the wall thickness changed. As a result, the stress cycles based on the pressure cycles are nearly as large as those at the pump station where the wall thickness is greater. The point is that several areas have to be checked to determine which one governs the retest interval.

The choices of cases for analyses are driven by changes along the pipelines as mentioned previously. Case 1, for example, was chosen because it was just downstream of the first pump station where one would expect the largest ranges of pressure cycles. Cases 2 and 5 were chosen because of the relatively low test-pressure-to-operating-pressure ratios at those locations. Cases 4 and 6 were chosen because even though both are quite a ways downstream from the first pump station, they represent changes in wall thickness. The pressure cycles are smaller, but the stress cycles are actually fairly large.

There are other ways to display the data obtained from RETEST analyses. These include plots of initial defect depth versus years to failure and plots of defect depth versus time (the inverse of the previous plots). The latter type of plot is useful as discussed below for illustrating the effects of test-pressure-to-operating-pressure ratio and for comparing the effectiveness of testing to in-line inspection.

It may already be clear to the reader that this type of analysis could be used to predict times to failure after an appropriate in-line inspection. Certainly that is the case. A reliable in-line tool for locating and characterizing longitudinally oriented cracks typically will have a threshold detection size. Below that threshold size, detection and sizing will be less than highly certain. Above that threshold detection and sizing is expected to be reliable to a high degree of certainty. Using that threshold size (length and depth), one can conduct a remaining-life assessment for the flaw that is at the detection threshold size limits. The reinspecting interval can then be based on that predicted time to failure.

SAFETY FACTOR

Given the relatively recent application of remaining-life assessment to pressure-cycle fatigue in the pipeline industry, no standard exists for setting a safety factor. Traditionally, we have recommended a safety factor of two. That is, we believe that it is prudent to retest or reinspect a pipeline in which fatigue crack growth is suspected after one-half of the predicted time to failure has elapsed. This choice is based on our standard practice of making all other assumptions on a worst-case basis. For example, we assume that the largest possible undetected flaw is present. We also use worst-case crack-growth rates unless a less aggressive crack-growth rate has been demonstrated. And, we use the most aggressive pressure-cycle spectrum when the spectra change from time to time. We believe that the factor of two adequately covers the uncertainties regarding changes in operations and unknown factors in the environment that might accelerate crack growth.

OTHER CIRCUMSTANCES

In the foregoing discussions, we have described only the mechanics of the analysis process and the standards for its use. In this final section, we think it is important to point out factors that should be taken into account if and when a pipeline operator chooses to conduct periodic hydrostatic testing or in-line inspections to deal with a known or suspected fatigue-crack problem. The following discussion leads to the conclusion that if an operator is going to the trouble and expense to conduct retesting, the highest possible test-pressure-to-operating-pressure ratios should be used. This discussion also shows that because in-line inspection will locate smaller flaws than a hydrostatic test, it can be done with less frequency than a hydrostatic test.

Figure 5 presents an actual crack-depth-versus-cycles relationship similar to one type of plot that can be obtained from a RETEST analysis. However, Figure 5 is based on an actual experiment with a particular type of pipe into which a flaw was machined. Once the flaw began to grow by the application of uniform pressure cycles, the “a”-versus-”N” relationship shown in Figure 5 was generated by continuous monitoring of the crack using the d.c. electric-potential technique. Notice that the relationship is highly nonlinear. This is because the crack-driving force, ΔK, is a function not only of ΔP (the change in pressure that was constant throughout the test), but also a function of “a” that is growing larger with each cycle. The crack-growth rate da/dN is proportional to ΔK; hence, it increases steadily.

Shown on Figure 5 are three potential levels of hydrostatic tests, each of which is considerably above the maximum pressure in the service-simulating pressure cycles (0 to 1,000 psig). The levels represent the crack depth (for a fixed crack length) that will just barely survive the test to the level shown. In other words, a crack that is 0.10-inch deep will just survive the 1,300-psig test, a crack that is 0.12-inch deep will just survive the 1,250-psig test, and a crack that is 0.13-inch deep will just survive the 1,200-psig test. The "a"-versus-"N" curve shows that the crack was initially just over 0.09-inch deep at the start of pressure cycling, and that it grew to failure in about 8,000 cycles. None of the three tests would have revealed the initial crack with its depth of only 0.09 inch. If a hydrostatic test to 1,300 psig had been conducted at any point during the 8,000-cycle life, one of two things would have happened. If the test had been conducted before the 2,000th cycle, the defect would have survived and failed 6,000 cycles later. If the test had been conducted after the 2,000th cycle but before the 8,000th cycle, the defect would have failed in the test and, thus, would not have failed in service. The important thing to remember is that the test assures a life of at least 6,000 cycles.

In a similar manner, one can assess the possible outcomes of testing to levels of 1,250 or 1,200 psig. In the case of the 1,250-psig test, the important conclusion is that the test assures a life of only 3,500 cycles because it will find the defect only after 4,500 cycles have elapsed. In the case of the 1,200-psig test by similar reasoning, one finds only a 2,200-cycle life is assured because the test would only find the defect after 5,800 cycles had elapsed.

The critical finding here is that relatively small increases in test pressure buy considerably greater assurance of serviceability. The life assured by the 1,300-psig test is 6,000/2,200 or 2.7 times that assured by the 1,200-psig test. The effect of using an in-line tool with a threshold depth detection size of 25 percent of the wall thickness (0.0625 inch in this case) is even more dramatic. The flaw would have been revealed even before the cycling started in that case.

The effect of being able to find ever-smaller flaws by means either of higher test pressure or of in-line tools with small-flaw-detection thresholds is illustrated in Figure 6. First, let us compare the relative effective intervals required for the 1,200-psig hydrostatic test versus the 1,300-psig hydrostatic test. A 1,200-psig test would have necessitated five tests within the period required for 10,000 cycles to accumulate, if one assumes that the first test is carried out before the first cycle. The second test is made at 2,500 cycles and nothing happens because the flaw is only 0.10-inch deep. It would have to be 0.13-inch deep to fail at 1,200 psig. Similarly, the third test is made at 5,000 cycles and still nothing happens. Finally, on the fourth test of 7,500 cycles, the flaw fails because it has grown to 0.16 inch (more than the 0.13-inch depth required for failure at 1,200 psig).

Now consider the 1,300-psig test. Only three tests in the 10,000-cycle time period would have been sufficient. The second test at 5,000 cycles causes the flaw to fail. Note the three tests (at 0, 5,000, and 10,000 cycles) would not have been sufficient at a test pressure level of 1,200 psig. The 1,200-psig test at 5,000 cycles would not have revealed the flaw, but the flaw would have failed in service before the third test was conducted. It should be clear on extrapolation of the "ILI" (in-line inspection) threshold size level in Figure 6 to the left, that an interval between in-line inspections much longer than the 1,300-psig retest interval would be sufficient.

The rationales derived from the discussions of Figures 5 and 6 show that great benefits are to be derived from small increases in test pressure levels or the use of in-line inspection in lieu of hydrostatic testing when it becomes necessary to address periodic revalidation of pipeline integrity. The rationale for using in-line inspection is even stronger when one considers the benefits of reduced service disruption and the fact that hydrostatic testing can be less than 100 percent effective as we describe in a companion paper(7).

Table 1. Results of RETEST Analysis

				Years to Failure for Defect with Depth-to-Thickness Ratio as Shown				
Case No.	**MP**	**Test Pressure, psig**	**Wall Thickness, inch**	**0.9**	**0.7**	**0.5**	**0.3**	**Comments**
1	368.0	2215	0.219	11.39	15.73	26.09	61.30	Pump Station
2	361.5	2159	0.219	25.74	35.46	58.14	137.39	High point
3	353.0	2376	0.219	22.59	28.70	45.47	98.43	Low point
4	347.5	1940	0.188	13.31	18.49	30.13	71.26	Change in WT
5	339.0	1880	0.188	15.93	22.83	36.84	88.72	High point
6	330.0	1626	0.156	11.78	16.32	26.63	68.15	Change in WT

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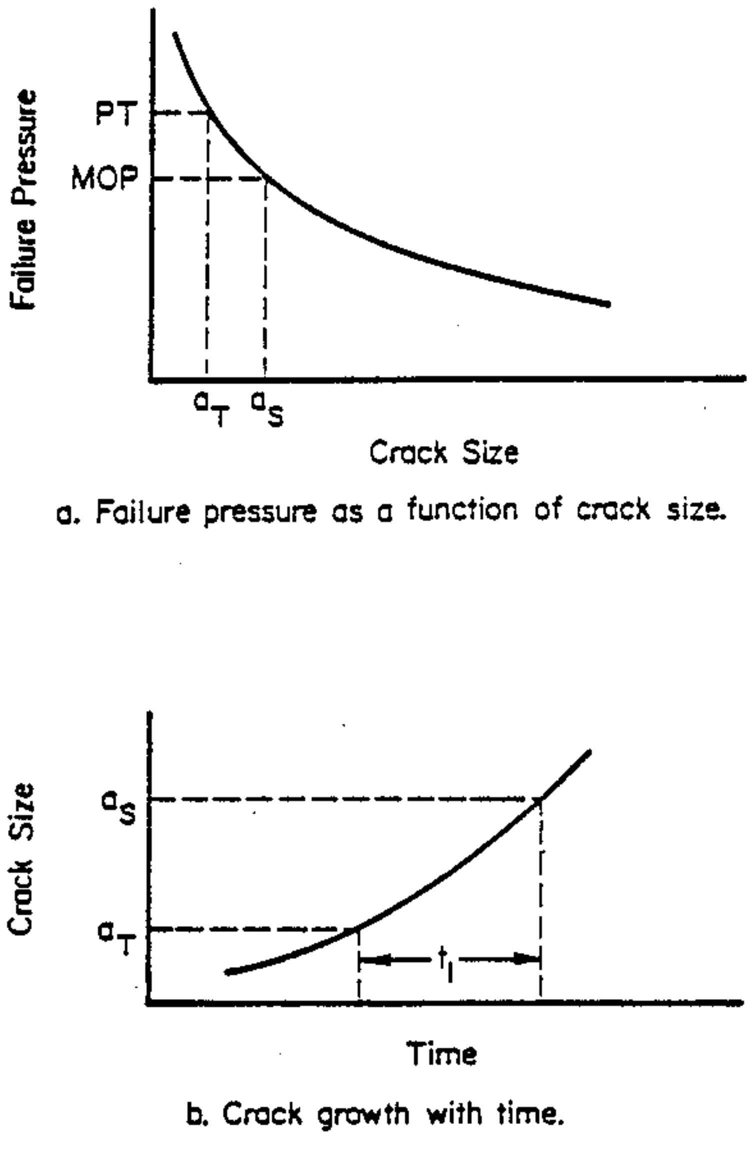

Figure 1. Effect of Crack Growth on Pipeline Integrity

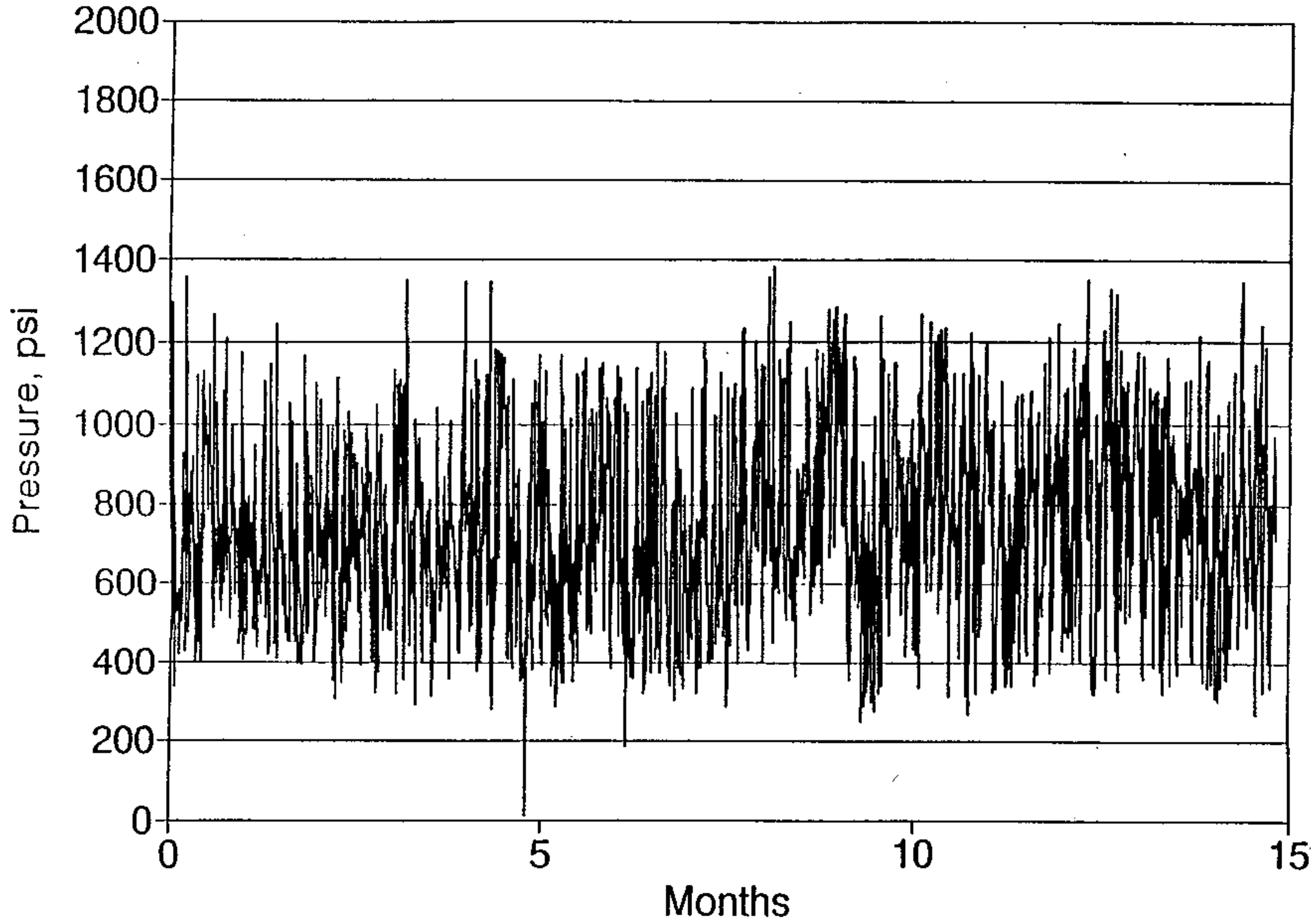

Figure 2. Pressure Versus Time for a Typical Petroleum Products Pipeline

$$K = C_1 S \sqrt{\pi \frac{a}{Q}}$$

K = stress intensity factor

S = applied stress

a = crack depth

C_1 = constant

π = π

Q = elliptical integral

Figure 3. Relationship Between Stress-Intensity Factor (Crack-Driving Force) and Applied Stress

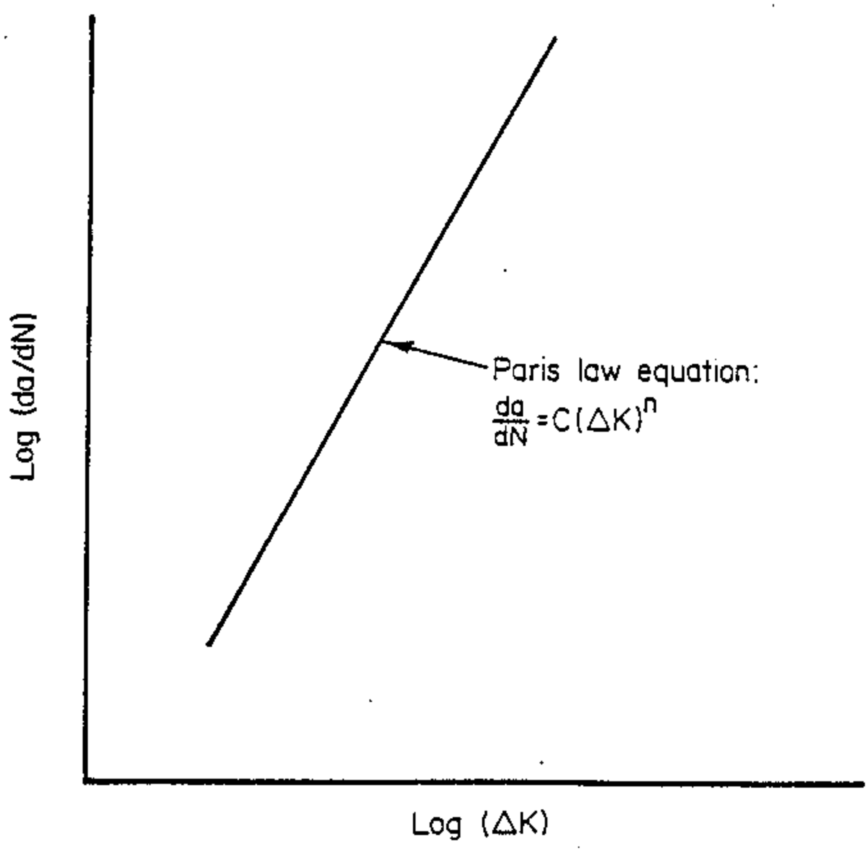

Figure 4. Typical Plot of Fatigue-Crack-Growth Rate (da/dN) Versus Change in Stress-Intensity Factor (Δk) on Log-log Coordinates Showing Paris Law Fit of the Data

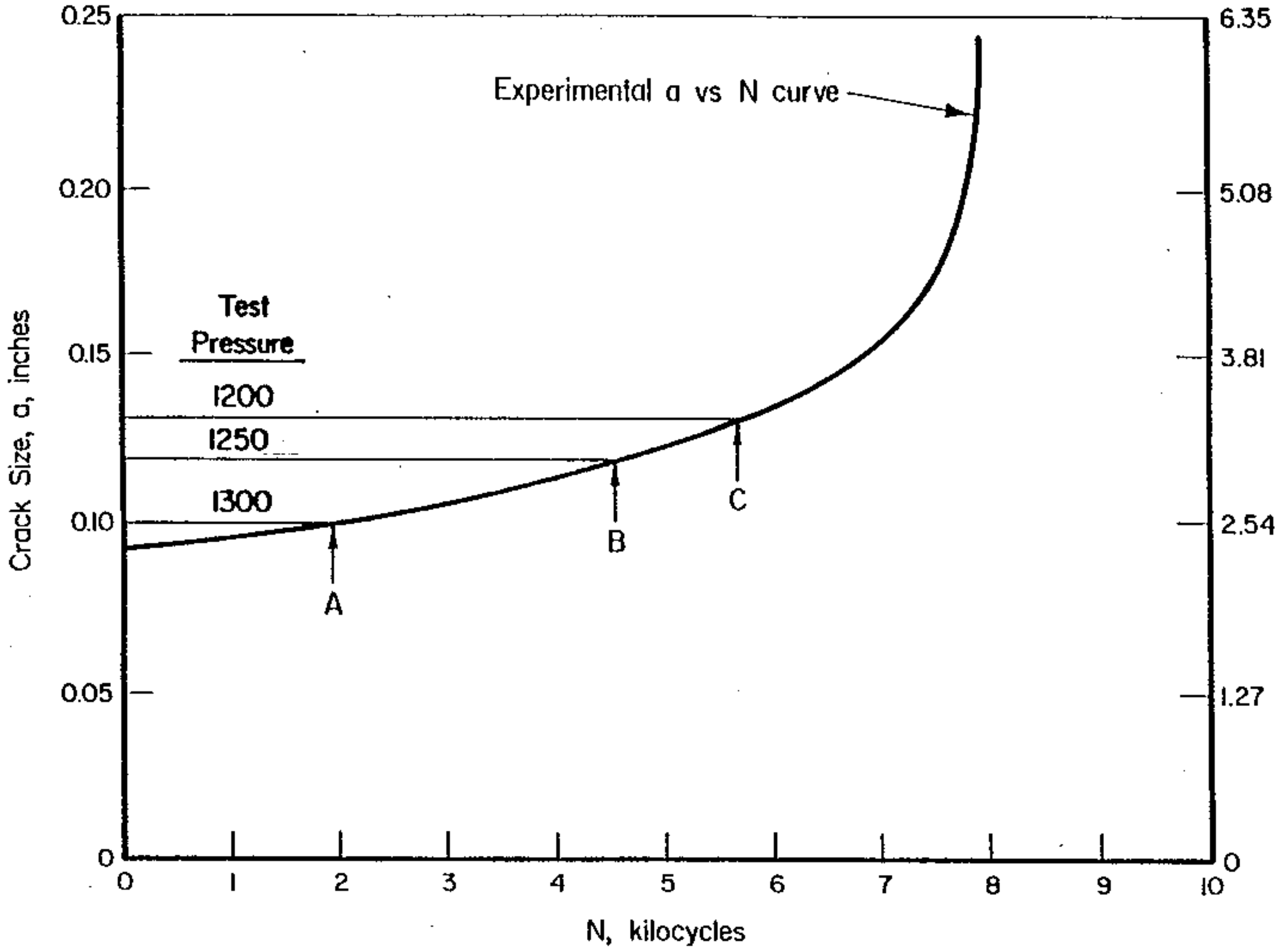

Figure 5. Example of an Actual a-Versus-N Relationship Used to Compare Effects of Initial Flaw Size

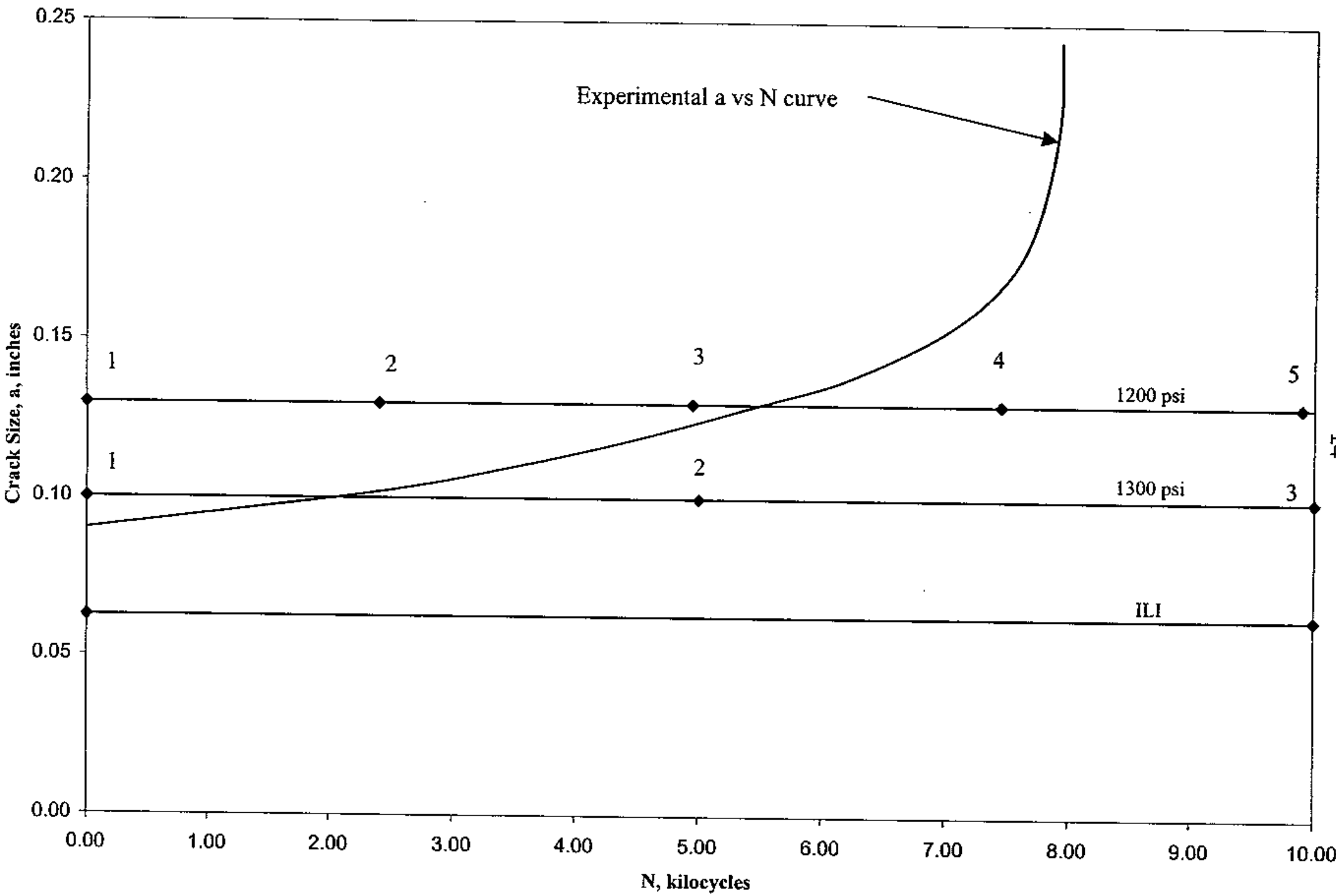

Figure 6. Example of a-vs-N Relationship Used to Compare Effects of Retest Interval