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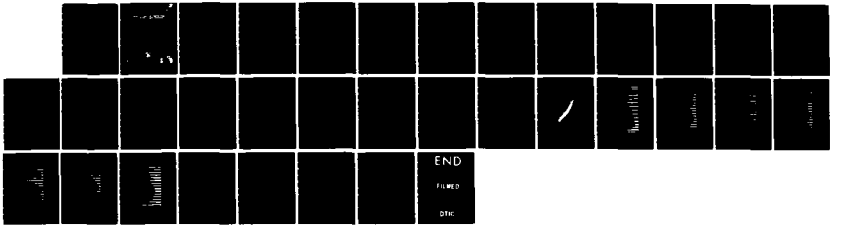

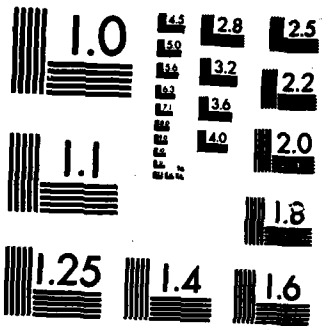

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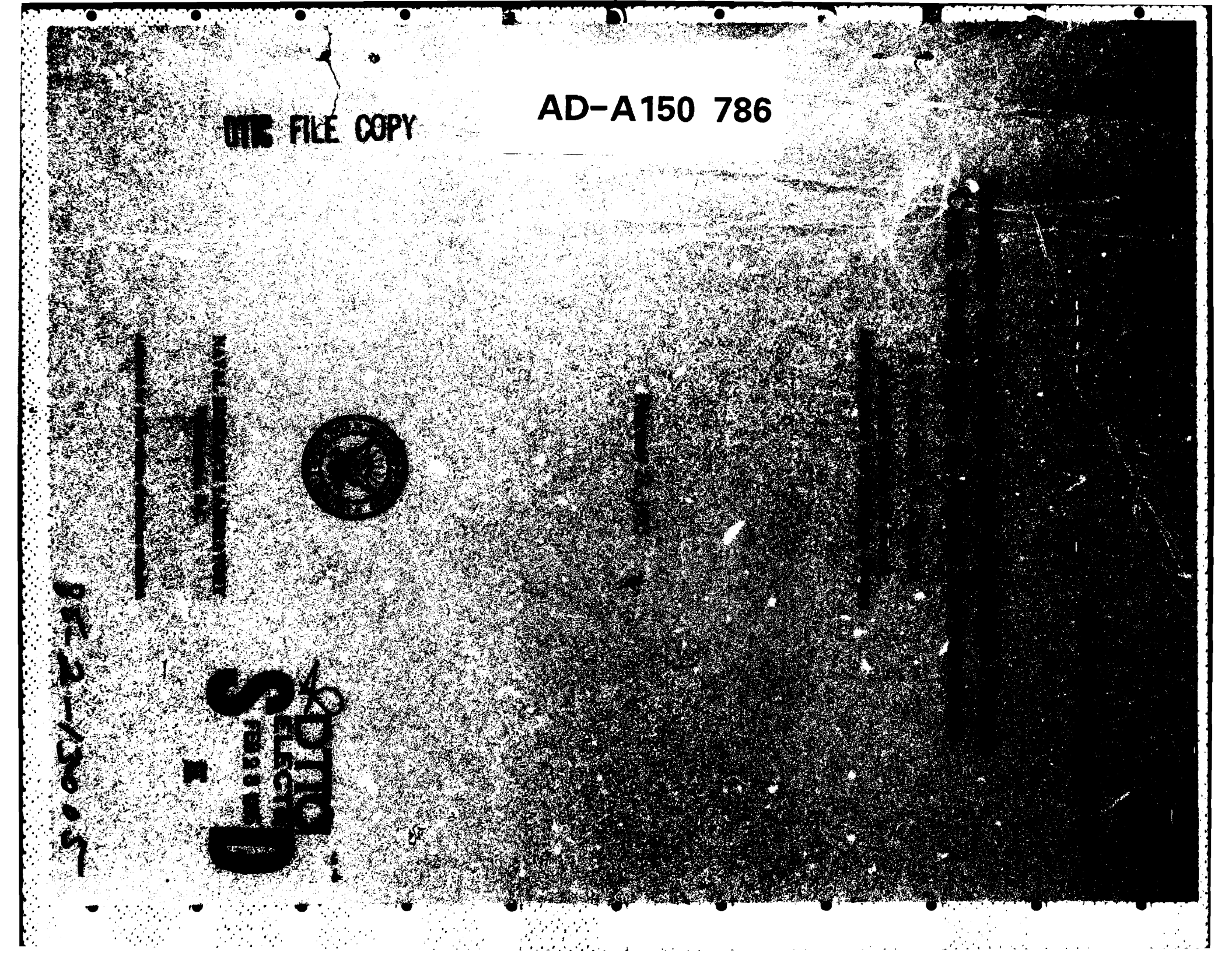

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This report describes the results of an interlaboratory test program conducted to 1) assess the variability in corrosion fatigue crack growth rate data obtained while using a proposed Navy standard test method, 2) identify and resolve problems with the proposed standard test method and 3) provide verification of the proposed standard test method. Data were generated for an HY-80 steel by 15 laboratories using 10 mm (0.4 in.) thick 1-T wedge-opening-loaded specimens. The crack growth rate data was analyzed graphically and statistically and the interlaboratory variability was determined for each set of test conditions. Owing to the lack of replicate tests, it was not possible to assess intralaboratory variability. The interlaboratory variability was evaluated on the basis of crack growth rates estimated at regular intervals of the stress intensity factor range, ΔK, from a regression analysis of the da/dN-versus-log ΔK data. Scatter in da/dN was expressed in terms of coefficients of variation, which are defined as the standard deviation divided by the mean. This statistic was used to obtain

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19. ABSTRACT (Continued)

a measure of the scatter that was independent of the mean, as the mean varied with ΔK. The coefficients of variation obtained for these estimates ranged between 0.11 and 0.37 after two outlying specimens were removed from the analysis. The highest values for the coefficient of variation were found at the two extremes of ΔK level. The corrosive effects of the aqueous environment were negligible when ΔK exceeded 60 MPa$\sqrt{m}$ (55 ksi$\sqrt{in}$) at a frequency of 0.5 Hz. It was found that use of the standard method for fatigue crack growth rates in air keeps interlaboratory variability to a minimum. The test program also revealed two areas in the proposed standard test method which require expansion. These include errors which may arise in the use of a compliance calibration to estimate crack lengths and difficulties in obtaining consistent values for electrochemical potential and pH.

CONTENTS

VARIABILITY IN CONSTANT-LOAD-AMPLITUDE FATIGUE CRACK GROWTH RATES IN MARINE ENVIRONMENTS

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INTRODUCTION

The development and application of a reliable Navy data base on corrosion fatigue crack growth rates in marine environments requires standard test methods. Experience has shown that, in the absence of common experimental procedures, interlaboratory variability amongst the data is sufficient to mask significant effects and cast doubt upon the basic premises of this technology. Therefore, a test method document was prepared to serve as an aid in enhancing the value of existing fracture mechanics fatigue crack growth rate measurement techniques for naval applications [1]. This test method document was used as a basis for an interlaboratory test program to assess the variability in constant-load-amplitude fatigue crack growth rates in marine environments.

OBJECTIVES

The objectives of this interlaboratory test program were to:

1. Assess the variability in crack growth rate (da/dN) versus stress-intensity range (ΔK) data obtained from specimens tested in marine environments by various laboratories according to the proposed Navy standard test method.

2. Identify and resolve problems with the proposed Navy standard test method.

3. Provide verification of a proposed standard test method.

APPROACH

An interlaboratory test program was planned which embodied the following characteristics:

- Material: HY-80 steel

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- Specimen type: 1-T WOL
- Number of specimens: 2 minimum
- Precracking: to be performed by participants
- Crack length measurement: COD method recommended but not required. All other methods were optional.
- Load amplitude: constant
- Load ratio: 0.1
- Waveform: sinusoidal
- Frequency: 0.5 Hz
- Environment: 3.5% NaCl solution (flowing or quiescent)
- ΔK range: approximately 25 to 95 MPa $\sqrt{m}$ (23 to 86 ksi $\sqrt{in.}$)
- Corrosion potential: freely corroding required (cathodic potential optional)
- Maximum load: 23.66 kN (5300 pounds)

15 Laboratories participated and are listed below:

Air Force Materials Laboratory
Army Materials and Mechanics Research Center
Battelle Columbus Laboratories
Benet Weapons Laboratory
Conoco, Inc.
David W. Taylor Naval Ship Research and Development Center
LaQue Center for Corrosion Technology, Inc.
Lehigh University
National Bureau of Standards
Naval Air Development Center
Quality Engineering Test Establishment
Southwest Research Institute
University of Toronto
Westinghouse Research and Development Center

Laboratory data sheets were provided to assist in the recording and reporting of data. It was requested that these data sheets be forwarded along with the reduced data and that da/dN-versus-ΔK data be reported in both tabular and graphical forms. Copies of these laboratory data sheets are included as Appendix 1.

MATERIAL

The broad scope of this program dictated that only one material be tested at this time. A 552 MPa (80 ksi) yield strength HY-80 steel plate,

manufactured by the Lukens Steel Company and donated by the David W. Taylor Naval Ship Research and Development Center, was used. HY-80 steel was selected because it is a material in use in marine environments and it is of sufficiently high yield strength that the assumptions of linear elasticity are valid over a wide range of growth rates. The chemical composition and pertinent room temperature mechanical properties of the plate used, as given by the manufacturer, are listed in Tables 1 and 2, respectively.

TEST SPECIMENS

Wedge-opening-loaded (WOL) specimens with planar dimensions corresponding to the 1-T configuration were used. Width $\underline{W}$ was 65 mm (2.55 in.) and thickness $\underline{B}$ was 10 mm (0.40 in.). Notches were machined in the T-L orientation, that is , parallel to the final rolling direction of the plate [2]. Fig. 1 shows the specimen geometry. The specimens were machined to these dimensions before distribution to participating laboratories. Additional machining for the mounting of crack-opening-displacement (COD) devices was carried out by the participants according to their individual requirements. Table 3 presents the specimen distribution and a summary of all the test conditions used in this program.

TEST PROCEDURES

Specific instructions for testing the specimens were supplied to all participants. Precracking of the specimens was performed by the participants. All tests were conducted on servo-hydraulic testing machines and at a load ratio, R (also known as stress ratio, where R = minimum load/maximum load) of 0.1. Generally, crack growth rates in salt water tend to increase with decreasing cyclic frequency [3, 4]. For medium strength steels under freely corroding conditions, a salt water environment generally has little effect on crack growth rates at frequencies greater than 1 Hz. The frequency of 0.5 Hz used for the tests in this investigation was chosen because it falls within the range of frequencies where environmental sensitivity is known to occur and it approaches loading rates which can occur in surface ship structures. The stress intensity expression recommended was taken from the literature [5]. The applied stress-intensity factor ranged from 25 to 95 MPa$\sqrt{m}$ (23 to 86 ksi$\sqrt{in}$). The relatively high initial value of the applied stress intensity factor was chosen to shorten the duration of the tests, thus making it easier for volunteer participants to fit this work into their schedules. An environment of 3.5% NaCl solution was chosen because it is easy to make and because it would vary little from laboratory to laboratory. The environment was to be either flowing or quiescent, according to the capabilities and preferences of the participants. All participants were required to test two specimens with overlapping ranges of applied stress-intensity factor under freely-corroding conditions. Additional specimens were made available to those participants who wanted to conduct tests with applied potentials.

A COD technique [6] was recommended as a means of crack length measurement. The crack length measurement interval recommended in the proposed standard test method was adopted from ASTM E 647-83, "Standard Test Method for Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8} m/Cycle" [7], in which the technique cited for crack length measurement was a

visual one. It was recognized that less precision may have been possible in the calculation of the crack length while the test was underway in the round robin test program. This was due to the fact that at low a/W ratios, a large increment in crack growth corresponds to only a small increment in crack-opening-displacement. Apart from the recommendation in the round robin test program that a COD technique be used, it is not always possible in corrosion-fatigue testing to use a visual technique because corrosion products from ferrous alloys render the environment almost opaque. In view of these considerations, laboratories were advised to use a measurement interval based on crack-opening-displacement. It was thought possible for all laboratories using a COD method to measure 0.0254 mm (0.001 in) of COD with ±10% accuracy so that COD measurement intervals of 0.0254 to 0.127 mm (0.001 to 0.005 in) were recommended to provide reasonably accurate measurements of crack length increments without sacrificing too many data points. Since the COD increment that will result from a given number of cycles can only be estimated beforehand, participants were advised to aim for COD increments of less than 0.0254 mm (0.001 in) so that a large number of COD measurements will be available at the data reduction stage. It would then be possible to discard some of the more closely spaced data points and to provide the maximum number of COD or crack length increments known with a chosen degree of precision.

It was suggested that all laboratories measure COD at two loads since it is the slope of the COD-versus-load $\underline{P}$ plot which is used to calculate the crack length. To facilitate comparison of data from different laboratories, these two loads were to be the same for all laboratories. Since it is only the upper portion of the plot which is linear, the two points recommended were P_{max} and 1/2 P_{max}. Laboratories were asked to report the effective difference in COD between the $P = P_{max}$ and $P = 0$ conditions by reporting twice the difference between the two COD values as measured above.

The participating laboratories were asked to record and report all of the pertinent information associated with precracking and crack growth. Table 4 presents a summary of the pertinent test conditions for all the tests conducted in this program. Note that while all of the laboratories were required to use the COD technique, five used additional techniques. Four laboratories used the visual technique, two used a KRAK-GAGE®* strain gage technique and one used a potential drop technique. All laboratories conducted precracking at a higher frequency than the 0.5 Hz required for crack growth rate testing and some stepped down loads and frequency during precracking. Seven laboratories measured pH and eight measured potential.

RESULTS

Participants were asked to report their results both in terms of raw COD versus-cycles (N) data and in terms of the final da/dN-versus-ΔK data. This was done to provide the opportunity to check for variability resulting from the data reduction procedures. The raw data reported, in most cases

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COD-versus-N, was converted to crack length $\underline{a}$ versus N at NRL using a compliance calibration from the literature [5]. This data was then reduced to da/dN using a seven-point incremental polynomial fit [7]. With the exception of the data for the specimen tested in air, a plot of all the data thus obtained is shown in Fig. 2. It is obvious from this plot that some specimens are outliers. These specimens, X1-16 and X1-18, were excluded from further analysis. An attempt to determine why these two specimens were outliers revealed no errors in reducing $\underline{a}$-versus-$\underline{N}$ data to da/dN-versus-ΔK, but no other conclusions could be drawn from the data on these tests.

A standard deviation approach to the assessment of interlaboratory variability was used. This involved determining the mean value of da/dN and its corresponding standard deviation (expressed in terms of a percent of the mean da/dN) at several ΔK levels. The following computational forms were used to estimate the mean and its associated standard deviation.

$$\text{mean } da/dN = \bar{Y} = \sum Y_i \; / \; Z$$

$$S = \sum \frac{Y_i - \bar{Y}}{Z - 1}$$

where Y_i is the ith value of da/dN at ΔK, $\underline{Z}$ is number of observations, and $\underline{S}$ is standard deviation. The use of a standard deviation approach to the analysis of a set of data requires that the data have a normal distribution [8, 9]. An investigation [10] into the distribution of da/dN data from 68 replicate tests within one laboratory concluded that the distribution of da/dN-versus-ΔK was described as well by a normal distribution as by any of the five other distributions considered.

A limitation of this analysis, as it applies to the as-received fatigue crack growth rate data, is the fact that all laboratories did not report da/dN values at exactly the same ΔK levels. Thus, it was necessary to either analyze data over narrow ranges of ΔK, or fit lines to the da/dN points so that da/dN estimates could be obtained for any ΔK level.

A commercially available curve-fitting computer program for a Hewlett Packard Model 9845 computer was modified to fit lines to the da/dN-versus-ΔK data. The program attempted to fit four different types of curves to the data; linear, logarithmic, exponential, and polynomial. Virtually all of the data was best described by either a first order polynomial (linear) fit or a second order polynomial fit. Therefore, the data reduction was simplified by approximating all the data by a first or second order polynomial fit. Specifically, the curves fit were of the form

$$\log \frac{da}{dN} = C_0 + C_1 (\log \Delta K) + C_2 (\log \Delta K)^2$$

where the case $C_2 = 0$ represents a linear fit. If C_2 is taken to be zero and the constants C_0 and C_1 are replaced by log C and n, respectively, then this expression, when raised to the power 10, results in the more familiar Paris Law [11]

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

Data which violated the remaining elastic ligament criterion [7]

$$W-a > \frac{4}{\pi}\left(\frac{K_{max}}{\sigma_{ys}}\right)^2$$

(where K_{max} is the maximum stress-intensity factor reached and σ_{ys} is the tensile yield strength) was excluded during the calculation of the best fit lines. The best fit lines were used to obtain da/dN estimates only within the ΔK range experienced by that specimen. Also, da/dN was not estimated for ΔK levels which violated the remaining elastic ligament criterion. Table 5 presents the goodness-of-fit statistics for each of the specimens. A high value for the F statistic indicates a good fit to the data. The goodness-of-fit represented by a particular F number is dependent upon the degrees of freedom associated with that data set. Therefore, direct comparisons between F numbers for different specimens are only possible when they share the same number of degrees of freedom. Comparison of F numbers under other circumstances requires the use of tables of the F statistic. These tables and the comparison procedures can be found in statistics texts [8, 9].

The best fit representation of da/dN was used to find fitted da/dN at regular ΔK intervals. Variability in the fitted da/dN at regular intervals of ΔK was then analyzed for each set of test conditions. (The term "fitted da/dN" is used here to describe the da/dN value falling on a line fit to all the data for a particular specimen by the curve fitting program. The da/dN values used as input to this curve-fitting program were themselves obtained by a seven-point incremental polynomial fit applied to the a-versus-N data.) Table 6 shows the variability in fitted da/dN at regular intervals of ΔK for each set of test conditions. Variability within laboratories was not analyzed as, except for one laboratory, there were virtually no replicate tests other than tests which overlapped over only a small range of ΔK.

The coefficient of variation (the ratio of the standard deviation to the mean) was computed for all of the data in Table 6. Coefficients of variation were used to describe scatter because, unlike standard deviation, they are not affected by differences in mean values. This information is plotted in Fig. 3. It is apparent from Fig. 3 that the least scatter in da/dN occurs at a ΔK level of 50 MPa$\sqrt{m}$ (46 ksi$\sqrt{in}$). It must be noted that this result may be an artifact resulting from the testing of specimens over different ranges of ΔK. The ΔK level that was most common was 60 MPa$\sqrt{m}$ (55 ksi$\sqrt{in}$) so it is possible that the low variance resulted from a sample size effect on the standard deviation. In fact, the number of points included in the estimates

of coefficients of variation varied with both ΔK level and test condition. The effects of sample size on variance are shown in Figs. 4 to 9, where variance, number of specimens and number of participating laboratories are plotted versus stress-intensity range level for each set of test conditions. Figure 4 shows that the da/dN data for the quiescent 3.5% NaCl (freely corroding) condition from 35 to 75 MPa$\sqrt{m}$ (32 to 68 ksi$\sqrt{in}$) include a relatively constant number of specimens and laboratories. Over this range, the variance of da/dN falls to a low at a ΔK level of 45 MPa$\sqrt{m}$ (41 ksi$\sqrt{in}$) and then rises again. The data shown in Fig. 5 for the quiescent 3.5% NaCl (zinc potential) condition shows the lowest variance at a ΔK level of 50 MPa$\sqrt{m}$ (46 ksi$\sqrt{in}$) and a steady rise thereafter until the number of specimens involved drops from four to two. The variance in da/dN for the flowing 3.5% NaCl (freely corroding) condition is shown in Fig. 6. The lowest value for the variance is seen at a ΔK level of 50 MPa$\sqrt{m}$ (46 ksi$\sqrt{in}$). Variance data for the flowing 3.5% NaCl (zinc potential) condition is plotted in Fig. 7. The lowest value for the variance is seen at a ΔK level of 40 MPa$\sqrt{m}$ (36 ksi $\sqrt{in}$) with higher values at all other ΔK levels. Fig. 8 is a plot of the variance data for the flowing sea water (freely corroding) environment and it shows that the variance of da/dN is a minimum at a ΔK level of 55 MPa$\sqrt{m}$ (50 ksi$\sqrt{in}$). The variance data for all specimens taken as a whole is shown in Fig. 9 along with the sample size for each computation of variance. The minimum variance is seen at a ΔK level of 50 MPa$\sqrt{m}$ (45 ksi$\sqrt{in}$). Figs. 4 to 9 show that the variance, or scatter, in da/dN is at a minimum at intermediate ΔK levels of 40-55 MPa$\sqrt{m}$ (36-50 ksi$\sqrt{in}$) and increases almost uniformly as ΔK increases or decreases beyond this intermediate range. Due to the differences in the number of specimens and laboratories involved, it is not possible to draw any conclusions about how the variance changes with environment.

The mean values of fitted da/dN from Table 5 are plotted in Fig. 10. It can be seen that, at the ΔK levels investigated, electrochemical potential, flow rate and the composition of environment have little effect on da/dN. Above 50 MPa$\sqrt{m}$ (46 ksi$\sqrt{in}$) corrosivity of the environment has no noticeable effect on da/dN.

DISCUSSION

The finding that electrochemical potential and flow rate have little effect on da/dN is an indication that, at the ΔK levels investigated, neither one of these factors has as large an effect on da/dN as the presence or absence of the 3.5% NaCl environment. It is also an indication that the standard test method [7] provides a good means of reducing the scatter in the data.

A previous interlaboratory program on fatigue crack growth rate testing [12] also found that the scatter in da/dN was at a minimum at intermediate levels of ΔK. The variability found at the highest and lowest values of ΔK was considered to be increased by the deviations from the model used to describe da/dN-versus-ΔK.

During the conduct of the interlaboratory test program, several participants requested clarifications of areas of the proposed standard test method. Available clarifications and unresolved problem areas are discussed below.

It was found necessary to take into account the COD measurement location when converting COD measurements to crack lengths. The original document [5] from which the compliance calibration in the proposed standard test method document was taken lists compliance calibrations for several COD measurement locations. The proposed standard test method document mentions neither the change in compliance calibration with measurement location nor the availability of compliance calibrations for several measurement locations.

The compliance technique requires knowledge of the elastic modulus, E. In practice, the value of E which is used is often not that obtained from a standard test for elastic modulus, but rather is a value chosen to force the compliance calibration to yield some optically measured crack length. Problems arise in that the value calculated for E varies with crack length and load. Many optical measurements of crack length introduce a significant degree of uncertainty into the calculation of E. Measurements made before a test is completed do not detect or include the effects of crack front tunnelling. If a beach mark is not available between the end of the precrack and the point at which the remaining linear elastic ligament criterion is no longer satisfied, then questions arise concerning the validity of the compliance calibration. The optically measured crack length is usually substituted into an equation for compliance as a function of dimensionless crack length, (a/W). The modulus can be determined from this equation because it is the only unknown on either side of the equation. Crack lengths are determined from compliance measurements by substituting this modulus into an equation for (a/W) as a function of compliance. A small error arises because the two equations differ by more than a rearrangement of terms.

The electrochemical variables of pH and potential were found to vary with measurement location. These phenomena are not discussed in the proposed standard test method document. In view of the observed dependence of pH and potential on measurement location, it would seem that the minimum requirements for these measurements be that they be consistently made in the same location and that the measurement location be reported.

One participant noted that pH would rise considerably over the reading period. Since the electrodes were within 50 mm (2 in.) of the specimen it was believed that local effects rather than bulk solution properties were being measured. This pH rise was found to occur even when the size of the environmental chamber was increased from approximately 1150 ml (1.2 qt.) to approximately 4500 ml (4.7 qt.) capacity. The final procedure adopted involved removing a small amount of the bulk solution (approximately 50 ml) (1.7 oz.) and measuring the pH while stirring the sample of environment. Readings taken in this manner stabilized fairly readily. Another participant obtained stable pH readings using a similar procedure in which a small amount of solution was sampled out of the environmental chamber.

The proposed standard test method recommends that the COD gage be mounted on knife edges which are either integral or attached. No methods of attachment are specified. Common practice is to attach the knife edges with screws. One participant reported that he successfully used adhesive bonding for tests in air but that this method was unsuccessful for tests in an aqueous environment.

In addition to the recommended clip gage, two participants used a thin-film bondable transducer, commercially available under the name KRAK-GAGE®*, to measure crack lengths. The basic principle of the KRAK-GAGE employs an indirect direct current potential measurement technique. One participant reported using the following procedure. A KRAK-GAGE was bonded on one side of the specimen surface with adhesive. The gage was subsequently coated with Petro Wax to provide protection against the corrosive attack of salt water. A small pump was employed to continuously circulate the salt solution across the crack front so that the build-up of sediments on the small fractured surfaces of the KRAK-GAGE could be avoided, ensuring the correct measurement of crack length. KRAK-GAGE estimates of crack length were found to agree more closely with visual measurements than with compliance estimates possibly because compliance estimates of crack length are influenced by crack front tunneling, while visual measurements and KRAK-GAGE estimates are not. The KRAK-GAGE was also found useful for automated data acquisition [13].

SUMMARY

An interlaboratory (round robin) testing program was conducted to (1) assess the variability in corrosion fatigue crack growth rate data obtained while using a proposed Navy standard test method document, (2) identify and resolve problems with the proposed standard test method and (3) provide verification of the proposed standard test method. Data on fatigue crack growth rates in marine environments were generated for an HY-80 (80 ksi or 552 MPa yield strength) steel, and the results were expressed in terms of linear-elastic fracture mechanics parameters. Data were generated at 15 different laboratories with 10 mm (0.4 in.) thick WOL specimens. The crack growth rate data (da/dN-versus-ΔK) were analyzed graphically and statistically and the interlaboratory variability was determined for each set of test conditions. Owing to the lack of replicate tests, it was not possible to assess intralaboratory variability.

The interlaboratory variability encountered in the round robin test program was evaluated on the basis of growth rates estimated at regular intervals of the stress intensity factor range from a regression analysis of log da/dN-versus-log ΔK. The coefficients of variation obtained for these estimates were found to range between 0.11 and 0.37 when the data for all the specimens except for two was considered. The larger values for the coefficient of variation were found at the two extremes of ΔK level, both when all the specimens were considered and when each set of test conditions were considered. This was in part due to the smaller number of data points

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available at the two extremes of ΔK level. However, the same results were obtained from an analysis of the data over ranges of ΔK level where the number of data points at each ΔK was constant.

An analysis of the mean crack growth rates for all the sets of test conditions revealed no noticeable effects of potential, flow rate or composition of the simulated sea water environment at the loading frequency investigated. In addition, the corrosive effect of the aqueous environment was negligible above a stress intensity factor range of 60 MPa$\sqrt{m}$ (55 ksi$\sqrt{in.}$).

The interlaboratory test program also revealed two areas of the proposed Navy standard test method document which require expansion. The first involves possible sources of error which could arise in the use of a compliance calibration to estimate crack lengths. The two most common sources of error are failing to account for the distance of the compliance gage from the standard location and errors in the estimation of an elastic modulus. The second area involves changes in the measured values of pH and potential. Although the proposed standard test method document mentions the variation of potential with time, it does not mention that both pH and potential vary with measurement location.

CONCLUSIONS

- Variability in da/dN is a minimum at intermediate values of ΔK.
- The corrosive effects of the aqueous environment became negligible when ΔK exceeded 60 MPa$\sqrt{m}$ (55 ksi$\sqrt{in.}$) at a frequency of 0.5 Hz.
- The standard test method for fatigue crack growth rates should stress the importance of compliance measurement location.
- An optimum technique needs to be defined for estimating Young's modulus from a combination of optical and compliance measurements.
- An optimum procedure for pH measurements needs to be defined.
- Use of the standard method for fatigue crack growth rates in air keeps interlaboratory variability to an acceptable minimum.

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13. P. K. Liaw, H. R. Hartmann and E. J. Helm, "Corrosion Fatigue Crack Propagation Testing with the KRAK-GAGE● in Salt Water," Engineering Fracture Mechanics 18 121-131 (1983).

Table 1 - Chemical Composition of HY-80 Steel Test Plate

Element	Weight Percent
Carbon	.14
Manganese	.28
Phosphorus	.005
Sulfur	.017
Copper	.12
Silicon	.20
Nickel	2.21
Chromium	1.23
Molybdenum	.24
Vanadium	.003
Titanium	.002

Table 2 - Room Temperature Mechanical Properties of HY-80 Steel Test Plate

Yield Strength		Ultimate Strength		Elongation
MPa	ksi	MPa	ksi	%
607	88.0	692	100.3	34
633	91.8	716	103.8	35

Table 3 - Summary of Specimen Identifications

LAB	TEST CONDITIONS					
	QUIESCENT 3.5% NaCl (FREELY CORRODING)	QUIESCENT 3.5% NaCl (ZINC POTENTIAL)	FLOWING 3.5% NaCl (FREELY CORRODING)	FLOWING 3.5% NaCl (ZINC POTENTIAL)	FLOWING SEAWATER (FREELY CORRODING)	AIR
	X1-5					
A	X1-41					
	X1- 7					
B	X1-26					
	X1-16					
C	X1-18					
	X1-35					
D	X1-36					X1-21
	X1-69					
E	X1-50					
	X1-51					
F	X1-62					
	X1-63					
G		X1-43	X1-27	X1-23		
		X1-44	X1-30	X1-37		
		X1-46	X1-47	X1-70		
		X1-68	X1-48	X1-71		
H				X1-3		
			X1-4			
I			X1-31			
			X1-33			
J			X1-49			
K			X1-54			
			X1-55			
			X1-56			
L			X1-57			
M			X1-60			
			X1-61			
N			X1-67	X1-17		
			X1-72	X1-19		
				X1-64		
				X1-65		
					X1-13	
O					X1-15	

Table 4 - Summary of Test Conditions

Identification		Precracking			Testing			Environment						Growth Data	
Lab ID	Specimen ID	P_{max} ksi	P_{max} ksi	Frequency Hz	P_{max} ksi	P_{max} ksi	Frequency Hz	pH	Conductivity mmhos	Temperature °C	Dissolved Oxygen ppm	Potential mV	Solution	Form of Raw Data Reported	Other Crack Length Monitoring Methods
A	X1-5		10.01	Varied	1.001	10.01	0.5	6.9		21			OPC	COD	Vis.
A	X1-11		Varied	Varied	1.007	10.07	0.5	6.9		20			OPC	COD	Vis
B	X1-7		Varied	10	1.000	10.00	0.5	8					OPC	COD	
B	X1-13		Varied	Varied	1.453	14.53	0.5	8					OPC	COD	
C	X1-10	2.000	8.000	20	8.004	8.24	0.5			20		-1000	OPC	a,ii	
C	X1-12	8.000	8.000	10	8.000	8.40	0.5			20		-1000	OPC	a,ii	
D	X1-21	1.165	11.65	10	1.400	10.50	2			21			AIR	a,ii	
D	X1-35	Varied	Varied	Varied	1.201	12.01	0.5	6.0-8.0		21		-650 vs Ag/AgCl	OPC	a,ii	
D	X1-36	Varied	Varied	Varied	2.207	22.07	0.5	6.0-8.0		21		-650 vs Ag/AgCl	OPC	a,ii	
D	X1-60	Varied	Varied	Varied	1.201	12.01	0.5	6.0-8.0		21		-650 vs Ag/AgCl	OPC	a,ii	
E	X1-59	2.207	22.07	Varied	2.207	22.07	0.5	6.3				-650 vs SCE	OPC	a,ii	
E	X1-61	1.400	14.00	Varied	1.400	14.00	0.5	6.3		20		-650 vs SCE	OPC	a,ii	
F	X1-62	1.400	14.00	5	1.400	14.00	0.5	6.1				-650	OPC	COD	
F	X1-63	2.100	21.00	5	2.100	21.00	0.5	6.9				-650	OPC	COD	
G	X1-33	1.400	14.00	5	1.400	14.00	0.5						FSN	COD	
G	X1-37	1.400	14.00	5	1.400	14.00	0.5						FPC	COD	
G	X1-38	2.207	22.07	5	2.207	22.07	0.5						FPC	COD	
G	X1-37	1.400	14.00	5	1.400	14.00	0.5						FSN	COD	
G	X1-43	1.400	14.00	5	1.400	14.00	0.5					-1000	GSN	COD	
G	X1-44	1.400	14.00	5	1.400	14.00	0.5					-1000	GSN	COD	
G	X1-45	2.207	22.07	5	2.207	22.07	0.5					-1000	GSN	COD	
G	X1-47	1.400	14.00	5	1.400	14.00	0.5						FPC	COD	
G	X1-48	2.207	22.07	5	2.207	22.07	0.5						FPC	COD	
G	X1-69	2.207	22.07	5	2.207	22.07	0.5					-1000	GSN	COD	
G	X1-70	2.207	22.07	5	2.207	22.07	0.5						FSN	COD	
G	X1-71	2.207	22.07	5	2.207	22.07	0.5						FSN	COD	
H	X1-3			1	2.222	22.22	0.5			22			FPC	a,ii	
H	X1-4			5	1.344	13.44	0.5			22			FPC	a,ii	
I	X1-31	2.200	22.00	10	2.200	22.00	0.5	5.6		21			FPC	a,ii	
I	X1-32	1.400	14.00	10	1.400	14.00	0.5	5.5		21			FPC	a,ii	
J	X1-40	1.017	10.17	1	1.017	10.17	0.5	6.5	47.00	27.5	7.5	-650	FPC	COD	Vis,P.D.
K	X1-34	1.200	13.34	10	1.779	17.70	0.5			22			FPC	a,ii	
K	X1-58			10	0.000	0.000	0.5			22			FPC	a,ii	
L	X1-46	1.201	13.34	10	1.201	13.34	0.5					-650 vs SCE	FPC	COD	Vis.
L	X1-67	1.201	13.34	10	1.007	10.07	0.5					-650 vs SCE	FPC	COD	Vis.
M	X1-49	1.200	12.00	20	1.412	13.00	0.5			24			FPC	a,ii	Vis., IG
M	X1-51	1.200	12.00	20	2.200	22.40	0.5			24			FPC	a,ii	Vis., IG
N	X1-17		Varied	10	2.207	22.07	0.5			21.1			FSN	a,ii	IG
N	X1-18		Varied	10	1.201	13.34	0.5			21.1			FSN	a,ii	IG
N	X1-66		Varied	10	2.207	22.07	0.5			21.1		Varied	FSN	a,ii	IG
N	X1-68		Varied	10	1.201	13.34	0.5			21.1		Varied	FSN	a,ii	IG
N	X1-57		Varied	11	1.201	13.34	0.5			21.1		-650	FPC	a,ii	IG
N	X1-72		Varied	11	2.207	22.07	0.5			21.1		Varied	FPC	a,ii	IG
O	X1-13				2.207	22.07	0.5						SSA	COD	
O	X1-16				1.400	14.00	0.5						SSA	COD	

ksi = 6.895 kpa
*OPC is Quiescent 3.5% NaCl (freely corroding)
AIR is Air
FSN is Flowing 3.5% NaCl (slow potential)
FPC is Flowing 3.5% NaCl (freely corroding)
GSN is Quiescent 3.5% NaCl (slow potential)
SSA is Flowing Seawater (freely corroding)
**Vis. is Visual
P.D. is Potential Drop
IG is KRAK-GAGE® *

*Hurcon Corporation, Chaska, MN 55318, U.S.A.

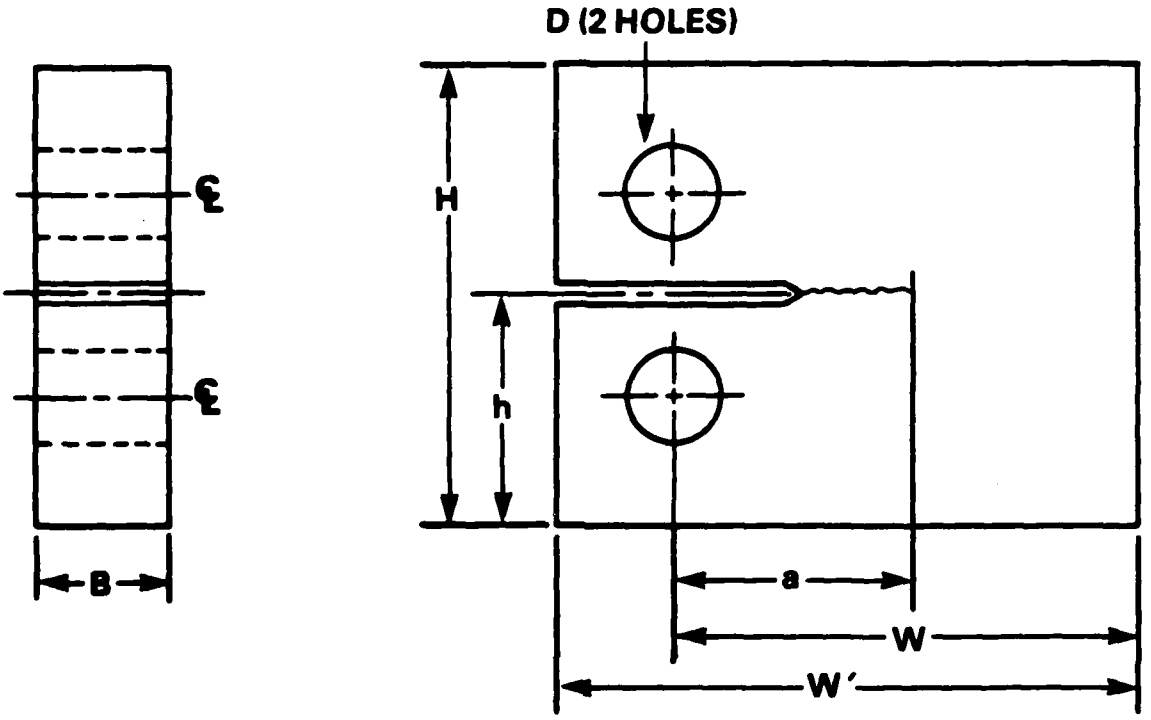
Table 5 - Statistics for Regression Lines Fit to da/dN Versus ΔK Data

Specimen	Degrees of Freedom		Sum of the Squares		Mean Squares		F	Line Fit Coefficients log ((da/dN) = C_0 + C_1 (log Δk) + C_2 (log Δk)^2)		
	Regression	Residual	Regression	Residual	Regression	Residual	Regression	C_0	C_1	C_2
X1-3	2	23	0.544	0.001	0.272	0.000	10207.686	11.13544	-21.28579	6.50386
X1-4	1	38	0.699	0.008	0.699	0.000	3161.188	-6.40882	1.28544	0.00000
X1-5	1	35	1.839	0.003	1.839	0.003	716.199	-11.67524	3.16277	0.00000
X1-7	1	16	0.183	0.005	0.183	0.000	598.897	-6.51016	1.31845	0.00000
X1-13	2	98	3.475	0.011	1.737	0.000	6876.343	0.03686	-9.53815	3.44360
X1-15	2	89	6.629	0.030	3.313	0.000	9940.910	3.52602	-13.99013	4.80363
X1-16	2	16	2.512	0.228	1.256	0.014	88.039	-71.95317	71.68957	-19.98086
X1-17	2	45	2.511	0.353	1.256	0.008	160.048	38.23002	-61.28316	14.81949
X1-18	2	15	4.355	0.184	2.177	0.011	199.712	-36.84938	31.23185	-8.28023
X1-19	1	47	1.933	0.228	1.933	0.005	397.636	-6.83376	2.14849	0.00000
X1-21	2	43	9.204	0.051	4.602	0.001	3888.970	-7.81236	-1.08210	1.17030
X1-23	2	6	0.510	0.004	0.255	0.001	422.510	12.61470	-24.82714	8.10891
X1-26	2	80	0.486	0.003	0.248	0.000	4072.248	-5.16734	-2.98067	1.35344
X1-27	2	13	0.465	0.011	0.247	0.001	287.923	13.38873	-24.90107	7.63103
X1-30	1	8	0.642	0.006	0.642	0.001	1119.474	-13.14734	3.93736	0.00000
X1-31	2	21	1.271	0.003	0.635	0.000	4699.223	3.20185	-12.98038	4.31161
X1-33	2	26	0.906	0.020	0.453	0.001	581.447	1.11514	-10.48833	3.64235
X1-35	2	36	2.967	0.016	1.486	0.000	3313.982	0.82021	-10.51477	3.74027
X1-36	2	19	1.016	0.002	0.508	0.000	4269.142	3.98987	-13.40798	4.49464
X1-37	1	19	1.472	0.022	1.472	0.001	1346.397	-10.84161	2.61219	0.00000
X1-41	1	99	4.722	0.399	4.722	0.007	657.022	-16.39721	2.44987	0.00000
X1-43	2	16	1.556	0.018	0.778	0.001	694.611	1.64823	-11.38570	3.97140
X1-44	2	14	1.357	0.043	0.679	0.003	222.133	6.04839	-16.48051	5.48510
X1-46	2	11	0.624	0.006	0.312	0.001	604.939	3.68239	-13.27311	4.38946
X1-47	2	15	1.292	0.015	0.646	0.001	644.046	12.57277	-23.70948	7.48791
X1-48	1	10	0.515	0.005	0.515	0.001	976.037	-11.87383	3.24788	0.00000
X1-49	2	7	0.425	0.031	0.212	0.004	48.010	29.60191	-44.34217	13.89160
X1-50	2	39	1.875	0.003	0.937	0.000	9886.469	4.01940	-13.74957	4.54271
X1-51	2	12	1.455	0.003	0.728	0.000	2928.648	8.67618	-20.63857	6.63882
X1-54	2	25	3.151	0.039	1.576	0.002	1017.513	7.31689	-18.28570	6.08539
X1-55	2	21	2.898	0.074	1.299	0.004	367.834	-23.90695	29.61473	-8.94889
X1-56	2	28	1.482	0.236	0.741	0.008	87.974	7.10188	-16.61288	5.34882
X1-57	2	35	2.660	0.146	1.325	0.004	316.085	0.68819	-10.48883	3.77479
X1-58	2	47	1.871	0.023	0.936	0.000	1913.682	7.35857	-18.24288	6.09132
X1-61	2	31	1.166	0.009	0.583	0.000	2029.695	6.28891	-16.68043	5.04774
X1-62	2	7	0.076	0.001	0.037	0.000	434.983	1.51276	-11.03888	3.68883
X1-63	1	16	1.072	0.023	1.072	0.001	788.881	-11.69494	3.18089	0.00000
X1-64	1	28	0.679	0.078	0.679	0.003	243.036	-11.73651	3.16210	0.00000
X1-65	1	46	1.429	0.044	1.429	0.001	1697.808	-9.34888	1.65444	0.00000
X1-67	1	46	0.361	0.042	0.361	0.001	343.129	-9.19700	1.73882	0.00000
X1-68	1	12	0.537	0.003	0.537	0.000	2341.727	-11.3351	2.99832	0.00000
X1-69	2	39	3.431	0.018	1.716	0.000	3707.389	-.76212	-6.66666	3.21883
X1-70	2	14	0.674	0.009	0.337	0.001	898.083	15.95799	-28.98144	7.98474
X1-71	2	12	1.391	0.011	0.695	0.001	738.389	30.21386	-42.19111	12.27888
X1-72	2	40	0.966	0.008	0.483	0.000	2427.619	3.33246	-13.3343	4.61988

Table 6 - Variability in Fitted Crack Growth Rates

Test Conditions	Statistic*	Stress Intensity Factor Range, MPa$\sqrt{m}$														
		25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
Quiescent 3.5% NaCl (Freely Corroding)	Mean	–	.24638	.32161	.38340	.46834	.58462	.71628	.82632	1.1772	1.5178	1.8371	2.1887	2.6861	3.3355	–
	S.D.	–	.05357	.04471	.03080	.02823	.04584	.06887	.08200	.16949	.27772	.44550	.18758	.19084	.20556	–
Quiescent 3.5% NaCl (Zinc Potential)	Mean	–	–	–	–	.58879	.68752	.87311	1.0048	1.2701	1.6079	2.0386	2.5784	3.2630	3.1113	4.2473
	S.D.	–	–	–	–	.08137	.09807	.13082	.16550	23213	.33778	.49984	.72913	1.0923	.43479	–
Flowing 3.5% NaCl (Freely Corroding)	Mean	.16813	.29047	.35744	.44553	.53165	.63334	.74168	.92022	1.1886	1.4197	1.8115	2.2496	2.6786	3.1672	3.9538
	S.D.	–	.04547	.04852	.07098	.06242	.04891	.07745	.14017	.23980	.22043	.35480	.57213	.77210	.31038	.57885
Flowing 3.5% NaCl (Zinc Potential)	Mean	–	.24579	.31476	.42058	.54215	.68774	.79882	.97112	1.2034	1.5729	1.7576	2.2274	2.7765	3.7080	6.1235
	S.D.	–	–	.01751	.01883	.03782	.06838	.14700	.19883	.33047	.54246	.38478	.38832	.43886	.88072	–
Flowing Sea Water (Freely Corroding)	Mean	–	.29880	.32948	.38741	.47636	.58577	.76362	.96125	1.2321	1.5837	2.0380	2.6225	2.8434	3.5406	–
	S.D.	–	–	–	–	–	.00529	.02289	.05382	.10542	.18803	.30801	.48783	–	–	–
Air	Mean	.09163	.13892	.20279	.29886	.39867	.53374	.70856	.92016	1.1812	1.4972	1.8763	–	–	–	–
	S.D.	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Overall	Mean	.12388	.25708	.32868	.41251	.51006	.61782	.76336	.94391	1.2002	1.5081	1.8868	2.3321	2.9068	3.3352	4.5886
	S.D.	.04560	.05877	.05381	.06365	.06263	.06869	.09805	.13979	.22555	.31183	.37805	.49706	.66196	.44191	1.0889

* $\times 10^{-6}$ m/cycle



	INCHES	MM.
W	2.55	64.8
W′	3.20	81.3
a	VARIABLE	VARIABLE
h	1.24	31.5
H	2.48	63.0
D	0.50	12.7
B	0.40	10.2

Fig. 1 - 1T Wedge-opening-loaded specimen

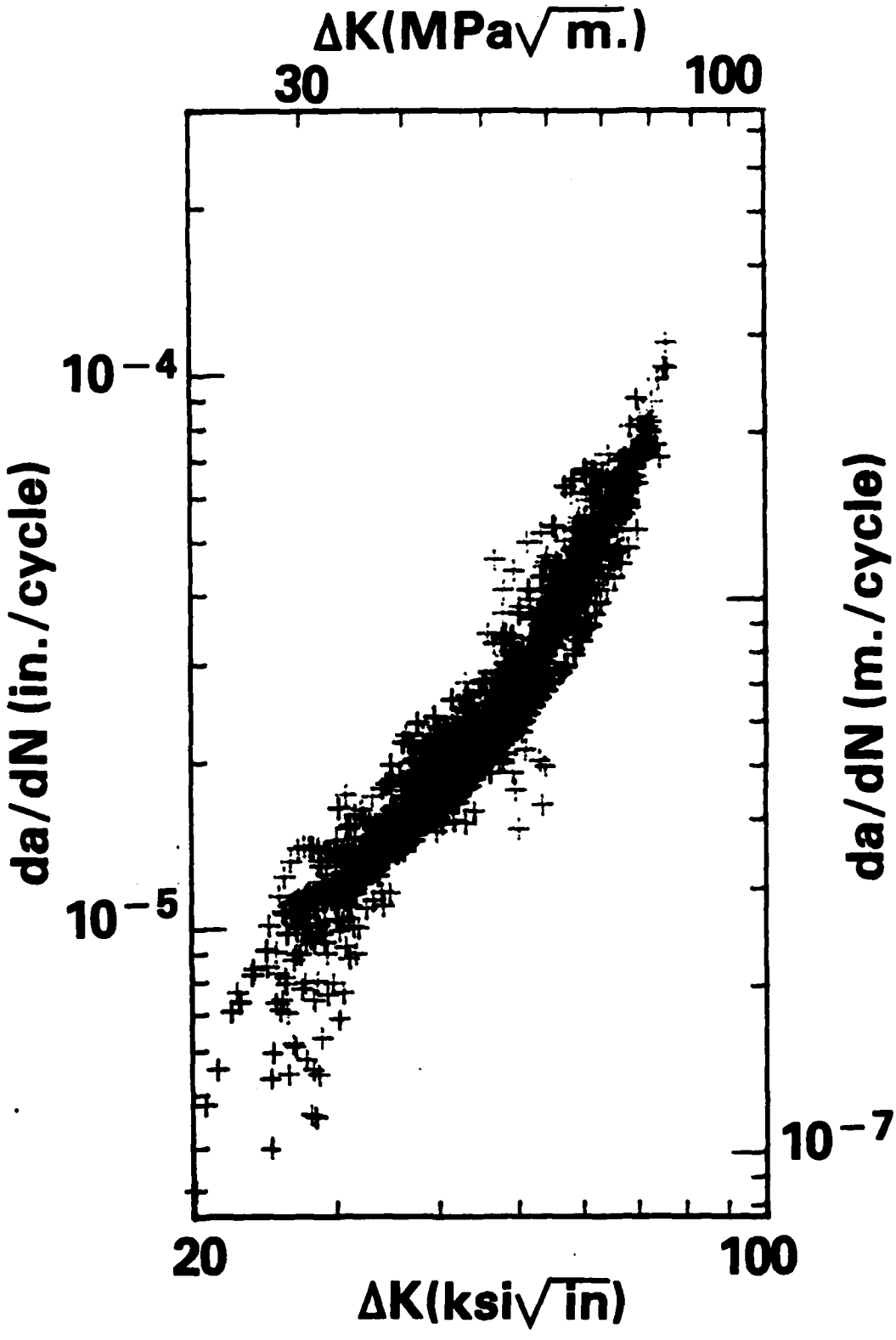


Fig. 2 - Summary of reported crack growth rate data for tests in marine environments

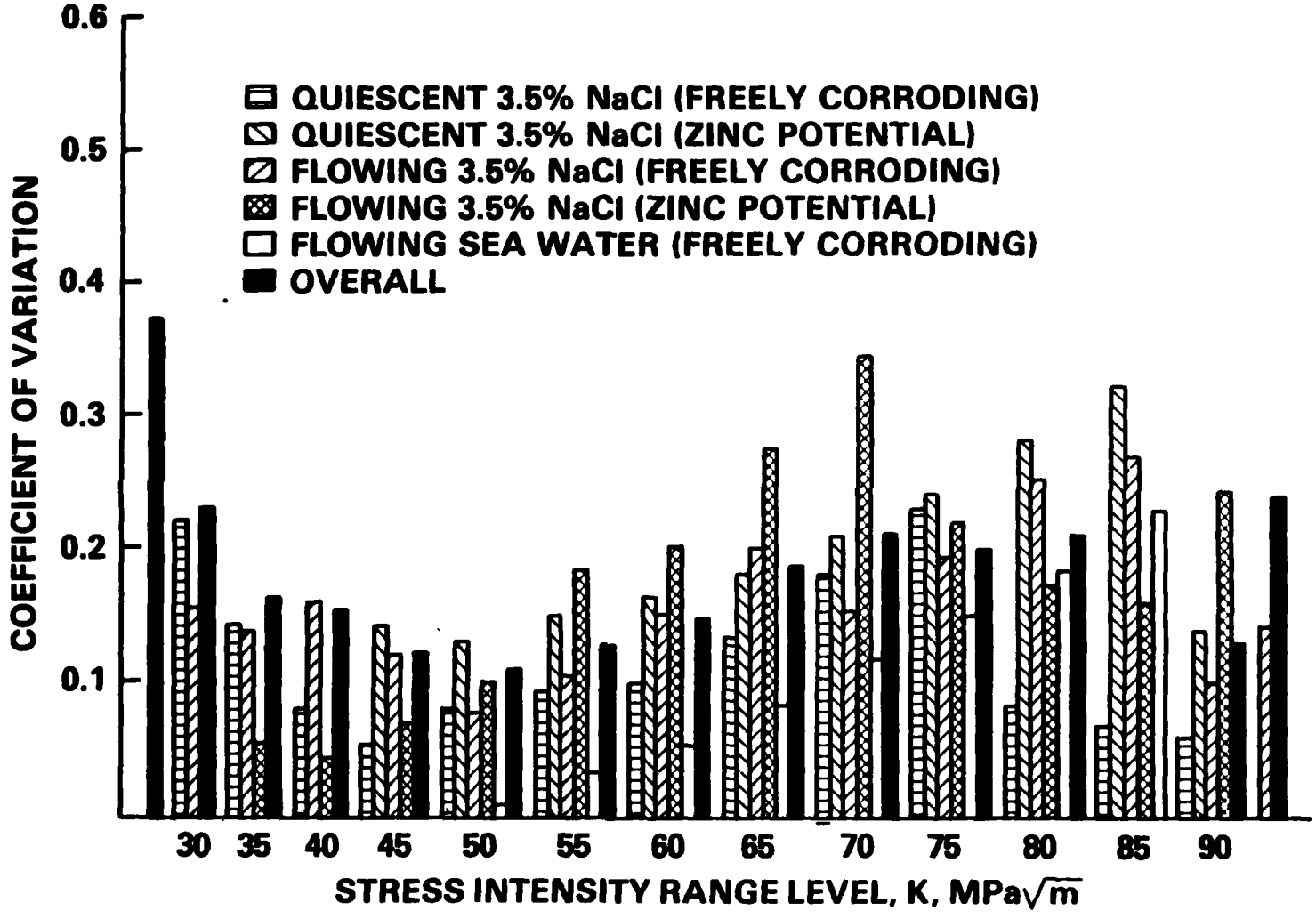


Fig. 3 - Range of variance of da/dN versus ΔK level

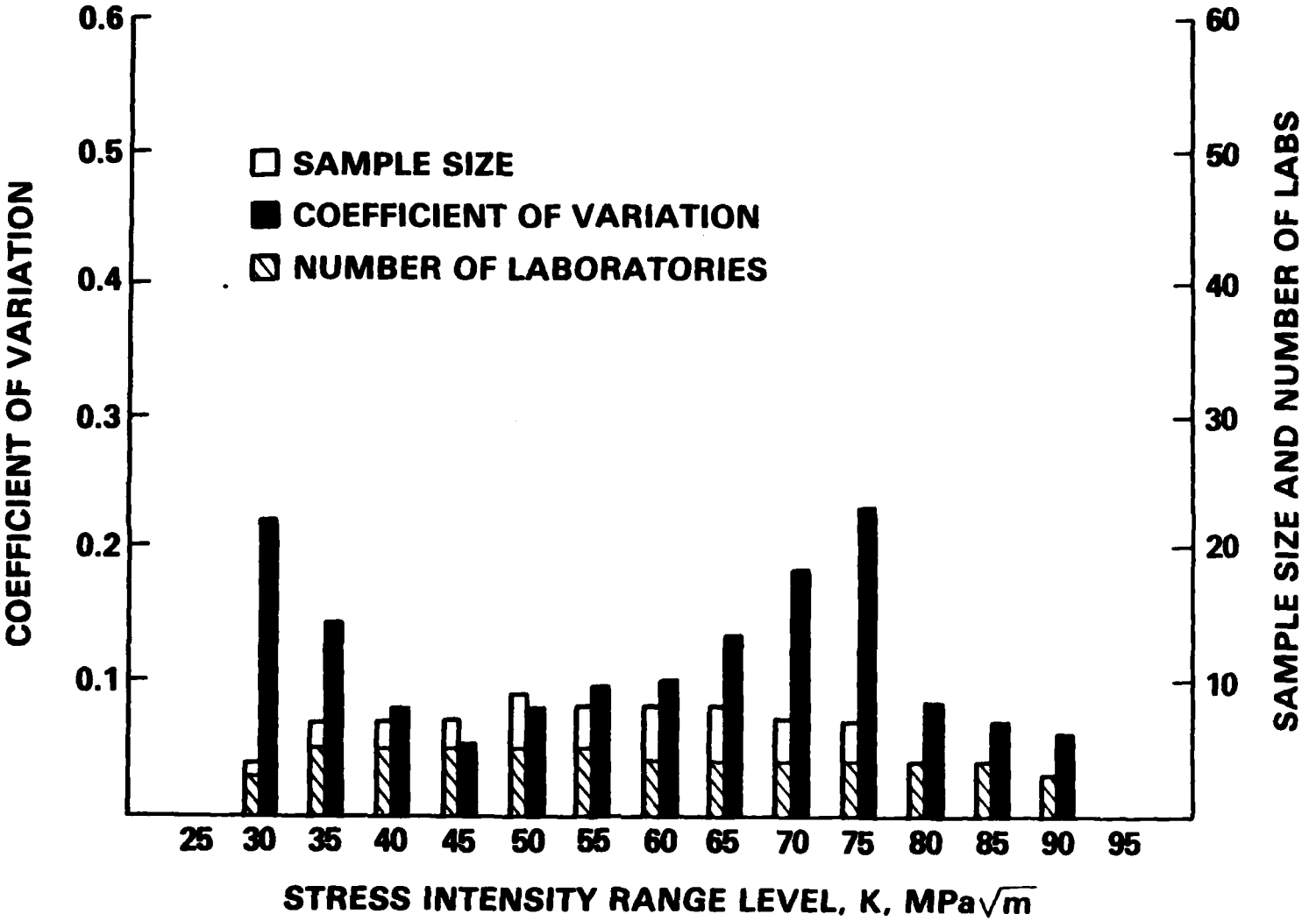


Fig. 4 - Variance of da/dN versus ΔK level for the quiescent 3.5% NaCl (freely corroding) condition

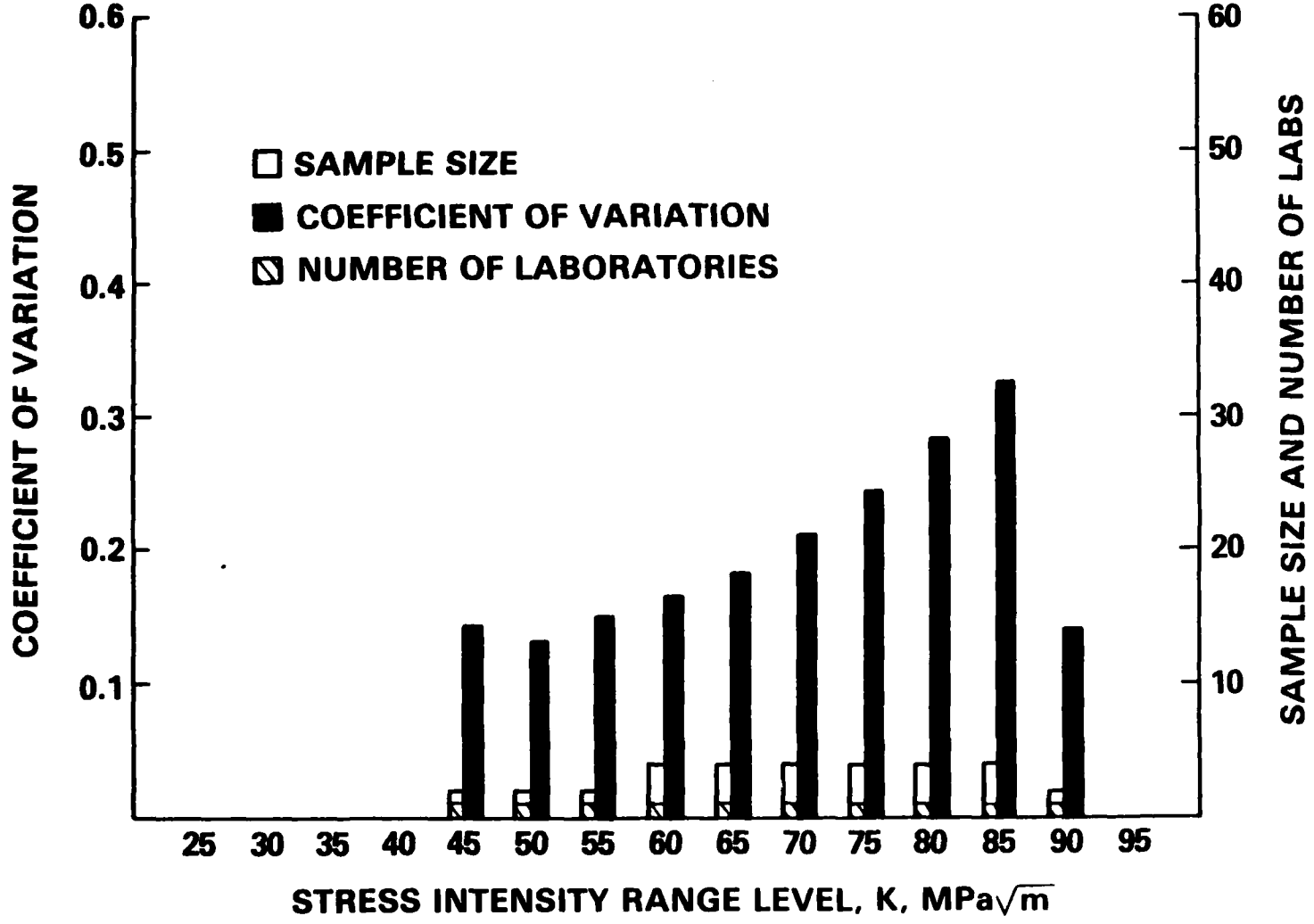


Fig. 5 - Variance of da/dN versus ΔK level for the quiescent 3.5% NaCl (zinc potential) condition

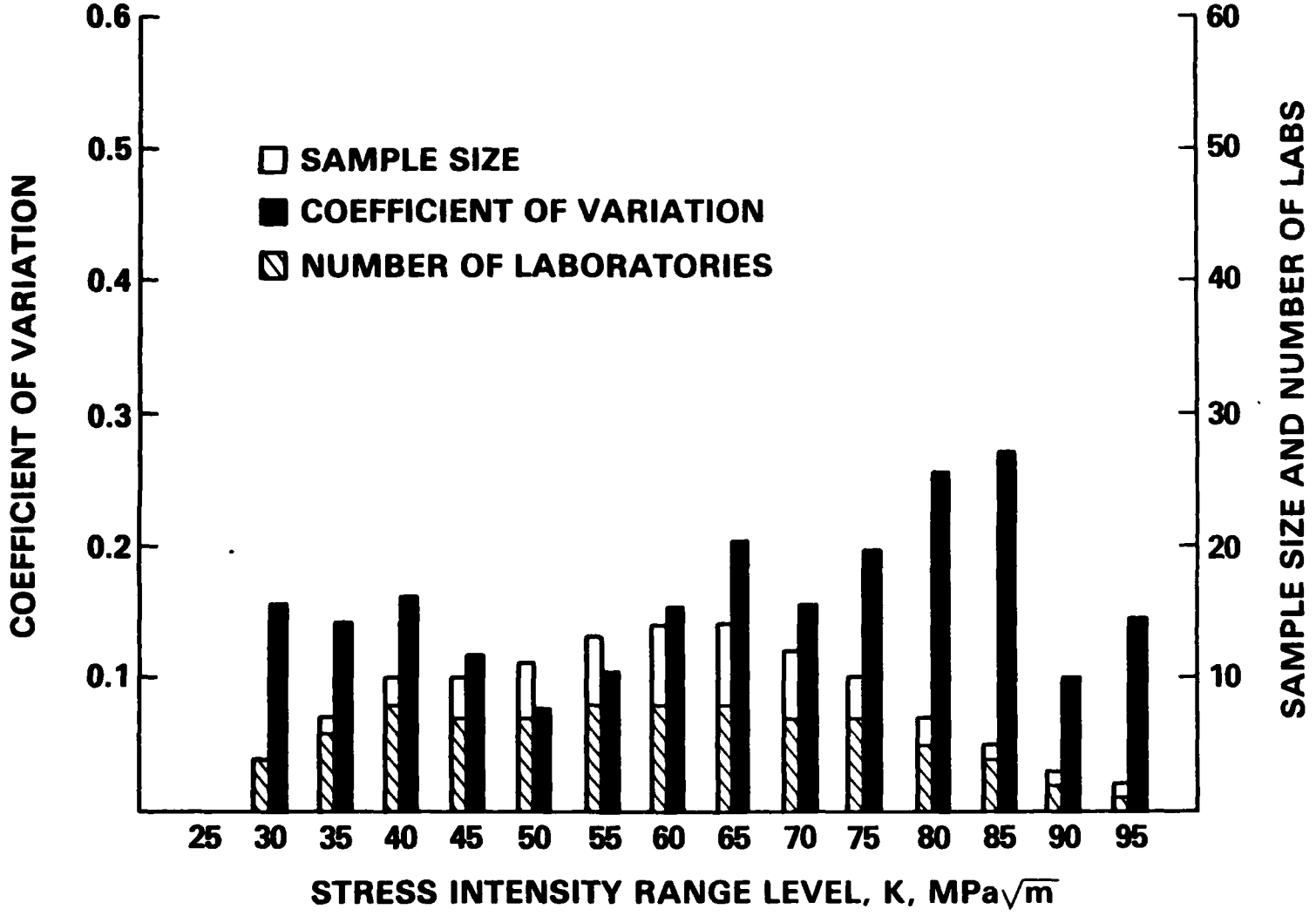


Fig. 6 - Variance of da/dN versus ΔK level for the flowing 3.5% NaCl (freely corroding) condition

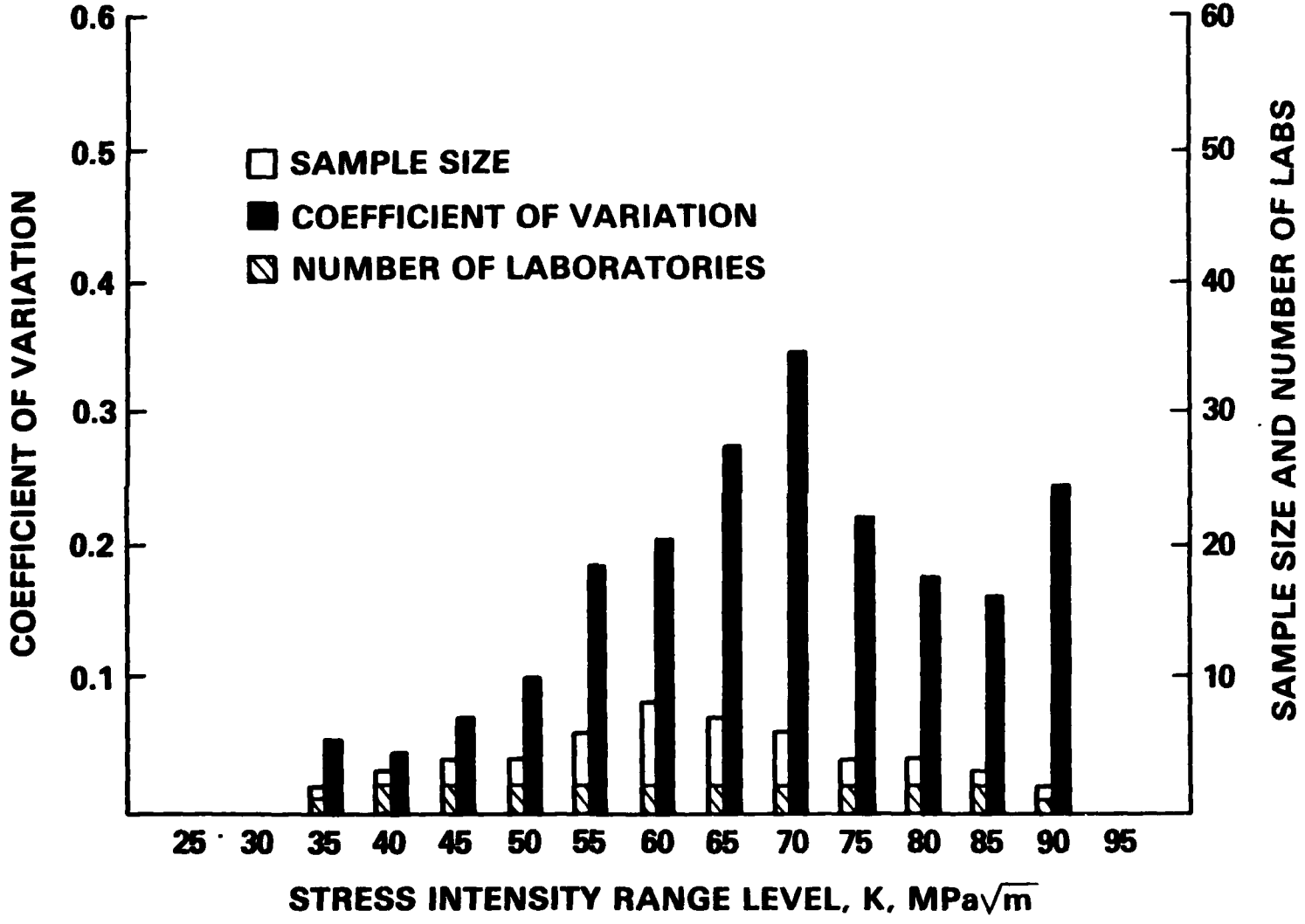


Fig. 7 - Variance of da/dN versus ΔK level for the flowing 3.5% NaCl (zinc potential) condition)

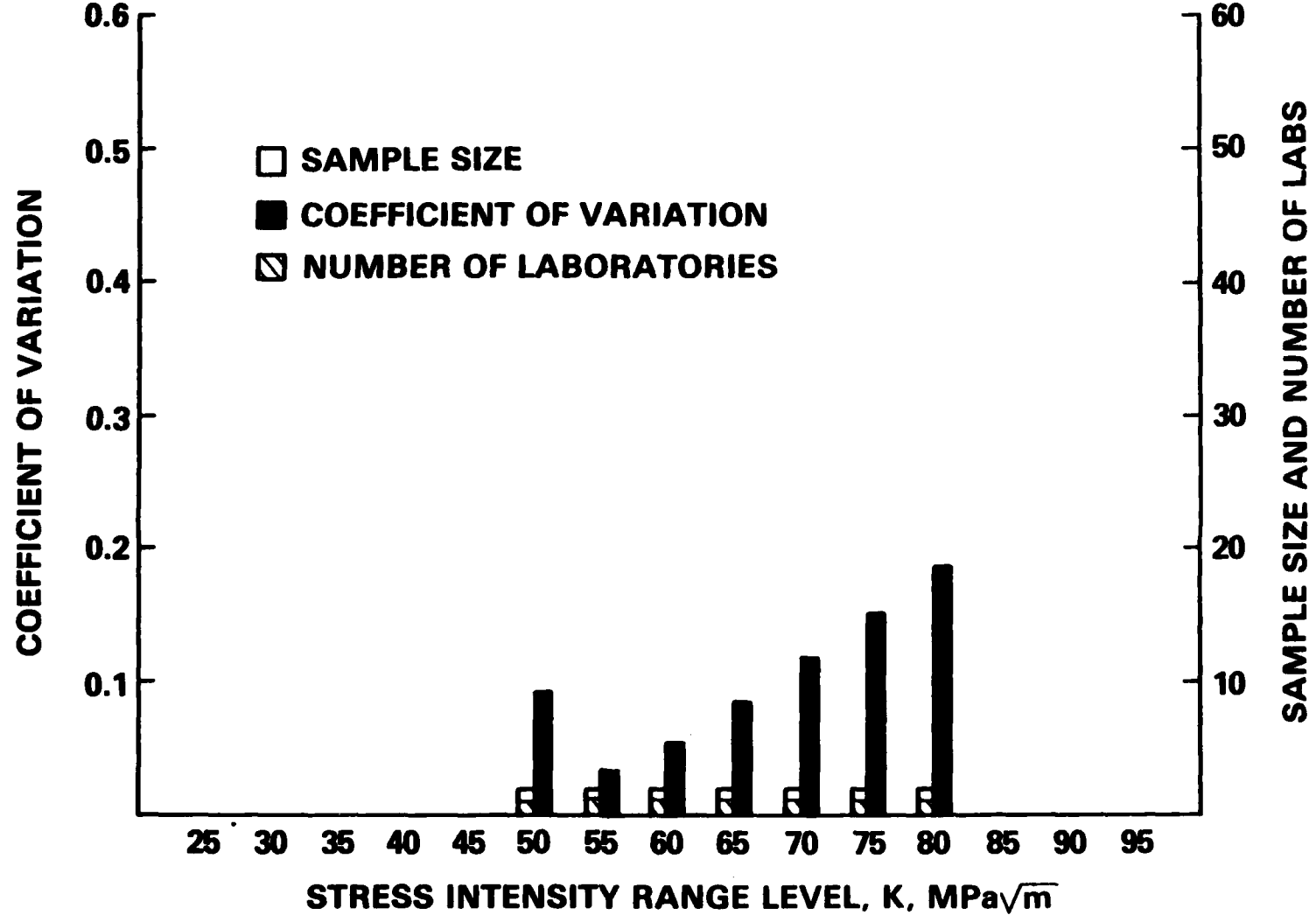


Fig. 8 - Variance of da/dN versus ΔK level for the flowing sea water (freely corroding) condition

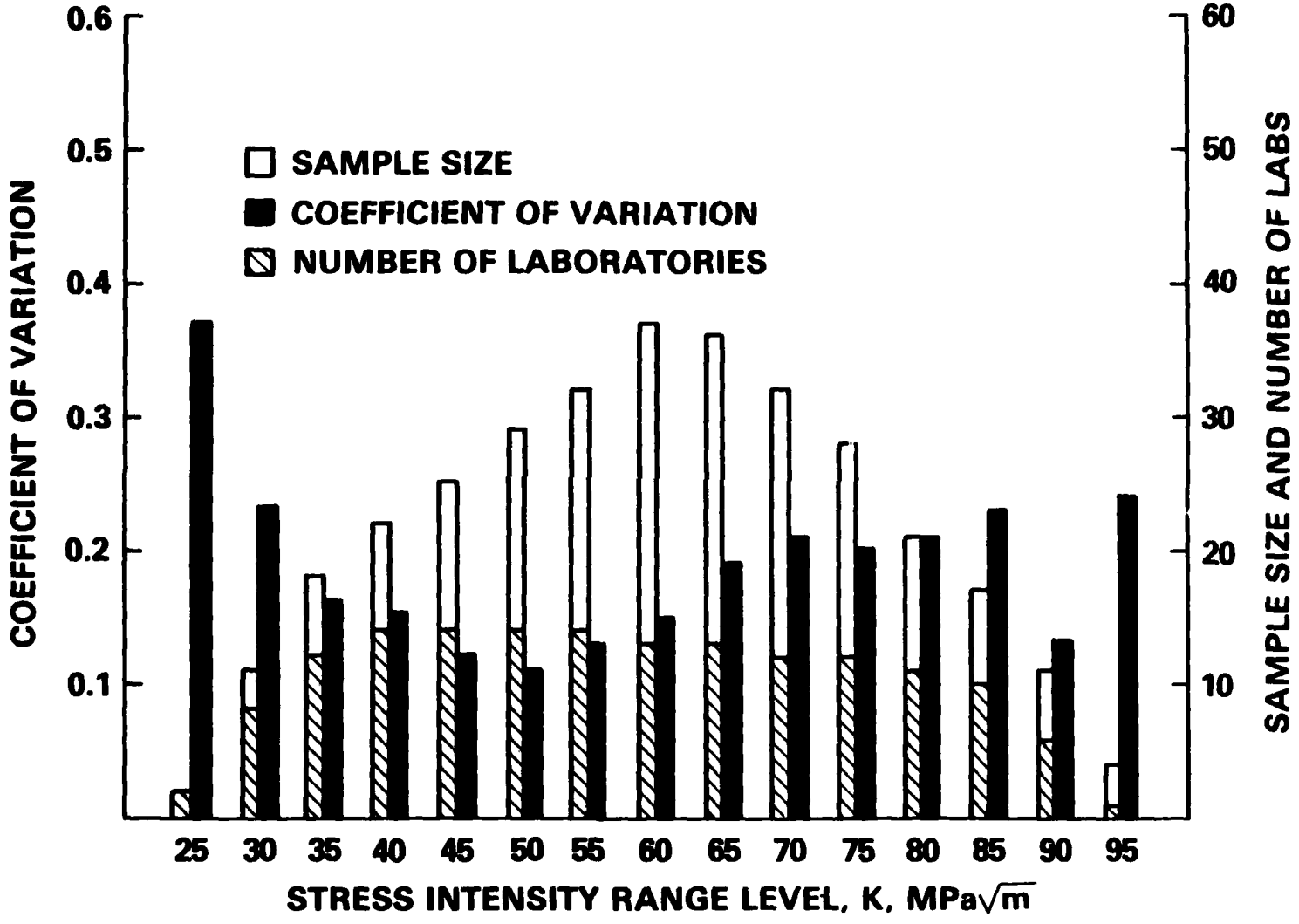


Fig. 9 - Variance of da/dN versus ΔK level for all specimens

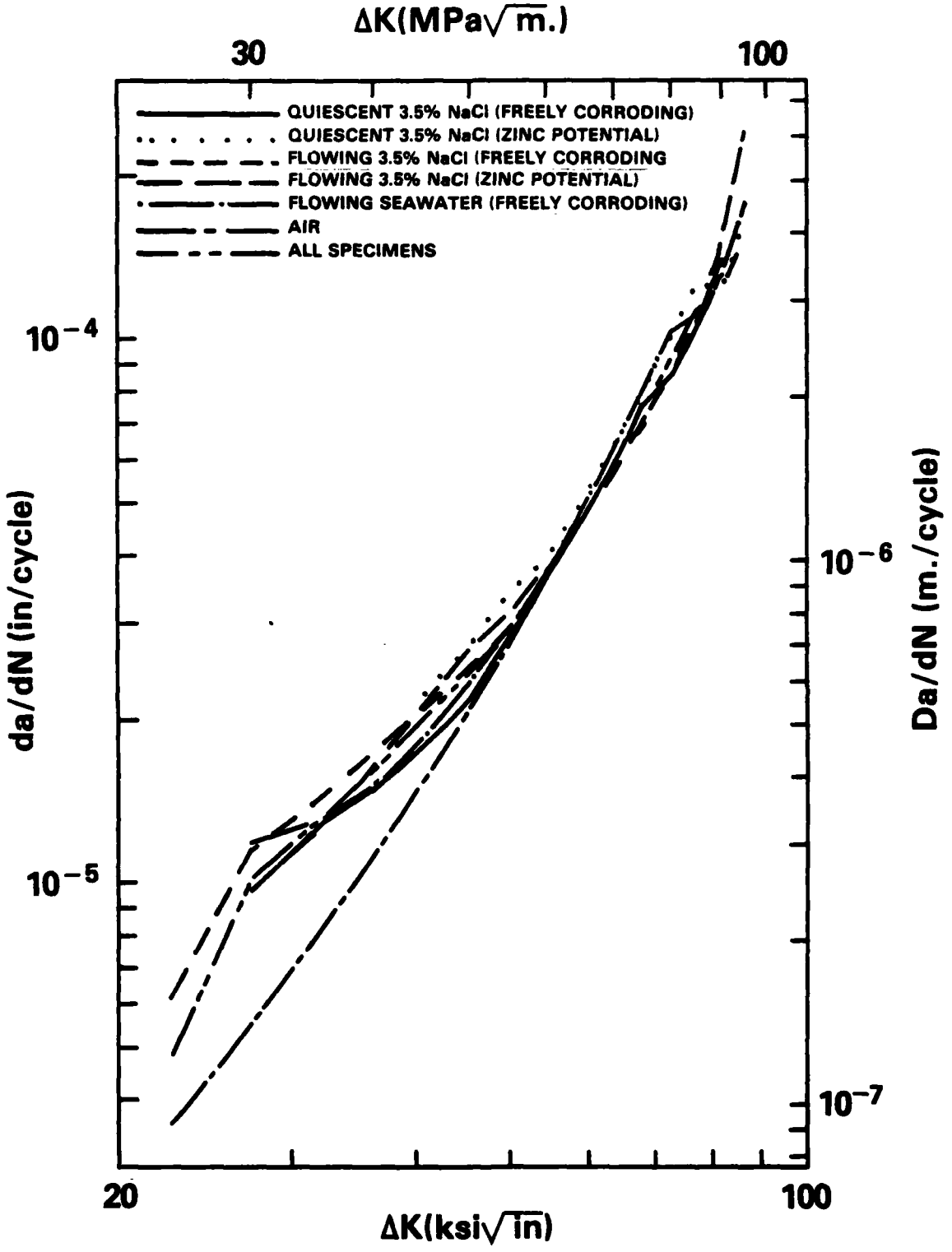


Fig. 10 - Mean crack growth rates for each set of test conditions

APPENDIX 1

Laboratory Data Sheets

CORROSION FATIGUE CRACK GROWTH RATE ROUND PORIN

SUMMARY SHEET

Laboratory: _____

Specimen ID: _____

Material: HY-80, Lukens Melt No. D9562

Specimen Type: WOL

Orientation: T - L

Yield Strength (ksi): 89.9

Modulus of Elasticity (psi): _____ where a_o = _____, $2\Delta COD$ = _____

B (in.): _____

W(in.): _____

H (in.): _____

a_o (in.): _____

Initial Precracking

Loads (ksi): _____

Environment: _____

Frequency: _____

Wave form: _____

Length (in.): _____

Frequency: 0.5 Hz

R ratio: 0.1

Flowing 3.5% NaCl in distilled water ☐

Quiescent 3.5% NaCl in distilled water ☐

Check One

Wave Form: Haversine

Investigator: _____

Telephone Number: _____

CORROSION FATIGUE CRACK GROWTH RATE ROUND ROBIN

OBSERVED DATA

Observations at the End of Each Growth Increment						Daily Observations					
Cycles	Pmin (Lbs)	Pmax (Lbs)	COD at ½ Pmax	COD at Pmax	2 Δ COD	Date M/D/Y	pH	Temp °F	Conduc-tivity (Optional)	Dissolved oxygen (Optional)	Potential (V)

* Environment Renewal Date

ROUND ROBIN CORROSION FATIGUE CRACK GROWTH RATE
TEST PROGRAM – GENERAL INFORMATION

Laboratory ID#_____
Investigator_____
Telephone Number_____

1. Description of Test Machine_____

_____

Manufacturer_____ Model No:_____
MachineCapacity_____
LoadCell Capacity_____
Load Cell Range Used_____

2. Method of Measuring Crack Length_____

_____

Describe Equipment Used_____
Manufacturer_____ Model No:_____
Crack Length Precision?_____

_____

How Was It Determined?_____

_____

3. Describe Data Analysis Method_____

_____

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4. Additional Comments_____

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END

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