NASA TECHNICAL MEMORANDUM

NASA TM X-64904

(NASA-TM-X-64904) PRECISION COMPLIANCE TECHNIQUES FOR SLOW CRACK GROWTH MEASUREMENTS (NASA) 24 p HC $3.25 CSCL 14B

N75-16790

Unclas

G3/35 09709

PRECISION COMPLIANCE TECHNIQUES FOR SLOW CRACK GROWTH MEASUREMENTS

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January 10, 1975

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.
NASA TM X-64904

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
Precision Compliance Techniques for Slow Crack Growth Measurements

5. REPORT DATE
January 10, 1975

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Pascal J. Noronha

8. PERFORMING ORGANIZATION REPORT #

9. PERFORMING ORGANIZATION NAME AND ADDRESS

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS

National Aeronautics and Space Administration
Washington, D.C. 20546

13. TYPE OF REPORT & PERIOD COVERED

Technical Memorandum

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Materials and Processes Laboratory, Science and Engineering

16. ABSTRACT

This report presents a method of using simple electronic components to obtain the high sensitivity needed to measure very slow crack growth rates. The technique presented can reduce the experimental time considerably and also yield a greater amount of data more accurately than optical techniques for measuring crack growth rates.

17. KEY WORDS

18. DISTRIBUTION STATEMENT
Unclassified-unlimited

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	24	NTIS

MSFC - Form 3292 (Rev December 1972)

For sale by National Technical Information Service, Springfield, Virginia 22151

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PRECISION COMPLIANCE TECHNIQUES FOR SLOW CRACK GROWTH MEASUREMENTS

INTRODUCTION

One important area of study in fracture mechanics is that of stable crack extension [1]. Recently, this area has expanded to encompass aspects of crack growth under cyclic loading conditions and stable crack growth under creep loading conditions. Also crack growth under static loading can occur in the presence of a particular environment, as in stress corrosion cracking [2-5], or in the presence of hydrogen, which causes hydrogen embrittlement [6, 7] of metals. The occurrence of these phenomena if undetected and uncorrected usually results in the failure of the component.

Experimental studies in stable crack growth generally use compliance measurement techniques to detect crack extension under load as a function of time. This enables the measurement of a parameter of primary interest – namely, crack growth rates. The rate of crack extension in any given alloy is known to depend on parameters such as the stress intensity at the tip of the crack, the environment present at the crack tip, or the hydrogen concentration in the metal and thus covers a wide range of growth rate. Additionally, different metals and alloys have different ranges of crack growth rates. Thus it is necessary to be able to measure growth rates accurately at both ends of the spectrum. For higher rates of growth, optical techniques prove adequate and are generally used. However, for low rates of growth in the range of 0.0005 in. (12.7 μm) per hour and below, instantaneous rates of growth are difficult to measure, and it becomes necessary to resort to measuring averages over a long period of time and non-steady-state conditions.

This paper describes an experimental compliance technique that has been improved to allow measurement of instantaneous crack growth rates as low as 0.0001 in. (2.54 μm) per hour and less over short durations. The experiment actually performed using this technique is described to illustrate its application to any measurement of crack extension.

THEORY

With the increasing use of high strength steels in hostile environments and in critical applications, it becomes essential to characterize more completely the kinetics of the stress corrosion cracking of these materials. A knowledge of the kinetics allows more accurate life expectancy predictions to be made. Until recently the two factors of primary importance in design have been the incubation time prior to initial crack growth and the rate of growth. Both parameters are known to be directly dependent on the stress intensity present at the tip of the crack. A third factor considered important is the threshold stress intensity, K_{ISCC}, developed by Brown [8-10] using precracked cantilever beam specimens. The K_{ISCC} value for a particular material and environment is the plane-strain stress-intensity threshold below which subcritical cracks will not propagate.

In the cantilever beam technique, several precracked specimens are required to establish K_{ISCC} for a particular material and environment as shown in Figure 1. A more efficient testing technique for K_{ISCC} determination was developed by Smith et al. [11] using wedge-force tension test specimens. Novak et al. [2] further modified this specimen by using a bolt and loading tup to enable self-stressing without the use of a tensile machine. This investigation uses the specimen of Novak et al., which is shown in Figure 2 loaded in a creep testing machine under dead-weight load to investigate all three parameters mentioned earlier. In addition, it has been determined[1] that the application of peak overloads affects the subsequent incubation times and crack growth rates. This aspect of the kinetics has also been successfully studied using the technique to be described.

The stress intensity, K_I, at the tip of the crack for the modified-wedge open-loaded (MWOL) specimen is given by

$$K_I = \frac{PC_3(a/W)}{a^{1/2}} \quad , \qquad (1)$$

and the load may be calculated from the expression

---

[1] Unpublished data.

$$P = \frac{EB\ V}{C_6\ (a/W)} \quad , \tag{2}$$

where

P = load

a = crack length

B = specimen thickness

B_N = net specimen thickness (at shallow face notch)

W = specimen depth

and

C_3 and C_6 are functions of (a/W) as shown in Figures 3 and 4.

For this investigation C_3 and C_6 are given by

$$\begin{aligned} C_3\ (a/W) &= 30.96\ (a/W) - 195.8\ (a/W)^2 + 730.6 - 1186.3\ (a/W)^4 \\ &\quad + 754.6\ (a/W)^5 \end{aligned} \tag{3}$$

$$\begin{aligned} C_6\ (a/W) &= e\ [2.256 + 1.650\ (a/W) + 12.975\ (a/W)^2 - 26.004\ (a/W)^3 \\ &\quad + 18.365\ (a/W)^4] \quad . \end{aligned}$$

INSTRUMENTATION

A block diagram of the experimental arrangement used for this investigation is shown in Figure 5. The specimen under investigation is loaded to the desired K_I value in a creep machine, as shown in Figure 6, and crack opening displacement is measured using a NASA-type clip gage. The technique has been developed to allow very high sensitivity and stability of measurement, and an increase of 0.001 in. (25.4 μm) in the crack opening displacement has been magnified to obtain 36 in. (92 cm) of displacement on the Y-axis of an X-Y recorder. It is believed that this may be increased without difficulty to obtain 50 in. (127 cm) of displacement for a 0.001-in. (25.4-μm) increase in crack opening displacement. A detailed description of all components of the system and measuring procedures follows.

Clip Gage

The standard double-cantilever clip-in displacement gage is used for measuring crack opening displacement, and an adequate description of this gage is contained in ASTM-399-74. Resistances used on these gages varied from 350Ω to 3000Ω. Model 632 clip gages manufactured by MTS were provided with 350-Ω strain gages, while all others fabricated in-house had resistances of 500Ω, 1000Ω, and 3000Ω. All resistances used were found to be adequate for the intended purpose. There is greater stability for the same excitation voltage as the resistance increases, but this may be offset by greater noise pickup in the bridge. The optimum resistance can be chosen for the operating conditions present. The clip gage should be enclosed to provide adequate shielding for the strain gages so as to minimize the pickup of noise.

DC Power Supply

This is an important component of the system, and high system sensitivity requires the use of a stable dc power supply. The power supply must be required to provide a stable voltage that is unaffected by fluctuations in line voltage and is free of drift and noise. A small change in the excitation voltage of the strain gage bridge can cause a larger change in the final voltage output at the dc amplifier. If, for example, the power supply undergoes drift at a constant rate for any length of time, in the resulting X-Y plot this could be erroneously interpreted as crack growth. The instrument used was a Hewlett-Packard Model 6111A power supply. It is advisable to use as low an excitation voltage as possible to reduce the possibility of drift resulting from heating of the strain gages. For this study, one power supply proved adequate to excite eight clip gages connected in parallel at an excitation voltage of 10 V without affecting the stability.

DC Amplifier

To obtain a signal from the clip gage that is completely free of noise after amplification, it is essential to have a dc low noise amplifier. The amplifier must also have very low drift over a long period and a low drift due to temperature. There are several commercial amplifiers that fit the requirements. A Dana Model 3640 amplifier was found to provide the best signal and is used in this system. The output from the clip gage is amplified and is fed to the Y-axis of an X-Y recorder.

The remainder of the instrumentation used consists of an X-Y recorder, a ramp generator, and a potentiometer arrangement for zero control. The ramp generator supplies a continuous ramp signal to the X-axis of the recorder to observe crack opening displacement as a function of time. Since crack opening displacement under dead-weight loading can be correlated to crack length, a continuous record of crack length may be obtained over a required time span.

The circuit used for the system described is shown in Figure 7. To reduce the pickup of extraneous electrical signals, it is necessary to ground each component of the system as shown in the figure. Limiting the length of wire and shielding between components will also reduce noise pickup. It has been found that coaxial cable, type RG174/U, has the most desirable noise pickup characteristics.

RESULTS

Examples of crack growth data obtained with the technique are shown in Figures 8 and 9. Figure 8 shows the incubation period in D6AC steel, corresponding to the flat portion of the curve, resulting from the application of a peak overload of 2 ksi$\sqrt{\text{in.}}$ (2.214 MPa$\sqrt{\text{cm}}$) to the specimen at a nominal stress intensity of 90 ksi$\sqrt{\text{in.}}$ (99.63 MPa$\sqrt{\text{cm}}$). The straight portion of the curve corresponds to a constant crack opening displacement under dead load. As crack extension begins following the initial incubation period, the crack opening displacement increases and is indicated on the recorder. The initial rate of crack growth following incubation decreases and reaches a steady-state rate for D6AC steel. Off-scale travel of the recorder can easily be adjusted using the potentiometer arrangement. The sensitivity in this case was adjusted to allow a displacement of 6 in. (15.24 cm) of the recorder pen for an increase of 0.001 in. (25.4 μm) in crack opening displacement. For the case of D6AC steel, the rates of growth were high so as to permit a low amplification to be used. The X-axis has been ramped to allow full scale displacement over 24 hours.

Increasing the amplifier gain has resulted in the increased sensitivity seen in Figure 9. Here the X-axis again corresponds to a full scale displacement at 24 hours, but the Y-axis has a displacement of 36 in. (92 cm) for an increase of 0.001 in. (25.4 μm) in crack opening displacement. Though this degree of sensitivity is not essential for this study, it serves to illustrate the capability of the technique for other applications. Figure 9 is similar to Figure 8, showing incubation caused by the application of a peak overload followed by a resumption of crack extension.

DISCUSSION

With the high degree of sensitivity shown in Figure 9, it is possible to measure very slow crack growth rates over relatively short periods. Whereas other techniques using a traveling microscope must necessarily wait several days to observe the presence of slow crack growth [with accuracies of measurement of 0.001 in. (25.4 μm)] to some degree of certainty, the time is considerably reduced using this technique. For example, using a sensitivity of 36 in. (92 cm) of displacement for the recorder per 0.001-in. (25.4-μm) increase in crack opening displacement, it is possible to detect crack length changes manifested by 1 in. (2.54 cm) of recorder displacement with certainty. This corresponds to a change of crack opening displacement of 0.00028 in. (7.1 μm). For a specimen approximately 0.75 in. (19.05 mm) thick, this is due to a crack extension of 0.0005 in. (12.7 μm).

For the case of steady-state crack growth, if a displacement of 1 in. (2.54 cm) of the recorder occurs over a period of 24 hours, this would correspond to a crack growth rate of approximately 0.00002 in. (0.508 μm) per hour. Furthermore, this observation may be made in a period of 24 hours as opposed to the several days required using optical techniques. As seen in Figures 8 and 9, initial and intermediate incubation periods (resulting from overloads) may be measured with much higher accuracy. Thus, this technique shows several advantages over others, although it is limited in its use to deadweight-loaded systems. It is envisioned that it may be applied to the study of stable crack growth in environmental stress corrosion cracking, hydrogen embrittlement, creep, and creep fatigue studies.

CONCLUSIONS

The degree of sensitivity obtained using simple electronic components instead of standard signal conditioning equipment is found to be significantly increased. In addition, the resulting signal is seen to be completely free of extraneous noise and long-term drift, making the system suitable for monitoring crack opening displacement over extended periods.

The ability to monitor continuously makes it possible to observe the more detailed aspects of the kinetics of stress corrosion cracking, and it is expected that this advantage can be applied to the study of stable crack growth under other conditions. In addition, this technique can reduce the experimental time required considerably and also yield a greater amount of data more accurately than optical techniques for measuring crack growth rates.

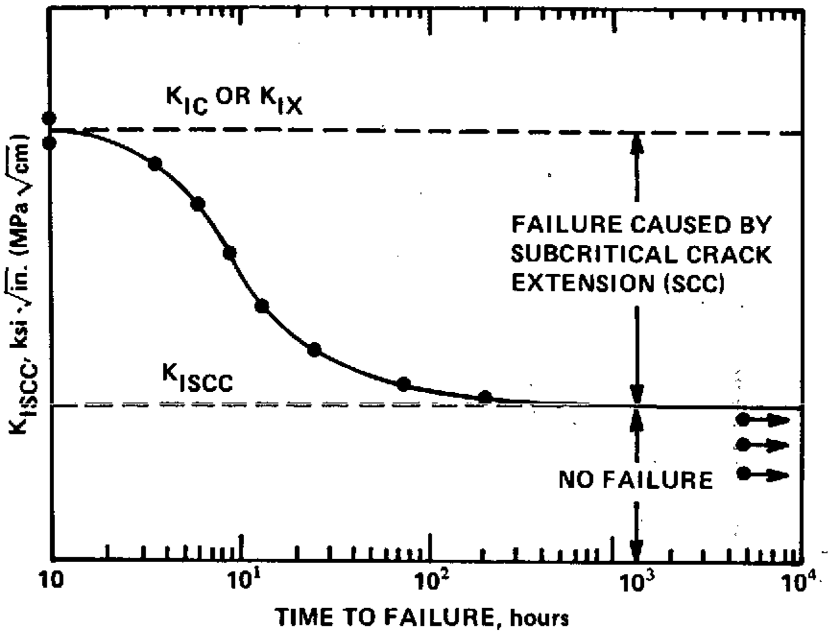
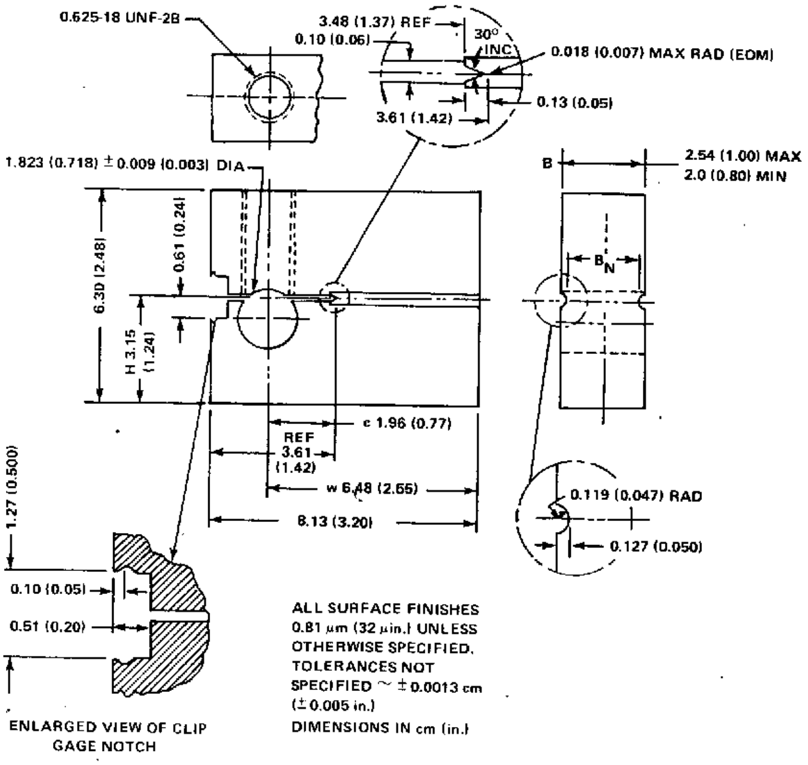


Figure 1. K_{ISCC} with precracked cantilever beam specimens using the time-to-failure criterion.



ALL SURFACE FINISHES 0.81 μm (32 μin.) UNLESS OTHERWISE SPECIFIED.
TOLERANCES NOT SPECIFIED ~ ± 0.0013 cm (± 0.005 in.)
DIMENSIONS IN cm (in.)

Figure 2. Detailed machine drawing for modified WOL specimen.

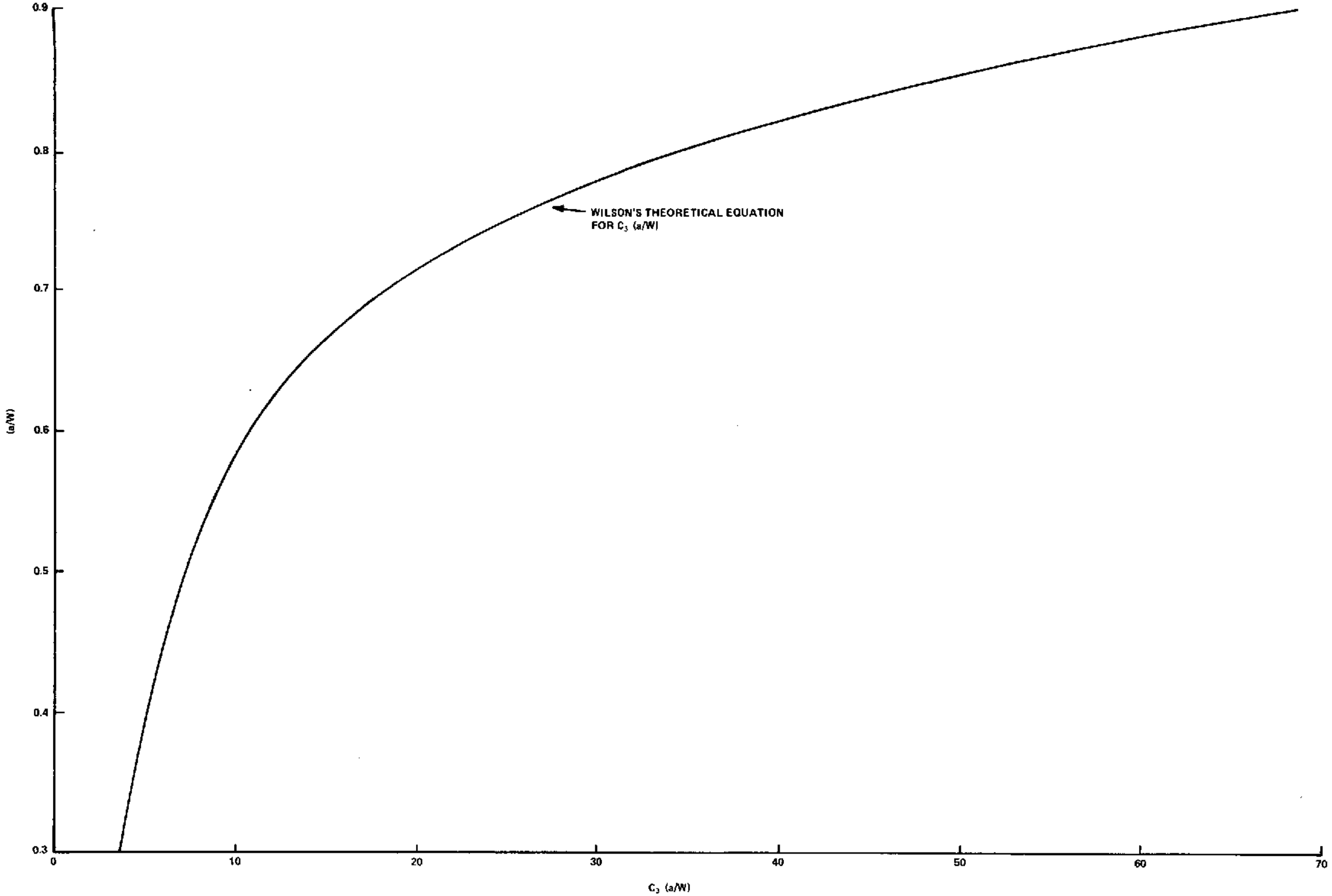


Figure 3. Compliance relation for $C_3(a/W)$ versus (a/W).

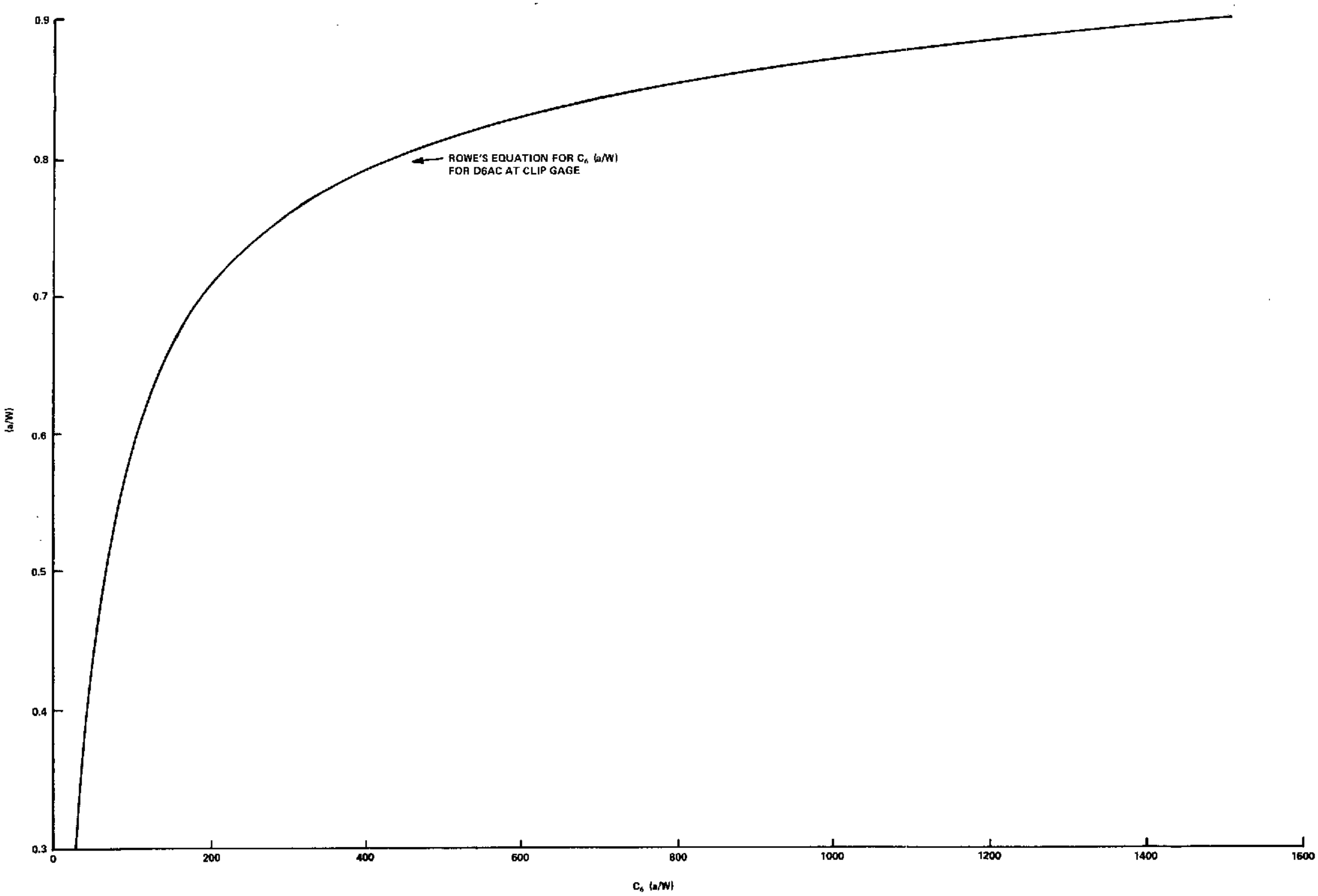


Figure 4. Compliance relation for C_6 (a/W) versus (a/W).

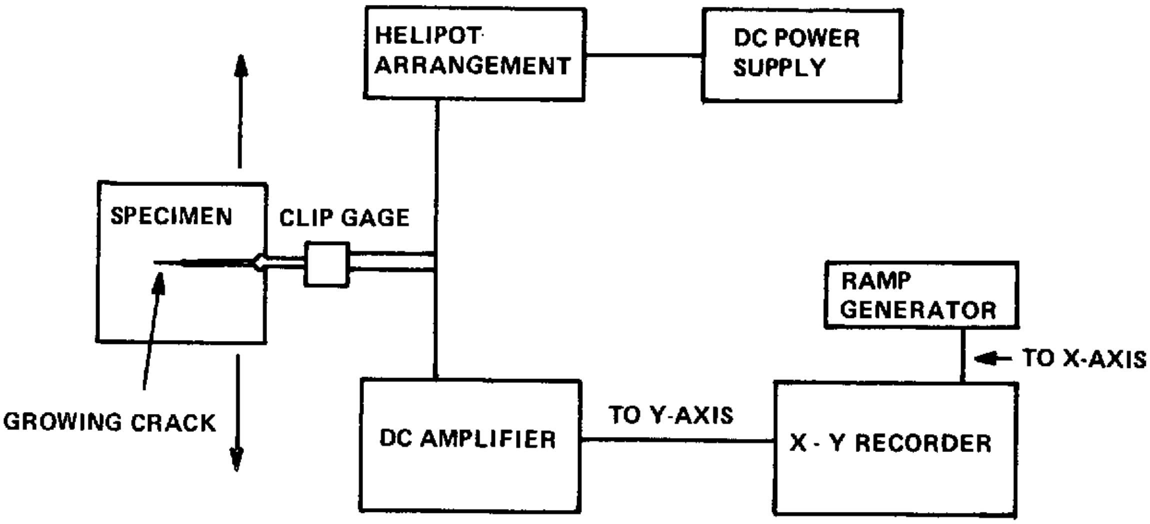


Figure 5. Block diagram of instrumentation used in stable crack growth measurement technique.

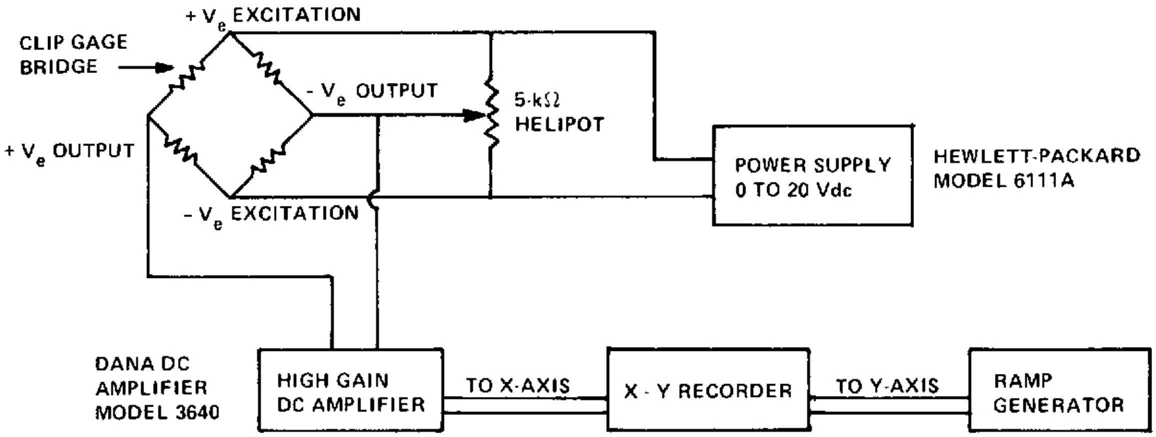


Figure 6. Circuit diagram for clip gage measuring technique.

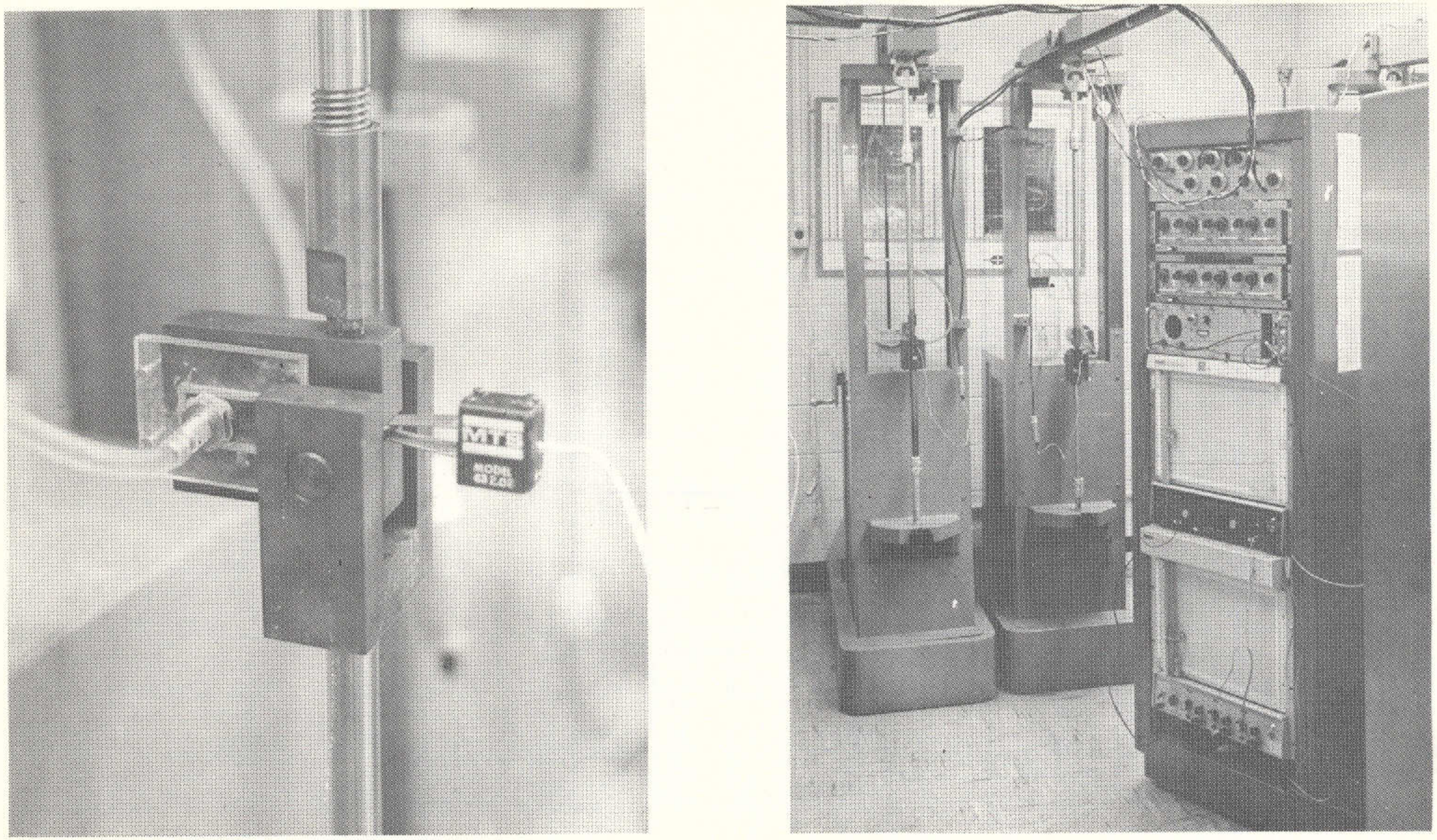


Figure 7. Experimental arrangement for study of stress corrosion cracking.

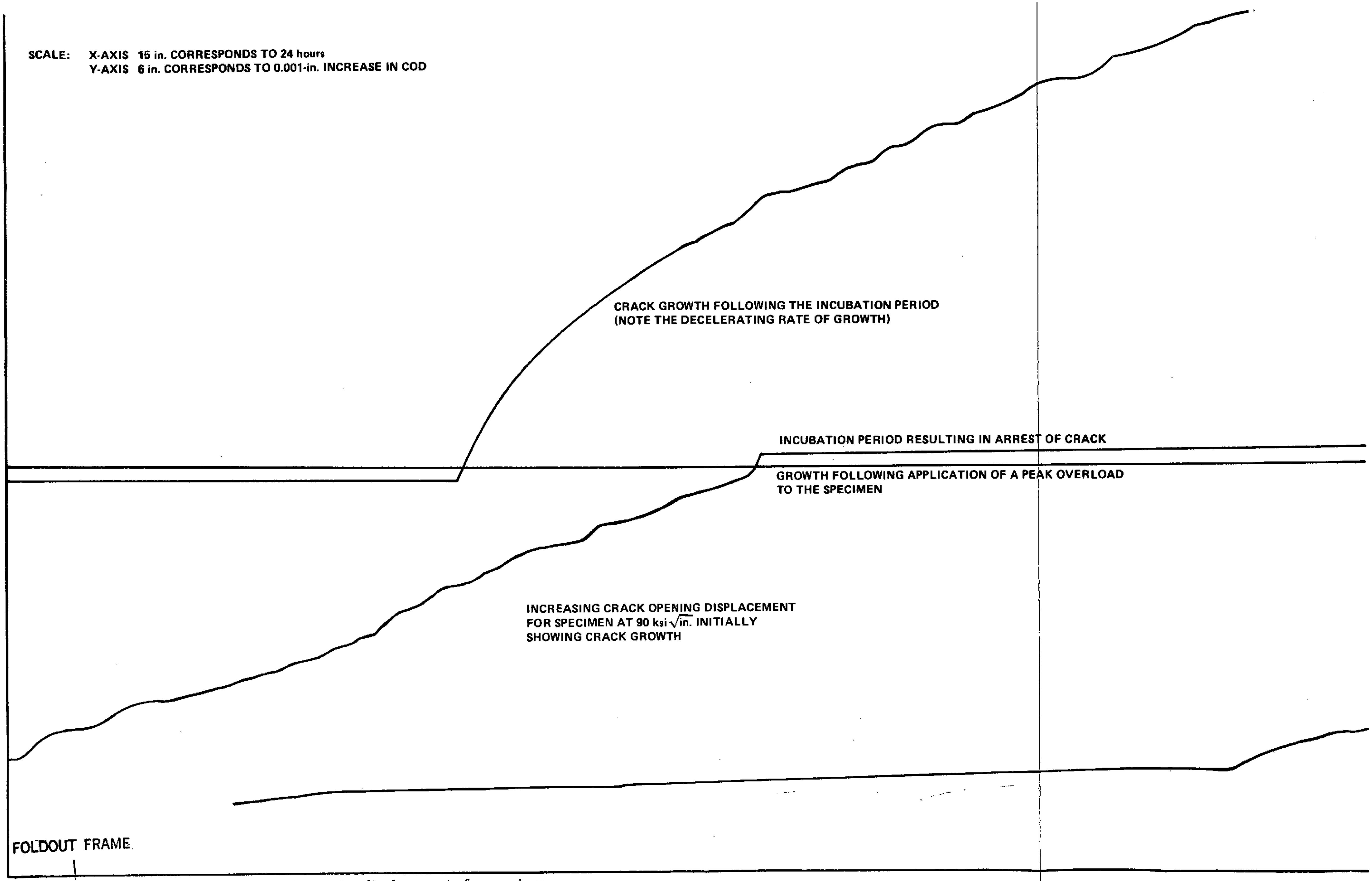


Figure 8. An accurate tracing of the crack opening displacement of a specimen of D6AC steel showing initial crack growth followed by crack growth arrest and further growth.

FOLDOUT FRAME

2

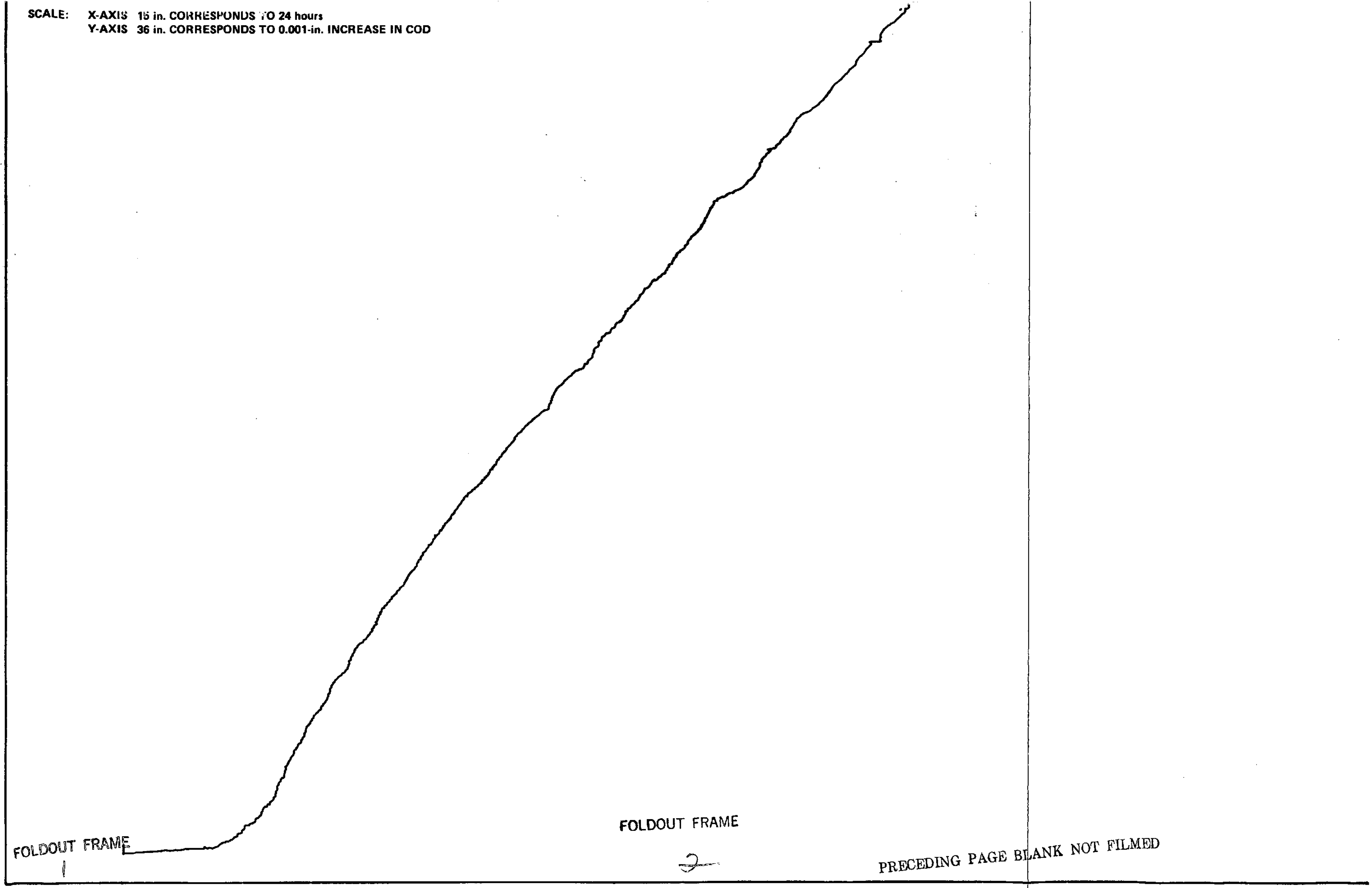


Figure 9. Incubation caused by application of a peak overload followed by crack growth at a high degree of sensitivity of instrumentation.

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APPROVAL

PRECISION COMPLIANCE TECHNIQUES FOR SLOW CRACK GROWTH MEASUREMENTS

By Pascal J. Noronha

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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