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TECHNICAL BASES FOR INTERIM LICENSING ACTIONS RELATED TO BWR PIPE CRACKING

Warren S. Hazelton, William H. Koo, and Raymond W. Klecker

U.S. Nuclear Regulatory Commission

Washington, D.C. 20555

Introduction

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Although IWB-3640 is relatively simple to apply, it required that an analysis for further crack growth be performed. As there was no generally accepted procedure for such IGSCC crack growth calculations, the NRC staff developed a set of bases and calculational methods that would be acceptable to the staff.

This paper describes the staff approach and provides the specific parameters used.

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Crack growth calculations are required to evaluate the continued structural integrity of a weld with known cracks, if it is desired to continue operation without repair or reinforcement. The rate of growth of IGSCC is not easy to predict, because the several important factors are usually imperfectly known. Research work in this area has been helpful in defining the general effect of these factors, but a large uncertainty in crack growth predictions still remain.

Nevertheless, crack growth calculations can be performed within certain limits with enough confidence to ensure plant safety without excessive conservatism.

Crack growth calculations are based on the fundamental concept that the crack growth rate of a specific material in a specific environment will be a function of the applied stress intensity factor K_I. Laboratory crack growth data are usually presented in this manner. Details of the calculational methods used to calculate K_I are provided later in this paper, but an important point to note here is that K_I depends on the crack depth, therefore it changes continuously during crack growth.

Crack growth analysis methods are, therefore, iterative in nature. Given an initial crack depth, the K_I is calculated for the particular stress distribution of interest. Knowing the K_I, the amount of growth for a specific time is calculated, the growth is added to the initial crack depth, a new K_I is calculated, and the process is repeated. Time intervals selected can vary from 1 hour to 1000 hours, depending on the rate of growth and rate of change in K_I with crack depth.

Selection of Crack Growth Rate Parameters

Although only two parameters, crack growth rate and K_I, are used, they are both highly dependent on several factors. Crack growth rate is affected by the degree of sensitization of the material and by the severity of the environment. Our interest as it relates to BWR piping is primarily in a degree of sensitization normally caused by welding, and in an environment similar to normal BWR water conditions.

Most formal crack growth studies are carried out with standard fracture mechanics specimens, which makes K_I determination easy. These specimens are not readily machined from pipe welds, so the material is given an artificial sensitization treatment, intended either to simulate the effect of welding or, in some cases, the more severe effect of furnace sensitization. Tests to ascertain whether the intended degree of sensitization has been obtained are still inexact, causing significant scatter in laboratory test results intended to apply to a similar metallurgical state.

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In addition to these standardized tests for crack growth rate, results of actual pipe tests are available. Many hundreds of welds have been tested in General Electric's pipe test facility. These tests, although generally more relevant in terms of material condition and environment, are more difficult to evaluate. K_I is more difficult to calculate, and accurate crack growth rates are also more difficult to measure. Nevertheless, this body of data has been used to augment those data from the more standard laboratory tests, to select appropriate crack growth rates.

Figure 1 (from NUREG/CR-3292, reference 1) shows much of the relevant laboratory data in the conventional form, where measured rates are plotted against K_I. This plot clearly shows the large scatter resulting from a wide variation in material condition and environment. This information, together with additional information from actual pipe tests, was used to select a crack growth curve that is appropriate for use in safety evaluations. Note that if the fastest crack growth rate shown in Figure 1 is used, cracks would be predicted to grow completely through pipe walls in a matter of days. Clearly this would not reasonably represent reality.

The curve selected for use by the NRC staff is shown on Figure 2. Note that it is a curved line on the semilogarithmic chart. On log-log coordinates, it plots as a straight line. For conversion or in calculations, it is expressed as:

$$\frac{da}{dt} = 3.590 \times 10^{-8} \cdot K_I^{2.161} \text{ inches per hour}$$

As can be seen, the crack growth rate is a very strong function of K_I. In laboratory tests, K_I is easily determined with good accuracy. This is not the case for real pipes and real pipe cracks. There are two major sources of uncertainty: knowledge of the actual crack size and shape, and the actual stress distribution in the area of the crack to be evaluated. The service distribution at a pipe weld is made up of the stress caused by the service loading and the residual stresses caused by the welding process. Of these, knowledge of the residual stress is the more uncertain. Nevertheless, a residual stress distribution through the pipe wall must be defined, if realistic crack growths are to be calculated. Although this is covered later in more detail, several comments are in order here.

The residual stress distribution caused by welding is the major stress component causing IGSCC. Welding causes a high tensile residual stress on the inside surface of the pipe near the root of the weld where the material is sensitized.

This residual stress level has been calculated and measured to be up to or above the yield strength of the material. It typically is four or five times as high as the service-induced stress. In fact, without this very high residual stress at the sensitized area, IGSCC would not be a problem in BWR piping. This fundamental observation is helpful; wherever this combination of stress and sensitization occurs, cracking occurs. In actual cases, if there are significant cracks, there must be significant tensile residual stresses, and this should be accounted for in the crack growth analysis. The method used by the staff is described below.

Stress Intensity Factor Calculations

There are several analytical methods available for calculating the stress intensity factor (K_I) caused by stress distributions of the type found at BWR pipe welds. The method using influence functions is the one used by the staff and will be summarized here. Other methods, such as those described in the ASME Boiler and Pressure Vessel Code, Section XI, Appendix A, may also be used where appropriate.

Stress Analysis

The total stress state, including residual stress, pressure stress, and other stresses caused by normal operation must be known or assumed. Note that factors such as stress indices used for purposes of other stresses should not be used when calculating stress levels that apply to K_I calculations.

Residual Stress

The laboratory-measured throughwall axial residual stresses on pipe wall thickness $\geq$ 1 inch are presented in Figure 3, taken from NUREG/CR-3292 (reference 1). The solid line in Figure 3 is the axial residual stress distribution used for the calculation of stress intensity factors for pipe sizes of 12" diameter and larger. The residual stress distribution is handled by fitting the curve of residual stress distribution through the wall by an analytical expression. For this particular residual stress distribution, the nondimensional expression given below is used.

$$\frac{\sigma}{\sigma_i} = \sum_{j=o}^{4} \sigma_j \xi^j$$

where

$$\begin{aligned}
\sigma_0 &= 1.0 \\
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\sigma_2 &= 8.687 \\
\sigma_3 &= -0.480 \\
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\xi &= x/t \\
\sigma_i &= \text{stress magnitude at } \xi = 0 \text{ (inner surface)}
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The above formula permits calculation of the residual stress value at any point (x) through the vessel wall thickness (t) as a function of the peak residual stress value at the inside diameter (ID), σ_i.

The stress intensity factor caused by the residual stress from welding (K_{IR}), is calculated using influence functions taken from NUREG KR-3384, page A.19, Table (7), (reference 2). The influence functions, i_j, given in this Appendix are for a 360° circumferential crack in a cylinder with an R/t ratio of 10. In view of other analytical conservations and uncertainties (i.e., assumed crack geometry and initial depths), it is believed that they may be used for cylinders with R/t ratios of from 9 to 11 to obtain reasonable and conservative estimates of crack growth versus time. For R/t ratios significantly different from 10, other influence functions or other analytical methods should be used.

The specific formula used by the staff is:

$$\frac{K_{IR}}{\sigma_i \sqrt{t}} = \sqrt{\pi\alpha} \sum_{j=o}^{4} \sigma_j \alpha^j i_j$$

where:

$\sigma_o, \ldots \sigma_4$ and σ_i are as above

$$
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The membrane stresses are assumed constant through the wall thickness, so

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where

α, t are as above
P = pressure
R = radius to center of pipe wall

The total stress intensity factor, K_{IT}, is given by

$$K_{TT} = K_{IP} + K_{IR}$$

where

K_{IP} and K_{IR} are as above.

Correlation with Service Experience

Although the residual stress is assumed to be the same for all welds, the applied stresses, primary and secondary, vary from weld to weld; therefore, calculations must be performed for each weld evaluated. Figure 4 shows the results of K_I calculations for several pipe sizes using a nominal applied stress of 7500 psi. Note that at relatively shallow depths, the K_I is high; therefore, the crack growth rate will be relatively fast. However, the K_I actually diminishes as the crack grows to about half way through the wall. This prediction is consistent with service experience; very few, if any, actual cracks of significant circumferential extent have been found deeper than about 50% of the wall thickness.

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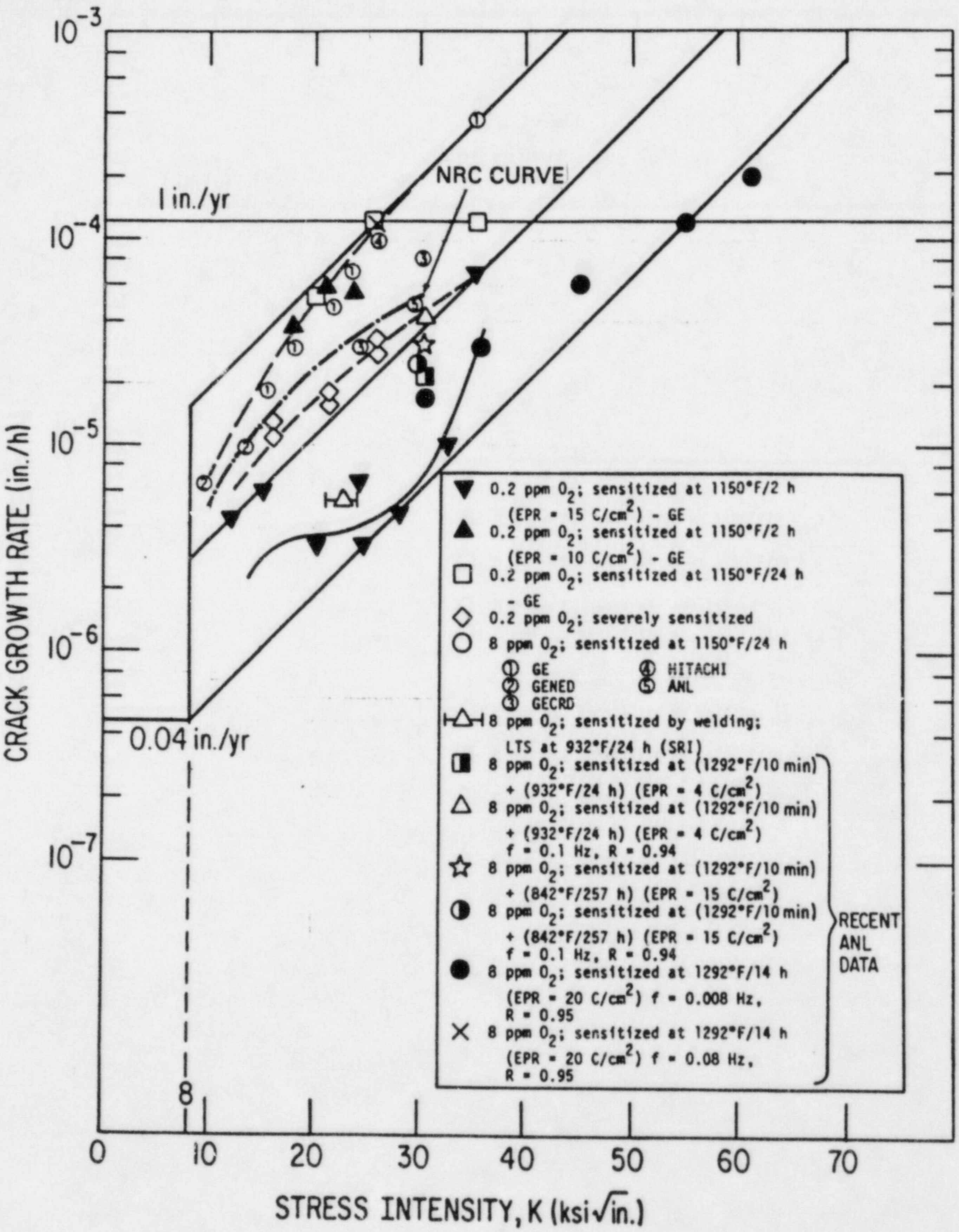

NRC CURVE
1 in./yr
0.04 in./yr
8
CRACK GROWTH RATE (in./h)
STRESS INTENSITY, K (ksi√in.)
0.2 ppm O2; sensitized at 1150°F/2 h (EPR = 15 C/cm2) - GE
0.2 ppm O2; sensitized at 1150°F/2 h (EPR = 10 C/cm2) - GE
0.2 ppm O2; sensitized at 1150°F/24 h - GE
0.2 ppm O2; severely sensitized
8 ppm O2; sensitized at 1150°F/24 h
1 GE
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3 GECRD
4 HITACHI
5 ANL
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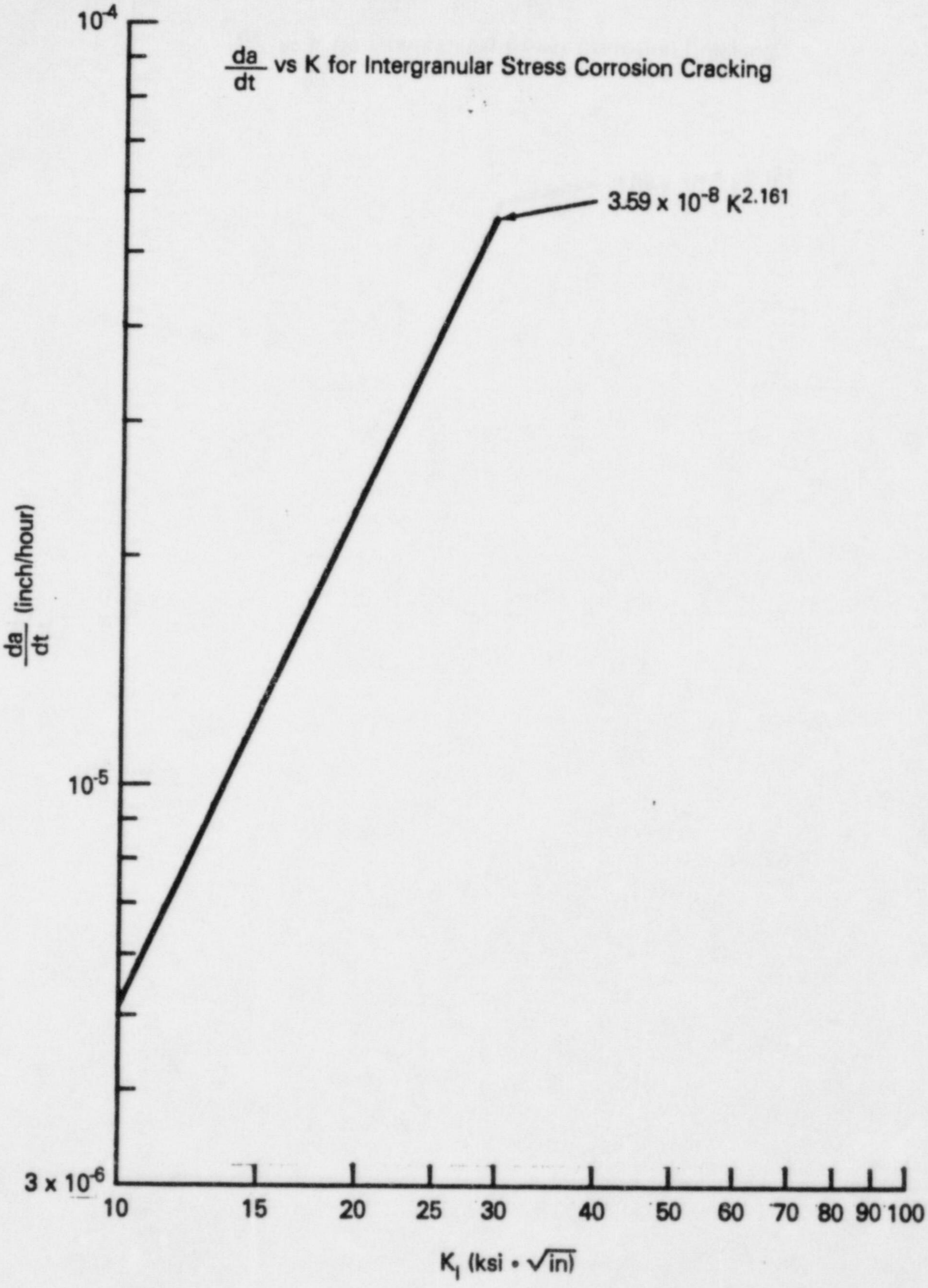
RECENT ANL DATA

Figure 1



$\frac{da}{dt}$ vs K for Intergranular Stress Corrosion Cracking
$3.59 \times 10^{-8} K^{2.161}$
10^{-4}
10^{-5}
3×10^{-6}
$\frac{da}{dt}$ (inch/hour)
10
15
20
25
30
40
50
60
70
80
90
100
K_I (ksi • $\sqrt{in}$)

Figure 2

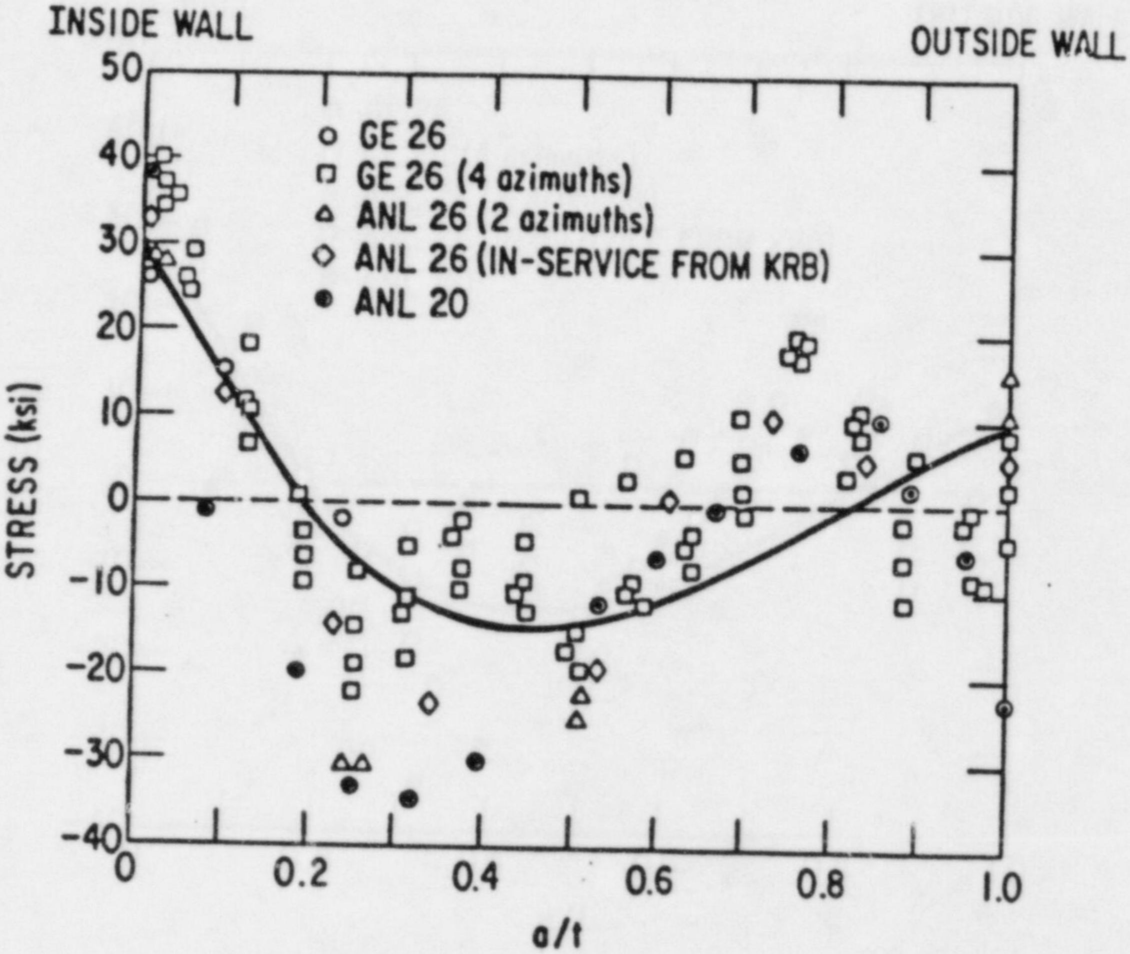


Fig. 3 Through-wall Distribution of Axial Residual Stress in Large-Diameter Pipes (t $\geq$ 1 in.).

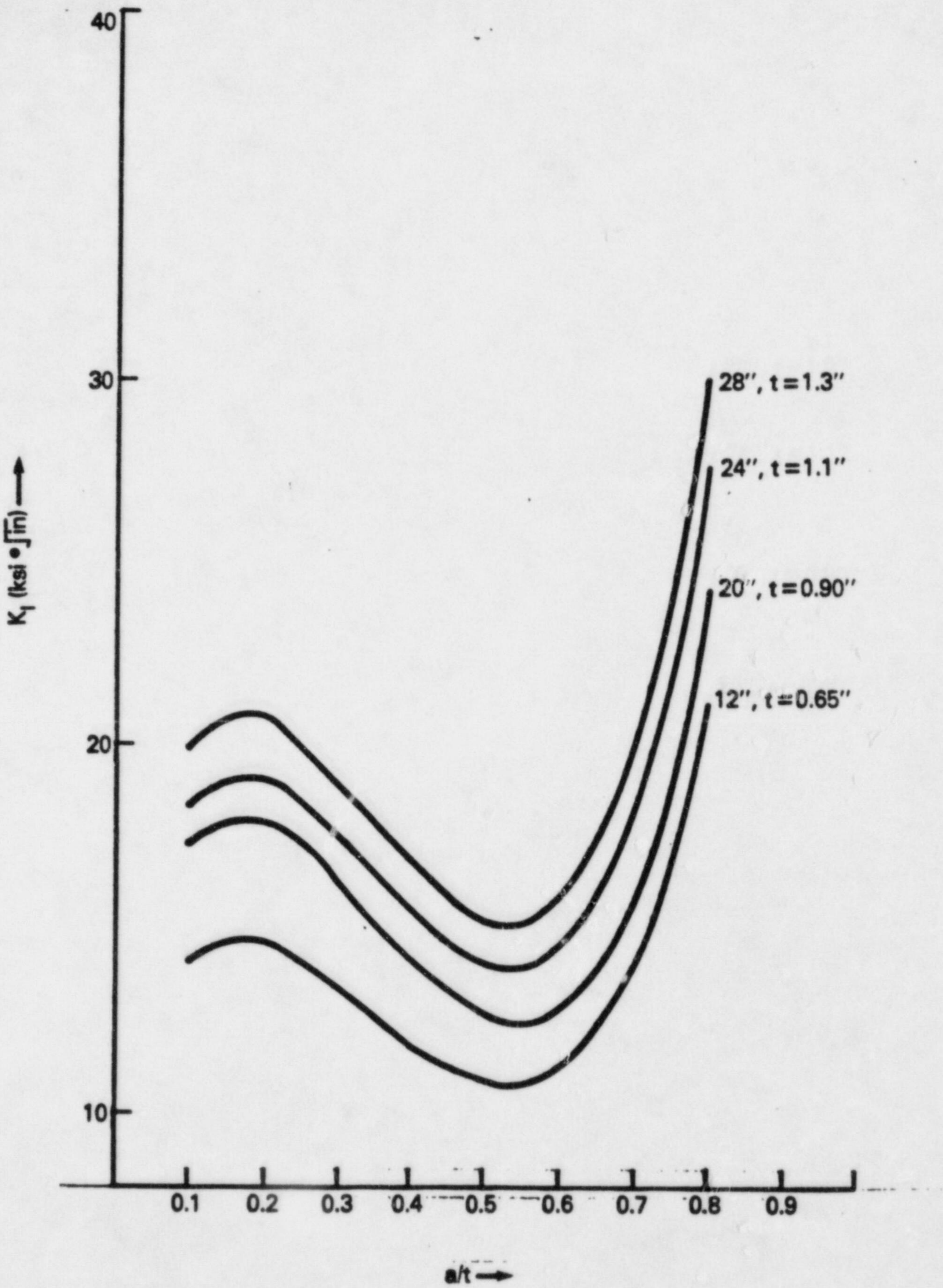

40
30
20
10
K_I (ksi • $\sqrt{in}$) ⟶
28", t=1.3"
24", t=1.1"
20", t=0.90"
12", t=0.65"
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
a/t ⟶

Figure 4

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The total stress intensity factor, K_{IT}, is given by

$$K_{TT} = K_{IP} + K_{IR}$$

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Correlation with Service Experience

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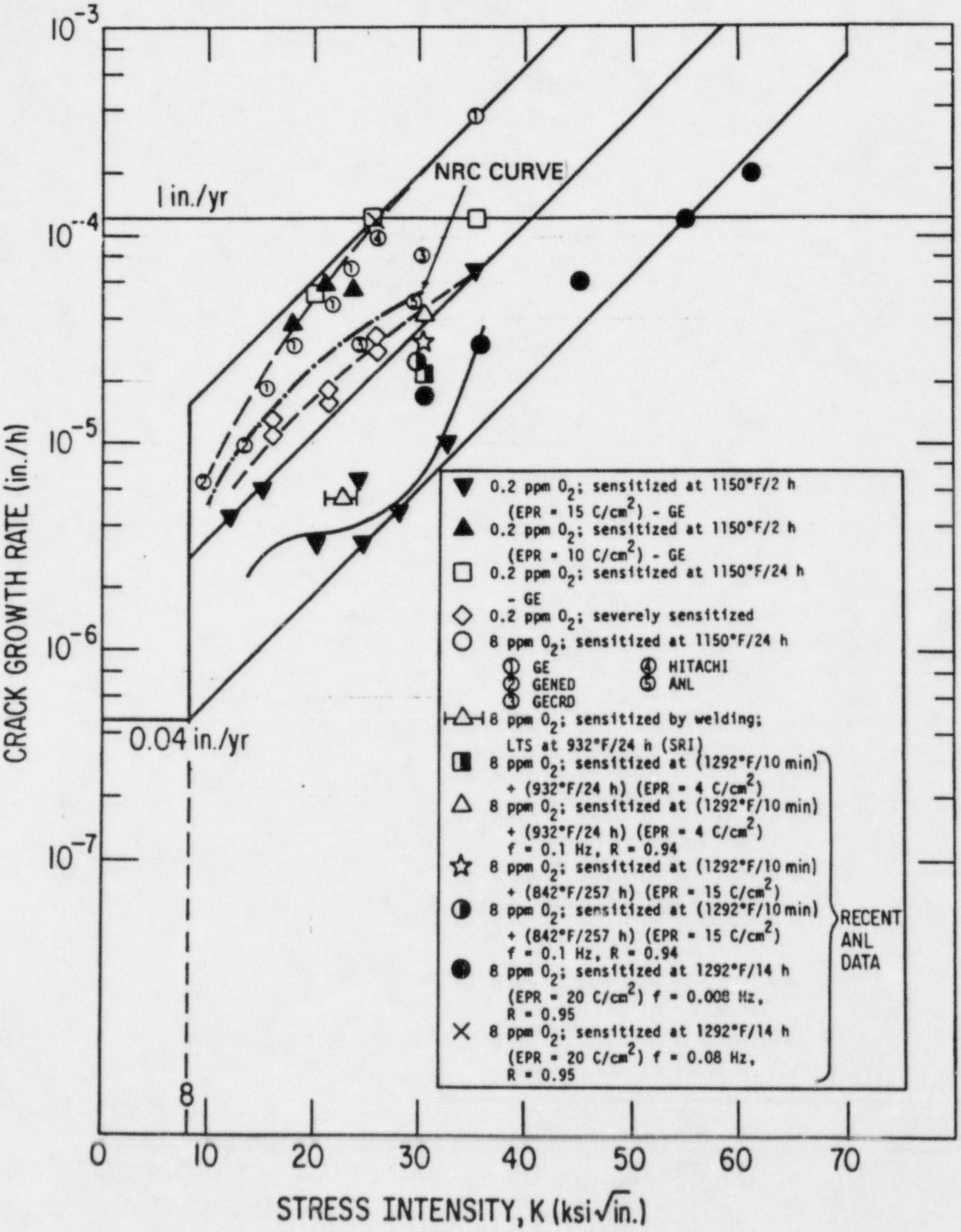

10^-3
10^-4
10^-5
10^-6
10^-7
1 in./yr
0.04 in./yr
NRC CURVE
8
0
10
20
30
40
50
60
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CRACK GROWTH RATE (in./h)
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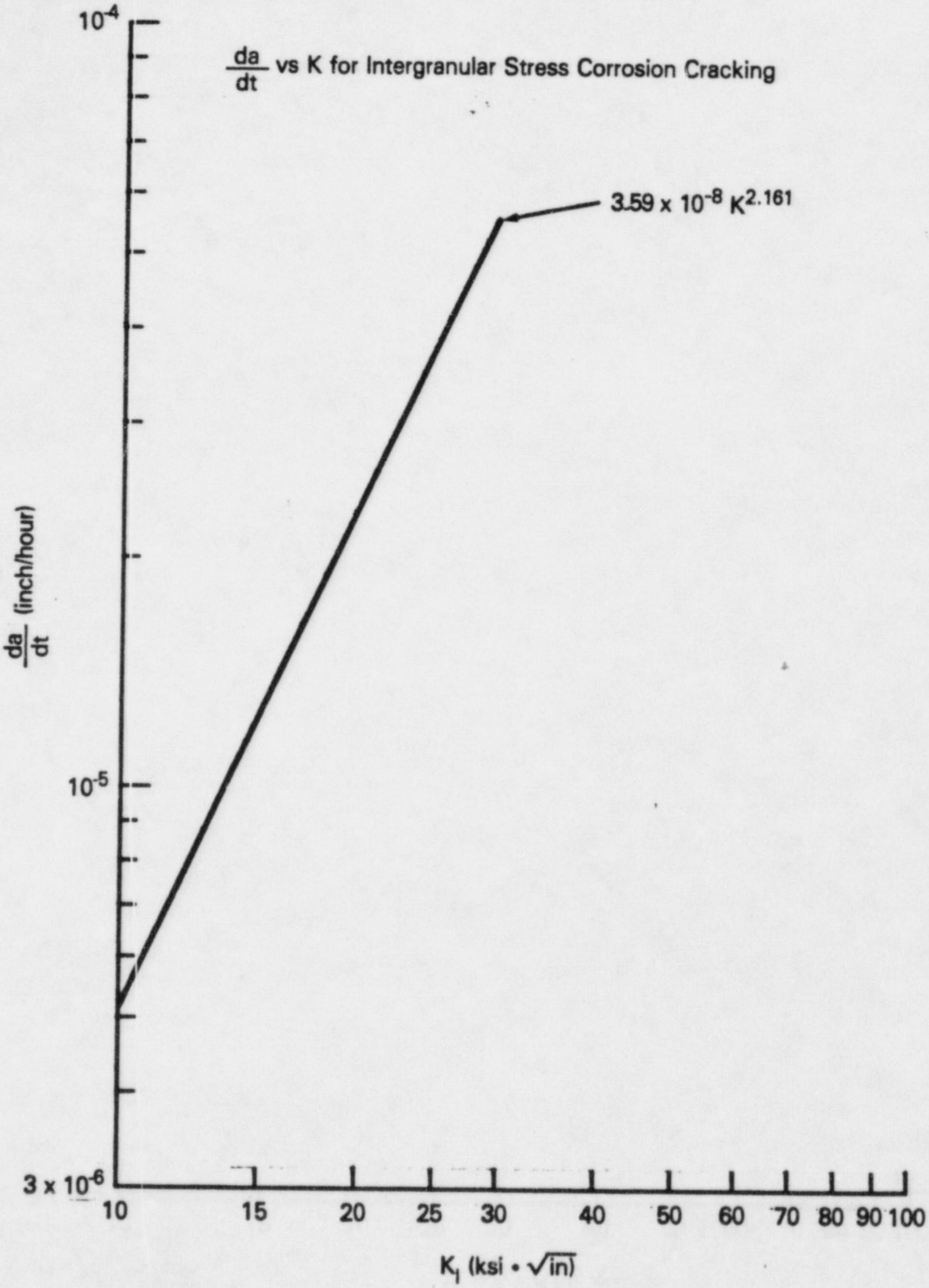
RECENT ANL DATA

Figure 1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3.59 x 10-8 K2.161
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10-5
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da/dt (inch/hour)
10
15
20
25
30
40
50
60
70
80
90
100
KI (ksi • √in)

Figure 2

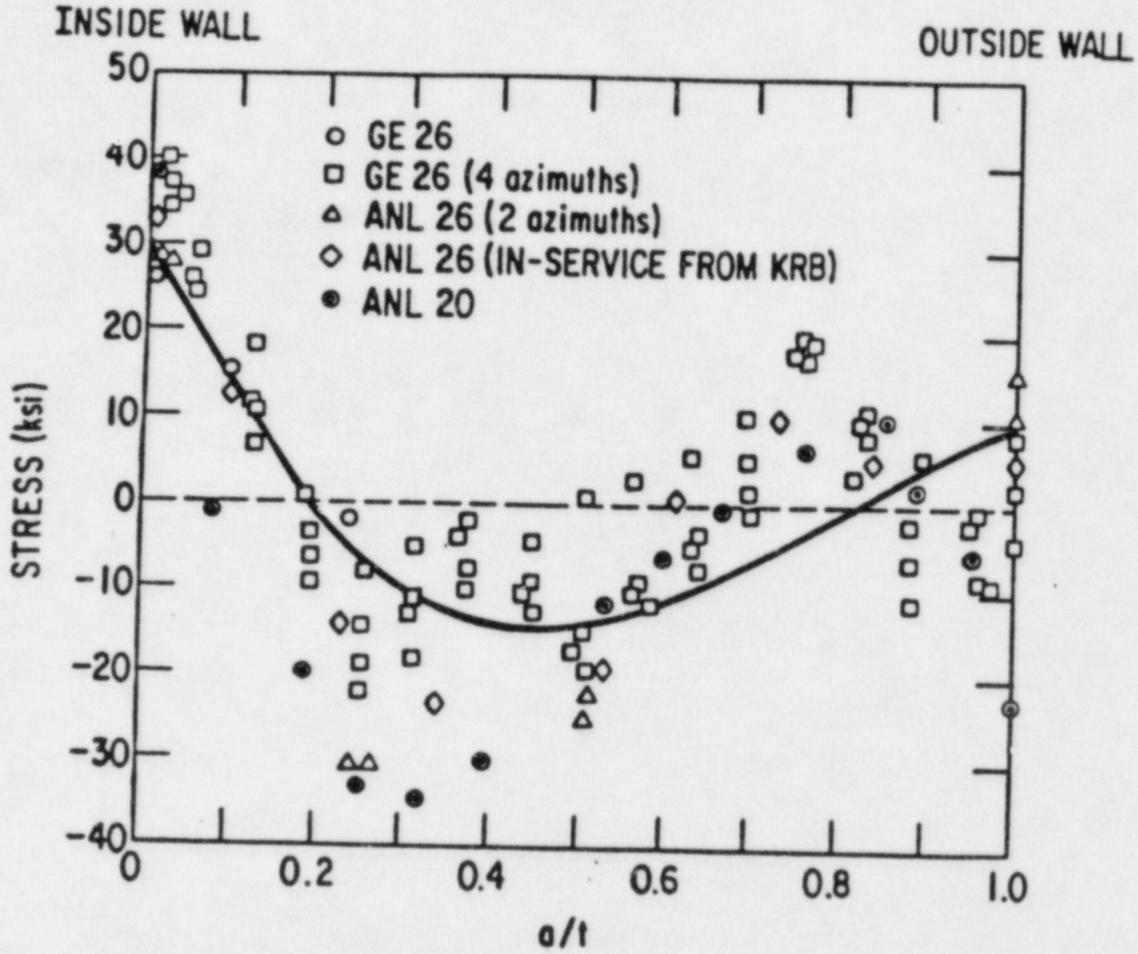
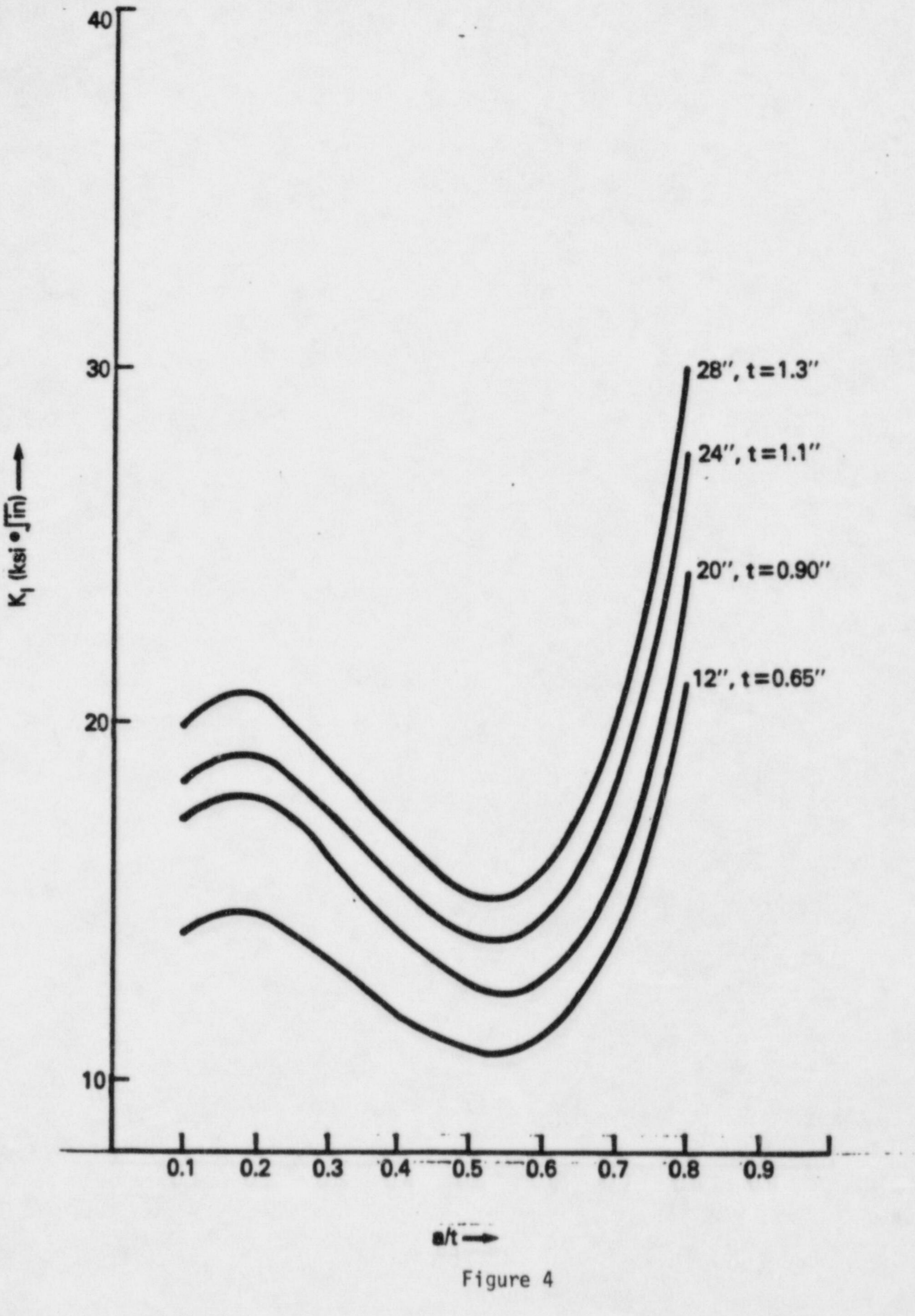


Fig. 3 Through-wall Distribution of Axial Residual Stress in Large-Diameter Pipes (t $\geq$ 1 in.).



40
30
20
10
K_I (ksi • $\sqrt{in}$) ⟶
28", t=1.3"
24", t=1.1"
20", t=0.90"
12", t=0.65"
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
a/t ⟶

Figure 4