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INTEGRITY OF AUSTENITIC STAINLESS STEEL PIPING WELDS FOR NUCLEAR SERVICE

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A criterion applying K_{Id} concept was developed to determine the fracture mechanics properties of austenitic stainless steel nuclear piping welds. The critical dimensions, length and depth, for crack initiation were established and plotted in a chart. This study enables the dimensions of a discontinuity detected in an in-service inspection to be compared to the critical dimensions for crack initiation, and the indication can be judged critical or non-critical for the component.

INTRODUCTION

The nuclear power industry has utilized thorough inspection and testing of components during manufacture, construction and initial start-up phase.

However, the industry also recognizes the need for a continuing in-service inspection program.

The purpose of ASME Code Section XI (1) is to assure the mechanical integrity of the pressure boundary of a plant for its expected service life. Prior to the introduction of an evaluation technique into section XI, the only possible action if non-acceptable indications were detected during service was to repair or replace the component.

In some cases, however, either repair or replacement is difficult for both economical and technical reasons. Changes and additions to section XI have been made to provide a conservative flaw evaluation procedure based on the principles of fracture mechanics.

Flaws that exceed the inspection standards can be analytically evaluated to determine if the indication detected in an in-service inspection would grow to a dangerous size during the remaining service life of the component.

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Upon satisfying the flaw acceptability criteria the component may be returned to service without repair.

Although the majority of nuclear components in a nuclear power plant are built of austenitic stainless steel, the flaw analytical evaluation of section XI (1) has only been developed for ferritic materials.

The purpose of this study was to develop an evaluation criterion for discontinuities detected in austenitic stainless steel nuclear piping welds.

K_{1d} tests were performed on type 304 stainless steel piping weld metal and heat affected zone: relationships between the length and depth of discontinuities were established. The critical dimensions for flaw initiation for a given pipeline were determined and plotted in a chart.

Materials and Experimental Tests

K_{1d} Determination

Weld metal and heat affected zone specimens from coupons welded according to the same essential variables used in the production welding were impact tested according to ASTM STP 563 "Instrumented Impact Testing". The tests were performed in a Tinius Olsen equipment with an instrumented tup. The specimens were pre-cracked with crack lengths between 4,5 and 5,5 mm. All specimens presented elastic-plastic behaviour (Figures (1) and (2)). K_{1d} values were obtained by the equivalent energy method and the following equation was used:

$$K_{1d} = \frac{p \cdot s}{B.\ W^{3/2}} \left[2,9\ (t/W)^{1/2} - 4,6\ (t/W)^{3/2} + 21,8\ (t/W)^{5/2} - 37,6\ (t/W)^{7/2} + 38,7\ (t/W)^{9/2} \right] \ldots\ldots(1)$$

B - specimen thickness: 10,0 mm
W - specimen width
t - crack depth

TABLE 1 - The highest and lowest K_{1d} values obtained experimentally

	Highest MPa$\sqrt{m}$	Lowest MPa$\sqrt{m}$
Weld metal AWS ER 308 AWS E 308	153	128
Heat affected Zone AISI 304	132	115

The lowest K_{1d} values were employed in this study.

Material. The weld metal presented the following chemical analysis:

C = 0,05%; S = 0,015%; P = 0,021%; SI = 0,45%;

Mn = 1,53%; Cr = 20,6%; Ni = 9,8%; Mo = 0,18%;

Nb + Ta = -; Cu = 0,18%; W = 0,01%; V = 0,07%;

Co = 0,24%

Mechanical Tests. The tensile tests were performed in a 10 ton Instron machine, according to the requirements of the ASME code, section IX

K_1 Determination

For the determination of the stress intensity factor K_1, the plasticity of the material for flaw initiation was considered.

The analysis has been performed on Reactor Coolant System Piping Welds: Hot, Intermediate and Cold Leg. The longitudinal stress was considered and determined by the equation:

$$\sigma = \frac{1}{2}\left(\frac{pxr}{e} - 0{,}1\ p\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Once the longitudinal stress had been determined, the study developed by Sih and Hagendorf (3) for K_1 determination considering a cylindrical shell subjected to a uniform extensional load was applied. For the present study, a flaw parallel to the weld bead was considered, subjected to an equal and opposite uniform extensional load due to hydrostatic pressure. The stress intensity factor at the top and bottom surface layers is given by the following equations:

$$K_1 \left(+ \frac{e}{2} = F_1 \left(\frac{e}{2a}, \frac{e}{R}, \nu\right) \frac{No\sqrt{a}}{e} \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$K_1 \left(- \frac{e}{2} = F_2 \left(\frac{e}{2a}, \frac{e}{R}, \nu\right) \frac{No\sqrt{a}}{e} \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Some assumptions were made for K_1 determination:

- No values were obtained for flaw lengths equivalent to $\pi/8$, $\pi/4$, $3\pi/8$, $5\pi/16$ and $3\pi/16$.
- For each length the following depths were considered: 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% of the pipe thickness.

No values referred to equation (3) were calculated multiplying the flaw area by the longitudinal stress.

Once No values had been calculated, it was determined the ratio between the pipe thickness and flaw length. Depending on this parameter, it was used the ratio between the pipe diameter and flaw length or the ratio between the pipe thickness and pipe radius for F Factor Determination (Figure (3) and (4)). K_1 is then obtained by the equation in reference (3).

Results / Discussion

For austenitic stainless steel type 304 piping, K_{1d} values from weld and heat affected zones were obtained experimentally. In order to analyse the integrity of the pipe those values were compared to the K_1 values obtained mathematically.

Making a comparison between K_1 and K_{1d} values, when the following correlation is satisfied:

$$K_1 < K_{1d}$$

instability for flaw initiation is not expected.

The critical length and depth that satisfy the correlation

$$K_1 = K_{1d}$$

where the instability may start to occur are presented in Figures (5) to (10).

Flaws were considered in this study that show up the internal or external surface of the pipe. Internal indications that do not show up the internal and external surface of the pipe are considered less critical for the component.

Fatigue and stress corrosion cracking were not considered in this study.

The critical length and depth of indications were determined considering hydrostatic pressure and room temperature. For service conditions higher temperatures and lower pressures are expected.

K_{1d} were determined by the Equivalent Energy Method. Flaws that exceed the "critical size" are expected to present ductile-tearing rupture.

In an inservice inspection the length and depth of indications detected by a non-destructive testing volumetric method can be compared to the length and depth for flaw initiation, Figures (5) to (10) and an indication can be considered critical or non-critical for the component.

Conclusions

Considering circumferencial welds in austenitic stainless steel nuclear pipelines, hot, intermediate and cold leg:

It was possible to derive a chart relating length and depth of discontinuities to their corresponding stress intensity factor.

Following the criterion $K_1 = K_{1d}$ several critical dimensions for crack initiation could be evaluated.

REFERENCES

(1) *American Society of Mechanical Engineers ASME*, 1980, XI Division 1, 14

(2) Rebello, J.M.A., and Soares, G.F.W., 1982

"Weld Qualification Joints", *ECEPEL Centro de Pesquisas de Energía Elétrica*, Report 160, 4.

(3) Americal National Standard Institute B - 31.3., Longitudinal Stress Calculation

(4) Sih and Hagendorf, 1974, *Stress Intensity Factors*, 73,1-1.

SYMBOLS USED

a = one-half the total length of a surface crack (in)

B = specimen thickness: 100 mm

e = pipe thickness (in)

F = factor to be determined in the Figures (3) and (4) for K_1 calculation

K_{1d} = critical plane strain stress intensity factor (dynamic) ($\mathrm{MPa}\sqrt{\mathrm{m}}$)

K_1 = defect stress intensity factor ($\mathrm{ksi}\sqrt{\mathrm{in}}$)

N_o = uniform extensional load applied perpendicular to the crack plane (pounds)

ν = Poisson's ratis (ν = 0,3 for austenitic stainless steel)

p = hydrostatic pressure (psi)

σ = longitudinal stress (psi)

R = pipe internal radius (in)

r = pipe external radius (in)

S = distance between the supports (during the test: 40 mm)

t = crack depth (in)

W = specimen width (mm)

Conversion factor:

1 in = 25,4 mm

1 psi = 145,038 Mpa

1 $\mathrm{ksi}\sqrt{\mathrm{in}}$ = 0,90 $\mathrm{Mpa}\sqrt{\mathrm{m}}$

TABLE 2 - Example: K_1 values obtained from cold leg pipe of a typical nuclear plant

Cold leg 32,19" OD e = 2,32" p = 3107 psi

For $\frac{\pi}{8}$ r indication length

Indication depth (t) % of thickness	K_1 value $(MPa\sqrt{m})$ + e/2	 - e/2		
10	17,17	15,03		
20	33,71	29,50		
30	50,63	44,30		
40	67,01	58,63		
50	83,13	72,74		
60	99,02	86,65		
70	114,44	100,33	critical	$K_1 = K_{1d}$
80	130,09	113,33	propagation	$K_1 > K_{1d}$
90	145,15	127,00	propagation	$K_1 > K_{1d}$
100	160,07	140,06	propagation	$K_1 > K_{1d}$

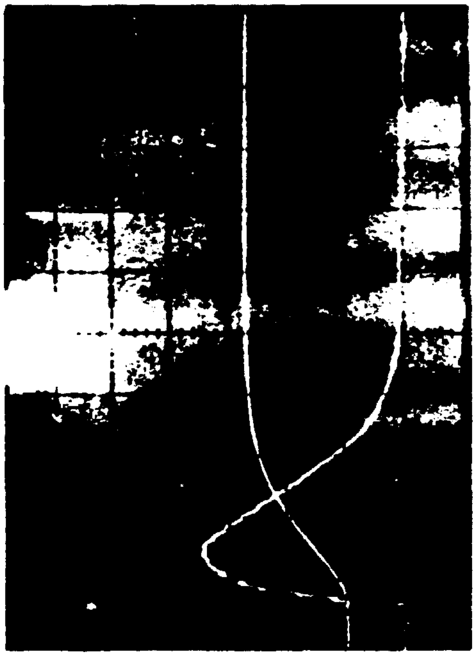

FIGURE 1 K_{1d} Determination

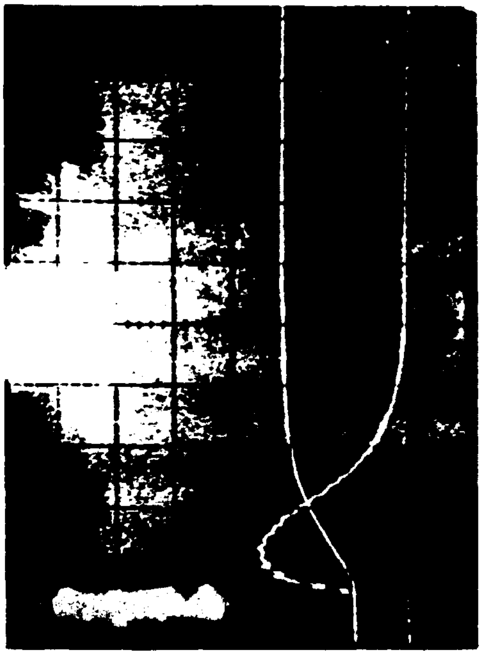

FIGURE 2 K_{1d} Determination

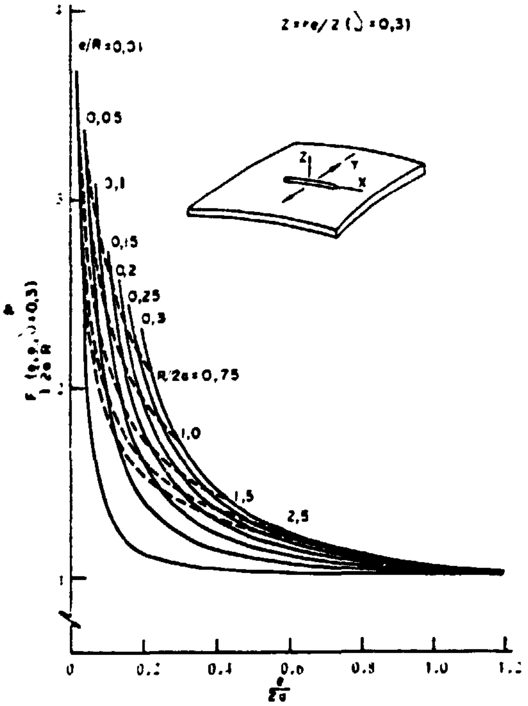

FIGURE 3 F_1 determination for K_1 calculation - Reference (3)

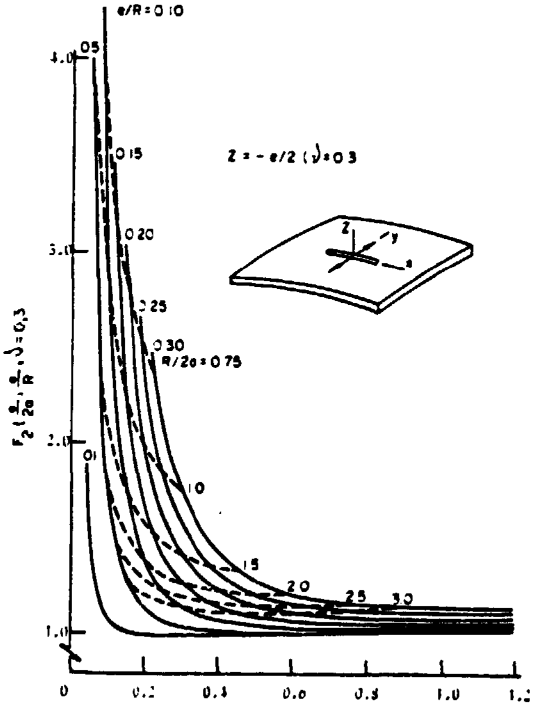

FIGURE 4 F_2 determination for K_1 calculation - Reference (3)

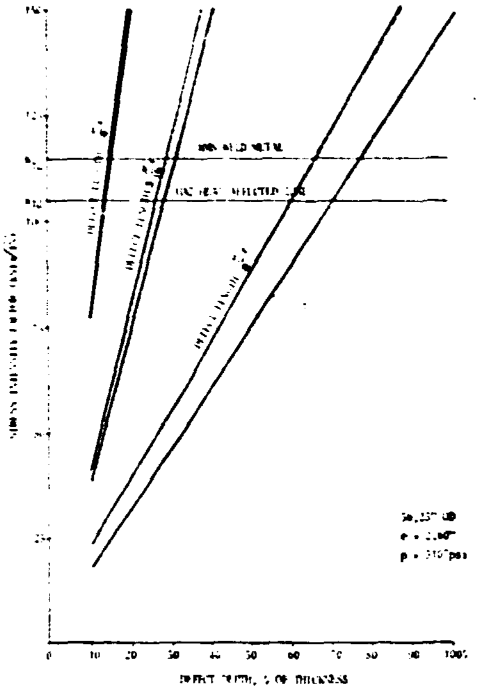

FIGURE 5 Stress intensity factors as function of the defect sizes for the intermediate leg pipe

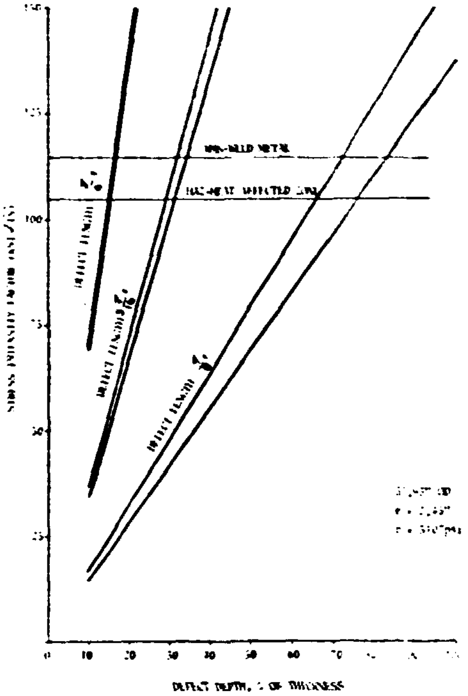

FIGURE 6 Stress intensity factors as function of the defect sizes for the hot leg pipe

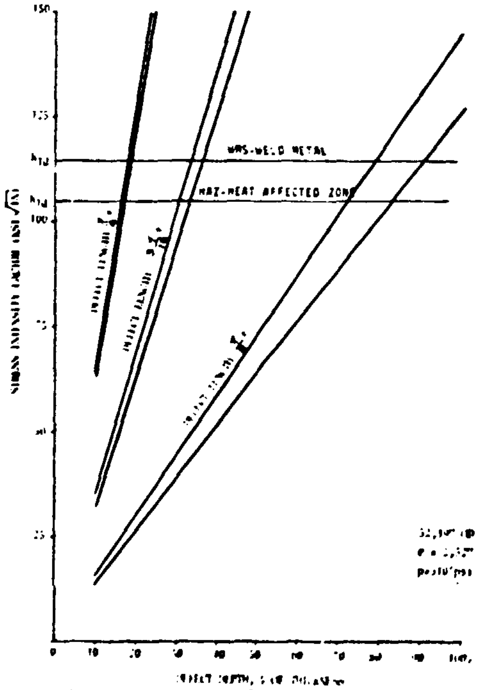

FIGURE 7 Stress intensity factors as function of the defect sizes for the cold leg pipe

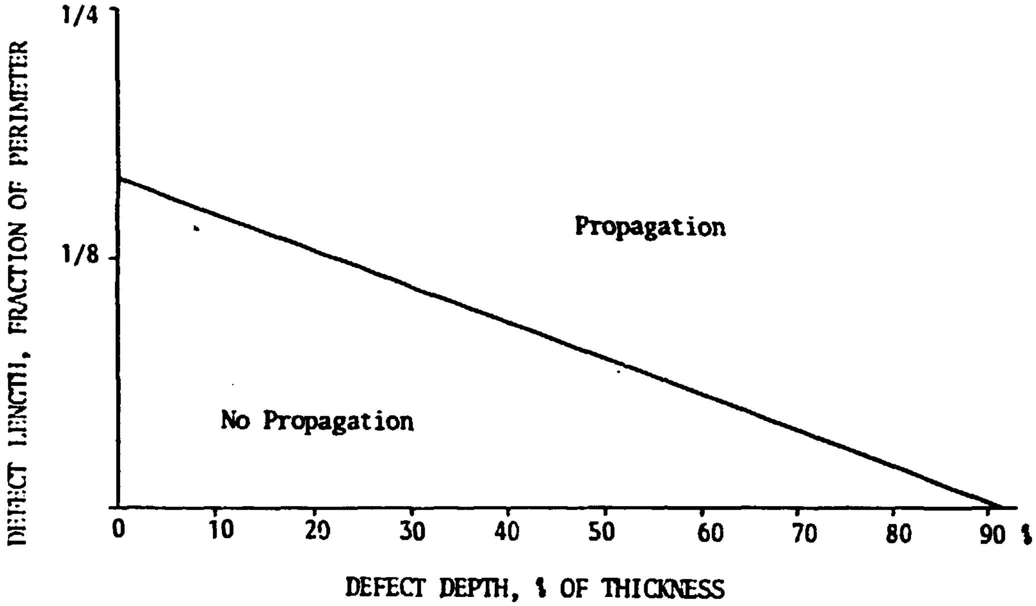

FIGURE 8 - Critical sizes for a circumferencial defect in the intermediate leg

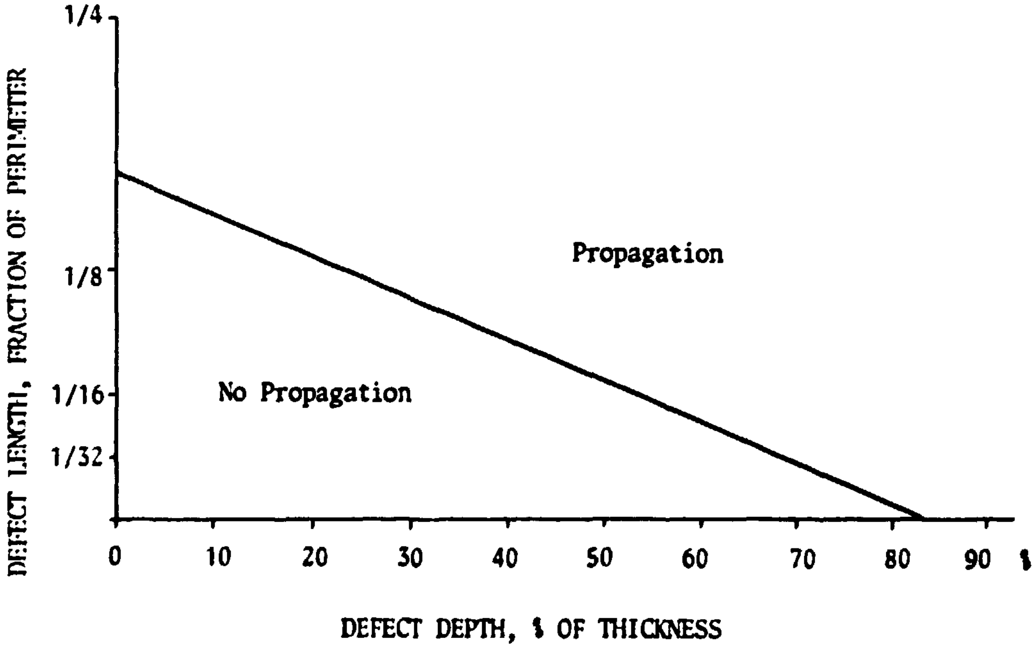

FIGURE 9 Critical sizes for a circumferencial defect in the hot leg pipe

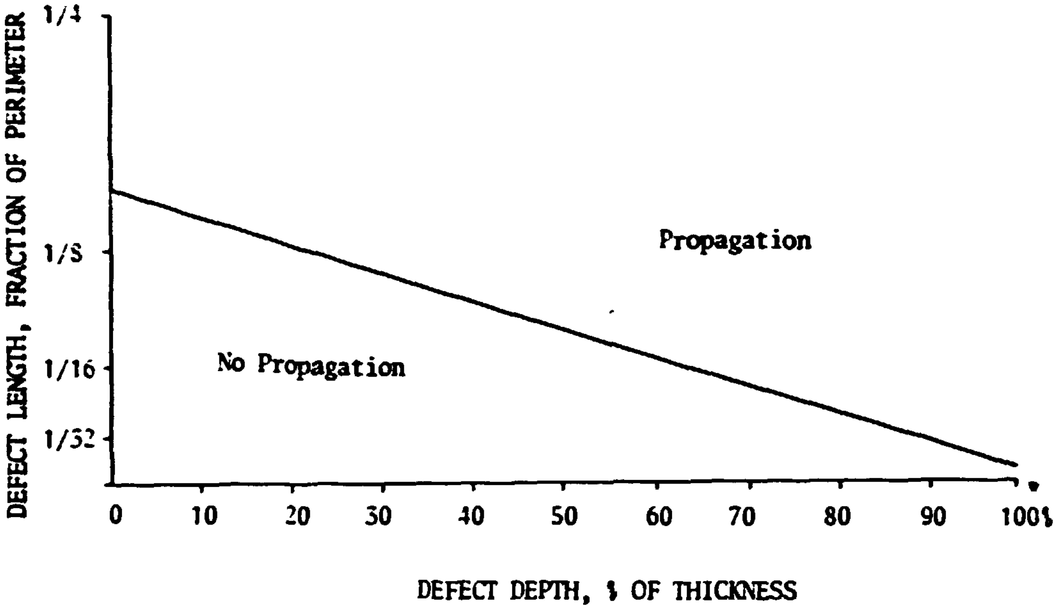

FIGURE 10 Critical Sizes for a circumferencial defect in the cold leg pipe