Three types of overlay designs (see Figure 2) have been generally used in the actual practice. The Type I weld overlay design is based on the very conservative assumption that the crack extends through-wall and around the entire 360° circumference of the pipe. The overlay alone must then restore the entire structural design basis margin. The Type II weld overlay addresses the condition where the crack length is known to be significantly less than the total circumference, but the crack depth is assumed to be through-wall. Credit for the uncracked portion is taken in the structural margin evaluation. Type I and II overlays are referred to as full structural overlays since they restore the structural margin to Code minimum values without relying on the crack depth estimates. Type III overlay is utilized if short, shallow flaws are detected in the pipe. For this case, the principal objective is to provide a favorable residual stress distribution that will retard the growth of shallow cracks on the inside surface of pipe.

The weld overlays are sized: (1) by using the Tables in IWB-3640 in Reference 5, or (2) by using the basis equations of IWB-3640 with a safety factor of 3.0. The IWB-3640 flaw assessment procedure used in the weld overlay designs assure adequate margin against collapse but does not explicitly consider failure by tearing stability. A detailed fracture mechanics evaluation [6] is presented in the next section to show that IWB-3640 based procedure also provides adequate margin on tearing stability also.

3 EPFM BASED DUCTILE FRACTURE MARGIN

Configurations representing each of the three weld overlay types were selected for the EPFM evaluations. For each overlay type, it was assumed that the applied stress (P_m+P_b), based on the nominal pipe wall thickness, was 1.1 S_m or 18.6 ksi (see Table 1). The pipe size was assumed as 24 inch schedule 80 and the overlay thickness was calculated using Table IWB-3641-1 of Reference 5. The EPFM evaluation was then performed for the same overlay geometry to obtain the elastic-plastic instability stress. The evaluation considered the weld toughness properties through the selection of appropriate material J-T curves. The calculated instability stress was then converted to nominal pipe thickness basis for the evaluation of safety factors.

3.1 EPFM Calculation Methodology and Parameters

The J-integral and the applied tearing modulus, T, were evaluated as a function of applied loading using the estimation scheme procedure given in Elastic-Plastic Fracture Handbook [7] and its supplement [8]. The TIG weld J-T curve (curve 2 in Figure 3) was developed from J-R data given in reference 9. A lower bound weld J-T curve (curve 1 in Figure 3) for shielded metal arc wels (for evaluation of Type 3 overlays) was obtained from data given in reference 10. The intersection of ($J_{applied}$, $T_{applied}$) curve and the appropriate (J_{mat}, T_{mat}) curve gave the value of J-integral at instability. The applied stress at instability was determined corresponding to this J value.

In using the estimation scheme procedure, only one type of loading (i.e. pure tension or pure bending) can be considered. On the other hand, the applied stress at a weld overlay generally includes both a

membrane stress (P_m) and a bending stress (P_b). Therefore, the instability stress was calculated for two separate cases: pure tension, and pure bending. The instability bending stress corresponding to an applied P_m was then calculated using a linear interaction formula.

The following Ramberg-Osgood parameters from Reference 9 based on an experimentally-determined true stress-true strain curve of a GTAW weldment were used:

$$\alpha = 2.83,\ n = 11.84,\ \sigma_0 = 53{,}900 \text{ psi}$$

3.2 Type I Weld Overlay Evaluation

A 360° crack with depth equal to the original thickness of the pipe was conservatively assumed in this configuration. For an applied (P_m+P_b) of 1.1 S_m and using Table IWB-3641-1, the weld overlay thickness was calculated as 0.81 inch. This gives an a/t ratio of 0.60. The instability stress for this geometry was calculated using the estimation scheme formulas of Reference 8 for 360 degree crack geometry.

Since the estimation scheme parameters for bending loading are currently unavailable, therefore, only the pure tension loading case was evaluated. It was assumed that the instability stress for bending is 1.33 times the corresponding tension stress.

Figure 3 shows a plot of the (J_{app}, T_{app}) for a/t = 0.60. Since the crack tip for this case would advance essentially in a GTAW weld metal, GTAW J-T (Curve 2) was used to determine the value of J at instability. The instability stress was determined as 66.6 ksi and the corresponding factor of safety is listed in Table 1.

3.3 Type II Weld Overlay Evaluation

This overlay configuration assumes a part circumference crack with the depth equal to the original wall thickness of the pipe. The crack length was assumed to be 30% of the circumference. The overlay thickness was calculated as 0.34 inch based on a (P_m+P_b) of 1.1 S_m.

The assumed flaw geometry in the Type II overlays cannot be evaluated by the available estimation scheme procedures which consider either a through-wall or a 360° flaw. Therefore, a 23% of the circumference long through-wall flaw, which had the same area as the subject part-through geometry was used for the EPFM evaluation purposes.

Pure tension and pure bending cases were separately considered in the EPFM calculations. The J-integral values were obtained using the formulas from Reference 8.

The (J_{app}, T_{app}) lines for both the loadings are shown in Figure 3. It should be noted that the Type II weld overlay configuration could be a combination of the GTAW overlay and the original sub arc weldment. Thus, the overall characteristic may be a combination of the properties of the two weldments. However, the crack extension is expected to be predominantly in the TIG weld metal. Therefore, the (J_{mat}, T_{mat}) curve 2 in Figure 3 was used to determine the instability stress. For the pure tension case, the instability stress was determined as 42 ksi and the same was 50 ksi for the pure bending. The instability stress shown in Table 1 (P_m = 0.5 S_m or 8.5 ksi and remaining bending) was obtained by assuming a linear interaction relationship between the tension and bending instability stresses.

3.4 Type III Weld Overlay

The primary purpose of this type of overlay is to produce a favorable residual stress pattern. The assumed crack is smaller in depth than the pipe wall thickness. As a limiting case, the crack tip was assumed to be in the submerged arc weld material. The crack was assumed to be 50% through-wall in depth and 30% of circumference in length. For this crack geometry and the assumed (P_m+P_b) of 1.1 S_m, the calculated overlay thickness per Table IWB-3641-1 is zero. However, consistent with the typical Type III overlay design practice, a 1/8 inch thick overlay was assumed. The instability stress calculations for this geometry were based on the same through-wall flaw approximation that was used for analyzing the Type II overlay. The equivalent through-wall flaw in this case was 13.6% of the circumference. The (J_{mat}, T_{mat}) curve 1 for submerged arc welds was used for the instability load determination. The tensile and bending instability stresses were determined to be 39.7 ksi and 44.5 ksi, respectively. Table 1 shows the combined instability stress and the safety factor. As expected, the instability stress and the corresponding factor of safety for this case are somewhat lower than the values for a Type II overlay.

4 DISCUSSION OF RESULTS AND CONCLUSION

Table 1 presents the EPFM calculated safety factors on loads for the specific cases of weld overlays and design stresses. The results are based on a set of material stress-strain parameters and weld J-resistance curves that were considered lower bound values.

From a review of the safety factors shown in Table 1, it is concluded that when conservative estimates of the weld toughness properties are considered and when the overlay thickness are designed with allowable stress essentially equal to the calculated applied stress, the EPFM calculated factors of safety for Type II and III overlays may be slightly less than those implied in IWB-3640. In all other cases, which are more typical, the IWB-3640 implied safety margins are expected to be met or exceeded. Although the calculations were performed for selected cases, the same conclusions are expected for other pipe sizes, weld overlay thicknesses, and material J-T curves also.

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Table 1 Fracture Mechanics Based Margins

Weld Overlay Type	Assumed Flaw and Weld Overlay Geometry[1]	IWB-3640 Allowable Based on Nominal Pipe Section (ksi)	Instability ($P_m + P_b$) by EPFM (ksi)	Factor of Safety
I	360° crack, 1.218 in. deep. Overlay thickness 0.81 in.	18.6	66.6	3.6
II	1.218 in. deep crack, 30% of circumference long, overlay thickness 0.34 in.	18.6	48.3	2.6
III	0.609 in. deep crack, 30% of circumference long. Required overlay thickness 0.0. Assume overlay thickness 0.125 in. (Note 2).	18.6 (Note 2)	43.5	2.3 (Note 2)

Notes: 1. The assumed pipe geometry for all three weld overlay configurations is 24-inch Sch. 80 (OD = 24.0 in., t = 1.218 in.)
2. For the assumed flaw geometry and stress level, the IWB-3640 acceptance criteria are met without an overlay. However, calculations were performed assuming a thin weld overlay of 1/8 inch. The factor of safety without the weld overlay would be 2.08 instead of 2.3 shown above.

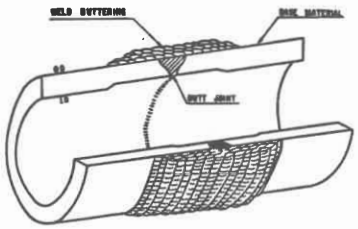

Figure 1 Typical Weld Overlay for Pipe Crack Repair

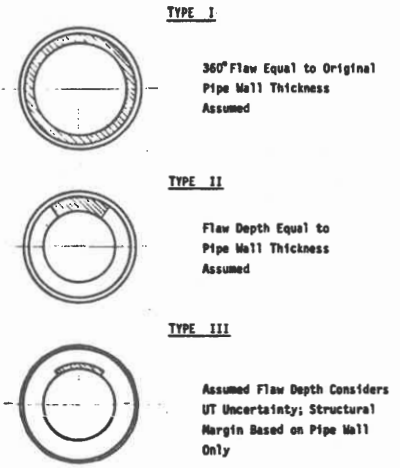

Figure 2 Types of Weld Overlays

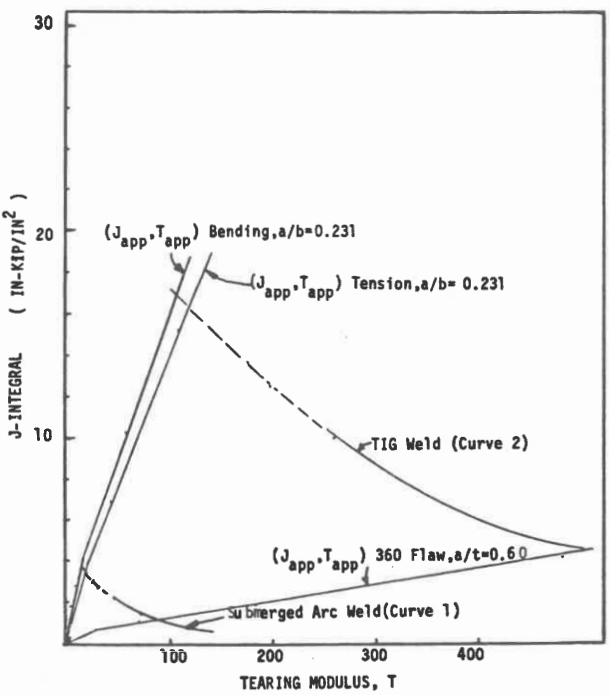

Figure 3 Tearing Stability Evaluation