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**Computer Optimizing of Bevel Angles  
for Welded Pipe Joints**

U.S. DEPARTMENT OF THE NAVY  
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COMPUTER OPTIMIZING OF BEVEL ANGLES

WELDED PIPE JOINTS

By

Professor H.W. Mergler

Case Institute of Technology

ABSTRACT

The most common method for preparing the bevel-angle for welded pipe construction is to keep it at a constant value (say 37 degrees) around the entire periphery of the branch pipe. This paper explores the "optimized bevel-angle" as a function of pipe radii, wall thicknesses, centerline offset, and intersecting angle to keep the resulting weld cross section constant and thus minimize the weld volume while insuring' clearance for total weld penetration. The advantages of using the "optimized bevel angle" are demonstrated by computer simulation for pipe diameters from 4-1/2" to 24" for wall thicknesses over the range of 0.237" to 1.312". The ratio of the fixed bevel weld volume to the optimized bevel weld volume are shown to range from 1.5 to 5 which implies phenomenal reductions in the attendant welding time.

# Computer Optimizing of Bevel Angles for Welded Pipe Joints

by

Professor H.W. Mergler  
Case Institute of Technology

Introduction - This paper is based on the following statements:

1. Pipe joint welding times are directly proportional to the applied weld volume.
2. To optimize (minimize) the joint weld volume requires the preparation of the mechanical joint such that the bevel angle  $\beta$  of the branch component be optimized along its periphery as a function of the outside radii of the joint components  $R_m$  (main), and  $R_b$  (branch), the wall thickness of the branch  $T_b$ , the angle of intersection of the joint components  $\theta$ , the offset of the centerlines of the joint components  $X_0$ , two practical boundary limits on minimum and maximum values of  $B$  dictated respectively by the destructive burning of the joint lip and torch accessibility **for total weld penetration and the independent variable  $\phi$**  defining the position along the periphery of the branch where the local value of  $B$  is defined. These parameters are shown in Figure 1.

The implied calculation in (2) above is straight-forward though formidable. This paper will discuss the computations necessary to define the locus for the branch saddle as a function of the above mentioned variables as well as of the determination of the optimized bevel angle.

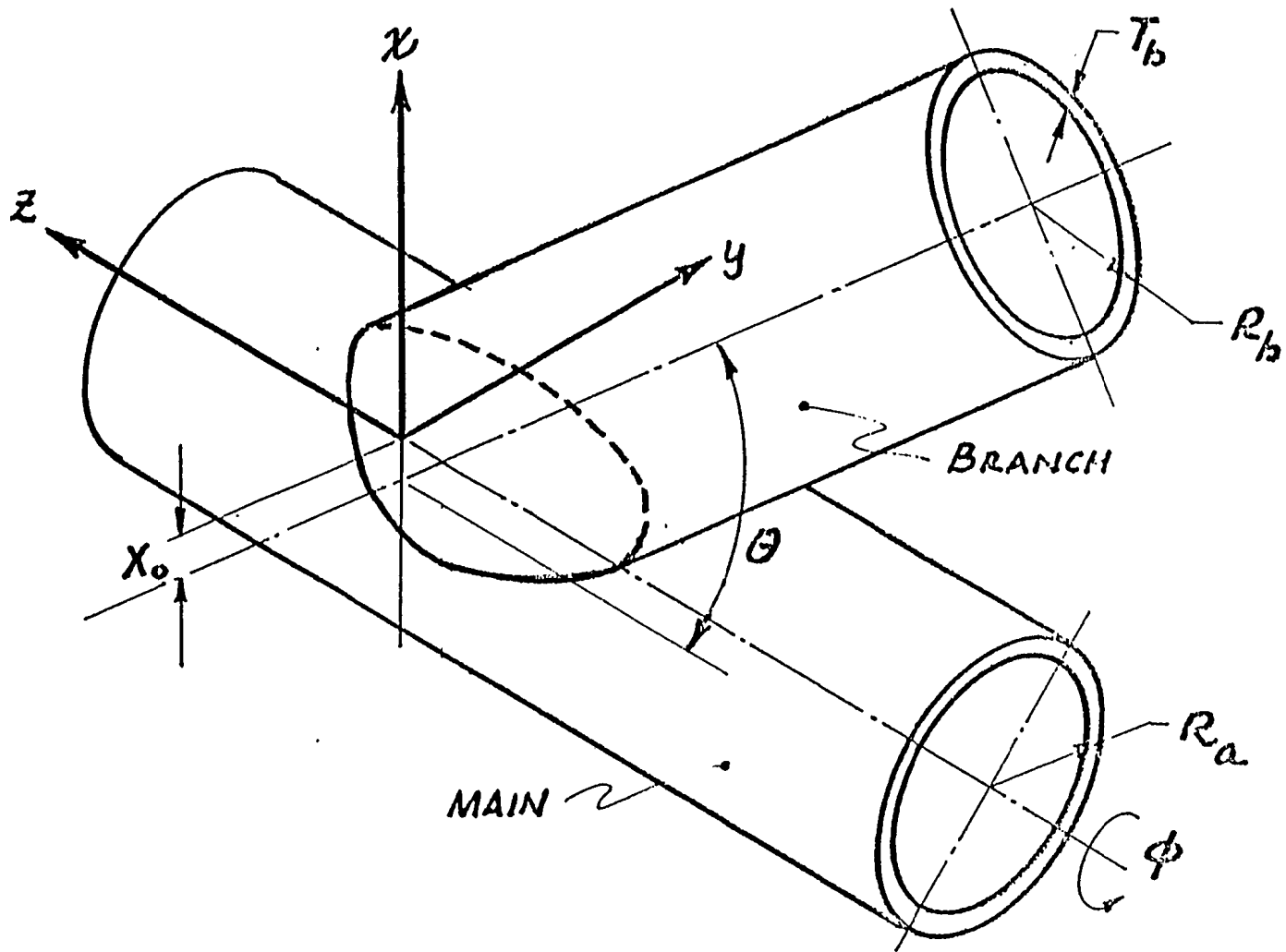


Figure 1. A Generalized Joint Configuration.

From these expressions the implied optimized weld volume may be determined and this weld volume will be shown to be dramatically smaller than those of pipe joints prepared with a constant bevel angle.

### Symbols

- $x, y, z$  - a reference coordinate frame
- $z_b$  - a linear cylindrical coordinate (a function of  $\theta$ )  
defining the branch saddle profile
- $R_a$  - the outside radius of the main component
- $R_b$  - the outside radius of the branch component
- $T_b$  - the wall thickness of the branch component
- $X_0$  - the center line offset between the main and the branch
- $\theta$  - the angle between the main and the branch
- $\phi$  - the angle in a plane perpendicular to the branch centerline  
defining a line on the branch parallel to its centerline
- $Y$  - the transformed coordinate  $\theta$
- $A$  - the transformed coordinate  $X_0$
- $D_a$  - the outside diameter of the main component
- $D_b$  - the outside diameter of the branch component
- $B$  - the bevel angle measured from the inner surface of the  
branch to the beveled surface
- $D$  - the weld preparation included angle
- BEAN - the weld preparation angle being the complement of  $B$
- $L_1$  - the length of the weld section adjacent to the beveled surface
- $L_2$  - the length of the weld section adjacent to the outer surface  
of the main component
- $L_2$  - the modified length of  $L_2$

- $P_n$  - the area of the  $n^{\text{th}}$  weld section  
 $P_M$  - the modified area of weld section  
 $v_c$  - the weld volume with  $B = \text{constant}$   
 $v_o$  - the weld volume with  $B$  optimized

Computing the Space Trajectory (Locus) of the Intersection of Two Pipes - The  
 preparation of the mechanical joint of a main-branch pair may be thought  
 of as three processes, the first two of which are done concurrently.  
 They are

1. Preparation of the intersection profile on the branch
2. Preparation of the bevel angle along the profile of (1) above
3. Preparation of the saddle hole in the main

To develop the intersection locus (1) above consider a pipe joint with  
 the following orientations shown in Figure 1.

1. The main component's centerline is coincident with the  $z$  axis  
and of radius  $R_a$ ,
2. The branch component's centerline is parallel to the  $x$ - $z$  plane  
and of radius  $R_b$ ,
3.  $X_0$  is the offset and is the  $x$  intercept of the branch's center-  
line on the  $X$  axis.
4.  $\theta$  is the angle between the branch centerline and the  $x$ - $z$  plane.
5.  $\phi$  is independent variable measured around the  $z$  axis.

The resulting equation of the intersecting locus defined on the surface  
 of the main component and expressed as a function of  $\phi$  for fixed values  
 of  $R_a$ ,  $R_b$ ,  $\theta$ , and  $X_0$  is

$$Z(\phi) = R_a \cot \theta \sin \phi \pm \sqrt{R_a^2 - (R_a \cos \phi - X_0)^2} \quad (1)$$



Through coordinate translation the locus may be expressed in terms of the branch component as

$$z_b = R_b \cot(-\theta) \sin \phi \pm |\csc(-\theta)| \sqrt{R_a^2 - (R_b \cos \phi + X_o)^2} \quad (2)$$

This (2) is the equation which describes the shape of the end of the branch for proper mechanical profile preparation of the joint. It does not, however, address the nature of the bevel angle associated with this profile.

Computation of the Weld Cross Sectional Area - The thrust of this paper is not the space trajectory of the intersecting surfaces as given by equations (1) and (2) but rather the determination of how to adjust the bevel angle on this trajectory to minimize the total weld volume.

Following a somewhat complex transformation<sup>2</sup> of coordinates and an integration over the range set by  $R_a$  and the wall thickness  $T_b$  a general expression for the weld area  $P$  may be derived as a function of  $y$  (the cylindrical angular coordinate around the  $z$  axis which is the axis of the branch component).

$$\begin{aligned} &= \frac{T_b^2}{2} \cot \theta - \frac{T_b^2 \cos \gamma}{2 \tan \theta} + \frac{T_b \cdot \sqrt{R_a^2 - [(R_b - T_b) \sin \gamma + A]^2}}{2 \sin \theta} \\ &+ \frac{(R_b \sin \gamma + A)}{2 \sin \theta \sin \alpha} \left\{ \sqrt{R_a^2 - [(R_b - T_b) \sin \gamma + A]^2} - \sqrt{R_a^2 - (R_b \sin \gamma + A)^2} \right\} \\ &+ \frac{R_a^2}{2 \sin \theta \sin \gamma} \left\{ \sin^{-1} \left( \frac{R_b \sin \gamma + A}{-R_a} \right) - \sin^{-1} \left[ \frac{(R_b - T_b) \sin \gamma + A}{-R_a} \right] \right\} \quad (3) \end{aligned}$$

Here A is the transformed offset  $X_0$  in the original joint description.

Equation (3) is derived using a weld area bounded by the bevel surface of the branch, the surface of the main, and an extension of the outer surface of the branch to the main. A proper weld however strives to have both weld surfaces  $L_1$  and  $L_2$  be the same length. If  $L_2 < L_1$ , a point N Figure 2 will be moved to  $N'$  so that the length  $L_2$  of  $N'I$  is equal to  $L_1$ . Figure 3 shows the general profile where  $L_2 < L_1$ . The point N is moved to a new position  $N'$  ( $y_1, z_1$ ) on the ellipse so that  $L_2$  of  $N'I$  is equal to  $L_1$ . The modified weld area  $P_m$  may be computed by making the following substitutions in equation (3)

$$T_b = T'_b = |Y_1 - Y_0| \quad (4)$$

$$R-b = R'_b = |Y_1|$$

Yielding a weld area  $P'$ . The area  $F$  of the triangle  $M'MN$  must then be subtracted from  $P'$  to get the new modified weld area with equal legs i.e.  $L_1 = L_2$ .

$$\text{Thus } F(B) = \frac{1}{2}(T'_b - T_b) [ (T'_b \cot B + (Z_0 - z_1)) ] \quad (5)$$

$$\text{and } P_m = P' - F \quad (6)$$

The Bevel Angle and Weld Preparation Angle - Equation (3) may be rewritten to express the bevel angle as a function of  $R_b$ ,  $T_b$ ,  $A$ ,  $\theta$ ,  $P$  and the independent variable  $y$  as

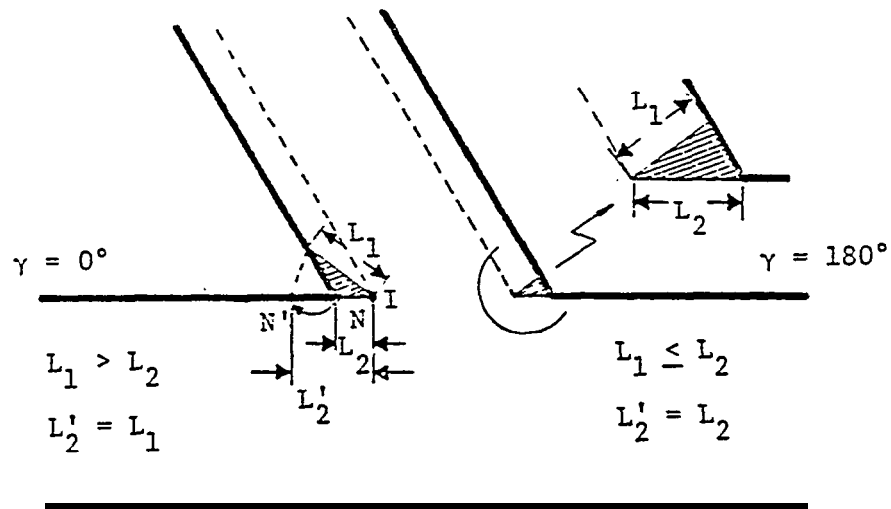


Figure 2. Modified Weld Areas in Pipe Joints for 6 # 90°, and  $\gamma = 0^\circ, 180^\circ$ .

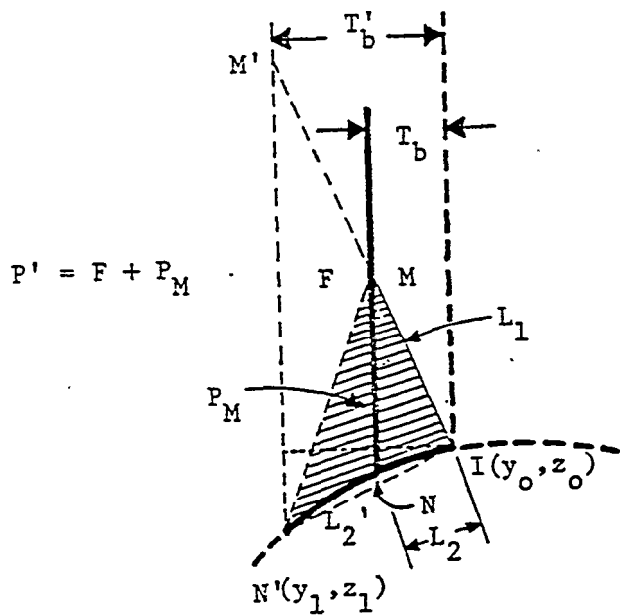


Figure 3. Intersection of the Modified Weld Area  $P_n$  in a General Profile for  $L_2 < L_1$ .

$$\begin{aligned}
B = \cot^{-1} \left( \frac{2P}{T_b} + \frac{\cos y}{\tan \theta} \right) - \frac{\sqrt{R_a^2 - [(R_b - T_b) \sin y + A]^2}}{T_b \sin \theta} \\
\frac{1}{T_b^2 \sin^2 \theta} \left[ (R_b \sin y + A) \sqrt{R_a^2 - [(R_b - T_b) \sin y + A]^2} \right. \\
\left. - \sqrt{R_a^2 - (R_b \sin y + A)^2} \right] \frac{1}{\sin \theta} + R_a^2 \left( \sin^{-1} \left( \frac{R_b \sin y + A}{R_a} \right) \right. \\
\left. - \sin^{-1} \left( \frac{(R_b - T_b) \sin y + A}{R_a} \right) \right) \quad (7)
\end{aligned}$$

Figure 4 shows this bevel angle  $\beta$  at two points on a typical branch. Of practical interest here are the limits placed on this angle. We designate the weld preparation angle as BEAN (the complement of  $B$ ) as the angle of torch bevel measured from a line perpendicular to the surface of the branch pipe such that the wall will not be distorted by the torch heat. Experience indicates this should be no greater than  $55^\circ$  for plasma and  $68^\circ$  for oxyacetylene. This maximum angle is designated DI in Figure 5. The minimum angle (TI) of  $37^\circ$  (Figure 6) has been found to be the minimum angle to allow torch access to the joint to permit 100% weld penetration.

With these practical boundaries on the weld preparation angle we can compute the optimized weld volume ( $V_o$ ) implied by the variable and optimized bevel angle and the fixed joint parameters  $R_a, R_b, T_b, \theta, A$  around the branch-profile (expressed in the angle  $y$ ).

The Weld Volume - From equation 3, which gives the localized weld area

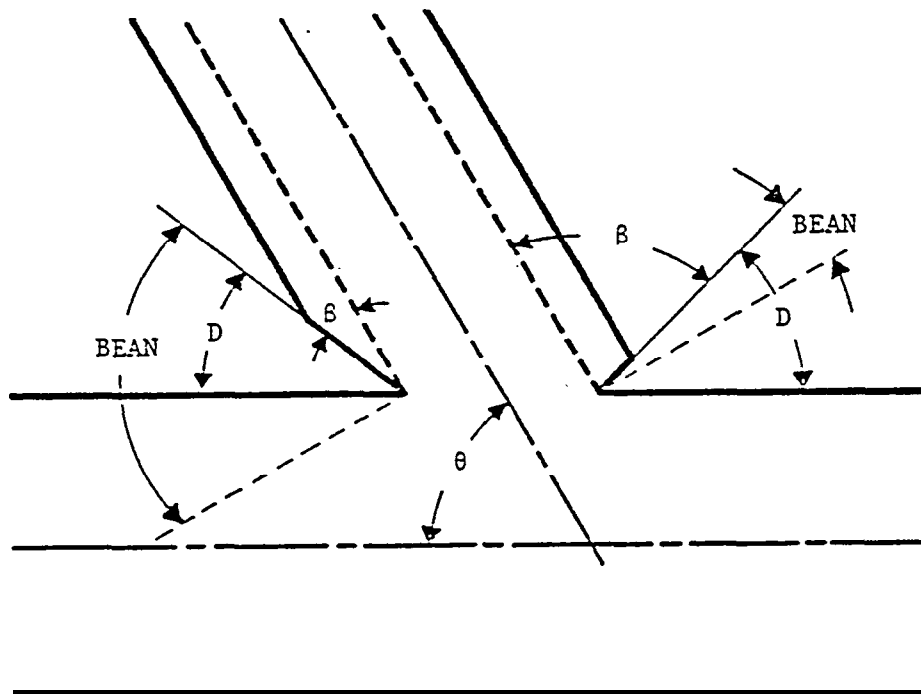


Figure 4. Interpretation of Bevel Angles BEAN, B Angles, and Weld Preparation Included Angles D.

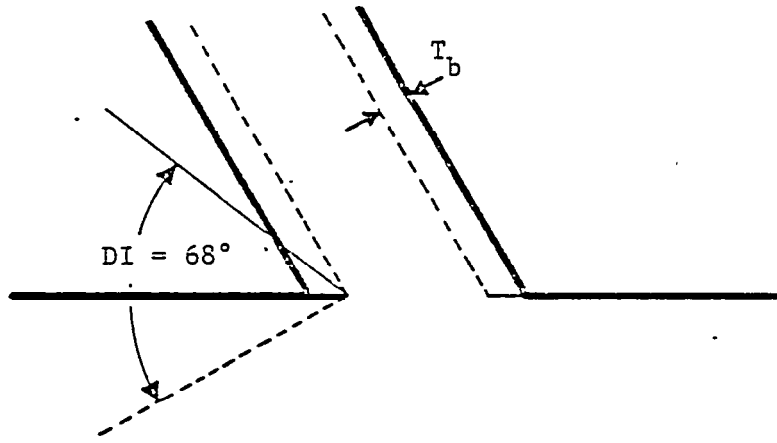


Figure 5. Maximum Allowable Bevel Angle DI in a Welded Pipe Joint.

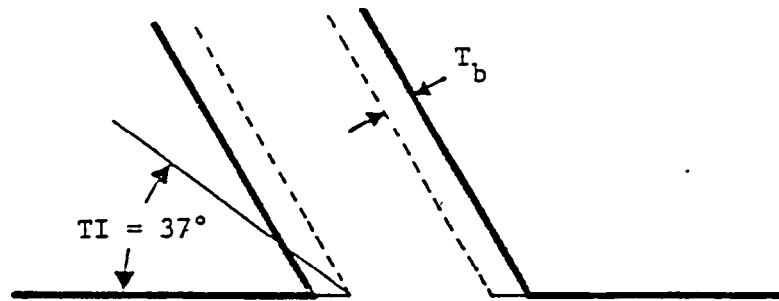


Figure 6. Minimum Allowable Weld Preparation Included Angle TI in a Welded Pipe Joint.

we may use numerical integration to compute the weld volume by the equation

$$\text{weld volume WEV} = \sum_{n=1}^P \frac{G\pi}{180} R_M P_n \quad (8)$$

where  $n=1, 2, \dots, \frac{360}{G}$

$G$  = sample interval of  $y$  in degrees and  $R_M = R_b + 1/3 (T_b' - 2T_b)$

weld Volume for a Fixed Bevel Angle - Figure 7 - The weld volume may be readily calculated with equation (8) using a constant value for  $B$  in equation (3). Here  $P_n$  is calculated for a constant  $B$  which is in turn dictated by the minimum weld preparation angle  $(BEAN)$  permitting 100 weld preparation. Here,  $(BEAN)_{CONSTANT}$  is computed as

$$(BEAN)_{CONSTANT} = D - (TA)_{MINIMUM} \quad (9)$$

where  $D = \text{say } 37^\circ$

and  $(TA)_{MINIMUM}$  = Minimum tangent angle which is the angle between a perpendicular to the interior wall of the branch and a line tangent to the main where the main is tangent to the branch interior wall.

Weld Volume for an Optimized Bevel - Figure 8 - Here we must first determine all tangent angles around the circumference of the branch. Then each optimized weld preparation angle  $(BEAN)_n$  equals the included angle  $D$  minus the local tangent angle  $(TA)_n$ .

$$\text{i.e.} \quad (BEAN)_n = D - (TA)_n \text{ where } n = 1, 2, \dots, \frac{360}{G} \quad (10)$$

Thus, as the tangent angle changes, the corresponding bevel angle changes

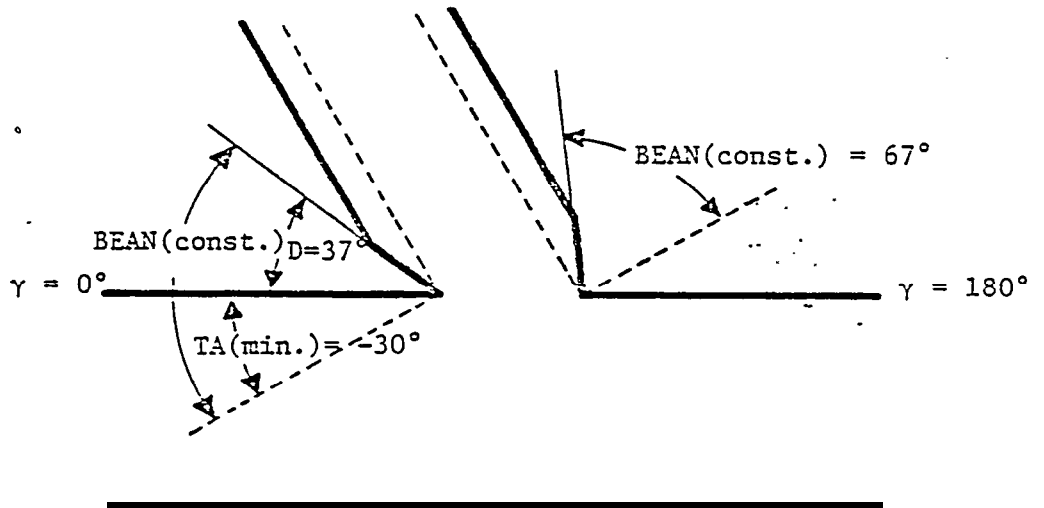


Figure 7. Profile of the Pipe Joints with Fixed Bevel Angle.

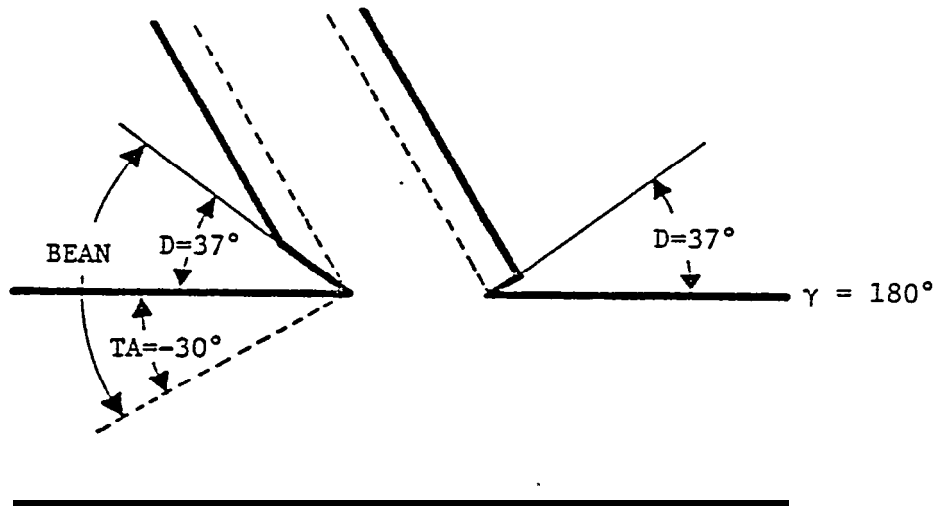


Figure 8. Profile of the Pipe Joints with Optimized Bevel Angle.



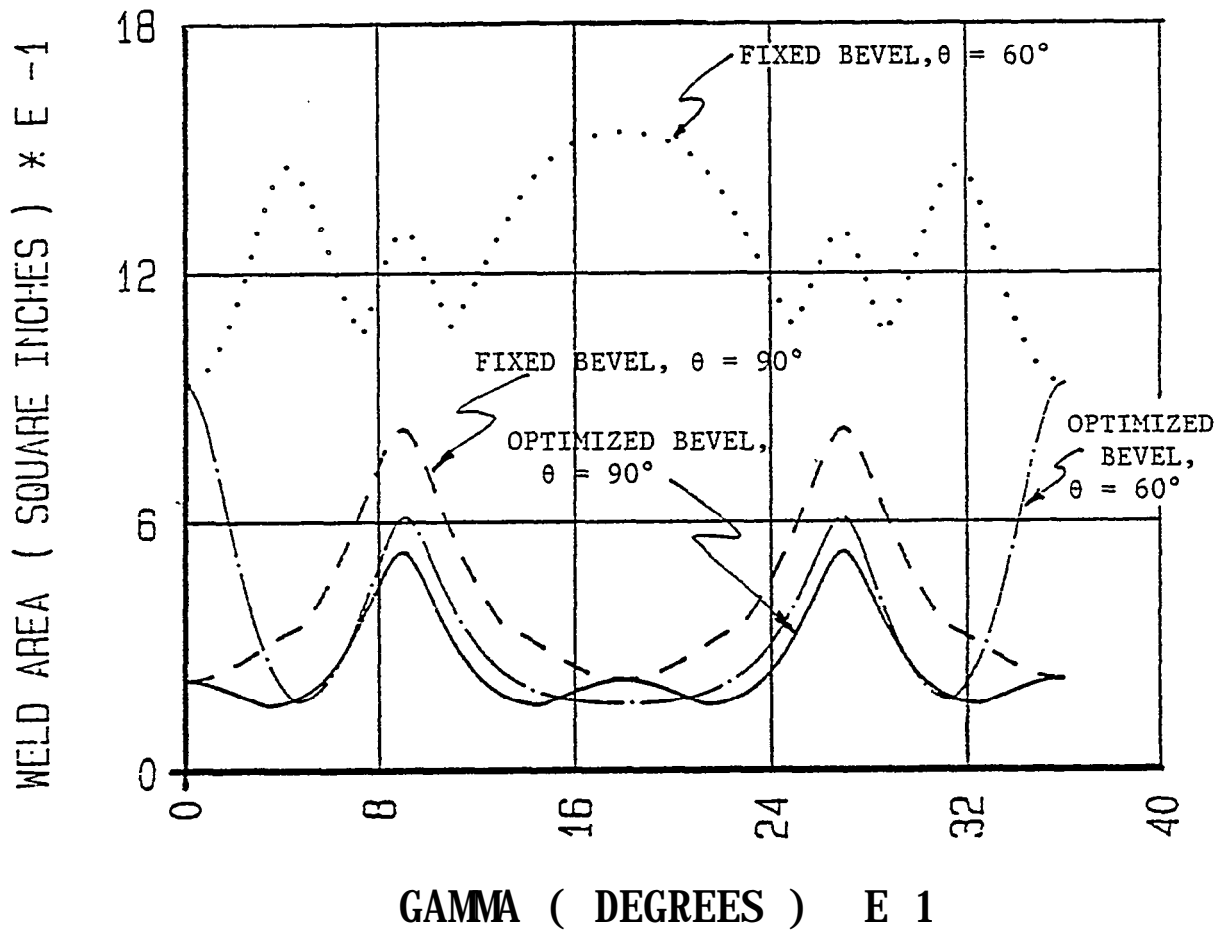
Table I - Weld Volume Comparison for Selected Joint Sizes and Configurations

$D_a$ INCHES	Sched <sub>a</sub> INCHES	$D_b$ INCHES	Sched <sub>b</sub> INCHES	$T_b$ INCHES	$\theta$ DEGREES	V IN <sup>3</sup>	v IN <sup>3</sup>
4.5	40	4.5	40	.237	90	.681	.420
	40		40	.237	60	2.124	.597
	80		80	.337	90	1.275	.789
	80		80	.337	60	4.184	1.142
	120		120	.438	90	2.023	1.262
	120		120	.438	60	6.915	1.859
	160		160	.531	90	2.828	1.784
	160		160	.531	60	9.975	2.667
	DBL.E.H.		DBL.E.H.	.674	90	4.255	2.742
DBL.E.H.	DBL.E.H.	.674	60	15.614	4.192		
6.625	STD.40	6.625	STD.40	.280	90	1.461	0.093
	STD.40		STD.40	.280	60	4.431	1.272
	80		80	.432	90	3.182	1.964
	80		80	.432	60	10.229	2.823
	120		120	.562	60	5.072	3.147
	120		120	.562	90	16.958	4.592
	160		160	.719	60	7.805	4.897
	160		160	.719	90	27.154	7.271
	DBL.E.H.		DBL.E.H.	.864	60	10.719	6.817
DBL.E.H.	DBL.E.H.	.864	90	38.451	10.279		
8.625	STD.40	8.625	STD.40	.322	90	2.575	1.596
	STD.40		STD.40	.322	60	7.693	2.237
	80		80	.500	90	5.691	3.510
	80		80	.500	60	17.992	5.015
	120		120	.719	90	10.853	6.730
	120		120	.719	60	36.118	9.810
	160		160	.906	90	16.272	10.191
	160		160	.906	60	56.307	15.093
	DBL.E.H.		DBL.E.H.	.875	90	15.314	9.572
DBL.E.H.	DBL.E.H.	.875	60	52.690	14.141		

$D_a$ INCHES	Sched <sub>a</sub>	$D_b$ INCHES	Sched <sub>b</sub>	$T_b$ INCHES	$\theta$ DEGREES	$V$ IN <sup>3</sup>	$V$ 13 <sup>03</sup>
12.750	STD	12.750	STD	.375	90	5.391	3.362
	STD		STD	.375	60	15.669	4.671
	40		40	.406	90	6.231	3.876
	40		40	.406	60	18.272	5.401
	60		60	.562	90	11.235	6.941
	60		60	.562	60	34.254	9.797
	80		80	.688	90	16.169	9.972
	80		80	.688	60	50.616	14.201
	120		120	1.000	90	31.481	19.487
	120		120	1.000	60	103.994	28.303
	160		160	1.312	90	50.712	31.723
	160		160	1.312	60	174.886	46.911
	DBL.E.H.		DBL.E.H.	1.000	90	31.481	19.487
	DBL.EeH.		DBL.E.H.	1.000	60	103.994	28.303
16.	80	16.	80	.844	90	30.678	18.921
	80		80	.844	60	95.744	26.917
	160		160	1.594	90	94.713	59.151
	160		160	1.594	60	324.915	87.264
20.	80	20.	80	1.031	90	57.493	35.464
	80		80	1.031	60	178.880	50.397
	160		160	1.969	90	181.190	113.093
	160		160	1.969	60	620.392	166.703
24.	80	24.	80	1.219	90	96.737	59.676
	80		80	1.219	60	300.392	84.747
	160		160	2.344	90	308.753	192.642
	160		160	2.344	60	1055.813	283.798
8.625	80	4.5	80	.337	90	.921	.600
8.625	80	4.5	80	-.337	60	4.737	.975

$D_a$ INCHES	Sched 80	$D_b$ INCHES	Sched 80	$T_b$ INCHES	$\theta$ DEGREES	V IN <sup>3</sup>	V IN <sup>3</sup>
12.750	80	6.625	80	.432	90	2.245	1.455
12.750	80	6.625	80	.432	60	11.473	2.354
16	80	8.625	80	.500	90	3.964	2.542
16	80	8.625	80	.500	60	19.996	4.067

PIPE SIZE: 12; N: 80; SIZE ON SIZE



The Weld Areas around the Branch Pipe Circumference  
for  $DA = DB = 12.75$  in. and  $TB = 0.688$  in.

accordingly, while the weld preparation included angle  $D$  remains constant.

The implied local optimized bevel angle derived from equation (10) is then used in equations (3) and (8) to give the optimized weld volume.

Conclusions - FORTRAN computer programs have been written to execute all computations implied by the preceding discussion. One hundred and twenty different joint configurations were studied for weld area variations for both fixed and optimized bevel angle configuration. The studied cases included size on size and differing diameters, intersecting angles of  $60^\circ$  and  $90^\circ$ , offsets, pipe sizes from 4 inches to 24 inches and schedules from 40 to 160.

All cases studied showed a dramatic reduction in weld volume when the optimized volume ( $V_o$ ) was compared to that ( $V_c$ ) obtained using a fixed bevel angle. The results of this weld volume comparison are shown in Table I.

The results of this comparison are so dramatic that modification of current yard practice in the mechanical preparation of welded pipe joints must be given consideration. Existing pipe fabrication machinery may be realistically modified to permit this optimization and cost recoveries achieved using fabricated joints vs. the use of prefabricated couplings can be demonstrated to be rapid and persuasive.

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