Det Norske Veritas

Phase 2 Final Report

Guidance for Field Segmentation and Welding of Induction Bends and Elbows

for

Joint Industry Project

on

Welding of Field Segmented Induction Bends and Elbows for Pipeline Construction

to

A Group of Participants

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DET NORSKE VERITAS

Report for A Group of Participants

Guidance for Field Segmentation and Welding of Induction Bends and Elbows

MANAGING RISK

Guidance for Field Segmentation and Welding of Induction Bends and Elbows		Det Norske Veritas (U.S.A.), Inc. Asset Risk Management 5777 Frantz Road Dublin, OH 43017-1886 United States Tel: (614) 761-1214 Fax: (614) 761-1633 http://www.dnv.com	
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Summary: This report describes Phase 2 of a three-phase project related to specification, manufacture, and installation of segmentable pipeline induction bends and elbows. Optimal methods for mapping, cutting, beveling and transitioning induction bends and elbows were developed. Recommended practices for welding in the field and for a variety of related issues were also developed. A generic specification for segmenting and welding of induction bends and elbows is included.

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EXECUTIVE SUMMARY

The overall goal of this project was to develop practical guidelines for using segmented induction bends and long-radius elbows for pipeline construction and to identify practices which should be avoided. The scope of this project was limited to large diameter pipelines (e.g., 30 inch diameter and above), as the challenges to achieving proper fit-up and ultimately acceptable weld quality are complicated by such factors as ovality.

The need to use segmented induction bends and elbows can arise for a variety of reasons during construction of new pipelines or during pipeline repair and maintenance activities. Bends having a tighter radius than can be accomplished by cold field bending may be required to accommodate abrupt directional changes. While some tight-radius directional changes can be accommodated by ordering induction bends with specific bend angles, the specific bend angles required are not always known prior to construction. Therefore, the use of segmentable induction bends and elbows may also be required during pipeline repair activities.

This report describes the second of three phases of work, with each phase addressing a specific objective developed by the nine project participants. The first objective was to develop guidance regarding the specification and purchase of segmentable induction bends and elbows. The second objective was to develop guidance for field construction practices. The third objective was to evaluate the use of in-line caliper and deformation tool data to identify areas of concern in existing pipelines. This report pertains to the second objective only.

In this second phase of this work, optimal methods for mapping, cutting, beveling and transitioning induction bends and elbows were developed. Recommended practices for welding in the field and for a variety of related issues were also developed. The information was summarized and used to develop a generic specification for segmenting and welding of induction bends and elbows.

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1. INTRODUCTION

The use of cold field bends is not practical for some pipeline construction applications, particularly for large diameter pipelines built with restricted work space. This may include work sites with rough terrain and insufficient room to store ditch spoil, replacement of smaller diameter lines with large diameter lines when existing profiles require shorter radius points of inflection, pipeline construction in streets where field bends are insufficient to provide clearance from other utilities, etc. For many reasons, segmenting long-radius elbows[1] and induction bends becomes necessary as part of normal construction practice.

There is currently inadequate guidance regarding the use of segmented induction bends and elbows for pipeline construction, and in particular 30-inch diameter pipe and larger. This includes a lack of consistency regarding the purchase of "segmentable" elbows and bends, the dimensional characteristics of segmentable fittings, field cutting/beveling/transitioning practices for these fittings, and verification methods to insure adequate girth weld fit-up. When fit-up (internal alignment) is not within specified limits, improved guidance is needed with respect to pipe wall transitioning and backwelding.

Recognizing the need to develop guidelines for the use of field segmented induction bends and elbows for pipeline construction, Spectra Energy organized a joint industry project (JIP) that was conducted by Det Norske Veritas (U.S.A.), Inc. (DNV). Participation in this project included:

Alliance Pipeline
CenterPoint Energy
El Paso
Kinder Morgan
NiSource
Panhandle Energy
Spectra Energy
TransCanada
Williams

The project had three main objectives. The first objective was to develop guidance regarding the specification and purchase of segmentable induction bends and elbows. The second objective was to develop guidance for field construction practices. The third objective was to evaluate the use of in-line caliper and deformation tool data to identify areas of concern in existing pipelines. This report pertains to the second objective only.

2. BACKGROUND

The need to use segmented induction bends and elbows can arise for a variety of reasons during construction of new pipelines or during pipeline repair and maintenance activities. There are often instances where bends with a tighter radius than can be accomplished by cold field bending are required to accommodate abrupt directional changes; either points of inflection, changes in topography, or both (Figure 1). Some tight-radius points of inflection or changes in topography can be accommodated by ordering elbows or induction bends with specific bend angles. This is generally true for points of inflection which can be surveyed in detail prior to construction. However, the specific bend angles required are not always known prior to construction,

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[1] Radius of curvature equal to 3 times the pipe diameter.

particularly for changes in topography during pipeline construction in challenging and hilly terrain. The use of segmentable induction bends and elbows may also be required during pipeline repair activities. Often times the pipeline has to be taken out of service during these activities, and due to time constraints, purchasing a precise bend angle from a supplier would be logistically impossible. While some bend angles can be accommodated using a combination of standard (pre-manufactured) bend angle fittings and field bends, it is often useful to order segmentable induction bends and/or elbows that can be cut to the required bend angle in the field.

Figure 1. Induction bend being used during construction of a cross-country pipeline

There are several welding aspects that are unique to the use of segmented induction bends and elbows. By definition, segmented induction bends and elbows are located at points of inflection, or at changes in topography, which tend to be more susceptible to high stresses from bending loads caused by pipeline movement due to soil settlement. The use of segmented induction bends and elbows often involves transition welds between dissimilar wall thickness materials, which tend to concentrate stresses due to bending. The use of segmented induction bends and elbows often involves the need to cope with high-low misalignment because of out-of-roundness and/or diameter shrinkage of the segmented fitting, which also tend to concentrate stresses due to bending.

2.1 Field Bends

The radius of curvature for cold field bends is generally limited to 40 times the pipe diameter (1.5 degrees per pipe diameter of length) to minimize damage to fusion bonded epoxy (FBE) coatings, although cold field bends with a radius of curvature as small as 15 to 8D may be achievable in some pipe diameter and wall thickness combinations. Beyond this, wrinkling along the intrados tends to occur as well as excessive strains and wall thinning along the extrados. The practice of field bending is also heavily reliant on equipment availability and operator knowledge and experience. Unlike segmented inductions bends and elbows, use of field bends allows directional changes to be made at locations that are not coincident with girth welds. While field bends should be used where practical, they are not always an option.

2.2 Induction Bends

Induction bends are formed in a factory by passing a length of straight pipe through an induction bending machine (Figure 2). This machine uses an induction coil to heat a narrow band of the pipe material (Figure 3). The leading end of the pipe is clamped to a pivot arm. As the pipe is pushed through the machine, a bend with the desired radius of curvature is produced. The heated material just beyond the induction coil is quenched with a water spray on the outside surface of the pipe. Thermal expansion of the narrow heated section of pipe is restrained due to the unheated pipe on either side, which causes diameter shrinkage upon cooling. The induction bending process also causes wall thickening on the intrados and thinning on the extrados. The severity of thickening/thinning is dependent on the bending temperature, the speed at which the pipe is pushed through the induction coil, the placement of the induction coil relative to the pipe (closer to the intrados or extrados), and other factors.

Figure 2. Induction bending machine

Figure 3. Heated portion of pipe material during induction bending process

Most induction bends are manufactured with tangent ends (straight sections) that are not affected by the induction bending process. Field welds are made or pipe pup sections are attached to the unaffected tangent ends (Figure 4), allowing for fit-up similar to that found when welding straight sections of pipe together.

Induction bends come in standard bend angles (e.g. 45, 90 degree, etc.) or can be custom made to specific bend angles. Compound bends (out-of-plane) bends in a single joint of pipe can also be produced. The bend radius is specified as a function of the diameter. For example, common bend radii for large diameter induction bends are 5D, 6D, and 7D, where D is the nominal pipe diameter.

Figure 4. Pipe pup section being attached to factory-segmented induction bend

2.3 Elbows

Elbows are formed in a factory using one of several manufacturing methods. The first method involves the use of plate material that is heated and forged into two halves (clamshells) using a press and a die that will produced the desired radius and diameter (Figure 5). The edges of each half are trimmed (Figure 6) and the two halves are then assembled and welded together (Figures 7 and 8) using two separate multi-pass submerged-arc welds (one along the intrados and the other along the extrados). The weld reinforcement is ground flush (Figure 9). Following radiographic inspection of the seam welds (Figure 10), the ends of the elbow are trimmed and prepared for field welding. Dimensional checks are then performed on the end preparations (Figure 11) and throughout the length of the elbow for diameter and out-of-roundness (Figure 12).

Figure 5. Hot forming of elbow halves

Figure 6. Trimming of elbow halves

Figure 7. Assembly of elbow halves

Figure 8. Seam welding using submerged arc welding

Figure 9. Grinding of longitudinal seam welds

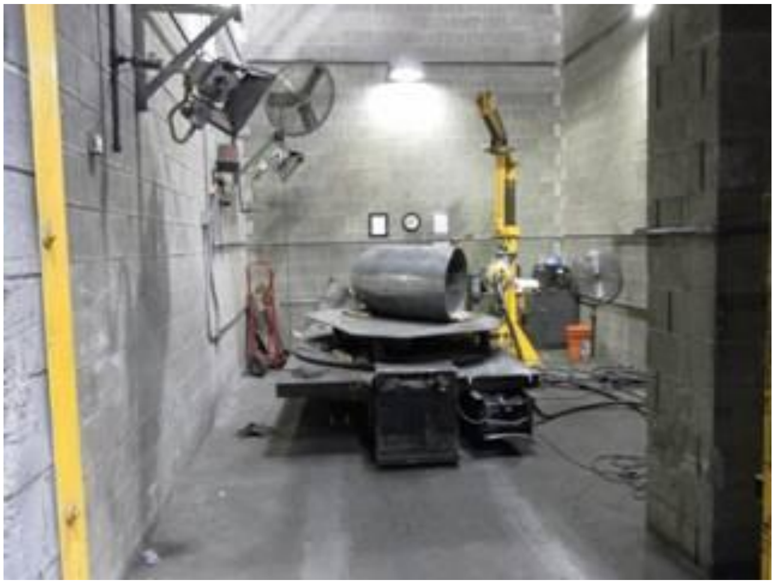


Figure 10. Radiography

Figure 11. Dimensional check of end preparations

Figure 12. Dimensional check of diameter and out-of-roundness

Elbows can also be manufactured using the “bend over mandrel” process (Figure 13). Pipe material is heated and bent while a mandrel is drawn through. The mandrel prevents ovalization and maintains a constant inside diameter throughout the length of the elbow.

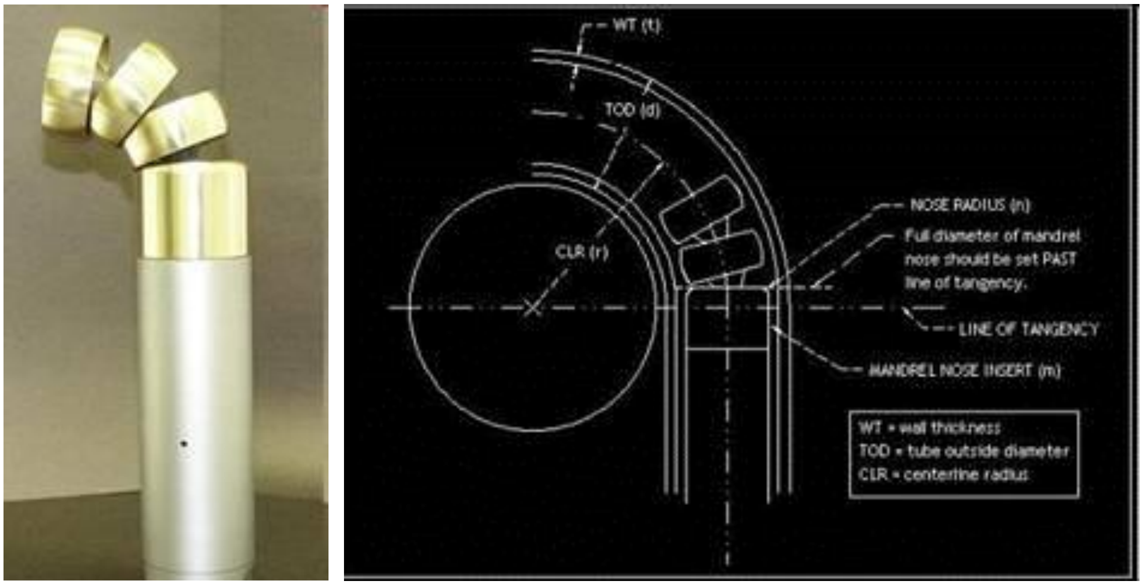


Figure 13. Illustration of drawn-over-mandrel process

Elbows also come in standard bend angles (e.g. 45, 90 degree, etc.). Elbows can be custom made (i.e., cut in the factory) to specific bend angles. The bend radius is specified as a function of the diameter. For the purposes of this project, “long radius” when used to describe an elbow refers to a radius of curvature equal to three times the pipe diameter (i.e., a 3D elbow).

3. SCOPE OF WORK

The overall goal of this project was to develop practical guidelines for using segmented induction bends and long-radius elbows for pipeline construction and to identify practices which should be avoided. The scope of this project was limited to large diameter pipelines (e.g., 30 inch diameter and above), as the challenges to achieving proper fit-up and ultimately acceptable weld quality are complicated by such factors as ovality.

The scope of work for this project was divided into phases to address the three main objectives. The scope of work for Phase 1, to which a previously issued report pertains, was to address the first objective (develop guidance regarding the specification and purchase of segmentable induction bends and elbows). The work scope included the following activities:

- Review current industry codes and company specifications
- Review current manufacturing practices including procedure qualifications and testing, heat treatment, and quality assurance/documentation
- Establish dimensional control capabilities of various manufacturers with regard to supply of segmentable induction bends and long-radius elbows. Verify these dimensional

control capabilities through dimensional measurements and review of quality control records. Evaluate actions taken by each manufacturer to achieve segmentable dimensional capability.

- Develop proposed specification requirements for purchasing segmentable induction bends and long-radius elbows

The scope of work for Phase 2, to which this report pertains, addresses the second objective (develop guidance for field construction practices), and includes the following issues:

- Requirements for pipe pup sections
- Optimal methods for mapping, cutting, beveling and transitioning
- Limits for high-low misalignment during field fit-up, alternative joint designs for unequal wall thickness
- Methods for measuring high-low in the field and methods for addressing excessive misalignment
- Backwelding methods and practices
- Radiographic issues for welds with internal transitions
- Guidance for revision of construction specifications

The scope of work for Phase 3, to which a subsequent report will pertain, will address the third objective (evaluate the use of caliper and deformation tool data), and will include the following:

- Evaluate the use of caliper and deformation tool data to identify areas of concern in existing pipelines

4. RESULTS FOR PHASE 2

The results for Phase 2 of this project (develop guidance for field construction practices) are provided in the following sections. These results were used to develop a generic procedure for segmenting induction bends and elbows, which is described in Section 4.5.

4.1 Optimal Methods for Mapping, Cutting, Beveling and Transitioning

The use of segmented induction bends and elbows often involves transition welds between dissimilar wall thickness materials and the need to cope with high-low misalignment due to out-of-roundness and/or diameter shrinkage of the segmented fitting. Because of the potential for misalignment issues, the segmented end should always be welded to a short transition pup first. The use of a transition pup also allows a pipe-to-pipe weld to be made in the field. The use of a transition pup allows access for backwelding (if necessary) and for inspection after welding.

Practical information pertaining to methods for mapping, cutting, beveling, and transitioning induction bends and elbows was collected during a series of field exercises. The purpose of these exercises was to document current practices. These methods were optimized and the results were used to develop a draft generic procedure for segmenting.

The first and most comprehensive of these field exercises was carried out March 2-5, 2010, at the fabrication facility of C.J. Hughes in Nitro, West Virginia. This exercise was organized by Spectra Energy and involved segmenting a 36-inch diameter 90-degree 6D-radius segmentable induction bend (Figures 14 and 15). During this exercise, dimensional characteristics of the induction bend were determined both before and after cutting, various methods for beveling and transitioning were documented, and segmented sections were welded to pipe pup sections (partial welds in some cases). A description of this field exercise is shown in Figures 16 through 21. Representatives from both Spectra Energy and DNV were in attendance. The results of a second field exercise, which was conducted at a Spectra Energy jobsite in Pennsylvania the week of April 12, 2010, were used to refine and further develop the draft generic procedure for segmenting. A third field exercise was conducted at a Florida Gas Transmission jobsite in Florida the week of June 7, 2010, which involved 36-inch diameter 90-degree forged elbows. The development of the generic procedure for segmenting is described in Section 4.5.1 and the resulting procedure is shown in Appendix A.

Figure 14. 36-inch Diameter 90-Degree 6D-Radius Segmentable Induction Bend

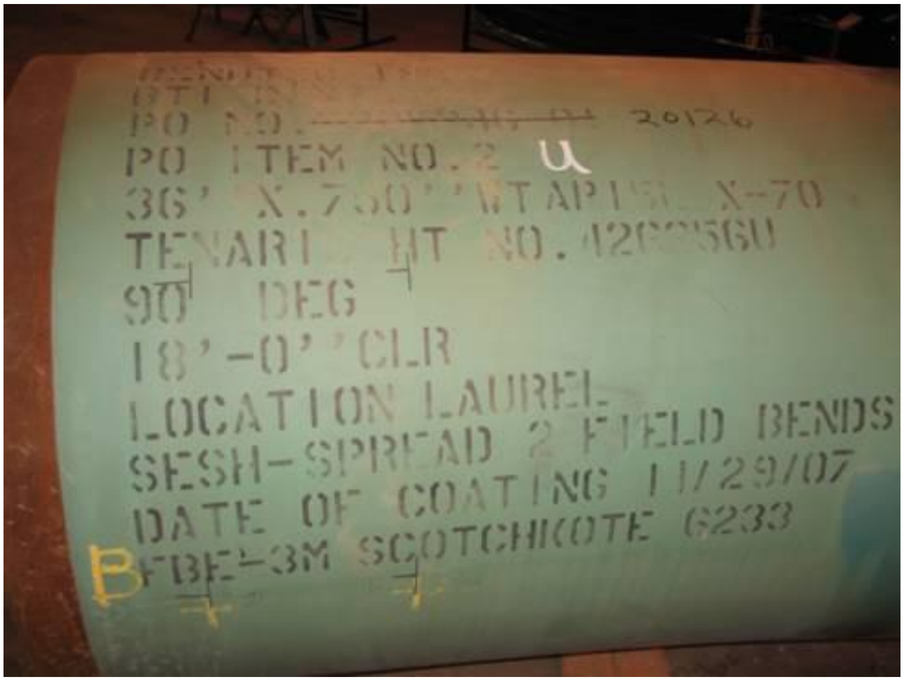


Figure 15. Stencil information

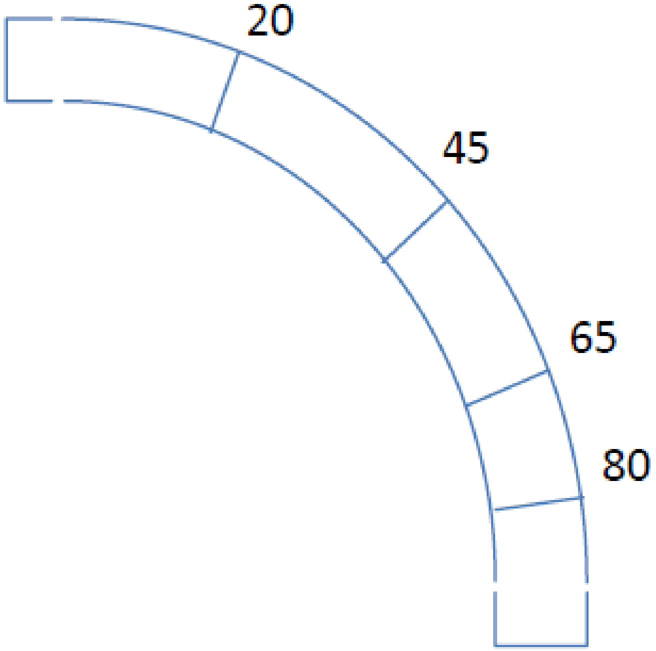
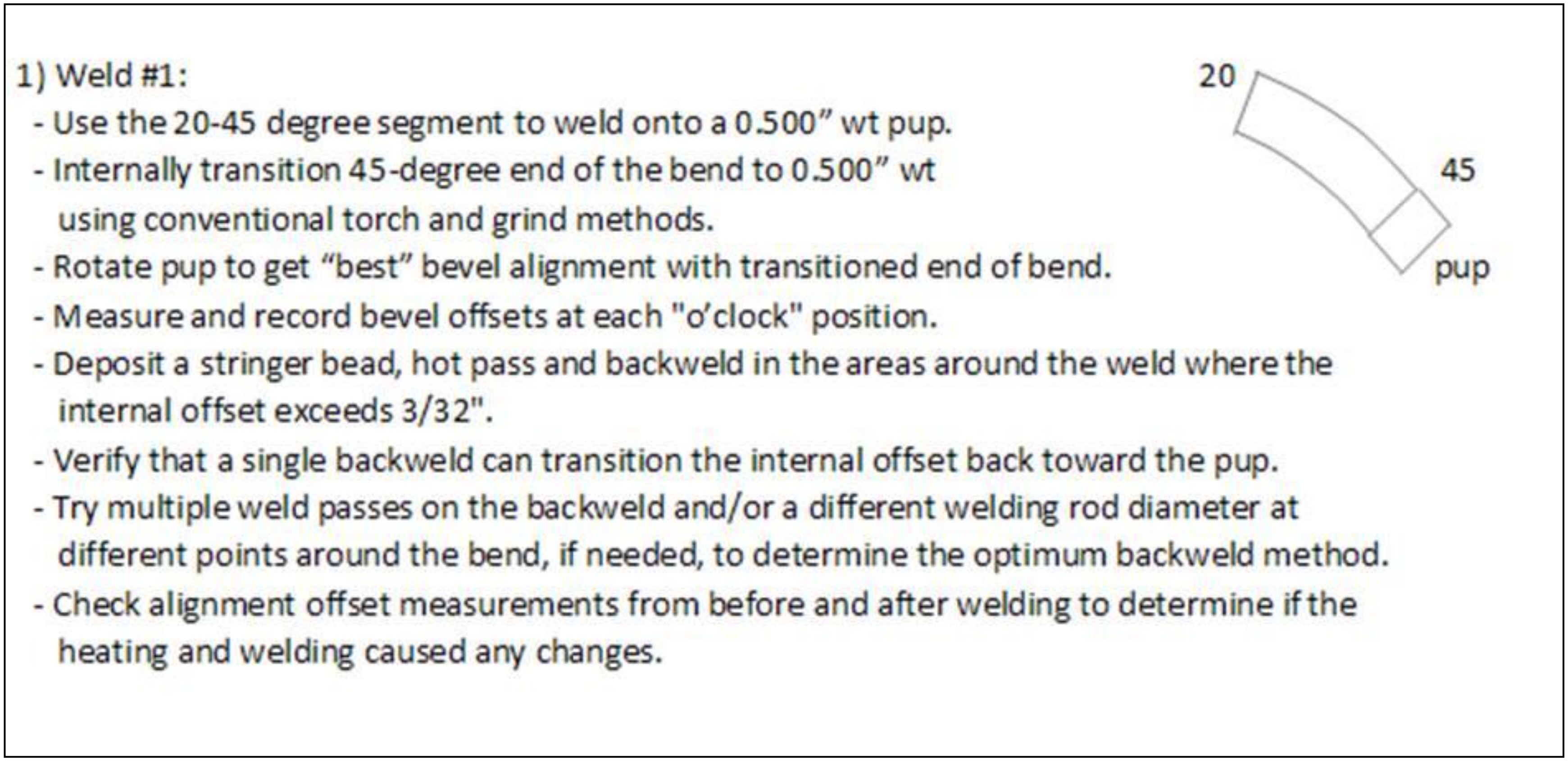


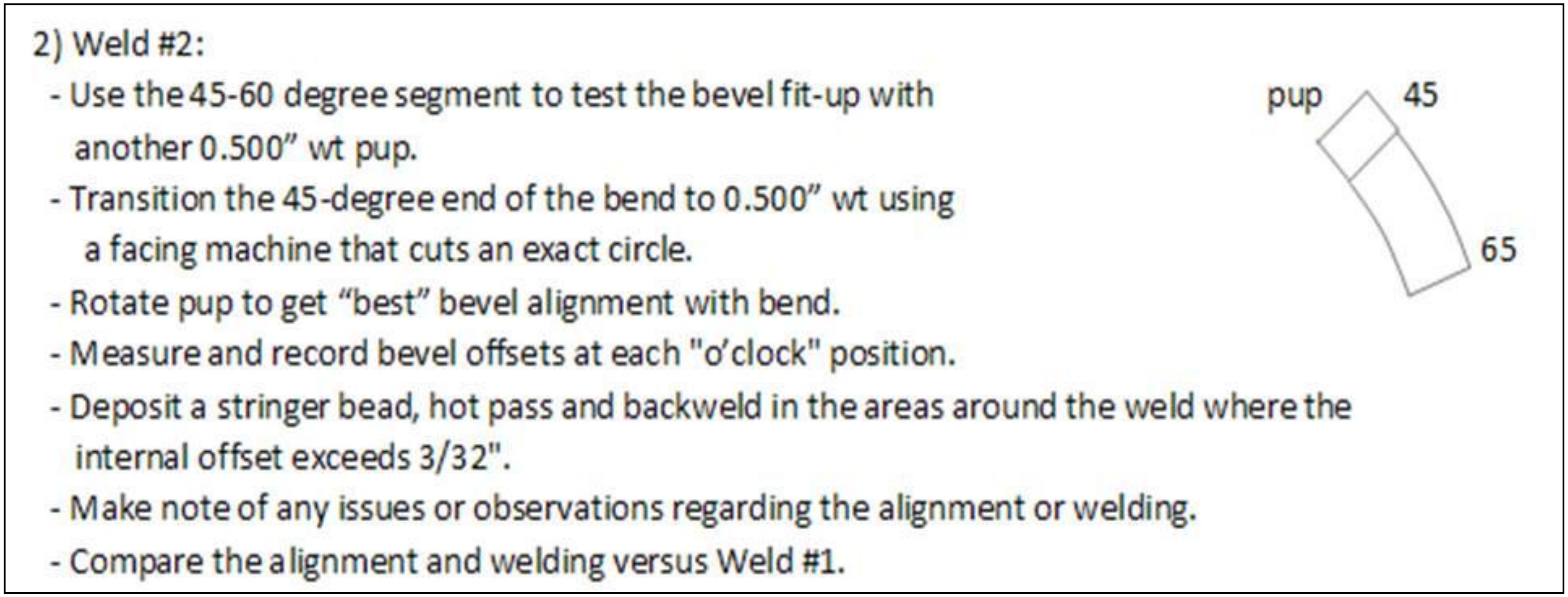
Figure 16. Segmenting plan for field exercise in Nitro, West Virginia



1) Weld #1:

- Use the 20-45 degree segment to weld onto a 0.500” wt pup.
- Internally transition 45-degree end of the bend to 0.500” wt using conventional torch and grind methods.
- Rotate pup to get “best” bevel alignment with transitioned end of bend.
- Measure and record bevel offsets at each "o’clock" position.
- Deposit a stringer bead, hot pass and backweld in the areas around the weld where the internal offset exceeds 3/32".
- Verify that a single backweld can transition the internal offset back toward the pup.
- Try multiple weld passes on the backweld and/or a different welding rod diameter at different points around the bend, if needed, to determine the optimum backweld method.
- Check alignment offset measurements from before and after welding to determine if the heating and welding caused any changes.

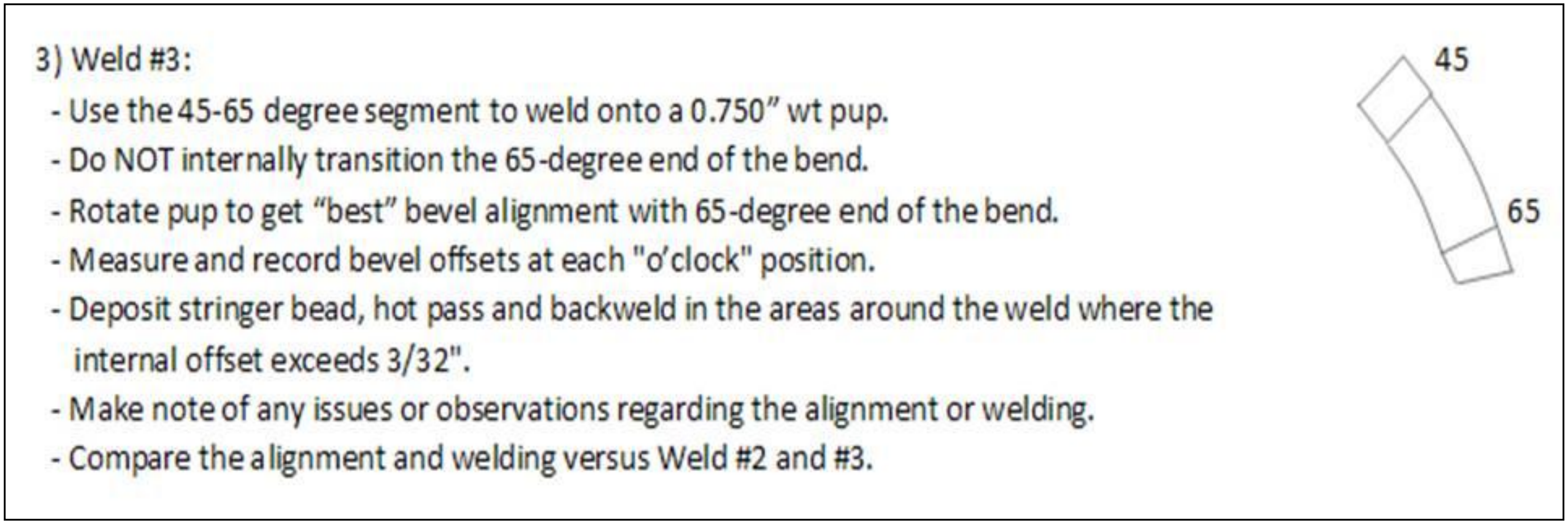
Figure 17. Plans for Weld No. 1 of field exercise in Nitro, West Virginia



2) Weld #2:

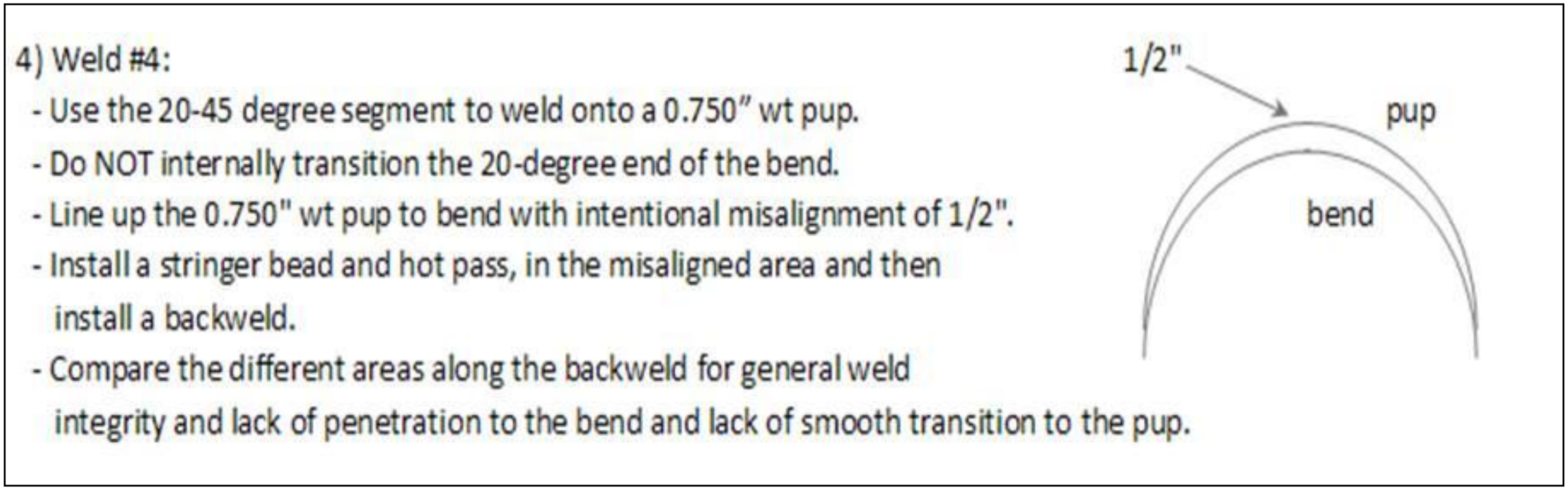
- Use the 45-60 degree segment to test the bevel fit-up with another 0.500" wt pup.
- Transition the 45-degree end of the bend to 0.500" wt using a facing machine that cuts an exact circle.
- Rotate pup to get "best" bevel alignment with bend.
- Measure and record bevel offsets at each "o'clock" position.
- Deposit a stringer bead, hot pass and backweld in the areas around the weld where the internal offset exceeds 3/32".
- Make note of any issues or observations regarding the alignment or welding.
- Compare the alignment and welding versus Weld #1.

Figure 18. Plans for weld No. 2 of field exercise in Nitro, West Virginia


3) Weld #3:

- Use the 45-65 degree segment to weld onto a 0.750" wt pup.
- Do NOT internally transition the 65-degree end of the bend.
- Rotate pup to get "best" bevel alignment with 65-degree end of the bend.
- Measure and record bevel offsets at each "o'clock" position.
- Deposit stringer bead, hot pass and backweld in the areas around the weld where the internal offset exceeds 3/32".
- Make note of any issues or observations regarding the alignment or welding.
- Compare the alignment and welding versus Weld #2 and #3.

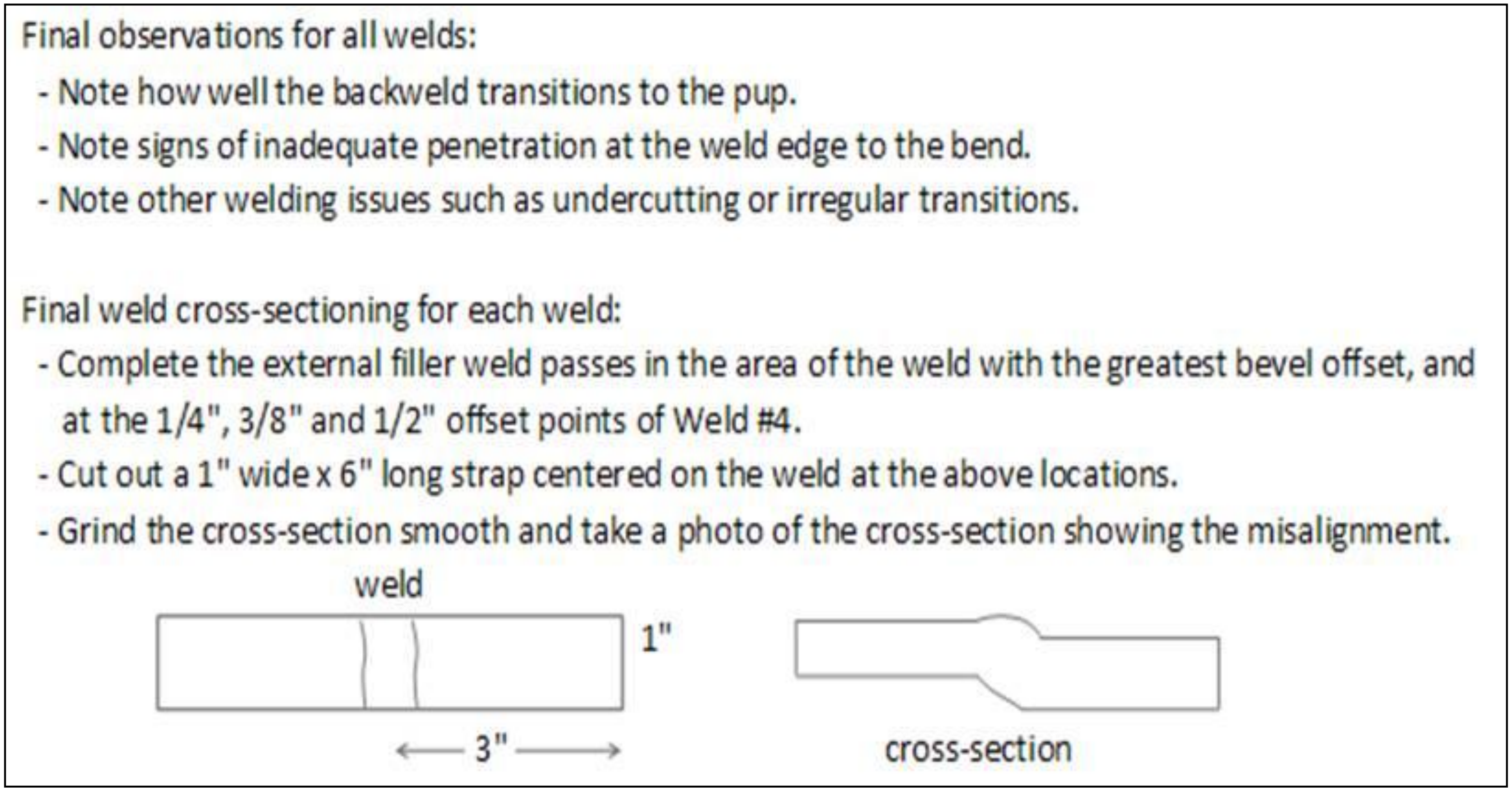
Figure 19. Plans for weld No. 3 of field exercise in Nitro, West Virginia



4) Weld #4:

- Use the 20-45 degree segment to weld onto a 0.750" wt pup.
- Do NOT internally transition the 20-degree end of the bend.
- Line up the 0.750" wt pup to bend with intentional misalignment of 1/2".
- Install a stringer bead and hot pass, in the misaligned area and then install a backweld.
- Compare the different areas along the backweld for general weld integrity and lack of penetration to the bend and lack of smooth transition to the pup.

Figure 20. Plans for weld No. 4 of field exercise in Nitro, West Virginia



Final observations for all welds:

- Note how well the backweld transitions to the pup.
- Note signs of inadequate penetration at the weld edge to the bend.
- Note other welding issues such as undercutting or irregular transitions.

Final weld cross-sectioning for each weld:

- Complete the external filler weld passes in the area of the weld with the greatest bevel offset, and at the 1/4", 3/8" and 1/2" offset points of Weld #4.
- Cut out a 1" wide x 6" long strap centered on the weld at the above locations.
- Grind the cross-section smooth and take a photo of the cross-section showing the misalignment.

Figure 21. Plans for results of field exercise in Nitro, West Virginia

The three field exercises described above focused on conventional methods for segmenting induction bends and elbows – i.e., oxy-fuel cutting and hand grinding. During the course of this project, a potentially useful piece of equipment for machine cutting, beveling, and transitioning was identified. The suitability of this equipment for segmenting induction bends and elbows was investigated during a demonstration at the manufacturer's facility. Representatives from DNV and several project representatives were in attendance. The results of the three field exercises are described in Sections 4.1.1 through 4.1.4. The results of the equipment demonstration are described in Section 4.1.5.

4.1.1 Mapping

Mapping refers to determining the location of cut points so that the desired bend angle is produced. Two methods of locating cut points were investigated. Both involve the use of geometry/trigonometry, although the segmenting procedure that was developed includes tables that minimize the need for manual calculations. The first method involves determining and measuring arc lengths along the intrados and extrados of the induction bend or elbow. The second method involves determining and measuring chord lengths along the neutral axis (top or bottom) of the bend or elbow. Both methods require that the bend or elbow is situated so that it is flat and level. The use of a center finder to locate the neutral axis is shown in Figures 22 and 23.

Figure 22. Center finder for locating top-dead-center, intrados, and extrados

Figure 23. Center finder being used to locate TDC

Induction bends are typically provided with tangent ends. To locate cut points on an induction bend, it is first necessary to precisely locate the tangent point (i.e., the point of first deviation from straight on the tangent end), which is performed with the use of straight edges (Figure 24). For both bends and elbows, the cut point is established by measuring either along the intrados (Figure 25) and extrados or measuring the chord length. During the first field exercise, it was determined that establishing the location of cut points by measuring the chord length was more accurate and simpler than measurement along the intrados and extrados.

Both methods require that, once a cut point is located, a flexible steel band is used to establish the cut point around the entire circumference (Figure 26). For bends and elbows that are coated, punch marks are made through the coating, the coating is removed, and the cut point is re-established using the flexible steel band.

Prior to making rough cuts, it is advisable to measure out-of-roundness at the proposed cut point. This is performed using calipers and a linear scale (Figure 27 and 28) or a micrometer (Figure 29). If out-of-roundness is excessive, the cut point can be re-established from the other end of the bend or elbow to determine if the out-of-roundness at the alternative cut point is more favorable.

Figure 24. Determining location of true tangent

Figure 25. Measuring along intrados

Figure 26. 3/4 inch wide steel strap and marked line for rough cutting

Figure 27. OD measurement using calipers – Part 1

Figure 28. OD measurement using calipers – Part 2

Figure 29. OD measurement using micrometer

4.1.2 Cutting

After a cut point has been established, rough cutting a bend or elbow is performed manually using an oxy-fuel torch. Since beveling will be performed later, rough cuts are made without a bevel. After rough cutting, it is advisable to measure out-of-roundness again, this time from the inside (Figure 30) using either calipers and a linear scale (Figure 31) or a micrometer (Figure 32).

4.1.3 Beveling

Equipment that is typically used to oxy-fuel bevel line pipe material in the field (i.e., band-type equipment) is not suitable for use on bends and elbows. When the equipment is mounted on the bend or elbow, the curvature prevents a square end from being produced. The technique that is used to bevel a segmented bend or elbow involves tack welding the bend or elbow to a straight section of pipe. Alignment to the straight section of pipe is accomplished using a Dearman style clamp (Figure 33). The beveling equipment is then mounted to the straight section of pipe and the cutting head is positioning the so that the cut is made back towards the straight section of pipe (Figure 34).

Figure 30. Locations for diameter measurement

Figure 31. ID measurement using calipers

Figure 32. ID measurement using micrometer

Figure 33. Temporary alignment of segmented bend to pipe pup section using Dearman-style clamp

Figure 34. Flame cutting bevel on segmented induction bend from straight pipe side

4.1.4 Transitioning

Pipe pup sections should always be welded to the segmented end of bends and elbows during the segmenting operation so that field tie-in welds can be made between straight pieces of pipe. Bends and elbows typically have greater wall thickness than the pipe pup sections, which requires that the wall thickness of the bend or elbow be transitioned at the weld bevel or that backwelding is used. Transitioning involves aligning the pipe pup section to the bend or elbow, again using a Dearman style clamp (Figure 35). The inside diameter of the pipe pup section is scribed onto the square-cut end of the segmented bend or elbow using a soapstone (Figure 36). The transition is produced by grinding or by a combination of oxy-fuel cutting (Figures 37 and 38) and grinding. The resulting weld bevel/transition must meet the requirements of Figure I-5 from ASME B31.8 or §434.8.6 of ASME B31.4. Additional discussion pertaining to joint design for unequal wall thickness transitions is provided in Section 4.2. When producing transitions, rounding (convexity) of the ground surface of the transition should be avoided. The purpose of a transition is to avoid a stress concentration where the ground surface intersects with the toe of the root pass. Convexity of the ground surface tends to result in an acute angle at the weld toe which acts as a stress concentration (Figure 39). Ideally, the angle at the weld toe should be as obtuse as possible (Figure 40). After the transition is complete, the wall thickness at the weld bevel is measured using calipers (Figure 41) to ensure compliance with minimum requirements.

Figure 35. Fit-up of segmented bend to pipe pup section prior to transitioning

Figure 36. ID of pipe pup section marked on bevel of segmented bend with soapstone

Figure 37. Flame cutting of transition on segmented bend

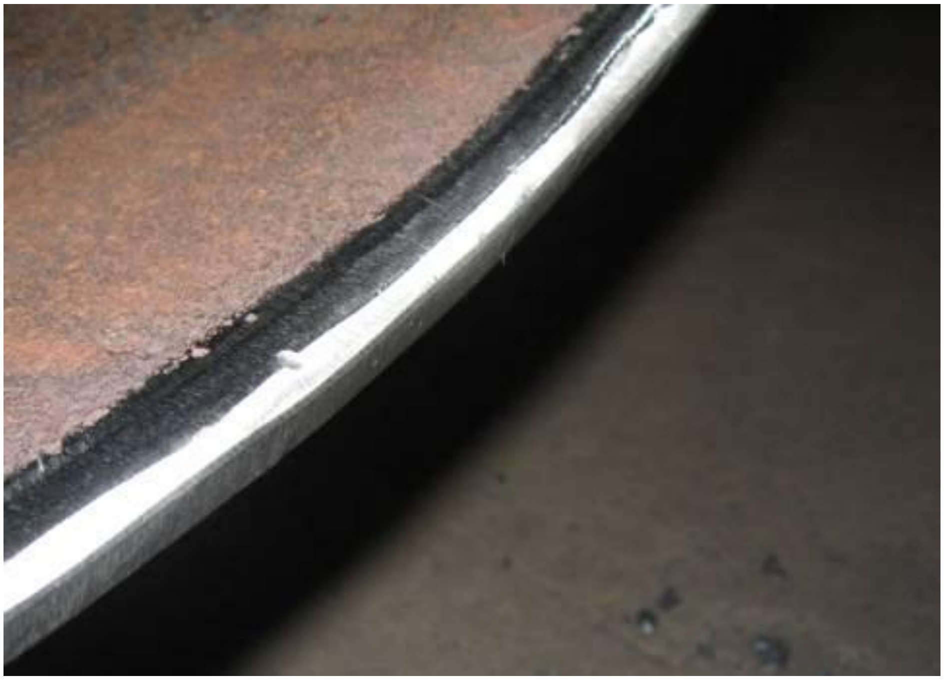


Figure 38. Transition on segmented bend after grinding

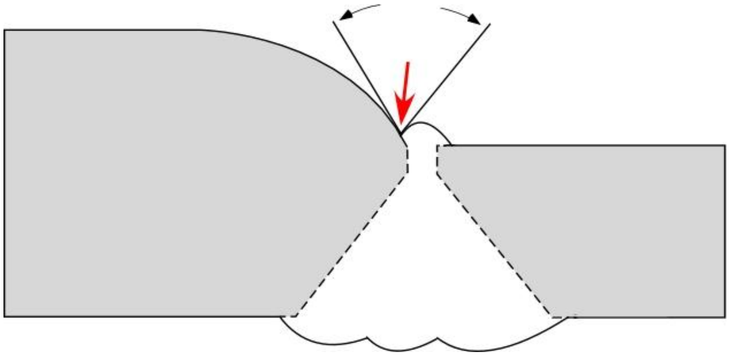


Figure 39. Rounding (convexity) of ground surface and associated stress concentration from acute angle at weld toe

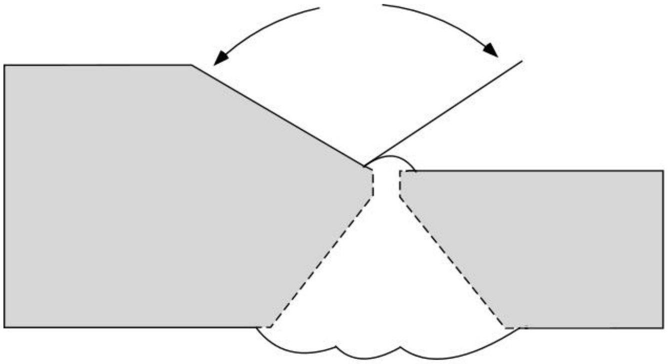


Figure 40. Flat ground surface and obtuse angle at weld toe

Figure 41. Measurement of wall thickness at weld bevel after transitioning

4.1.5 Welding

Fit-up for welding pipe pup sections to segmented bends and elbows is again accomplished using a Dearman style clamp. Any internal misalignment should be distributed evenly around the circumference (Figure 42) using the adjustment capabilities of the Dearman style clamp. Prior to root pass welding, internal misalignment should be measured using a purpose-built measuring device (Figures 43 and 44). Additional discussion pertaining to limits on internal misalignment (i.e., high-low), methods for measuring internal misalignment for unequal wall thickness transitions, and methods for addressing excessive misalignment is provided in Sections 4.3.1 through 4.3.3, respectively. Once optimal alignment is achieved, root pass welding is carried out in a conventional manner following a qualified welding procedure. If excessive internal misalignment prevents an acceptable root pass from being made, backwelding can be used as a remedial measure. Additional discussion pertaining to backwelding is provided in Section 4.3.4. Transition welds made between unequal wall thickness material and/or near points of inflection, particularly those made in field conditions, can be particularly susceptible to hydrogen cracking because high levels of stress tend to develop at these welds. General guidance pertaining to avoiding hydrogen cracking in pipeline girth welds is provided in Section 4.3.5.

Figure 42. Fit-up of segmented bend to pipe pup section after transitioning

Figure 43. Measurement of high-low misalignment – Part 1

Figure 44. Measurement of high-low misalignment – Part 2

4.1.6 Cutting and Beveling Machines

Aggressive Equipment Corporation's Steel Split Frame® equipment (Figure 45) was identified as being potentially useful for cutting, beveling, and tapering segmented induction bends and elbows. The design is such that it can easily be attached to curved surfaces (i.e., it has clamping feet that swivel). Unlike conventional pipe cutting equipment, the profile is very narrow (Figure 46). All three operations (cutting, beveling, and tapering) can be accomplished with a single setup. Steel Split Frame® equipment is available in diameter sizes from 4 to 80 inch OD and is available for rent or for purchase and is able to cut and bevel straight pipe or bends simultaneously. Attachment heads include those for cutting, beveling, and internal tapering. The equipment can be operated either pneumatically or hydraulically. Purchase price is approximately $1000/inch of diameter. Rental locations include Rock Hill, South Carolina, Fairfield, California, Gonzales, Louisiana, Lake Bluff, Illinois, Pasadena, Texas, and Edmonton, Alberta.

Figure 45. Aggressive Equipment Corporation's Steel Split Frame® equipment

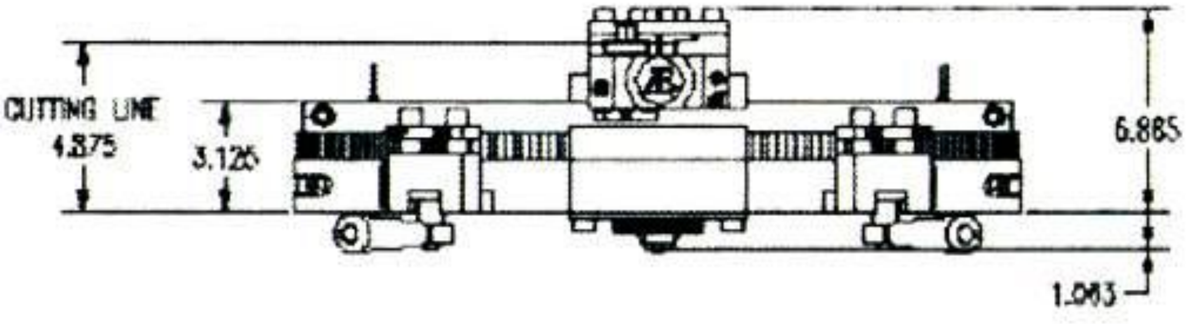


Figure 46. Profile of Steel Split Frame® equipment

To evaluate this equipment for segmenting induction bends and elbows, a demonstration was conducted April 6, 2011, at the manufacturer's facility in Rock Hill, South Carolina. The Split Frame® was first demonstrated on a 36 inch OD by 1 inch thick X70 90-degree 3R elbow manufactured by Custom Alloy (donated by Panhandle Energy). This elbow was manufactured using the clamshell technique and contained two submerged arc weld (SAW) seams; one on the intrados and one on the extrados. The equipment was also demonstrated on a 36 inch OD by 0.500 inch thick X52 induction bend (donated by BendTec).

The basic components of each Split Frame® are two half rings that make up the frame (Figure 47), either a pneumatic or hydraulic motor (Figure 48), and cutting and/or beveling attachments (Figures 49 and 50). The frame can be mounted on either straight sections of pipe or bends using adjustable feet and pins that hold it in place. These pins and feet allow the Split Frame® to be adjusted in any direction perpendicular to the pipe axis. For the purpose of segmenting an induction bend or elbow, it is suggested that a Split Frame® one size larger than the pipe size be used, which allows for more room to make adjustments. The pins will damage fusion-bonded epoxy (FBE) coating; however this area of coating will likely be removed during subsequent welding activities.

There are several options for attachments that mount to and rotate around the frame. The equipment can be set up to cut, cut and produce a single bevel, or cut and produce a compound bevel. Once the cut has been made, there is also an attachment that can be used to produce an internal taper (Figure 51). There are also out-of-round attachments (Figure 52), which will follow the outside diameter of the pipe as opposed to a perfect circle. This attachment is spring loaded causing a pin on either side of the tool to contact the pipe. The use of the out-of-round attachment will also damage FBE coating. The feed of the cutting and beveling blades into the pipe is controlled by pins around the frame (Figure 53). As the attachment encounters a pin, it feeds into the pipe wall at 0.002 inch (0.05 mm) increments. Up to 4 pins can be used on the frame at a given time. The pins can be manually retracted by the operator during operation so that the attachment is not fed into the pipe wall on that revolution.

Figure 47. Body of Steel Split Frame® equipment showing split clamshell design

Figure 48. Pneumatic motor of Steel Split Frame® equipment

Figure 49. Steel Split Frame® equipment with cutting blade attachments mounted on 36 inch by 0.500 inch thick induction bend

Figure 50. Cutting blade attachment and ground longitudinal seam weld

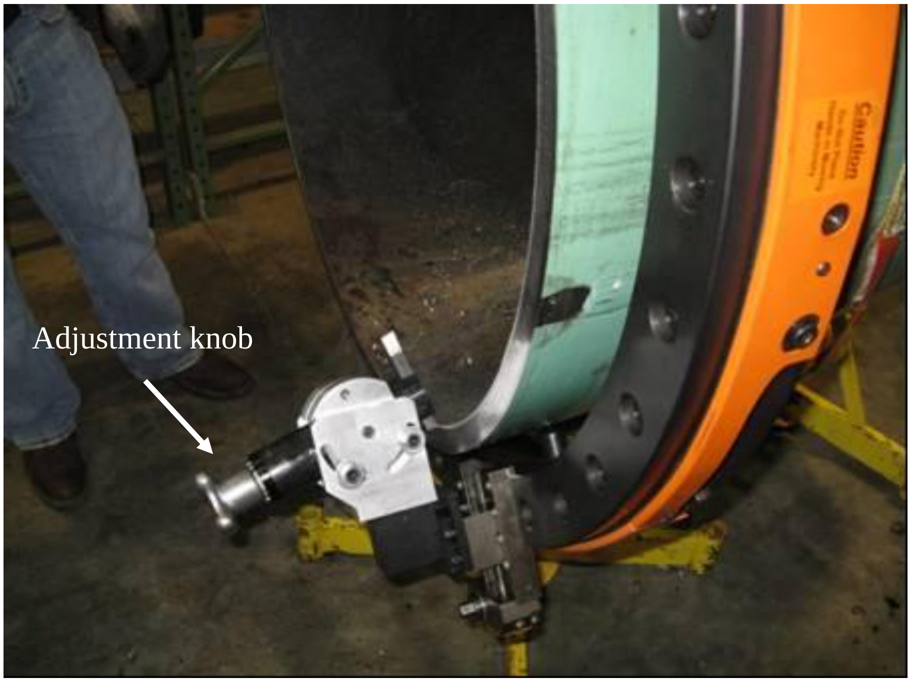


Figure 51. Internal taper attachment

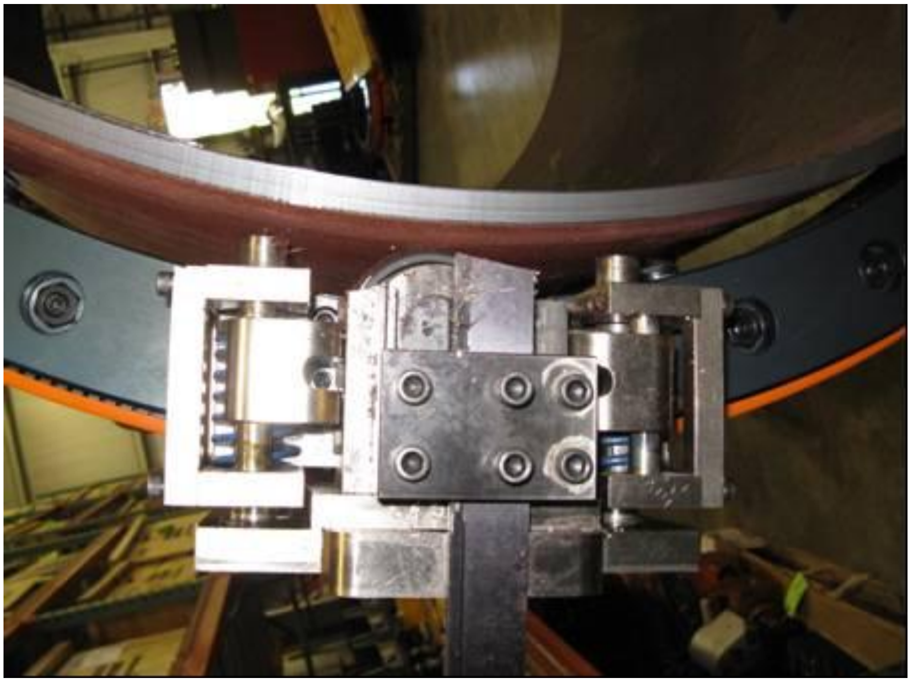


Figure 52. Out-of-round attachment for following outside diameter

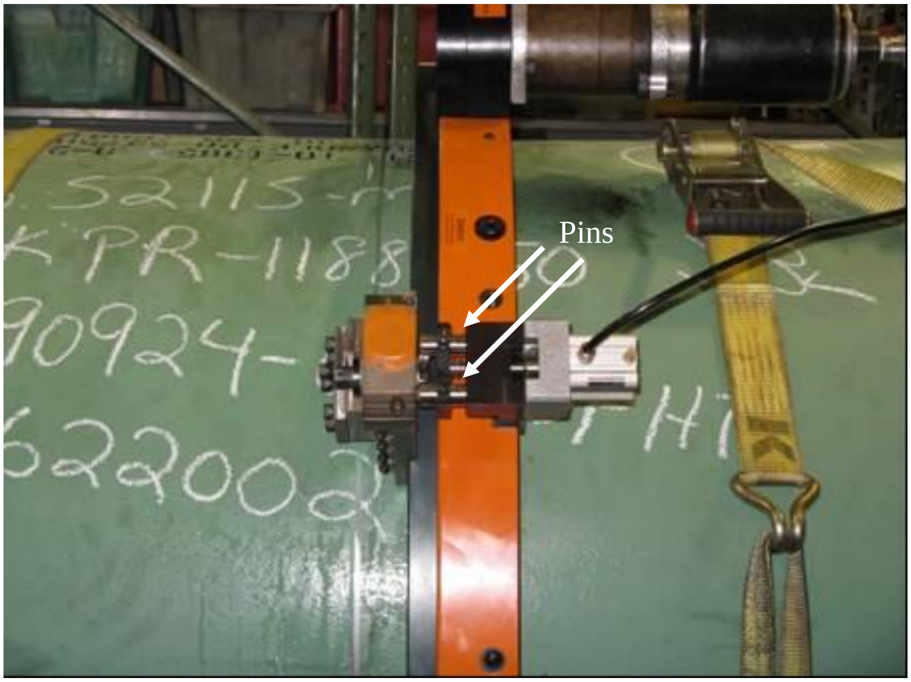


Figure 53. Controller pins engaging cutting blade

A single operator can run the equipment; however setup and adjustment seem best performed by two trained technicians. A control similar to a twist grip throttle is used to control the speed of rotation. There is also a control unit available that allows for finer speed adjustments to be made and also allows the tool to be reversed. Coolant is periodically sprayed along the cut/bevel or on the tool as it passes by the operator. The Aggressive technicians indicated that the hydraulically powered tool is more powerful than the pneumatically powered option and will not bog down during operation. This may be better suited for pipeline applications especially on higher strength material. The equipment is moderately loud inside of a closed shop although it was possible to hold a discussion with the operator during operation.

4.1.6.1 Elbow Demonstration

A 36 inch Split Frame® equipped only with cutting attachments was demonstrated on the elbow first. The leading blade was 3/16 inch wide, which was followed by a blade that was 1/4 inch wide. The cut took approximately 50 minutes to complete with almost continual cutting. Due to equipment constraints, the ovality could only be measured after the cut was made and was found to be 1.4% of the OD or approximately 0.5 inches. The elbow was designed to have a minimum wall thickness of 0.688 inches therefore the technicians were asked to machine an internal taper to a minimum wall thickness of 0.688 inches.

Unlike the attachment for cutting and bevelling the attachment used to produce an internal taper is adjusted manually by turning a knob on the actual attachment piece while it moves around the circumference of the pipe (Figure 51). The process of machining an internal taper is much more manual and took approximately 40 minutes. The equipment must be stopped to measure the wall thickness and to make adjustments. The internal SAW seam on the intrados had been ground beyond flush creating a low spot on the ID. Machining an internal taper in that area would have caused the minimum wall thickness to have been violated in other areas of the pipe. A section of the completed internal taper can be seen in Figure 54. The taper angle varied around the circumference and ranged from 13 to 17 degrees. The equipment was then fitted to produce a 30 degree external bevel. This process was quick and produced good results. Once again, the irregularity around the seam weld forced the operation to be stopped slightly before it otherwise would have been.

Figure 54. Completed internal taper

4.1.6.2 Induction Bend Demonstration

The 36 inch Split Frame® was demonstrated on the induction bend next. The out-of-round attachment was used to both cut and bevel the bend at the same time. This was completed in approximately 25 minutes. An acceptable bevel was produced even though the bend was approximately 1.5% out of round. It should be mentioned that toward the end of the cut the equipment got caught up on a small ligament of weld metal from the seam. This caused the blade to move within the groove and the remaining ligament had to be manually broken to free the complete cut (Figure 55).

Figure 55. Completed weld bevel

4.1.6.3 Cutting and Beveling Machine Summary

The Split Frame® is a versatile and useful piece of equipment that is certainly a viable option to use for segmenting induction bends or elbows. It offers an attractive alternative to a flame cut bevel and a manually produced internal transition. The process of cutting and beveling potentially takes longer; however time can be saved when these two operations are performed simultaneously. The cut that is produced is much more uniform than a hand cut made by torch. The machined bevel provides a more welder-friendly surface than a surface produced using a torch and grinders. A hand-made internal taper is often rounded, which can be avoided using the equipment. The Split Frame® does have some draw backs, however. There is a learning curve associated with using the equipment initially. The quality of the beveling and cutting is very much affected by positioning which is a manual operation performed by the operator. It is also important to have materials that are relatively round (i.e. ovality less than 1%). However, this is the case with manual segmenting and torch beveling also. Overall, when used correctly, this equipment is a potentially valuable tool in the segmenting process.

4.2 Optimization of Joint Designs for Unequal Wall Thickness Transitions

Guidance pertaining to joint designs for unequal wall thickness transitions and/or unequal strength materials is provided in Appendix I of ASME B31.8[1] and in §434.8.6 of ASME B31.4.[2] The requirements for transition joints in these two codes are essentially identical, so while the following discussion focuses on Appendix I of ASME B31.8, it also pertains to §434.8.6 of ASME B31.4. These codes allow transitions to be accomplished by tapering and/or by backwelding.

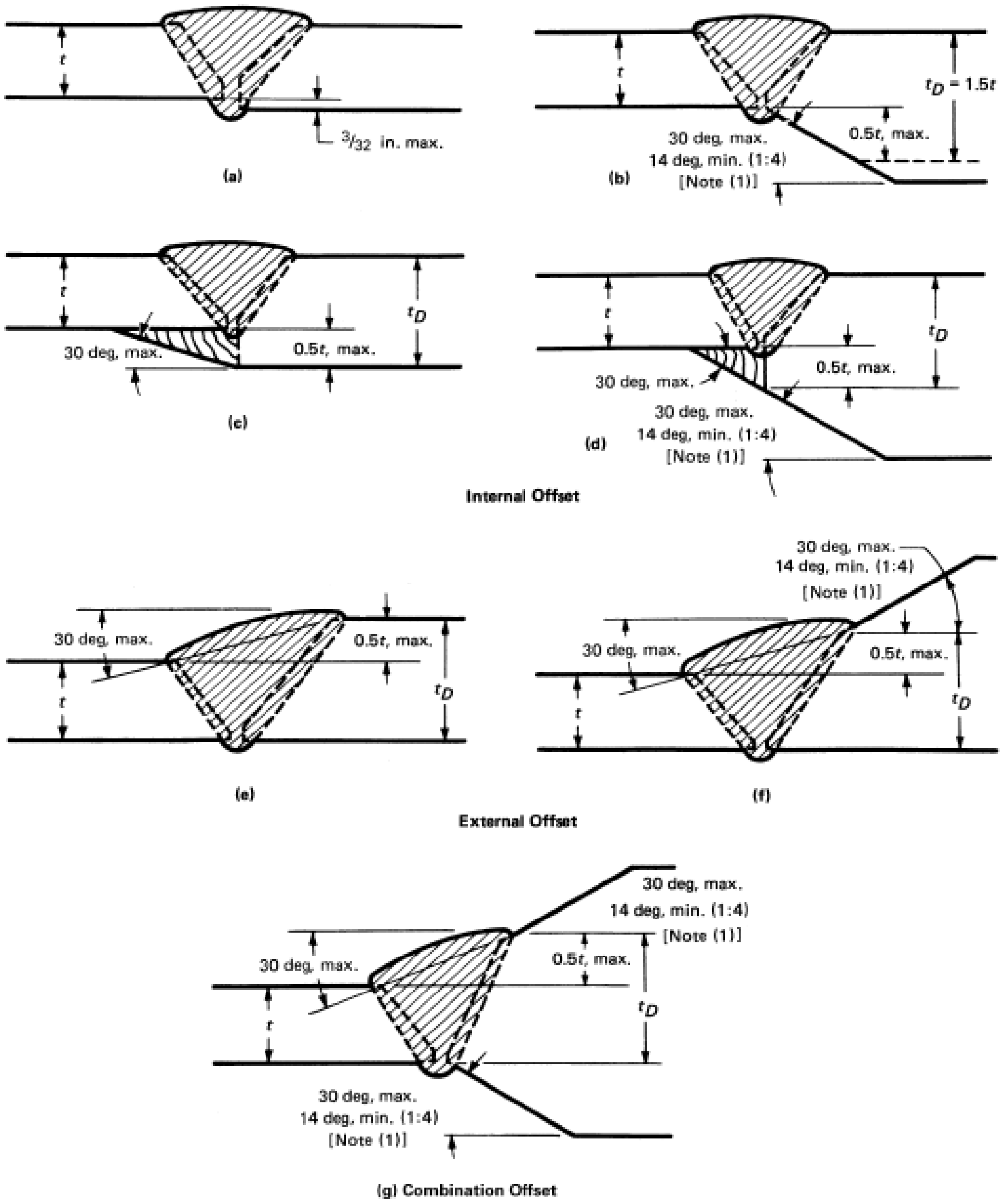
Appendix I of ASME B31.8 refers to the joint designs shown in Figure I-5 (Figure 56). Figure I-5 includes acceptable joint designs for internal offset (i.e., when the outside diameters match but the wall thicknesses are unequal), external offset (i.e., when the inside diameters match but the wall thicknesses are unequal), and combination offset (i.e., when the wall thicknesses are unequal and one side of the joint has both a smaller inside diameter and a larger outside diameter). However, Figure I-5 does not cover all situations that may arise in the field. For example, a situation that is not addressed by Figure I-5, which often occurs when welding segmented induction bends, is internal and external offset in the same direction (i.e., when one side of the joint has both a smaller inside diameter and a smaller outside diameter).

Unequal wall thickness transitions are particularly problematic when the component on one side of the joint has diameter shrinkage, as in the example given above. The use of internal tapering alone applied to a component with diameter shrinkage can lead to a reduction in wall thickness that can reduce the axial load carrying capacity of the joint. If the inside diameter of a component with diameter shrinkage is tapered so that the lands on the weld bevel match, the resulting material on the low side of the joint may be insufficiently thick. In these cases, the use of a joint design that involves backwelding is a better approach, as the wall thickness throughout the joint is maintained. It should be noted that not all induction bends have diameter shrinkage and elbows are less likely to have diameter shrinkage than induction bends.

4.2.1 Review of Previous Work

In the late 1990s, work was conducted by Leis at Battelle for PRCI[3, 4] pertaining to the performance and limitations of butt welded transition joints. This work, the results of which are summarized in Appendix A, concluded that there is a significant difference between joint designs that are adequate to avoid failure by plastic collapse and those needed to avoid failure by fracture. The report for this work covers failure by plastic collapse but states that more work is needed to determine what is required to prevent failure by fracture. Work in this area has also been conducted by Law at ANSTO for APIA.[5] Results of this work, also summarized in Appendix A, indicated that restrictions on wall thickness and grade mismatch could be eliminated as long as limits on axial and bending loads were applied.

Fig. I-5 Acceptable Design for Unequal Wall Thickness



NOTE:
(1) No minimum when materials joined have equal specified minimum yield strengths.

Figure 56. Figure I-5 from ASME B31.8 Appendix I

4.2.2 Appendix I from ASME B31.8

As noted in Appendix A, the joint designs shown in Appendix I in ASME B31.8 are based on work by George and Rodabaugh in the 1950s and were developed considering only pressure loading. The results of this work concluded that, when joining higher-strength thinner-wall line pipe to lower-strength thicker-wall line pipe, transition tapers in the lower-strength material benefit from the so-called “bridging effect” where the thin end of the taper is supported by the adjacent thicker material. A minimum taper of 1:4 (14 degrees) was recommended and subsequently specified in the ASME codes. While the joint designs shown in Appendix I have served the industry well, they do not explicitly take axial loading into account.

For axial loading of joints with high-low misalignment caused by diameter shrinkage of the thicker side, it is clearly advantageous to use joint designs that involve backwelding such as those shown in Figures I-5 (c) and (d) as opposed to those shown in Figures I-5 (a) and (b). Joint designs with backwelds tend to maintain wall thickness throughout the joint, as the size and position of the backweld can simply be adjusted to account for the high-low misalignment.

Figure 57 shows an unequal wall thickness joint with no misalignment joined using option (b) in Figure I-5. Figures 58 and 59 show the effect of high-low misalignment on the same joint. By using option (d) in Figure I-5 (backwelding), wall thickness throughout the joint is maintained. The use of joint designs that do not involve backwelds for this application, such as those shown in Figure I-5 (b), tends to result in areas of reduced thickness when there is diameter shrinkage on the thicker side. These areas of reduced wall thickness occur in what is likely to be the lower-strength material side of the joint and represent area of potential weakness. Figures 60 and 61 show the effect of high-low misalignment on the same joint using option (b) in Figure I-5 (tapering only and no backweld). Areas of reduced thickness are introduced as high-low misalignment from diameter shrinkage is increased.

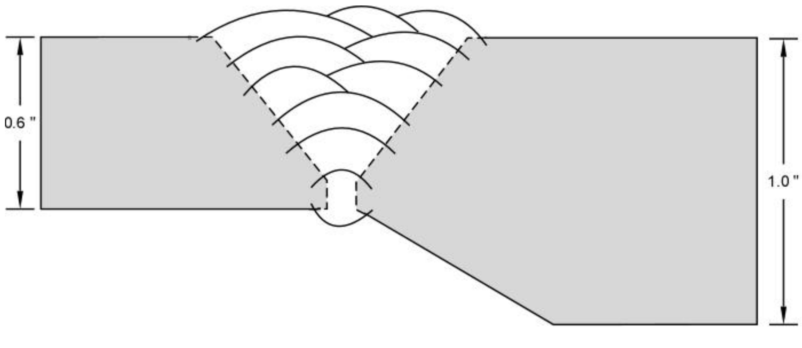


Figure 57. Example of unequal wall thickness joint with no misalignment joined using option (b) in Appendix I, Figure I-5

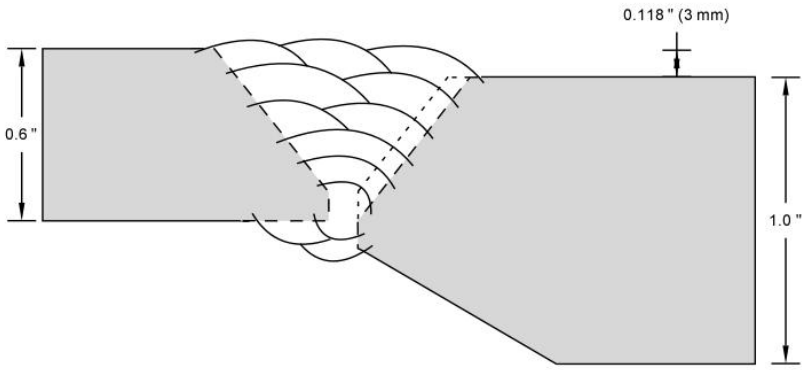


Figure 58. Example of unequal wall thickness joint with 3mm misalignment joined using option (d) in Figure I-5

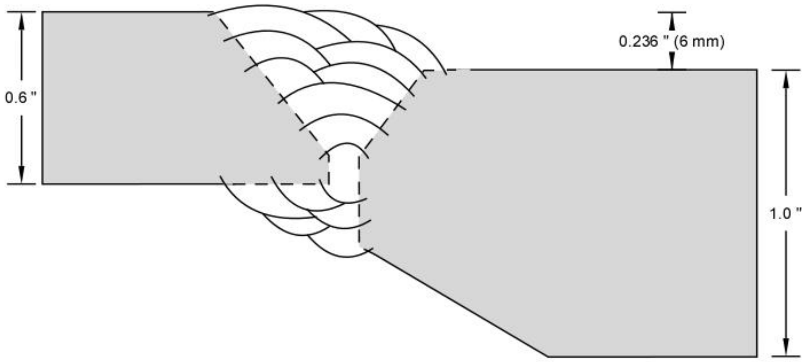


Figure 59. Same as Figure 58 with 6mm misalignment

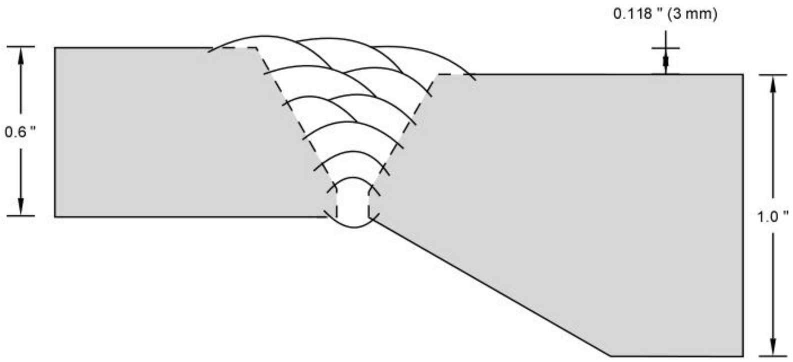


Figure 60. Example of unequal wall thickness joint with 3mm misalignment joined using option (b) in Figure I-5

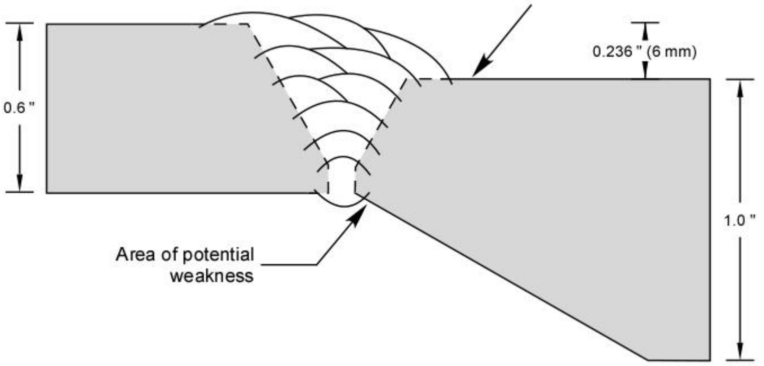


Figure 61. Same as Figure 60 with 6mm misalignment showing area of potential weakness

The same is true for *equal* wall thickness joints with diameter shrinkage on one side of the joint or when significant out-of-roundness exists. Even though Appendix I does not address equal wall thickness joints, features of the joint designs shown in Figure I-5 may occasionally be applied when excessive misalignment is present. Figure 62 shows an equal wall thickness joint with no misalignment. Figures 63 and 64 showing this same joint as high-low misalignment is introduced. By using option (c) in Figure I-5, wall thickness throughout the joint is maintained. The use of a joint design that does not involve a backweld for this application, such as that shown in Figure I-5 (b), tends to result in areas of reduced thickness when there is diameter shrinkage on one side. Figures 65 and 66 showing this same joint as high-low misalignment is introduced using option (b) in Figure I-5 (tapering only and no backweld). An area of reduced thickness is introduced as high-low misalignment from diameter shrinkage is increased, resulting in areas of potential weakness.

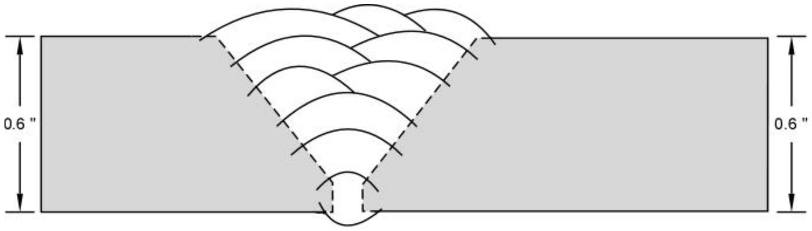


Figure 62. Example of equal wall thickness joint with no misalignment

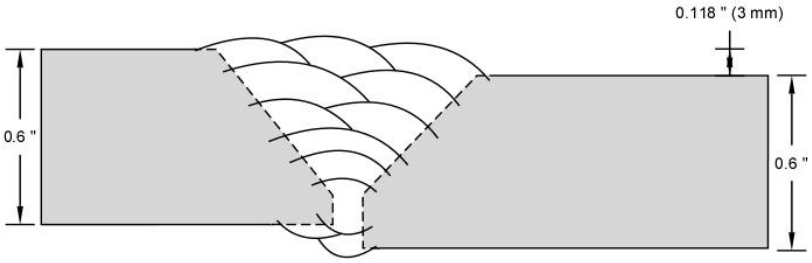


Figure 63. Example of equal wall thickness joint with 3mm misalignment joined using option (d) in Figure I-5

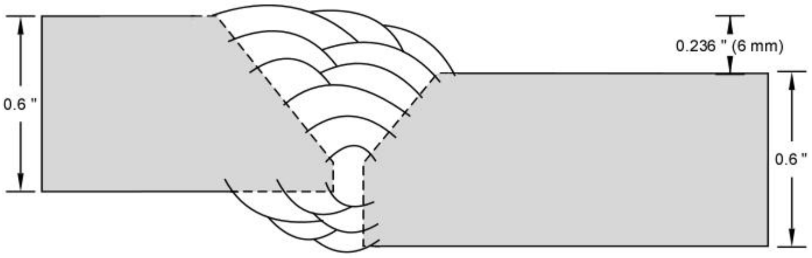


Figure 64. Same as Figure 63 with 6mm misalignment

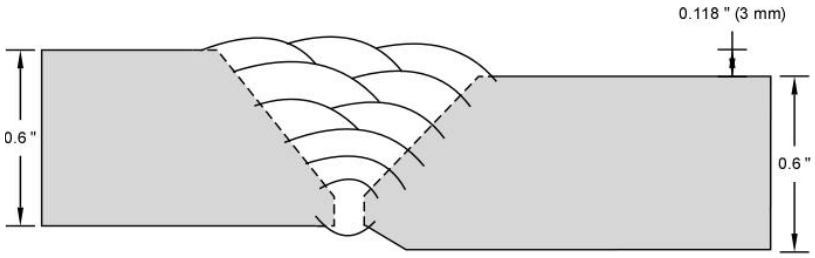


Figure 65. Example of equal wall thickness joint with 3mm misalignment joined using option (b) in Figure I-5

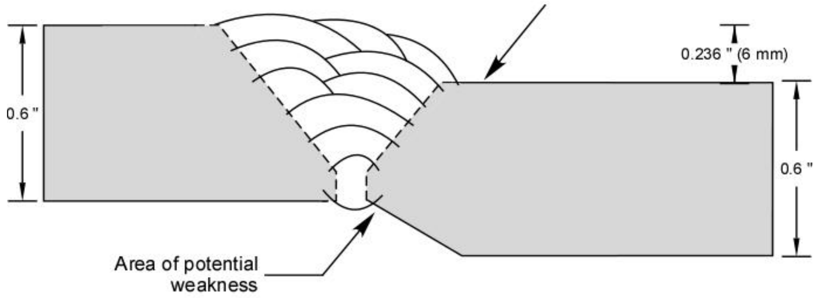


Figure 66. Same as Figure 65 with 6mm misalignment showing area of potential weakness

A potentially attractive option for joints with high-low misalignment caused by diameter shrinkage of the thicker side is the use of a double-Vee butt weld. This concept, which is shown with no misalignment and as high-low misalignment is introduced in Figures 67 through 69, is similar to the option shown in Figure I-5 (d), except that a weld preparation is provided on both sides (ID and OD) of the joint. Potential advantages of this option include a reduced overall volume of weld metal and root pass defects that are located mid-thickness where their severity is decreased. While applicable in principal, it is not known how often this practice is used in this application.

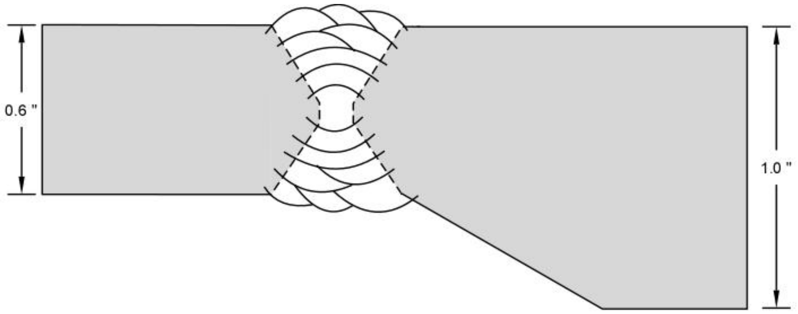


Figure 67. Example of unequal wall thickness joint with no misalignment joined using double-vee butt weld option

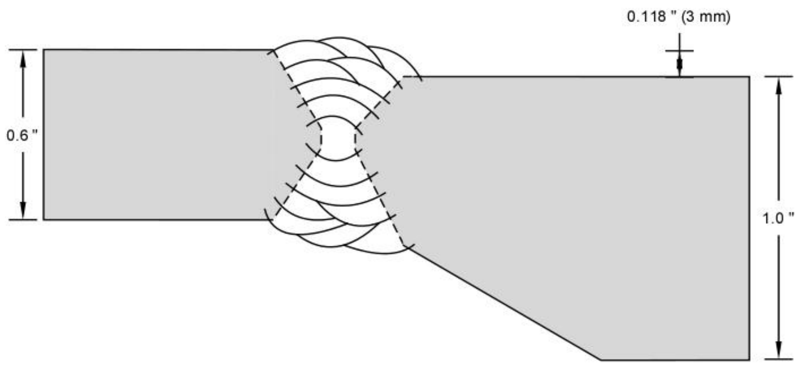


Figure 68. Same as Figure 67 with 3mm misalignment

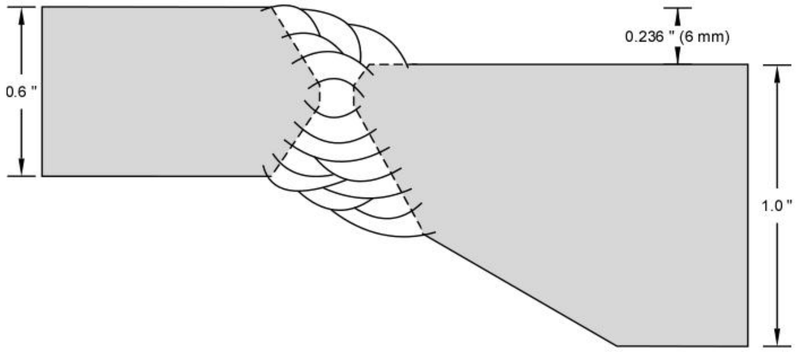


Figure 69. Same as Figure 67 with 6mm misalignment

Another potential option for joints with high-low misalignment caused by diameter shrinkage of the thicker side is to apply weld metal build-up (weld metal buttering) to the inside of the side without diameter shrinkage prior to beveling. This concept is shown in Figure 70. This option is similar to backwelding except that the "backweld" is deposited prior to beveling. Weld metal is deposited to the inside of the side without diameter shrinkage until the thickness is such that the inside diameter is just less than the inside diameter at the weld bevel of the side with diameter shrinkage. The weld metal buildup should taper to the inside diameter at an angle of no more than 30 degrees (same as for backweld). After the weld metal buildup is complete, a weld bevel that matches at the weld root can be produced on both sides of the joint. While applicable in principal, it is not known how often this practice is used.

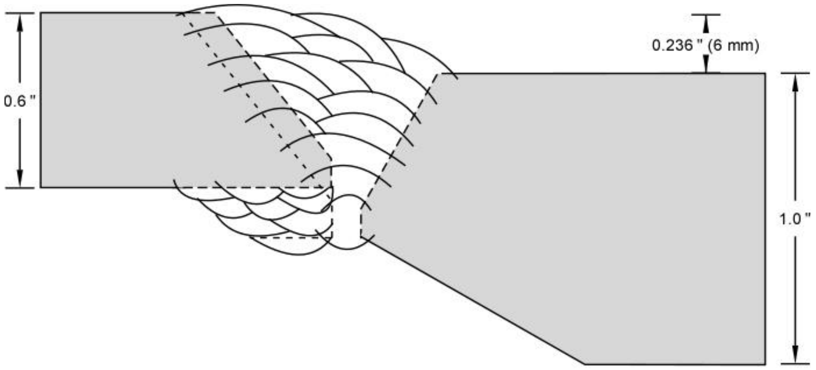


Figure 70. Example of unequal wall thickness joint with 6mm misalignment addressed using weld metal buildup option

A misalignment of 6mm (0.236 inch) as shown in some of the figures described above represents 39.3% of the wall thickness of the thinner material (0.6 inch), which may be excessive for some applications. Guidance pertaining to limits on maximum allowable misalignment (high-low) is provided in Section 4.3.1. In the generic procedure for segmenting of induction bends and elbows, the development of which is described in Section 4.5.1, the maximum misalignment is limited to no more than 1/3 of the wall thickness of the thinner material. The generic procedure also prohibits the use of option (b) in Figure I-5 if there is misalignment due to diameter shrinkage.

4.2.3 Guidance for Application of Figure I-5

Guidance pertaining to which joint design options to use in Appendix I, Figure I-5 for which applications is provided below.

- For unequal wall thickness transitions for which the outside diameters are equal, any of the joint designs shown in Figures I-5 (a) through (d) are appropriate. Outside diameters should be considered equal if they differ by no more than 3/16 inch (4.7 mm).
- For unequal wall thickness transitions for which the inside diameters are equal, either of the joint designs shown in Figures I-5 (e) and (f) are appropriate. Inside diameters should be considered equal if they differ by no more than 3/16 inch (4.7 mm).
- When there is diameter shrinkage on one side of the joint (i.e., when one side of the joint has both a smaller inside diameter and a smaller outside diameter), joint designs that involve backwelds, such as those shown in Figures I-5 (c) and (d) should be used. Diameters should be considered unequal if they differ by more than 3/16 inch (4.7 mm).

- For components that are sufficiently thick (e.g., one side of the joint has both a smaller inside diameter and a larger outside diameter), the joint design shown in Figure I-5 (g) is appropriate.

Many users of Appendix I tend to focus on Figure I-5 without paying sufficient attention to the text in Appendix I. The following guidance should be followed when using the joint designs Figures I-5.

- While not specifically required in the text of Appendix I, Figures I-5 (c) and (d) specify a 30 degree maximum angle for the backweld, as does the generic procedure for segmenting. Because of confined space conditions, there is a tendency for welders to under-weld backwelds, which may result in angles greater than 30 degree and associated stress concentrations.
- While not specifically required by Figures I-5 (c) and (d), the text of Appendix I indicates that "…sharp notches or grooves at the edge of the weld… … shall be avoided". Weld toes, particularly those at the thin-wall side of backwelds, should blend smoothly into the base metal so that stress concentrations are avoided.
- Care should be taken when attempting to combine features from the various sub-figures in Figure I-5. For example, it may not be appropriate to combine Figures I-5 (c) and (e) (internal and external offset, respectively) and apply the maximum allowable internal and external offset to an equal wall thickness joint with diameter shrinkage on one side (Figures 71). The resulting 0.5t offset may be excessive for an equal wall thickness joint. Similarly, it is not appropriate to apply the taper requirements in Figures I-5 (b) and (f) to an equal wall thickness joint with diameter shrinkage on one side (Figure 72).
- When using joint designs that involve backwelds, the guidance provided in Section 4.3.4 pertaining to backwelding should be followed. The joint design guidance provided above indicates a strong preference for backwelding unless conditions are ideal. When backwelding is used, it is very important that the guidance pertaining to backwelding is followed.

When drawn in cross section, it is simple to see what combinations of joint design and diameter shrinkage lead to a reduction in wall thickness or stress concentrations that can reduce the axial load carrying capacity of the joint. In practice however, this is much more difficult to determine, as the internal and external features of the weld can only be viewed separately without relative position to one another. Advance planning is required to ensure that areas of reduced wall thickness and stress concentrations are not produced.

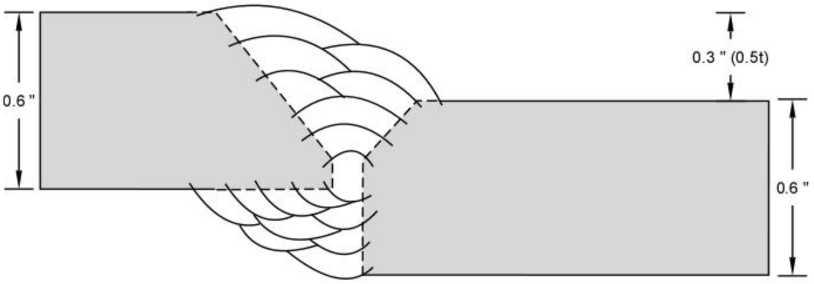


Figure 71. Potentially inappropriate combining of features from Figures I-5 (c) and (e) applied to equal wall thickness joint with 0.5t misalignment

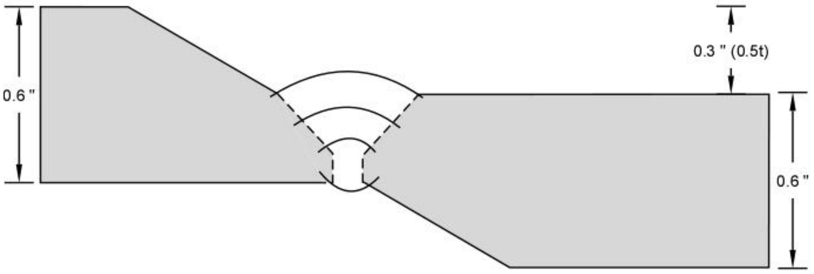


Figure 72. Inappropriate combining of features from Figures I-5 (b) and (f) applied to equal wall thickness joint with 0.5t misalignment

4.2.4 Summary of Joint Design Guidance for Unequal Wall Thickness Transitions

The joint design guidance developed above id summarized below.

- For unequal wall thickness transitions for which the outside diameters are equal, any of the joint designs shown in Figures I-5 (a) through (d) are appropriate.
- For unequal wall thickness transitions for which the inside diameters are equal, either of the joint designs shown in Figures I-5 (e) and (f) are appropriate.
- When there is diameter shrinkage on one side of the joint (i.e., when one side of the joint has both a smaller inside diameter and a smaller outside diameter), joint designs that involve backwelds, such as those shown in Figures I-5 (c) and (d) should be used.
- For joint designs that involve backwelds, care should be taken to ensure that the backweld is of sufficient size and that the angle is no more than 30 degrees.

- For components are sufficiently thick (e.g., one side of the joint has both a smaller inside diameter and a smaller outside diameter), the joint design shown in Figure I-5 (g) is appropriate.
- For all joint designs, sharp notches or grooves at the edge of the weld should be avoided.

4.3 Field Welding of Segmented Fittings

4.3.1 General

There are several welding aspects that are unique to the use of segmented induction bends and elbows. By definition, segmented induction bends and elbows are located at points of inflection, or at changes in topography, which tend to be more susceptible to high stresses from bending loads caused by pipeline movement due to soil settlement. The use of segmented induction bends and elbows often involves transition welds between dissimilar wall thickness materials, which tend to concentrate stresses due to bending. The use of segmented induction bends and elbows often involves the need to cope with high-low misalignment because of out-of-roundness and/or diameter shrinkage of the segmented fitting, which also tend to concentrate stresses due to bending.

To alleviate problems caused by these potential difficulties, whenever segmented induction bends and elbows are used, transition pups should always be welded to the end of a segmented fitting so that a pipe-to-pipe weld can be made in the field. Since transition pups can be relatively short, welds to transition pups are simpler to make than welds to full or longer lengths of pipe. Short transition pups alleviate difficulty with alignment and provide access for backwelding (if necessary) and for inspection.

Transition pups should be long enough to distribute stresses away from transition welds but short enough to allow access for visual inspection and backwelding if necessary. Access for visual inspection and backwelding is also dependent on pipe diameter, with larger diameter pipe allowing better access than smaller diameter pipe. For larger diameter pipe where access is not restricted by pipe diameter (e.g., 20 inch diameter and above), transition pup length should generally be at least 24 inch or one pipe diameter, whichever is smaller. For smaller diameter pipe, transition pups can be shorter but should not be less than one-half pipe diameter in length.

Segmented induction bends and elbows are generally thicker than the line pipe material to which they will eventually be joined. It is preferable for the wall thickness of transition pups to be in between the wall thickness of the fitting and the wall thickness of the line pipe material. For typical pipeline designs, it is preferable for the transition pup to be at least 1/8 inch (3.2 mm) less than the nominal wall thickness of the fitting but no more than 1/4 inch (6.4 mm) less than the nominal wall thickness of the fitting. However, in cases where diameter shrinkage is high (more common with segmented induction bends than with segmented elbows), it may be necessary to use a transition pup of the same nominal wall thickness as the bend to ensure sufficient wall thickness at the transition bevel. When determining wall thickness for transition pups, the design pressure requirements must always be met.

Even with the dimensions of the pipe pup optimized, it is important that the toe of the root pass or backweld transition smoothly from the ground surface to minimize stress concentrations. The angle between the weld toe and the ground surface should not create a sharp notch, and defects such as undercut should not be allowed. Remedial action for less than ideal geometry at the toe of a completed root pass or backweld include light weld toe grinding and depositing additional backweld passes.

4.3.1 Limits for High-Low Misalignment

The difficulty associated with high-low misalignment in pipeline girth welds is two-fold; it makes root pass welding difficult and it results in stress concentrations in completed welds. There are currently no absolute limits for misalignment in API Standard 1104[6] provided that the misalignment is distributed evenly around the circumference. When lining up for girth welding, API 1104 allows for some degree of offset between adjoining edges of the pipe. Since the word ‘should’ is used to describe the 1/8 in. (3 mm) maximum offset specified, this is a recommended practice and not a requirement. Offsets larger than this are allowed provided that they are the result of pipe and fitting end dimensional variations that are within the limits of the specification to which they were purchased and that the offset has been distributed uniformly around the circumference. End dimensional variations that can result in offset include diameter variations, out-of-roundness, diameter shrinkage, local peaking, and wall thickness variations. Large misalignments are possible even when the line pipe and fittings are manufactured within their respective specifications.

It may be possible for the most talented of welders to make an acceptable root pass from the outside with high-low misalignment approaching 1/8 inch. Even root passes that are made with high-low misalignment approaching 1/8 inch and are considered to be acceptable (i.e., meets acceptance standard for incomplete penetration) often have poor root pass profiles (i.e., do not blend smoothly into the base metal) that can results in stress concentrations (Figures 73). To avoid stress concentrations, the weld toe should blend smoothly into the base metal and the angle at the weld toe should be as obtuse as possible (Figure 74). Beyond 1/8 inch misalignment, the probability of producing root pass discontinuities, such as incomplete penetration, burnthrough, etc., increases significantly.

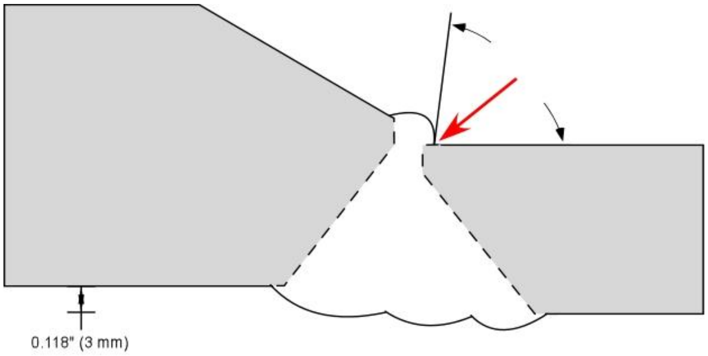


Figure 73. Joint with high-low misalignment (3 mm) and associated stress concentration from acute angle at weld toe

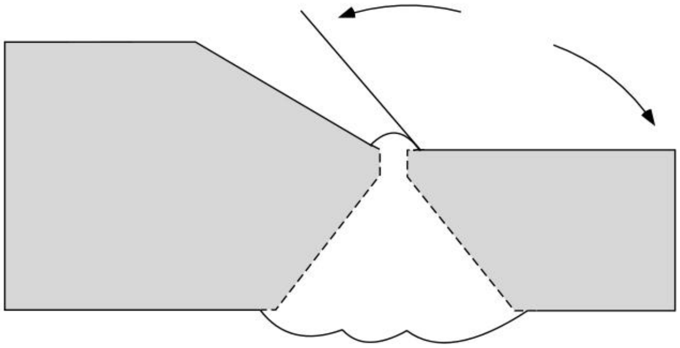
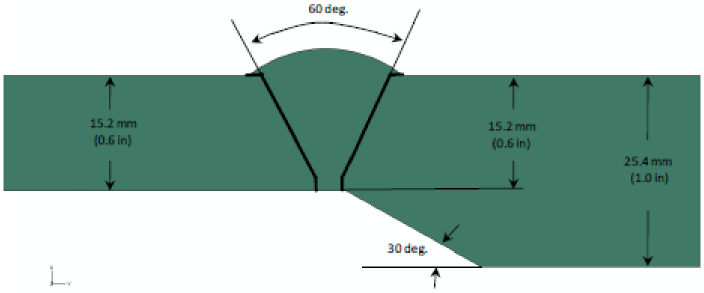


Figure 74. Joint with no high-low misalignment and obtuse angle at weld toe

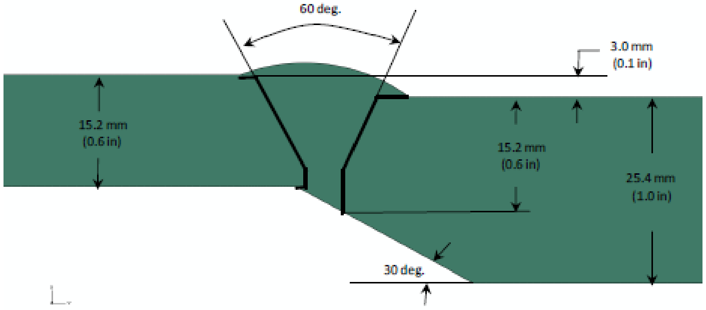
The detrimental effects of misalignment in completed welds are related to the magnitude of the misalignment relative to the pipe wall thickness. Girth welds in thin-wall line pipe materials are more likely to have greater stress concentration than girth welds in thick-wall materials for the same absolute amount of misalignment. High-low misalignment of 1/8 inch represents 50% of the pipe wall thickness of 0.250 inch thick pipe but only 25% for 0.500 inch thick pipe.

Center for Reliable Engineering Systems (CRES) used finite element analysis to predict the reduction in axial load carrying capacity of unequal wall thickness joints with various amounts of misalignment and for different weld profiles. Figure 75 shows an unequal wall thickness joint with no misalignment joined using option (b) in Figure I-5. Figure 76 shows this same joint made using option (d) in Figure I-5 as high-low misalignment is introduced. The load capacity reduction factor goes from 1.00 (no reduction factor) for no misalignment to 0.998, 0.996, and 0.994 for misalignment of 3, 6, and 9 mm, respectively, when there is a smooth internal transition from the thicker side to the thinner side. Load capacity reduction factor is defined as the reciprocal of stress concentration factor (e.g., 0.994 indicates 99.4% of strength of joint with no misalignment). Load capacity reduction factors less than 1.000 are acceptable provided pup wall thickness is greater than minimum required by design.

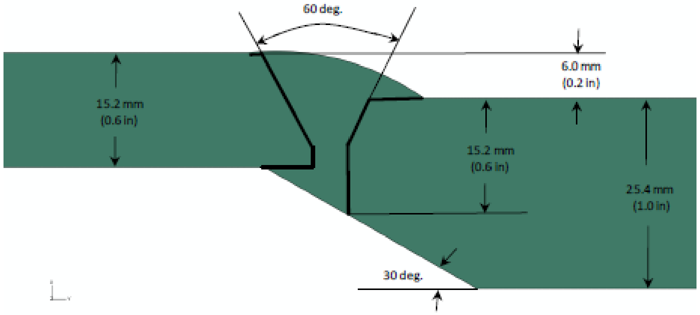


Misalignment = 0.0 mm, Likely location of Failure = Base Metal of Pup, Load Capacity Reduction Factor = 1.000

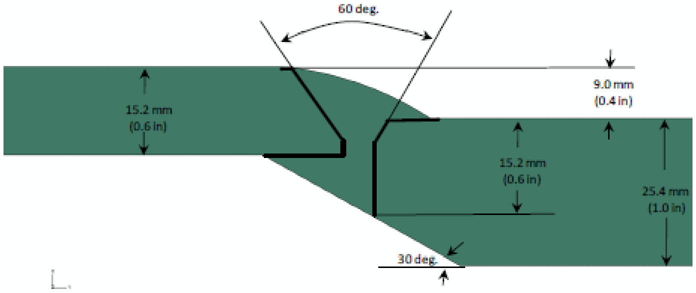
Figure 75. Example of unequal wall thickness joint with no misalignment joined using option (b) in Figure I-5



Misalignment = 3.0 mm, Likely location of Failure = Base Metal of Pup, Load Capacity Reduction Factor = 0.998



Misalignment = 6.0 mm, Likely location of Failure = Base Metal of Pup, Load Capacity Reduction Factor = 0.996

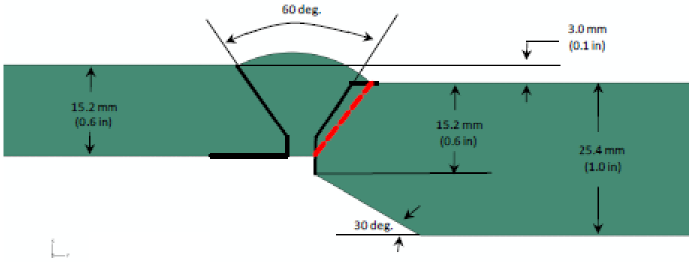


Misalignment = 9.0 mm, Likely location of Failure = Base Metal of Pup, Load Capacity Reduction Factor = 0.994

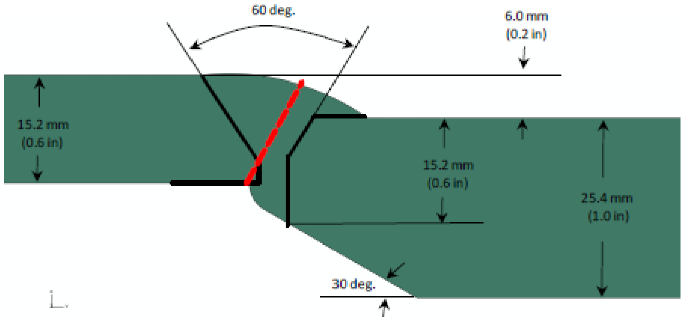
Figure 76. Unequal wall thickness joint using option (d) in Figure I-5 with misalignment and Smooth Internal Transition

Figure 77 shows the same weld with a smooth internal transition from the thicker side but a sharp angle at the weld toe on the thinner side. The load capacity reduction factors decrease to

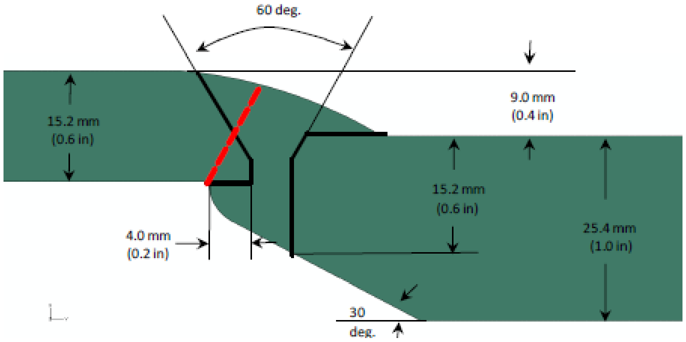
0.988, 0.959, and 0.952 for misalignment of 3, 6, and 9 mm, respectively. Figure 78 shows the same weld with a 45 degree internal transition (as opposed to the 30 degree maximum specified in Figure I-5). The load capacity reduction factors are 0.948 and 0.954 for misalignment of 6 and 9 mm, respectively. The red dashed lines in Figures 77 and 78 represent the path of plastic flow or the area of potential weakness.



Misalignment = 3.0 mm, Likely location of Failure = Weld/HAZ, Load Capacity Reduction Factor = 0.988

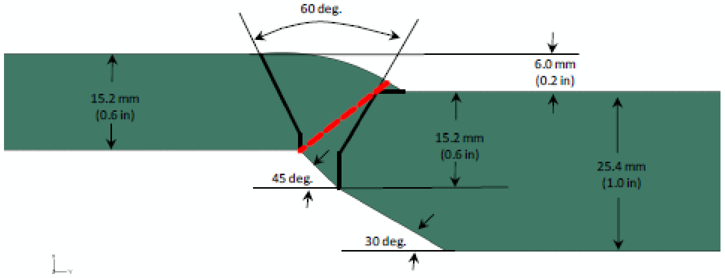


Misalignment = 6.0 mm, Likely location of Failure = Weld, Load Capacity Reduction Factor = 0.959

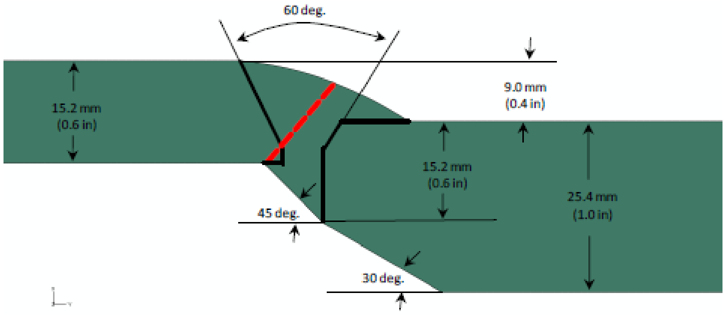


Misalignment = 9.0 mm, Likely location of Failure = Weld, Load Capacity Reduction Factor = 0.952

Figure 77. Unequal wall thickness joints with misalignment and sharp reentrant angle on thinner side (plastic flow path indicated by red dashed line)



Misalignment = 6.0 mm, Likely location of Failure = Weld, Load Capacity Reduction Factor = 0.948



Misalignment = 9.0 mm, Likely location of Failure = Weld, Load Capacity Reduction Factor = 0.954

Figure 78. Unequal wall thickness joints with misalignment and 45 degree internal transition to thinner side (plastic flow path indicated by red dashed line)

The results of the finite element analysis described above indicate that significant misalignment can be tolerated with only a slight reduction in load carrying capacity when there is a smooth internal transition from the thicker side to the thinner side. A more significant reduction occurs when the internal transition to the thinner side is not smooth and when the internal transition is steeper than allowed by Figure I-5. Misalignment of 3, 6, and 9 mm represents 19.7, 39.4, and 59.1% of the thinner (0.6 inch thick) side of the joint, respectively, in the figures described above. In the generic procedure for segmenting induction bends and elbows, the development of which is described in Section 4.5.1, the maximum misalignment is limited to no more than 1/3 (33.3%) of the wall thickness of the thinner material. While the finite element results indicate that larger misalignment can be tolerated with only a slight reduction in load carrying capacity, the limit chosen for the generic procedure is intended to account for less than perfectly smooth transitions to the thinner side of the joint. It should be noted that, when the thickness of the thinner side of the joint is less than 3/8 inch, the maximum high-low misalignment allowed by the generic procedure is less than the 1/8 inch limit recommended in API 1104.

4.3.2 Methods for Measuring High-Low

Prior to root pass welding of segmented induction bends and elbows to transition pups, internal misalignment should be measured using a purpose-built measuring device (Figure 79). Preliminary work using variety of commercially-available high-low measuring devices was conducted during the field exercise in West Virginia. The results of this work indicate that while both devices shown in Figure 79 work equally well for equal wall thickness joints, internal misalignment for joints with an internal taper on one side is best measured using the device shown in the top portion of Figure 79. This device uses wire feelers, one of which can be bent to match the angle of the internal taper (inset to Figure 79).

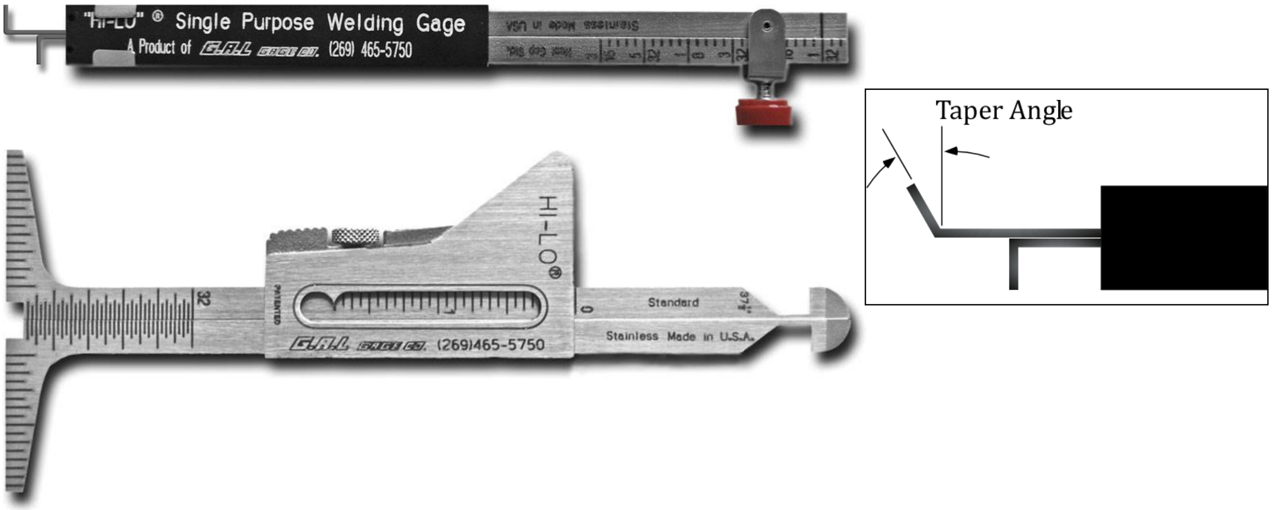


Figure 79. Commercially available devices for measuring high-low misalignment

More-sophisticated devices for measuring internal misalignment are also available, an example of which is shown in Figure 80. These devices are intended primarily for use in fatigue-sensitive applications, such as butt welds in steel centenary risers on offshore platforms. While these devices are quite accurate for measuring internal misalignment for equal wall thickness joints, they are not well suited for joints with an internal taper on one side.

Figure 80. More-sophisticated device for measuring internal misalignment

4.3.3 Methods for Addressing Excessive Misalignment

During production welding of thinner-wall line pipe materials, internal line-up clamps can alleviate some high-low misalignment problems due to out-of-roundness. The hydraulic cylinders built into a well-maintained clamp can simply re-round thinner-wall line pipe materials during root pass welding. Internal line-up clamps cannot be used for welds that join segmented bends and elbows to transition pups, however. For these welds, the only option for addressing excessive misalignment appears to be backwelding. Even if backwelding is to be used, efforts should be taken to minimize misalignment and misalignment should be limited to the limits described above (no more than 1/3 of the wall thickness). Load frames, like the one shown in Figure 81, are occasionally used to re-round fittings during the manufacturing process. This practice is acceptable during manufacture provided that it is followed by stress-relief heat treatment. The use of hot or cold re-rounding (plastic deformation) of segmented induction bends and elbows in the field should be prohibited.

Figure 81. Load frame used for factory re-rounding of elbows

4.3.4 Backwelding Methods and Practices

Backwelding (i.e., depositing one or more weld pass from inside the pipe) is a relatively common technique for repairing or otherwise making the root region of what are normally intended to be single-sided, open root butt welds acceptable. One potential problem with this technique is that the backweld is normally deposited last and does not benefit from tempering associated with the thermal cycle from subsequent passes. Unlike cap passes, backwelds can consist of relatively small beads that are deposited at relatively low heat input levels. Hard crack-susceptible weld microstructures have been known to result from backwelds that are deposited last. Another potential problem with backwelds is that their location (often 40 feet or more from the open end of the pipeline during production welding) makes them difficult to make (confined space, difficult to see [poor lighting, smoke], potential for arc burns, etc.) and visually inspect (often inspected by no one other than the welder). Achieving adequate preheat temperature with the welder inside is another potential problem. Because of these potential problems, backwelding is normally thought of as an undesirable practice. It is often carried out as a last-ditch effort to make the root region of an otherwise completed weld acceptable. When carried out properly however, backwelding is an attractive and perfectly acceptable solution to misalignment problems.

For attaching transition pups to segmented induction bends and elbows, potential problems associated with confined space, preheating, and visual inspection are minimized because the pup can be relatively short. The use of short pups also allows visual inspection to be carried out by the inspector without having to crawl inside a long length of pipe. There are two ways to overcome potential problems related to the formation of crack-susceptible weld microstructures. One is to develop suitable welding parameters for backwelds that are deposited last. The other is to deposit the backweld first (i.e., to deposit the root pass from the inside) or to deposit the backweld prior to completing the weld from the outside.

The current version of API 1104 (20th Edition) does not require the use of a specific welding procedure specification (WPS) for backwelding (i.e., bead sequence is not an essential variable for procedure qualification). However, if backwelding is to be permitted, it is good practice to weld and test joints with and without backwelds (i.e., it is good practice to consider the addition of a backweld to be an essential variable for procedure qualification). The 20th Edition requires that the sequence of beads must somehow be designated and this is normally accomplished by providing a sketch. If backwelding is to be prohibited for a given WPS, this should be specified. The proposed 21st Edition of API 1104[7] will have specific provisions for qualifying welding procedures with backwelds.

When qualifying a procedure for backwelding, consideration should be given to specifying and using low-hydrogen electrodes for the backwelds. While backwelds made using cellulosic-coated electrodes are acceptable provided that a WPS has been developed and qualified using cellulosic-coated electrodes, backwelds made using low-hydrogen electrodes are more desirable since the risk of hydrogen cracking is significantly reduced. Preheating requirements for welds made using low-hydrogen electrodes are typically less than for welds made using cellulosic-coated electrodes, which alleviates concerns for achieving adequate preheat temperatures with the welder inside the pipe.

Depending on the extent of misalignment, there may be the need for a single backweld pass or for multiple backweld passes. While single-pass backwelds are acceptable provided that a WPS has been developed and qualified using a single pass backweld, multi-pass backwelds are more desirable since previous passes benefit from tempering associated with the thermal cycle from subsequent passes. However, if the extent of misalignment is small, there may not be sufficient space for a multi-pass backweld (unless a second pass is used primarily to temper the heat affected zone of the first pass and is subsequently ground off). For multi-pass backwelds, the beads should be deposited in such a way as to maximize the tempering in more crack-susceptible area (i.e., the beads should be stacked away from the thinner side of the joint – Figure 82).

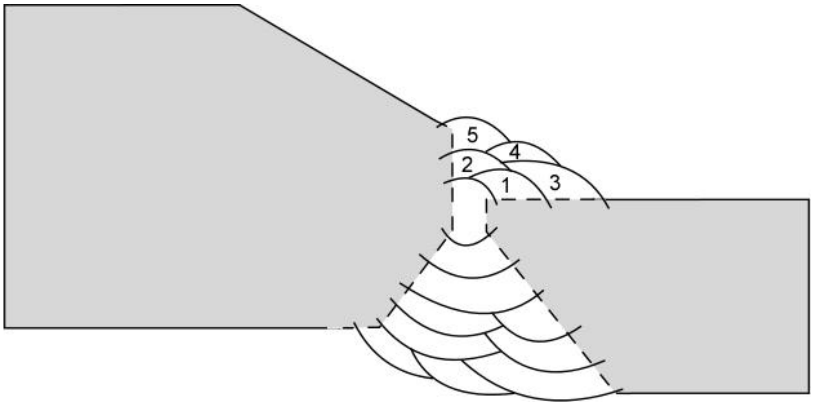


Figure 82. Multi-pass backweld with beads stacked away from thinner side

If a weld requires backwelding only at a particular location, a full circumferential backweld is not required. Backwelding is only required where the extent of misalignment makes it necessary. However, backwelds should be long enough so that steady-state heat flow conditions are established. Backwelds should be a minimum of 2 inches in length, but are only required at areas of excessive high-low misalignment.

Completed backwelds should transition smoothly into the pipe material. The profile of the completed backweld should follow the requirements in Figures I-5 (c) and (d), which specifies a 30 degree maximum angle for the backweld. Weld toes, particularly those at the thin-wall side of backwelds, should blend smoothly into the base metal so that stress concentrations are avoided. Because of confined space conditions, there is a tendency for welders to under-weld backwelds, which may result in angles greater than 30 degree and associated stress concentrations (Figure 83). The geometric details of a completed backweld should be the subject of careful visual inspection by the welding inspector. Remedial measures for completed backwelds that are found to have unacceptable geometry include grinding and depositing additional backweld passes (Figure 84).

When carried out properly, backwelding is a perfectly acceptable solution to misalignment problems. It is particularly well-suited for attaching transition pups to segmented induction bends and elbows since potential problems associated with confined space, preheating, and visual inspection are minimized because the pup can be relatively short. While not necessarily required by the current edition of API 1104 (20th Edition), it is good practice to weld and test joints with and without backwelds (i.e., it is good practice to consider the addition of a backweld to be an essential variable for procedure qualification). When qualifying a procedure for backwelding, consideration should be given to specifying and using low-hydrogen electrodes for the backwelds.

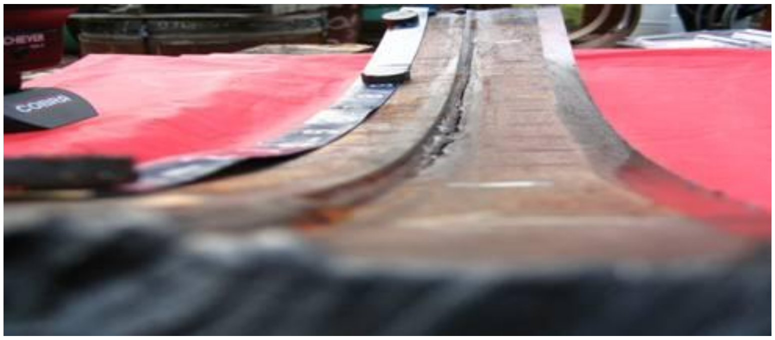


Figure 83. High-low misalignment with inadequate backweld

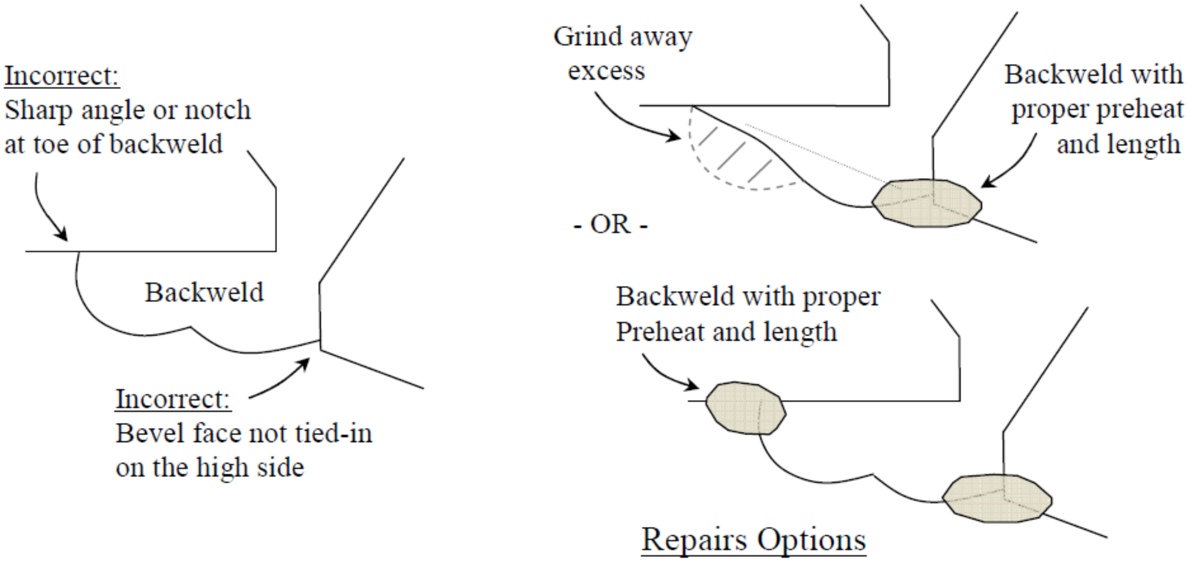


Figure 84. Remedial measures for poor geometry backweld

4.3.5 General Guidance for Avoiding Hydrogen Cracking

A number of pipeline girth weld failures have occurred in the US recently, some in newly-constructed pipeline during pre-service hydrostatic proof testing.[8, 9] A number of these hydrotest failures have been attributed to hydrogen-induced cracking in repair and tie-in welds. Of the various types of defects that can occur in pipeline girth welds, cracks are the most significant since these are most likely to cause subsequent failures.

Hydrogen cracking requires that three primary independent conditions be satisfied simultaneously; (1) hydrogen must be present in the weld, (2) there must be a susceptible weld microstructure, and (3) tensile stresses must be acting on the weld. Cellulosic-coated electrodes (AWS EXX10-type) have been traditionally used for pipeline construction activities because they are well suited for depositing one-sided welds and are capable of high deposition rates when welding downhill. The use of cellulosic-coated electrodes provides an ample source of hydrogen for hydrogen cracking. The formation of susceptible weld microstructures is promoted by fast weld cooling rates. Tensile stresses can be either residual or applied and can be magnified by stress concentrations such as high-low misalignment. Repair and tie-in welds are particularly susceptible since high levels of restraint tend to cause high levels of residual stresses to develop. Many of the concerns for repair and tie-in welding are also applicable to mainline production welds made using conventional stove-pipe techniques.

Detailed guidance for preventing hydrogen cracking in pipeline girth welds is presented in Appendix B. None of the factors related to the occurrence of hydrogen cracking that are presented in Appendix B are new. Of these however, the factor that appears to be most misunderstood is control of weld hydrogen levels. When pipeline girth welds are made using cellulosic-coated electrodes, the amount of hydrogen that remains in the weld following completion must be managed. This is most effectively accomplished by proper application of preheating and the use of properly-developed welding parameters.

4.4 Inspection Issues for Welds with Internal Transitions

The severity of a given discontinuity depends on its shape, in addition to a variety of other aspects (e.g., location within the weld, type of loading, etc.). Planar discontinuities are more severe than volumetric discontinuities. The severity of planar discontinuities depends on end sharpness. Planar discontinuities with sharp ends are more significant than those with blunt ends. Hydrogen cracks are planar discontinuities with sharp ends, so they tend to be the most significant with respect to the integrity of welds in completed pipelines. Radiographic inspection (RT) is effective at detecting volumetric discontinuities, but is not particularly well-suited to detecting planar discontinuities such as hydrogen cracks unless they happen to align with the radiation source (Figure 85). Radiographic inspection of unequal wall thickness joints even more difficult due to the grossly different radiographic density on one side of the joint compared to the other.

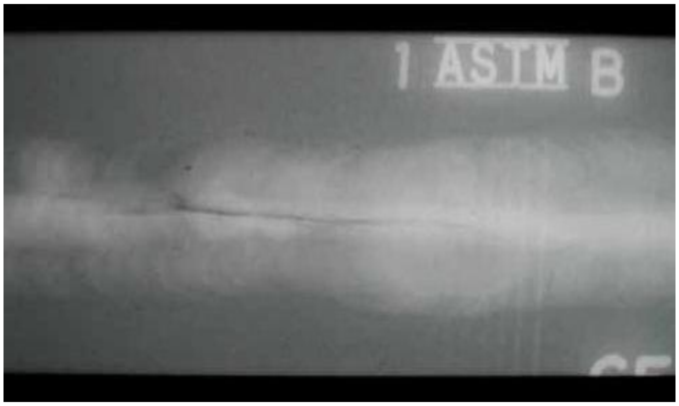


Figure 85. Radiograph of pipeline girth weld with crack

When inspecting critical pipeline girth welds (e.g., repair and tie-in welds) for cracks using RT, parameters for radiographic inspection should be optimized. For example, radiographic inspection using an X-ray source is more effective at detecting cracks than radiographic inspection using a gamma ray source. Similarly, Class 1 film is more sensitive than Class 2 film. For RT of welds made between segmented induction bends and elbows and transition pups, consideration should be given to using an X-ray source and Class 1 film.

4.4.1 Special Radiographic Techniques for Unequal Wall Thickness Transitions

Radiographic inspection of unequal wall thickness joints is made difficult by the grossly different radiographic density on one side of the joint compared to the other. One of two techniques can be used to accomplish effective RT examination of transition welds. The first involves film cassettes that are double loaded with one fast-speed film and one slow-speed film to accommodate the large variation in penetrated thickness across the weld. The slower speed film should be the first film (closer to the radiation source) in the film cassette and the faster-speed film should be the second film (further away from radiation source) in the film cassette. The second technique involves making two radiographic exposures utilizing the same speed film for both exposures but different exposure times. A radiograph of the thin wall section of the weld is made while maintaining the proper film densities for that portion of the weld. A radiograph of the thicker portion of the weld is then made while maintaining the proper film densities for that portion of the weld. This results in two radiographs that can be used for complete evaluation of the weld. Detailed guidance pertaining to special radiographic techniques for unequal wall thickness transitions is presented in Appendix C.

For inspection of critical pipeline girth welds, consideration should be given to the use of alternative or complementary inspection techniques such as ultrasonic testing (UT).

4.4.2 Time Delay Prior to Inspection

Hydrogen cracking, which is also referred to as delayed cracking, often requires time to occur. The reason is that time is required for the hydrogen to diffuse to areas with crack susceptible microstructures. Prior to inspection for hydrogen cracking, a sufficient delay time should be allowed to elapse. The time required for hydrogen cracking to occur depends on the diffusion rate of hydrogen in the steel (which in turn depends on the alloying elements in the steel) and the thickness of the steel. For some applications, such as thick wall pressure vessels constructed from highly alloyed materials, hydrogen cracking can occur up to 72 hours after the welds are completed. Much shorter delay times are typically required for pipeline girth welds (e.g., 12 hours for some applications).

When determining appropriate delay times prior to inspection, the time-dependent nature of hydrogen cracking should be considered, as well as the expected susceptibility of the weld to cracking. Longer delay times decrease the chance that cracking can occur after inspection has been completed. The probability of cracking, and thus the importance of determining an appropriate delay time, can be minimized by using more conservative welding procedures. For example, if the hydrogen in the weld is allowed to diffuse away after welding by careful application of preheating and slow cooling, post-heating (i.e., post-weld preheat maintenance), or if low-hydrogen electrodes are used, the probability of cracking is significantly reduced, and immediate inspection may be justified.

4.5 Proposed Guidance for Revision of Construction Specifications

The results of the three field exercises described in Section 4.1 were used to develop a generic procedure for segmenting induction bends and elbows using conventional methods – i.e., oxy-fuel cutting and hand grinding. The procedure, which is shown in Appendix D, includes the following topics:

- Identifying Bends to be Cut
- Required Equipment
- Selecting the Transition Pup
- Bend Layout
- Checking Angle, Ovality and Squareness
- Cutting the Bend
- Aligning the Weld Bevel
- Grinding the Internal Transition
- Final Bevel and Alignment Checks

- Welding the Pup to the Bend

The requirements contained in the procedure are for a hypothetical pipeline company. Individual pipeline companies may want to alter these requirements and/or add additional requirements. For example, it has been suggested that segmenting induction bends and elbows should be joined using two pups on each end; a transition pup with a wall thickness between the wall thickness of the fitting and the line pipe material and a second pup with a wall thickness equal to that of the line pipe material (Figure 86). The use of a double pup allows not only a pipe-to-pipe weld to be made in the field, but the pipe-to-pipe weld is between materials of equal wall thickness. While there may some benefit to this practice, the additional cost may outweigh the potential benefits.

Figure 86. Segmented induction bend with double pups

5. SUMMARY FOR PHASE 2

Phase 2 of this project involved development of guidance for field construction practices. In this second phase of this work, optimal methods for mapping, cutting, beveling and transitioning induction bends and elbows were developed. Recommended practices for welding in the field and for a variety of related issues were also developed. Recommended practices for welding in the field include optimization of joint designs for unequal wall thickness transitions, limits for high-low misalignment, backwelding methods and practices, and general guidance for avoiding hydrogen cracking. The joint design guidance that was developed indicates a strong preference for backwelding unless fit-up conditions are ideal. Recommended practices for related issues include inspection issues for welds with internal transitions and time delay prior to inspection. The information was summarized and used to develop a generic specification for segmenting and welding of induction bends and elbows.

6. ACKNOWLEDGMENTS

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Appendix A – Joint Designs for Unequal Wall Thickness Transitions – Review of Previous Work

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A.1 Joint Designs for Unequal Wall Thickness Transitions – Review of Previous Work

The information in this section summarizes key aspects of the work with regard to the performance and limitations of butt welded transition joints by researchers at two institutions. They include Dr. Brian Leis and his associates at Battelle, and Michael Law, of ANSTO.. The work scopes included pipe or pipe components having mismatched thickness and/or grade. The details of the work are described in several publications(A1-A5). The work by each is described separately below.

A.2 Background (Leis)

Leis concluded that transition joint designs in Appendix I of ASME B31.8 and in §434.8.6 of ASME B31.4 are identical. The designs apparently have been based on the full-scale testing done by George and Rodabaugh(A6) and the trending of some elastic stress analysis and fatigue tests(A7). Leis found little other full-scale test data involving plastic-collapse conditions available to guide code transition joint design provisions. He concluded from the discussion of the testing by George and Rodabaugh that the code (B31) provisions do not have a strong foundation in full-scale testing, and reflect somewhat limited trending of analytical work. As a result, PRCI undertook a program of further evaluating the capabilities and limitations of various transition joint designs.

A.3 Scope of Work (Leis)

The work scope of Leis addressed in this summary included a review of transition joint failure history and analysis of the effects of various parameters on the expected performance of transition joints. As directed by the PRCI committee, the work included evaluation of a nominally large diameter line pipe and fittings (48- inch outside diameter) with a high degree of grade mismatch (Y52 fitting material and X80 line pipe) and high operating pressure (ANSI Class 600, 1440 psi) as the focus for the project.

The scope of the analytical work included assessment of the following parameter ranges:

- Thickness Mismatch: $1 \leq t_t/t_p \leq 1.8$, where t_p is the wall thickness of the pipe and t_t is the wall thickness of the transition or fitting. This range addressed wall-thickness mismatch well beyond the present Code upper limit of 1.5,
- Transition Angle: 7 ≤ angle (degrees) ≤ 40, where the term angle denotes the taper angle in the heavier wall as defined in Appendix 1 in ASME B31.8 or §434.8.6 in B31.4. This range of transition angle is significantly wider than the upper and lower current Code limits on taper angle,

- Grade Mismatch: Grade mismatch from Gr. B ≤ SMYS ≤ X80, where SMYS denotes the specified minimum yield stress. This range of grade mismatch significantly broadens the range of grade mismatch considered in the full-scale tests done by George and Rodabaugh, and
- Effect of Yield/Tensile Ratio: Y/T between 1 and 0.59, where Y/T is the yield stress to ultimate tensile stress ratio that roughly corresponds to the noted range for grade mismatch.

A.4 Failure Frequency (Leis)

Leis found that the database of reportable incidents assembled by the OPS for the interval from 1985 through 2002 is the most complete. However, regardless of being “most complete”, the database was found to lack the information needed to conclusively determine the role (if any) of transition joint design practices in the incidents. None of the reported gas transmission pipelines incidents included in the database conclusively identifies a transition joint as the cause of an incident. Yet, Battelle’s archives include failure analyses where a transition joint has been the cause of an incident. Trending of reportable incident cause data by Kiefner, Mesloh, et.al. for PRCI indicates a continuing decline in the failure rate associated with construction-related threats in general, although the rate of transition joint failure cannot be determined from the available data. A low failure rate for transition joints (as indicated by the absence of OPS incidents data identifying transition joints as the cause of failure) does imply this construction feature is potentially less significant than other threats on average.

A.5 Summary of Historical Failures from Battelle Records (Leis)

Leis summarized the information in Battelle records of transition joint failures as follows:

- In most cases, the failed transition joints involved section changes from a line pipe into a heavier-wall hub from a flange, or a stub on a fitting such as a valve.
- Generally, the grade difference across the transition joint was small, or nonexistent, (except for the “X” grade versus “Y” grade distinction between the line pipe and the fitting).
- Typically, the transition joint involved an external taper cut onto the hub of a flange or stub of the heavier wall fitting, rather than an ID taper-bore.
- In most cases the fitting or flanged connection was seated and/or connected to a substantial anchor.

- Loadings typically involved pressure combined with axial tension or local bending created by differential loading conditions, such as differential settlement.
- In most cases, there was a significant cyclic loading component, which reflected a mechanical or thermal source.
- Occasionally a preexisting defect served as an origin. In such cases, cyclic loading in the presence of a defect couple as the root cause.
- In cases where preexisting defects were not involved, failure was typically tracked to significant secondary loading, such as local bending or tension and usually involved a cyclic loading component.
- In the transition joint failures reviewed, serviceability was limited by crack growth that was *fracture* controlled.

One failure analysis report described a leak at the transition-side of the weld in a joint from an elbow into the hub of a flange. Cracking was associated with several small lack-of-penetration flaws related to local (code acceptable) diametral misalignment. Leis concluded that such failures do not reflect on the adequacy of the transition joint design, but in instead, reflect workmanship used to join the transition to the station piping and components, and the presence of Code-acceptable mismatch.

A.6 Recommendations Resulting From the Review of Failure Analyses (Leis)

1. Consider design provisions that go beyond plastic collapse where quality control or other practices do not protect against secondary loadings and/or workmanship problems. As previously noted, Leis found an apparent trend for serviceability becoming limited by fracture-controlled crack growth.
2. Consider the effects of both secondary loads and cyclic loads on both collapse and fracture controlled failures at transition joints.
3. Develop guidance that reflects the constraints of existing pipeline systems – where a fracture limit state is as likely as plastic collapse.

A.7 Conclusions from Previous Work (Leis)

1. The newer, limited strain hardening materials (up to and including $Y/T \leq 0.9$) provide the same apparent reinforcing effect as the lower Y/T steels used as the basis for development of the current B31.4 and B31.8 code joint designs.

2. The grade differential for which the current transition designs are effective for limited strain hardening materials depends upon on the specific combinations of property and geometry mismatch, ~20 ksi (138 MPa) appears reasonable for many mismatch situations, with as high as Gr. B to X80 viable for some geometries and Y/T combinations.
3. Because no collapse-controlled field failures were found in Battelle's archives the joint designs in the B31Code appear to be effective in avoiding failure by plastic collapse given the range of property mismatch dealt with to date. Current code transition joint design requirements are conservative with respect to a plastic collapse limit state. However, guidance that assumes plastic-collapse will occur will be non-conservative where failure occurs by fracture.
4. Anisotropy is not a major effect for failure by plastic collapse.
5. High strength pipe grades with high Y/T can be used beyond current code limitations on transition joint wall-thickness mismatch, for a wide range of transition joint strength mismatch (up to Gr. B to X80 in some cases) conditions.
6. Lower strength components can be matched to modern high strength, high Y/T grades. Cost savings can be realized by not having to purchase high-strength fittings for new construction or rehabilitation.
7. Failure by plastic collapse at transition joints is effectively independent of the taper geometry and mismatch location (i.e. taper on OD or ID). However, taper angle is expected to have a significant effect on failure controlled by fracture.
8. A simple rule expressed in terms of limits on wall-thickness mismatch cannot be used to characterize the interaction between property mismatch and geometric mismatch and its influence on the changes in failure location for plastic-collapse across a transition joint.
9. Weld-induced residual stresses do not have a major effect on failure by plastic collapse. However, high local stresses and strains and steep gradients could be important for fracture-controlled failure. Axial and hoop residual stresses at girth welds can produce stress gradients on the order of 100 ksi per inch (28 MPa per mm). Those gradients are sufficient to nucleate cracking in the presence of relatively small defects in lower-toughness steels, including those sometimes found in early vintage pipelines. A more symmetric taper (tapered on both the ID and OD) is better as weld residual stress distributions are reduced as compared to eccentric designs. Small taper angles develop lower residual stresses compared to large taper angles. Weld metal mismatch has little effect on axial residual stresses, but stronger weld metal leads to higher hoop residual stresses. The effect is

accentuated as mismatch and thickness mismatch increases. Hydrotesting to 110% of SMYS significantly relieves hoop residual stress, while the effect on axial residual stresses is much smaller.

10. In cases where the toughness of the steel is sufficient such that plastic collapse controls failure, secondary loading can cause a shift of the failure location from the pipe into the region of the transition. Loading other than pressure, such as bending and axial forces, is a potential threat to the serviceability of transitions. For lower toughness steels, large localized strains have the potential to cause cracking. If the welds in these systems are free of external loading or pressure cycling, there is no need for concern. However, if service conditions or environmental conditions change, resulting in an increase in axial or bending strain, the potential for failure increases.

11. Current ASME Code limits on wall-thickness mismatch could force collapse to occur in the lower-strength fitting, particularly for cases involving significant strength mismatch across the joint (Figure A1). Revisions to the Code may be required to address the effects of grade mismatch and geometric mismatch. Consideration should be given to requirements on strain-to-failure, the effects of combined loading and boundary conditions, and the possibility of failure by other than plastic collapse.

12. Failure (by plastic collapse) in the thinner higher strength pipe can be ensured by satisfying the inequality:

$$(T/Y)_2 / (T/Y)_1 > (F_{y1} / F_{y2}) / (t_1 / t_2)\,, \quad \text{(equation 1)}$$

Where:

The subscript i = 1 denotes pipe and i = 2 denotes the transition,
T/Y = the ratio of the ultimate tensile stress to SMYS,
F_{yi} = yield stress, and
t_i = thickness.

13. Full-scale verification testing to validate Equation 1 or otherwise address the viability of transition joints should include measures of Y/T properties and consider their contribution to the results of the testing. Use of Equation 1 as a design guideline involves selecting the steel and thickness for the transition such that the properties ratio is consistent with the wall thickness ratio, for failure in the higher strength component. Concerns involving possible failure by a fracture-controlled process must be evaluated independently. The current Code lower bound on t2/t1 is not appropriate, and could be too liberal. Likewise, the analysis results indicate that the current Code upper bound on $t2/t1 \leq 1.5$ may be overly restrictive.

A.7 Summary (Leis)

The results of work by Leis at Battelle pertaining to the performance and limitations of butt welded transition joints indicate that there is a significant difference between joint designs that are adequate to avoid failure by plastic collapse and those needed to avoid failure by fracture. The report for this work covers work related to plastic collapse but states that more work is needed to determine what is required to prevent failure by fracture.

A.8 Scope of Work (Law)

Australian standard AS 2885.2 requires that the design thickness for the thicker component shall not be greater than 1.5 times the nominal thickness of the thinner component. Since design thickness is grade dependent, ratio of $SMYS_{max}$ to $SMYS_{min}$ for the two components cannot exceed 1.5. Law compared the results of finite element analyses on joints that met the 1.5 grade ratio limit to joints that exceeded the limit. Transitions with SMYS ratios exceeding 1.5 were modeled with D/t ratios of 25, 55, and 100. All tapers were 4:1. The modeled fitting thickness was equal to the design thickness.

Analyses included consideration of internal pressure alone, axial loading in the absence of internal pressure, combined loading, and fatigue.

A.9 Summary of Results (Law)

For internal pressure loading, all joints failed at a hoop stress of greater than 114.5% SMYS. The high failure stress was attributed to the “bridging effect” in which the thinner, stronger pipe provides support to the taper area in the thicker, lower strength pipe. The differences in performance among joints with SMYS ratios of less than 1.5 and greater than 1.5 were very small (no greater than 0.5% SMYS). The lowest failure pressure in all cases was when the thicker pipe was grade B. At low SMYS ratios the failures generally occurred in the lower SMYS pipe. As the ratio of SMYS increased, the failure location moved to the taper.

Unlike the case of internal pressure loading in which the “bridging” effect is significant, under axial loading, the joints can fail at less than SMYS. For axial strain in the absence of internal pressure, all grade combinations, except one (X42 joined to grade B) failed at greater than 79% SMYS axial stress (based on the thin pipe) at a general strain greater than 0.15%. The axial failure stress was the lowest for joints having the highest SMYS ratio. All joints failed in the taper.

Weld metal strength was found to have little effect on the strength of the joint. Stronger weld metal was slightly beneficial.

The position of the taper on the ID or the OD was found to have little effect on strength of the joint. However, with regard to fatigue performance, Law noted that DNV RP C203, which pertains to design of offshore steel structures, recommends that tapers be used on the OD surfaces and that the ID be constant since stresses are higher on the inner wall.

For combined axial and pressure loading, axial tensile loading increased the failure pressure up to a point, after which the burst pressure decreases rapidly. Compressive axial loading significantly reduced pressure capacity. For joints having an SMYS ratio of greater than 1.5, buckling occurred at as little as 20% SMYS. For joints having acceptable SMYS ratios no buckling was observed.

A.10 Recommendations (Law)

Testing of pipes with widely differing grades should be performed to validate the results of the FEA work summarized above. However, on the basis of the FEA modeling, Law recommended eliminating the existing limits on grade ratio, provided the pipe is subject to bending or axial stress between -10% SMYS and +60% SMYS. Greater axial or bending loads may be tolerated but project specific modeling and testing should be performed.

A.8 References

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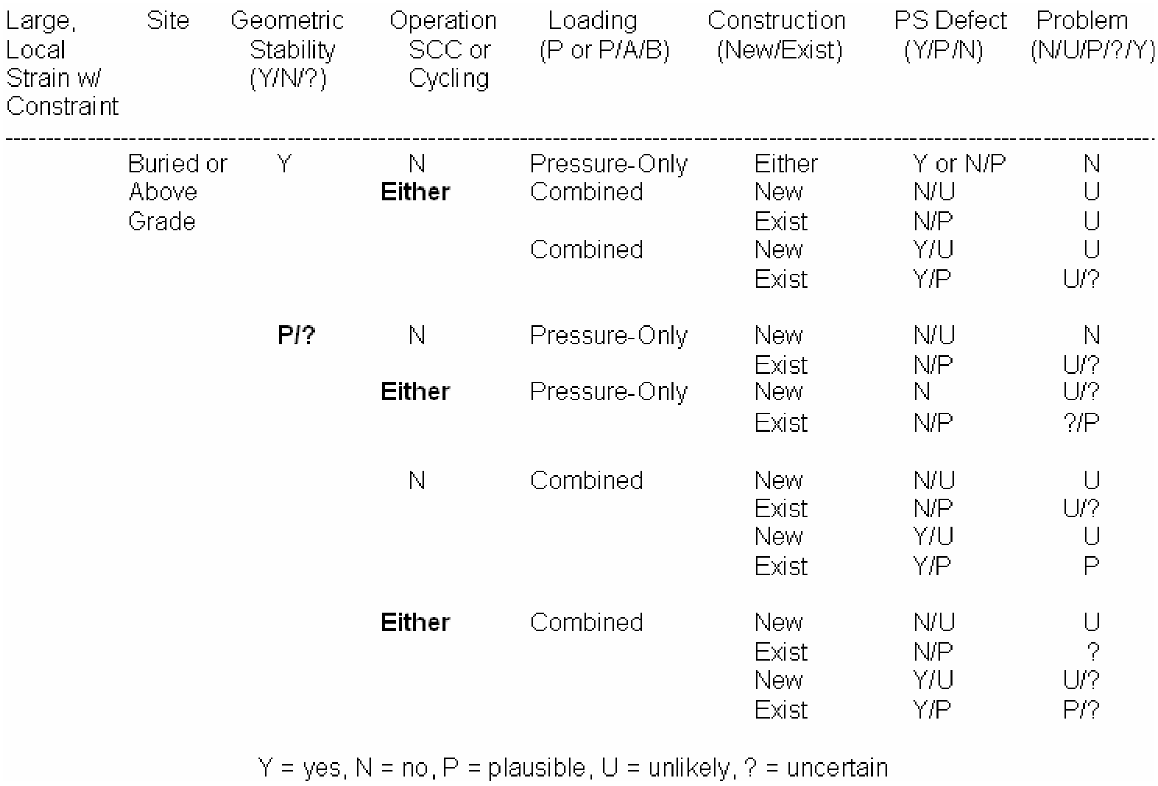

Large, Local Strain w/ Constraint	Site	Geometric Stability (Y/N/?)	Operation SCC or Cycling	Loading (P or P/A/B)	Construction (New/Exist)	PS Defect (Y/P/N)	Problem (N/U/P/?/Y)
	Buried or Above Grade	Y	N	Pressure-Only	Either	Y or N/P	N
			Either	Combined	New	N/U	U
					Exist	N/P	U
				Combined	New	Y/U	U
					Exist	Y/P	U/?
		P/?	N	Pressure-Only	New	N/U	N
					Exist	N/P	U/?
			Either	Pressure-Only	New	N	U/?
					Exist	N/P	?/P
			N	Combined	New	N/U	U
					Exist	N/P	U/?
					New	Y/U	U
					Exist	Y/P	P
			Either	Combined	New	N/U	U
					Exist	N/P	?
					New	Y/U	U/?
					Exist	Y/P	P/?

Y = yes, N = no, P = plausible, U = unlikely, ? = uncertain

Figure A1 Factors identified as affecting failure susceptibility transitions joints in service

Appendix B – General Guidance for Avoiding Hydrogen Cracking

B.1 General Guidance for Avoiding Hydrogen Cracking

Hydrogen cracking requires that three primary independent conditions be satisfied simultaneously; (1) hydrogen must be present in the weld, (2) there must be a susceptible weld microstructure, and (3) tensile stresses must be acting on the weld. Cellulosic-coated electrodes (AWS EXX10-type) have been traditionally used for pipeline construction activities because they are well suited for depositing one-sided welds and are capable of high deposition rates when welding downhill. The use of cellulosic-coated electrodes provides an ample source of hydrogen for hydrogen cracking, however. The formation of susceptible weld microstructures is promoted by fast weld cooling rates. Tensile stresses can be either residual or applied and can be magnified by stress concentrations such as high-low misalignment. Repair and tie-in welds are particularly susceptible since high levels of restraint tend to cause high levels of residual stresses to develop. Many of the concerns for repair and tie-in welding are also applicable to mainline production welds made using conventional stove-pipe techniques.

B.2 Factors Related to Hydrogen Cracking

To prevent hydrogen cracking, at least one of the three conditions necessary for its occurrence must be eliminated or reduced to below a threshold value.

B.2.1 Hydrogen in the Weld

Because cellulosic-coated electrodes result in the introduction of a considerable amount of hydrogen in the weld, the hydrogen that remains in the weld following completion must be controlled.

Figure B1 shows the solubility of hydrogen in steel as a function of temperature. As the weld is deposited, moisture (water) and other compounds in the electrode coating can break down into atomic hydrogen in the intense heat of the welding arc. This atomic hydrogen in the arc atmosphere is readily absorbed by the molten weld metal because liquid weld metal has a very high solubility for hydrogen. When the weld solidifies, there is a significant reduction in solubility. As the weld cools to ambient temperature, the hydrogen becomes supersaturated (i.e., trapped) in the solid steel.

While the specific mechanism for hydrogen embrittlement is not well agreed upon, it is generally recognized that hydrogen reduces the ductility of welds in steel structures.

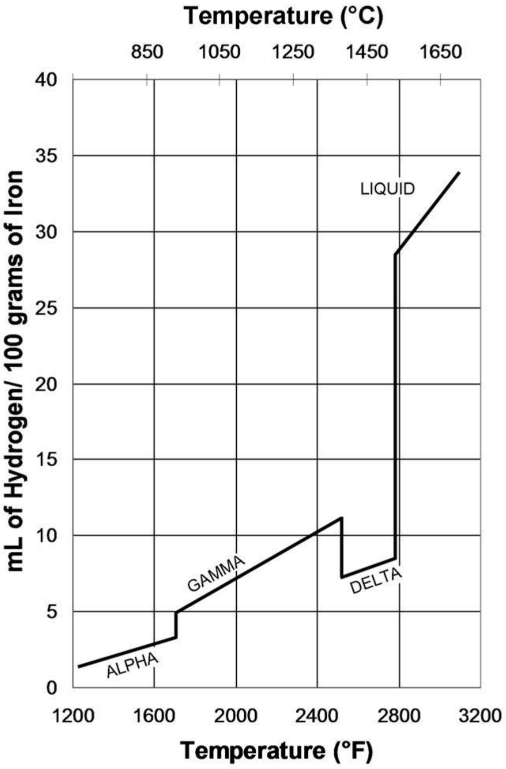

Figure B1. Solubility of hydrogen in steel as a function of temperature

B.2.2 Weld Microstructures

Crack-susceptible microstructures in the weld heat-affected zone (HAZ) tend to be characterized by high hardness. The formation of high hardness HAZ microstructures is promoted by steels that have high carbon content and/or high carbon equivalent (CE) value and by fast weld cooling rates. Most modern line pipe steels have very low carbon content and a very low CE compared to older line pipe steels. The use of preheating and properly-developed welding parameters tends to result in relatively slow weld cooling rates. The low carbon content/low CE material and the relatively slow weld cooling rates combine to result in low hardness levels in the HAZ of girth welds in modern line pipe steels.

While HAZ microstructures have traditionally been considered to be the most susceptible to hydrogen cracking, weld metal microstructures deposited using higher strength welding consumables can also be susceptible to cracking.

B.2.3 Tensile Stresses Acting on the Weld

In addition to residual stresses, which are unavoidable in welds, the largest applied tensile stresses that occur in partially-completed girth welds occur following completion of the root pass when the line-up clamp is removed and the pipe string is re-set by lifting and/or lowering. The largest tensile stresses that occur in completed girth welds typically occur during lifting and lowering-in.

Applied tensile stresses can be magnified by stress concentrations such as weld defects and at areas of misalignment (high-low). There is also concern for stresses related to tie-in welds. Tie-in welds are more highly restrained by the fixed pipe ends than mainline construction welds.

B.2.4 Interaction of Contributing Factors

When the magnitudes of two of the three necessary conditions for hydrogen cracking are extreme, levels of the third that are not normally associated with cracking can become problematic. For example, when the hydrogen level in a weld and the tensile stresses acting on that weld are extreme, even weld microstructures that are not normally considered to be susceptible can lead to cracking (i.e., cracking can occur at low hardness levels).

B.3 Prevention of Hydrogen Cracking

Of the three requirements for hydrogen cracking described above, the most misunderstood seems to be hydrogen in the weld. When pipeline girth welds are made using cellulosic-coated electrodes, the amount of hydrogen that remains in the weld following completion must be managed. This is most effectively accomplished by proper application of preheating and the use of properly-developed welding parameters. This and other factors that affect the occurrence of hydrogen cracking in pipeline girth welds are discussed below.

B.3.1 Preheating/Slow Cooling

The application of preheat for the prevention of hydrogen cracking is carried out for one of two reasons: to allow diffusion of hydrogen and to control or limit the formation of crack susceptible microstructures. To achieve the latter, preheat temperatures in excess of those generally applied to pipeline girth welds are required. The primary benefit of preheating is diffusion of hydrogen. To achieve this, preheat temperatures of at least 200 to 250°F (93 to 121°C) are typically used.

Lower preheat temperatures are also effective at allowing hydrogen diffusion, but the time required becomes exponentially longer as preheat temperature is reduced. The driving force for hydrogen diffusion is time at temperature (i.e., the area beneath the time-temperature curve).

The diffusion rate of hydrogen in steel is strongly dependent on temperature. Figure B2 shows that, for an increase in temperature from ambient (20°C) to 100°C (considering the middle of the range shown for ferritic materials, including line pipe steels), the diffusion rate of hydrogen in steel increases by two orders of magnitude (i.e., 100 times). Therefore, if a weld remains warm for a longer period of time after completion, a greater portion of the hydrogen in the weld can diffuse away. The importance of allowing a weld to cool slowly depends on the wall thickness (more important for thicker materials where the diffusion distances are greater) and the ambient temperature (more important for lower ambient temperatures where the weld tends to cool more quickly and hydrogen tends to become more readily trapped). The proper use of preheating and uninterrupted welding promotes slow cooling after weld completion.

Material conditions that may necessitate the use of preheating/slow cooling include heavy wall thickness and/or high carbon equivalent values. Weather conditions that may necessitate the use of preheating/slow cooling include low ambient temperatures and/or moisture in the air (e.g., precipitation, high humidity, etc.). During inclement weather, temporary shelters should be used to protect the weld and its immediate surroundings.

Preheating carbon steel to a precise temperature is generally not required. It is usually acceptable to exceed the minimum-required preheat temperature by approximately 100°F (56°C). However, maximum-allowable interpass temperature requirements, if any, should not be violated. Common methods used to preheat pipelines prior to welding include gas torches (radiation methods), electric resistance heaters (conduction methods), and induction heaters (induction methods).

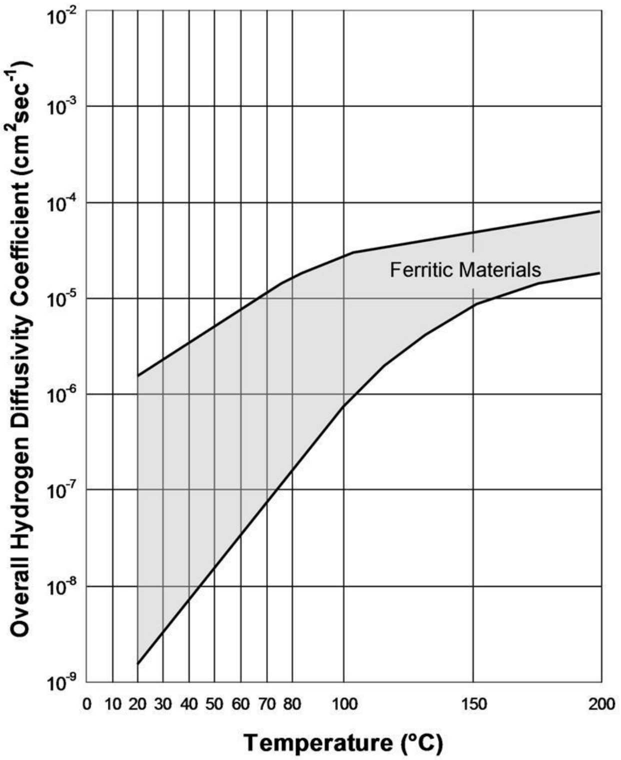

Figure B2. Diffusion rate of hydrogen in steel as a function of temperature

Preheating should be applied in a manner that ensures that the full volume of material surrounding the joint is thoroughly heated to above the specified minimum temperature. General preheating guidance suggests that the material should be thoroughly heated for a distance equal to the thickness of the material being welded, but not less than 3 in. (75 mm) in all directions from the point of welding. When possible, heat should be applied to the side opposite of that which is to be welded (Figure B3), and measurements should be made on the surface adjacent to the joint (i.e., the temperature should be measured on the opposite side of that which is heated). Where this is impractical, time should be allowed for the temperature to equalize after removal of the heat source before the temperature is measured.

Figure B3. Preheating during pipeline construction activities

During mainline construction activities, the preheating crew should not be allowed to get too far ahead of the root pass welding crew. If this occurs, preheat should be reapplied prior to depositing the root pass. For girth welds in large diameter pipe, the preheat temperature could fall to below the minimum-required temperature before an individual weld pass is completed. If this occurs, welding should be interrupted and preheat should be reapplied. It may be useful to think of preheat temperature as the "arc start temperature," or the temperature of the weld zone prior to the start of welding for any weld pass (i.e., not just the first weld pass).

Temperature measurement methods commonly used include contact thermometers (digital or analog), non-contact infrared pyrometers, and temperature indicating crayons (e.g., Tempilsticks™).

The minimum-required preheat temperature should be maintained throughout the welding operation. Once welding begins, this temperature is generally referred to as the interpass temperature. If the welding operation is interrupted, preheating should be reapplied until the minimum-required preheat temperature is reestablished. The minimum-required interpass temperature should be equal to the minimum-required preheat temperature unless otherwise indicated. For many welding applications, the heat from the welding operation is sufficient to maintain the desired temperature without the continuous external application of heat.

If preheating is specified in the welding procedure, it should also be applied when tack welding. Cracks that develop in tack welds that are not completely consumed can initiate cracks in the final weld.

When using post-heating (or post-weld preheat maintenance) to minimize the risk of cracking (i.e., to allow hydrogen diffusion), the post-weld heating must be applied prior to the onset of cracking. Wrapping completed girth welds in insulation can also promote slow cooling and allow hydrogen diffusion.

B.3.2 Time Between Passes

Welding without interruption can have the same beneficial effect of preheating. In many cases, the heat from the welding operation is sufficient to maintain the desired temperature without the continuous external application of heat. In lieu of specifying a minimum-required interpass temperature, API 1104 requires that the time between completion of the root pass and the start of the second pass be considered an essential variable for procedure qualification. API 1104 also requires that the maximum time between the completion of the second pass and the start of other passes be specified. These time limits must be followed in the field.

When determining what value to specify for time between passes, the time-dependent nature of hydrogen cracking should be considered, as well as the probability of cracking. Shorter times decrease the chance that cracking can occur prior to the completion of the weld. Longer times can be justified when the probably of cracking is low (e.g., high ambient temperatures, careful application of preheating, etc.).

B.3.3 Weather Conditions

Inclement weather conditions that can have an adverse effect on weld quality include low temperatures, moisture in the air (e.g., precipitation, high humidity, etc.), high winds, etc. Preheating is often specified when the ambient temperature is lower than a specified value. When the surface temperature is below the ambient dew point, moisture will condense on the pipe surface, which, if welded over, will contribute to increased weld hydrogen levels. The use of preheating will eliminate moisture and other evaporative contaminants prior to welding. High winds can also contribute to accelerate cooling and can disrupt the shielding of the molten weld metal, which can lead to porosity. Low temperatures can cause increased weld cooling rates, which can lead to the development of crack-susceptible weld microstructures and can cause hydrogen to become trapped in the weld. Preheating can slow weld cooling rates somewhat and allow hydrogen diffusion following welding.

B.3.4 Adherence to Qualified Welding Procedures

The purpose of qualifying a welding procedure is to demonstrate that the parameters specified in that procedure are capable of producing sound welds under production conditions. A qualified welding procedure consists of a welding procedure specification (WPS) and a procedure qualification record (PQR). The ranges specified in a WPS should be wide enough so that the qualified welding procedure can be implemented in the field. The ranges should not be so wide that operating at the edges of the ranges produces an unacceptable weld, however.

While current regulations require that qualified welding procedures are followed in the field, the level of oversight practiced to ensure that this happens varies widely. For some applications (e.g., large diameter, thick-wall, high strength pipelines), this activity is more critical than for others (e.g., smaller-diameter, thinner-wall, lower-strength pipelines). For large diameter, high strength pipelines, it is imperative that the qualified welding procedure is closely followed in the field, yet little guidance exists for the level of oversight required for a particular application. Guidance for welding inspection personnel should be provided pertaining to what level of oversight is required. Guidance should include how best to monitor certain parameters, such as fit-up (e.g., measurement of high-low misalignment), welding parameters (e.g., current, arc voltage, and travel speed), preheat and interpass temperature, etc. General descriptions of why monitoring of each of these parameters is important (e.g., the importance of preheating and what it does) should also be provided. Guidance pertaining to remedial measures for excessive high-low misalignment, both in and of itself and due to pipe material ovality/out of roundness should also be provided.

B.3.5 Control of Weld Microstructures

The use of preheating and properly-developed welding parameters tends to result in relatively low hardness levels in the HAZ of girth welds in most modern line pipe steels. Several of the incidents described above occurred in spite of very low measured hardness levels in the HAZ – in the 200 to 260 HV range. It would appear that controlling weld hydrogen levels and stresses acting on the weld is a more appropriate strategy for controlling the risk of hydrogen cracking in the HAZ of girth welds in modern line pipe steels.

Since weld metal microstructures can also be susceptible to hydrogen cracking, careful selection of higher strength cellulosic-coated consumables should be practiced to control the risk of hydrogen cracking in the weld metal (e.g., avoid the use of AWS E9010 electrodes).

B.3.6 Control of Stresses Acting on Weld

As noted earlier, one of the most significant stresses experienced by completed pipeline girth welds typically occur during construction during lifting and lowering-in (Figure B4). The most significant stresses for partially completed girth welds occur following completion of the root pass when the line-up clamp is released and the pipe string is re-set by lifting and lowering. Other longitudinal stresses that can lead to girth weld failures are less predictable. These stresses are primarily associated with differential ground settlements and ground movements, in locations such as road crossing, different soil conditions (settled vs. new soil), anchor points (e.g., adjacent to points of inflection), spans, landslide, etc. In the absence of ground-movement related stresses, the stresses on the girth welds are generally low. The long-term survival of vintage girth welds with very poor quality by modern standards attests to this fact.

Figure B4. Pipeline lifting and lowering-in

Many of the incidents described above involve pipelines targeted for operation at higher stress levels than have traditionally been used in the U.S. As a result, a number of the hydrotest failures have involved large diameter line pipe made from high-strength steel, heavy wall thickness material in certain locations, or both, which increases the stiffness of the pipeline and tends to concentrate bending stresses during movement at the girth welds. High-low misalignment and unequal-wall-thickness transitions (Figure B5) both tend to concentrate stresses at girth welds.

Figure B5. Girth weld failure at unequal-wall-thickness transition

Early release of the line-up clamp can also result in high tensile stresses, since the root pass may only be partially complete and has a smaller cross-sectional area than a more-complete root pass. During lowering-in activities, care must be taken during lifting and lowering so that excessive applied tensile stresses are avoided. Proper oversight is required to ensure that excessive tensile stresses are avoided during root pass welding and lowering-in activities.

Weld metal strength compared to the strength of the pipe material being joined can also have an effect on the concentration of strains in the weld area. In most welding applications, including pipeline girth welding, it is desirable for the weld to match or overmatch the strength of the base material. This ensures that the strains caused by loads imposed on the completed structure do not concentrate in the vicinity of the weld. Welds are more likely to contain discontinuities than base materials, so it is desirable to avoid the concentration of strains in the vicinity of welds.

In areas of hilly terrain, it is important that the contour of the pipeline fits the ditch or that the ditch be contoured to fit the pipeline so that strains caused by differential ground settlements due to different soil conditions are avoided.

B.3.7 Repair and Tie-In Welding

Tie-In and repair welds can experience high stresses, although these tend to be dominated by residual stresses as opposed to applied stresses. Both tie-in and repair welds are (or can be) highly restrained. High levels of restraint combined with thermal contraction upon cooling results in these high levels of residual stress, which make tie-in-and repair welds particularly susceptible to hydrogen cracking. Tie-in and repair welds are also made under more challenging conditions than mainline production welds. Factors that make tie-in welds more challenging to make include line-up issues (external line-up clamp as opposed to internal and two fixed end points instead of one), weld bevel issues (field cut and prepared bevels instead of factory bevels), access issues (welds made in the ditch as opposed to the surface adjacent to the ditch), and often unequal wall thicknesses. Many of these issues result in poor root pass profiles in completed welds, which cause stress concentrations that act as initiation sites for hydrogen cracking. Whenever possible, tie-in welds should be made between equal wall thickness materials. Factors that make repair welds more challenging to make include excavation geometries (produced by hand grinding), particularly for the root region of through-wall repairs, restraint provided by surrounding weld metal (higher levels of residual stress), and thermal severity (faster weld cooling rates) caused by surrounding material.

For pipelines constructed using conventional stove-pipe methods (i.e., manual welding with cellulosic-coated electrodes), there tends to be a preference by pipeline construction contractors to make tie-in and repair welds using welding processes and procedures that are the same as those used for mainline production welds. For pipelines constructed using mechanized gas metal arc welding (GMAW) equipment, there also tends to be a preference by pipeline construction contractors to make tie-in and repair welds using cellulosic-coated electrodes. These electrodes are well-suited to making single-sided open-root butt welds at relatively high production rates, but their use introduces a significant amount of hydrogen in the weld. If this hydrogen is not properly managed (e.g., using preheat and slow cooling to allow hydrogen diffusion), a significant risk of hydrogen cracking can result. Guidance pertaining to tie-in and repair welding should include, but not necessarily be limited to, provisions necessary for controlling the risk of hydrogen cracking in welds made using cellulosic-coated electrodes (e.g., minimum required preheat temperatures, practical guidance on the application of preheating, etc.) and options for using welding processes and consumables (e.g., AWS EXX18-type electrodes) that control the level of hydrogen that enters the weld.

B.4 Summary

While many new pipelines are now constructed using high-productivity mechanized welding equipment, many pipelines are still constructed the old-fashioned way – using cellulosic-coated electrodes. Repair and tie-in welds in pipelines constructed using mechanized welding equipment are also commonly made using cellulosic-coated electrodes. None of the factors related to the occurrence of hydrogen cracking in pipeline girth welds that are presented here are new. Of these however, the factor that appears to be most misunderstood is control of weld hydrogen levels.

When pipeline girth welds are made using cellulosic-coated electrodes, the amount of hydrogen that remains in the weld following completion must be managed. This is most effectively accomplished by proper application of preheating and the use of properly-developed welding parameters. Since the use of these tends to result in relatively low hardness levels in the HAZ of girth welds in most modern line pipe steels, controlling weld hydrogen levels and stresses acting on the weld appears to be the most appropriate strategy for controlling the risk of hydrogen cracking.

Appendix C – Special Radiographic Techniques for Unequal Wall Thickness Transitions

C.1 Special Radiographic Techniques for Unequal Wall Thickness Transitions

(Excerpted from United States Air Force Technical Manual TM-1-1500-335-23 – Nondestructive Inspection Methods, Basic Theory)

While conventional film radiography offers a very versatile tool for the detection and identification of material discontinuities, there are a variety of special techniques that may be employed to extend the capabilities of conventional radiography. One category of these techniques relates to radiographic techniques with a specific objective of extending the capabilities of the inspection method in general and includes the multi-thickness and multiple film techniques.

C.2 Multi Thickness Techniques

Many situations require radiography of parts with varying thicknesses, and sometimes these may be made of two or more materials. If concentration on one area, with a nearly constant thickness is all that is required, optimization of image density is straightforward. However, it may be necessary to obtain an acceptable exposure for two or more varying thicknesses using the same radiographic image. For example, small thickness variations, of 0.8 to 0.6 inches, can lead to large variation in density ranging from 1.2 to 1.7 respectively. The goal is to ensure all areas of interest have densities not so low as to lose film contrast, and not so high that they cannot be evaluated. An acceptable range of densities is 1.0 to 3.5. The procedure recommended during technique development is to identify the thickest area of interest, and then, from exposure charts and trial-and-error, determine the exposure and kilovoltage that provides a density of 1.0. A trial exposure will then show the density of the image of the thinnest area of interest. There are three possible courses of action an inspector can take:

- If the density of the thinnest section of the image is approximately 3.5, and the image can be satisfactorily interpreted, the technique is optimized.
- If this density is too low, the exposure should be increased to raise the average density of thick and thin areas.
- If the density of the thinnest section is too high, the range of thicknesses is too great for satisfactory imaging. One possible solution is to raise the kilovoltage substantially, as this reduces contrast of thin areas. A better (and more common) solution is to load the cassette with two films of different speed and expose them simultaneously. This technique is commonly known as “multi-film or double-

loading." In the latter case, care is required to ensure that an acceptable image density is obtained for all areas of interest.

C.3 Multiple Film Techniques

Multiple film techniques (commonly known as double-loading) permit the inspection of parts with multiple thicknesses using a single radiographic exposure. Since a major expense associated with radiographic inspection can be attributed to setup, it may be desirable to expose a multi-thickness component in a single exposure, rather than set up an exposure for each cross section of the component. Using multiple film techniques allow this to be achieved.

An example of this technique is to load a cassette with both a Class 1 and a Class 3 film to provide wide latitude. The faster Class 3 film provides a readable density film for the thicker sections of the component, while the slower Class 1 film provides the appropriate film density for the thinner sections of the component. Thus, in a single radiographic exposure, two images with varying density will be generated covering the required latitude for the inspection of a multi-thickness component.

If a part has even more complexities than what was described in the previous paragraph, it is possible to use three classes of films and cover even wider latitudes.

C.3.1 Technique Parameters

Several parameters must be considered when choosing a multiple film technique. In addition to the exposure parameters always of concern in radiographic inspection, the radiographer must be concerned with the choice of film to be used and the combination of these films with various screens.

C.3.1.1 Film Choice

The film combination selected is based on the range of thicknesses that must be covered in a single exposure. The simplest multiple film techniques employ two different films, such as a Class 1 and a Class 2 film, to cover the range of densities for the inspection of an object. An exposure must then be determined which best provides the combination of contrast and sensitivity in the two films.

C.3.1.2 Film Positioning

When film is double-loaded, realize the film nearest the X-ray source acts as an absorber and the film furthest from the source will receive less exposure. This absorption effect is of considerable magnitude at low kilovoltages and decreases with increased radiation energies. The choice of film position will affect the range of material thickness that can be visualized in a single exposure. Typically, the slowest film is placed nearest to the source, while the faster film would be placed farthest from the source. Pre-packaged double-loaded film will normally be marked "source-side" by the manufacturer to make positioning easier. Once a technique has been established, care shall be taken to assure the same film is always placed in the same position for the exposure. If the positions of the films are inadvertently switched, the resulting densities in the final images will be different than expected.

C.3.1.3 Multiple Film Techniques with Lead Screens

Lead screens have a definite effect on the quality of a radiographic image. Lead screens are very dense, and preferentially absorb the lower energy scattered radiation. This reduces the fog on the final image and allows a higher contrast, higher quality image. Also, at energies above 125 kVp, lead screens provide a definite intensification. This intensification is due to the efficient conversion of X-ray photons into electrons in lead foils. These electrons in turn expose the X-ray film and thus provide intensification in the final image. These properties of lead screens may be useful in developing a multiple film technique.

As discussed earlier, combinations of films can be used for radiography of multi-thickness materials, but the optimum image quality may not be achieved. Therefore, the use of lead screens may be introduced to help regulate the relative speeds of the films used. As an example, assume the combination of a Class 1 and a Class 2 film could not provide the required latitude for a given component. Lead screens can be used to increase the latitude of the total exposure.

Most lead screens consist of thin lead foils backed on one side by cardboard, rubber, or vinyl. With this configuration, lead screens have a filtration effect on the films beneath them, and an intensification effect on films facing the foil-coated side. If a combination of a Class 1 and a Class 2 film is used, and insufficient latitude is provided, the latitude may be increased by placing the faster Class 2 film nearest the source with a backed 0.005-inch lead screen between the two films with the lead screen in contact with the Class 2 film. This increases the latitude through two effects. First, the lead foil intensifies the near Class 2 film, and second, the lead acts as a filter, slowing the response of the Class 1 film. Thus, over all the latitude of the exposure is increased.

On the other hand, if the latitude was excessive with the two films using no screens, the opposite effect can be achieved by placing the slower film nearest the source and the faster film farthest the source, with lead screens in between facing the slower film. This combination speeds up the slower film by intensification and slows down the faster film by filtration. Thus, the total latitude is reduced.

When only a slight increase in latitude is required, two sheets of the same film class may be employed, and lead screens may be used as described above to achieve a relative speed difference between the two films.

There is no end to the combinations that may be employed in multiple film radiography. Using the principles outlined above, any capable radiographer should be able to accommodate a wide variety of complex components with a multiple film exposure. Experience provides the required proficiency.

Appendix D – Generic Procedure for Segmenting

	Orig. Issue Date:	*Section* **I** *of* **I**
	Revision Date: **12/02/2010**	*Page* **1** *of* **21**
Title: **SEGMENTING INDUCTION BENDS AND 3R ELBOW FITTINGS**		

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1 SCOPE

1A A segmentable bend is one that was purchased and manufactured to meet 1% ovality throughout the bend arc. Some bends are not purchased as segmentable, and thus must not be cut.

1B Where it becomes necessary to segment an induction bend or 3R bend fitting (i.e., cut a smaller bend angle out of a larger bend), the requirements of this procedure must be met in addition to following all other Company welding and construction specifications.

1C On a project where induction (hot) bends or 3R bend fittings have been furnished to enhance construction, any bends with exact angles that were purchased for use at specific station numbers must be marked to identify their designated locations and installed at those locations.

1D Cold field bends should be used on piggable pipelines, where practical, for all bend angles that can be made with a field bending machine.

1E Special care shall be used to ensure that all cutting, alignment and welding parameters have been met. Dimensions and measurements should all be double-checked.

2 IDENTIFYING BENDS TO BE CUT

2A Prior to cutting a bend segment, the following information must be confirmed with the purchase order and/or material test report (MTR): **bend is segmentable, bend radius, and bend number**. The bend radius and bend number shall be recorded on a “Bend Segmenting Report”.

2B The description of bend radius can be referred to as either D or R, such as 6D or 6R. This description 6D or 6R means the radius of the bend is 6 times the nominal pipe diameter (6 x OD).

2C Bends which are ordered as “segmentable” shall be marked “SEGMENTABLE” and the material documentation for segmentable bends should specifically state the bend is segmentable. Non-segmentable bends may also be marked as “Do Not Cut” or “Do Not Segment”.

2D A bend shall **NOT** be cut if it is marked with a specific station number (e.g., 237+22) which indicates that the bend is intended to be installed at a specific location without being cut.

3 REQUIRED EQUIPMENT

3A The following Measurement Equipment is needed to use this inspection procedure:

3A1 OD Calipers and rule with 1/64” or less graduations or OD Micrometers

3A2 Slide Calipers

3A3 Tape Measure

3A4 Squares

3A5 Hi/Lo Gage

3A6 Protractor

3B The following Fabrication Equipment is needed to follow this procedure:

3B1 Dearman Style Clamp – required for diameters greater than 18”

3B2 Center Punch

3B3 Level – various lengths

4 SELECTING THE TRANSITION PUP

4A Transition pups are required on the segmented end of induction bends to provide for pipe-to-pipe welds at all tie-ins and to facilitiate back-welding, if required, at the bend bevel. Restrictions are placed on the length of the transition pup based on pipe diameter to facilitate access to the interior of the pipe-to-bend weld for visual inspection and potential backwelding.

4A1 For pipe diameters 20” and greater, the transition pup installed on the segmented end of a bend must be a minimum of a 2 feet long.

4A2 For pipe diameters 18” and smaller, the transition pup installed on the segmented end of a bend must be a minimum of 6 inches long and a maximum of 8 inches long.

4B The wall thickness of the transition pup should typically be less than the wall thickness of the bend. This may not always need to be the case because the manufacturing process for an induction bend will reduce the average diameter within the bend arc by about 1/8” to 1/4”.

4C The nominal wall thickness of the transition pup must be:

4C1 No more than 1/4” (0.250”) less than the nominal wall thickness of the bend

4C2 Preferably at least 1/8” (0.125”) less than the nominal wall thickness of the bend (if pipe is available), provided the design pressure is met

4C3 No greater than the nominal wall thickness of the bend (if thinner pipe is not available)

4D In cases where the bend diameter shrinkage is high, it may be necessary to use a transition pup of the same nominal wall thickness as the bend to ensure sufficient wall thickness at the bend transition bevel (subject to the limitations of §8F1.2). The pup pipe may require external transition to ensure the weld cap angle does not exceed 30 degrees.

5 BEND LAYOUT

5A For marking, cutting, and beveling, the bend should be situated so it sits in a flat and level position. The cut point for the desired angle shall be precisely measured and marked at top and bottom using the **arc chord length from Tables 1 – 6, as shown in Figure 1**, being sure to use the table with the appropriate pipe diameter (e.g., 16” or 42”) and the column for the bend radius (3D, 6D or 7D). It is important that the true top and true bottom (neutral axis) are determined for correct marking location using a center finder tool similar to the one shown in Figure 2. For arc chord lengths for pipe diameters other than those listed in the table, the chord equation is provided in the Table.

5B The following steps should be followed to lay out the bend angle:

5B1 Check the end for vertical squareness and re-bevel the end if it is out of square by more than the following tolerances:

5B1.1 1/2 inch for pipe 24” to 42” diameter

5B1.2 3/8 inch for pipe 12” to 22” diameter

5B1.3 1/4 inch for pipe smaller than 12” diameter

5B2 For induction bends with straight tangents, find the true tangent length on both the intrados and extrados (the inside radius and outside radius of the bend; i.e., +/- 90 degrees from the neutral axis (see Figure 1). The neutral axis is located in the 12:00 and 6:00 clock positions when the bend is in a flat and level position per §5A). This can be done using a straightedge to check when the pipe deviates from straight or starts to bend.

Note: The nominal bend radius, tangent to start of bend transition point, and original starting bend angle may not be exact for all bends. The transition point between the tangent and the start of bend may vary between intrados and extrados of the bend (see Figure 1).

Note: Elbows are typically furnished without straight tangents (See §6G).

5B3 Calculate the average tangent length using the intrados tangent length and extrados tangent length. The average tangent length is marked at the true top and true bottom (neutral axis) of the bend. Any out-of-squareness must be taken into consideration when marking the top and bottom locations. It is important that the top and bottom points align since the chord length will be measured from these locations. For example, if the top is ½” longer, a ½” must be added to the average tangent length when marked on the top.

$$\text{Average Tangent} = (\text{Intrados Tangent} + \text{Extrados Tangent}) \div 2$$

5B4 Starting at the average tangent length mark, measure the chord length along the true top and the true bottom, and mark the location for the desired angle (see Figure 1).

5C Mark the circumference at the cut location with a soap stone or marker by using a pipe wrap or metal band with a suggested width no wider than 1”. Ensure the band lines up with the top and bottom marks and is pulled tight to produce a square end.

5D Mark the clock positions (12:00, 1:30, 3:00, 4:30, 6:00, 7:30, 9:00, and 10:30) using a flexible tape measure and a soap stone or other temporary marker. Extend the marks to preserve the locations after cutting since they will be used again for measurements.

6 CHECKING ANGLE, OVALITY AND SQUARENESS

6A Using calipers (see Figure 3) and a ruler with at least 1/64” increments or large diameter micrometers, measure the outside diameter of the bend at the proposed cut location across the following 4 clock positions: 12:00-6:00, 1:30-7:30, 3:00-9:00, and 4:30-10:30 (i.e., every 45 degrees). Company Welding Inspector shall record the “prior to cut” diameter measurements on a “Bend Segmenting Report”. The ovality must be calculated using the following:

%Ovality = 100 x [Maximum Diameter – Minimum Diameter] ÷ Nominal Pipe Diameter

6B If ovality at the desired cut location is > 1.0%, then the bend angle shall be measured from the opposite tangent or bend end, repeating the steps in Section 5, to determine if the ovality is within 1.0%. If ovality is > 1.0% in both cases, then the bend must be set aside for use at a different location that needs a different bend angle. The Technical Champion of this procedure or designee and Company Field Engineer responsible for the project shall be advised that the ovality is > 1.0%. Another segmentable induction bend, unless approved by the Technical Champion, must be selected for this angle and the above steps must be repeated. In other words, do not cut a segmentable bend at a location where the ovality is > 1.0%.

6C After the cut-line has been marked, the bend angle must be checked to confirm it is accurate and the cut-line is square using a reliable method, such as the ones shown in Figures 4 and 5 with squares and string-lines, or possibly using a laser system. Dimensions should be re-checked and the bend cut-line adjusted, if necessary.

6D A punch should be used to mark the clock locations on the cut-line previously marked with a soap stone (§5D) through the coating and onto the pipe surface so that the location marks are visible after the coating has been removed.

6E Remove the coating where the cut is to be made. Remark the cut-line around the circumference aligning the band with the punch marks.

6F Make adjacent marks next to the punch marks with a soap stone or marker on both sides of the cut-line to preserve the measurement locations for use after cutting. **No punch marks shall remain in the surface after welding is complete.**

6G A bend angle may be cut out of a bend section with no tangents by using the same methods outlined in this procedure using chord lengths, angle and squareness checks, and a transition pup on both ends of the bend.

7 CUTTING THE BEND

7A Cut the bend and then check the end for squareness. Several possible methods for checking end squareness are shown in Figures 4, 5 and 6. The ends should be square to within the tolerances provided in §5B1, top to bottom and side to side.

7B A temporary pup must be tack-welded to the cut end of the bend to mount the beveling machine band squarely, and the **back-bevel technique** shall be used to cut a standard external 30° bevel (-0°, +5°) on the cut end of the bend. A Dearman style chain clamp (see Figure 10) shall be used for line-up to achieve the best possible alignment of the pup pipe for tack welding. After cutting the 30^o bevel on the bend, check the end squareness as described in §7A above.

8 ALIGNING THE WELD BEVEL

8A Ovality of pup pipe shall be checked at both ends to ensure it does not exceed 1% maximum. Using calipers (see Figure 3) and a ruler with 1/64” increments or large diameter micrometers, measure the outside diameter of the pup across the following 4 clock positions: 12:00-6:00, 1:30-7:30, 3:00-9:00, and 4:30-10:30 (i.e., every 45 degrees). Company Welding Inspector shall record diameter measurements on a “Bend Segmenting Report”. The ovality must be calculated using the following formula:

%Ovality = 100 x [Maximum Diameter – Minimum Diameter] ÷ Nominal Pipe Diameter

8B The specific transition pup that will be welded to the bend cut end shall have a standard 30^o weld bevel, shall be lined-up with the bend positioned in a Dearman style clamp for large diameter pipe, and shall be rotated to achieve the best possible alignment that minimizes the effects of ovality, thus achieving the least amount of average high/low around the entire weld bevel. The weld seam of the pup may be rotated to any o’clock position necessary to ensure that the weld bevel meets the alignment requirements of this procedure, as long as the 2 inch minimum offset between seams of the pup and bend is maintained.

8C The internal alignment shall be inspected, and the areas with the greatest amount of high/low shall be measured. The high/low should be evenly distributed as best as possible and the pup shall be locked into position. The alignment location of the pup weld seam shall be marked on the bend to ensure realignment during subsequent fit-ups.

8D The external offset between the pup and bend shall not exceed 1/3 the nominal wall thickness of the pup pipe (see Figure 8) at any location. A straight-edge and vernier caliper may be used to make these measurements.

8E Once the optimum bevel alignment has been determined, a sharpened soap stone or marker shall be laid flat on the inside of the pup to scribe a line on the bend bevel that represents the extent of material to removed to create the internal transition on the inside of the bend, shown as the “First Mark” in Figure 7.

8F Remove the pup pipe from the clamp. Measure on the bend bevel the minimum wall thickness from the mark on the bend bevel to the outside surface of the bend pipe, at a minimum of the following 8 clock positions: 12:00, 1:30, 3:00, 4:30, 6:00, 7:30, 9:00, 10:30 (i.e., every 45 degrees), and in addition also measure the location where visual inspection indicates the remaining thickness appears to be the least.

8F1 The measured thickness of the bend must meet one of the following:

8F1.1 No less than the nominal wall thickness of the pup pipe, or

8F1.2 No less than 0.83 times the pup nominal wall thickness, where the remaining bend end thickness after grinding is confirmed by the Engineer to meet a:

0.6 design factor in a Class 1 area

0.5 design factor in a Class 2 area

0.4 design factor in a Class 3 area

Note: This second case is typically used where the transition pup thickness is near to or the same as the bend wall thickness.

8F2 If the thickness is less than the above limit, the pup shall be realigned and adjusted to achieve a better fit-up. Repeat Steps §8A through §8F1.

8F3 If a better alignment cannot be obtained, then a second line shall be marked on the bend bevel at a distance of one transition pup wall thickness from the outside surface of the bend, shown as the "Second Mark" in Figure 7 (or mark at a minimum of 0.83 times nominal wall thickness of pup, if allowed per §8F1.2).

8F4 If the difference between the two lines on the bend bevel is ≤ 3/8" (0.375"), then the second line will be the start point for the internal transition on the bend (see "Second Mark" in Figure 7). If the offset between the lines is > 1/16" (0.062"), then a backweld will be required. Backwelds shall be a minimum of 3" in length, but are only required at these offset locations. Full circumferential backwelds are not required.

8F5 If the difference between the two lines on the bend bevel is > 3/8" (0.375"), then a different pup pipe shall be used, and Steps §8A through §8F4 must be repeated.

9 GRINDING THE INTERNAL TRANSITION

9A Once the above requirements are met, the inside surface of the bend shall be ground to the appropriate mark to form the internal transition bevel. The angle of the transition bevel must be 14^{o} to 30^{o}. The use of a hand-held torch or any other thermal cutting method to cut any portion of the internal bevel is not acceptable.

9B After grinding of the bevel (including the land face) and internal transition is complete, Company Welding Inspector shall measure the bevel thickness and internal transition bevel angle at the following 8 clock positions: 12:00, 1:30, 3:00, 4:30, 6:00, 7:30, 9:00, and 10:30 (i.e., every 45 degrees).

10 FINAL BEVEL AND ALIGNMENT CHECKS

10A The following limits must be met for the bend weld bevel and internal transition bevel (as shown in Figure 8):

10A1 Minimum actual measured bevel thickness on the bend after transitioning:

10A1.1 ≥ 92% nominal wall thickness of pup (ie. an under-tolerance of up to 8% of the nominal pup wall thickness is allowed), or

10A1.2 ≥ 83% nominal pup thickness, if allowed in §8F1 (ie. this absolute minimum bevel thickness is subject to the requirements of §8F1, and no under-tolerance is allowed)

10A2 Internal transition bevel angle:

10A2.1 Minimum 14°

10A2.2 Maximum 30°

10B If the bend cannot meet the above limits, then the bend must be set aside and a Company Engineer must be advised to determine further action.

10C If the bend bevel measurements are within the above tolerances, then refit-up the weld joint by aligning the pup weld seam with the mark on the bend. Adjust the clamp to get the best fit-up minimizing high/low and evenly distributing any high/low. Once the joint is in position, the high/low shall be measured and shall meet the following limits (as shown in Figure 8).

10C1 The targeted maximum internal high/low after transitioning is 1/16” (0.062”). If internal high/low exceeds 1/16” (0.062”), an approved backwelding procedure must be used to weld all locations. The maximum internal high/low offset that can be backwelded is 3/8” (0.375”).

10C2 The maximum external high/low offset of the OD shall not exceed 1/3 nominal wall thickness of the pup pipe. No internal transition on the pup pipe is allowed.

10D If the above limits have not been met, then the alignment must be adjusted or the pup must be rotated to try to eliminate any offset greater than the above limits in §10C. Further modifications to the internal transition bevel may be performed as long as the requirements listed in §10A have been met. Any modification to the internal transition or bevel will require measurements to be recorded again.

10E If the limits in §10C are still not met, the fit-up shall be rejected, and another pup with different ovality characteristics will need to be used which will line-up properly with the bend segment. If the bend segment is determined to be too far out of alignment, then another bend will need to be cut for this angle. It may still be possible to use the trimmed bend by finding another location with a lesser angle where it can be trimmed again and properly aligned with a transition pup.

11 WELDING THE PUP TO THE BEND

11A When an acceptable fit-up is achieved and all measurements are taken as required and recorded on a “Bend Segmenting Report”, welding may start. All welds to segmented bends shall be preheated to 250^{o}F minimum or as high as may be required by Company Engineer, Company welding specification, or the welding procedure specification (WPS).

11B In areas where the internal high/low offset exceeds 1/16” (0.062”):

11B1 An approved backwelding procedure must be used.

11B2 The internal high/low offset shall be tied-in continuously by the backweld (i.e., no unwelded face on the high side of the bevel – see example in Figure 9).

11B3 The profile of the completed backweld must provide a smooth transition from the offset down to the inside diameter of the transition pup that generally follows the angle of the internal transition bevel on the bend within a range of 14^{o} to 30^{o}, as shown in the “Backweld Bead Detail” in Figure 8. The purpose of the backweld is not to increase the wall thickness but to provide a smooth transition between the inside diameter of the bend and the pup. Large weld bead irregularities that create a sharp angle or notch at the toe of the weld should be corrected by depositing another weld bead or by carefully grinding back the high bead to shape a smooth transition (see examples in Figure 9).

11B4 Where multiple backweld beads are required, the weld bead sequence must be from the transition pup up to the bend as shown in the "Backweld Bead Detail" in Figure 8.

11C Company Welding Inspector shall also visually inspect the weld for inadequate penetration (IP), cracks, pinholes, internal and external undercut.

11D The results of the visual inspection shall be reported on a "Bend Segmenting Report".

12 FIGURES

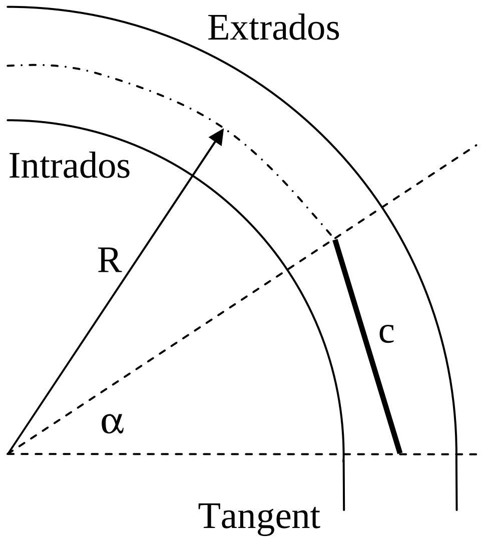

Figure 1: Bend Layout Using Chord "c" to Determine Segment Angle α (Look-up values of "c" in Tables 1 to 6)

Figure 2: Center Finder Marking Tool

Figure 3: Top – Calipers ; Bottom – Large Diameter Micrometer

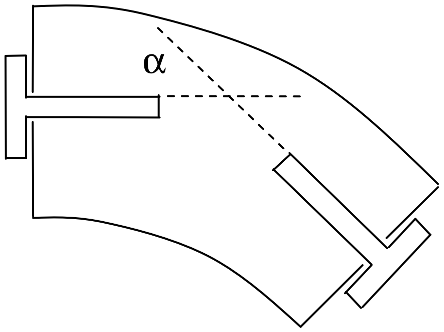

Figure 4: Confirm Bend Angle α With Two Squares

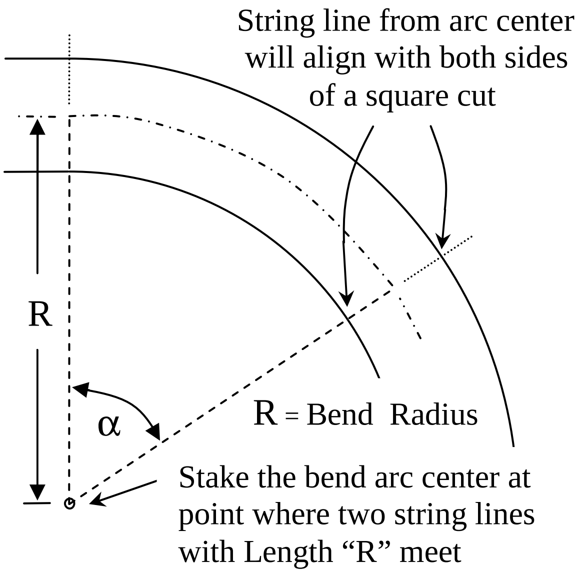

Figure 5: Confirm Angle and Squareness With Two String Lines

(Angles and squareness should be checked after initial marking and after cutting)

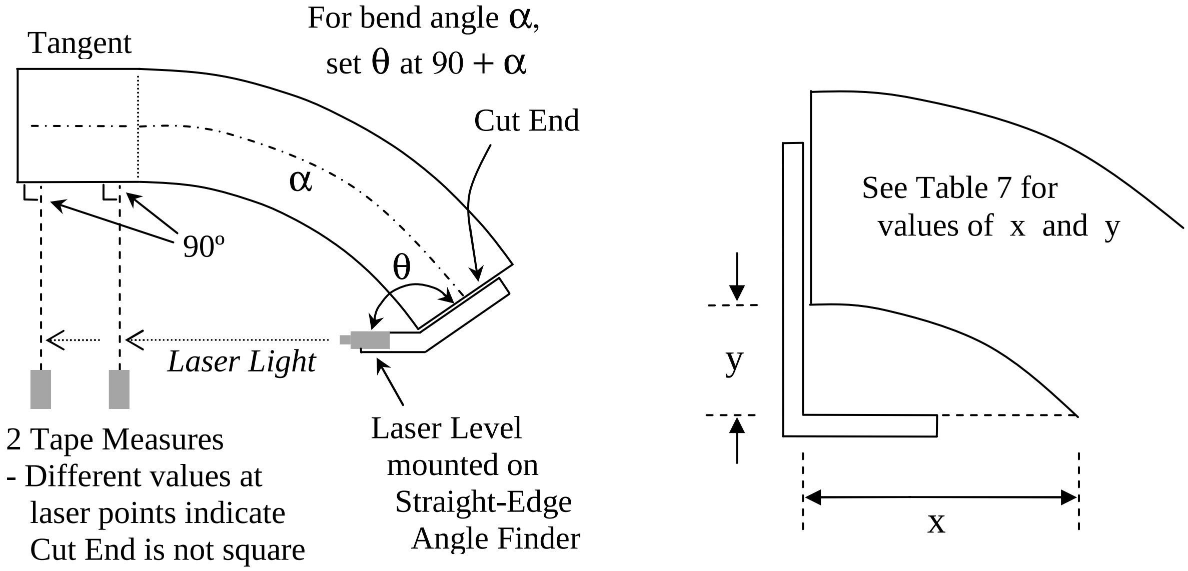

Figure 6: Two Optional Methods for Checking End Squareness

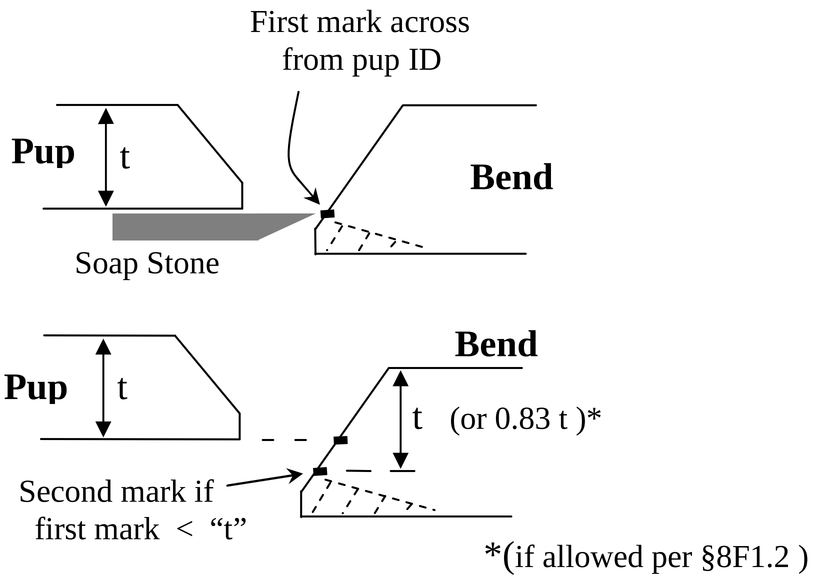

Figure 7: Mark Bend for Transition

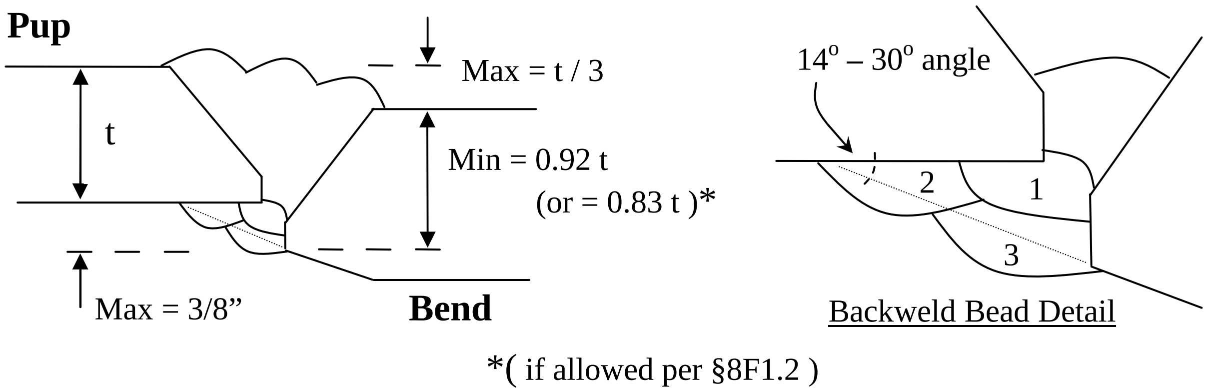

Figure 8: Weld Alignment Limits and Details

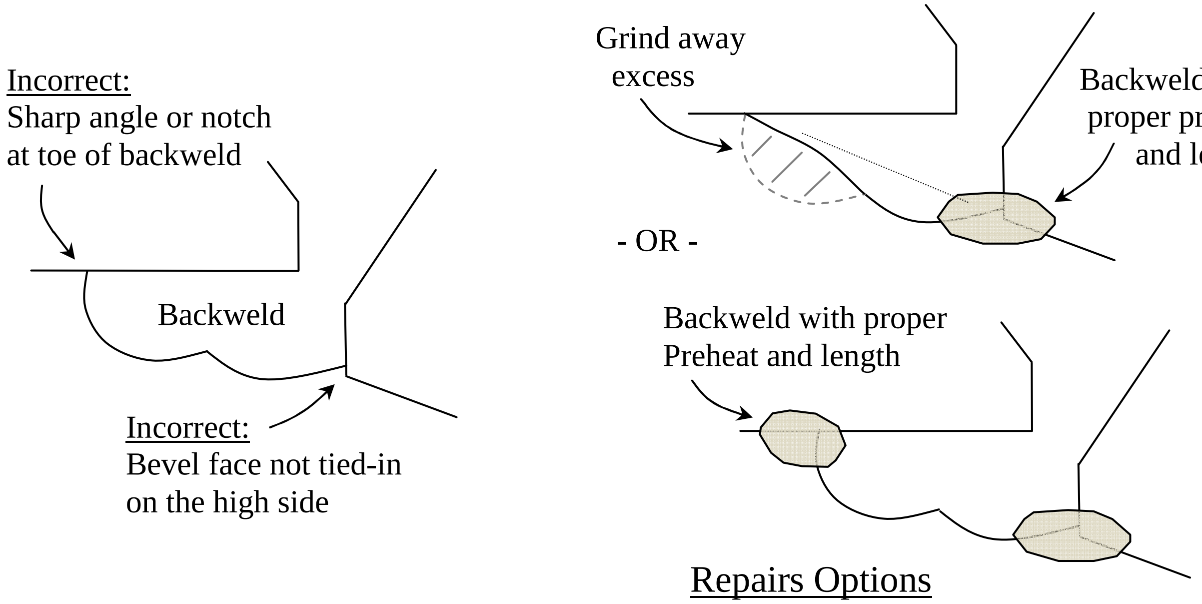

Figure 9: Correction of Improper Backweld Technique

Figure 10: Dearman Style Chain Clamp

13 TABLES

Table 1 **Chord Length for Pipe OD** = **16** **inches** c = 2 x R x sin(α / 2)

	Chord Length "c" (inches) for Radius of				Chord Length "c" (inches) for Radius of		
Angle	3D =	6D =	7D =	Angle	3D =	6D =	7D =
α (degr)	48	96	112	α (degr)	48	96	112
9	7.5	15.1	17.6	45	36.7	73.5	85.7
10	8.4	16.7	19.5	46	37.5	75.0	87.5
11	9.2	18.4	21.5	47	38.3	76.6	89.3
12	10.0	20.1	23.4	48	39.0	78.1	91.1
13	10.9	21.7	25.4	49	39.8	79.6	92.9
14	11.7	23.4	27.3	50	40.6	81.1	94.7
15	12.5	25.1	29.2	51	41.3	82.7	96.4
16	13.4	26.7	31.2	52	42.1	84.2	98.2
17	14.2	28.4	33.1	53	42.8	85.7	99.9
18	15.0	30.0	35.0	54	43.6	87.2	101.7
19	15.8	31.7	37.0	55	44.3	88.7	103.4
20	16.7	33.3	38.9	56	45.1	90.1	105.2
21	17.5	35.0	40.8	57	45.8	91.6	106.9
22	18.3	36.6	42.7	58	46.5	93.1	108.6
23	19.1	38.3	44.7	59	47.3	94.5	110.3
24	20.0	39.9	46.6	60	48.0	96.0	112.0
25	20.8	41.6	48.5	61	48.7	97.4	113.7
26	21.6	43.2	50.4	62	49.4	98.9	115.4
27	22.4	44.8	52.3	63	50.2	100.3	117.0
28	23.2	46.4	54.2	64	50.9	101.7	118.7
29	24.0	48.1	56.1	65	51.6	103.2	120.4
30	24.8	49.7	58.0	66	52.3	104.6	122.0
31	25.7	51.3	59.9	67	53.0	106.0	123.6
32	26.5	52.9	61.7	68	53.7	107.4	125.3
33	27.3	54.5	63.6	69	54.4	108.7	126.9
34	28.1	56.1	65.5	70	55.1	110.1	128.5
35	28.9	57.7	67.4	71	55.7	111.5	130.1
36	29.7	59.3	69.2	72	56.4	112.9	131.7
37	30.5	60.9	71.1	73	57.1	114.2	133.2
38	31.3	62.5	72.9	74	57.8	115.5	134.8
39	32.0	64.1	74.8	75	58.4	116.9	136.4
40	32.8	65.7	76.6	76	59.1	118.2	137.9
41	33.6	67.2	78.4	77	59.8	119.5	139.4
42	34.4	68.8	80.3	78	60.4	120.8	141.0
43	35.2	70.4	82.1	79	61.1	122.1	142.5
44	36.0	71.9	83.9	80	61.7	123.4	144.0

Table 2 **Chord Length for Pipe OD** = **20** **inches** c = 2 x R x sin(α / 2)

	Chord Length "c" (inches) for Radius of				Chord Length "c" (inches) for Radius of		
Angle	3D =	6D =	7D =	Angle	3D =	6D =	7D =
α (degr)	60	120	140	α (degr)	60	120	140
9	9.4	18.8	22.0	45	45.9	91.8	107.2
10	10.5	20.9	24.4	46	46.9	93.8	109.4
11	11.5	23.0	26.8	47	47.8	95.7	111.6
12	12.5	25.1	29.3	48	48.8	97.6	113.9
13	13.6	27.2	31.7	49	49.8	99.5	116.1
14	14.6	29.2	34.1	50	50.7	101.4	118.3
15	15.7	31.3	36.5	51	51.7	103.3	120.5
16	16.7	33.4	39.0	52	52.6	105.2	122.7
17	17.7	35.5	41.4	53	53.5	107.1	124.9
18	18.8	37.5	43.8	54	54.5	109.0	127.1
19	19.8	39.6	46.2	55	55.4	110.8	129.3
20	20.8	41.7	48.6	56	56.3	112.7	131.5
21	21.9	43.7	51.0	57	57.3	114.5	133.6
22	22.9	45.8	53.4	58	58.2	116.4	135.7
23	23.9	47.8	55.8	59	59.1	118.2	137.9
24	24.9	49.9	58.2	60	60.0	120.0	140.0
25	26.0	51.9	60.6	61	60.9	121.8	142.1
26	27.0	54.0	63.0	62	61.8	123.6	144.2
27	28.0	56.0	65.4	63	62.7	125.4	146.3
28	29.0	58.1	67.7	64	63.6	127.2	148.4
29	30.0	60.1	70.1	65	64.5	129.0	150.4
30	31.1	62.1	72.5	66	65.4	130.7	152.5
31	32.1	64.1	74.8	67	66.2	132.5	154.5
32	33.1	66.2	77.2	68	67.1	134.2	156.6
33	34.1	68.2	79.5	69	68.0	135.9	158.6
34	35.1	70.2	81.9	70	68.8	137.7	160.6
35	36.1	72.2	84.2	71	69.7	139.4	162.6
36	37.1	74.2	86.5	72	70.5	141.1	164.6
37	38.1	76.2	88.8	73	71.4	142.8	166.6
38	39.1	78.1	91.2	74	72.2	144.4	168.5
39	40.1	80.1	93.5	75	73.1	146.1	170.5
40	41.0	82.1	95.8	76	73.9	147.8	172.4
41	42.0	84.0	98.1	77	74.7	149.4	174.3
42	43.0	86.0	100.3	78	75.5	151.0	176.2
43	44.0	88.0	102.6	79	76.3	152.7	178.1
44	45.0	89.9	104.9	80	77.1	154.3	180.0

Table 3 **Chord Length for Pipe OD** = **24** **inches** c = 2 x R x sin(α / 2)

	Chord Length "c" (inches) for Radius of				Chord Length "c" (inches) for Radius of		
Angle	3D =	6D =	7D =	Angle	3D =	6D =	7D =
α (degr)	72	144	168	α (degr)	72	144	168
9	11.3	22.6	26.4	45	55.1	110.2	128.6
10	12.6	25.1	29.3	46	56.3	112.5	131.3
11	13.8	27.6	32.2	47	57.4	114.8	134.0
12	15.1	30.1	35.1	48	58.6	117.1	136.7
13	16.3	32.6	38.0	49	59.7	119.4	139.3
14	17.5	35.1	40.9	50	60.9	121.7	142.0
15	18.8	37.6	43.9	51	62.0	124.0	144.7
16	20.0	40.1	46.8	52	63.1	126.3	147.3
17	21.3	42.6	49.7	53	64.3	128.5	149.9
18	22.5	45.1	52.6	54	65.4	130.7	152.5
19	23.8	47.5	55.5	55	66.5	133.0	155.1
20	25.0	50.0	58.3	56	67.6	135.2	157.7
21	26.2	52.5	61.2	57	68.7	137.4	160.3
22	27.5	55.0	64.1	58	69.8	139.6	162.9
23	28.7	57.4	67.0	59	70.9	141.8	165.5
24	29.9	59.9	69.9	60	72.0	144.0	168.0
25	31.2	62.3	72.7	61	73.1	146.2	170.5
26	32.4	64.8	75.6	62	74.2	148.3	173.1
27	33.6	67.2	78.4	63	75.2	150.5	175.6
28	34.8	69.7	81.3	64	76.3	152.6	178.1
29	36.1	72.1	84.1	65	77.4	154.7	180.5
30	37.3	74.5	87.0	66	78.4	156.9	183.0
31	38.5	77.0	89.8	67	79.5	159.0	185.5
32	39.7	79.4	92.6	68	80.5	161.0	187.9
33	40.9	81.8	95.4	69	81.6	163.1	190.3
34	42.1	84.2	98.2	70	82.6	165.2	192.7
35	43.3	86.6	101.0	71	83.6	167.2	195.1
36	44.5	89.0	103.8	72	84.6	169.3	197.5
37	45.7	91.4	106.6	73	85.7	171.3	199.9
38	46.9	93.8	109.4	74	86.7	173.3	202.2
39	48.1	96.1	112.2	75	87.7	175.3	204.5
40	49.3	98.5	114.9	76	88.7	177.3	206.9
41	50.4	100.9	117.7	77	89.6	179.3	209.2
42	51.6	103.2	120.4	78	90.6	181.2	211.5
43	52.8	105.6	123.1	79	91.6	183.2	213.7
44	53.9	107.9	125.9	80	92.6	185.1	216.0

Table 4 **Chord Length for Pipe OD** = **30** **inches** $c = 2 \times R \times \sin(\alpha / 2)$

Angle	Chord Length "c" (inches) for Radius of			Angle	Chord Length "c" (inches) for Radius of		
	3D =	6D =	7D =		3D =	6D =	7D =
α (degr)	90	180	210	α (degr)	90	180	210
9	14.1	28.2	33.0	45	68.9	137.8	160.7
10	15.7	31.4	36.6	46	70.3	140.7	164.1
11	17.3	34.5	40.3	47	71.8	143.5	167.5
12	18.8	37.6	43.9	48	73.2	146.4	170.8
13	20.4	40.8	47.5	49	74.6	149.3	174.2
14	21.9	43.9	51.2	50	76.1	152.1	177.5
15	23.5	47.0	54.8	51	77.5	155.0	180.8
16	25.1	50.1	58.5	52	78.9	157.8	184.1
17	26.6	53.2	62.1	53	80.3	160.6	187.4
18	28.2	56.3	65.7	54	81.7	163.4	190.7
19	29.7	59.4	69.3	55	83.1	166.2	193.9
20	31.3	62.5	72.9	56	84.5	169.0	197.2
21	32.8	65.6	76.5	57	85.9	171.8	200.4
22	34.3	68.7	80.1	58	87.3	174.5	203.6
23	35.9	71.8	83.7	59	88.6	177.3	206.8
24	37.4	74.8	87.3	60	90.0	180.0	210.0
25	39.0	77.9	90.9	61	91.4	182.7	213.2
26	40.5	81.0	94.5	62	92.7	185.4	216.3
27	42.0	84.0	98.0	63	94.0	188.1	219.4
28	43.5	87.1	101.6	64	95.4	190.8	222.6
29	45.1	90.1	105.2	65	96.7	193.4	225.7
30	46.6	93.2	108.7	66	98.0	196.1	228.7
31	48.1	96.2	112.2	67	99.3	198.7	231.8
32	49.6	99.2	115.8	68	100.7	201.3	234.9
33	51.1	102.2	119.3	69	102.0	203.9	237.9
34	52.6	105.3	122.8	70	103.2	206.5	240.9
35	54.1	108.3	126.3	71	104.5	209.1	243.9
36	55.6	111.2	129.8	72	105.8	211.6	246.9
37	57.1	114.2	133.3	73	107.1	214.1	249.8
38	58.6	117.2	136.7	74	108.3	216.7	252.8
39	60.1	120.2	140.2	75	109.6	219.2	255.7
40	61.6	123.1	143.6	76	110.8	221.6	258.6
41	63.0	126.1	147.1	77	112.1	224.1	261.5
42	64.5	129.0	150.5	78	113.3	226.6	264.3
43	66.0	131.9	153.9	79	114.5	229.0	267.2
44	67.4	134.9	157.3	80	115.7	231.4	270.0

Table 5 **Chord Length for Pipe OD** = **36** **inches** c = 2 x R x sin(α / 2)

	Chord Length "c" (inches) for Radius of				Chord Length "c" (inches) for Radius of		
Angle	3D =	6D =	7D =	Angle	3D =	6D =	7D =
α (degr)	108	216	252	α (degr)	108	216	252
9	16.9	33.9	39.5	45	82.7	165.3	192.9
10	18.8	37.7	43.9	46	84.4	168.8	196.9
11	20.7	41.4	48.3	47	86.1	172.3	201.0
12	22.6	45.2	52.7	48	87.9	175.7	205.0
13	24.5	48.9	57.1	49	89.6	179.1	209.0
14	26.3	52.6	61.4	50	91.3	182.6	213.0
15	28.2	56.4	65.8	51	93.0	186.0	217.0
16	30.1	60.1	70.1	52	94.7	189.4	220.9
17	31.9	63.9	74.5	53	96.4	192.8	224.9
18	33.8	67.6	78.8	54	98.1	196.1	228.8
19	35.7	71.3	83.2	55	99.7	199.5	232.7
20	37.5	75.0	87.5	56	101.4	202.8	236.6
21	39.4	78.7	91.8	57	103.1	206.1	240.5
22	41.2	82.4	96.2	58	104.7	209.4	244.3
23	43.1	86.1	100.5	59	106.4	212.7	248.2
24	44.9	89.8	104.8	60	108.0	216.0	252.0
25	46.8	93.5	109.1	61	109.6	219.3	255.8
26	48.6	97.2	113.4	62	111.2	222.5	259.6
27	50.4	100.8	117.7	63	112.9	225.7	263.3
28	52.3	104.5	121.9	64	114.5	228.9	267.1
29	54.1	108.2	126.2	65	116.1	232.1	270.8
30	55.9	111.8	130.4	66	117.6	235.3	274.5
31	57.7	115.4	134.7	67	119.2	238.4	278.2
32	59.5	119.1	138.9	68	120.8	241.6	281.8
33	61.3	122.7	143.1	69	122.3	244.7	285.5
34	63.2	126.3	147.4	70	123.9	247.8	289.1
35	65.0	129.9	151.6	71	125.4	250.9	292.7
36	66.7	133.5	155.7	72	127.0	253.9	296.2
37	68.5	137.1	159.9	73	128.5	257.0	299.8
38	70.3	140.6	164.1	74	130.0	260.0	303.3
39	72.1	144.2	168.2	75	131.5	263.0	306.8
40	73.9	147.8	172.4	76	133.0	266.0	310.3
41	75.6	151.3	176.5	77	134.5	268.9	313.7
42	77.4	154.8	180.6	78	135.9	271.9	317.2
43	79.2	158.3	184.7	79	137.4	274.8	320.6
44	80.9	161.8	188.8	80	138.8	277.7	324.0

Table 6 **Chord Length for Pipe OD =** **42** **inches** c = 2 x R x sin(α / 2)

	Chord Length "c" (inches) for Radius of				Chord Length "c" (inches) for Radius of		
Angle	3D =	6D =	7D =	Angle	3D =	6D =	7D =
α (degr)	126	252	294	α (degr)	126	252	294
9	19.8	39.5	46.1	45	96.4	192.9	225.0
10	22.0	43.9	51.2	46	98.5	196.9	229.7
11	24.2	48.3	56.4	47	100.5	201.0	234.5
12	26.3	52.7	61.5	48	102.5	205.0	239.2
13	28.5	57.1	66.6	49	104.5	209.0	243.8
14	30.7	61.4	71.7	50	106.5	213.0	248.5
15	32.9	65.8	76.7	51	108.5	217.0	253.1
16	35.1	70.1	81.8	52	110.5	220.9	257.8
17	37.2	74.5	86.9	53	112.4	224.9	262.4
18	39.4	78.8	92.0	54	114.4	228.8	266.9
19	41.6	83.2	97.0	55	116.4	232.7	271.5
20	43.8	87.5	102.1	56	118.3	236.6	276.0
21	45.9	91.8	107.2	57	120.2	240.5	280.6
22	48.1	96.2	112.2	58	122.2	244.3	285.1
23	50.2	100.5	117.2	59	124.1	248.2	289.5
24	52.4	104.8	122.3	60	126.0	252.0	294.0
25	54.5	109.1	127.3	61	127.9	255.8	298.4
26	56.7	113.4	132.3	62	129.8	259.6	302.8
27	58.8	117.7	137.3	63	131.7	263.3	307.2
28	61.0	121.9	142.3	64	133.5	267.1	311.6
29	63.1	126.2	147.2	65	135.4	270.8	315.9
30	65.2	130.4	152.2	66	137.2	274.5	320.2
31	67.3	134.7	157.1	67	139.1	278.2	324.5
32	69.5	138.9	162.1	68	140.9	281.8	328.8
33	71.6	143.1	167.0	69	142.7	285.5	333.0
34	73.7	147.4	171.9	70	144.5	289.1	337.3
35	75.8	151.6	176.8	71	146.3	292.7	341.5
36	77.9	155.7	181.7	72	148.1	296.2	345.6
37	80.0	159.9	186.6	73	149.9	299.8	349.8
38	82.0	164.1	191.4	74	151.7	303.3	353.9
39	84.1	168.2	196.3	75	153.4	306.8	358.0
40	86.2	172.4	201.1	76	155.1	310.3	362.0
41	88.3	176.5	205.9	77	156.9	313.7	366.0
42	90.3	180.6	210.7	78	158.6	317.2	370.0
43	92.4	184.7	215.5	79	160.3	320.6	374.0
44	94.4	188.8	220.3	80	162.0	324.0	378.0

Table 7 (all dimensions in inches)

					$x = [\ \text{Radius}^2 - (\text{Radius} - y)^2\ ]^{0.5}$	
Bend R =	**3**	**Diameter Radius**				
Pipe OD =	16	20	24	30	36	42
Radius =	48	60	72	90	108	126
y	x	x	x	x	x	x
3	16.7	18.7	20.6	23.0	25.3	27.3
6	23.2	26.2	28.8	32.3	35.5	38.4
9	28.0	31.6	34.9	39.2	43.2	46.8
12	31.7	36.0	39.8	44.9	49.5	53.7
Bend R =	**6**	**Diameter Radius**				
Pipe OD =	16	20	24	30	36	42
Radius =	96	120	144	180	216	252
y	x	x	x	x	x	x
3	23.8	26.7	29.2	32.7	35.9	38.8
6	33.4	37.5	41.1	46.1	50.6	54.7
9	40.6	45.6	50.1	56.2	61.7	66.7
12	46.5	52.3	57.5	64.6	71.0	76.8
Bend R =	**7**	**Diameter Radius**				
Pipe OD =	16	20	24	30	36	42
Radius =	112	140	168	210	252	294
y	x	x	x	x	x	x
3	25.7	28.8	31.6	35.4	38.8	41.9
6	36.2	40.5	44.5	49.8	54.7	59.1
9	44.0	49.4	54.2	60.8	66.7	72.2
12	50.4	56.7	62.4	70.0	76.8	83.1

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