GUIDELINES FOR WELD DEPOSITION REPAIR ON PIPELINES

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Prepared by the following Research Agencies:

Edison Welding Institute

Authors:
W. A. Bruce

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3801 Kirby Drive, Suite 340
Houston, Texas 77098
Tel: 713-630-0505
Fax: 713-630-0560
Email: info@ttoolbox.com
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*Ad hoc group member only or Alternate
Special thanks to the following PR-185-9734 Ad Hoc Group Members

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P. H. Boydell, BP Exploration (Alaska) Inc.
R. W. Delgatty, Iroquois Gas Transmission System
H. H. Haines, Gas Research Institute
A. J. Maghes, Duke Energy Corp.
J W. Seng, Great Lakes Gas Transmission Co
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Executive Summary

Pipeline repair by direct deposition of weld metal, or weld deposition repair, is an attractive alternative to the installation of full-encirclement sleeves for repair of wall loss caused by corrosion on in-service pipelines, particularly where the installation of full-encirclement sleeves is difficult or impossible. To allow the confident use of this repair technique and to provide a foundation for regulatory acceptance, it was first necessary to establish guidelines for carrying out this technique. The objective of this project was to provide a report that contains these guidelines.

The guidance provided in this report is contained in two basic parts. The main body of the report contains a review of the various technological factors pertinent to weld deposition repair, including a review of recently-completed research projects. The second part is an example guideline for carrying out weld deposition repair in the field, which was developed using the information contained in the main body of the report. This example guideline is in the form of a generic company specification and is contained in an appendix to the report.
Guidelines for Weld Deposition Repair on Pipelines

1.0 Introduction

Pipeline repair by direct deposition of weld metal, or weld deposition repair, is an attractive alternative to the installation of full-encirclement sleeves for repair of wall loss on in-service pipelines. This is particularly true where the installation of full-encirclement sleeves is difficult or impossible, such as for wall loss in bend sections and fittings. The results of recently completed work at EWI\(^{(1-2)}\) and previous work by others\(^{(3-8)}\) has shown that weld deposition repairs have the ability to restore the static strength of a pipeline and are resistant to pressure cycles over a wide range of applications.

Prior to the widespread use of this technique, it was necessary to establish guidelines for carrying out repairs using this technique. These guidelines must address not only the welding issues, but issues pertaining to inspection following welding, acceptance standards for discontinuities detected during inspection, and other related issues.

2.0 Background

There are significant economic and environmental incentives for performing maintenance and repair welding on pipelines without removing them from service. From an economic viewpoint, a shutdown involves revenue loss from the loss of pipeline throughput, in addition to that from the gas lost to the atmosphere. Since methane is a so-called “greenhouse” gas, there are also environmental incentives for avoiding the venting of large quantities of gas to the atmosphere. The primary method of in-service pipeline repair of corrosion and mechanical damage is the installation of full-encirclement sleeves, although this is not always practical in some instances and is impossible in others.

There are two primary concerns with welding onto in-service pipelines, including pipeline repair by weld deposition. The first is for “burnthrough,” or blowout as it is sometimes referred, where the welding arc causes the pipe wall to be penetrated, allowing the contents to escape. The second concern is for the integrity of the pipeline following repair.
The concern for the integrity of the pipeline following repair includes ensuring that the deposited weld metal has adequately restored both the static and fatigue strength, allowing the pipeline to be operated safely at its maximum allowable operating pressure. In addition, it is necessary to ensure that significant discontinuities, including heat-affected-zone (HAZ) hydrogen cracking, have not been introduced as the result of the repair. The concern for hydrogen cracking comes about as the result of the extreme cooling rates and high HAZ hardness levels that tend to be produced as the result of welding onto an in-service pipeline.

Weld deposition repair is attractive because it is direct, relatively inexpensive to apply, and requires no additional materials beyond welding consumables. Potentially the most useful aspect about weld deposition repair is that it can be applied where full-encirclement sleeves cannot, such as for repair in bend sections and fittings. Weld deposition, applied externally, can also be used to repair internal wall loss. An additional benefit of weld deposition repair for internal corrosion-caused wall loss is that it allows the use of ultrasonic testing (UT) for subsequent monitoring of the internal corrosion, which is not the case for a full-encirclement sleeve repair.

A provision for weld deposition repair on gas transmission pipelines is presently contained in ASME B31.8, but weld deposition repair is not permitted by CFR Part 192, by way of exclusion, for pipelines that operate at 40% or more of their specified minimum yield strength. It is also excluded by other Industry codes for gas transmission pipelines, such as CSA Z662. Weld deposition repair is permitted in other related industries, such as line pipe and fitting manufacturing, but is not performed in service and is followed by a hydrostatic test.

3.0 Objectives

The objective of this project was to establish guidelines for carrying out weld deposition repairs. It was anticipated that the results of this program would allow the confident use of this repair technique and provide a foundation for regulatory acceptance.

The work scope for this project included not only the welding issues, but issues pertaining to inspection following welding, acceptance standards for discontinuities detected during inspection, and other related issues. The guidance provided in this report is contained in two basic parts. The following sections in the main body of the report contain a review of the various technological factors pertinent to weld deposition repair, including a review of recently-completed research projects. The second part is an example guideline for carrying out weld deposition repair in the field, which was developed using the Information contained in the main
body of the report. This example guideline is in the form of a generic company specification and is contained in an appendix to the report.

4.0 Issues Pertaining to Weld Deposition Repair

4.1 Assessment Prior to Repair

The extent or nature of any given defect may not be apparent upon initial excavation. Sound engineering practice suggests that the pressure level should therefore be reduced until a defect assessment can be made. This lowering of pressure is necessary to protect the repair crew since any given defect may be on the verge of failure when it is discovered. Previous work suggests that a pressure reduction to 80% or less of the level which was present when the defect was discovered is adequate.\(^{(12)}\) Alternatively, consideration can be given to factors such as hydrostatic test history and recent peak pressure in determining a safe level of pressure reduction.

Upon detection of a defect, it is necessary to determine if a repair is indeed required. If the predicted failure stress of the defect, including hoop stress caused by internal pressure and secondary stresses, exceeds 100% of SMYS, then there is no reason to perform a repair. Repair, particularly by welding, can lead to the introduction of additional and sometimes more significant defects than the defect being repaired. Welding can also result in the degradation of the mechanical properties of the material and the introduction of significant residual stresses.

The most predominant corrosion damage assessment method used in the pipeline industry is the ASME B31G criteria\(^{(13)}\). The use of this criteria involves measuring the depth and longitudinal extent of the corroded area and estimating the remaining strength of the pipeline using an empirically derived formula or a table based on this formula. A semi-empirical evolution of the B31G criteria has been developed and incorporated into a computer program called RSTRENG\(^{(14)}\), which allows more accurate assessments of remaining strength provided that accurate measurements of the corroded area are made.

Aside from lowering the pressure to protect the repair crew, it would appear from the results of previous work at EW\(^{(1-2)}\) that weld deposition repairs can be made at pressures as high as the RSTRENG predicted safe pressure (i.e., RSTRENG predicted failure pressure multiplied by the design factor) for the defect, up to 900 psig (6.2 MPa).

Experiments conducted in the previous program at EW\(^{(1-2)}\) primarily addressed repair of corrosion damage, although this technique can also be used to repair locally-thinned areas that
result from grinding to remove mechanical damage, such as a gouge produced by excavating equipment. This technique should not be used for the repair of crack-like defects or for mechanical damage that has resulted in a dent in the pipeline however, as re-rounding of the dent upon pipeline re-pressurization could produce excessive strains in the vicinity of the repair. Also, this technique should not be used to repair selective corrosion in or adjacent to ERW seams since the ductility of this type of seam is often low, particularly in older materials.

4.2 Practical Limits for the Maximum Size of Repair

No technical limits were established in the previous work\textsuperscript{(1-2)} for the size of an area that can be effectively repaired using weld deposition. However, it would not be practical to use weld deposition repair for an area that extends around nearly the entire circumference for several pipe diameters in length. This size of an area would be more effectively repaired using an alternative method, such as a full-encirclement sleeve. Individual companies may want to establish limits, based on practicality, for longitudinally, circumferentially, and spirally oriented areas. Exceptions to these limits could be made for extenuating circumstances (e.g., larger areas in bend sections that cannot effectively be repaired using a full-encirclement sleeve). Similarly, individual companies may want to establish practical limits for the proximity of one weld deposition repair to another. Again, exceptions could be made for extenuating circumstances.

4.3 Determination of Remaining Wall Thickness

The ability to perform weld deposition repair depends on there being at least enough remaining wall thickness present to avoid burnthrough. The results of previous work\textsuperscript{(1-2)} have shown that weld deposition repair is feasible down to 0.125 in. (3.2 mm) remaining wall thickness provided that proper steps are taken to prevent burnthrough. Prior to repair, it is necessary to determine the remaining wall thickness and to unequivocally establish that there is at least 0.125 in (3.2 mm) of remaining wall thickness present.

Remaining wall thickness can be determined by measuring the depth of the corroded area, using a “pit gage” or the combination of a bridging bar and a depth micrometer, and subtracting this from the actual local wall thickness of the pipeline. The actual local wall thickness of the pipeline should be verified using an ultrasonic thickness gage. The remaining wall thickness can also be measured directly using an ultrasonic thickness gauge, provided that the diameter of the transducer is small enough to provide an accurate measurement in the bottom of the corroded area. “Pencil-probe” -type transducers are available for this purpose.
There are also more sophisticated methods for determining the remaining wall thickness of a corroded area. Mechanized ultrasonic scanning systems have been used for this purpose, which use a water column couplant to overcome the difficulties imposed by the rough surface. Recently completed PRCI-sponsored work at EWI resulted in the development of a laser-based system for mapping external damage on pipelines. The system uses a laser-based range sensor, which relies on optical spray, sensor movement, and the principal of triangulation to construct a three-dimensional measurement. Baseline subtraction, where a polynomial curve-fit is used to approximate the ideal pipe profile above the corroded area, is used. Future profiles are subtracted from the ideal profile, and when differences are significant, corrosion depth measurements are made by constructing normal vectors at points along the ideal profile. A software program titled “CorrosionPro” was developed to provide a means to play-back and display data files generated by the system. While mechanized ultrasonic scanning systems measure wall thickness directly, the laser-based system infers wall thickness by subtracting corrosion depth from the actual local wall thickness, which must be checked using an ultrasonic thickness gauge.

4.4 Surface Preparation

Prior to weld deposition repair, it is necessary to remove corrosion products from the damaged area and, in some cases, to grind the damage to a favorable profile for welding. In the previous program at EWI, preparation of corroded areas for welding began using an angle grinder with a 4-1/2-In (114.3-mm) -diameter disk to remove the steep-sided areas. Grinding was also applied to the bottom of the corroded area to remove the corrosion product while taking care not to significantly increase the depth of the corrosion (i.e., decrease the remaining wall thickness). Corrosion product was removed from portions of the corroded area that were inaccessible to the grinder using a rotary file (burr grinder).

4.5 Selection of Welding Parameters to Prevent Burnthrough

4.51 Factors Affecting Burnthrough

A burnthrough will occur if the unmelted area beneath the weld pool has insufficient strength to contain the internal pressure of the pipe. The occurrence of burnthrough is governed primarily by the pipe wall thickness and the penetration of the welding arc into the pipe wall. Weld penetration is primarily a function of the welding heat input and the ability of the pipeline contents to remove heat from the pipe wall. For a given welding process and electrode type, as heat input increases, penetration into the pipe wall increases, and for a given heat input level, penetration increases as the welding current increases. The ability of the pipeline contents to remove heat from the pipe wall, or the heat sink conditions, is a function of the temperature and
thermal properties of the contents, and flow parameters such as pressure (for gases only) and flow rate.

Previous research by Battelle and others concluded that a burnthrough will not occur unless the inside surface temperature exceeds 1800°F (982°C) when using low-hydrogen electrodes\(^{13-15}\) and that this temperature is unlikely to be reached if the wall thickness is 0.250 in. (6.4 mm) or greater, provided that normal welding practices are used.\(^{16}\) The risk of burnthrough is, therefore, extremely remote under these conditions if the wall thickness is 0.250 in. (6.4 mm) or greater. For areas that are thinner than 0.250 in. (6.4 mm), proper steps must be taken to prevent burnthrough.

The pipeline wall thickness is not normally a parameter that can be changed for a given in-service welding operation, but should be checked using appropriate ultrasonic testing equipment and techniques, such as ultrasonic mapping as described in Section 4.3.

Penetration of the welding arc into the pipe wall is a function of the welding parameters and, to a lesser degree, the welding process. Penetration increases as heat input increases and as the hydrogen potential of the welding process increases. A low-hydrogen process, such as shielded metal arc welding (SMAW) using basic-coated electrodes (e.g., EXX18-type) or gas tungsten arc welding (GTAW), in conjunction with a low heat-input level results in the least amount of penetration. Conversely, a high-hydrogen potential process such as SMAW using cellulosic-coated electrodes (e.g., EXX10-type) at a high heat input level results in much greater penetration. For a given heat input level, penetration increases as the welding current increases.\(^{21}\) The level of welding current required for a given electrode tends to increase proportionally with electrode diameter (a general rule of thumb is that the current level required for a given electrode diameter is the diameter in inches times 1000 [e.g., 125 amps for a 0.125-in diameter electrode]). When welding with direct current, electrode polarity can also affect weld penetration. Straight polarity (electrode negative) produces less penetration than does reverse polarity (electrode positive).

Steps required to prevent burnthrough when welding onto in-service pipelines with a wall thickness of less than 0.250 in. (64 mm) include minimizing the penetration of the arc into the pipe wall by using small diameter low-hydrogen electrodes and a low heat-input procedure. This may conflict with other requirements, such as the need to use a high heat-input procedure (if the procedure does not rely on tempering) to avoid hydrogen cracking. For some applications, the heat input required to avoid cracking may be greater than the heat input allowed to avoid burnthrough, prohibiting the use of this type of procedure. As an alternative to using a high heat-input procedure to avoid hydrogen cracking, a procedure that uses a temper
bead deposition sequence can be used. The application of this type of procedure to weld deposition repairs is described in Section 4.7.2.

The heat input level for the GTAW process is more difficult to control than for the SMAW process since GTAW travel speed can be varied independently of weld metal deposition. The fluidity of the weld pool and the deposition of weld metal prevent abnormally slow travel speed with SMAW. Special attention should be given to ensure that GTAW travel speed is maintained when welding onto thin-wall in-service pipelines.

Common misconceptions pertaining to operating practices required to prevent burnthrough are that some level of flow must always be maintained to prevent burnthrough and that the operating pressure must always be reduced. While maintaining flow does result in lower inside surface temperatures, it can be shown that inside surface temperatures are often less than the 1800°F (982°C) limit established by Battelle due to the thermal mass of the pipe wall itself and the thermal properties of the contents, even at little or no flow.

While a pressure reduction may be justified to prevent a defect from rupturing during the repair process on the basis of protecting the repair crew, pressure has a relatively small effect on the risk of burnthrough. When the unmelted area beneath the weld pool has been heated to a sufficient temperature (i.e., significantly above 1800°F [982°C]), a burnthrough will occur even at very low pressures. Because the size of the heated area is small, the stress in the pipe wall is redistributed around the heated area, as it does similarly around a small corrosion pit. Pressure reductions are, therefore, relatively ineffective at preventing burnthrough and are often unnecessary.

Interestingly, the results of previous work by Battelle can be used to show that, since flowing gas more effectively conducts heat at higher pressure (assuming a constant linear flow rate greater than zero), pressure reduction results in higher inside surface temperatures and an increase in burnthrough risk. The phenomenon does not occur for liquid pipeline contents however, as the thermal conductivity of liquids do not vary greatly with pressure.

4.5.2 Experimentally-Derived Heat Input Limits

In the previous work at EWI, two series of experiments were conducted on reduced wall thickness, pressurized pipe to develop limits for the maximum allowable heat input as a function of remaining wall thickness. These experiments also considered the effect of electrode size (current level) on the maximum allowable heat input. These heat input limits, for various diameters of low-hydrogen (EXX18-type) electrodes, are summarized in Table 1.
The limits shown in Table 1 are for a worst-case condition in terms of heat sink conditions, since the experiments were conducted with nitrogen gas under no-flow conditions. Methane gas and most typical liquid pipeline contents remove heat from the pipe wall more effectively than does nitrogen gas, adding some conservatism to the use of these limits for typical applications. It should be noted, however, that these limits are based on nominal current levels of 50, 80, and 110 amps for 5/64-, 3/32-, and 1/8-in. (2.0-, 2.4-, and 3.2-mm) -diameter electrodes, respectively. The use of these limits for higher current levels may be non-conservative.

4.5.3 Battelle-Model-Derived Heat Input Limits

A useful tool in evaluating the risk of burnthrough is the Battelle thermal analysis computer model.(5) The model in addition to predicting weld cooling rates, predicts inside surface temperatures as a function of the welding parameters (current, voltage and travel speed), geometric parameters (wall thickness, etc.) and the operating conditions (contents, pressure, flow rate, etc.). The risk of burnthrough for a given application can be evaluated or the limiting welding parameters for a given set of operating conditions can be determined. The model in its present configuration cannot provide results for the bead-on-plate configuration of a weld deposition repair, but a fillet weld geometry can be used as an approximation.

The Battelle model defines safe parameters as those which produce an inside surface temperature of less than 1800°F (982°C) when using low hydrogen electrodes. This limit was based on the observation that burnthroughs tended to be produced when the inside surface temperature exceeded 2300°F (1260°C) in a series of previously-conducted experiments.(22-23) The 500°F (278°C) temperature difference was introduced as a margin for safety.

In the previous work at EWl,(1-2) the Battelle model was used to produce guidelines that allow the relative effects of wall thickness, methane flow rate and pressure on allowable heat input to avoid an inside surface temperature above 1800°F (982°C) to be evaluated. The guidelines arise from modeling a fillet weld geometry rather than a bead-on-plate configuration. Nevertheless, they provide interesting comparisons. For all cases, the sleeve thickness was fixed at 0.125 in. (3.2 mm), which appears to be the minimum allowable value for the model to run in its present configuration. The guidelines indicate that, for non-flowing methane at 900 psig (62 MPa), the maximum allowable heat input is 13.7 kJ/in. (0.54 kJ/mm) for 0.125 in. (3.2 mm) remaining wall and 198 kJ/in. (0.78 kJ/mm) for 0.156 in. (4.0 mm) remaining wall. These limits correlate well
with the experimentally-derived limits described in Section 4.52, provided that 1/8-in. (3.2-mm) -diameter or smaller electrodes are used for 0.156 in. (4.0 mm) remaining wall thickness, and 3/32-in. (2.4-mm) diameter or smaller electrodes are used for 0.125 in. (3.2 mm) remaining wall. A modified version of the previously-developed Battelle-model-produced guidelines that include these electrode diameter limits are shown in Appendix A.

The guidelines shown in Appendix A are not intended to be used to plan safe procedures for weld deposition repair but, rather, to show the predicted relative effects of wall thickness, methane flow rate, and pressure on allowable heat input. Validation of these predictions, particularly at flow rates greater than zero, would be required prior to their use for planning safe welding procedures.

4.6 Qualification of Procedures and Welders

The purpose of qualifying a welding procedure is to demonstrate that the procedure is capable of producing sound welds under productron conditions. The purpose of a welder qualification is to show that a particular welder is capable of executing a qualified procedure under production conditions. There are presently no industry-accepted standards specifically intended for the qualification of procedures and welders for weld deposition repairs. Therefore, an adaptation of Sections 2 and 3 of API 1104 \(^{24}\) is proposed. Other standards, such as those found in CSA Z662, \(^11\) BS 4515, \(^25\) ASME Section IX, \(^26\) etc. could be similarly adapted to weld deposition repair

For welding onto in-service pipelines where fast weld cooling rates are anticipated, it is clearly unrepresentative to qualify procedures and welders using a length of pipe that contains still air. Without simulating the ability of the in-service pipeline to remove heat from the pipe wall, unrealistically slow weld cooling rates result, in addition to different solidification characteristics of the weld pool. Procedures and welders for welding onto in-service pipelines should be qualified under conditions that simulate those that will be in effect at the time the procedure is used.

Several approaches exist for qualifying procedures and welders where the thermal conditions experienced when welding onto an actual in-service pipeline are simulated, the most simple of which involves circulating either water or a representative liquid (crude oil, fuel oil, etc.) through the length of pipe while procedure qualification welds are made. Previous work at EWI \(^27\) demonstrated that the use of water as a flow medium is more severe with respect to the resulting weld cooling rates than high-pressure methane and most hydrocarbon liquids. The use of flowing water is simple and reduces the complications associated with handling
hazardous liquids. This previous work also demonstrated that circulating 10W30 motor oil through the length of pipe while procedure qualification welds are made results in weld cooling rates that are representative of those experienced when welding onto low pressure/low flow rate methane lines.

Once a procedure has been qualified under simulated conditions, the pipeline operating conditions (pipe contents, flow rate, etc.) for which the procedure applies should be specified on the procedure qualification record. These conditions should be considered as an “essential variable” for procedure qualification (i.e., requalification should be required if the procedure is to be used under more-severe thermal conditions). Since the risk of hydrogen cracking is more dependent on the carbon equivalent of the pipe material than on the strength level, the pipe material carbon equivalent level to which the procedure applies should replace the specified minimum yield strength as an essential variable (i.e., requalification should be required if the procedure is to be used on a higher carbon equivalent material). Carbon equivalent (CE), calculated using the IIW formula, is as follows:

\[
CE_{IIW} = \%C + \%Mn / 6 + (%Cu + \%Ni) / 15 + (%Cr + \%Mo + \%V) / 5
\]  
\[ (1) \]

As an additional test to investigate the soundness of the weld, a macro-section test, such as that contained in API 1107 or CSA Z662, should be conducted.

Once a welder has been qualified under simulated conditions, the pipeline operating conditions for which he is qualified should also be specified. Requalification should be required if the welder is to be used under significantly different thermal conditions than those for which he is qualified. Welders who will be used to weld onto in-service pipelines should be accustomed to the risk associated with this type of welding, particularly for thin-wall pipe (less than 0.250 in [64 mm]). These risks justify an additional amount of welder instruction, with regard to both safety concerns and welding procedure details, prior to welding. A welder qualified for welding onto in-service pipelines should be able to demonstrate the ability to maintain a heat input level within the specified range of the procedure for which he is being qualified. He should be considered to be qualified to perform weld deposition repair within the essential variable ranges of his qualification, including position.
4.7 Deposition of Repair

4.7.1. Factors Affecting Hydrogen Cracking

The conditions under which weld repairs to in-service pipelines are made favor the production of high hardness levels. Fast cooling rates result from the presence of the pressurized, flowing contents which tends to remove heat from the pipe wall, and from heat input limitations needed to control the risk of burnthrough. These fast weld cooling rates combined with high CE material of older pipelines tend to result in the development of hard, crack-susceptible weld microstructures. The development of these microstructures tend to make repair welds made onto In-service pipelines particularly susceptible to hydrogen cracking. For hydrogen cracking to occur, three primary independent conditions must be satisfied simultaneously. These conditions are: hydrogen in the weld, the development of a crack-susceptible weld microstructure, and a tensile stress acting on the weld.

To prevent hydrogen cracking, at least one of the three conditions necessary for its occurrence must be eliminated. The first step taken towards avoiding hydrogen cracking in welds made onto in-service pipelines is to minimize the hydrogen level by using low-hydrogen electrodes or a low-hydrogen process. As added assurance against hydrogen cracking, since low hydrogen levels cannot always be guaranteed, procedures that minimize the formation of crack-susceptible microstructures are also used. A significant amount of residual tensile stress acting on the weld cannot be avoided and must always be assumed.

The most commonly used options for preventing hydrogen cracking in welds made onto in-service pipelines, beyond the use of low-hydrogen electrodes, are, specification of a minimum-required heat input level, and the use of a temper-bead deposition sequence.

The heat input levels predicted by the Battelle model or the EWI heat sink capacity method (28) can be used to achieve acceptable Weld cooling rates and hardness levels, although the use of high heat input levels represents a greater risk of burnthrough than do lower heat input levels, particularly for thin areas. As an alternative approach, HAZ hardness levels can be minimized by using procedures designed to make use of tempering from subsequent passes or tempering from subsequent layers of a multi-layer repair. These procedures are generally referred to as temper bead procedures.

A temper bead procedure generally involves depositing a first layer or “buttering” layer using stringer beads that are deposited in such a way as to maximize the amount of grain refinement.
and tempering by subsequent passes within the layer. For repairs requiring multiple layers, higher heat input levels are used for the second layer and subsequent layers to further refine and temper the HAZ of first layer.

4.7.2 Weld Deposition Sequence

The results of the procedure development experiments in the previous work at EWl\(^{(1-2)}\) indicate that the use of the temper bead technique is well suited for weld deposition repairs. The most effective technique for making weld deposition repairs was found to be a series of perimeter welds that are followed by layers of consecutive parallel fill passes that are deposited in a “stringer bead” manner. This technique is illustrated in Figure 1.

The initial perimeter weld defines the boundary beyond which no subsequent welding is allowed. The intent is to avoid any inadvertent un-tempered heat-affected zones beyond the perimeter. This initial perimeter pass also allows starts and stops of the first layer to be made on weld metal as opposed to base metal, which results in completed repairs that are a bit neater than those made using other techniques. Following the completion of the first layer (described below), grinding is performed on the initial perimeter pass so that a corner is produced at approximately 1/16 in (1-2 mm) from the toe of the perimeter pass. A second perimeter pass is then deposited prior to depositing the second layer, the toe of which just consumes the corner that was produced by the grinding step. The second perimeter pass is intended to temper the HAZ at the toe of the first perimeter pass. In previous work\(^{(29)}\) it was found that, for a tempering pass to be effective, a toe separation of approximately 1/16 in (1-2 mm) is required. The use of the grinding step facilitates proper weld toe placement (i.e., the welder can see the corner produced at the intersection of the ground surface and the perimeter pass).

The first layer of fill passes must be deposited using established heat input limits to minimize the risk of burnthrough. The fill passes of both layers are deposited using stringer beads in a parallel, consecutive, or buttering layer, manner. During deposition of the buttering layers, the electrode is armed at the toe of the previous pass, resulting in a bead overlap of approximately 50%. Cosmetic grinding between layers is performed only to remove layer height irregularities (i.e., a “half-bead” technique is not used). Higher heat input levels are used for the second layer to refine and temper the HAZ of first layer. Higher heat input fill passes can be used for the second and subsequent layers since deposition of the first layer increases the remaining wall thickness.
Multiple layer repairs result in the highest amount of tempering. Multiple layers are not ideal for shallow repairs, however, as excessive reinforcement may result. The need for either one or multiple layers of weld metal depends on the depth of corrosion and the need for tempering. The results of the previous work at EWI indicate that multiple layer repairs were appropriate for simulated corrosion depths of 0.125-m. (3.2-mm) or greater. An area of simulated corrosion that was 0.94 in. (2.4 mm) deep could be filled using a single layer and bead overlap could be an adjusted slightly to insure proper filling. Additionally, the choice of electrode size, whether for a single or multiple layer repairs, can be used to achieve proper reinforcement height. Since multiple layers result in more tempering than single layers, the deletion of multiple layers should be considered an essential variable for procedure qualification (i.e., requalification should be required if a multi-layer procedure is to be used for a single layer repair).

The use of this sequence results in the most consistent weld profile, the least amount of welder induced discontinuities and the highest amount of tempering from subsequent passes. This tempering, combined with the use of low hydrogen electrodes and the relatively low level of restraint inherent with weld deposition repairs, minimizes the risk of hydrogen cracking. The results of the previous work at EWI indicate that the developed procedure could be executed in all positions around the pipe circumference with consistent quality.

The factors that render this technique effective are believed to be as follows. The first layer of fill passes is deposited using established heat input limits to minimize the risk of burnthrough. Depositing these passes in a buttering layer manner maximizes tempering by subsequent passes within the first layer. Higher heat input fill passes used for subsequent layers, if used, tend to further temper the initial passes. Welder induced discontinuities are minimized by the use of small diameter electrodes. These electrodes permit the welder to maintain a low heat input level comfortably, minimizing the inherent risk of burnthrough.

In the previous work at EWI, some difficulty was experienced in overcoming the heat sink provided by the simulated pipeline contents (i.e., circulating water) in areas with 0.125-m (3.2-mm) -thick remaining wall using the established heat input limits for the first layer. Using 1/8-(3.2-mm) diameter electrodes, heat input levels higher that those desired for the first layer were required to avoid creating welder induced discontinuities. Unlike other welding applications, as the remaining wall thickness decreases, the cooling rate of welds made onto in-service pipelines increases as the result of the welds being made in close proximity to the flowing pipeline contents. To overcome this, 5/64-in. (2.0-mm)-diameter low hydrogen electrodes were used for the first layer. The current range recommended by the manufacturer for these electrodes is 40 to 70 amps. These electrodes
were found to be effective for areas with 0.125-in. (3.2-mm) -thick remaining wall using the heat input limits established for the first layer.

In the early part of the previous work at EWI,\(^1\) the simulated corrosion damage was produced by a portable clamp-on milling machine, which produced a uniform depth. The depth of the simulated corrosion damage produced by the carbon arc gouging process in the later part of the previous work\(^2\) was irregular, which resulted in the need to modify the previously-developed technique somewhat. Where necessary, the general technique (i.e., a perimeter weld followed by consecutive parallel fill passes) was first applied to the deepest areas of wall loss until a uniform remaining depth was established. The general technique was then again applied to the entire area of wall loss until the desired amount of weld metal was deposited. A repair sequence for a typical repair is shown in Figures 2 through 9.

In the previous work at EWI\(^2\), some repairs were limited to restoring just enough of the wall thickness to meet the RSTRENG criterion (partial repairs); in other cases the welding was continued until the full-thickness was restored. During cyclic pressure testing of these repairs, fatigue cracks first reached through-thickness from initiations at the toe of the partial repairs. These partial repairs concentrated the stress not only by providing a smaller cross-sectional area, but also by causing additional bending stresses in the thinner area. These results indicate that partial repairs are not appropriate for high-cycle applications (e.g., a liquid petroleum pipeline that batch feeds a refinery).

4.7.3 Amount of Reinforcement Required for External Repair of Internal Wall Loss

In recently-completed work at EWI\(^3\) an adaptation of the previously-developed technique was developed for external repair of internal wall loss. The amount of reinforcement required was determined using finite element analysis. The adaptation of the previously-developed technique involved applying the general technique (i.e., a perimeter weld followed by consecutive parallel fill passes) to an area larger than the area of wall loss (as mapped out using an ultrasonic thickness gauge) by at least one wall thickness in all directions. This was followed by a second perimeter pass and a second layer. If this did not restore the wall thickness to at least the nominal thickness (as determined using the ultrasonic thickness gauge), the technique was applied again to an area larger than the area of less-than nominal-thickness by about one wall thickness in all directions. This process was repeated until all areas were restored to at least the nominal thickness. This adaptation is illustrated in Figure 10. A series of full-scale experiments involving a repaired straight section of pipe, several elbows, and a tee, demonstrated the ability of external weld deposition repairs to restore the strength of these components.
4.7.4 Avoidance of Welder-Induced Discontinuities

Weld discontinuities, including those that can occur in weld deposition repairs, can be classified into two separate categories: welder-induced discontinuities and hydrogen-induced cracking. Welder-induced discontinuities are those that can be controlled by the skill of the welder and include slag inclusions, porosity, undercut, lack of fusion, etc. When welding onto an in-service pipeline, welder-induced discontinuities can be controlled by the welder maintaining good practice with regard to procedural aspects and welding technique. Welder comfort and ambient conditions can also greatly influence the occurrence of welder-induced discontinuities. In production, efforts should be made to protect the welder from inclement conditions and to provide for the comfort of the welder.

As noted in Section 4.6, a welding procedure qualification is used to demonstrate that a procedure is capable of producing sound welds under production conditions. Welder qualification is used to show that a particular welder is capable of executing the qualified procedure. Proper use of welding procedure and welder qualification, combined with close monitoring in the field to ensure that the welding procedure is being followed, should minimize the occurrence of welder-induced discontinuities.

4.8 Inspection of Completed Repairs

To insure that significant discontinuities have not been produced as the result of a weld deposition repair, a thorough nondestructive inspection following repair should be carried out. Based on the results of previous PRCI-sponsored work conducted jointly between TWI and EWI, the optimized inspection method for weld deposition repairs would involve the use of a combination of magnetic particle inspection and angle beam ultrasonic testing for the weld toes and straight-beam ultrasonic testing or radiography for volumetric inspection. Ultrasonic testing for volumetric inspection requires that the weld reinforcement be removed or ground smooth. The results of experiments in the previous work at EWI indicate that removal of the weld reinforcement does not adversely affect the integrity of the repair.

Surface techniques such as liquid penetrant testing (PT) and magnetic-particle inspection (MPI) rely on discontinuities being slightly below or open to the surface, which is not necessarily the case with all significant discontinuities that can occur in weld deposition repairs. Magnetic particle testing can be effective for the detection of toe cracking, provided that proper procedures are used and that the weld toe has a favorable profile. A favorable weld profile can be produced using a high-speed rotary file (i.e., a burr grinder) to clean up the weld toes.
previous program, it was concluded that MPI performed significantly better than PT. Both the wet fluorescent and visible (black) ink over white contrast paint techniques performed equally well. The choice of the optimum technique depends on illumination conditions available.

Radiography is well suited for volumetric inspection of weld deposition repairs, except for difficulties caused by the presence of liquid pipeline contents. The alternative for a full-volumetric examination is ultrasonic testing. Inspection procedures, reference standards and reporting criteria that have been developed for the specific weld geometries of interest should also be employed.

There may be psychological benefits of any NDT requirement in the form of increased welder performance with respect to welder Induced discontinuities. If a welder knows that a completed weld will be subjected to through NDT, regardless of how effective the NDT method might be, he is more likely to ensure that welder induced discontinuities are avoided.

It is important to note that hydrogen cracking can occur following a substantial time delay after welding. Therefore, inspection should not occur immediately. At present, there is no industry-accepted method for predicting delay intervals for specific applications.

4.9 Acceptance Standards

There are presently no Industry-accepted workmanship-based acceptance standards specifically intended for discontinuities located during inspection of weld deposition repairs. Therefore, the use of a workmanship-based criteria that is based on Section 6 of API 1104\(^{(24)}\) is proposed. Other workmanship-based acceptance criteria, such as those found in CSA Z662, BS 4515, etc., could be similarly adapted to weld deposition repair.

The adaptation of the workmanship-based criteria in Section 6 of API 1104 must consider the requirements imposed by the geometry of weld deposition repairs and the types of discontinuities that these repairs are likely to contain. To develop this criteria, Section 6 of API 1104 was evaluated in terms of how each paragraph applies to weld deposition repair. Tables 2 through 5 contain a summary of this evaluation. Some items do not apply to weld deposition repair and can be ignored when using Section 6 to evaluate discontinuities located during inspection of weld deposition repairs. Other items can be directly applied to weld deposition repairs. The acceptance limits for some discontinuities are given both as an absolute length and as a percentage of the weld length. These items can be directly applied to weld deposition repairs provided that the “weld length” for a weld deposition repair is defined. A reasonable
definition of weld length might be the maximum length of the repair along the longitudinal axis of the pipeline.

As an alternative or a supplement to a workmanship-based criteria, a defect acceptance criteria based on fitness-for-purpose concepts could be developed for weld deposition repairs. Fitness-for-purpose assessment procedures, such as those contained in the appendix of API 1104, are based on fracture mechanics principles and are used to set more rational flaw tolerance levels than those contained in acceptance standards that are based on good workmanship practices. Using this approach, a weld containing a flaw is considered acceptable providing the conditions for failure are not reached during the required service lifetime, i.e., the weld is fit for its intended purpose.

4.10 Repair and Removal of Defects

If a discontinuity in a weld deposition repair that is detected by nondestructive testing is found to be unacceptable according to the acceptance criteria, it should be removed and repaired. Care should be taken during the removal of the defect to ensure that the wall thickness is not reduced to less than that which is acceptable for the operating pressure of the pipeline (i.e., the RSTRENG-predicted safe pressure of the repair cavity should be greater than the operating pressure of the line). The defect should be entirely removed to sound metal prior to repair. Defects other than cracks should be repaired using a procedure similar to the one used to deposit the original repair. A procedure for the repair of cracks should account for the deficiencies in the procedure and/or technique used to deposit the original repair that resulted in the crack (e.g., insufficiently-low hydrogen levels caused by improper electrode handling, etc.). Following repair, the repaired area should be re-inspected using the same method used previously.

4.11 Other Aspects

Guidance pertaining to other aspects of in-service repair in general, and repair by weld metal deposition in particular, is included in the following sections.

4.11.1 Handling of Low-Hydrogen Electrodes

To limit the amount of hydrogen entering the weld, suitably prepared low-hydrogen electrodes should be used. It should be stressed that “low-hydrogen” when applied to consumables (basic and rutile-type coatings) does not mean “no hydrogen.” Even low-hydrogen consumables can lead to hydrogen-induced cracking under adverse conditions, as hydrogen can be introduced through moisture in the electrode coating. Low-hydrogen electrodes should be stored at an
appropriate temperature in portable field ovens or used from freshly opened, airtight containers. Low-hydrogen electrodes are now available in small quantity, sealed packages and have been used with much success for this purpose.\(^{(32)}\)

The moisture content of low-hydrogen electrode coatings can be reduced following exposure to the atmosphere by drying them according to manufacturers recommendations, usually at temperatures between 500 and 850°F (260 and 454°C), and storing at temperatures above 200°F (93°C). Also, some electrode manufacturers specify that their low-hydrogen electrodes should be baked prior to use to achieve sufficiently low hydrogen levels. Ovens should not be overloaded, and drying should last long enough to ensure that all the contents receive the minimum baking time as specified by the manufacturer.\(^{(33)}\) Manufacturer recommendations should be followed so that the lowest hydrogen level results without adversely affecting the operating characteristics of the electrodes.

4.11.2 Chemical Composition Determination

For heat input control procedures, the use of the Battelle model or the EWI heat sink capacity method\(^{(28)}\) for determining required heat input levels requires knowledge of the pipe material chemical composition. Unfortunately, records that contain chemical composition information for older, existing pipelines and piping systems are usually difficult or impossible to locate. In these cases, estimates of chemical composition are often made based on the maximum allowable limits of the specification to which the materials were produced. This usually results in an overestimation of the tendency for unacceptably high hardness levels to result and can, therefore, be restrictively over-conservative.

The chemical composition of an In-service pipeline can be determined by direct analysis using portable equipment or by removal of samples for laboratory analysis. The most promising technique for performing an analysts in the field is optical emission spectrography via a fiber-optic umbilical cord. Several companies make systems that can be used in the field, although these are cumbersome and expensive and require a significant calibration and maintenance effort. A recently introduced piece equipment, however, shows considerable promise.\(^{(34)}\)

Chemical composition determination by removal of samples for laboratory analysis is relatively simple and can be quite accurate, provided that care is taken in removing the samples and that they are properly analyzed. A flat area can be machined on an in-service pipeline provided that the remaining wall thickness is greater than the specified nominal wall thickness minus the pipe mill tolerance, which can up to 12.5 percent\(^{(35)}\) The amount of material required for direct spectrographic analysis of re-melted machining chips is 10 to 20 grams,\(^{(36)}\) with 20 grams being
ideal. Care should be taken to prevent oxidation (i.e., overheating) of the machining chips. Low-cost portable milling machines that are used primarily to cut key-ways in shafts can be used for this purpose. \(^{(37)}\) Separate spectrographic calibration standards are required for re-melted and solid samples. \(^{(38-39)}\) Care must also be taken to prevent oxidation during re-melting, as this can result in lower apparent content of certain elements.

A second method of analyzing a sample of material removed from a pipeline is to analyze the sample directly (i.e., without re-melting). This method is advantageous in that chips of a certain size are not required, which allows removal using a simpler piece of equipment, such as a high-speed rotary file (burr grinder). The rotary file should be inspected following use to insure that teeth have not broken off. The inclusion of teeth in the filings can raise the apparent content of certain elements, particularly carbon. The filings can be analyzed using traditional wet chemistry (i.e., titration methods) or using the inductively coupled plasma (ICP) method. The combustion-in-oxygen method using a LECO analyzer can be used to accurately determine carbon and sulfur levels of samples composed of filings.

A third method that involves analysis of emery cloth rubbings has been used in the past for determining the chemical composition of an unknown material. \(^{(40)}\) The technique involves rubbing emery cloth over a suitably polished area on the pipe and sending the emery cloth to a laboratory for analysis. One serious limitation is that carbon content cannot be determined.

### 4.11.3 Control of Heat Input Levels

The ability to accurately control heat input levels is also an important aspect of being able to safely perform weld deposition repair. Control of heat input levels is particularly important in the case of corroded areas where the remaining wall thickness is near the 0.125 in. (3.2 mm) minimum wall thickness limit. Heat input, \(H\) (in kJ/in), is calculated as follows:

\[
H = \frac{VI60}{1000s} \tag{2}
\]

where \(V\) is the voltage (in volts), \(I\) is the current (in amps) and \(s\) is the travel speed \(D/t\) (in in/min), \(D\) being the distance traveled in time \(t\).

Alternately, heat input in kJ/mm is calculated as follows:

\[
H = \frac{VI}{1000s} \tag{3}
\]

where \(s\) is the travel speed in mm/sec.
Accurate measurement of heat input levels can be achieved using conventional equipment (amp tongs, voltmeter, stop watch, etc.) or purpose-built arc monitoring equipment. The run-out ratio scheme can also be used to control heat input levels. Using this scheme, the length of weld deposited is specified as some percentage of the electrode length consumed. Regardless of the method chosen to control heat input levels, a test plate should be used by the welder prior to depositing weld on In-service pipeline to ensure that the proper heat input level is being achieved.

4.11.3.1 Conventional Equipment

Arc voltage is commonly measured using a standard voltmeter. The positioning of voltmeter leads as close to the welding arc as possible is desirable, as this eliminates measurement of the additional voltage drop through the leads and work-piece.

Welding current is commonly measured using one of two methods. The first involves the use of a meter that operates on the principle of the Hall Effect, where the magnetic field generated by the current is measured directly, from which the current level is determined. This method is advantageous in that the Hall Effect meter can be clipped onto the current lead without breaking the circuit Digital meters or analog devices (amp tongs) are available for this purpose. The second common method for measuring welding current involves the use of a current shunt of known resistance, over which the voltage is measured. The current level is then calculated using Ohm’s Law.

Welding travel speed is commonly calculated using the arc time as measured using a stopwatch and the weld length as measured using a measuring scale (tape measure). Measurement of the arc time should include compensation for the time required for arc initiation. Proper measurement of the weld length is also important. For an accurate indication of how far the electrode traveled, the measurement should extend from the beginning of the weld deposit to the center of the crater at the end of the weld deposit.

4.11.3.2 Dedicated Arc Monitoring Equipment

There are a number of monitoring devices on the market that are dedicated to the monitoring of welding parameters. These operate primarily on the principals outlined above except that all of the equipment is self-contained. Arc voltage, current, and arc time are automatically monitored and recorded continuously. For the calculation of travel speed, the weld length must be measured and input manually Some devices have the ability to monitor and record welding parameters for more than one welding operation without the need to reconnect the monitoring
leads. The primary disadvantage of these devices is that some are somewhat cumbersome and relatively expensive.

4.11.3.3 Run-Out Ratio Scheme

The run-out ratio scheme, which is widely used in Europe, is a simple method of monitoring heat input levels without the need to measure arc voltage, current, or travel speed. The run-out ratio scheme is based on the relationship between welding current and the rate at which an electrode is consumed. It has been shown that the rate at which an electrode is consumed and the welding current are proportional\(^{(41)}\) and can be expressed as:

\[
\pi r^2 L \rho / t = K I
\]  
\(\text{(4)}\)

where \(r\) is the radius of the electrode core wire, \(L\) is the length of the electrode consumed in time \(t\), \(\rho\) is the density, \(K\) is a proportionality constant, and \(I\) is the welding current. Heat input, \(H\), is given by:

\[
H = VI / s
\]  
\(\text{(5)}\)

where \(s\) is the travel speed \(D/t\), \(D\) being the distance traveled in time \(t\). Substituting equation (4) for current in equation (5) gives

\[
H = \pi r^2 \rho V / K (L / D)
\]  
\(\text{(6)}\)

Therefore, for a given electrode diameter, the ratio of the length of electrode consumed to the length of weld deposited \((L/D)\) is proportional to the heat input, \(H\). This ratio is defined as the run-out ratio.

The run-out ratio scheme is used to control welding heat input by either specifying a run-out ratio that corresponds to the required heat input level or by specifying a run-out length for an entire electrode. Tables for run-out ratios for various types of electrodes depending on the iron powder content in the coating, and for various electrode sizes, are shown in Tables 6 through 8.\(^{(42)}\) Most low-hydrogen electrodes (EXX18-type) fall into the “electrodes-with-some-iron-powder” category (Table 7). To control the risk of burnthrough, the minimum required run-out ratio that corresponds to the maximum allowable heat input should be specified. Alternatively, minimum required run-out length for an entire electrode could be specified.
4.11.4 Application to Sour Service Pipelines

If weld deposition repair were to be applied to pipelines that transport or will transport wet and sour products, procedures must be developed and used that result in hardness levels that meet the NACE limits\(^{(43)}\) (i.e., 248 HV maximum) to ensure sulfide stress cracking resistance. The extent to which the pipe wall may be charged with hydrogen should also be considered, as this can affect the susceptibility of the weld to hydrogen cracking. The internal corrosion resistance following repair may also be affected, although no more so than following the installation of a welded full-encirclement sleeve. Additional work is required to fully address this.

4.11.5 Application to Duplex Stainless Steel Pipelines

Duplex stainless steels offer good corrosion resistance and relatively high tensile properties as the result of their approximately 50/50 austenite/ferrite phase balance. A potential problem with in-service repair of duplex stainless steel pipelines is that the accelerated cooling experienced by repair welds may significantly influence the balance between the austenite and ferrite phases, promoting a ferrite-rich microstructure. A recently completed project at EWI\(^{(44)}\) demonstrated that acceptable weld metal and HAZ microstructures, in terms of their phase balance and absence of secondary phases, could be achieved over a wide range of simulated thermal conditions and welding heat input levels for the 22% Cr materials studied, indicating the feasibility of hot tap welding onto duplex stainless steel pipelines. The ease with which these were achieved is due in part to the level of nitrogen, which is an austenite stabilizer, in the materials studied, which was above current Industry code requirements.

5.0 Development of Guidelines

The information presented in the previous section can be used by individual companies to develop a guideline or specification for carrying out weld deposition repair in the field. An example company specification was developed and is contained in Appendix B. This specification addresses the major topics of scope, policy, definitions, application, inspection and documentation, repair and removal of defects, and recoating and backfilling. The requirements outlined in Appendix B are for a hypothetical pipeline company. Individual pipeline companies may want to alter these requirements and/or add additional requirements.

6.0 Summary

The guidance provided in this report is based on the results of the most recent research and development in the area of weld deposition repair. This information was used to develop an
example guideline, in the form of a generic company specification. This guidance will allow the confident use of this repair technique, which is an attractive alternative to the installation of full-encirclement sleeves, and provide a foundation for regulatory acceptance.

7.0 Acknowledgments

The author would like to thank the project coordinator, Jim Swatzel at Columbia Gas Transmission, and the In-Service Welding Ad Hoc Group for their guidance, patience, and support. The skill and patience of EWI secretarial staff is also duly acknowledged. Finally, a special thanks is extended to John Kiefner at Kiefner and Associates for his contribution to the previous work on which this project is based.

8.0 References


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Stephens, S M Private communication November 1990.


Tables
Table 1. Summary of Heat Input Limits* for Non-Flowing Nitrogen Gas

<table>
<thead>
<tr>
<th>Remaining Wall Thickness, in. (mm)</th>
<th>Maximum Allowable Heat input, kJ/in (kJ/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5/64-in. (2.0-mm) -Diameter Electrodes at 50 amps</td>
</tr>
<tr>
<td>0 125 (3.2)</td>
<td>22 (0.87)</td>
</tr>
<tr>
<td>0 156 (40)</td>
<td>25 (0.98)</td>
</tr>
</tbody>
</table>

*Heat input limits contained in this table are the maximum allowed to prevent burnthrough using low-hydrogen (EXX18-type) electrodes.
<table>
<thead>
<tr>
<th>API 1104 Paragraph No.</th>
<th>Discontinuity Description</th>
<th>Discontinuity Definition</th>
<th>Applicability to Weld Deposition Repairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3.1</td>
<td>Inadequate penetration (IP)</td>
<td>The incomplete filling of weld root</td>
<td>Not applicable since weld deposition repairs have no root.</td>
</tr>
<tr>
<td>6.3.2</td>
<td>Inadequate penetration due to high-low (IPD)</td>
<td>The condition that exists when one edge of the root is exposed (or unbonded) because adjacent pipe or fitting joints are misaligned</td>
<td>Not applicable since weld deposition repairs have no root.</td>
</tr>
<tr>
<td>6.3.3</td>
<td>Incomplete fusion (IF)</td>
<td>A discontinuity between the weld metal and base metal that is open to the surface</td>
<td>Applicable to weld deposition repairs. Acceptance standards given in API 1104 are appropriate.*</td>
</tr>
<tr>
<td>6.3.4</td>
<td>Incomplete fusion due to cold lap (IFD)</td>
<td>A discontinuity between two adjacent weld beads or between the weld metal and base metal that is not open to the surface</td>
<td>Applicable to weld deposition repairs. Acceptance standards given in API 1104 are appropriate.'</td>
</tr>
<tr>
<td>6.3.5</td>
<td>Internal concavity (IC)</td>
<td>A bead that is fused to and completely penetrates the pipe wall thickness along both sides of the bevel, but whose center is somewhat below the inside surface of the pipe wall</td>
<td>Applicable to weld deposition repair (although indicative of an incipient burnthrough) Acceptance standards given in API 1104 are appropriate.*</td>
</tr>
<tr>
<td>6.3.6</td>
<td>Burn-through (BT)</td>
<td>A portion of the root bead where excessive penetration has caused the weld puddle to be blown into the pipe</td>
<td>Increased significance since pipe is pressurized. Should a burnthrough occur and then be repaired, the acceptance standards given in API 1104 are appropriate.*</td>
</tr>
<tr>
<td>6.3.7</td>
<td>Slag inclusions, elongated (ESI) or isolated (ISI)</td>
<td>A nonmetallic solid entrapped in the weld metal or between the weld metal and the pipe metal</td>
<td>Applicable to weld deposition repairs. Acceptance standards given in API 1104 are appropriate.'</td>
</tr>
<tr>
<td>6.3.8</td>
<td>Porosity, individual or scattered (P), cluster (CP), or hollow bead (HB)</td>
<td>Gas trapped by solidifying weld metal before the gas has had a chance to rise to the surface of the molten puddle and escape</td>
<td>Applicable to weld deposition repairs, except for HB (since weld deposition repairs have no root) Acceptance standards for P and SP given in API 1104 are appropriate.'</td>
</tr>
<tr>
<td>6.3.9</td>
<td>Cracks (C)</td>
<td>Cracks</td>
<td>Applicable to weld deposition repairs. Acceptance standards given in API 1104 are appropriate.*</td>
</tr>
</tbody>
</table>

(continued)

* Provided that weld length for weld deposition repairs is defined
<table>
<thead>
<tr>
<th>API 1104</th>
<th>Discontinuity Description</th>
<th>Discontinuity Definition</th>
<th>Applicability to Weld Deposition Repairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3.10</td>
<td>Undercutting (EU or IU) -</td>
<td>A groove melted into the base metal adjacent to the toe or root of the weld and left unfilled my weld metal.</td>
<td>Applicable to weld deposition repairs. Acceptance standards given in API 1104 are appropriate *</td>
</tr>
<tr>
<td>6.3.11</td>
<td>Accumulation of discontinuities</td>
<td>Accumulated discontinuities excluding inadequate penetration due to high-low and undercutting</td>
<td>Applicable to weld deposition repairs Acceptance standards given in API 1104 are appropriate. *</td>
</tr>
<tr>
<td>6.3.12</td>
<td>Pipe or fitting discontinuities</td>
<td>Arc burns, long seam discontinuities, and other discontinuities in the pipe or fittings detected by radiography</td>
<td>Applicable to weld deposition repairs</td>
</tr>
</tbody>
</table>

* Provided that weld length for weld deposition repairs is defined

<table>
<thead>
<tr>
<th>API 1104</th>
<th>Description</th>
<th>Definition</th>
<th>Applicability to Weld Deposition Repairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>641</td>
<td>Classification of indications</td>
<td>Non relevant indications are those with a maximum dimension of 1/16 in (1.6 mm) or less Relevant indications are those caused by discontinuities Linear indications are those in which the length is more than three times the width Rounded indications are those in which the length is three times the width or less</td>
<td>Applicable to weld deposition repairs</td>
</tr>
<tr>
<td>642</td>
<td>Acceptance standard</td>
<td>Linear and rounded indications</td>
<td>Applicable to weld deposition repairs Acceptance standards given in API 1104 are appropriate *</td>
</tr>
<tr>
<td>643</td>
<td>Pipe or fitting discontinuities</td>
<td>Laminations, arc burns, long seam discontinuities, and other discontinuities in the pipe or fittings detected by magnetic particle testing.</td>
<td>Applicable to weld deposition repairs</td>
</tr>
</tbody>
</table>

* Provided that weld length for weld deposition repairs is defined

---

* Provided that weld length for weld deposition repairs is defined
### Table 4. API 1104 Acceptance Standards for Liquid Penetrant Testing as Applied to Weld Deposition Repairs

<table>
<thead>
<tr>
<th>API 1104 Paragraph No.</th>
<th>Description</th>
<th>Definition</th>
<th>Applicability to Weld Deposition Repairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5.1</td>
<td>Classification of indications</td>
<td>Non relevant indications are those with a maximum dimension of 1/16 in. (1.6 mm) or less. Relevant indications are those caused by discontinuities. Linear indications are those in which the length is more than three times the width. Rounded indications are those in which the length is three times the width or less.</td>
<td>Applicable to weld deposition repairs</td>
</tr>
<tr>
<td>6.5.2</td>
<td>Acceptance standard</td>
<td>Linear and rounded indications</td>
<td>Applicable to weld deposition repairs</td>
</tr>
<tr>
<td>6.5.3</td>
<td>Pipe or fitting discontinuities</td>
<td>Laminations, arc burns, long seam discontinuities, and other discontinuities in the pipe or fittings detected by liquid penetrant testing</td>
<td>Applicable to weld deposition repairs.</td>
</tr>
</tbody>
</table>

* Provided that weld length for weld deposition repairs is defined

### Table 5. API 1104 Acceptance Standards for Ultrasonic Testing as Applied to Weld Deposition Repairs

<table>
<thead>
<tr>
<th>API 1104 Paragraph No.</th>
<th>Description</th>
<th>Definition</th>
<th>Applicability to Weld Deposition Repairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.6.1</td>
<td>Acceptance standards</td>
<td>See 662 and 663</td>
<td>Applicable to weld deposition repairs</td>
</tr>
<tr>
<td>6.6.2</td>
<td>Linear indications</td>
<td>Indications that produce a response greater than 20% of the reference level.</td>
<td>Applicable to weld deposition repairs.</td>
</tr>
<tr>
<td>6.6.3</td>
<td>Pipe or fitting discontinuities</td>
<td>Laminations, long seam discontinuities, and other discontinuities in the pipe or fittings detected by ultrasonic testing</td>
<td>Applicable to weld deposition repairs.</td>
</tr>
</tbody>
</table>

* Provided that weld length for weld deposition repairs is defined
<table>
<thead>
<tr>
<th>Electrode Diameter, in. (mm)</th>
<th>Heat Input, kJ/in. (kJ/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15 (0.6)</td>
</tr>
<tr>
<td>3/32 (2.4)</td>
<td>0.53</td>
</tr>
<tr>
<td>1/8 (3.2)</td>
<td>0.87</td>
</tr>
<tr>
<td>5/52 (4.0)</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Table 7. Run-Out Ratios for Electrodes Containing Some Iron Powder (including most EXX18-type electrodes)

<table>
<thead>
<tr>
<th>Electrode Diameter, in. (mm)</th>
<th>Heat Input, kJ/in. (kJ/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15 (0.6)</td>
</tr>
<tr>
<td>3/32 (2.4)</td>
<td>0.62</td>
</tr>
<tr>
<td>1/8 (3.2)</td>
<td>1.01</td>
</tr>
<tr>
<td>5/52 (4.0)</td>
<td>1.57</td>
</tr>
</tbody>
</table>

Table 8. Run-Out Ratios for Electrodes Containing High Iron Powder Contents
Figures
1. First Perimeter Pass

2. First Layer

3. Grinding Applied to Perimeter Pass

~ 1/16 in. (1-2 mm)

4. Second Perimeter Pass

5. Second Layer

Toe of second perimeter pass just consumes corner produced by grinding step. No new heat-affected zone in base material permitted.

Figure 1. Illustration of Typical Weld Deposition Sequence
Figure 2. Area of Wall Loss Following Clean-Up Grinding. Deeper Areas Are Marked With Soap Stone. Note: Initial attention to deeper areas such as these is not necessary, although simplifies filling of the remaining area.

Figure 3. Deposition of Perimeter Pass and First Layer in Deeper Areas, Followed By Perimeter Pass Grinding. Remaining Area to be Repaired is Marked With Soap Stone. Note: In this example, a portion of the wall loss was to be left un-repaired.
Figure 4. Deposition of Perimeter Pass and Several First Layer Passes. Note: First layer passes in this example were begun in the middle of the area of wall loss, then proceeded to one side and then the other. First layer passes may be begin at one side or the other.

Figure 5. Deposition of Additional First Layer Passes. Note: First layer passes should not be allowed to melt any new base material beyond the perimeter pass.
Grinding Applied to Perimeter Pass and First Layer. Separation Between Weld Toe and Ground Surface Should Be About 1/16 in. (1-2 mm). Note: Grinding applied to the first layer is only for evening the height of the layer.

Deposition of Second Perimeter Pass. Separation of the First and Second Perimeter Pass Weld Toes Should Be Approximately 1/16 in. (1-2 mm). Note: The welder can use the intersection of first perimeter pass and the ground surface as an aid for the placement of the second perimeter pass weld toe. The second perimeter pass should not be allowed to melt any new base material beyond the first perimeter pass.
Figure 8. Deposition of Several Second Layer Passes. Note: In this example, two layers were sufficient to fully restore the wall thickness. Additional layers may be applied as necessary. Additional perimeter passes are not necessary.

Figure 9. Completed Repair. Note: The weld reinforcement may be left as-welded or removed by grinding.
Figure 10. Illustration of Weld Deposition Sequence Adapted to External Repair of Internal Wall Loss.
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Appendix A

Battelle Model-Produced
Heat Input Limit Guidelines
Figure A1. Battelle Model-Predicted Heat Input Limits* - Methane at 300 psig (2.0 MPa)  
* Heat input limits contained in this figure are the maximum allowed to prevent burnthrough using low-hydrogen (EXX18-type) electrodes.
Figure A2. Battelle Model-Predicted Heat Input Limits* - Methane at 600 psig (4.1 MPa)
*Heat input limits contained in this figure are the maximum allowed to prevent burnthrough using low-hydrogen (EXX18-type) electrodes
Figure A3. Battelle Model-Predicted Heat Input Limits* - Methane at 900 psig (6.1 MPa)
*Heat input limits contained in this figure are the maximum allowed to prevent burnthrough using low-hydrogen (EXX18-type) electrodes.
Appendix B

Example Weld Deposition Repair Specification
1. Scope

This document outlines the requirements for carrying out repair of damaged or defective pipelines and related components by direct deposition of weld metal, or weld depositron repair. The use of this document is limited to external defects in carbon steel pipelines and components within the following ranges:

- Diameter 2-3/8 in. through 48 in.
- Wall thickness 0.156 in. through 0.750 in.
- Grade B through X70

This document is limited to repairs made using the SMAW process using low-hydrogen (EXX18-type) electrodes.

2. Policy

The overriding concern addressed by this document is safety. Safety in this context includes, but is not limited to insuring that no harm comes to any person or persons during the application of a repair, and that the repair adequately restores the integrity of the damaged or defective pipeline segment.

3. Definitions

- Company - Refers to the owner company or its authorized representative
- Defect - Refers to an area of external wall loss caused by corrosion or by grinding to remove mechanical damage.

4. Application

4.1 Pressure Reduction - Prior to the commencement of any repair activities, the pipeline operating pressure should be reduced to 80% or less of the level which was present when the defect was discovered. Following assessment (see Section 4.2 below) the pressure may be increased to the RSTRENG-predicted safe pressure (i.e., failure pressure multiplied by the design factor).

4.2 Assessment Prior to Repair

4.2.1 Remaining Strength - B31 G, RSTRENG or another Company-approved method should be used to determine the remaining strength of the defect. If the predicted failure pressure exceeds 100% of SMYS, then no repair is necessary.

4.2.2 Maximum Permissible Size of Repair - The maximum allowable size of an area for which repair is permissible is shown below. Prior Company approval is required for repair of larger areas.
4.2.2.1 Longitudinal length - 6 in. (150 mm) or 25% of the pipe diameter (whichever is larger).

4.2.2.2 - Circumferential width - 3 in. (75 mm) or 12-1/2% of the pipe diameter (whichever is larger).

4.2.3 Proximity to Other Repairs - Individual repairs should be separated by at least 1 in. (25 mm).

4.2.4 Dented Areas - Weld deposition repair of an area that is associated with a dent in the pipeline is prohibited.

4.3 Determination of Remaining Wall Thickness - The remaining wall thickness should be measured using appropriate equipment and techniques. Care should be taken to ensure that the remaining wall thickness is measured in the thinnest area. The minimum remaining wall thickness on which a repair should be attempted is 0.156 in. (4.0 mm). Prior Company approval is required for repair of thinner areas (down to 0.125 in. [3.2 mm]).

4.4 Surface Preparation - The surface of the area should be prepared to produce a favorable profile and to remove corrosion products from the area. Care should be taken to ensure that the surface preparation does not significantly increase the depth of the area.

4.5 Selection of Welding Parameters - If the minimum remaining wall thickness is less than 0.25 in. (6.4 mm), a value for the maximum allowable heat input level should be established to minimize the risk of burnthrough.

4.6 Qualification of Procedures and Welders

4.6.1 - Procedure Qualification - Welding procedures should be qualified to the requirements of Section 2 of API 1104. Pipeline operating conditions that affect the ability of the flowing contents to remove heat from the pipe wall, where applicable, should be simulated by filling the test section with water and allowing water to flow through the test section while the test joint is being made. The pipe material carbon equivalent level for which the procedure applies replaces the specified minimum yield strength as an essential variable. The macrosection test from API 1107 should be added to the procedure qualification test requirements.

4.6.2 - Welder Qualification - Welders should be qualified to the requirements of Section 3 of API 1104. Pipeline operating conditions that affect the ability of the flowing contents to remove heat from the pipe wall, where applicable, should be simulated by filling the test section with water and allowing water to flow through the test section while the test joint is being made. Welders should be able to
demonstrate the ability to maintain a heat input level within the specified range of the procedure for which he is being qualified.

4.6.3 - Other Requirements - All welders performing weld deposition repair work should be familiar with the safety precautions associated with welding onto in-service pipelines.

4.7 Deposition of Repair

4.7.1 Handling of Low-Hydrogen Electrodes - Low-hydrogen electrodes should be stored at an appropriate temperature in portable field ovens or used from freshly opened, airtight containers.

4.7.2 Sequence - A weld deposition sequence that is suitable for the geometry of the area being repaired, and that results in a significant amount of tempering from subsequent passes, should be used. A perimeter pass should be used to establish a boundary beyond which no subsequent welding is allowed. The first layer of fill passes should be deposited using established heat input limits to minimize the risk of burnthrough. A second perimeter pass should be used to temper the HAZ at the toe of the first perimeter pass. Higher heat input fill passes should be used for subsequent layers to further temper the initial passes, again observing established heat input limits to minimize the risk of burnthrough if necessary. Additional layers should be deposited, as necessary, for proper filling.

4.7.2.1 Areas with Irregular Depth - Where necessary, the general technique (i.e., a perimeter weld followed by consecutive parallel fill passes) can be first applied to the deepest areas of wall loss until a uniform remaining depth was established.

4.7.3 Control of Heat Input Levels - If the minimum remaining wall thickness is less than 0.25 In. (6.4 mm), the heat input level should be monitored using appropriate equipment and techniques. The heat input level should not be allowed to exceed the maximum allowable level established to minimize the risk of burnthrough

4.7.4 Clean-Up - The completed repair should be cleaned-up by grinding or using rotary files, as necessary, to facilitate inspection and recoating.

5 Inspection and Documentation

5.1 Inspection of Completed Repairs - The toe area of the completed repair should be inspected using magnetic particle inspection or angle beam ultrasonic testing, or a combination of these. Volumetric Inspection of the completed repair should be carried out using straight-beam ultrasonic testing or radiography.
5.2 Acceptance Standards - The disposition of discontinuities detected during inspection should be determined using Section 6 of API 1104. For weld deposition repairs, weld length is defined as the maximum length of the repair along the longitudinal axis of the pipeline.

5.3 Documentation - Following acceptance of the repair, pertinent information concerning the repair should be recorded.

6. Repair and Removal of Defects -

Repair and removal of defects should be carried out in accordance with the requirements in Section 7 of API 1104 or API 1107. Care should be taken during the removal of the defect to ensure that the wall thickness is not reduced to less than that which is acceptable for the operating pressure of the pipeline.

7. Recoating and Backfilling

After the repair has been inspected and accepted, the pipeline should be recoated with an approved coating material and backfilled. Care should be taken to assure that the pipeline is properly supported prior to backfilling.