APPENDIX A

RESEARCH REPORT REVIEWS

PR-185-815

Review of Procedures for Welding Onto Pressurized Pipelines

This report is a summary report describing the state of practice for welding of attachments to pressurized pipelines and storage vessels (hot tapping). The review was based upon open literature and accounts describing successful procedure developments or applications with the outcome of the review indicating that no national standards exist and that areas in need of further work include identification of welding parameters for sour service, thin wall and stainless steel pipe in-service welding. In addition, techniques for assessing hydrogen cracking delay times and weld/HAZ flaws need further work.

The report focuses on in-service welding where the primary concerns are state to be: 1) excessive penetration or burn (melt) through and 2) rapid cooling due to the high pipeline heat sink leading to a hard microstructure that is susceptible to hydrogen cracking. To this end in-service welding recommendations and observations were collected from open literature, field experience and laboratory / numerical modeling results. The focus of in-service welding concerns related to the sleeve end fillet weld and to a lesser extent the long seam welds that could be deposited on to a backing bar or be achieved using a lap connection.

The review of industry techniques for in-service pipeline welding were discussed, including burn-through, preheating, wall thickness limits, pipe pressure limits and inspection. This review suggested that burn-through could be controlled by controlling heat input. While it is noted that direct control of heat input is impractical, a sufficient level of heat input control could be achieved through: control of electrode diameter (e.g. use dia < 2.5mm), maximum current limits, using 2mm thick backing bars and specifying stringer bead welding techniques. It was noted that only about 75% of the industry applied pre-heat (levels between 50 and 250^{o}C) on a regular basis to control hydrogen cracking, however, where preheat was not specified, low hydrogen electrodes were specified. It is recommended that pre-heat be applied using resistance heating to avoid torch introduced condensation. In the review of minimum wall thicknesses for in-service welding, it was noted that short welds and those deposited with low hydrogen electrodes were least susceptible due primarily to the relatively low hoop stresses. In-service welds using low hydrogen electrodes are considered to have a low burn through risk for pipe wall thicknesses as low as 4.7mm (3/16 in) and have been safely deposited on 3.2mm (1/8 in) wall thicknesses. As far as maximum safe pipe pressure is concerned, there was no industry consensus, however, it is noted that the ASME Gas pipeline recommendations are most widely followed. It is also suggested that lowering pipeline pressure to achieve pipe compression under a sleeve is ineffective and the sleeve can only be relied upon to provide local support to prevent bulging. Inspection of in-service deposited welds is recognized as the most significant issue since no reliable inspection techniques were considered to exist. As an alternative to inspection it was suggested that a 1.25 MAOP pressure test could be used.

In discussing the prevalence and implications of various welding processes, consumables, materials and environment (e.g. sour service or hazardous materials, the review notes that the majority of North American in-service welding is accomplished using SMAW with cellulosic coated (Exx10) or basic low hydrogen (Exx18) electrodes and some use of rutile coated (Exx13) electrodes being used in Europe. To improve weld quality and reduce hydrogen cracking potential interest in GMAW and FCAW are being pursued. A significant concern for in-service welding is older steels (high carbon and sulphur) where no guidance was published. It was also noted that very clean steels (sulphur < 0.002%) sometimes can exhibit high hardenability and that an increasing amount of sour service duplex stainless pipe is being used and can suffer from reduced corrosion resistance if rapid cooling occurs. Sour service pipelines or pipelines that are carrying increasingly sour products are identified as a concern, with regards to hydrogen assisted cracking in high hardness areas, since the integrity of in-service welds in these situation may not have been completed with due consideration for hydrogen cracking.

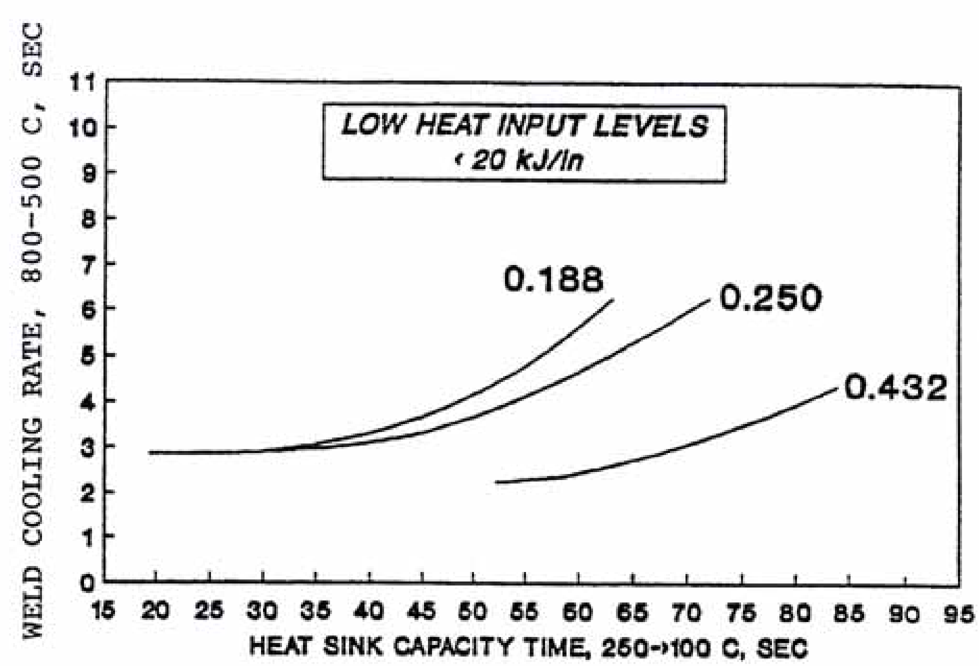
Hydrogen cracking is identified as the most widespread type of HAZ defect and the factors affecting it (hydrogen concentration, microstructure susceptibility, restraint, temperature) are reviewed. Techniques to prevent hydrogen cracking include the control of hydrogen entering the weld pool through the selection of a low hydrogen welding process, moisture control (electrode coatings, preheating/drying and gas moisture content) and cleanliness (remove grease, paint, rust). Microstructure control is described in terms of controlling weldment cooling rate (higher heat input), using multi-pass welding procedures (tempering), control of inter-pass times and temperatures. The effect of restrain is in its definition of the local tensile stress level, however, this effect is difficult to control in practice thus it is recommended that procedure development trials include appropriate restraint conditions.

In-service welding procedure development techniques are briefly discussed in the paper to suggest that few published methods for developing safe welding procedures are available. The most significant weld procedure development support tools discussed include: BG standards BGC/PS/P9, the Battelle hot tap model, and the EWI spot heating / heat sink criteria. It is noted however, that at the time of publication none of these models was highly regarded as the final answer to in-service weld procedure development.

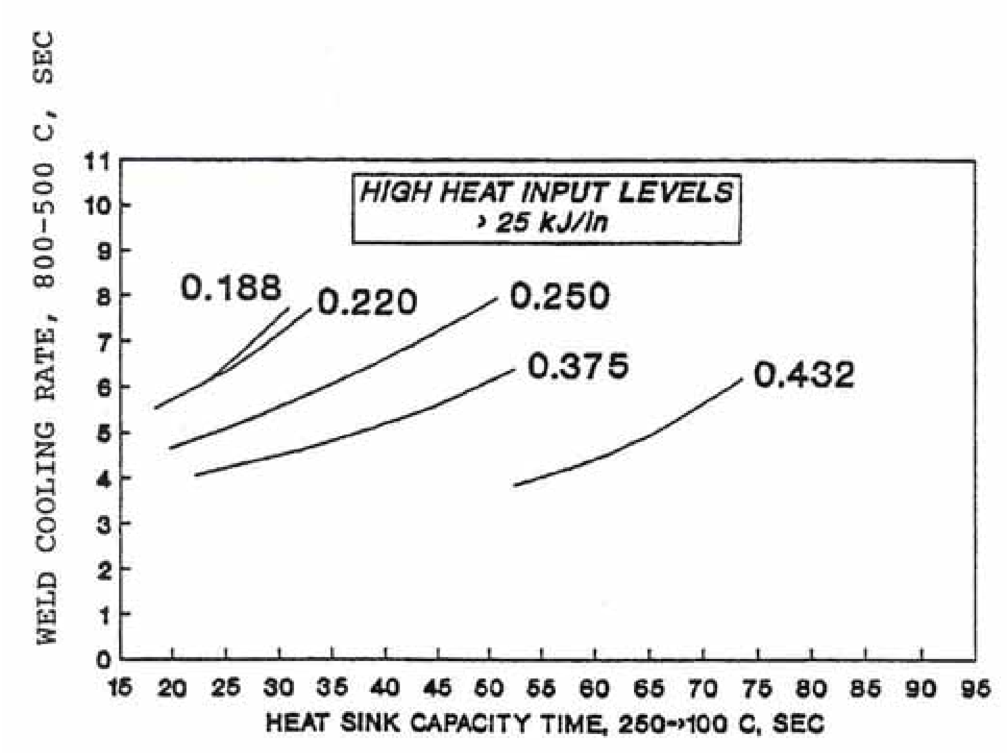
The report concludes by indicating that most of the in-service welding information available in the literature is qualitative in nature. It is recommended that the safety of in-service welding could be improved by considering the following research topics:

- how to weld thin walled pipe ($t < 1/4$ in) without burn through,
- how to weld on pipes carrying sour products,
- how to weld on other pipe materials (i.e. duplex stainless steel)
- how long does it take for hydrogen cracking to manifest (i.e. delay time to cracking)
- how to weld on internally clad pipes
- how to realistically proof test welds, and
- how to assess flaws in weldments (i.e. weld and HAZ)

The EWI cooling capacity empirical relations (Figure 1.1) provide a link between the 250 to 100^{o}C cooling time ($\Delta t_{2.5/1}$) and 800 to 500^{o}C cooling time ($\Delta t_{8/5}$) for various pipe geometry (pipe wall thickness) and heat input (welding parameters) combinations. The $\Delta t_{2.5/1}$ value represents the cooling capacity of the flow medium during “in-service” welding in pipes, for example, in liquid lines, gas lines. The approach is “extended” for spot heating test simulations in the field. The draw back is the need for extensive empirical parametric data from experimental runs so that typical variations of the parameters (wall thickness, fluid types, flow rates, welding parameters) are included.



(a) heat input < 20 kJ/inch (0.78 kJ/mm)



(b) heat input > 25 kJ/inch (1kJ/mm)

Fig .1.1: Weld cooling rate relations for two heat input levels in hot tap welds.

The Battelle thermal-analysis model, on the other hand, is more versatile as it can be applied to any number of heat input, pipe geometry cooling medium, and flow rate combinations. It has been developed for modeling 2D heat transfer behaviour when welding; a) reinforcement sleeve (fillet weld) or b) hot tap simulation (groove weld). The inputs to the thermal model include, welding parameters (heat input), cooling capacity parameters (physical properties of the cooling medium carried in the line and its flow velocity and pressure data), and pipe geometry. The two outputs are the temperature-time data after welding and the peak temperature on the ID surface of the pipe. Figure 1.2 and 1.3 shows typical outputs. Figure 1.3 can be used for developing safe welding envelopes.

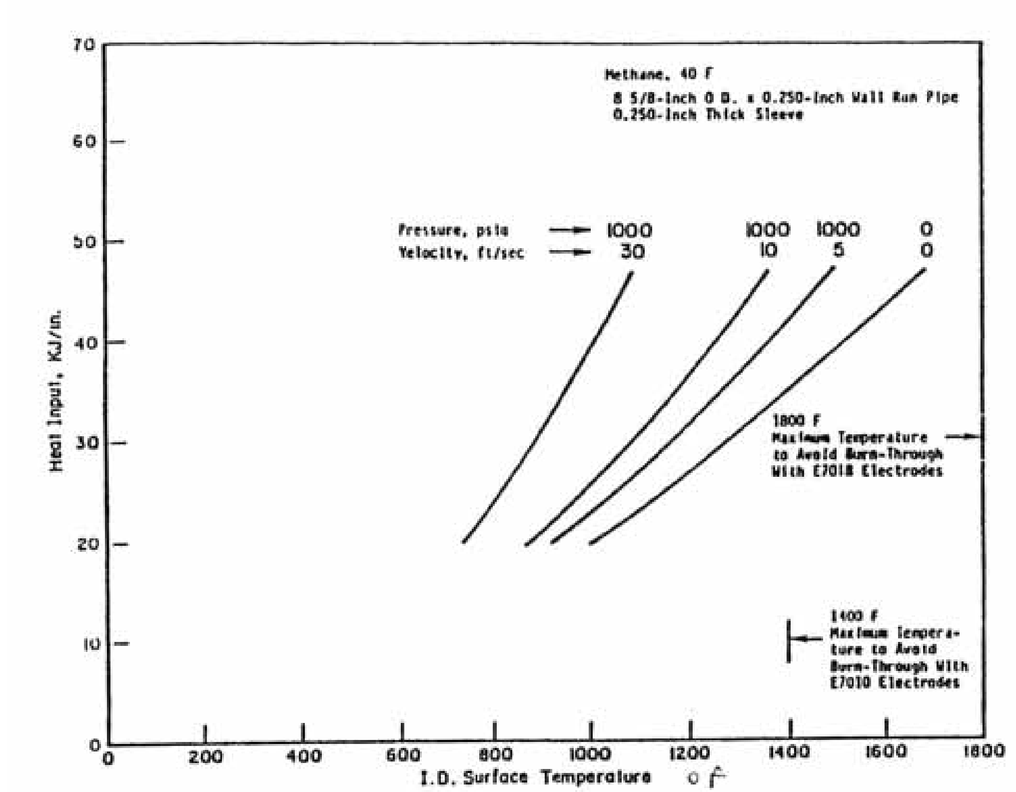


Fig .1.2: Prediction of ID surface temperature as a function of heat input for sleeve repair (fillet welds). Burn through temperature limits appear to be related to penetration profile.

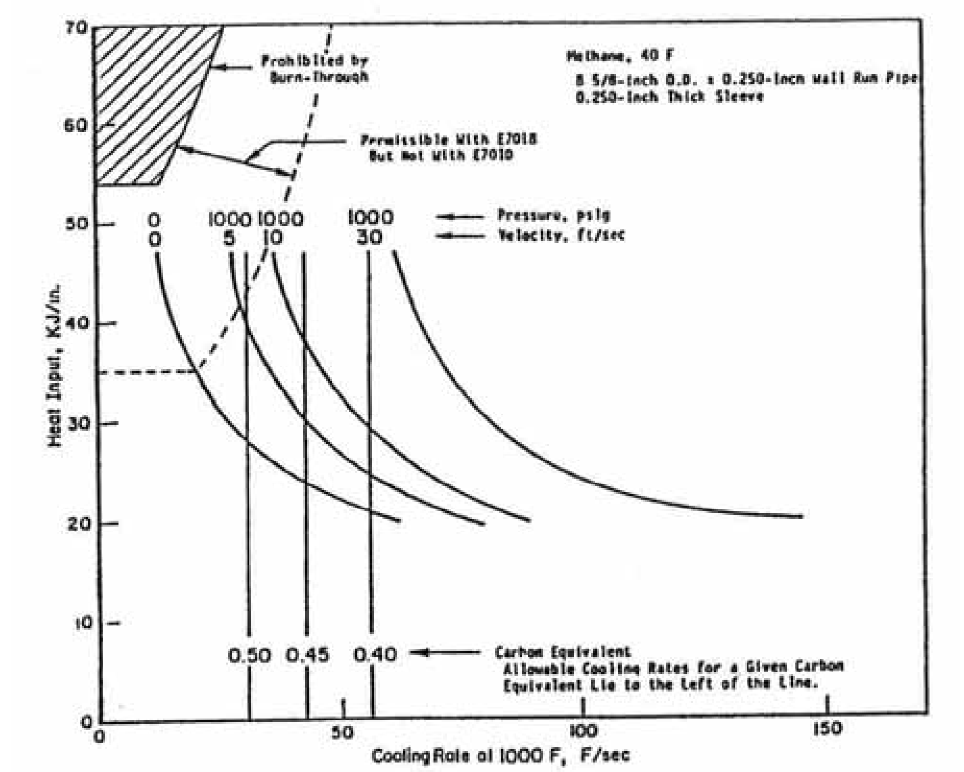


Fig .1.3: Prediction of weld cooling rates as a function of heat input for sleeve repair (fillet welds). The C.E. limits are based on critical cooling rate in the HAZ.

The cooling rate at 1000^{o}F (540^{o}C) (similar to $\square t_{8/5}$ value) is used in conjunction with the carbon equivalent (C.E.) to predict the risk of cracking in the base metal HAZ on the basis of critical hardness (350VHN). *(Note that the 350VHN level is based on weld made without hydrogen control, for those welds made with diffusible hydrogen below 5 ml/100gr deposited weld metal, the critical hardness can be raised to 400VHN.)* The peak temperature on the ID surface of the pipe is the basis to avoid "burn-through" during live welding. The peak temperature to avoid burn-through is set at 1800^{o}F and 1400^{o}F for EXX18 and EXX10 type electrodes. A lower critical peak temperature has been set for EXX10 type electrodes due to the deeper penetration of the weld bead.

To compare/combine the results of the EWI cooling capacity empirical relation with the Battelle thermal model output to determine safe welding parameters to use for sleeve reinforcements and hot tap procedures. The primary objectives are to avoid HAZ cracking and burn-through.

Two types, pipe to sleeve (fillet) and Branch connections (groove welds) were evaluated. For the first case, an arc efficiency of 75% was used with the SMAW process. The cooling effect of stationary and flowing mediums were considered. In the case of liquid medium "film boiling" was considered. For the groove welds, the effect of flow parallel with and perpendicular to the weld were not differentiated (the effect was assumed to be small in comparison to the effects of flow it self).

Validation of the thermal analysis models of hot taps was preformed with natural-gas, nitrogen-filled and liquid propane pipeline loops. Case studies for three separate pipes are presented. Two were hot tap welds and the other was a sleeve weld. Two were SMAW process and the other was GMAW (100% CO_2). All had IIW C.E. greater than or equal to 0.4. The pipe diameters ranged from 8.5 to 26 inch. In total 20 welds were made with 14 single pass and the remaining ones were 3-pass. The EWI hot tap approach was also used; the data collected included $\square t_{8/5}$ value for the weld pool, heat sink capacity times, and welding parameters.

The clock position of welding was not considered in the Battelle models. Similarly, for branch connections, the models were simplified by setting position and flow direction to default values. Thus "size on size" branch connections are not covered in the model.

An appurtenance field-welding situation is evaluated using the Battelle thermal model, using a "flow diagram". The objective is to determine the minimum heat input level for single welding to reach a maximum hardness of 350VHN. Alternatively, if this heat input "window" is impractical how the cooling capacity can be adjusted to enlarge the window. In the field the EWI cooling capacity empirical relationships are adopted to check the model cooling capacity output. This is termed the "dual approach".

Correlations between weld cooling times ($\square t_{8/5}$) and heat input for single pass welds have been developed for various heat sink capacities ($\square t_{2.5/1}$) and pipe wall thickness. Experimental results, from over 100 welds, for liquid lines (fuel and crude oil) display scatter and "best fit" curves have been obtained for various wall thicknesses ranging from 0.156 to 0.375 inch (4 to 9.5 mm). No reference is made to fluid type or weld configuration (groove or fillet). For the 0.25 inch (6.4 mm) wall pipe the experimental heat sink capacity ($\square t_{2.5/1}$) range is 8 to 44s. Similar info can be gathered for all wall thicknesses.

The following are significant outcomes:

- The effect of the sleeve weld location w.r.t to flow direction, on the cooling capacity, of the carrier pipe was found to be negligible by performing model runs with sleeve down stream or up stream of the fillet weld.

- For sleeve repair the effect of the thermal boundary layer growth in the direction of flow was found to be significant.

- Model runs are used to determine the relation between the cooling rate at 1000^{o}F (540^{o}C) and $\Delta t_{8/5}$ value. These do not seam to link with pipe geometry. The cooling rate is related to the maximum C.E. using critical cooling rate empirical curves.

- Results from validation experiments include the $\Delta t_{8/5}$ - $\Delta t_{2.5/1}$ relation (EWI hot tap relation), comparison of model out put vs field experiments (see Figure 1.4 for a typical example). The results in the report include wall thickness range of 0.219 to 0.312 inch, cooling capacity range of 70 to 20s, heat input range of 0.7 to 1 kJ/mm, flow rates of 5 to 45 fps.

- Limitations and comments: (a) Wall thickness <0.5 inch (although the results presented have an upper value of only 0.312 inch). (Wall thickness beyond 0.5 inch is expected be insensitive to cooling effect from fluid flow), b) validations were made for fluid types included gas and hydrocarbon liquids.

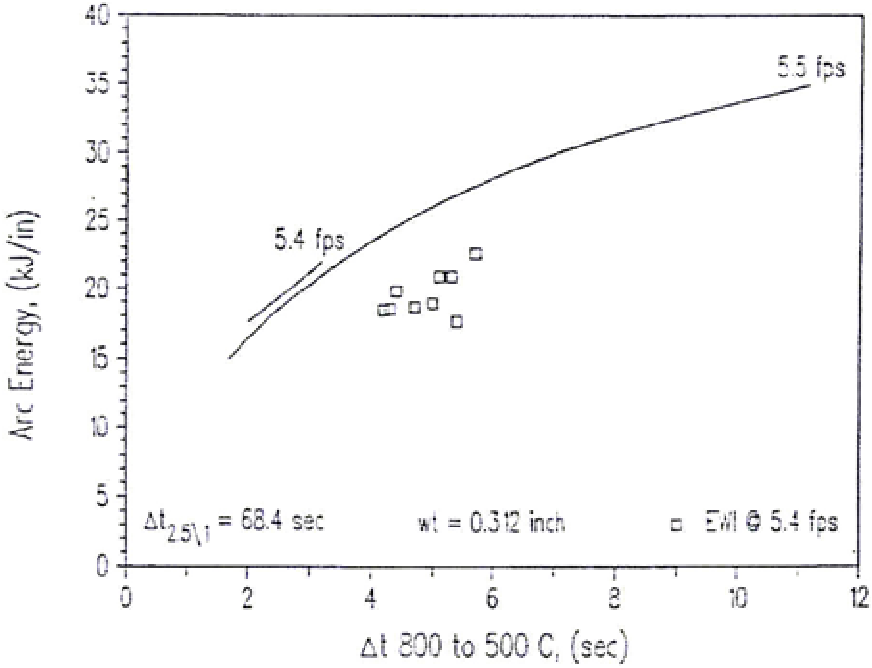
- The heat transfer models over-predict the inside surface temperature and therefore give a conservative burn-through prediction and result in safe estimates of welding parameters to prevent burn-through. The models have default electrode angles of 40^{o} and 22.5^{o} for groove and fillet welds, respectively. These default angles are less than the typical angles used for the two categories of welds, thus leading to higher weld penetration profiles also leading to a higher inside surface temperature prediction.

- Post-test examination indicated HAZ hardness close to 350VHN, but HAZ cracking was not discovered. In a few cases the hardness exceeded 400, but still cracking was not observed using both MPI and subsequent cross section metallography.

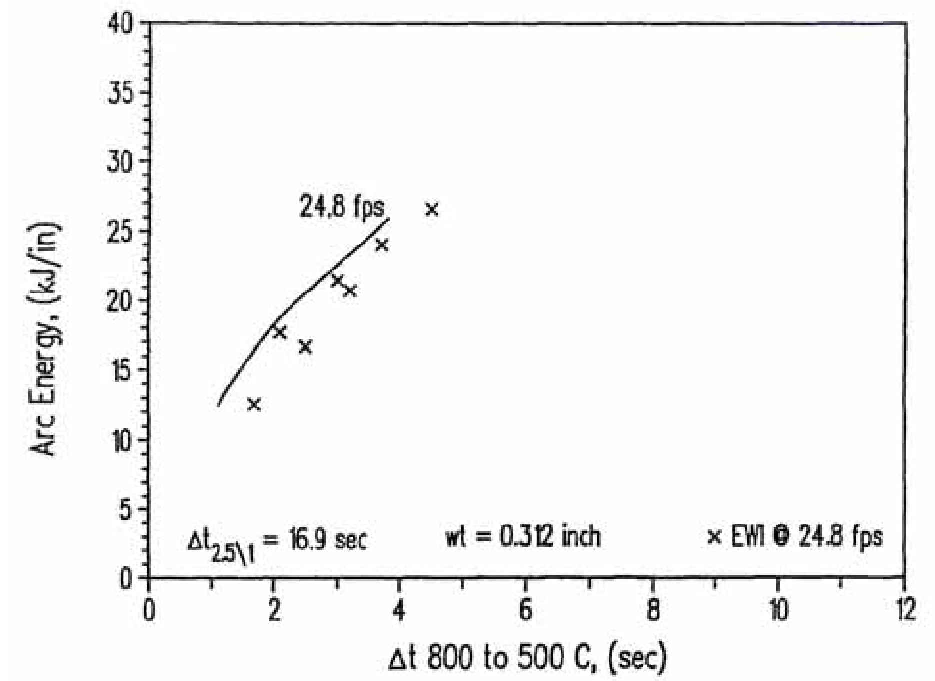
- Examples are presented for applying the “dual approach” and the typical results are presented in Figure 1.5.

- Correlations between weld cooling times ($\Delta t_{8/5}$) and heat input for single pass welds have been developed for various heat sink capacities ($\Delta t_{2.5/1}$) and pipe wall thickness. Two examples, “heat input selection curves”, are presented in Figure 1.6. These plots show the “best fit” curves and the EWI experimental data on which these curves were developed. The two cases presented show the significance of the cooling capacity ($\Delta t_{2.5/1}$) on weld cooling rate as a function of heat input for thin wall pipe and how the significance diminish as the wall thickness is increased.

- The agreement between the thermal model and the results from the EWI heat sink capacity technique is not good. This may be a result of the scatter in the experimental data used for developing the correlations in the EWI heat sink capacity technique. The scatter in the cooling capacity data is claimed to be from the variability associated with welding in examples presented in Figure 6.

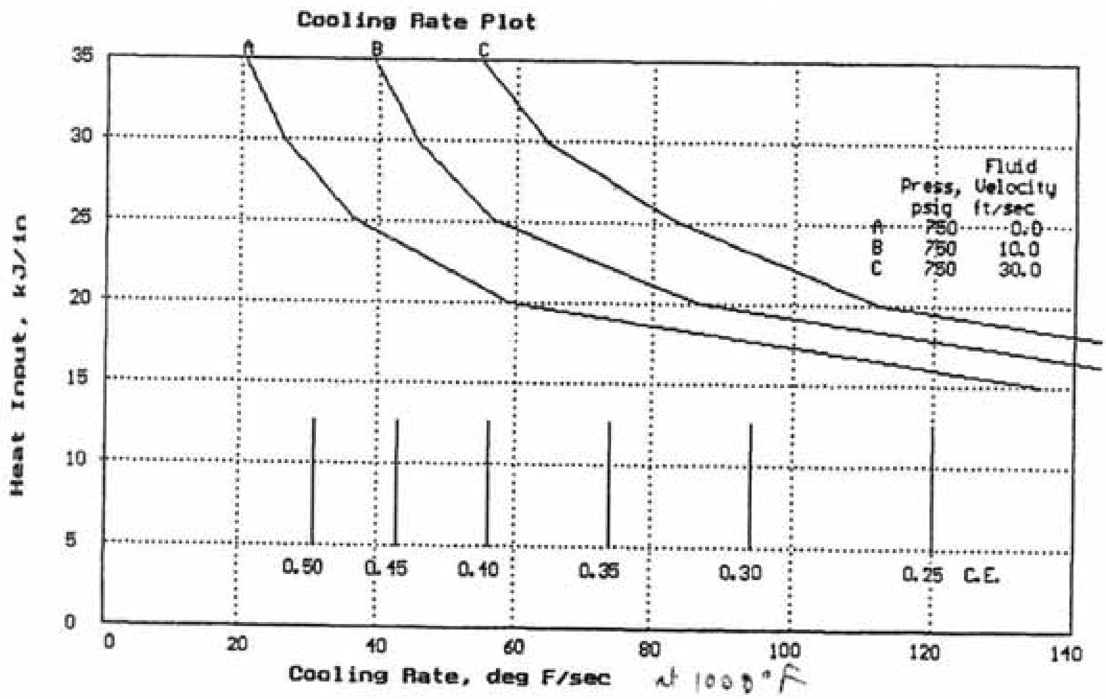


(c) (□$t_{2.5/1}$) = 68.4s

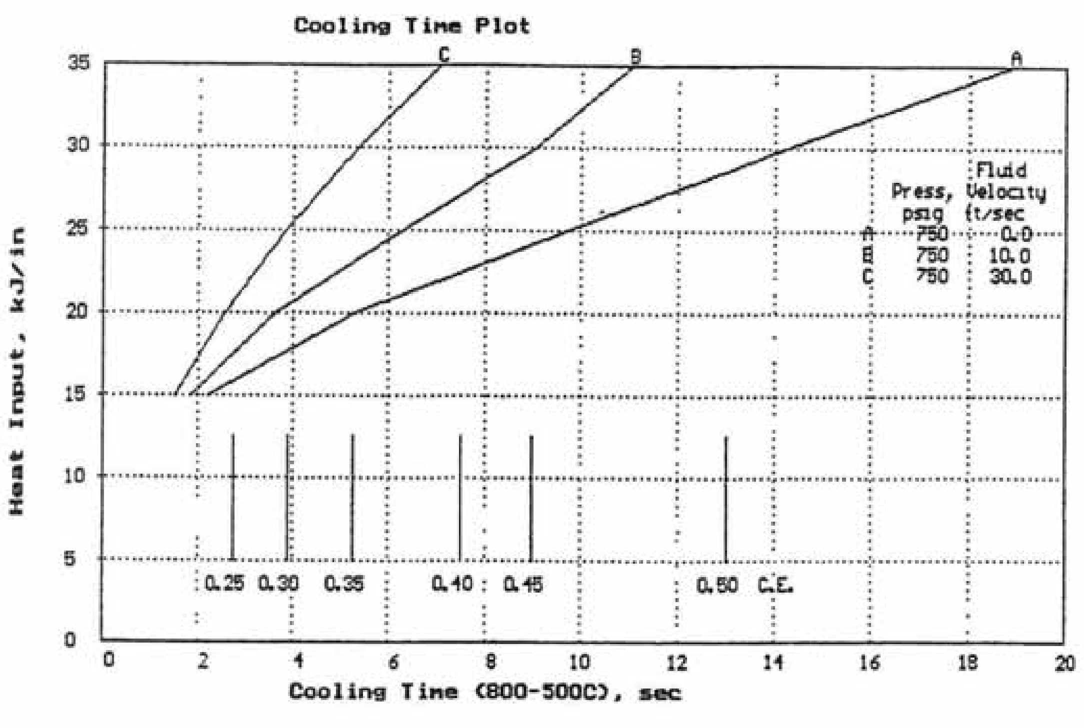


(d) (□$t_{2.5/1}$) = 16.9s

Fig .1.4: Arc energy vs. □$t_{8/5}$ cooling rate for two flow rates.

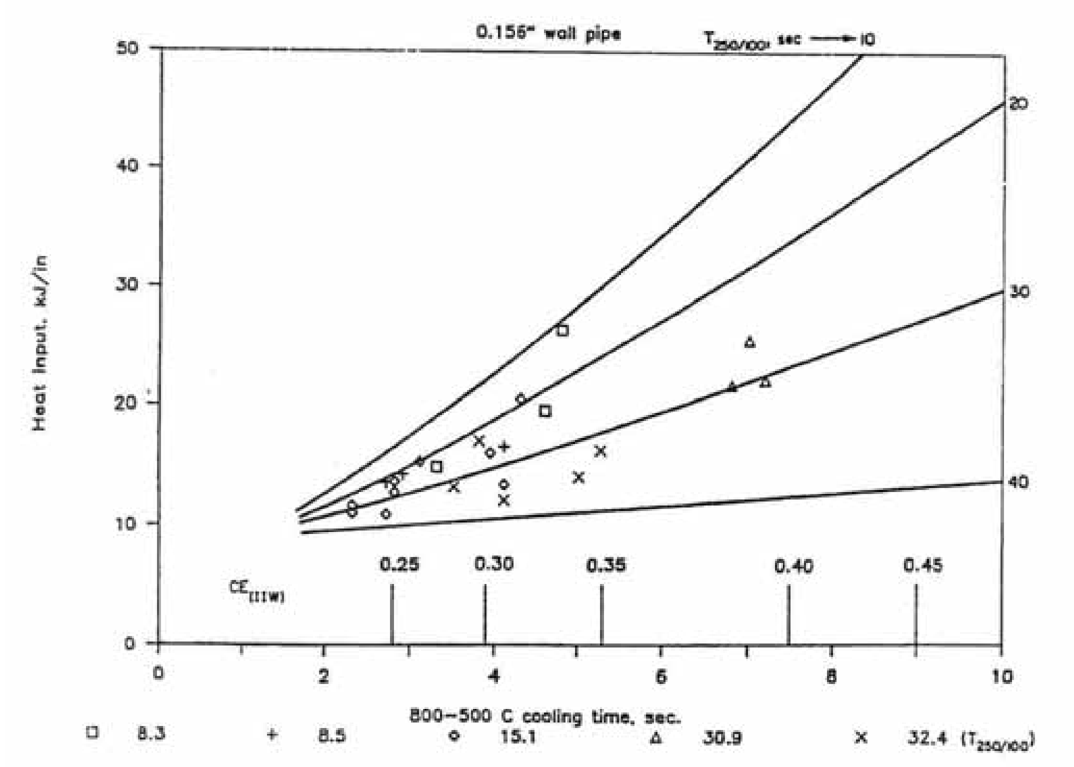


(a)

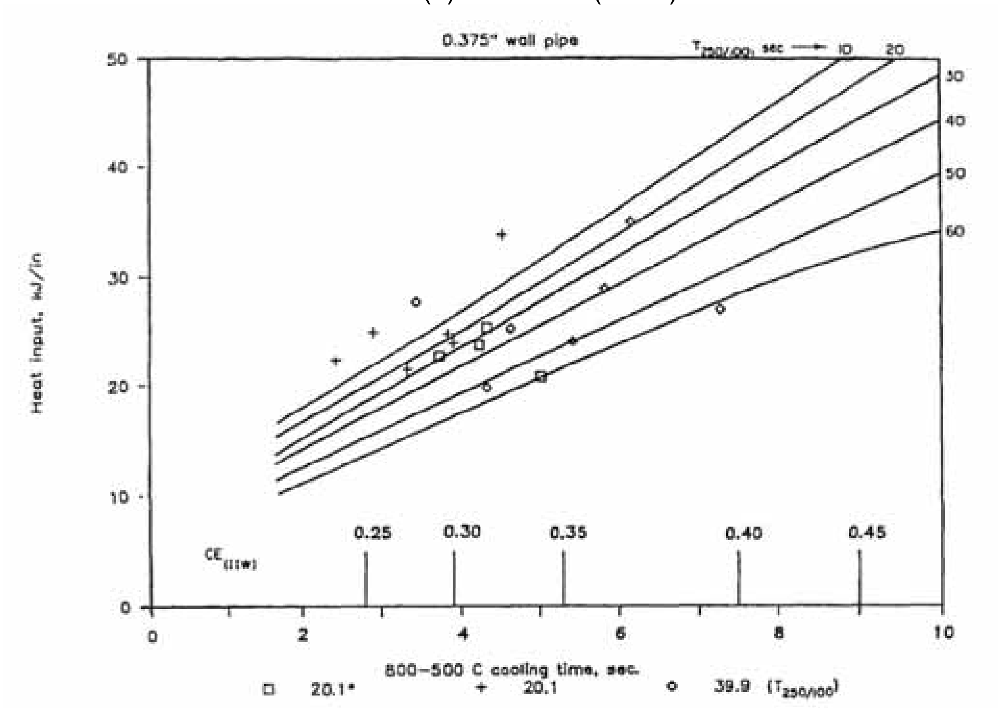


(b)

Fig .1.5: Fillet weld heat input selection curves based on a) cooling rate, b) cooling time.



(a) 0.156 inch (4 mm) wall



(b) 0.375 inch (9.5 mm) wall

Fig .1.5: Heat input selection curves.

PR-185-9908

WELDING ONTO IN-SERVICE THIN WALL PIPES

Prohibition/restriction is placed on welding onto pipe with wall thickness below specified limits, i.e. 4 to 4.8 mm (0.156 to 0.188 inch). However, risk of burn through is also a function of welding parameters and operating parameters of the pipeline. Previous work indicated that burn-through will not occur unless the inside surface temperature exceeds 982^{o}C (1800^{o}F) when using low-hydrogen electrodes. This incorporated a 278^{o}C (500^{o}F) safety factor based on experimental observations. In other words, when the inside surface temperature reached 1260^{o}C there was no strength in the pipe to retain the pressure. The Battelle thermal analysis model indicates that temperatures in excess of 982^{o}C are unlikely if the pipe wall is equal to or greater than 6.4 mm (0.25 inch). This latter condition is under "normal welding practices" i.e., a limit of heat input?, and when using low-hydrogen electrodes.

Therefore for pipe wall with thicknesses less than 6.4 mm guidelines need to be developed to prevent burn-through. The methods include minimizing the penetration of the heat from the weld arc by using limits for heat input as well as electrode size (welding current).

To develop guidelines for safe welding into pipes with wall thickness down to 3.2 mm (0.125 inch). The safe welding guidelines are to be used to allow in-service repair and "modification" as a function of wall thickness for thin wall pipes.

Overview

The focus was on performing burn-through experimental trials on thin wall pipe. (The thin wall was obtained by slotting a 7.9 mm wall, 20 NPS, X60 grade pipe, to obtain "remaining wall" thickness of 3.2 and 4 mm (0.125 and 0.156 inch) in lab experiments.) The experiments were done in two series; a) in the lab and b) prototype in the field. The lab experiments were done at what was believed to be two extremes thermal severity (heat sink levels) by water filled or Nitrogen gas filled "pressured vessels" fabricated from pipe with no flow, while the field experiments were performed in a "flow loop" using methane gas and flow rates up to what is believed to be at the high end in real situations. The latter were expected to capture intermediate thermal severity levels. In both sets of experiments, the desired levels of heat input was obtained by varying both the electrode diameter and associated range of welding current and travel speed in order to investigate the separate effects of welding current and heat input. The experiments were conducted with reverse polarity. The SMAW process was used. A mechanized travel carriage was used. When sleeve fillet welds were made the welding was in the longitudinal direction of the pipe.

These experiments were preceded by simulation of in-service fillet welds, with sleeve thickness of 3.2 mm, using the Battelle thermal analysis computer model. The purpose was to get guidelines of welding parameters to use in the experimental trials to obtain the "boundary" of burn-through. The "critical' situation was assessed from the peak inside surface temperature in the pipe. The risk of burn-through would be high when this temperature exceeds 982^{o}C (1800^{o}F) for low hydrogen situation.

Detail – Lab Experiments

Pressure vessel design: longitudinally slotted pipe using RSTRENG to account for the reduced wall from slotting. Bead-on-pipe (BOP) welds were deposited in slots using E7018 electrodes with diameters, 2, 2.4 and 3.2 mm. For each electrode different heat inputs were used with some heat inputs above the safe heat input boundary to obtain burn-through. Pressure: 800 psi (5.5 MPa). For nitrogen gas pressurization a third of the water was removed and replaced by the gas. Metallographic examination results along with the assessment of inside surface appearance were used to categorize the welds as safe (free from evidence of inside bulging from metallography), marginal (exhibited inside bulging) and burn-through.

Detail – Field Experiments

Test section: 114 mm (4.5 inch) diameter 1.8 m (6 feet) long, wall thickness (3.2 and 4 mm) API 5LX grade. Flow loop: inlet pressure 650 psi (4.5 MPa) and this is equivalent to 33 and 27% SMYS) for 3.2 and 4 mm wall, respectively, ambient temperature 13^{o}C over a range of flow rates. This test matrix in terms of welding parameters was similar to those used in the lab experiments. The flow rates categorized as zero, low, medium, and high.

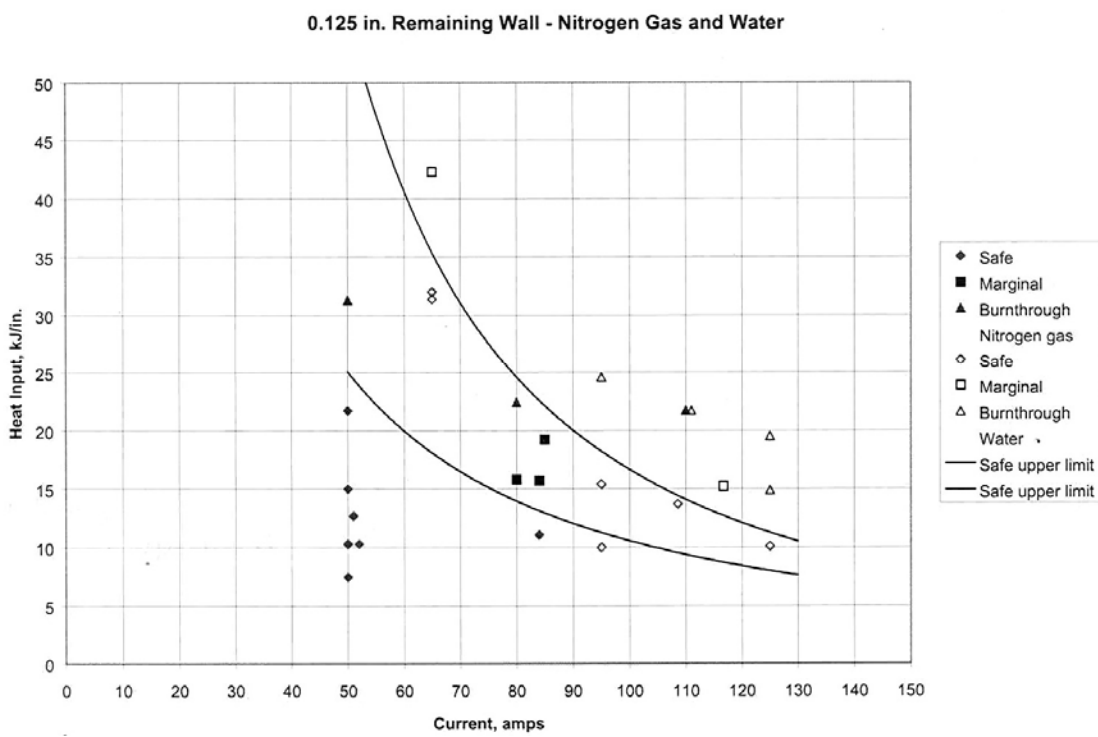
Four out of 94 welds resulted in burn-through. When burn-through occurred, it tended to immediately extinguish the welding arc and expel the molten contents of the weld pool. As a safety precaution, fire extinguishers were immediately discharged towards the location of the weld, and the welding current was disconnected. During one of these events, the gas on the periphery of the escaping gas plume briefly ignited.

Majority of the welds were made BOP, although several welds were "replicated" using a sleeve fillet weld configuration.

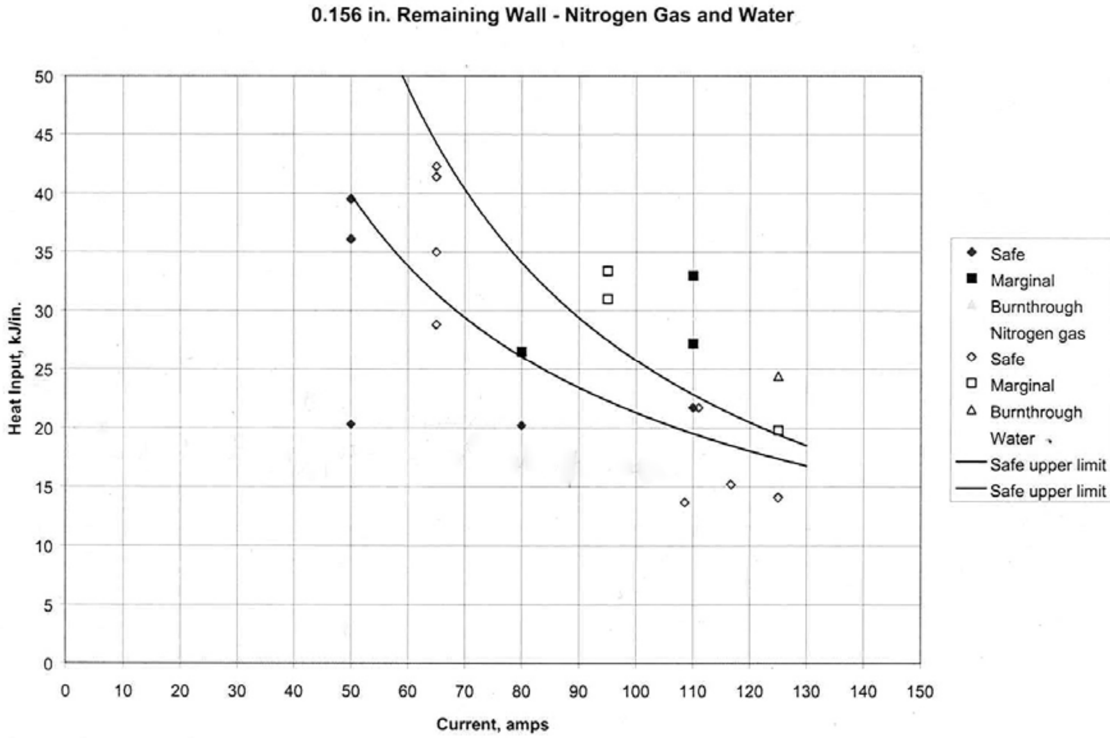
The burn-through assessments were made following the same procedure as for those in the lab experiments, i.e from metallography sections.

The following are considered significant outcomes from the lab experiments:

- For the 3.2 and 4 mm longitudinal slots the BOP test were used to assess the boundary of safe welding heat input for a range of applicable welding currents for the electrodes examined. The results are presented in Figure X.1 (Figure 15 & 16 in report). The results show; a) that the heat input can be increased with decrease in welding current, b) the heat input can be increased for the higher thermal severity, and c) higher heat input for the higher wall thickness.



(e) Areas of 3.2 mm (0.125 inch) remaining wall



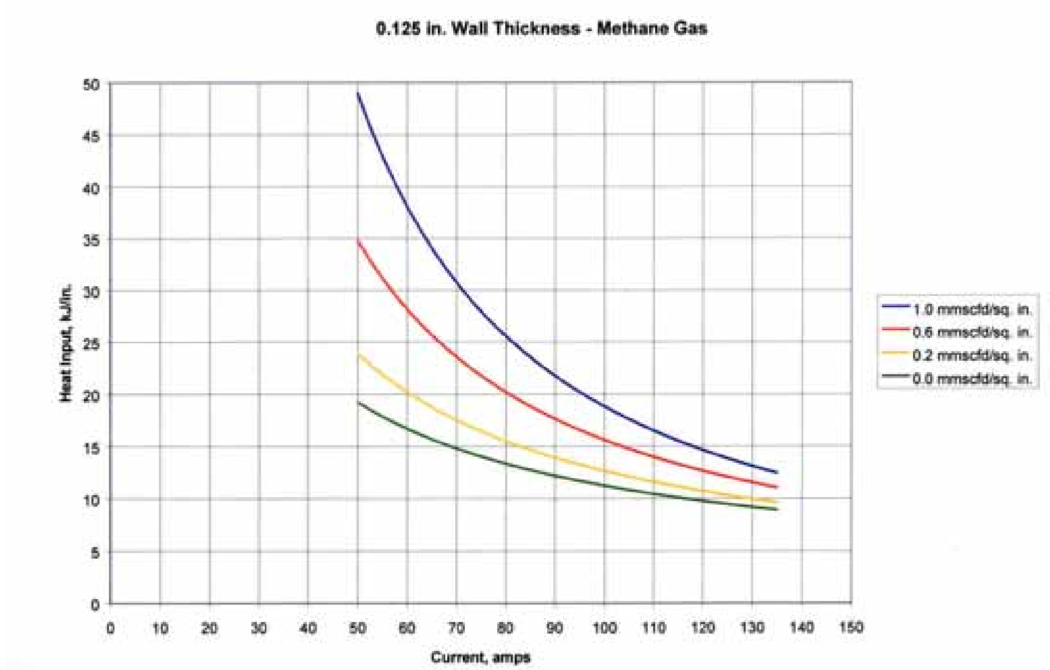
(f) Areas of 4 mm (0.156 inch) remaining wall

Fig .X.1: Lab experimental results for welds made with N-gas and water pressurization.

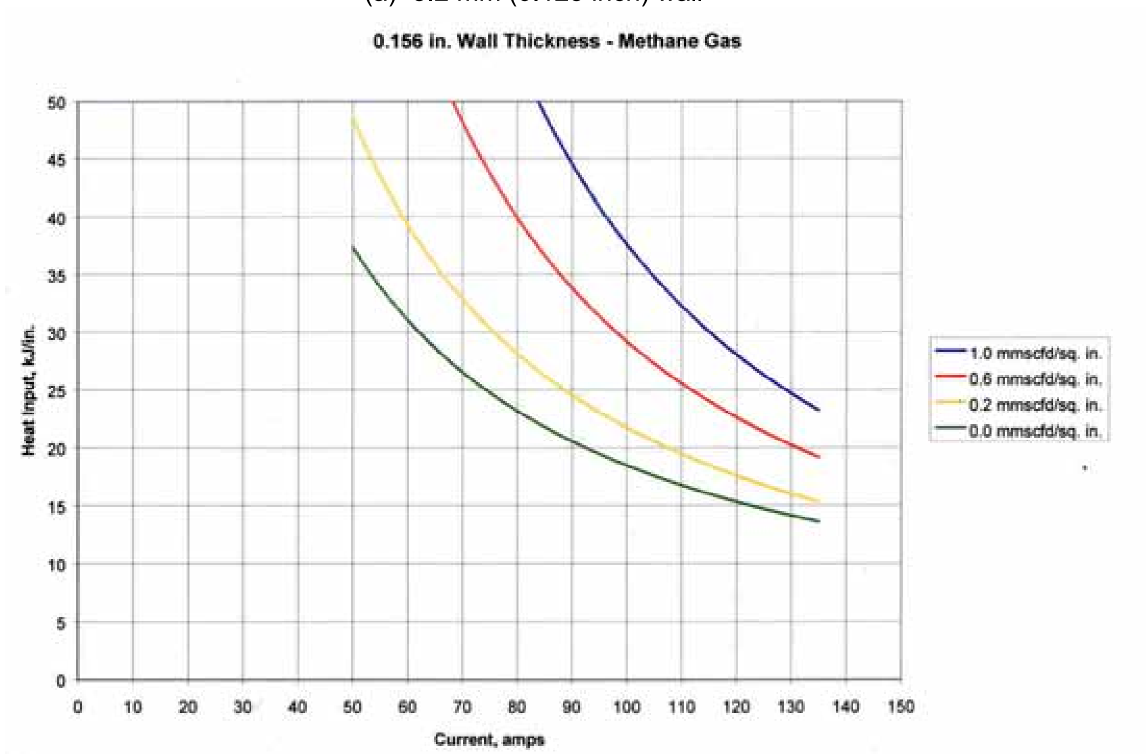
The following are considered significant outcomes from the field experiments:

- The results are presented in Figure X.2 (Figure 35 & 36 in report) and display the same trends as those from the lab experiments. With four normalized gas flow rates and corresponding levels of thermal severity the sensitivity to the flow rate is demonstrated. Also noted in Figure X.2 is that increased thermal severity enhances the difference in heat input at lower current levels, and this can be visualized in Figure X.1 as well. These curves could be used to support the use of smaller electrode size (corresponding to lower current) pipe with flowing fluid as the range of safe heat input is larger for lower current compared to higher current.

- Comparing field experimental results and those from the lab need to consider the differences in heat sink capacity resulting from pipe diameter differences in addition to the effects of non-flowing fluid in the lab experiments compared to flowing fluid in the field experiments. The field pipe was 4.5-inch diameter while the lab experiments were performed in a slotted NPS 20 and 7.9 mm wall pipe. Thus the bracketing attempt in the lab of obtain the extremities of thermal severity using no flow conditions with water and gas may be subjective as observed in the experiments that were performed. The comparisons are made in Figure 37 and 38 in the report for 3.2 and 4 mm wall, respectively.



(a) 3.2 mm (0.125 inch) wall



(b) 4 mm (0.156 inch) wall

Fig .X.2: Field experimental results for welds made with pressurized CH_4-gas.

- Comparison of a few BOP welds with sleeve fillet welds at similar welding and flow conditions displayed that for the fillet welds the depth of penetration to the pipe wall was less when some of the heat from the weld arc is directed to the sleeve. This is based on limited tests and metallography. Thus further work is recommended to investigate the effect such factors as electrode angle, gap and sleeve thickness. (Note that the sleeve fillet welds were made in the longitudinal direction.)

- At excessive heat input levels, beyond those considered to be safe, two types of faults occurred. The conventional puncture type burn-through or cracking along the longitudinal weld. Both are associated with high heat input former was with low current and slow travel speed and the latter is associated with high current and fast travel speed. At high heat input and current levels above safe conditions also resulted the a carburized layer on the ID surface of the pipe associated with hydrocarbon contents in the pipe. It has been previously noted that this takes place when the ID surface temperatures above1130^{o}C (2066^{o}F).

The simplified guidelines are developed from the comparison of results from the Battelle heat sink model and the experimental results of this program. In general, the comparisons demonstrate the applicability of the guidelines from the model to develop safe welding procedures. The Battelle heat sink model uses a relation between the heat input and current shown in Figure X.3 (Figure 44 in report). Figure X.4 (Figure 46 in report) displays the superimposition of this relationship on the experimental curves shown in Figure X.2b for the case of 4 mm wall (0.156 inch). The intersection of the relation between heat input and welding current used in the Battelle model with the experimental curves for the "normalized" flow rates gives rise to specific heat inputs for the various flow rates. These heat input levels, developed from experiments, are shown to be in agreement with what is obtained from the Battelle model. The thermal severity for each flow rate is normalized with respect to the cross-sectional area of the pipe. This measure of thermal severity is claimed to be independent of pipe diameter.

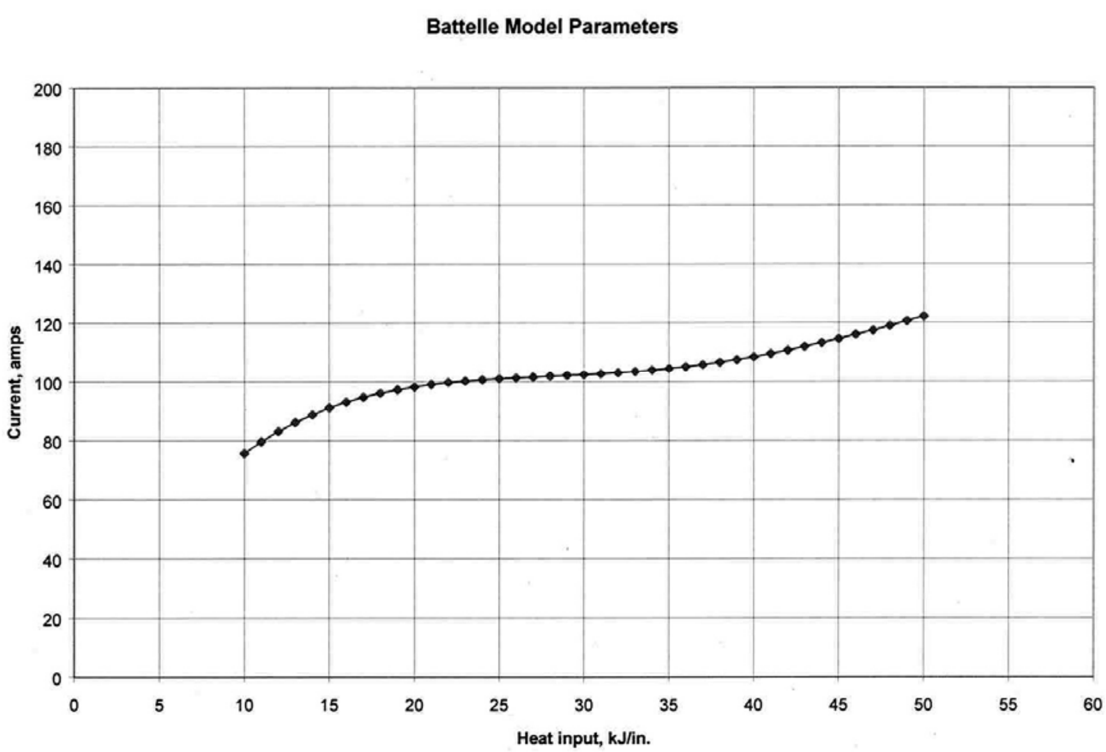


Fig .X.3: Current vs. heat input relationship used in the Battelle thermal model.

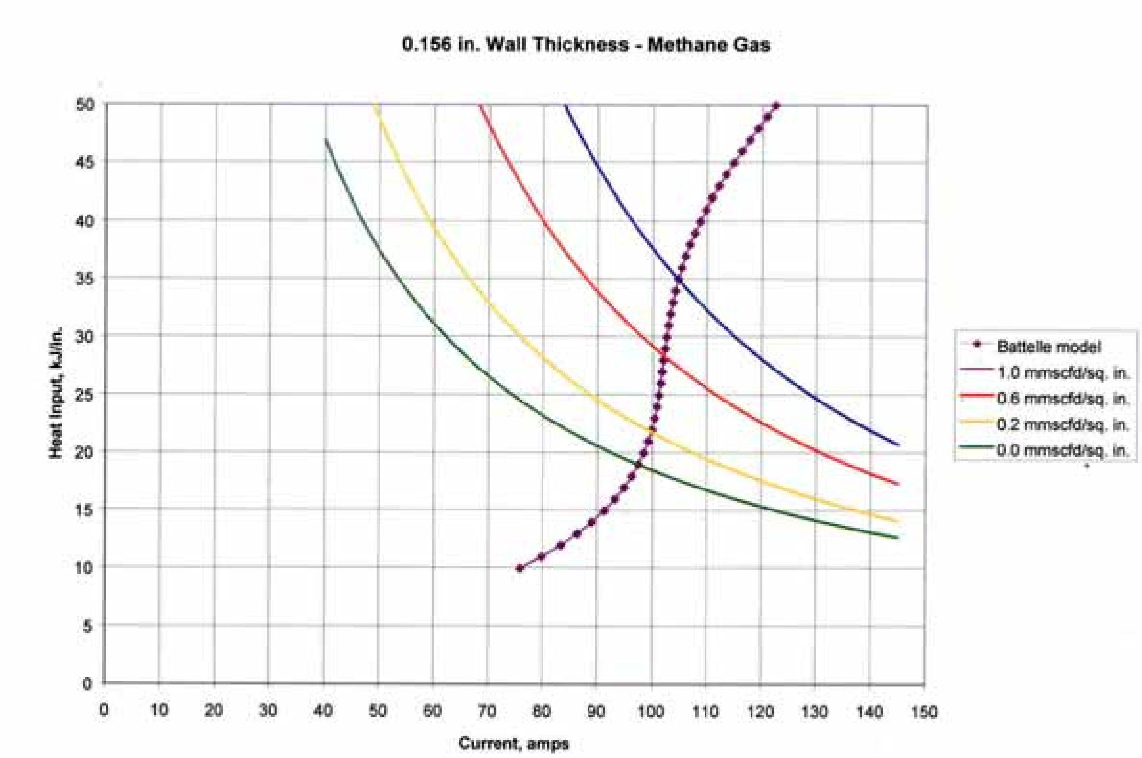
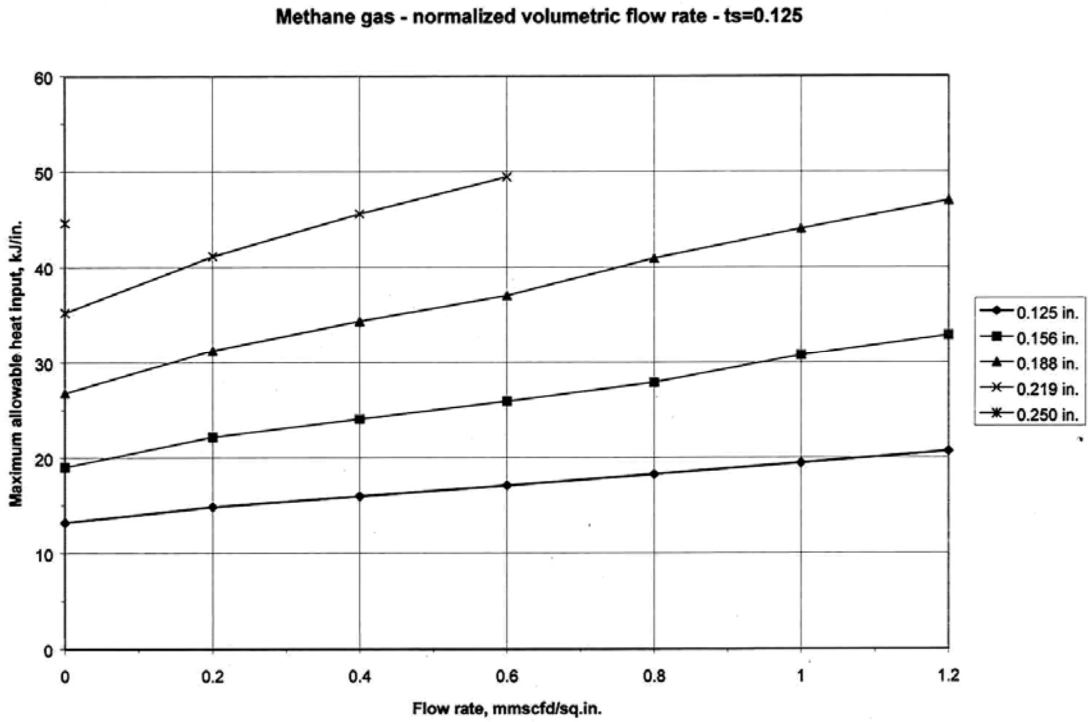
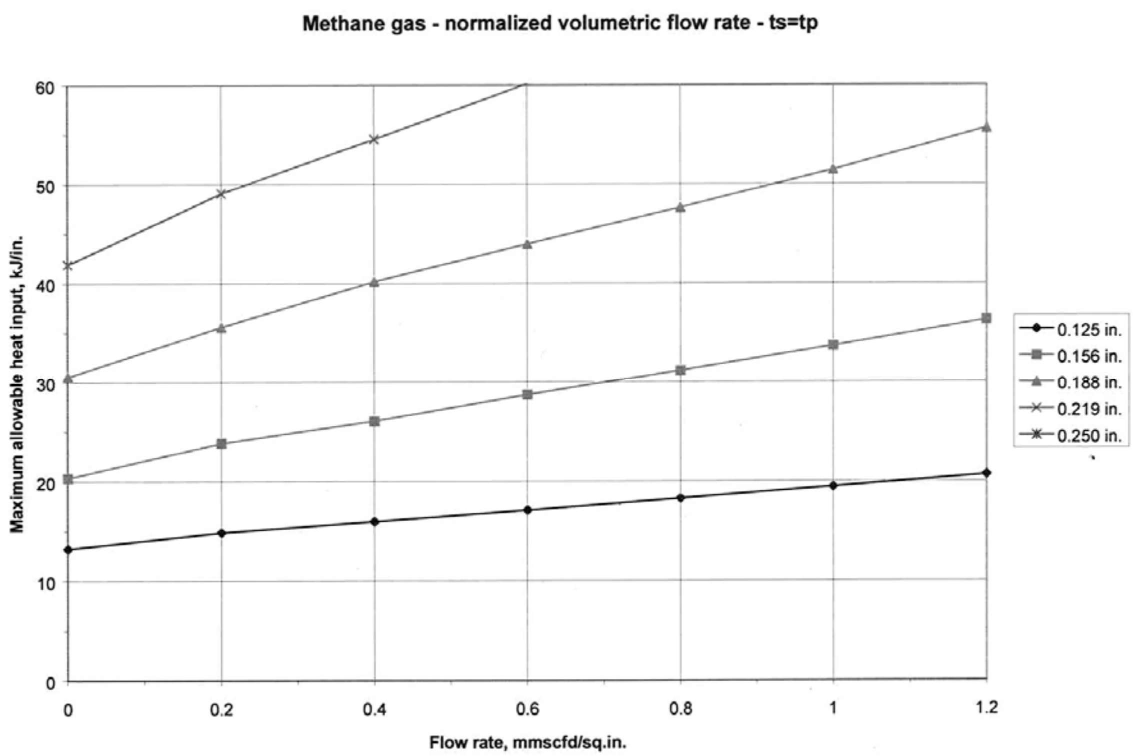


Fig .X.4: Experimental results for welds made into 4 mm (0.156 inch) wall pipe with heat input -current relationship from Figure X.3.

The simplified guidelines for safe (maximum) heat input levels for various pipe wall thicknesses in the range 3.2 to 6.4 mm (0.125 to 0.25 inch) are provided as a function of the normalized flow rate (see Figure X.5a) (Figure 47 in report). The sleeve thickness is this case is 3.2 mm. Figure X.5b (Figure 49 in report) is the guidelines when the sleeve thickness is equal to the pipe wall. Figure X.5a and X.5b show that for the wall thickness of 0.125 inch, the same allowable maximum heat input as function of flow rate, as the sleeve thickness in both cases are the same (0.125 inch). In contrast, for higher thicknesses Figure 4.5b displays a higher heat input at fixed flow rate as the sleeve thickness is larger than 0.125 inch and provides additional heat sink capability. Also in this latter case a sleeve weld is simulated compared to a BOP weld simulation in Figure X.5a. It should be noted that the validation of these guidelines were based on experiments conducted on two wall thicknesses and for wall thicknesses greater than 4 mm (0.156 inch) they are indeed extrapolations.



(c) Sleeve thickness (t_s) = 3.2 mm (0.125 inch), BOP welds



(d) Sleeve thickness (t_s) = pipe wall (t_p), sleeve fillet welds

Fig .X.5: Guidance based on simplified Battelle thermal model predicted heat input limits for BOP welds. The heat input limits are when using low-hydrogen electrodes at current levels no higher than those displayed in Figure 4.3

The above guidelines do not consider the possibility of cold cracking. If the safe heat input level is below that is required to avoid cold cracking then temper bead processes are recommended.

PR-185-9329

Effective Procedure Variables for Welding onto In-Service Pipelines

Summary

This reference collects the cooling rate data from several previous reports and in that it is very useful, giving $t_{800-500}$ against heat inputs. The report goes on to measure cooling rates during procedure trials and measurements on in-service gas and liquid lines and the GRI flow loop with flowing gas. It mainly presents results with little discussion from a metallurgical side. The report was completed as several distinct tasks and these are described below.

Task 1: Review of Previous Work and Industry Experience

They note that welding procedure qualifications have been simulated using the following:

- Permanent high pressure flow loops,
- Temporary atmospheric pressure flow loops circulating water or oil, and
- Water spray onto the back of weld simulations in a lab setting.

The authors suggest that the heat sink capacity measurements are used to ensure that cooling conditions simulate the actual welding conditions.

Section 3 describes some of the early results of welding trials on liquid-filled pipelines and Appendix A contains a summary of heat inputs and cooling times; details are described below.

Previous work for Amoco involved WPS qualification on a temporary water-filled line and the cooling times from 800 to 500°C, and compared these to measurements taken during welding on in-service crude and gasoline pipelines. They conclude that the pipeline contents have the greatest influence on weld cooling times, but no examples are shown how they come to this conclusion. (See Table A1)

Early work at Battelle developed a thermal analysis computer model that has been the basis for several experimental programs. In this first one sleeve fillet welds and branch welds had cooling rates at 1000°F (540ºC) recorded using thermocouples attached to the pipe outside surfaces at the weld fusion lines on liquid propane pipelines. (Tables A2 and A3, respectively)

Beginning in 1988, EWI began work on a heat sink capacity measurement technique to predict sleeve cooling rates from heat inputs. The completed a series of welds at two target heat inputs and a variety of pipeline operating conditions on natural gas pipelines, recording time to cool between 800 and 500°C, $t_{800-500}$, and cooling rates at 1000°F (540ºC), R_{540}, using thermocouples harpooned into the molten weld pool. (Tables A4 to A8)

Battelle and EWI completed a couple of follow-on projects to link the Battelle computer model and the EWI heat sink capacity method using thermocouple harpoons. Results for qualification trials on fuel oil and crude oil loops showing $t_{800-500}$ and R_{540} are listed in Tables A9 to A14, and trials on a natural gas loop list $t_{800-500}$ in Tables A15 and A16.

Task 2: Qualification Trials Over a Rang of Heat Inputs and Pipe Wall Thicknesses

The trials involved welding on seven thicknesses (0.188 to 0.75 in.) using five heat input levels (15 to 50 kJ/in.) on water-filled, oil-filled, and air-cooled sections of piping, and recording the $t_{800-500}$ cooling times using thermocouples in the welds. The heat input variations were obtained by adjusting only the weld travel speed using a nominal current of 100 amps with a 3/32 in. diameter E7018 electrode. (See Tables 1, 2, and 3)

Task 3: Compare Task 2 Results to Trials on a High Pressure Flow Loop

The first field trials were completed at two Columbia Gas locations on pipe at 275 and 620 psi and wall thickness from 0.275 to 0.5 in. The heat inputs and $t_{800\text{-}500}$ are listed in Table 5.

The second set of field trials were completed at the GRI test loop at SwRI, aiming at producing heat input (15 to 50 kJ/in.) vs. $t_{800\text{-}500}$ for a range of wall thickness (0.188 to 0.594 in.) and gas flow conditions. The results of the welding trials are found in Tables 7 to 10, and heat sink capacity measurements for the flow loop are listed in Table 11.

Task 4: Analysis to Determine WPS Suitable for Actual In-Service Conditions

Analysis of the procedure qualification tests showed the following:

- For air and oil, $t_{800\text{-}500}$ decreases with increasing wall thickness;
- For water, $t_{800\text{-}500}$ increases then decreases with increasing wall thickness. The decrease with the thin-walled pipe shows the influence of the water flow.
- For all conditions, there is little effect of contents or wall thickness at WT>0.5 in.

Individual results are plotted in Appendix C and are used to interpolate points for Figures 14 and 15. They suggest that an upturn in cooling times for the 0.75 in. results are due to a different composition and speculate significantly different thermal properties, but supporting data is not provided.

The procedure qualification results were plotted against field measurements and it was found that the cooling effect of natural gas was best simulated using either using the flowing water or oil results, depending on the gas flow conditions.

Additional analysis was aimed at determining if the forced air procedures could simulate natural gas flow conditions. The GRI results plotted as $t_{800\text{-}500}$ versus wall thickness at 25 and 40 kJ/in. showed the following:

- $t_{800\text{-}500}$ decreases with increased WT due to the increased thermal mass of the pipe
- there is little effect of WT and flow conditions > 0.5 in.
- the weld cooling rate is affected by the gas flow conditions for thin-walled pipe
- as the WT is reduced, $t_{800\text{-}500}$ at first increases due to lower thermal mass of the pipe, but then decreases as the flow begins to remove heat from the pipe.

The outcome of their analysis was that there did not appear to be a simple relationship between actual flow conditions and procedure qualification tests. They suggest that flowing water could be used to qualify procedures for welding onto in-service pipelines under any flow conditions, and that flowing oil could be used under less severe cooling. Procedures completed using forced air resulted in cooling rates slower than even the lowest gas flow conditions. They provide the following guidelines:

- "Procedures for welding onto in-service pipelines with wall thicknesses of 0.5 in. (12.7 mm) and above should be qualified on 0.5 in. (12.7-mm)-wall-thickness[sic] pipe and above using the flowing water (or possibly the flowing motor oil) procedure qualification condition.
- Procedures for welding onto in-service pipelines with wall thicknesses less than 0.5 in. (12.7 mm) should be qualified on 0.375 in. (9.5-mm)-wall-thickness[sic] pipe and above using the flowing water procedure qualification condition.

The authors go on to provide examples how the results can be used to determine conditions for procedure qualification welds. With the example on the middle of page 19 the curves that are referenced are quite flat and a lot of trust is made in choosing conditions for welding.

In Section 8 the authors describe some of the shortcomings of API 1104 and API 1107, and refer to some procedure requirements of Z184 and BS 6990 that are useful for qualifying in-service welds. For example, the 'run-out' ratio defined as the maximum allowable weld length deposited per length of electrode consumed to achieve the required heat input is useful to ensure proper heat inputs (see BS 5185 for details).

The next task in this project was to qualify a typical procedure They used an NPS 10, 0.25 in. WT API X42 pipe with a CE_{IIW} of 0.35. They did hardness testing and one of the sections had a 352 HV reading; they state that it is acceptable. (to what?)

The final task compared the Columbia Gas and SwRI trials to the Battelle hot tap model. The comparisons suggest the following:

- The Battelle program overestimates $t_{800-500}$ for thinner wall materials, particularly for cooling times longer than 4 to 5 seconds. This is non-conservative and should be noted as this is in the range of expected cooling times for in-service welds.
- At higher wall thickness the Battelle model is conservative, and at high cooling times the predicted times are about one-half of those measured. This could lead to undue concern over hydrogen-induced cracking.
- The Battelle model is conservative for very rapid cooling conditions ($t_{800-500}$ < 4 s) for all wall thickness.

The conclusions listed in the report have already been noted as the review proceeded.

Shortcomings

1. None of the results referred to the materials being welded in terms of their compositions.
2. There were no weld dimensions to compare heat inputs against bead sizes.
3. The experimental procedures suggested that 3 thermocouple plunges were used for some of the trials, but only one value was ever reported. The additional data would have proven to be useful for some of the analysis to test anomalies.

PR-185-9110

Repair of Pipelines by Direct Deposition of Weld Metal

Summary: This reference includes a review of work completed to date and uses this to direct the experimental variables that were examined. Welds were made on pipe with wall thickness of 0.079 in. and greater, and at several heat inputs typical of deposited metal repair, i.e. <15 kJ/in. Results show penetration and weld details for making successful repairs on in-service pipelines. Simulated repairs were cyclic pressure tested and the pressure later raised to failure to show that the repairs did not adversely affect the integrity of the pipe.

One of the first tasks of this project was to review the results of past research on deposited weld repair of pipelines. The four groups of research areas are as follows:

1. Data was obtained on weld metal temperature and pipe ID surface temperatures during welding;
2. Welds were made remotely on pressurized pipe to determine the conditions for burnthrough;
3. Welds made on low pressure pipe demonstrated that deposited weld metal restored the pressure-capacity of the pipe; and
4. Between 1978 and 1990, a series of hot tap were completed by Battelle and later jointly with EWI to develop and refine a computer model to predict the conditions necessary for burnthrough.

The summary indicated that it seems possible to extend the thermal analysis model to deposited metal repairs. The introduction in Appendix A of the report states that the review was to provide guidance on directing the research on deposited metal repair, providing procedures and defining limitations of this repair method. The following paragraphs further describe the Appendix A results.

Hahn completed a series of welds at different heat inputs and pipe thickness, and then measured the depth of penetration.

Wade measured ID surface temperatures at several heat inputs and wall thickness which could be used to establish upper levels on heat input for welding on pressurized pipe. His results are as follows:

Wall Thickness, in.	Heat Input, kJ/in. ID Surface Temperature, ºF		
	15	30	45
1/8	1652	--	--
1/4	932	1562	1724
3/8	--	1022	1238
1/2	--	707	896

Wada also completed welds on pressurized pipe, showing that heat inputs of up to 40 kJ/in. could be made on ¼ in. WT pipe pressurized to 50% SMYS, but that welding on 1/8 in. pipe should be done with extreme caution. When burnthrough occurred, it appeared to be hot cracking of weld metal, and cellolosic electrodes were more likely to produce burnthrough than low hydrogen electrodes.

The early PRC work at Battelle involved welding over corrosion pits followed by burst tests. As the failure pressures of the corroded pipe were at or above yield to begin with, the tests showed only that the as-repaired pipes were ductile. In a second series of tests with deeper slots and pressures up to 20 psi, burnthrough occurred when welding on pipe with a remaining WT of 0.070 in. A third series of test welds on machined pipe included ID surface temperature measurements, with the results showing the weld metal and HAZ penetration. These experiments were accompanied by the development of thermal analysis techniques, which was later used for additional modeling.

Howden completed a series of tests on 0.25, 0.188, and 0.156 in. WT pipe to determine conditions necessary for burnthrough, with welds made on unpressurized and pressurized pipe. The failures that he observed were weld hot cracks. He showed that longitudinal welds are more likely to fail that circumferential welds, and that low hydrogen welds are less likely to promote burnthrough than cellulosic welds, and they suggested a relationship between heat input and ID surface temperature.

Appendix A continues with descriptions of research at British Gas. The first series of tests by Cassie investigated burnthrough and HAZ cracking. The comments relate mainly to burnthrough with pressures as high as 1000 psi and WT as low as 0.125 in. Welds were made that led to burnthrough at high heat inputs and were in line with results by Wade and Howden. It is noted that reference 10 includes HAZ hardness results; they were not discussed as they were not relevant to their investigation. The next group of tests by BG included a deposited metal repair, pressure cycling, and then loading to failure. The results showed that this repair method restores the pipe original strength. The next tests investigated weld penetration characteristics at different heat inputs and pipe WT. They concluded that pressure did not have an influence on penetration characteristics for circumferential welds and their results showed the following related to burnthrough:

Burnthrough of	Minimum Heat Input, kJ/mm	ID Surface Temperature, ºF[(a)]
0.125 in. WT	33	2648
0.156 in. WT	38	1806
0.188 in. WT	43	2462

(a) Temperature predicted using Battelle model.

Additional testing confirmed that penetration was not greatly affected by pressure, but that the direction of welding was a factor, in that burnthrough did not occur for circumferential welds but did occur with longitudinal welds at higher pressures.

Research completed at Battelle from 1978 to 1990 is summarized, noting the following:

1. The problem of burnthrough is addressed;
2. Good correlations were obtained between heat input and penetration; and
3. The thermal analysis model provided a method of determining maximum heat inputs for safe weld repairs.

Figures A-3 and A-4 show ID surface temperatures versus HAZ penetration, showing that the HAZ completely penetrates the pipe wall when the ID temperature reaches about 1500 ºF.

The overall summary of Appendix A states that deposited weld metal repairs can be made on pipe with WT as low as 0.125 in. provided that heat input is controlled carefully, and that burnthrough can be avoided by limiting the ID surface temperature to 1800 ºF.

The first group of experiments in this project are described in Section 5, entitled “Remaining Wall Thickness Limit Experiments”, with welding done on water-filled pipe. They use an automatic stick welder and weld into a machined groove of diminishing WT at 600 and 800 psi with heat inputs between 12 and 22 kJ/in. The highest heat input resulted in burnthough, while at heat inputs approaching 15 kJ/in. slight bulging was found following sectioning. The results include weld penetration and maximum temperature readings, and show sections through the welds. The metallography was limited to examination for cracks and weld dimensions. They conclude that heat input should be limited to 13 kJ/in. for welding on 0.125 in. WT pipe.

Later experiments used nitrogen gas with pressure of 400 psi and deposited welds at several heat inputs, with some on pipe as thin as 0.079 in. They showed similar results to the water tests where burnthrough was imminent on the thinnest sections at heat inputs of about 13 kJ/in.

They somehow come up with a comment suggesting that smaller diameter electrodes are better, but show no comparisons on electrode size, and then propose additional work to study this issue.

The last task on welding trials involved using the Battelle model to produce a set of heat input limits that result in an ID surface temperature of 1800 ºF. The trials include pressures up to 900 psi and flow rates from 0 to 32 feet/second.

The next task involved weld repair of corrosion damage on NPS 16, 0.25 and 0.375 in. WT pipe and NPS 20, 0.25 in. pipe with compositions typical of low and high carbon steels. The authors discuss HAZ concerns and then describe the weld deposition sequence to obtain maximum tempering from previous passes. The resultant hardness for the 0.39 CE pipe ranges from 252 to 419 HV-10 kg, and 198 to 267 HV-10 kg for the 0.25 CE pipe. They suggest that small diameter electrodes are best for controlling heat input and minimizing weld defects. The results include a graph showing weld cooling time, $t_{800\text{-}500\,^{\circ}\mathrm{C}}$, versus heat input for different WT pipe.

Section 7 describes integrity experiments where three vessels with simulated corrosion and weld repairs were tested in fatigue and later burst tested. The weld repairs returned the vessels to their full strength conditions. Photographs of sections through each of the welds show the bead placement and locations of hardness measurements. A comparison that is made between the integrity welds and repair welds states the following:

- Water-backed welds have average HAZ hardness values approximately 35 HV-10 kg greater than the air-backed or nitrogen-backed welds.
- Pressurized welds have HAZ average hardness values 10 HV-10 kg higher than the non-pressurized equivalents.

Weld repairs on actual corrosion damage are also included and produce similar results to those mentioned above.

Other considerations are briefly discussed, such as:

- Measurement of remaining WT;
- Pressure reduction during weld repair;

- Application to mechanical damage and ERW seam repair;
- Application to the repair of sour gas pipelines;
- Control of heat input; and
- Inspection of completed repairs.

The recommendations for further work include the following:

- Experimental validation of the Battelle model for thickness exceeding 0.125 in.
- Investigate the influence of electrode size on the risk of burnthrough;
- Cyclic testing or repairs using pressure cycles typical of gas pipelines; and
- The application of repair methods to lines transporting wet and sour products.

PR-185-815

Criteria for Hot Tap Welding Further Studies

Summary: This project extended the results of earlier studies where a heat sink capacity technique was developed to assist with hot tap welding determination. The current results incorporated laboratory trials for ER70S and ER80S-D2 welds to add to E6010 and E7018 weld results for cracking versus cooling times between 800 and 500 ºC. The current field results were completed at NOVA facilities and were aimed to complement the earlier trials at Panhandle Eastern which seemed to have large scatter. The welds at NOVA were only done with E6010 and E7018 electrodes. There is much discussion about the scatter in the field results and the use of the cooling time determination method. The results are useful in that they give heat input and cooling times for a range of conditions, but they should be used as a guide as the authors seemed to have low confidence in the results.

This project is an extension of an earlier study that developed a simple field measurement technique to measure the heat sink capacity of in-service pipelines to ensure that safer welding procedures are used. Specifically, this study is intended to:

1. Extend existing data for different pipe compositions, cooling rates, and cracking data with GMAW
2. Field validation to improve the correlation between the pipe heat sink capacity and weld cooling rates, especially at higher flow rates.

GMAW weldability tests were completed using branch and sleeve simulations with either water spray or compressed air on the backside of the plates being welded. Weld cooling history was obtained from thermocouples that were harpooned into the welds at the 1/3 and 2/3 positions; the parameters recorded for each weld included the heat input and the following:

- Cooling time from 800ºC to 500ºC, $\Delta t_{8\text{-}5}$;
- Cooling time from peak temperature to 100ºC, $\Delta t_{p/1}$
- Cooling rate at 540ºC, dT/dt 540ºC.

Each weld was sectioned in three places to examine for cracks, and one of the sections was subjected to HV1 kg hardness measurements in the weld and HAZ.

The laboratory weldability tests included (13) CTS Tests, (11) branch welds, and (15) sleeve welds completed using ER80S-D2 and ER70S-3 consumables. None of the branch welds exhibited cracking. The cracks in the CTS and sleeve welds occurred in the HAZ and only under severe cooling conditions with high CE pipe with HAZ hardness above 350 DPH. Some welds with hardness above 350 DPH did not show cracks. All of the welds did not have hardness measurements completed on sections.

Field validation trials were completed with natural gas flowing through loops connected to the mainline at both NOVA and Panhandle Eastern. Three different pipe were welded into the line for each series of tests. The field validation trials at Panhandle Eastern were all fillet welds and completed at a maximum flow rate of 0.417 mmcfd. The NOVA welds were fillet, branch, and saddle welds, and the flow rates were 2.3 and 3.4 times greater than the maximum Panhandle flow rate. Weld thermal cycles and cooling rates were recorded at each location, and heat sink capacity tests were completed at NOVA. The weld evaluations included Nondestructive Examination (NDE) of welds completed using basic and cellulosic electrodes at high flow rates. Some of the welds were also prepared for metallographic examination and examined for cracks, while others were prepared for nick break testing.

The field validation welds selected for examination included branch and sleeve welds for the most severe cooling conditions and made using both E6010 and E7018 electrodes. NDE of the welds did not show any cracks, but metallography found some weld metal cracks with cellulosic electrodes.

The discussion of the field validation trials concentrated on the quality of the data and the reasons for the scatter that was observed. The variables that were identified for scrutiny were the heat input, flow conditions, and pipe WT. The WT case was not consistent between the two field locations, and variations in heat input were believed to be the main cause of the differences. The recommendation was therefore to incorporate the heat input into the cooling time predictions. The authors suggest further that the location of the thermocouple in the weld pool could also influence the results, with shorter cooling times observed when the T/C is closer to the pipe as opposed to being close to the sleeve or branch. Another source of error is the local variation in heat input along the length of the weld compared to the average value. Their discussion seems to end with reference to Figures 12 to 16 and stating simply that there are differences between NOVA and Panhandle results.

The discussion ends with comments related to the incidence of cracking in the NOVA welds and the inability of dye penetrant NDE to detect cracking. The examples of cracking shown in the figures indicate root cracking and weld cracking (presumably near the root), so it is not surprising that dye penetrant showed no cracks.

The last discussion item addressed the “Operation of the Method” for heat sink capacity measurements. The steps are as follows:

1. Obtain $\Delta t_{2.5/1}$ using a gas torch and digital thermometer.
2. Use Figure 10 or 11, depending on heat input, to obtain $\Delta t_{8/5}$
3. With $\Delta t_{8/5}$, go to the appropriate laboratory results to determine whether cracking would be expected for the cooling time and heat input combination for that joint type. If cracking is predicted, adjust parameters.

PR-185-617

Criteria for Hot Tap Welding

The objective of this work was to examine the effects of heat input, electrode type and base metal composition on the potential for hydrogen cracking in hot tap and sleeve welds on gas pipelines. Also contains a description of the heat sink capacity measurement technique and a correlation of the technique to a limited amount of 800 to 500ºC cooling times for welds based upon thermocouple plunges into the weld pool at 1/3 and 2/3 of the weld length.

- E6010, E8010 and E7018 electrodes used
- Eight pipe steels (X52, X65 and X70) used with CE (IIW) values between 0.307 and 0.504 (Pcm range 0.162 to 0.352 and CEN range from 0.213 to 0.507)
- E6010 and E7018 electrodes supplied by Hobart and E8010-G electrodes supplied by Bohler Thyssen
- 3.2 mm and 4.0 mm electrodes were used
- Hot tap welds simulated with box sections welded to a stiffened flat plate, 45 degree weld preparation used
- Sleeve welds simulated with plate on stiffened plate weld, notch placed at root of weld to simulate root gap, essentially a CTS type set-up without bolt, plates clamped with C-clamp during tack welding
- Back of stiffened plates cooled using water spray or compressed air
- Single pass welds generated using either 1 kJ/mm or 2 kJ/mm heat inputs
- Double pass welds created using 1 kJ/mm heat input for each pass
- 250 – 100ºC cooling times used, single pass welds:
    - Steel A, 1 kJ/mm heat input, E6010 electrodes – 9.8 to 62.0 sec
    - Steel A, 2 kJ/mm heat input, E6010 electrodes – 12.1 to 84.5 sec
    - Steel A, 2 kJ/mm heat input, E7018 electrodes – 11.8 to 89.7 sec
    - Steel B, 1 kJ/mm heat input, E6010 electrodes – 5.8 to 167.0 sec
    - Steel B, 1 kJ/mm heat input, E7018 electrodes – 6.5 to 78.2 sec
    - Steel F, 1 kJ/mm heat input, E8010 electrodes – 14.9 to 45.3 sec
    - Steel F, 1 kJ/mm heat input, E7018 electrodes – 10.8 to 59.2 sec
    - Steel H, 1 kJ/mm heat input, E6010 electrodes – 8.0 to 73.0 sec
    - Steel H, 2 kJ/mm heat input, E6010 electrodes – 15.3 to 111.4 sec
    - Steel J, 1 kJ/mm heat input, E6010 electrodes – 5.7 to 157.0 sec
    - Steel J, 1 kJ/mm heat input, E7018 electrodes – 5.9 to 113.1 sec
    - Steel J, 2 kJ/mm heat input, E6010 electrodes – 6.1 to 64.4 sec
    - Steel J, 2 kJ/mm heat input, E7018 electrodes – 7.8 to 78.3 sec
    - Steel K, 1 kJ/mm heat input, E6010 electrodes – 4.5 to 130.0 sec
    - Steel K, 1 kJ/mm heat input, E7018 electrodes – 7.8 to 132.0 sec
    - Steel K, 2 kJ/mm heat input, E6010 electrodes – 8.3 to 95.0 sec
    - Steel K, 2 kJ/mm heat input, E8010 electrodes – 7.1 to 59.6 sec
    - Steel L, 1 kJ/mm heat input, E6010 electrodes – 16.5 to 18.0 sec
    - Steel L, 1 kJ/mm heat input, E7018 electrodes – 11.9 to 47.2 sec
    - Steel L, 2 kJ/mm heat input, E7018 electrodes – 15.6 to 99.4 sec
    - Steel M, 1 kJ/mm heat input, E6010 electrodes – 6.0 to 61.7 sec
    - Steel M, 1 kJ/mm heat input, E8010 electrodes – 9.2 to 61.8 sec
    - Steel M, 1 kJ/mm heat input, E7018 electrodes – 11.6 to 57.4 sec
    - Steel M, 2 kJ/mm heat input, E6010 electrodes – 6.0 to 61.7 sec

- Steel M, 2 kJ/mm heat input, E8010 electrodes – 11.3 to 90.7 sec
    - Steel M, 2 kJ/mm heat input, E7018 electrodes – 13.9 to 75.0 sec

- 250 – 100ºC cooling times for double pass welds in steels J, K and L with E6010 electrodes: 7.8 to 63.4 sec

- All welds deposited in the flat position, automatic traverse used in simulated sleeve welds, manual welding used for simulated branch welds

- Ni-Cr/Ni-Al thermocouples used, temperatures recorded every 0.2 sec

- Vickers 1000g microhardness tester used for hardness measurements

- Four cooling measurements analyzed (data recorded):
    - 800 to 500ºC
    - Peak temp to 100º C
    - 250 to 100ºC
    - Cooling rate at 540ºC

- Heat sink capacity measurements performed in lab and field trials on a natural gas flow loop, pressure 3.3 MPa, flow rate 47.0 to 417.0 million cubic feet per day (mcf/d)
    - Fillet welds also made using SMAW and GMAW to obtain other cooling measurements, 1 kJ/mm heat input
    - 250 to 100ºC cooling times: 29.0 to 90.0 sec

- Single pass weld results
    - E6010 welds, 1 kJ/mm: cracking did not occur in low CE material (CE IIW = 0.307) but did in all others
    - E6010 welds, 2 kJ/mm: cracking in all steels
    - E8010 welds, 1 kJ/mm: cracking occurred in all tests
    - E8010 welds, 2 kJ/mm: cracking in all tests except for pipe with lowest CE (0.307)
    - E7018 welds, 1 kJ/mm: cracking only in highest CE pipes (0.427 and 0.504) for sleeve welds none for branch welds
    - E7018 welds, 2 kJ/mm: cracking only in highest CE pipe (0.504)

- E6010 single pass weld observations:
    - Risk of cracking not strongly dependent on pipe composition
    - Slower cooling rates do not produce cracking
    - Increasing heat input has little effect on risk of cracking at a specific composition

- E8010 single pass weld observations:
    - Risk of cracking not strongly dependent on pipe composition
    - Slower cooling rates do not produce cracking
    - Increasing heat input has little effect on risk of cracking at a specific composition

- E7018 single pas weld observations:
    - Risk of cracking controlled by HAZ hardness, below 400 HV very little cracking observed
    - Lorenz-Duben hardening model best at predicting HAZ hardness based on composition and 800-500ºC cooling time

- Double pass welds observations, E6010 electrodes:
    - Cracks in all steels tested
- For cellulosic electrodes, cooling rate controls risk of cracking

For low hydrogen electrodes, HAZ hardness controls cracking therefore combination of cooling rate and pipe composition are the cracking control variables