EFFECT OF WELD PARAMETERS AND STACKED ERRORS ON THE QUALITY OF PE WELDS

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ABSTRACT

Following the 2011 Christchurch earthquake the use of welded polyethylene (PE) pressure pipelines for water supply networks and for pressure sewer mains continues to increase.

To achieve the design lives required from these pipelines the welded joints must be fully fused and be ductile. Despite the increasing use of this pipeline material the incidence of brittle welds with varying degrees of fusion is still causing concern.

This paper reviews options that Designers and Contract Supervisors can employ to improve the quality of PE welding in construction.

These options include:

- guidelines for acceptance of pipe and materials offered at time of tender
- the development of useful pre-construction welding trials to reduce the downstream construction risks to the Contractor, the Principal, and the Materials Supplier.
- selection of welding parameters, including comparison of some of the welding parameters available to the industry and likely to be submitted at time of tender.
- consideration of the effect of stacked errors during the welding process and the control of these.

These options are based on lessons learned from investigations of welding failures and theoretical considerations of welding parameters offered by the industry.

KEYWORDS

SCG RCP stacked error critical error welding parameter

1 INTRODUCTION

Like all pipelines, plastic pipelines have a finite design life. The design life is the period of time during which the pipeline should not rupture due to internal pressure and the service conditions it is operating under.

Where the PE pipe material and the pipe manufacture conform to the relevant standards, it can be reasonably assumed the pipe will not contribute to premature failure and will remain in its ductile mode throughout the design life.

In the case of PE pipe, which is typically joined by fusion welding, the quality of the welded joints can have a profound effect on the pipeline's design life. We have seen pipelines with low strength, brittle welds condemned before commissioning because they suffered multiple failures at the joints during filling and commissioning testing. It has been our experience that higher strength, brittle welds typically fail somewhere between 5 and up to 20 years after commissioning (depending on the degree of ductility and fusion across the weld).

When considering a pipeline is typically designed to provide a service life of between 50 to 100 years it is a concern that low quality, brittle welds can reduce the design life of the pipeline to approximately 20% of its intended design life.

This paper is based on our field experience investigating weld failures and pipeline failures over the past fifteen years. The conclusions presented are not necessarily new, or innovative, but are very often ignored by constructors and asset owners. When considering the risk associated with this action, we suggest the question of adopting basic, proven QA principals for PE welding should be re-thought.

2 NOTES ON PE PIPELINE DESIGN LIFE AND DUCTILITY

2.1 DESIGN LIFE

AS/NZS 4130 (PE Pipes for Pressure Applications) requires that P E pipe be capable of withstanding a specific hydrostatic pressure, which is continuously applied for a specified time and at a specified temperature.

This effectively is the definition of the pipeline's design life. The specified time and specified temperature is assumed by the standard to be a period of 50 years at a temperature of 20 ^{o}C. Therefore a pipeline with a nominal pressure rating (PN) of PN12.5 will not rupture when pressurized at a constant internal hydrostatic pressure of 1.25 MPa for a period of 50 years and at a temperature of 20 ^{o}C.

Because the operating conditions of a pipeline are never exactly those defined by the standard the final design life of the pipeline will vary. And where the operating conditions of the pipeline negatively affect the design life either the Maximum Allowable Operating Pressure (MAOP) is reduced (which requires the use of a higher rated pipe), or the design life is reduced to compensate for this.

2.2 REGRESSION TESTING

PE like other plastic materials will, over time, lose strength and become less ductile when subjected to stress.

The stress and time required for this to occur is established by regression testing, where PE pipes are subjected to constant pressures at various temperatures until they fail. The graph of regression testing typically looks like Figure 1. Testing has not been ongoing for long enough to establish the time to failure at 20 ^{o}C, and this is currently estimated by extrapolating data from higher temperature tests where failure occurs in a shorter period of time.

The design life is defined as the point where the required pressure rating intersects the regression curve. The pipeline may, or may not be, still be in its ductile mode at the end of its design life.

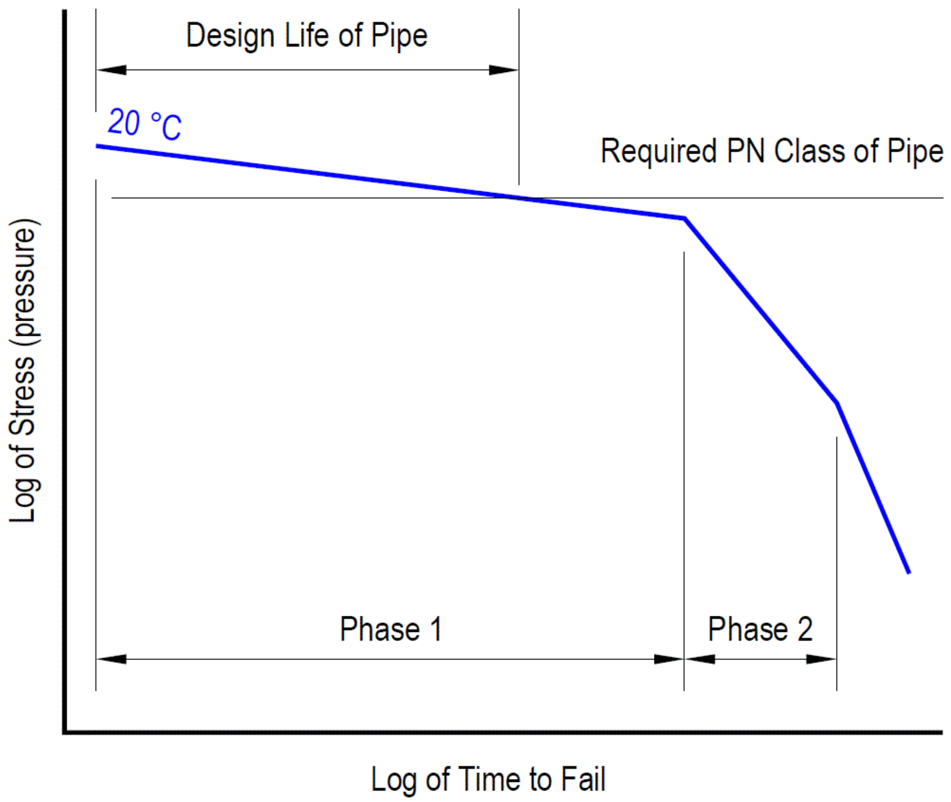
The knee between Phase 1 and Phase 2 defines the point where the pipeline transitions from ductile behaviour to brittle behaviour.

It is important to note that in Phase 1 the PE pipe behaves in a ductile mode where it will not rupture at a pressure equal to or less than its MAOP, and when over-pressurized it will deform plastically before failure (exhibit "parrots beak" failure). It will fail in a ductile manner. Failures can be predicted and should only occur when the pipe is over pressurized.

In Phase 2 the PE pipe behaves in a brittle mode. It will fail by stress cracking – Slow Growth Cracking (SGC) and Rapid Crack Propagation (RCP). Failures will occur at random intervals (which typically increase in frequency over time) and can occur at pressures lower than the PN class of the pipe.

Anything that is done by designers, constructors, or operators that alters the boundary between Phase 1 and Phase 2 de-rates the design life or PN class of the pipeline. The focus of this paper is to ensure the quality of the welding does not result in this occurring.

Figure 1: Typical Regression Curve for PE Pipe



3 RISKS ASSOCIATED WITH PE WELDING

Construction of pipelines using welded PE pressure pipe has been commonly practised in New Zealand for at least three decades and overseas for at least five decades.

Over these years weld failures have been attributed to pipe quality and fitting quality and installation errors.

With improvements in PE materials, and manufacturing practices, failures due to installation errors now account for the majority of failures compared to those attributed to pipe or fittings. In our experience we have only encountered two electrofusion fittings that were defective, and although it is difficult to quantify, we would estimate that the percentage of failures due to installation errors would exceed more than 90% of all failures.

PE welds that are fully fused and ductile will provide a pipeline that remains in the ductile phase of Figure 1 and will have a predictable design life.

3.1 CATEGORIES OF BRITTLE WELDS

PE welds that are brittle typically fall into one of two categories:

3.1.1 BRITTLE WELDS WITH LITTLE OR NO FUSION

Brittle welds with little or no fusion exhibit very little tensile strength and will have a very limited capacity to sustain stress. They often fail during installation, filling, commissioning testing, or very shortly after commissioning.

3.1.2 BRITTLE WELDS WITH A HIGH DEGREE OF FUSION

Brittle welds with a high degree of fusion will exhibit good tensile strength, but will have a very limited capacity to sustain stress. Such welds are expected to survive commissioning testing, but fail in service after only a small portion of the design life of the pipeline has elapsed.

The time to failure varies, and from our experience occurs between five and twenty years after commissioning of the weld. (We have investigated the brittle failure of an electrofusion coupler that occurred approximately five years after it was installed and we have investigated the brittle failure of both butt-welds and electrofusion welds that occurred approximately twenty years after they were installed). The varying length of time to pipe failure is related to the degree of fusion and the degree of ductility in the weld.

3.2 RISK TO THE CONTRACTOR

In practice brittle welds with little or no fusion offer the most risk to the Contractor because this defect will prevent the Contractor from completing the contract to the Engineers satisfaction.

The risk to the Contractor can include:

- not being able to complete the contract on time and to budget
- all welds already in the ground may be condemned, which effectively requires the Contractor to re-lay the pipeline at their own cost
- having liquidated damages applied by the Principal
- failure due to poor workmanship is not an insurable risk
- costs associated with investigating the cause of failure when it is suspected that materials have contributed to the failure
- poor attribute grades for future contracts
- insolvency if they are not able to meet their contractual obligations
- risk of not being able to procure ongoing PE pipeline work

3.3 RISK TO THE PRINCIPAL

In contrast to the Contractor the principal is at risk from both brittle welds with little or no fusion, as well as brittle welds with high a degree of fusion across the weld.

In the case of welds with little or no fusion the risk to Principal can include:

- poor public relations when the contract goes over time
- claims from the Contractor regarding any material supplied to the contract by the Principal
- costs associated with investigating the cause of failure where the Principal has supplied materials to the contract
- costs associated with resolving contract disputes, which inevitably are associated with weld failures
- costs associated with additional contract monitoring or supervision
- costs associated with additional contract administration

In practice however, brittle welds with a high degree of fusion offer the most risk to the Principal. This is because this defect tends to manifest itself after the Principal has released the Contractor from their defects liability obligations.

These welds will limit the service life of the pipeline because of the increasing maintenance costs required to keep the pipeline in service. The risk to the Principal can include:

- inability to maintain reliable supply to consumers, including essential uses
- increasing maintenance costs because the frequency of bursts will increase with time
- potential liabilities for uncontrolled sewage discharges (where the pipeline is a rising sewer)
- costs associated with clean-ups
- costs associated with investigating the cause of failure
- cost associated with designing a replacement pipeline
- capital costs of replacing the pipeline before the end of its design life

3.4 CONTROL OF WELDING RISKS

Although these risks can never be eliminated, they can be managed.

We can look at the continual work done by Christchurch City Council (CCC) to control these risks. Immediately after the earthquakes there was an unacceptably high rate of electrofusion weld failures (anecdotally we have heard figures where up to nine out of ten electrofusion welds tested failed the requirement for ductility and fusion). By rigorously applying QA steps such as weld sampling and testing CCC has achieved an improvement in the quality of welding, and electrofusion weld failures are now less than one in ten welds.

Some of this improvement is due to attrition among the less skilled contractors, and some of it is due to increased supervision and early weld sampling, which indicates to the Contractor that there is a problem that requires correcting.

It is our opinion that a pre-construction weld testing programme is invaluable in correcting potential problems before construction begins. This is based on our experience investigating welding failures on contracts where no pre-construction programme had been completed. To put this in perspective, in the past two years we have been engaged to investigate welding failures on two contracts where the contingent, combined claim against the Principals is expected to exceed $50 million dollars. We stress that when involvement occurs at this stage it is very difficult to limit risk, and the best resolution is often just being able to determine quickly the cause of the failure so corrective action can be agreed.

In both these cases the lesson learned should be that claims of this magnitude would not have occurred if the welding issues were resolved before construction started and tight welding QA was practised during the construction of the pipelines.

Pre-construction weld programmes significantly reduce the risk that unacceptable welds will be incorporated in the contract works. They offer the Principal a greater level of confidence that the welding is correct and reduces the considerable costs to the Contractor associated with identifying and correcting welding problems on-site where contract costs and site overheads are at their greatest.

Where a contract is completed without any problems it may be difficult to justify the time and cost spent undertaking the pre-construction welding programme, however when weld failures occur the value of such a programme is apparent.

4 ACCEPTANCE CRITERIA FOR PE PIPE AND MATERIALS

It seems to be an industry fact that when a weld fails there is vigorous debate as to whether the failure is because of the contractor's welding method, or because of the quality of the pipe and/or fittings.

This is only human nature. But when one party claims the pipe or the coupler is defective, and the other party claims it was an installation fault, there is not much option for the asset owner other than expensive testing.

This is the situation that authorities in Christchurch found themselves in in the early stages of recovery after the earthquakes. To some extent the requirement of NTC 22 that every batch of pipe be tested with electrofusion couplers to prove their compatibility was intended to break this circular argument.

4.1 ACCEPTANCE CRITERIA FOR PIPE

Although there will always be exceptions, typically if the pipe complies with the relevant standards it will be weldable.

In Australasia there are two standards which must be complied with. These are:

- AS/NZS 4131- PE Compounds for Pressure Pipes and Fittings
- AS/NZS 4130 PE Pipes for Pressure Applications

4.1.1 COMPLIANCE WITH AS/NZS 4131

AS/NZS 4131 specifies the material properties of the PE compound used to manufacture the pipe including its melt flow, density, thermal stability, colour, dispersion of additives, material strength, volatile content, and suitability for contact with potable water.

In addition to this 4131 also specifies the performance properties of the materials once they are extruded into pipe including strength (resistance to internal pressure), and resistance to stress cracking.

Compliance with AS/NZS 4131 is normally demonstrated by obtaining Conformance Certificates from the material manufacturer.

Material Conformance Certificates should be available from the pipe manufacturer, who is required to keep these as part of their quality assurance plan.

4.1.2 COMPLIANCE WITH AS/NZS 4130

AS/NZS 4130 requires that all PE pressure pipes be manufactured from pre-compounded materials complying with AS/NZS 4131.

AS/NZS specifies the performance requirements of the pipe and the residual material properties of the PE compound, as these may be adversely affected by incorrect pipe manufacture. Pipe performance requirements include colour, freedom from visual defects, effect on potable water, dimensions, out of roundness, and pipe branding. Residual materials properties include strength (resistance to internal pressure), thermal stability, and crack resistance.

Compliance with AS/NZS 4130 is normally demonstrated by obtaining Batch Test Certificates from the pipe manufacturer.

4.1.3 SOME MATERIAL PROPERTIES THAT MAY AFFECT THE PIPE'S DESIGN LIFE AND WELDABILITY

Dispersion
Pre-compounding is the process of mixing an additive package to the natural PE. Essentially the additive package comprises antioxidants, colour, and melt flow modifiers.

These additives must be evenly dispersed throughout the PE so that all of the PE molecules are equally protected from the effects of temperature during extrusion and welding.

Dispersion testing is by microscopic examination of the colour package and is more effective on black pipe or pipe that is coloured using crystalized colour instead of dyes.

Thermal Stability
It is important to realize that the thermal stability of the PE is a measure of the amount of antioxidant present in the PE. Every time PE is heated above its melting point antioxidant is consumed as it protects the PE from

thermal degradation. Thermally degraded PE will be brittle and would typically fail by stress cracking of the pipe or the weld.

The manufacturing (extrusion) of PE pipe and the joining (welding) of PE pipe both require that the PE be melted. Therefore it is important that the PE has sufficient antioxidant content to satisfy the thermal stability requirements of 4131 before manufacture, and have sufficient residual antioxidant content to satisfy 4130 after manufacture.

4.2 ACCEPTANCE CRITERIA FOR FITTINGS

In this case we are concerned with electrofusion fittings. These include both socket fittings and saddle fittings.

Electrofusion socket welding can be split into two categories: electrofusion welding of pipe DN400 and smaller; and electrofusion welding of pipes DN450 and larger. This is because the skill level of the welder and performance required of the fitting to weld large diameter pipe are greater than that required to weld smaller diameter pipe. There are a number of reasons for this, some of which include:

- large pipes are physically more difficult to work on and align
- large pipes are physically more difficult to peel correctly
- there is a greater risk of cross contamination occurring when working on larger pipes
- the ovality of larger pipes often exceeds the coupler’s working tolerances and re-rounding of the pipe is required
- aligning pipes is physically more difficult to achieve for large diameter pipes than it is for smaller diameter pipes
- the relatively close fit tolerances between pipe and coupler, when expressed as a percentage of the pipe diameter, are finer for large pipe than they for smaller pipe
- the Contractor has to exercise a high degree of control over final pipe diameter, square-ness of the pipe end, and ovality when preparing the pipe ends

Acceptance of electrofusion fittings is normally based on a two part evaluation.

4.2.1 COMPLIANCE WITH AS/NZS 4129

In the first instance fittings should be assessed for their standards compliance. Third Party accreditation for the fitting demonstrating compliance AS/NZS 4129 (Fittings for PE Pipes for Pressure Applications) should be available from the fitting supplier.

<u>Additional Compliance for Large Diameter Electrofusion Fittings</u>

In addition to this careful consideration of large diameter fittings should be made to establish if the fitting manufacturer has addressed issues ensuring a close fit between the fitting and pipe wall.

An example of this would be the pre-heat feature offered on larger Friatec fittings. This feature is required because of the design of the Friatec fitting, which has surface mounted elements and therefore must have a close tolerance fit between the pipe and the fitting to work correctly. Irrespective of the reason requiring the pre-heat feature Friatec can show they have a mechanism for achieving the close tolerances required for large diameter fittings, and this would make them acceptable for use.

Other examples include pressure bags that control outward expansion of the fitting so it better conforms to the pipe, and manufacturing methods that ensure the fitting will be dimensionally stable when energized.

4.2.2 PRE-CONSTRUCTION WELD TESTING PROGRAMMES

In the second instance fittings should be shown to be capable of welding to the pipe correctly during a properly designed and monitored pre-construction electrofusion test weld programme.

On successful completion of the pre-construction test weld programme and provision of evidence of standards compliance it would be appropriate to accept the fittings.

5 DESIGN OF PRE-CONSTRUCTION WELD TESTING PROGRAMMES

Before any PE welding contract is undertaken a pre-construction test weld programme should be undertaken. Without the information available from the pre-construction weld testing:

- the pipe supplier (which is often the Principal) is at risk that there may be a pipe issue
- the fittings supplier is at risk that there may be a fittings issue
- the Principal is at risk if the selected Contractor is not capable of completing the contract
- the Contractor is at risk if they are not capable of completing the contract

Weld failure may be the result of poor installation practice, fitting failure, or pipe failure, and a well-managed pre-construction test weld programme should be able to distinguish between the causes.

We believe a well-designed and monitored pre-construction welding programme is essential for correct QA control of the welding. Specifications that simply require all welding to be "completed to standard" (yes, we have seen this clause written in installation specifications!) and require no pre-construction test welding and no construction weld sampling offer absolutely no method of welding control and no method of welding QA.

Without welding QA the Principal may not know they have a welding issue for a period of between 5 to 20 years, at which stage the frequency of maintenance repairs will require the main be replaced after serving only a fraction of its intended design life.

5.1 PRE-CONSTRUCTION BUTT-WELD PROGRAMMES

A well designed pre-construction butt-weld test programme should have the following features:

- all welding shall be done to the Contractor's Work Method Statement (WMS) – which shall be agreed with the Engineer before welding starts
- the WMS shall be comprehensive and include (but not be limited to):
  - details about the set-out of the site and set-up of welding machines
  - details of the butt-weld machine proposed to be used (including its make, age, use and maintenance history, and current calibration certificate)
  - details of the welding parameter to be used – including sample calculations for each weld required to construct the contract works
  - details of pipe cleaning including initial cleaning and cleaning solvents to be used
  - details of pipe cutting
  - details of rollers and how the pipe is to be supported on each side of the machine – especially where the hot weld is pulled-off the machine
  - details of pipe facing and alignment checks
  - details of heater plate cleaning and heater plate temperature checks
  - details of weld data logging capability
  - details of control of environmental conditions
- welding shall be undertaken in conditions as close as possible to those expected on site – pre-construction test welds shall not be prepared in workshop conditions with short sections of pipe – we recognize that it is usually not cost effective to conduct pre-construction test welding on-site (especially where that site is in the CBD of a city), however previous experience has shown that shop welds are not a reliable indicator of the site weld integrity

- during the pre-construction test weld programme three consecutive samples of each type of weld required to complete the contract works shall be prepared for testing
- where more than one welding operator, or more than one welding machine shall be used to complete the contract, test welds shall be prepared by each welding operator and/or on each welding machine
- pre-construction welds shall be cut-out and tested in an accredited laboratory and shown to meet the performance requirements of the contract documents
- no construction welding shall take place before the Contractor can demonstrate they can produce three consecutive welds that satisfy the performance requirements stated in the contract documents
- where a weld does not satisfy the performance requirements the Contractor shall evaluate the information available and advise the reason and corrective action that is acceptable to the supervising Engineer before completing a further three welds for testing
- On satisfactory completion of the pre-construction test welding programme all construction welds shall be completed in accordance with the WMS used to prepare the acceptable welds

A well supervised pre-construction butt-weld test programme should:

- be supervised by the supervising Engineer or appropriately qualified person
- observe the welding practice of the Contractor and conclude whether their welding practice is sound, or requires improvement
- record temperature, time, and pressure parameters and ensure these comply with the agreed welding parameter
- observe any practices that could lead to cross-contamination
- observe that the welding site setout is acceptable and the control of environmental conditions is acceptable
- record bead sizes and any defects visible in the weld
- mark the welds as necessary before they are sent for testing

5.2 PRE-CONSTRUCTION ELECTROFUSION WELD PROGRAMMES

A well designed pre-construction electrofusion weld testing programme should have the following features:

- all welding shall be done to the Contractor's Work Method Statement (WMS) – to be agreed with the Engineer before welding starts
- the WMS shall be comprehensive and include (but not be limited to):
    - details of the electrofusion control box proposed to be used (including its make, age, use and maintenance history and current calibration certificate)
    - details of pipe cleaning including initial cleaning and cleaning solvents to be used
    - details of pipe cutting
    - details of pipe measurement and control of reversion
    - details of pipe peeling and peeling tools
    - details of pipe clamping, control of ovality, and control of alignment
    - details of weld data logging capability
    - details of control of environmental conditions
- welding shall be undertaken in conditions as close as possible to those expected on site – it is our experience that duplicating site conditions for electrofusion welding is more critical than it is for butt-welding

- pre-construction welds shall be cut-out and tested in an accredited laboratory and shown to meet the performance requirements of AS/NZS 4129 for electrofusion sockets, and meet the requirement of brittle decohesion not exceeding L/3 when measured radially at any location for electrofusion saddles
- otherwise the electrofusion pre-construction weld testing shall be the same as for butt-weld testing

A well supervised pre-construction electrofusion test weld programme should be the same as butt-weld programmes except that:

- the depth of peel cut by the Contractor's peeling tool be measured to determine if this complies with the current industry standards
- the pipe OD and ovality is measured to determine if this complies with the fitting manufacturer's recommendations
- misalignment or other welding defects likely to cause a brittle weld should be recorded

6 NOTES ON PE WELDING PARAMETERS

Butt-welding parameters are a specific combination of heater plate temperature, time, and pressure required to achieve a satisfactory weld.

PE welding parameters are critical to the quality of the weld. As designers, constructors and supervisors we are primarily concerned with butt-weld parameters as these are calculated and usually directly controlled by the welding contractor.

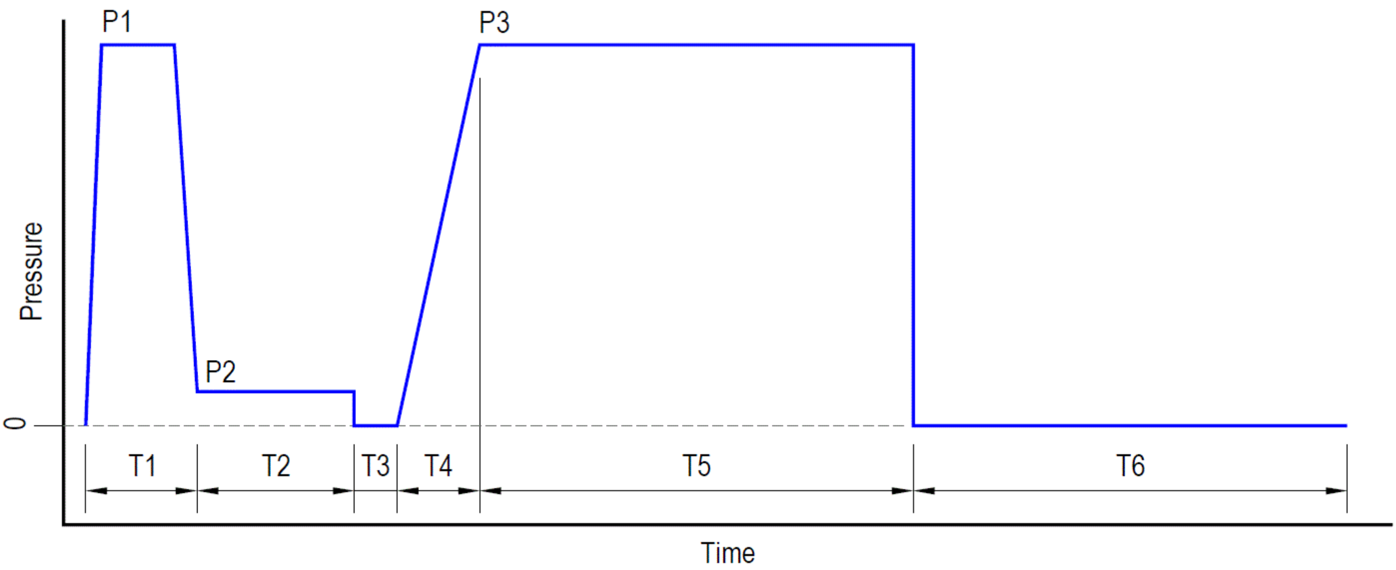
The following notes have been prepared to briefly explain the critical points regarding weld parameters.

6.1 BUTT-WELDING PARAMETERS

Any butt-weld is a combination of temperature and pressure.

There are many accepted butt-welding parameters in existence. They are all specific combinations of time, pressure and heater plate temperature and typically can be represented by the graph of time versus pressure in Figure 2.

Figure 2: Graphical Representation of a Butt-Weld Parameter



The welding pressure results from pressing the melted pipe ends together using a specified force (that is proportional to cross-sectional end area of the pipe). Because the weld is unconfined, some of the molten PE is displaced sideways by the closing pressure resulting in the distinctive weld bead typical in butt-welds.

Time, pressure and heater plate temperature may be directly controlled by the welding operator where a manual welding machine is used, or they may be controlled by the machine where a CNC machine is used. As long as the combination of time, pressure and temperature is correct, it is immaterial to the quality of the weld as to how they were controlled.

6.2 BUTT-WELDING PARAMETERS LIKELY TO BE SEEN IN NEW ZEALAND

Some of the parameters more likely to be seen in the New Zealand industry would include:

DVS 2207.1	This is the German welding method. This parameter is commonly programmed into Hurner and Ritmo machines.
ISO 21307 Single Pressure – Low Pressure	This method has been adopted in the latest revision of PIPA POP 003.
ISO 21307 Dual Pressure – Low Pressure	This method has been adopted in the latest revision of PIPA POP 003. This is an ISO standardization of the British WIS 4-32-08 welding method.
ISO 21307 Single Pressure – High Pressure	This method has been adopted in the latest revision of PIPA POP 003. This is an ISO standardization of the American welding method.
PIPA POP 003 Issue 5.1	The previous PIPA Single Pressure – Low Pressure welding parameter. Although this has been superseded by Issue 6.1, this parameter can still be used to produce high quality welds.

In addition to the welding parameters above, there are other welding parameters such as the NEN 7200 method, and the DS/INF 70-2 method. These are European welding parameters which are suited to welding large diameter, heavy walled pipes.

6.2.1 TIME COMPONENT

All time parameters are important to the integrity of the finished weld. Of all the parameters time is the most varied between each of the accepted butt-welding parameters.

The pipe wall thickness has a significant bearing on time parameters, and heavy walled pipes require very long heating and cooling times because of the low coefficient of thermal conduction in PE. It should be expected that the center of welds in heavy wall pipe will still be molten after the external weld bead has re-crystallized, and because of this the weld must be held at positive pressure for the full cool time to reduce tension stresses developing in the cooling weld.

The six basic time components illustrated in Figure 2 are defined as follows:

T1	Bead-Up Time	the time taken to generate a continuous bead around the ends of the pipe in contact with the heater plate – bead-up indicates the entire pipe end is in even contact with the heater plate
T2	Heat-Soak Time	the time that the pipe ends are in contact with the heater plate at no pressure – if excessive closing pressure is applied during T2 PE melt will be forced out and reduce the depth of the Heat Affected Zone (HAZ) - T2 is required for correct development of the HAZ
T3	Change-Over Time	the time taken to open the carriage, remove the heater plate, and close the carriage so that the molten pipe ends touch – the change over time must be as short as possible to prevent the development of a chilled skin of PE that will be trapped in the center of the weld and prevent fusion occurring across the weld plane
T4	Ramp-Up Time	the time taken to progressively increase the closing force of the carriage until welding pressure is achieved – the welding pressure must be increased in a controlled and linear fashion so that the velocity of the molten PE melt being rolled out of the weld is not too great – where the ramp-up time is too fast brittle welds will result
T5	Cool-Time in the Clamps	the time that the weld is maintained under positive pressure while it cools to a temperature below the re-crystallization temperature of PE
T6	Cool-Time out of the Clamps	the time taken for the weld to continue to cool to a temperature where it can be handled – T6 does not have to be under positive pressure

European researchers have concluded that Heat-Soak times and Cool Times are the two most critical parameters when welding heavy walled pipe (Christensen, T. / Borealis, 2002).

Heat-Soak Times are required to develop a HAZ of sufficient depth, and were assessed as being the most critical parameter when welding heavy walled pipe.

While Bead-Up Time is thought of as being distinct from Heat-Soak Time it is also important in development of the HAZ. The common practice of correcting badly faced pipe ends by applying additional Bead-Up Time should be discouraged because it can result in an uneven HAZ around the pipe circumference.

Weld cool Times were assessed as being the second most critical parameter when welding heavy walled pipe. Welds that are not kept under positive pressure while cooling can be brittle due to internal tension stresses developing in the weld as the pipe ends cool and contract.

It is our opinion that short change-over times are also equally important in in producing high quality PE butt-welds. Research has recorded the temperature drop on the pipe surface of 187 ^{o}C to 170 ^{o}C occurs in only three seconds (Wolters M. and Venema B.). At welding temperatures this rate of cooling will be even greater due to the greater difference in temperature between the PE melt and the atmosphere. And it will be even greater again where the welding site is not protected from environmental conditions and the weld is subjected to wind chill.

6.2.2 PRESSURE COMPONENT

Pressure is critical for ensuring the pipe ends contact the heater plate evenly and continuously during development of the HAZ. It is also critical to ensure the mixing of the melted PE molecules from each pipe end so that fusion across the weld is achieved.

With the exception of the Single Pressure/High Pressure welding parameter all other welding parameters weld within a generally accepted pressure band of between 150 kPa interface pressure and 190 kPa interface pressure. (The American high pressure parameter welds within 510 kPa interface pressure to 530 kPa interface pressure.)

There are three basic pressure parameters:

P1	Bead-Up Pressure	the pressure required to press the pipe ends against the heater plate with sufficient force to displace the initial melt - this ensures any high spots conform to the heater plate and every part of the pipe end touches the heater plate with equal pressure
P2	Heat-Soak Pressure	the pressure required to overcome frictional resistance in the welding machine and pipe string so that the pipe ends are held in contact with the heater plate, the pressure should be slightly positive but insufficient to displace molten PE from the HAZ
P3	Welding Pressure	the pressure required to hold the melted pipe ends together so that the molten PE in each pipe end inter-diffuse, before recrystallizing (pressure required for fusion across the weld plane) positive welding pressure is also required to prevent tension stresses developing in the weld as the PE cools and contracts

Provided the welding pressure is within the range defined by the parameter, the precise welding pressure is not believed to be critical. However it is our experience that interface pressures of around 180 kPa result in welds with reasonable weld bead displacement, good degrees of fusion (weld tensile strengths around 100% of the tensile strength of the unaffected pipe wall), and ductile short term test results.

When welding pipes that have a high Melt Flow Index (MFI) we have, in the past, reduced interface pressures in order to achieve high quality welds.

6.2.3 HEATER PLATE TEMPERATURE COMPONENT

Temperature is critical to the correct development of the HAZ and a PE melt that is sufficiently fluid that the molecules can readily mix together to produce good fusion across the weld plane.

Grades of PE100 suitable for pressure pipe application have about 60% crystalline molecules and 40% amorphous molecules. This ratio of molecules gives the material its desired properties of strength and ductility required for pressure pipe application. However because PE is not comprised of molecules of a single size and shape it does not have a discreet melting point. PE100 pipe material begins to melt at around 84 ^{o}C where the smaller amorphous molecules first melt, and is completely melted at around 132 ^{o}C where the large crystalline molecules have all melted. Any further increase in temperature simply results in the melt becoming more fluid.

Most welding parameters weld at a heater plate temperature of between 200 ^{o}C and 245 ^{o}C. Excluding the presence of other adverse conditions we typically observe that a heater plate temperature of between 220 ^{o}C and 230 ^{o}C and moderate to short change-over times will result in satisfactory welds.

Where heater plate temperatures are too hot (above 235 ^{o}C) there is a risk of thermal degradation of the PE material, which will result in brittle welds.

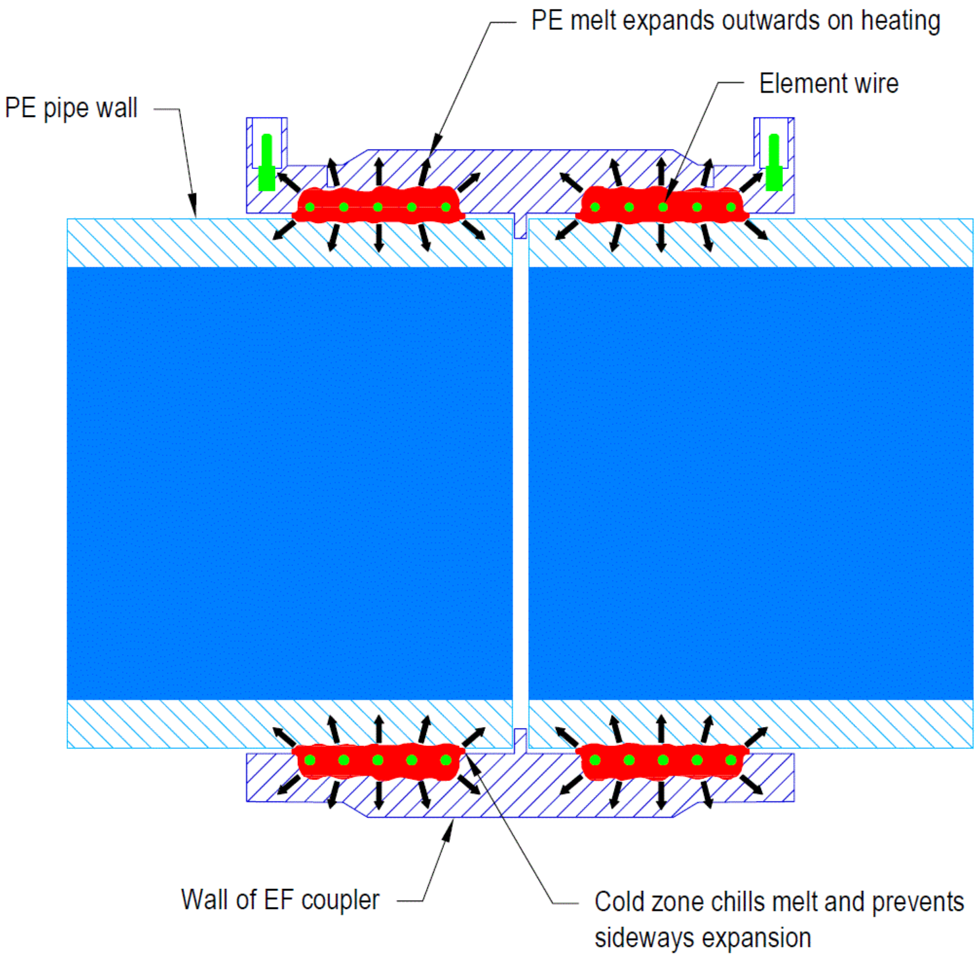
6.3 ELECTROFUSION WELDING PARAMETERS

Electrofusion welding also is a process of temperature and pressure. Temperature is provided by electrical heating elements and pressure is created by heating molten PE, which expands in the confined space between the pipe wall and the electrofusion socket (or the electrofusion saddle). We have tried to illustrate this in Figure 3.

The weld parameters for electrofusion welding are embedded in the barcode or resister pin on the fitting. They are uploaded to the electrofusion control box by swiping the barcode, or connecting the control box to the resister pin.

The welding parameter cannot be easily altered by the welding operator, and in general stacked errors causing electrofusion weld failures are caused by weld assembly errors not by the welding parameter embedded in the barcode.

Figure 3: Illustration of Pressure Generated by Expanding PE Melt Confined by Coupler and Pipe Walls



7 SELECTION OF BUTT-WELDING PARAMETERS

There are at least five butt-welding parameters commonly seen in the industry in New Zealand. These are:

DVS 2207.1	Commonly programmed into Hurner and Ritmo machines.
ISO 21307 Single Pressure – Low Pressure	This method has been adopted in the latest revision of PIPA POP 003.
ISO 21307 Dual Pressure – Low Pressure (the British WIS 4-32-08 method)	This method has been adopted in the latest revision of PIPA POP 003.
ISO 21307 Single Pressure – High Pressure	This method has been adopted in the latest revision of PIPA POP 003.
Watercare Specification 225 Method	Which simply is the ISO 21307 SP/LP method with the temperature and pressure variables tightened-up.

In addition to this we have successfully welded using the older PIPA POP003 method and customized parameters supplied by pipe manufacturers and by specialist pipeline Engineers.

Since publication of ISO 21307 the welding industry appears to be either moving to accept the ISO 21307 SP/LP method, or to remain using the DVS 2207.1 method (simply because their machines are programmed for this method).

Careful consideration of each parameter is required to assess its suitability for welding the proposed pipeline. This can be done during the selection of suitable tenders.

The most significant variation to the above parameters is the cool time. Welding and cool times for four parameters are compared in Figure 3. These have been calculated using the parameters published by PIPA (POP 003, 2011)

There has been some work to reconcile the relative effectiveness of the three methods published in ISO 31207. Research completed by the PE100+ Association found that the ISO 21307 SP/LP welding method produced welds with a greater tensile strength and better long term tensile creep properties (long term ductility) than welds produced by the ISO 21307 DP/LP and SP/HP welding methods (Beech, S. Salles, C. Schulte, U).

Considering each of the parameters in order, we have prepared the following notes.

<u>DVS 2207.1</u> This method is commonly offered because many welding machines are programmed for it.

It is one of the older, more established parameters. It was initially developed to weld pipes up to DN315, although it has been successfully adapted over the years to weld larger, heavier walled pipe. However when considering welding large, heavy walled pipe it may be prudent to consider other welding parameters that may be available during the selection process.

It has been developed using comprehensive long term test data, and when welding pipes up to DN500, or DN630 it has been our experience that the method is reliable and produces welds with good fusion and ductility.

The entire cool time takes place in the clamps under pressure. This is an advantage of this parameter because on release of the clamps the weld is considered strong enough to handle. It reduces the risk of tensile stresses occurring in the weld as it cools. Compared to parameters where half the cool time is in the clamps and half is out of the clamps, this parameter results in less risk if the weld is roughly handled when pulling it off the machine.

If the weld is not handled roughly and is not flexed coming off the pull-off side of the machine, the parameter's reliability will be improved at no cost to production rates or welding costs.

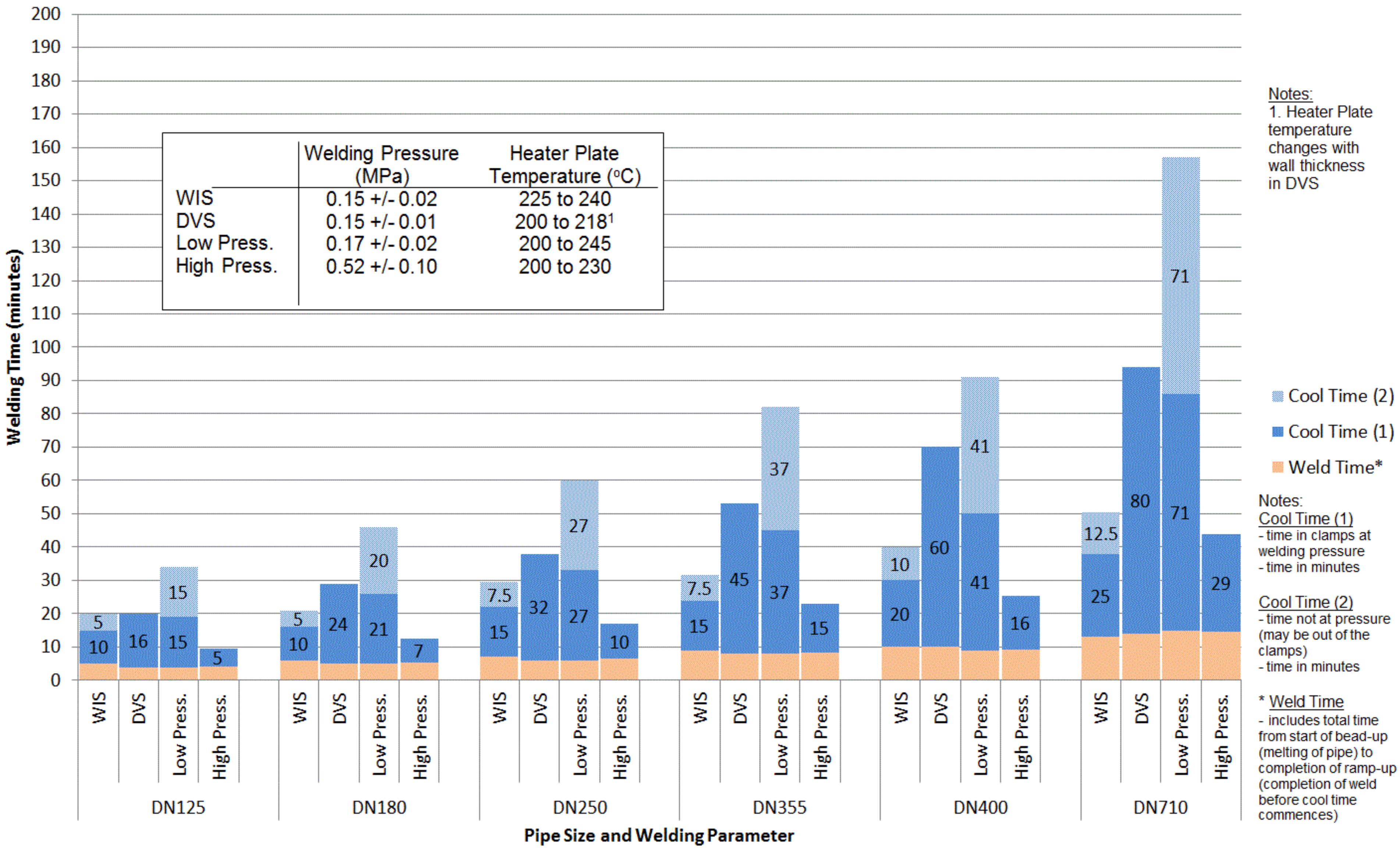
<u>ISO 21307 Single Pressure/Low Pressure</u> This method is becoming more common as the industry moves to adopt the ISO 21307 standard (or the current PIPA recommendations based on this standard).

This method is the basis of the Watercare Specification 225 method.

This is the established European single pressure method. It has been our experience that the parameter produces welds with satisfactory ductility and strength.

The cool time is suitably long with 50% of the cool time occurring in the clamps under pressure and the remaining 50% occurring out of the clamps. Splitting the cool time between time spent in the clamps and time spent out of the clamps allows reasonable production rates to be achieved, and the welds are expected to be ductile provided the contractor handles the warm weld correctly when pulling it off the machine.

Figure 4: Analysis of Welding Times for Different Welding Parameters



WIS 4-32-08 This method is commonly used to weld water pipelines in the UK. It is not commonly seen outside of the UK, however it is offered from time to time by welding contractors.

Again, this is a more established parameter initially developed to weld pipe up to DN315. It was developed specifically to weld the first generation Solvay PE100 resin, which was a highly crystalline PE.

Of concern is the relatively short weld cool time, especially when welding heavy walled pipe.

The parameter holds the weld at welding pressure for ten seconds before reducing the pressure to a small positive pressure during the cool time in the clamps. It is industry experience in Australia that some welding operators have trouble achieving the small positive cooling pressure, and cooling time in the clamps is effectively at drag pressure, which may result in tensile stresses developing in the weld as the PE cools and contracts. These stresses will result in brittle welds.

Unless the pipeline being welded is manufactured from first generation Solvay PE100 resin we see no advantage in using this welding parameter.

ISO 21307 Single Pressure/High Pressure This method is commonly used in North America. It is becoming common in the coal seam gas industry in Australia, but is not used in the water pipeline, or local reticulation gas industry in Australia.

It was originally developed to weld the early Phillips PE resins, which like the first generation Solvay resins, were highly crystalline. In contrast to the developers of WIS 4-32-08 the Americans adopted very high welding and cool pressures, and very short cool times.

This method is not suitable for welding thin walled pipe because of the risk of buckling of the HAZ under the high welding pressures.

To our knowledge this method was not developed using any long term ductility testing.

The very short cool times result in high production rates that make it popular with the Australian coal seam gas industry.

We have little experience with this parameter, but we have seen both ductile welds and brittle welds produced by this method.

Advice from experienced Australian welding contractors suggests the method produces a reasonably high rate of brittle welds. In their opinion raising the heater plate temperature above that allowed by the parameter reduces the occurrence of brittle welds.

Australian contractors also suggest that this parameter is less forgiving than the low pressure parameters. Consequently, careful consideration of the welding contractor’s skill level should be made before considering the use of this method.

We suggest that until comprehensive, independent long term ductility testing is available, the low pressure welding parameters should be considered in preference to this method.

WSL Specification 225 Method This method is simply the ISO 21307 SP/LP method with the following changes:

- P1 and P3 shall be 180 kPa (compared the allowable range of 150 kPa to 190 kPa)
- P2 shall be drag PLUS a small positive pressure less than 5 kPa (this is important to main contact between the heater plate and pipe end when using a skinned heater plate)
- facing allowances have been specified (these are not provided in ISO 21307)
- change-over times shall be as short as possible (ISO 21307 merely states a maximum)

- time parameters shall be calculated using the actual pipe wall thickness, or the mean wall thickness allowed in the standard (ISO 21307 uses the minimum pipe wall thickness stated in the standard, which reduces the cool times)

7.1 SUMMARY

Cooling times should not be sacrificed for higher weld production rates.

It is the observation of some Australian contractors that low pressure parameters are more forgiving compared to high pressure parameters, and as a whole the current industry skill levels probably better suit the use of low pressure parameters.

To our knowledge no long term testing (or short term testing) was used in the development of the high pressure welding parameters. Development of this data is considered critical to the acceptance of this method.

DVS 2207.1; ISO 21307 Single Pressure/Low Pressure; and Watercare's Specification 225 method are considered more suitable for welding small to medium sized pipelines. Where the pipeline is large diameter, or very heavy walled, and the pre-construction weld results are unacceptable then consideration of another welding method should be made.

8 STACKED ERRORS AND THE EFFECT OF THESE

Critical errors are errors that, when present in a weld that has no other fault, will result in a weld being brittle.

Errors such as weld contamination are critical errors, because this will result in failed welds without any other error being present.

Stacked errors are errors that by themselves are not expected to cause the weld to be brittle, but when more than one stacked error occurs in a weld the compound effect of the stacked errors is likely to cause the weld to be brittle.

Stacked errors can occur in butt-weld parameters and usually occur where the parameter is calculated or applied incorrectly.

Stacked errors may occur in the Contractor's welding method – both for butt-welding and for electrofusion welding.

Stacked errors do not occur in the welding parameters for electrofusion fittings as these are set by the manufacturer of the fitting and are embedded in the barcode.

8.1.1 STACKED ERRORS IN BUTT-WELD PARAMETERS

Butt-weld parameters are typically published where temperature and pressure must remain within a defined range and time is calculated as a function of the pipe wall thickness.

Weld Times

Studies have shown that the most important parameters in butt-welding are cool time, soak time and change-over time (Borealis, 2002).

Temperature

Butt-weld parameters have a fairly broad range for temperature, however we have observed that cold spots on a heater plate (where temperatures may not be significantly below those on the rest of the plate) produce brittle welds in that area. From this we must conclude that heater plate temperature is also important.

The upper end of the range 200 ^{o}C to 245 ^{o}C published in ISO 21307 risks thermal degradation of the pipe wall, especially in a pipe that has a thermal stability at the lower limit allowed by the standard. And the lower end of the range risks chilling of the melted face during change-over when welding in unfavourable conditions. The old PIPA document stated a heater plate temperature of 220 °C +/- 15 °C, which has been observed to produce good quality welds.

When considering how stacked errors may creep into welding parameters combinations of parameters that are likely to be unsafe should be looked for. For example the combination of a low heater plate temperature and a long change-over time is likely to result in chilled melt faces, which can result in brittle welds.

Another common mistake is to calculate the pipe wall thickness using the formula t = OD/SDR. This gives a wall thickness very close to the minimum wall thickness allowed by the standard (AS/NZS 4130). Using this value to calculate heat-soak times and weld cool times results in times about 5% less than those calculated using the mean value as recommended by PIPA. This becomes especially important when welding in warm conditions.

The tightened parameters seen in some specifications are designed to reduce the likelihood of these stacked errors occurring.

These considerations, as well as considering the suitability of the parameter, should be made when evaluating the parameter for acceptance prior to pre-construction welding.

8.1.2 STACKED ERRORS IN BUTT-WELDING METHODS

Typically stacked errors in butt-welding occur more often as a result of poor work methods, rather than as a result of poor parameter selection.

Errors such as: dirt building-up on the pipe clamps from not cleaning the pipe sufficiently, poor pipe facing, damaged or blunt facing plate cutters, dirty facing plate, misalignment across the weld, not protecting the welding site from environmental conditions such as strong cold winds, not checking heater plate temperatures, dirty heater plates, flexing of the hot welds when pulling the weld off the machine, are all examples of stacked errors, the cumulative effect of which can produce a brittle weld.

When method errors occur together with parameter errors the actual cause of the failure can be very difficult to determine.

Many of these errors can be identified and corrected at the pre-construction phase before contract welding commences. Just because the weld passed pre-construction testing is not a good enough reason to not have the contractor correct their welding method when these types of error are identified.

8.1.3 STACKED ERRORS IN ELECTROFUSION WELDING METHODS

In our experience nearly all failures in electrofusion welding are caused by errors in the Contractor's welding method. A very small minority of failures are caused by faulty pipe, or faulty fittings.

Contrary to some industry opinion it should be noted that the skill level required to produce an electrofusion weld is equal to the skill level required to produce a butt-weld. The skill level required to produce a large diameter electrofusion weld is probably greater than that required to produce an equivalent sized butt-weld.

PE electrofusion welding is extremely sensitive to contamination. And even apparently minor levels of contamination can cause catastrophic failures without any other error being present in the weld. Another common error is inadequate depth of peeling. This also causes catastrophic failure and therefore is not considered to be a stacked error.

Stacked method errors in electrofusion welding include (but are not limited to): not cutting the pipe ends square, not pre-cleaning the pipe correctly, not correcting reversion, not peeling sufficient length of pipe to assemble the weld, not measuring depth of peel, depth of peel that is too deep (resulting in the OD of the peeled pipe being smaller than the lower limit for the coupler), depth of peel that is not consistent, not marking the witness marks accurately, not assembling the joint to the correct stab lengths, not correcting ovality, not clamping the joint, not using alignment clamps or a suitable alternative, not swiping the correct barcode, and not controlling environmental conditions (such as strong, cold winds). Any combination of two or three of these method errors may result in a brittle weld.

Ideally these errors should be picked up during supervision of the pre-construction test weld programme. At this time the Contractor's WMS should be amended to correct these errors.

9 SUMMARY AND CONCLUSIONS

To achieve a service life satisfying the asset owner's design brief a PE pressure pipeline must remain in its ductile mode for the duration of its design period stated. Anything that results in a change to the ductile response of the pipeline will reduce its service life.

Therefore to achieve the design life requires that PE butt-welds and electrofusion welds be ductile and fully fused.

It is our experience that brittle welds will reduce the service life of a PE pressure pipeline to between 10% and 50% of its design life. This is because brittle welds cannot sustain the design stresses for the design period. They will fail at random intervals and at pressures lower than the designed operating pressure.

This is clearly not acceptable. Brittle welds impose significant risks on both the Contractor and the Principal, and significant operating risks on the asset owner.

We accept that some brittle welds result from faulty materials. This risk can be addressed by using a two part process for the acceptance of pipe and fittings. Part one is to check the standards compliance of the materials. Part two is to use the pre-construction weld testing results to confirm they are weldable. This process, while not completely infallible, will provide a reasonable level of confidence that the materials are fit for use.

When reviewing butt-weld parameters designers and contract monitors should be sufficiently trained and experienced to be able correctly calculate butt-welding parameters and identify stacked errors and inappropriate parameters. Parameters that sacrifice cooling times for high production rates should not be accepted.

We often, probably nearly always, see an example of a stacked error, or errors on site. This typically is more common on electrofusion welding sites. Control of these errors is critical on the construction site.

It is very expensive to fix faulty welding when it has been installed and buried. Therefore we conclude that undertaking a properly designed and supervised pre-construction weld test programme that will identify a lot of these errors and reduce the likelihood of them occurring during construction is essential. A pre-construction welding programme will establish:

- the Contractor's WMS is satisfactory
- the pipe can be welded
- the electrofusion fittings can be welded
- the Contractor has good welding technique (or their welding technique has improved during the pre-construction phase to an acceptable level)
- that as many stacked errors as possible have been identified and corrected
- the Contractor's welding equipment is in good working order and calibration
- the required level of confidence has been demonstrated for construction to proceed

In regard to the welding projects we have been engaged to investigate, the industry and asset owners have, for many reasons, abandoned the use of the pre-construction weld test programme as a QA tool. Repeatedly we have come to the conclusion that had a pre-construction weld test programme been in place a very expensive contract dispute probably would have been avoided.

We accept the pre-construction programmes can slow down the contract start-up process, and they can be expensive (especially when welding issues arise and must be solved during pre-construction). However we maintain that in most situations they are cost effective compared to the alternative of halting welding on-site (and possibly condemning any pipeline that has already been installed) while welding issues are resolved during construction.

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The author wishes to thank Borouge New Zealand and Glenwed Pipe Systems for their assistance over the years in providing research material regarding PE welding. Some of that material has been used in the preparation of this paper. It should be noted this material was originally published within the PE100+ Association, or within Borealis, and when searched by the author was not found to be publically available. This applies to the following material: Beech et al; Christensen, T.; Borealis Article 399; Wolter, M. Venema, B.

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