Rapport SGC 133

Lifetime Engineering analysis (pre-study) in order to set up an experimental evaluation programme of multi-layer and PEX pipes for use in gas distribution

Steven Brogden
Bodycote Polymer AB

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Johan Rietz

BODYCOTE POLYMER AB 2003-03-31

S-611 82 Nyköping, Sweden
Phone +46 155 22 14 72
Fax +46 155 26 31 25
E-mail brogden.s@bodycotepolymer.com

Handled by
Steven Brogden

Svensk Gastekniskt Center AB
Nobelvägen 66
205 09 Malmö
SWEDEN
Tech contact: Mr. Owe Jönsson

Lifetime Engineering analysis (pre-study) in order to set up an experimental evaluation programme of multi-layer and PEX pipes for use in gas distribution

Final report

Abstract

Svenskt Gastekniskt Center AB would like to undertake a test programme to determine the suitability of different types of multi-layer and PEX pipes for use in demanding applications where the use of conventional PE 100 pipes may be limited. In order to determine how such a test programme should be undertaken this pre-study was initiated by an order from Svenskt Gastekniskt Center AB on May 30th 2002.

The aim of this lifetime engineering analysis is to propose an experimental evaluation programme for the 4 different types of PE 100 and PEX pipe, including multi-layer pipes so that a long lifetime and cost effective solution can be ensured in demanding applications, particularly when using modern installation techniques.

The study has comprised of a literature survey and a meeting in Stockholm on August 26th 2002 where questions and answers relating to critical factors and one case study in particular were discussed relating to:

- Materials profile
- Loading profile
- Environmental profile
- Failures and/or damages
- Identifying and finding critical factors

The literature survey and discussion have helped to determine the most suitable test methods and lifetime models giving a diagnosis included in this report and the recommendation of a suitable test programme, with welding and point load resistance found to be the most critical factors.

Reviewed by Approved by

Jarno Hassinen Ulrika Andersson

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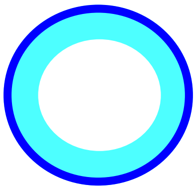
1 Introduction

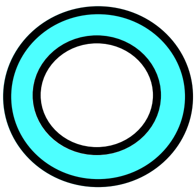
Svenskt Gastekniskt Center AB have approached Bodycote Polymer AB with the intention of conducting a lifetime engineering project on multi-layer and PEX pipes, for use in the Swedish Gas Industry. At present there is little experience, technical information, test methods and standards for the use of multi-layer and PEX pipes for Gas Distribution Applications. However there are currently many such products being developed for the market. Svenskt Gastekniskt Center AB would like to determine the factors most critical for allowing the use of these products in these applications. The object for Svenskt Gastekniskt Center AB is to have a ranking of the most critical factors so that suitable test methods can be developed by a third party, Bodycote Polymer AB, in order to gain approval for this product in its intended applications.

The following cross-sections show the types of pipes under consideration:

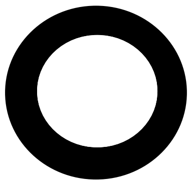
PE 100 pipe



PE 100 pipe with PP outer layer



PE 100 pipe with PEX outer and inner layers



PEX pipe

Svenskt Gastekniskt Center AB agreed to start this lifetime engineering analysis project on May 30th 2002 with the following personnel involved:

Mr. Owe Jönsson, Responsible Project Manager, Svenskt Gastekniskt Center AB
Dr. Steven Brogden, Responsible Project Manager, Bodycote Polymer AB

The ultimate goal is to develop a strategy for the gas industry on how to test multilayer pipes and convince the authorities that they can be used without sand backfill and in trenchless applications without any protection pipe with the same expected lifetime and safety as conventional PE pipes. Not only are the test procedures important but an international overview of installation methods for different types of pipe in different countries, jointing technologies, reparation possibilities, squeeze-off possibilities etc. It is not very economical if a pipe is cheap to install but expensive to repair or maintain. It is important to determine whether the mutli-layer pipe is an economical alternative not just during installation but also for the whole lifetime of the pipe.

2 Approach

The following steps were taken in order to conduct this lifetime engineering analysis:

2.1 Literature Survey

The literature survey covers a retrospective data base search of PE 100, multi-layer and PEX pipes. The data bank and experience at Bodycote Polymer AB were used. Contact was made with different resin and pipe manufacturers and other available contacts so that as much open literature and information as possible regarding PE 100, multi-layer and PEX pipes could be found. The study focuses on experience, failures, test methods, installation procedures and other items related to PE 100, multi-layer and PEX pipes for use in gas pipe installations.

2.2 Interview, Questions and Case Study

A meeting was held at the offices of Svensk Gas in Stockholm on 26th August 2002. Personnel from Svenskt Gastekniskt Center AB were interviewed and a large number of questions related to the applications were discussed. In particular the experience gained in one particular project was examined as an appropriate case study. The questions were related to the following:

- Materials profile
- Environmental profile
- Loading profile
- Failures and/or damages
- Identifying and finding critical factors

2.3 Identifying Test Methods and Lifetime Models

A list of relevant test methods for PE 100, multi-layer and PEX pipes was made and suitable lifetime models were identified. A summary of general factors affecting the lifetime of PE 100, multi-layer and PEX pipes is presented.

2.4 Diagnosis

All the information gained from Items 2.1-2.3 has been used in order to make a diagnosis. Different material, environmental and loading factors have been ranked. Critical factors have been defined and a testing programme presented based on existing facts and available data. This information will result in an offer for an experimental programme.

3 Literature Survey

The aim of this project is to evaluate the suitability of multi-layer and PEX pipes in comparison with PE in general and PE 100 pipes in particular, a very well established product with which the Gas Industry now has a history of long reliable performance. Therefore the first section of this literature survey is an overview of the history and experience with this product. The second and third sections of the survey are on PE 100 pipes with a PP outer layer and PEX pipes, including PEX pipes that are constructed with a PE 100 core surrounded by outer and inner layers of PEX. A final section brings together a comparison between the different pipe materials.

3.0 Material Selection for Gas Distribution Systems

The choice of a material will be a balance between material properties and design requirements. Some of the factors influencing this choice are [1]:

- Gas distribution pressure
- Cost of pipe and fittings
- Ease and cost of installation
- Skill of the installers
- Investment in jointing and ancillary equipment
- Simplicity and cost of repair
- Nature of the distribution area
- Required ductility and flexibility of the pipe
- Presence of other services
- Workable pipe lengths
- Availability of different pipe diameters and suitable fittings
- Lifetime expectancy of the system
- Chemical and corrosion resistance of the system
- Health, safety and environment

3.1 PE 100 pipes

3.1.1 Material Factors

The service experience of PE materials in water and gas pipelines over the last 50 years has been extremely good. One such example is the British Gas network, which includes more than 240 000 km of PE (mainly PE 80) of gas pressure pipe [2]. Experience over 24 years shows that failures are extremely rare and that pipes installed over this period retain their original mechanical properties. The few premature failures that have occurred have all been due to some form of external secondary loading combined with the reduced stress crack performance observed for 1st generation PE materials. More modern 2nd generation PE 80 materials have had virtually no problems at all. PE materials for pipe applications offer the following major advantages over traditional materials:

- Cost
- Durability and flexibility
- Ease of jointing and installation
- Corrosion resistance
- Environmentally friendly

Recently tandem reactor process technology has allowed the development of PE grades with bimodal molecular weight distribution [3]. Such 3rd generation PE resins can attain a PE 100 rating with a minimum required strength (MRS) of 10 MPa, giving several advantages over 1st generation (PE 63) and 2nd generation (PE 80) materials [4]:

- Increased service pressure
- Reduced wall thickness
- Increased hydraulic capacity
- Possibility of producing larger pipes
- Improved mechanical properties

The PE 100 pipe material itself is first evaluated to give an MRS of 10 MPa by a Standard Extrapolation Method (SEM) evaluation according to ISO/TR 9080:1992(E) [5] or ISO/FDIS 9080:2002(E) [6]. A safety factor is then usually added to this strength requirement at 50 years. Such evaluations are usually performed on small diameter thin wall pipes and the MRS value obtained is accepted for all sizes. Bodycote Polymer has carried more of these evaluations than any other laboratory in the world and has the widest experience in this field. Some of the results and experiences gained during SEM evaluations, according to ISO/TR 9080:1992(E), were published [7].

Whilst brittle behaviour is accounted for in SEM evaluations many standards allow damage of up to 10% of the wall thickness to occur during handling and installation. For this reason further testing is required on 20% notched pipes to determine the susceptibility of these materials to slow crack growth (SCG). However modern PE 100 (and PE 80) materials display a very high SCG resistance. In order to avoid failures the requirements in ISO 13479: 1997(E) [8] should be fulfilled. Many of these tests have also been undertaken at Bodycote Polymer.

Another possible failure mode for the material is rapid crack propagation (RCP). This is where the pipe unzips in a distinct wavy manner at high speed. Such a failure requires a combination of the following:

- External impact
- Entrapped gas or air inside the pipe
- Low temperature
- Large wall thickness
- High pressure

A full-scale test to determine the susceptibility of pipe materials to this failure mechanism was developed by British Gas and has been adopted as ISO 13478:1997(E) [9]. However the equipment is extremely large and the test is very costly to perform, so a small-scale test (S4) has been developed allowing appropriate data to be obtained by tests on smaller diameter pipes. In order to avoid failure by this mechanism the requirements in ISO 13477:1997(E) [10] must be satisfied. Bodycote Polymer has performed many of these tests on its own S4 equipment. PE 100 materials generally perform better in this test than PE 80 materials.

In summary the improved mechanical properties of PE 100 resins compared with 1st and 2nd generation PE materials are a result of a good balance of the 3 most critical mechanical properties for polyolefin pipes:

- Minimum required strength (MRS) of 10 MPa according to ISO 9080
- High resistance to slow crack growth (SCG) to ISO 13479
- High resistance to rapid crack propagation (RCP) to ISO 13477

Although many different factors including and in addition to the above will affect the service lifetime of a PE 100 pipeline, it is not yet known which of these will be the most critical in determining the ultimate lifetime. Experience of using PE for water pipelines over the last 50 years however suggests that even a 100 years maybe a conservative lifetime prediction for PE 100 pressurised water pipes [11] and such systems have smaller safety factors than gas pipes.

3.1.2 Loading Factors

3.1.2.1 Temperature

The operational temperature will have an effect on the service capability of a PE 100 pipeline. As with all thermoplastic piping, polyethylene pipe loses stiffness and tensile strength as temperature increases. As temperature rises, the normal operating pressure of the pipe should be de-rated. As temperature decreases the pipe gains strength, so if the pipe material has been evaluated and tested at 20°C, and the operational temperature is say 10°C there will be an additional factor of safety for the strength of the pipeline. The temperature of the external environment must also be considered when determining the correct SDR of the pipe, as well as compensation for any thermal expansion or contraction.

The external temperature will also have a significant effect on loading, as obviously a pipe system installed in a desert with a daily temperature range of 50°C will differ significantly from a pipe system installed in frozen tundra. It is though important to know the maximum and minimum external temperatures that will be encountered and also the possibility of sudden or rapid temperature changes that may cause thermal shock or temperature cycling effects.

3.1.2.2 Traffic and Backfill

Flexible plastic pipes are able to deform to accommodate surrounding soil movement without necessarily experiencing excessive pipe wall stress. This can have the advantageous effect of transferring vertical loads into the supporting earth. Rigid pipes such as metal, clay or concrete must carry any external ground loads within their own structure. In response to vertical crushing forces from overburden as well as any vehicle axle loads, the pipe wall reaction forces within a rigid pipe generate force moments that can potentially cause fracture. A less stiff plastic pipe deforms to translate the vertical load into lateral movement that generates lateral forces in the soil fill around the pipe sides which oppose further movement and prevent pipe collapse [12].

When designing plastic pipelines and particularly for larger diameter pipelines of 300 mm nominal diameter and greater, consideration of the following design criteria [13] might be advised:

Load is usually calculated in accordance with the standard vehicle load given in national load regulations.

Deflection of pressure pipe is governed by the external load, the pipe stiffness, the quality of the backfill and the installation method when the internal pressure in the pipe is zero and hence the pipe is at maximum deflection. The calculated deflection caused by the load together with the installation factor gives the average deflection. The maximum deflection will be obtained when the bedding factor is added. For a normal installation the average deflection will not exceed 5%.

Strain for pressure pipe the strain is a combination of bending strain and tensile strain. Design can be made separately for tensile strain caused by internal pressure and bending strain caused by external loads since PE has a high rate of relaxation of bending stress. Although there is obviously a relationship between strain and deflection, the allowable strain is so large for PE that it will have no influence on the deflection limit given above.

Buckling the short term values of pipe stiffness and soil modulus are used, together with an appropriate safety factor, to determine the risk of buckling in firm soil or at shallow burial depth. When making a calculation to determine the risk of buckling an assumption should be made that due to alternating pressure the pipe will eventually create a free space in the soil support and therefore no soil support can be counted upon.

Well-established equations have been derived for these and other design criteria [14]. Current European design practice is found in prEN 1295 [15].

However pipelines are designed from the perspective of an ideal world whereas the real world often sees pipes subjected to extremely severe conditions not usually envisaged by designers. One particularly significant problem for plastic pipelines has been the laying of pipes on large rocks that produce a stress concentration on the inner pipe wall. This phenomena known as point loading has led to many failures of plastic pipelines, PVC-U pipelines in the UK and Holland had some bad experiences particularly in the 1960s and 1970s. Although polyethylene materials have been less prone to such problems due to their higher ductility some failures have been reported for 1st generation polyethylene materials. Failures of polyethylene gas pipes constructed in the early 1970s from 1st generation polyethylene materials have been reported in Holland for example [16].

These 1st generation materials consisted of very long chains that tended to glide from each other when loaded. The comonomers that produced branching in the molecular chains of 2nd generation materials led to a significantly improved resistance to crack growth. 3rd generation PE materials have an even greater resistance still as the distribution of the branches is carefully controlled. Only PEX where there is a complete interlaced structure has superior crack growth resistance [17].

3.1.2.3 Scratches and Gouges

Scratches and gouges may be produced on the outside of pipes particularly during handling prior to installation and also during installation, particularly when using trenchless techniques. In such a widespread structure as a pipeline it must also be considered that further damage will occasionally occur in service too. An established rule for damage tolerance is that the notch depth shall be less than 10% of the pipe wall thickness.

3.1.2.4 Welding and Jointing

The two fundamental requirements for any pipe jointing system are that it should have a minimal detrimental effect on the performance of the remainder of the system and that it must be at an acceptable cost [18]. The minimal detrimental effects on the overall pipe system, in terms of key properties, embrace factors such as the following:

- life expectation
- physical strength
- resistance to internal pressure
- handling and flexibility
- resistance to physical abuse
- able to accept expansion/contraction/axial loading
- forces/movement
- influence on flow properties
- influence on fluid quality
- chemical resistance and corrosion

The optimum cost combination of any components plus labour are a function of:

- component or material cost
- associated assembly costs equipment costs
- ease of use
- time for assembly/make up
- skills/training requirements
- traceability/ownership cost
- reliability/quality
- replacement/repair cost
- transport costs
- availability
- health and safety considerations
- environmental effects

The jointing of PE by butt and electro-fusion welding techniques has long been recognised as the Achilles heel of PE pipe systems, particularly with larger diameter pipes as difficulties with cleanliness of the joint, out-of-roundness of pipe and inadequate equipment are exaggerated.

Electro-fusion welding in particular is very dependent on correct procedures being adhered to. Contamination of the outside of the pipe and inside of the electro-fusion sleeve is a particularly serious problem in the UK, due to the wet and windy climate. Also pipe-misalignment can be another problem, often due to a lack of correct clamps and working in confined spaces. Premature failures due to weak or brittle welds may well be picked up during the pressure test for commissioning the pipe, but even at this stage, costly delays in digging down and re-welding followed by subsequent re-testing can be incurred.

Similar problems can occur with butt-fusion welding, but contamination is less likely as the welding machine first strips the surface to be welded before the heat-soaking period. It is important to keep the heater plate as clean as possible, usually by wiping with a suitable solvent before starting. As with electro-fusion welding, misalignment can be a problem, although modern equipment has clamping as an integral part of the jointing machine.

A technical and installation guide produced by one of the major UK polyethylene pipe manufacturers outlines the different jointing methods and gives detailed instructions on proper jointing procedures [19]. Fusion jointing offers:

- A correctly fused joint should be as strong as the pipe itself, which also ensures that the corrosion immunity of the polyethylene pipe system is continuous and unimpaired.
- Fusion jointing enhances the inherent flexibility of polyethylene. With strong joints, flexible pipe strings can be fed easily into position from above ground, whatever installation technique is used.
- Fusion joints need introduce no bore impedance. The smooth internal finish of a de-beaded fused joint should ensure that there is no such impedance.
- Such techniques are much faster and less costly than mechanical jointing.

Two methods are now employed widely throughout the gas industry, butt fusion and electro-fusion:

3.1.2.4.1 Butt Fusion

In butt fusion the pipe ends to be joined are brought together in a dedicated butt fusion machine. The end faces are squared up by planing with a mechanical trimmer, then heated with a thermostatically controlled non-stick (usually PTFE coated) heater plate. Then the molten the faces are pushed together and allowed to cool. This process generates weld beads both inside and outside the pipe. These can be removed easily to produce a smooth bore or outer surface. Inspection of the beads also provides a useful quality check.

Only approved well-maintained butt fusion welding machines should be used [20]. Although manual machines have been used extensively in the past, automatic hydraulically operated machines where the welding cycle is computer controlled are now almost exclusively used. In fact such machines are now mandatory when laying pipelines for British Gas. It is important to ensure that all appropriate equipment is used and that the steps involved in the butt fusion process are strictly adhered to onsite, otherwise the possibility of producing welds of poor quality is greatly increased.

Despite the wide availability of welding instructions there are still many problems with poor site practice leading to unsatisfactory welding particularly for example in the UK Water Industry. Problems in the UK have been a lack of independent site supervision, causing contractors to take short cuts and continue to weld without the proper equipment, a lack of trace-ability and often poorly trained personnel. This has lead to the development of training and licensing initiatives. One specific improvement is trace-ability and the joint ownership of welds, which has now been adopted in prEN 13067 [21].

For butt fusion of thick walled PE 100 pipes, the UK Water Industry has developed some special conditions. Using a higher hot plate temperature of 230°C (+10-5°C) and an increase in the heat soak time have compensated for the higher molecular weight and heat of fusion of PE 100 materials [22]. For conventional PE 80 only a single fusion pressure of 0.15 MPa was generally needed to produce ductile welds, but for PE 100 materials this single fusion pressure could result in brittle welds for pipes of > 25 mm wall thickness.

When a welding pressure 0.15 MPa is used for PE 100 materials, as adopted not only within the UK but also in DVS 2207, Part 1:1995 [23] and other European standards, shear forces are produced that result in high molecular orientation and distortion of spherulites at the boundaries of the melt zone (this was also a problem for 1st generation HDPEs). The UK Water Industry Specification [24] gives the dual pressure welding conditions now used to overcome this problem. It has also now been adopted for PE 80 materials in order to harmonise conditions.

Dual pressure welding is now required for all pipes of greater than 22 mm wall thickness. The objective of dual pressure welding is to allow the molten polymer to cool with the minimum positive pressure, thus allowing the crystal structure to develop without distortion hence promoting ductility. This is particularly important with the more crystalline PE 100 materials. If the polymer has a large crystal structure, then the interface between the melted and solid PE material can become distorted when force is applied during cooling. This interface can act as a weak point in the weld area.

The Dual Pressure cycle, shown in Figure 1, is the same as for normal welding until the heater plate is removed, then (for the UK Water industry):

1. apply the conventional interface pressure of 0.15 MPa for 10 seconds after bringing the molten pipe ends together to allow the melt on each surface to mix and a bead to form – to clear any contaminants from the weld interface.
2. reduce the pressure to 1/6 th of the joining pressure (excluding drag) during cooling.

The use of dual pressure welding has been questioned [25]. It has been considered that there may be a risk because the secondary pressure might be lower than the drag forces for large diameter pipes, leading to uncontrollable tensile stresses within the weld producing voids.

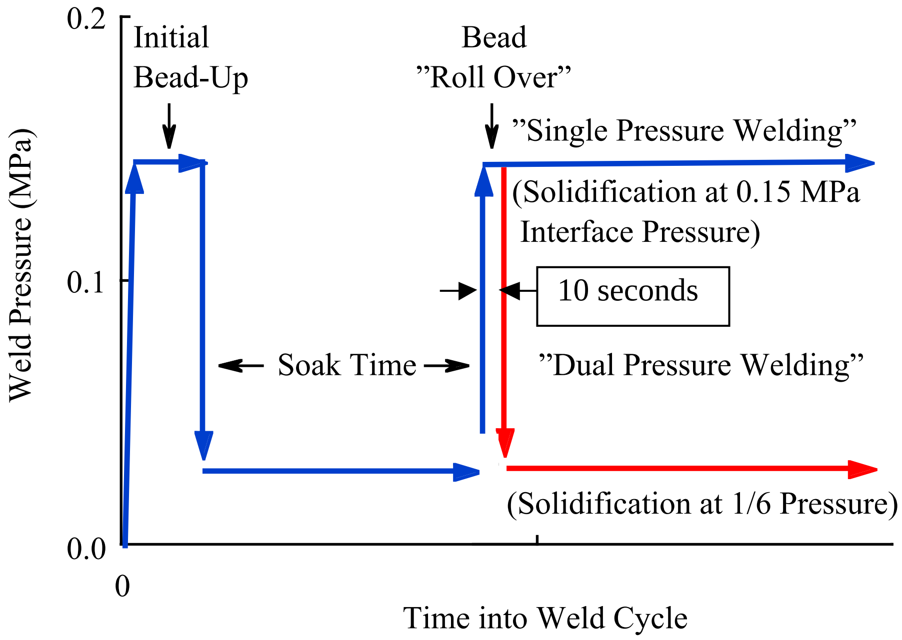


Figure 1: Comparison of Single and Dual Pressure Welding Cycles

However this problem has not shown up in UK site experience. In the case of PE 100 pipe welding the use of dual pressure, increased plate temperature and longer soak times can be seen to have benefited weld interface quality and also resulted in stress and orientation free weld zones.

3.1.2.4.2 Testing of Butt Fusion Joints

The external weld beads should have no wrinkles or discontinuities and be of symmetrical appearance. Provided that each half of the final bead is of a similar shape and size, the overall width should not be a critical factor for the assessment of a butt fusion joint. After cooling time has elapsed the external and internal beads should be removed using a de-beading tool in a clean continuous strip without damage to either the joint or the bead. This should be done without the bead removal tool inducing any slits, gouges or other defects into the pipe wall or bead. The bead should then be used as a check on weld quality:

- On examination of the underside of the bead surfaces and the external pipe joint surface after de-beading, there should be no sign of any circumferential slits, gouges or similar defects between the fused beads. It should not be possible to separate them by flexing parallel to the line of the weld.
- If such a defect is seen then the joint should be cut from the pipeline and the joint remade. If a similar defect recurs, all further production jointing shall cease until the equipment has been thoroughly examined, problems rectified and new trial joints made and tested.

Both the UK gas and water industries now require that no welded joint should ever fail in a brittle manner. This should be achieved providing that welding instructions are carefully followed. To ensure that joints have essentially the same properties as those of the parent materials, it is recommended that butt fusion welds be tested to destruction to ensure that high toughness characteristics are obtained [26]:

Test joints should be made prior to commencement on site using the certified welder and approved welding equipment to be used for the contract.

- For pipes of 355 mm diameter and greater, it is recommended to frequently test the mechanical properties of sample welds during the course of the contract.
- Up to six tensile samples may be cut from the selected weld and tested to failure using the procedures and criteria given in [26].
- It is a general requirement that the failure modes of all the test samples shall be ductile. Mixed and brittle failures are unacceptable.

Although these tests have been recognised to give a very good indication of the quality of butt welds, it is still a weakness of this specification that the frequency of such tests is not included. In such situations contractors often tend to do as little testing as possible because of the time restraints and financial penalties usually imposed on delays to the project.

The tensile tests developed for use in the UK Water Industry have proven to give a very good indication of the quality of welds produced in the field. These tests can be performed quickly either on site or in the laboratory, however they do not give a quantifiable indication of weld quality, since the test only requires a visual assessment of the fracture in order to gauge weld ductility. An improvement to the tensile test method is to use an extensometer, allowing the area under the load deflection curve to calculate the failure energy in terms of the energy/cross-sectional area, thus yielding quantitative information about the weld ductility [22]. Impact testing has also been considered [22], [27] and [28], but the practicality of this as a quality control test and the relevance to the whole area of the joint, particularly for large diameter pipes has to be questioned. Another short-term test is the bending test in DVS 2203, part 5 [29]. However in one study [27] neither this test nor a dumbbell test were found to be able to differentiate between welds made under either standard or extremely non-standard conditions.

A detailed study has been made comparing the different European specifications for welding methods and testing standards [25]. Together with the short-term test methods discussed above consideration was also given to long-term methods for assessing weld quality. The pressure testing of welded pipes, has been frequently used. However this method has a serious drawback in that the tangential wall stress is twice as high as the axial wall stress. This means that the weld is only subjected to half the load in the most critical direction, across the weld. Hence this method can only reveal whether the welding factor is above or below 0.5. This explains why very few failures in the weld rather than the pipe are found with this test method. Long testing times can also be a problem. These problems have been overcome at Bodycote Polymer by using steel sleeves around the pipe away from the weld and testing at elevated temperatures.

The German standard DVS 2203 part 4 [30] uses the long-term creep testing of tensile bars taken across the weld joint. This method can be undertaken in a few hundred hours and a long-term welding factor determined, for which there is a requirement in DVS 2204 part 1 [31]. The PENT test [32], which uses long-term constant tensile loading, can also be used to develop a long term welding factor.

Some non-destructive test methods have been investigated but have not yet been adopted in any standards. One such method is ultra-sound testing [33].

3.1.2.4.3 Electro-fusion

Electro-fusion uses socket-type fittings with integral heating elements to construct a pipe system [19]. Couplers are used to join mains pipes and saddle fittings are used to connect service pipes. Within an electro-fusion fitting there is a resistive heating wire connected to surface terminals. An electric current passed through the wire melts the polymer and fuses the fitting to the pipe wall. The pipe to be welded is first prepared by scraping away the outer surface layer, then the pipe and fitting are clamped together to restrain movement. An electrical current is applied across the terminals from a generator via a control box. After welding the assembly is allowed to cool thoroughly before unclamping.

The advantages of using under pressure electro-fusion branching saddles for gas and water mains of 280 to 355 mm were compared with traditional methods that involve squeeze off and branching [34]:

- Little or no inconvenience to the customer
- Small effect on the environment as no large excavations are needed
- Less disruption to the area due to the speed of the operation
- Easier planning of the work
- Less chance of failure due to reduced numbers of pipe and fitting joints

3.1.2.4.4 Testing of Electro-fusion Welds and Saddles

There were considerable numbers of failures of electro-fusion welds in the UK water industry in the early 1990's [35]. Many failures even occurred during the pressure test used when commissioning pipes, these failures occurred at something like 25% of the expected static burst pressure resistance of polyethylene pipes and were attributed to poor site practices. However operational failures still occurred, which could not be attributed to poor site practice. It was found that contamination of the pipe nearly always occurs before welding and some small degree of contamination is unavoidable. However some designs of fittings perform much better under contamination than others. Therefore a contamination test was developed. It was found that coating the surfaces to be joined with talc prior to burst testing in the laboratory gave very similar results to those of joints produced in the field. All electro-fusion joints for use in the UK Water Industry must now pass this talc contamination test [36].

Conventional methods for assessing the joint strength of electro-fusion fittings involve testing in either cleavage [36], see Figure 2, or peel [37], see Figure 3.

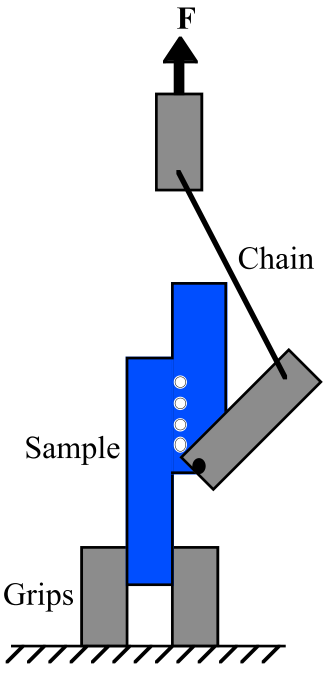


Figure 2: Cleavage test in WIS 4-32-14 [36].

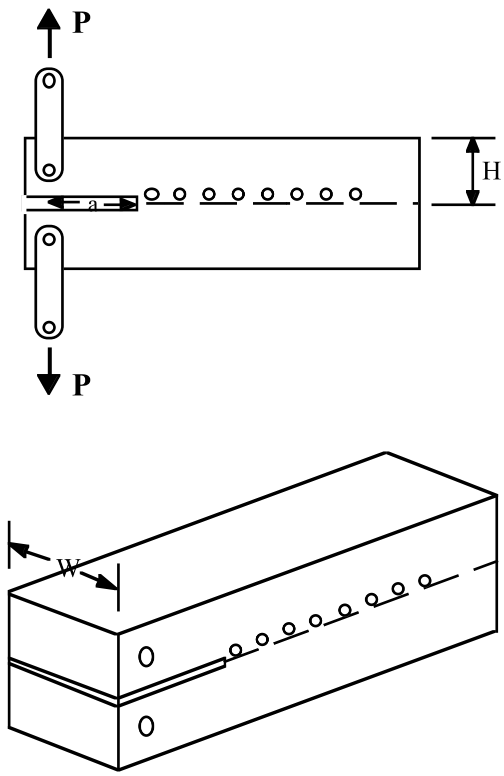


Figure 3: Peel test in BS 7336 [37].

These methods were compared in one study with the finding that the cleavage test requires more subjective judgements than the peel test [38]. An advantage of the cleavage test is that a fracture toughness evaluation can be made to assess electro-fusion weld quality [35]. However the applicability of such testing is difficult to quantify in terms of service performance and is invalid for ductile fractures.

Therefore a dynamic hydrostatic test method was proposed as a superior test method. Here a complete fitting assembly is internally pressurised until failure. The pressure end closures should be located very close to the fitting, thus constraining the diametric expansion of the pipe. This has the effect of enabling the pipe to withstand pressures well in excess of those normally expected for polyethylene. The internal pressure acts on the end closures of the sample generating high-end forces until a critical shear stress is acting on the joint. Ranges of couplers of the same design were pressure tested and the end loads at failure calculated, so that by plotting end load against joint area it could be shown that failure was by a critical shear stress criterion as in Figure 4 [35].

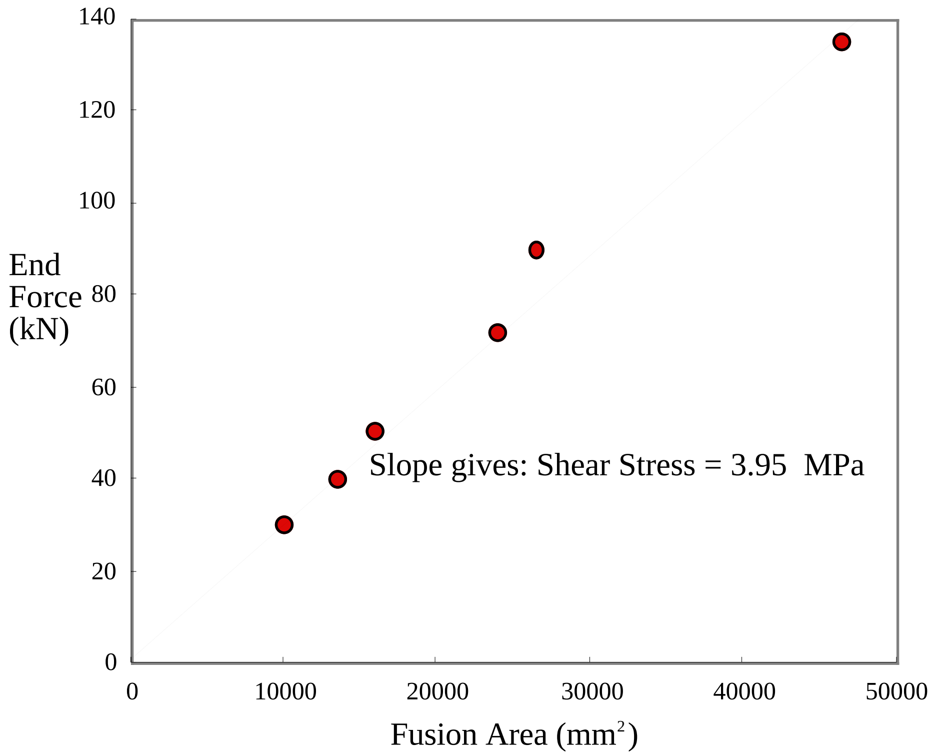


Figure 4: Fusion area versus end load, giving a critical shear stress criterion.

For this reason ramp to burst hydrostatic pressure testing of this kind is a very suitable test method for electro-fusion joints and branch saddles. Pressure regression data obtained using this test method was found to give approximately the same slope for different designs of fittings. This slope gave a decrease by a factor of 2.5 between short-term ramp to burst tests and the expected pressure after 50 years. Therefore these fittings now have to pass such a hydrostatic pressure test criterion [36] when introduced into the UK Water Industry. This is 2.5*the pressure rating of the service pipe. The test is conducted at a rate of 5 bar/minute in a water bath at 23°C.

The log term PN rating now accepted in the UK water industry [39] is:

$$PN = 0.4 * p_{av}$$

This is based on a factor of 0.5 for long term creep regression combined with a safety factor of 0.8, where p_{av} is the average value of three burst pressure tests. The highest pressure rating based on this criterion used in the UK water industry is PN16. This formula uses a factor of 2 for the relationship between short-term ramp to burst test and 50-year pressure rather than the 2.5 previously used [35].

In the test programme [35] it was found that fittings of an early design produced by different manufacturers failed to pass this test and that fittings produced by different manufacturers could exhibit variable performance. However it was also shown that with improvements in design the hydrostatic pressure performance of some fittings could comfortably exceed this requirement. It can be suggested for example that a fitting with a rating of PN16 may be able to withstand a long term pressure resistance at 50 years of say 20 bar if the short term burst test result was 50 bar rather than the 40 bar requirement.

Testing of the uncontaminated pipe to BS 7336 [37] is required to ensure that a fitting performs at least as well as the host pipe in terms of stress regression properties, meaning that the uncontaminated fitting has a ‘built-in’ safety factor of at least the same order as the host pipe. So for example a PN10 fitting used in a PE 100 PN10 pipe system has a safety factor of at least 1.25. However the use of such hydrostatic testing is not likely to produce failures in the fitting by the shear stress criterion shown to cause failure. This is because the hoop stress levels in the attached pipe will be much higher thus tending to produce failures in the host pipe rather than the fitting.

Using these assumptions couplers from different manufacturers could be pressure tested with end closures located very close to the fitting so that short term and longer-term regression data are obtained. It might be reasonably expected that fittings with superior long-term pressure resistance might be found that could therefore be used in higher-pressure applications. It is clear though that such results would depend heavily on the determination of an acceptable degree of contamination, if any, being agreed by the interested parties and the accurate determination of the long-term extrapolation factor.

The test methodology has recently been modified for electro-fusion tapping tees [39]. This may have been because there is greater likelihood of failure in the host pipe during high pressure ramp to burst testing, as such saddles do not completely surround and hence constrain the pipe. Tests are now performed by pressurising the untapped saddle through a very short length of PE connected to the service pipe outlet. The new criterion is that 3 test pieces should give an average burst pressure which is higher than the pressure reached during the ‘Type 2’ pipe commissioning test found in [40] for use by the UK water industry. Such fittings will therefore withstand short-term pressure of at least 1.5*PN rating of the host pipe.

As with butt fusion testing the non-destructive method of ultra-sound testing has been investigated but is not widely used and has not been adopted in any standards [33].

3.1.2.4.5 Flange Adapters

When butt-fusion is not possible or when joining the PE pipe to a metal pipe, flange adapters made of the same material as the host pipe may be used [41]. These have the same dimensions as the PE host pipe at one end. This end is then butt welded to the host pipe while a flange at the other end mates up with the flanged end of the metal pipe or another PE flange. A rubber gasket is used between the two surfaces. A metal flange slipped over the host pipe is then bolted to the flanged end of the metal pipe to ensure a tight seal. The bolts should be re-tightened after a set period of time, usually a few hours to the specified torques. When correctly installed, such mechanical joints give few problems but are used less often as they are more costly than welding.

3.1.2.5 Squeeze-Off

One problem with gas and water pipeline systems is that the flow of fluid might have to be stopped in order to carry out maintenance or repair a leak. When completely stopping the flow is the only viable solution a section of the pipeline must be isolated with the following disadvantages [42]:

- Interruption to supplies resulting in customers without gas or water
- Potential compensation claims
- Revalidation of existing pipeline networks
- Inconvenience to customers

A very large cost can easily be incurred depending on these factors. Therefore a rapid and effective method for stopping and re-starting the flow is required. For polyethylene pipes advantage can be made of the compliance and flexibility of this material by using the technique known as squeeze-off. This is a very effective procedure as it can be undertaken at almost any point on the pipeline allowing the shortest possible section to be isolated thus reducing inconvenience.

This procedure is routinely used to stop the flow in order to carry out repairs or maintenance downstream of the squeeze-off point [43]. The pipe is compressed between two bars until flow effectively ceases. After the downstream repairs have been completed the bars are released to allow the pipe to regain its former circular shape. Re-rounding is also often practised where the squeeze tool is turned through 90 degrees and the pipe partially recompressed in an attempt to return the pipe to its former shape. Because the pipe undergoes an extensive shape change during squeeze off and re-rounding it is important to determine whether these practices have any detrimental affect on the subsequent lifetime. New developments now mean that squeeze off can be performed on PE 100 pipes with internal pressures of as high as 7 bar.

The test method for determining the resistance of polyethylene pipes to external pressure after application of squeeze-off is EN ISO 12106:1997(E) [44].

3.1.3 Environmental Factors

3.1.3.1 Internal Environmental Factors

Polyethylene is biologically inert and the additives and stabilisers normally used in PE pressure pipes do not promote biological growth [11]. PE is not digestible, has no food value, cannot support bacterial growths and is too smooth for marine growths to adhere to [14].

Polyethylene for use in gas distribution systems should be resistant to the gas constituents present. ISO 4437:1997(E) [45] requires a conditioned pipe containing a synthetic condensate comprising a mixture of 50 % (m/m) n-decane (99 %) and 50 % (m/m) 1-3-5-trimethylbenzene to fulfil the hydrostatic pressure test requirements at 80°C in ISO 1167:1996(E) [46].

3.1.3.2 External Environmental Factors

External environmental factors have been identified [14]:

Modern PE materials contain additives, which give UV protection for the pipe when exposed to sunlight. ISO 4437:1997(E) has a requirement for resistance weathering in which pipes exposed to a specified energy of sunlight shall fulfil all the test requirements of the specification. Other factors relating to the weather do not require any special precautions other than the effect of temperature previously discussed.

Insects such as ants, termites, burrowing insects, earthworms or marine worms, do not attack PE 100 pipes. Gnawing rodents such as rats occasionally attack smaller diameter PE pipes, but it is not common since there is no food value.

Significant concentrations of oils or other hydrocarbons in the soil can affect PE pipelines. Although hydrocarbons do not attack the pipe, they can permeate the pipe wall causing elongation and loss of strength. These effects are reversible, however where such hydrocarbons are present the pipe should be upgraded to a heavier wall to provide adequate strength for the pipeline pressure.

PE 100 pipes should not be buried in areas where there is a high risk for potential severe chemical spills. In these circumstances, no piping system whether plastic or metal can be considered immune to contamination by permeation through the walls or joints. If the contaminating source cannot be safely controlled, it is best to change the piping route altogether.

PE pipe systems are normally exposed to external environments such as acid and saline ground water without detrimental effect [11].

3.1.4 Installation

There is a large amount of installation guidance available, for example [19] [40] and [41].

Although there are now numerous methods including the so-called No-Dig or trenchless technology methods, the majority of installations are performed using open-cut methods [47].

The various installation techniques can be divided into four categories [48]:

- Open-cut trenching
- Narrow trenching
- Trenchless installation
- Rehabilitation and Renovation

The first three techniques apply to new installations whereas the fourth is where an existing pipeline is replaced.

3.1.4.1 Open Cut Trenching

This is the most well established technique where a trench is dug to a suitable depth, the pipe is laid in the bottom of the trench and the trench is filled. Sand or other prescribed backfill materials are often used. These backfill materials are costly to purchase and transport to the site and disposal of the excavated material can also pose a problem. Although this technique is relatively easy to perform it can be very disruptive particularly in urban areas. It can also be dangerous for those working in and around the trench.

3.1.4.2 Narrow Trenching

This is an improvement on the traditional open cut technique where a trench just larger than the pipe diameter is excavated and then the pre-jointed pipe is installed into the trench in long lengths. By using the excavated material as the backfill rather than using sand bedding additional cost savings can be made. Narrow trenching is cheaper, causes less disruption, and is less dangerous. In rural areas, employing modern trenching trains, very fast installation rates of the order of several hundred metres per day can be achieved. However it is less successful in urban areas as the size of the extra equipment associated with this method often causes more disruption than is countered by the savings.

3.1.4.3 Trenchless Installation

Systems employing these so-called No-Dig techniques include various methods of drilling, tunnelling, or ramming the ground in order to make an opening for the pipe. The main advantage is that a pit can be dug at either end of the pipe length to be installed rather than a trench along the whole length of the pipe. This causes very little disruption and is particularly suitable for use in urban areas. Many different systems exist for different ground conditions, pipe sizes and lengths. These systems can be limited by the presence of other services, ground conditions and the need to make large numbers of service connections. Examples of trenchless installation methods are:

- Ploughing/Milling
- Soil Displacement
- Directional Drilling
- Pipe Bursting

3.1.4.4 Rehabilitation and Renovation

These techniques are actually other forms of trenchless installation; in these cases the structure of the original host pipe is left more or less intact. There are many methods for renovating existing pipelines, such as the techniques of swage lining and slip lining.

3.1.4.5 Benefits of Modern Installation Techniques

It is advantageous to use modern narrow trench and No-Dig installation techniques because they:

- Significantly reduce costs
- Save time
- Reduce public and environmental disturbance
- Are safer

3.1.5 Limitations of PE 100 Pipes in Demanding Applications

Modern installation techniques can lead to substantially increased damage to the outer wall of the pipe due to abrasion, scoring and scratching. Two methods, directional drilling and pipe bursting are particularly aggressive to the outer wall of the pipe. The directional drilling method first creates a hole in the ground that is then reamed out to a size allowing a coil of PE pipe to be pulled through [49].

Pipe bursting is where an existing metal pipeline is broken into fragments and then a PE pipe is pulled into the void created by the pipe bursting equipment directly behind the splitting tool. Around 100 metres are pulled through at a time, at diameters of up to 225 mm. One of the benefits of this technique is to allow replacement of pipes with pipes of the same diameter or even greater when in benign ground conditions. A concern with this process is the resulting sharp metal fragments as well as stones and gravel that are left in the ground surrounding the PE pipe. These all have the potential to score the pipe during insertion. Depending on the ground conditions scores can penetrate the pipe surface by between 0.5 and 1 mm [50]. Early pipe bursting operations used a sacrificial PVC duct through which the PE pipe was pulled, offering protection to the PE pressure pipe. More recently only PE pipes with outstanding slow crack growth resistance have been used allowing the expensive to install PVC duct to be dispensed with. Other techniques such as horizontal drilling or any technique where difficult ground conditions persist can lead to damage such as surface abrasion. This often leads to the specifying of thicker walled pipes with obvious economic disadvantages and perversely such thicker walled pipes are more likely to come into contact with embedded rocks therefore making them more susceptible to point loads due to the plane strain condition in the pipe wall.

The susceptibility of pipes to different types of damage in different installation processes was considered [51]. For methods such as pipe bursting and soil displacement protection against notch damage/crack initiation and point loading were considered to have a very high requirement. For relining applications notch damage/crack growth was considered to have a very high requirement, but there is no requirement for protection against point loading. Horizontal drilling was also considered to have a high requirement for protection against both notch damage/crack initiation and point loading. Ploughing and sandless installation were considered to have very high requirements for point loading resistance but not notch damage/crack initiation, whereas milling was considered to only have a high requirement for point load resistance.

Despite the good properties of PE 100 and its very well proven performance in gas distribution systems, such severe conditions will make extra demands that may put limitations on the product because there will be:

- Increased abrasion
- Increased risk of failure due to point loading
- Increased risk of external defects
- Increased risk of rapid crack propagation – here the increased wall thickness used to compensate for additional damage may increase the risk of failure.

In addition to these possible problems it is still recognised that welding and jointing of PE 100 pipes is still not 100% reliable.

For these reasons a number of competitive alternative material solutions are being developed and used by the industry for the most demanding applications, particularly where the modern installation techniques of narrow trenching and No-Dig are employed.

Alternative materials such as the use of PE 100 pipes with an outer protective PP coating, multi-layer PEX-PE 100-PEX pipes and PEX pipes may provide the solution in such cases as these may have:

- Higher long term strength
- Better slow crack growth resistance
- Better rapid crack propagation resistance
- Better point load resistance
- Better abrasion resistance
- Better corrosion and chemical resistance
- May enable more reliable welding and jointing

3.1.6 Economic Considerations

The flexibility and toughness of PE pipe allows it to be delivered and dispensed into ground workings from coils, avoiding the need for many joints and also reducing delivery costs. This results in a reduction in the total cost of the installation, which may offset any higher material costs [12].

The total cost of a pipeline can be broken down into a combination of:

1. Pipe and Fitting costs:
   Raw materials
   Production

2. Installation costs
   Jointing processes
   Excavation, pipelaying, reinstatement

3. Maintenance
   Repair of material/construction failures
   Repair of damage

4. Pipeline Lifetime
   Determined by design
   Determined by quality control

Environmental and re-cycling issues are also important. Minimising waste and re-utilising scrap are obviously not only important environmentally but for economic reasons too.

Although all these factors are very important the maintenance and pipeline lifetime may often be considered lower priorities in economic terms, provided that well known materials with a long service experience from around the world in similar applications are being selected. Therefore economic selection may be determined most critically by pipe and fitting and installation costs. As the ease of installation of PE pipes by modern installation techniques can offset any higher price for these materials it can be that the installation method is the most critical factor of all. It is therefore of great advantage to find pipes suitable for use with modern installation techniques, even if these are more costly multi-layer or PEX pipes.

3.2 PE 100 Pipes with a Protective PP Outer Layer

3.2.1 Material Factors

The beneficial properties of PE 80 and PE 100 pipes for use in gas and water distribution applications are well known and a long successful service history has been established. However there are two notable areas where further improvements can be made to these systems: excessive damage particularly when using modern No-Dig installation techniques and problems with welding, particularly due to on-site contamination. Therefore a new product has been developed by Uponor, known as “Profuse” with a peel-able sacrificial skin, intended to absorb the extra damage when using trenchless installation techniques [50]. After installation, removal of the skin using a simple tool reveals a contamination free surface readily prepared for welding. As this surface is protected until just before welding many of the problems associated with poor welds are eliminated.

“Profuse” pipes consist of a core pipe and a skin. The core pipe consists of an un-pigmented, UV and thermally stabilised PE 80 or PE 100 material. The pipes have dimensions that conform to the SDR, wall thickness and outside diameters as given in ISO 4437 [45]. By selecting the appropriate dimensions according to this standard a range of different pressure rated multi-layer pipes can be produced in the same way as solid wall single layer PE 80 and PE 100 pipes.

The 0.6 to 0.7 mm thick polypropylene skin can be coloured or have stripes to indicate the utility and pressure rating and/or the type of PE resin core pipe, whether PE 80 or PE 100. The skin adheres well enough to the core pipe for it to remain in place during installation but it can also be removed relatively easily when jointing. The good adhesion is because the PE melt and PP melt first come into contact in the co-extrusion die and this interface is kept intact throughout the extrusion line, with the two materials being cooled to ambient temperature together. Since the PE pipe is not exposed to the cooling baths surface oxidation of the outside wall does not occur, as it is not exposed to the environment. Since the PP skin is kept intact until shortly before welding, minimal surface oxidation occurs when the PP skin is peeled off.

The “Safety Line Coated” (SLM) pipe [52] from Egeplast in Germany is also a standard PE 80 or PE 100 pipe with an external skin of PP. This product is available in sizes 25 to 400 mm in all common SDR ratings. The major difference between this and the Uponor product is that the outer coating of recyclable modified PP is added to the core pipe as an additional downstream operation, therefore the outer surface of the PE core pipe could still have some surface oxidation. Egeplast have also developed a tool for removal of the outer skin prior to jointing. If extruders are available any PE pipe can be coated. This product has been in use with German gas and water utilities since 1994. Over 200 km has now been installed, largely in diameters up to 63 mm.

Although pipes made from both PE 80 and PE 100 resins can be used as the core pipes the present study will consider only multi-layer pipes constructed with a core pipe of PE 100. However the material factors for PE 100 are well known and as long as a PE 100 resin which passes the three most critical mechanical properties for this material the performance should be at least as good as a single layer PE 100 pipe. So the multi-layer core should have:

- Minimum required strength (MRS) of 10 MPa according to ISO 9080
- High resistance to slow crack growth (SCG) to ISO 13479
- High resistance to rapid crack propagation (RCP) to ISO 13477

The core material will also conform to all the other test requirements in ISO 4437.

The sacrificial PP skin is likely to confer extra enhancement of these properties, the difficulty is how to measure this, as there are no standards yet available for such multi-layer pipes. One approach is to look at how tests in the current standards can be used or adapted for these particular products. However, one should be cautious, as it does not necessarily follow that the addition of such a protective layer will improve all the mechanical properties of the pipe. With composite and multi-layer pipes unexpected and peculiar fracture phenomena can occur, due to the interaction between the different materials. If for example one material in a multi-layer pipe was more prone to crack growth than the other material then a crack with sufficient energy running easily through one material could accelerate and run through the other material too, even if the second material was not so susceptible to crack growth itself. In other words while it is most likely that the mechanical properties of a pipe will be improved by the addition of another layer it is possible for the extra layer to reduce the performance of the pipe as well.

Many new alternatives on similar themes are now being produced. One such example is the new “Robust” pipe from Pipelife [53]. Here the standard dimension SDR 11 or 17 PE core pipe has an outer protective layer consisting of a foamed PE rather than the PP used with the “Profuse” product. This may possibly provide greater protection against point loading due to a cushioning effect. Pipelife in the Czech Republic manufacture this product in the diameter range from 32 to 110 mm. Like Uponor and Egeplast, Pipelife have developed a special tool for removing the outer protective layer prior to welding.

3.2.2 Loading Factors

3.2.2.1 Temperature

As with PE 100 pipes, multi-layer PE 100 with a protective PP outer coating are expected to gain strength and stiffness as temperature decreases. However it is not known how the interface between the materials might be affected by decreases or increases in temperature. The materials may adhere better at lower or higher temperatures and this may cause problems when trying to remove the outer layer for welding. Also the different rates of thermal expansion of the two materials may cause detrimental effects to the pipeline at different temperatures and this is perhaps of greater concern when there are sudden variations in temperature.

3.2.2.2 Traffic and Backfill

Providing that essential design calculations have been made, such pipes should have few problems due to traffic loading and backfill when specified backfill materials are used such as sand or fine gravel. However problems may occur when modern No-Dig installation techniques are used. Pipe bursting for example leaves sharp metallic shards in the soil surrounding the pipe. Also various drilling techniques allow large rocks to be left in the ground that could potentially cause point loading after installation.

The structure of the pipe however is not necessarily likely to give much benefit in terms of additional point load resistance. This is because embedded rocks cause cracks to initiate and grow from the inner wall of the pipe, making the core pipe material the most critical area for point load resistance. However, modern PE 80 and PE 100 materials are highly resistant to slow crack growth, so the problem may not be too severe.

The only benefit likely to be gained from the thin PP layer is the increased cross sectional area over which the load is distributed, although this increased section may also contribute to the condition of plane strain, which is more likely to promote crack growth. Egeplast claim that there is a 50% reduction in the stress concentration due to point loads on the outside of the pipe [52]. However it is the stress concentration on the inside bore where cracks initiate that is most critical and the claim is only that this internal stress concentration is reduced. The percentage reduction is not specified and therefore the suspicion must remain that this is only marginal for this type of pipe.

3.2.2.3 Scratches and Gouges

Modern No-Dig installation techniques will lead to increased damage from scratches and gouges during installation particularly due to for example the metallic shards left after pipe bursting operations. The commonly accepted level of damage is 10% of the wall thickness.

Research on the measurement of scores and scratches on polyethylene pipe used in No-Dig operations [49] indicates that the scoring of polyethylene pipe will not exceed the specification of 10% during directional drilling operations in clay soils. Measurements taken on PE pipes with a PP outer layer showed improved protection against scoring under such conditions and in no case was the outer PP layer scored all the way through revealing the inner PE layer. However other types of ground conditions were not considered.

It was also shown that the depth of scratches and scores could exceed the specification of 10% when PE 80 pipes are installed by pipe bursting. Comparable data was not obtained for PP coated PE pipes or PE 100 pipes. However the data obtained for PE 80 would suggest that 10% damage could also occur for PE 100 pipes. This damage may also be severe enough to penetrate right through the PP protective outer layer and into the core pipe of PP coated PE pipes.

Further work is needed to determine the degree of damage for all these types of pipe for different ground conditions when directionally drilling and especially for pipe bursting operations.

3.2.2.4 Welding and Jointing

Although PE pipe materials have had a long proven history, it is the integrity of the whole pipeline system, which includes welds and joints that is of the most fundamental importance to the success of a particular material. Welding of PE pipelines has been described as the Achilles Heel of PE pipelines and so this is one particular area where a PE pipe with a PP skin has the potential for improvement over conventional PE 80 or PE 100 pipes.

3.2.2.4.1 Butt Fusion

Butt fusion jointing should pose few problems. One benefit is that it should be easy to see a proper joint by a uniform bead of the unpigmented core pipe contrasting in colour with the outer striped PP protective layer. There might be a danger of the PP becoming embedded in the PE weld and thus causing a point of weakness due to poor adhesion between the layers of different materials, however this seems unlikely as it is just a thin uniform outer layer and could easily be detected by non-uniformity of the bead colour. In practice during bead formation the skin is forced upwards and away from the heater plate. During welding the skin inverts and rolls under the bead back to the outside of the pipe.

One important consideration is that the standard butt fusion parameters developed for PE 80 and PE 100 can be used for PE pipes with a PP protective skin and no modification of the butt fusion machine is required. However there is a potential problem with the pipe not fitting in conventional butt fusion machines designed for conventionally dimensioned PE pipes. In this case it might be necessary to remove the outer PP skin at the end of the pipe to be welded. Welds can be checked for integrity in the usual way by flexing the beads after they have been removed. Welds have been found to pass tensile testing with a totally ductile response and a welding factor of 95%. The 10% offset butt fusion joint hydrostatic pressure test at 80°C has also been passed without problem [50].

3.2.2.4.2 Electro-fusion

Many of the problems with Electro-fusion welding have been due to contamination of the pipe electro-fusion coupler weld interface, prior to jointing. One of the ways that this problem is alleviated is to keep electro-fusion couplers in protective polyethylene bags until just before welding. However no such protection is afforded to the pipe itself that has often been exposed to the elements for a considerable period before jointing. Contamination is a problem particularly from dust and dirt but also due to surface oxidation that often leads to a poor quality weld. The practice of scraping pipe is recommended on PE 80 and PE 100 pipe, in order to remove the contaminated or oxidised outer layer. While usually effective, this is a time consuming operation that is very dependent on the skill of the operator even with the development of mechanical scrapers. By using a mechanical tool to score the PP outer layer of the pipe and aid removal by hand an even contamination free surface is revealed that should aid high quality welding.

One possible drawback to this method is that it may be difficult to remove the outer layer if it is bonded too well to the core pipe. This might occur due to a particularly extreme installation temperature. However providing the exposed core pipe is kept away from dirt prior to welding there should be no need for scraping meaning a much more even and intimate fit of the core pipe within the electro-fusion coupler. This is particularly important as poorer performances in the peel test have been noted when large gaps between the pipe and coupler have been present [50]. However should contamination occur the dimensioning of the core pipes to the relevant standard such as ISO 4437 means that scraping could be performed as a last resort if it were necessary. Profuse pipes have been shown to pass the peel test in BS 7336 with a gross ductility at or above 94%, well above the 75% requirement [50].

Egeplast have developed a technique to provide a protective coating over the area of the weld after welding in order to protect the weld seams in protective coating quality [52].

3.2.2.5 Squeeze-Off

Tests have been undertaken using conventional squeeze-off procedures for both plain PE 100 pipes and PP coated PE 100 pipes using all the same settings. Pipes of both materials passed the standard hydrostatic pressure test at 80°C. It was found that the extra PP layer neither inhibited the process from being effective nor did it reduce the strength of the pipe according to the pressure test. A further series of tests was undertaken to look at the rate of recovery in terms of attaining roundness of pipe after being subjected to squeeze off. The results showed that thicker walled pipes took longer to recover, but the addition of the skin had no observable effect on the rate of recovery. Also the addition of the skin means that squeeze tools do not need to be modified for these multi-layer pipes as the stops set for conventional solid wall pipes will suffice [50].

3.2.3 Environmental Factors

3.2.3.1 Internal Environmental Factors

Since the core pipe is a conventional PE 100 material these pipes will be suitable for gas distribution applications with little danger of any internal environmental effects. The PE 100 should however conform to the requirements of ISO 4437 and in particular the resistance to gas constituents hydrostatic pressure test.

3.2.3.2 External Environmental Factors

As with all pipeline materials, ground where there is heavy contamination of chemicals or oil etc. should be avoided as far as possible, however the PP outer layer should afford the PE core pipe some extra protection in such cases. As with the core pipe the requirements of ISO 4437 should be met, specifically the resistance to weathering test.

3.2.4 Advantages of PE 100 Pipes with a Protective PP Outer Layer in Demanding Applications

The structure of the outer of SLM pipes is specially designed to be highly abrasion resistant [54]. These pipes are described as being the most commonly used for trenchless installation due to their flexible abrasion resistant outer coating. Although details of the test method are not specified the results of abrasion tests showed that pipes with an SLM coating are about 1.1 times more abrasion resistant than PEX pipes, about 1.6 times more abrasion resistant than PE 100 pipes and about 1.9 times more abrasion resistant than PE 80 pipes. SLM pipes can also be produced with a special outer surface geometry of longitudinal grooves or an orange peel surface structure in order to increase the abrasion resistance still further. Such a modified outer geometry can also lead to a reduction in friction when drawing the pipe strand through the soil in trenchless installation processes.

The main advantages of a system with a PP outer protective layer on PE 100 pipes might be:

- Marginal improvement in resistance to point loading
- Better quality of jointing, particularly for electro-fusion
- Better corrosion and chemical resistance
- Additional protection during installation and transportation
- Increased abrasion resistance
- Allows more widespread use of modern installation techniques often reducing installation costs sufficiently to offset any higher material costs
- Less need for expensive specified backfill materials, making for easier installation with lower transport costs and less detrimental environmental impact
- Possibly slightly increased slow crack growth performance
- Possibly slightly increased resistance to rapid crack propagation

3.2.5 Economic Considerations

Egeplast “SLM” pipe sells at 1.5 to 2.0 times that of the price of conventional PE 100 pipe. Cost savings claimed for trenchless refurbishment of gas pipes of between 100 and 200 mm diameter cost SEK 1 160 to SEK 1 390 per metre. This is between 30 and 35% cheaper than by other techniques. Another German end user claimed a cost saving of 25% for installation [52].

“Profuse” costs 20% higher than conventional PE pipe of the same size and SDR in the UK [50].

3.3 PEX pipes

Cross-linked polyethylene pipe for gas distribution has long polymer chains which are connected by covalent bonds into a three dimensional network.

Like PE these systems offer flexibility, light weight, leak-free, corrosion resistance, ease of handling and installation, and less friction. PEX piping systems also offer the following performance improvements over PE piping systems:

- Greater thermal stability
- Higher long term strength
- Better slow crack growth resistance
- Better rapid crack propagation resistance
- Better point load resistance
- Better chemical resistance
- Greater abrasion resistance

These superior mechanical properties make PEX pipes very suitable for demanding installation techniques such as relining.

3.3.1 Material Factors

Conventional PE is a thermoplastic consisting of long polymer chains that can be readily reformed by the application of heat and pressure. The strength, toughness and flexibility of different grades of PE is dependent on the degree of entanglement of the individual polymer molecules [55]. PE 100 materials have a co-monomer structure, which contains branches on the long chains thus having improved mechanical properties compared with 1st generation PE materials where the long chains are able to easily glide over each other. Cross-linked PE or PEX is one step further, where the chains are cross-linked in a three dimensional network that can no longer be simply reshaped by the application of heat and pressure. The resulting thermoset structure has improved mechanical properties and is more heat resistant than its thermoplastic counterparts. However it retains much of the flexibility and the ductility of a thermoplastic as well. It has seen widespread use in small diameter heating and water supply systems for the last thirty years but has taken longer to penetrate larger sized water and gas distribution markets due to its high cost. Cross-linking can be achieved by a number of different techniques of which the three principle ones are peroxide, silane and radiation. All these techniques use free radical reactions to induce links between the single strands of PE to form a dense network.

PEX-a materials are produced by using the heat-activated generation of free radicals by peroxides to form PE radicals, which can then form links with other PE radicals or abstract hydrogen from another PE strand.

PEX-b materials are produced by the grafting of a reactive silane molecule to the polymer chain by means of a free radical mechanism that is initiated by a peroxide. Cross-linking occurs by hydrolysis of the silane groups in the presence of a catalyst and condensation of the resulting silanol groups on adjacent polymer molecules.

PEX-c materials are produced by radiation, where high-speed electrons rip hydrogen atoms off the polymer chain, allowing extra carbon-carbon bonds to form between adjacent chains.

An International Standard ISO 14531 [56] is being developed to extend the scope of PEX for use in gas distribution systems. The aim is to embrace a performance envelope beyond that covered by existing PE standards into regions of higher operating pressures and extremes of operating temperatures.

As for PE 100, the three critical properties are long term strength, resistance to slow crack growth and resistance to rapid crack propagation. The performance of PEX comfortably exceeds that of conventional PE 100 in all three of these critical mechanical properties.

The main reason the superior properties of PEX have not been fully utilised in applications such as gas distribution systems is the high price of the material. Recently Solvay [57] have partially overcome this problem by introducing a new multi-layer pipe that only has PEX material in the most critical areas of the pipe, the outer wall, where increased abrasion and scratch resistance is required and the inner wall where increased resistance to slow crack growth is required particularly due to possible point loading. The remainder of the pipe is a conventional PE 100 material, therefore offering a cost reduction over solid wall PEX pipes. The co-extruded tri-layer pipes consist of:

- An MRS 10 rated PEX-b as the internal layer for resistance to point loading induced slow crack growth
- Bimodal PE 100 resin as the core layer
- An MRS 10 rated PEX-b as the external layer for its resistance to scratches and scores

For 110 mm SDR 11 pipes both the external and internal PEX-b layers are about 1.5 mm thick. The PEX-b material used in these pipes has been observed to have failure times in excess of 10 000 h [58] in the notched pipe test according to ISO 13479, way beyond the requirements of 165 h for PE 80 and PE 100 materials. However these test were performed on a pipe made of the pure PEX-b material and not the tri-layer pipe described. If subjected to this test, the tri-layer pipe described may have no better performance than a PE 80 or PE 100 pipe as the test requires notches of 20% of the wall thickness of the pipe and would in this case remove all of the outer PEX layer, thus exposing PE 100 material to the test.

On a similar theme PE 100 pipes with integrated protective outer and inner layers of a hardened PE material have been developed by Wavin [50]. The aim for this material is to give greater resistance to point loads whilst still retaining many of the cost and jointing benefits of conventional PE 100 pipes. These pipes have performed much better than conventional PE materials in notched pipe testing, and most markedly in point loading tests performed using the constant deformation methodology of Hessel [59]. In these tests the hardened material was shown to give at least 3 times the point load resistance of conventional PE 100 pipes and also PE 100 pipes with a protective PP outer layer. The PP coated PE 100 pipes actually performed no better than conventional PE 100 pipes.

3.3.2 Loading Factors

3.3.2.1 Temperature

As with other plastic pipes PEX pipes gain strength and stiffness as temperature decreases. This is where PEX pipes have a significant advantage over PE 100 pipes, as they are more temperature resistant. For example they may pass the RCP test according to ISO 13477 for constant pressure at temperatures as low as –30°C or even –35°C [58] compared with 0°C for PE 100 materials. Not only do these materials have better mechanical properties at lower temperatures, they are more temperature resistant at higher temperatures too thus having a much greater operational temperature range.

3.3.2.2 Traffic and Backfill

PEX pipes, like PE 100 pipes and PP coated PE pipes, should encounter few problems due to traffic and backfill when specified backfill materials are used and once all appropriate design calculations have been made. However the greatest concern for all PE pipes has been incorrect backfilling procedures leading to possible problems with point loading due to the presence of large rocks. It is in this area that PEX pipes perform much better than conventional PE 100 pipes because their three dimensional network structure gives a markedly superior resistance to slow crack growth. This structure is present on the inner wall of the pipe where stress concentrations are most likely to lead to crack growth.

Experiments have been conducted on PE 100, PEX and PE 100 pipes with PEX inner and outer layers [57] using two different point loading tests; one developed to simulate the condition of constant strain or deformation and the other to simulate the condition of constant stress. Both these test methods use a detergent solution at 80°C in order to accelerate the slow crack growth mechanism.

One of these test methods has been developed for the condition of constant deformation. In this case the pipe is externally loaded by compression with a smooth 10 mm diameter steel ball [59]. The force applied on the ball is increased until a 5 mm horizontal flattening of the inner surface of the pipe wall is reached, thus the compression stress will be different for different materials depending on material stiffness. A mechanical device then keeps this deformation permanent throughout the duration of the test. In this constant strain test a conventional PE 100 pipe fails in 900 h, whereas a PEX-b pipe is still intact after 8 000 h and the multi-layer PEX pipe is still intact after 6 000 h in the test [60]. These results are despite a higher initial deformation force being required for the less compliant PEX materials.

A constant stress test has also been developed [17] which involves a constant load being applied to the outside of the pipe with a sharp rod. Although quantitative and relative predictions for different pipe materials are not possible, PE 100 pipes developed cracks on the bore during the test and failure occurred after 600 h, whereas PEX pipes did not develop cracks under the same test conditions, attaining lifetimes of longer than 1 000 h. Because of stress relaxation it has been calculated that these pipes will never fail under these conditions [60].

3.3.2.3 Scratches and Gouges

The increased damage from modern No-Dig installation techniques can be well tolerated by PEX pipes as these materials have a superior abrasion resistance to conventional PE materials. Results obtained [55] gave a depth of scratch of 7.4 microns for a PEX 80 and 10.1 microns for a PE 80 material when a 1 kg weight was used on a knife. When a weight of 2 kg was used the depth of the scratch was 19.3 microns for the PEX 80 material and 33.4 microns for the PE 80 material.

3.3.2.4 Welding and Jointing

Mechanical fittings have been widely used for small diameter PEX piping in water distribution and radiant floor heating applications. The difficulty is in welding these materials, as they do not deform as easily with the application of heat and pressure as they are not true thermoplastics like PE. It has been reported that electrofusion is possible for PEX-a pipes but not butt fusion.

A good summary of the state of play for welding of PEX pipes is given [61]. Ductile joints in PEX pipes joined by electro-fusion couplers constructed of PE 80 were made [62] and success was also reported [63]. Since trials at Gastec [64] gave positive results regarding electro-fusion jointing of PEX-a confidence has grown that this is a suitable jointing method for this material leading to the adoption in DVS guideline 2207-1, Part 1 Addendum 1 (5/99) [65] which allows for the electro-fusion of pipes made of PEX-a with fittings made of conventional PE. The criteria are almost identical to those for standard PE materials, with the most significant differences being the exclusion of butt fusion welding and the stipulation that a rotating scraper rather than a manual one is used for preparation of the pipe prior to jointing.

3.3.2.4.1 Butt Fusion

It has been demonstrated that butt fusion under standard welding conditions will join conventional PE materials to conventional PE or conventional PE materials to PEX materials, but not PEX materials to PEX materials [55].

Butt fusion welding trials were conducted on many different PEX/PE and PEX/PEX combinations with the conclusion being that high quality ductile welds could not be obtained [61]. However ductile welds could be obtained if un-cross-linked PEX-b pipes were butt-welded then cross-linked retrospectively after jointing. The result was a high strength joint with ductile welds.

A further study [67] has shown that PEX pipes can be butt welded with modification of welding parameters. However such joints still have drawback that they are only as strong as the non-cross-linked PE material that forms the weld interface.

3.3.2.4.2 Electro-fusion

Gastec have successfully welded PEX pipes using standard PE 80 and PE 100 electro-fusion fittings [55]. Studies are also being conducted to see if injection moulded fittings made from a PEX pipe grade can be used to weld such systems [58]. It is reported [50] that while laboratory tests show that electro-fusion sockets and T pieces etc give adequate performance in the laboratory that the performance of electro-fusion tapping saddles of different designs is still very variable.

ISO 14531:2002(E) [56] for PEX gas pipe systems requires PEX gas pipe systems to be down graded due to the use of electro-fusion couplers produced from conventional PE 80 and PE 100 materials. Also the coupler materials are less temperature resistant than the PEX pipes themselves, meaning that the full advantages of PEX pipe systems cannot be realised [67]. New couplers have been developed with a PEX body where a metallic cage within the coupler is induction heated with accurate temperature control to ensure high quality welding. Peel testing, high temperature hydrostatic pressure testing, thermal cycling and pull-out tests were used to assess joint performance and in all cases joints made with the newly developed couplers passed. In the peel test in prEN 1555-3 [68] ductility of 100 % was observed, well above the pass level of 75 %. Of particular interest were the high temperature hydrostatic pressure tests at 95 and 110°C, which indicated that the system might be able to operate at high temperatures.

3.3.2.5 Squeeze–Off

A study [69] was conducted on the comparison of squeeze off for PE 80, PE 100 and PEXa materials. These different pipe materials were squeezed off to 0.8 of double the pipe wall thickness and squeeze off was found to be effective. These pipes were then tested at 80 or 95°C in 1 000 h hydrostatic tests and all pipes were found to pass.

3.3.3 Environmental Factors

3.3.3.1 Internal Environmental Factors

As with the other pipe materials PEX pipes should demonstrate resistance to gas constituents. A PEX pipe grade developed by Solvay was shown to be more resistant than PE in the gas condensate test [58] passing the requirement for PE pipes by a factor of 50 times [70].

3.3.3.2 External Environmental Factors

It has been demonstrated that PEX 80 pipes have a greater chemical resistance than conventional PE 80 pipes [55]. In three different chemical environments a PEX 80 material showed a lower degree of swelling than a conventional PE 80 material.

3.3.4 Advantages of PEX Pipes and PE 100 Pipes with PEX Outer and Inner Layers

The biggest problem with modern installation techniques is having sufficient resistance against point loading. Two possible solutions are the use of a highly stress crack resistant material such as PEX, or a conventional PE 100 pipe with PEX outer and inner layers. Another solution is to use protective mats against stones in sandless embedding. The most effective of these is almost certainly using PEX only pipes but the very high material cost is usually too high to offset any benefit from reducing the quality of the backfill material [50].

The possible advantages of PEX pipes and PE 100 pipes with PEX outer and inner layers are:

- Better corrosion and chemical resistance
- Very good point loading resistance
- Additional protection during installation and transportation
- Increased slow crack growth performance
- Increased resistance to rapid crack propagation
- Increased range of safe operational temperatures

3.3.5 Economic Considerations

PEX pipes are about twice the cost of conventional PE, so the tri-layer pipe is somewhere in between in price [60].

4 Interview, Questions and Case Study

Of the issues discussed at the meeting between Mr. Owe Jönsson and Dr. Steven Brogden in Stockholm on 26th August 2002, the following were considered to be most relevant to this project:

- Damages likely to cause failures
- Welding and jointing, including any need for further training of personnel
- Squeeze-Off behaviour
- Pipe marking

The most important of these is the issue of damages likely to cause failures closely followed by the welding and jointing of the system.

The “Profuse” product is very much the preferred option at the moment as PEX pipes are considered to be too expensive. However the extra protection afforded against point loading by PEX pipes was considered important by Dr. Steven Brogden. Mr. Owe Jonsson suggested that the use of multi-layer pipes might be avoided altogether by using a thicker wall, say SDR 11 PE 100 pipe rather than a SDR 17 PE 100 pipe. This will have a drawback in that the increased section will actually be more susceptible to point loading due to the condition of plane strain in thicker walled pipes.

Sydgas recently undertook an 8 km installation using “Profuse” pipes from Uponor in Kristianstad, southern Sweden. This installation was in benign ground conditions, comprising of sand and clay. A shallow narrow trench technique was used with the excavated material used as the backfill. This project is typical of the sort of application that the Svensk Gastekniskt Center is interested in, together with modern No-Dig techniques and possibly other areas such as bridge crossings.

The techniques of both electro-fusion and butt-welding were used during the Kristianstad installation. It was found that if the PP outer layer was thicker than 1.0 mm for SDR 17 pipes there was a detrimental effect on the welding quality, but if the PP was less than 1.0 mm thick welding was satisfactory.

For electro-fusion the pipes were scraped, although this was subsequently found not to be necessary. A time a saving of 30 to 60% can be made by not scraping the pipe. Large scratches and damages were easy to see because of the penetration right through to the unpigmented PE layer showing a contrast in colour. Squeeze-off could be undertaken using the same stops as for PE 100 with no problem.

By using the same backfill in the narrow trench saved some 200 lorry loads, as it would have taken 155 lorry loads to remove the old backfill and 57 more to bring the new backfill to the site. The backfill cost was SEK 45 per metre. If specified backfill material had been it would have cost SEK 90 per metre. Therefore by using the excavated material as backfill a saving of SEK 45 per metre was made. For the total project cost SEK 126 000 was saved, comprising of 2.5% of the total cost despite the cost of the pipes being 20% higher than PE 100, the same price as reported in the UK. This is without the significant time saving that would have been made by not scraping the pipes prior to welding.

5 Diagnosis

The following table shows a ranking of the factors considered to be the most critical for the use of PE 100, multi-layer and PEX pipes in demanding applications. Each of the different types of pipe are given a performance ranking for each factor, with 1 = best, 4 = worst.

Table 1 *Ranking of critical factors for using different types of pipe in demanding applications*

Factor	PE 100	PE 100 with PP	PE 100 with PEX	PEX
Point loading	4	3	2	1
Abrasion	4	3	2	1
Electro-fusion welding	2	1	3	4
Butt-fusion welding	1	2	3	4
Rapid crack propagation	4	3	2	1
Squeeze-off ability	1	2	3	4
Long-term strength	4	3	2	1
Cost	1	2	3	4

It can be seen that we have two extremes in the table with the least costly and poorest mechanical properties of PE 100 compared with most costly and best mechanical properties of PEX pipes. Thus for these materials the ranks of 1 and 4 predominate. The multi-layer pipes are seen as a compromise between these extremes and therefore predominantly rank as 2 or 3, with the PE 100 pipes with a PP outer and inner layer giving the lowest overall total and hence perhaps the best balance of properties.

It is important to note that this table is not definitive; these rankings represent the best judgment from the information available in the literature and experience.

The key property, particularly for both point loading and abrasion is the slow crack growth resistance. Some degree of external damage from scratches and gouges can be accepted as long as the pipe material has very good resistance to slow crack growth. Any condition where point loading may occur is of concern but it will be the slow crack growth performance of the material that will eventually determine whether the pipe will fail. It is important therefore to undertake like-for-like tests using a suitable test method. However the usual method is for notched pipe testing according to ISO 13479 and this is not a suitable comparison as the standard test would involve making a notch which would score right through the PP outer layer of these particular multi-layer pipes. A more suitable test method may therefore be the use of an environment stress-cracking agent such as Lutensol to accelerate the slow crack growth process.

Also a ranking has been given for resistance to RCP, although it cannot be taken for granted for example that PE 100 pipes with a PP outer layer will perform better than PE 100 pipes in this test. Therefore tests should be undertaken to determine a comparison with pipes constructed of each combination rather than for example just testing pure PEX pipes or pure PP pipes and then assuming that improved results will automatically occur when these materials are tested as one material within a multi-layer pipe construction that includes another material as well.

Welding is a particularly critical area as the pipes may perform perfectly well themselves, but it has usually been found to be the welds that are most critical to the system as a whole. PEX pipes are seen to give the best performance for most of the important properties, but difficulties with welding mean that a welded PEX system may require far more maintenance in the future due to poorer quality jointing as the system is only as strong as its weakest link. The importance of fitted components and welds in the system are critical and even apparently good joints may only have a limited lifespan. Therefore regression data should be generated using hydrostatic pressure testing of electro-fusion couplers and fittings with pressure end closures very near to the fittings. This could allow a more realistic comparison of the lifetime of these critical components in the system for each type of pipe. By using metal sleeves around the pipes, or by tensile testing and determining the degree of ductility butt welds could also be compared.

The long-term strength and squeeze-off ability are adequately covered, as the long-term strength of these materials shall already have been assessed to ISO 9080 and squeeze-off behaviour has been shown to be satisfactory for all these types of pipe in several different studies.

In summary the complexity of materials selection means that there are also some significant disadvantages with these systems:

- Much higher material costs
- More difficult and more expensive jointing
- Each pipe system has a different balance of properties, therefore no specific pipe offers the obvious best solution.

No system is perfect as each of the alternatives studied has a perceived weakness in one of the two areas that have proved most critical to the long-term performance of PE 100 systems, ie. Jointing and Point Load Resistance:

- More difficult and less reliable jointing of PEX/PE 100/PEX and PEX systems compared with PE 100 systems
- No significant improvement in point load resistance for PP coated PE 100 systems compared with PE 100 systems

6 Identifying Test Methods and Lifetime Models

It is assumed that the multi-layer and PEX pipes to be used will already have been evaluated for their long-term hydrostatic strength or MRS. After the long-term strength, the most important factor is the susceptibility of the pipes to damages from point loading, abrasion or some unforeseen accidental damage such as being hit by a digger during installation. Although many different test methods exist the most critical is the resistance to slow crack growth, often referred to as the Stage II lifetime of plastic pipes. This is very important as it is good slow crack growth properties that give assurance against both point loading and damages due to external damages such as gouges and scratches. The other important property in respect to damages is the resistance to rapid crack propagation which is temperature dependent. Welding and squeeze-off ability are also very important not only as regards testing but also the ability of these pipes to be used under established standard conditions and whether new conditions need to be and are able to be established. Suitable tests that could be used for the multi-layer and PEX pipes are:

- Resistance to SCG by notched pipe testing or by using an environmental stress cracking agent.
- Point loading tests under constant strain deformation conditions.
- Resistance to RCP by S4 testing for critical temperature and pressure.
- Tests to establish the suitability of established welding parameters at different ambient temperatures and how these need to be modified for each of the multilayer and PEX pipes considered.
- The development of regression data by hydrostatic pressure testing of fittings and joints at ambient temperature to establish the long-term integrity of the whole system.
- Full-scale hydrostatic pressure testing of butt-fusion welds with metal sleeves.
- Tensile testing of butt fusion joints to establish weld ductility.
- Long term hydrostatic tests on pipes subjected to squeeze-off.

Some other test methods that might be considered but are of secondary importance:

- Long-term hydrostatic pressure tests on larger diameter and thicker walled pipes.
- Abrasion testing.
- Resistance to gas constituents.
- Corrosion resistance.

The hydrostatic pressure testing of thick walled large diameter pipes is considered of secondary importance, as it is the SCG performance that is most critical. The resistance to gas constituents and corrosion resistance are at least as good as PE 100 pipes and are therefore considered to be acceptable.

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SE-205 09 MALMÖ ● TEL 040-24 43 10 ● FAX 040-24 43 14
www.sgc.se ● info@sgc.se