"Managing Risk: Are Your Coated Pipes Fit for Purpose?"

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Abstract

The corrosion control of oil, gas and water pipelines is a major undertaking worldwide, and one which helps to maintain the integrity and asset value of pipelines.
Increasing physical and chemical demands on pipelines necessitates that part of the ***management*** of risk that is exercised by the use of protective coatings and a back-up cathodic protection system, is undertaken in a proven, logical and sequential manner.

This paper studies the methodology of application of pipeline protective coatings, both in a coating plant and on a pipeline spread. Case studies are presented, problem areas are examined, and suggestions are put forward in order to provide coated pipes that ***are*** fit for purpose.

INTRODUCTION

So, there you are at an Asset and Risk management meeting: you're the Operations Director for a high profile international transmission pipeline company, or possibly just the local Corrosion Engineer responsible for a section of a pipeline network and your world is crashing about you……
The integrity of your pipeline in the ground is under serious threat, only a short period of time into its design and expected service life.
The modern 3-Layer Polyolefin (3LPO) protective coating is failing; the cathodic protection (CP) current demand is fluctuating possibly signalling potential CP shielding problems; there is a growing and serious risk of corrosion and possibly stress corrosion cracking (SCC); and the costs of through-life monitoring, inspection, maintenance and possible rehabilitation work, not budgeted for, are spiralling……

What has gone wrong, and why?
How could all this have been prevented?

After further unbudgeted expense carrying out a full investigation of the situation, and a risk assessment, attention is drawn to the key contributor to the pipeline's threatened integrity - the failing protective coating system.
The reasons for what possibly went wrong and why, and their potential answers can be extremely wide ranging and may be simple or very complex issues. Sometimes, these issues can cause minor, resolvable difficulties but, too often of late have caused this type of major concern with inherent risk and cost implications. Many of these reasons, alone or in combination, can include:

- Lack of effective communication with or liaison between all parties involved in the pipeline build - client, contractors (coating, field jointing, inspection, construction, etc) and project engineering.
- Inadequate and not project specific coating specifications for both plant and field coating operations.
- Inadequate Quality Plans and Inspection & Test Plans (ITP's)
- Construction and Right of Way (ROW) issues - delays, storage, atmospheric conditions, damage, etc.
- Coating system issues - choice, testing, qualification and approval of the materials, their interaction in use, and their correct application.
- Inadequate or poorly serviced equipment in factory and field.
- Inadequate or insufficient surface preparation (SP) - inability to, or restrictions on, the use of all available technology ("tools") to ensure the required results.
- Unsuitable quality, operation or management of, and support for, the SP materials and technology available.
- Poor quality planning, inspection and approvals; inadequate, incorrect or non-relevant testing; lack of training; lack of procedure qualification trials before starting,
- Lack of knowledge about the pipe steel itself, its hardness, surface quality, condition and history of manufacture, transport and storage (provenance)
- Incomplete system design and poor interpretation of the specification - inadequate technical content, lack of understanding of the impact of the relationship between all the SP and coating procedures, and the need for flexibility of interpretation with the ability to respond to variation and change.
- Overconfidence and too much reliance on past experience.
- Lack of knowledge of, or reluctance to make use of, available expert advice and support.

Starting from this situation and the following actual case histories, the paper will work backwards through the key steps and procedures of the whole coating project as it focuses on how the risks of the impact of the effects of many of these issues can be managed and resolved. It will concentrate on the protective coating system and particularly, the preparation of the steel surface, describing how expected quality, performance and durability can be obtained correctly, consistently and with ease.

The paper will also address the likely cost of these issues - both in their resolution (direct cost) and their impact on the pipeline life costs (indirect).
For the coating contractor, the apparent cost benefits of improved quality, production efficiency and consistency(including any add-on direct costs) compared with the cost escalation from variation in quality, increasing inspection, concession, rejection and production delay will be highlighted.
For the pipeline owner, the inference of potential reduction in through-life and corrosion management costs from such consistently achieved and improved protective coating system quality, performance and durability will be drawn.

CASE STUDIES

Of the many instances of pipeline coating failures experienced by the authors, three have been chosen as representative of most of these issues and problem areas being experienced today. There are many more!

Case study 1 – South America

Pipe diameter:	762mm; sourced from Japan and Brazil; temporary protectives applied to all pipes
Bare pipe storage:	stored for 15 months in a marine environment
Coating system:	mono-layer FBE to be applied
Coating specification:	inadequate, as was the coating plant
Surface Preparation:	totally inadequate
Years in ground:	new onshore project
Operation:	new project
CP system:	new project

Very high daytime temperatures and heavy afternoon precipitation were experienced where the bare pipe was stored. In addition the atmosphere and the ground both exhibited a high degree of "chloride content".

The temporary "protectives" applied at both the pipe manufacturing works proved to be a major source of problems. The shellac type of material, was thin and brittle and tended to loose adhesion to the pipes. However it remained over about 30% of the surface. This caused differential rates of corrosion over the 15 months of storage and consequently problems in the abrasive blast cleaning processes.
The bitumen material softened and flowed to form raised areas on the pipes. A higher degree of corrosion was experienced next to these areas.
It was found impossible to effectively blast clean the pipes with bitumen on them. As the bitumen was soft the blast cleaning abrasive would not remove it. In addition the abrasives soon became highly contaminated with salts and bitumen.

A freezer unit was built, immediately prior to the first blast cleaning unit, to try to harden the bitumen. This did not work. Rotary wire brushing was reverted to. This process gave even worse problems.

All pipes were covered with a large amount of soluble salts, which were not removed prior to entering the first abrasive blast cleaning unit.
During the 15 months of pipe storage the bottom layer of pipes had been stored directly on the ground. Being between the sea and a sea-water estuary this ground was highly contaminated with salts. With the very high daily temperatures, and the heavy afternoon rains, corrosion rates were high. Initially, no attempt to remove the salts was made. Eventually, every pipe from the bottom layer at the pipe dump was individually treated by hand abrasive blast cleaning using a mixture of water and sand. Unfortunately the water was impure and the sand contained a high degree of chlorides!
Pitting corrosion was very prevalent on the bottom layer of pipe. Even so all the pipes were coated with FBE.
A late examination of some of the pipes, where pitting had been experienced, showed up to a 72% loss in wall thickness. These pipes were coated!

The coating plant being used had been brought from another location in South America, where it had been built to coat 356mm diameter pipe. Needless to say the coating of 762mm diameter pipe was extremely difficult.
No procedure qualification trial had been executed.
Following totally inadequate dual unit abrasive blast cleaning, chromate pre-treatment was applied to all of the ‘brown’ pipes. Even the chromate solution was applied in an inadequate manner – 26 drips of chromate solution encircling the pipes in spirals without any spreader blade to smooth them out into a thin and regular film.

The FBE application booth was totally inadequate, with large volumes of powder exiting to atmosphere, and some “clogging up” in the application booth.
All coated pipes were covered in a layer of partially reacted powder / overspray.
Some coated pipes exhibited hundreds of holidays, particularly where pitting corrosion had previously taken place. All these areas were ‘filled’ with a 2-part epoxy repair material!

No procedure qualification trials had been undertaken; the coating specification was very poor; the storage and coating of the pipe were totally inadequate.

Case Study 2 – Africa

Pipe diameter:	1219mm sourced from 4 European pipe mills
Bare pipe storage:	on ships and next to the sea
Coating system:	3LPE
Coating specification:	inadequate
Surface preparation:	very poor
Years in ground:	3
Operation:	ambient ground temperatures except near compressor stations
CP system:	operative, monitored, but incorrectly controlled

All pipes were shipped from Europe to Africa, some as deck cargo. Some of the bare pipe was stored, beside the sea, for 12 months prior to coating.

The pipe coating specification used was not acceptable. Surface preparation criteria were inadequate. No phosphoric acid treatment, or chromate pre-treatment were specified.
No procedure qualification trials were undertaken.

The coating specification, a 3-layer, low density, polyethylene system, called for 50 – 75 microns of fusion bonded epoxy powder, 150 microns of a polyethylene co-polymer adhesive, and an overall total film thickness of 2.3mm using a low density polyethylene (PE). The polyethylene was sourced from an unusual source. The coating specification was totally inadequate for large, heavy wall, 1219mm diameter pipe.

After only 3 years in-ground the adhesion of the coating to the substrate was seen to have lessened considerably. The LDPE was soft and easy to cut through. The total 3-layers of the coating system could be easily removed from the substrate. No FBE remained on the pipe surface.
Corrosion products were visible under the coating. Examination of the substrate and underside of the coating, using 30x illuminated magnification, showed:

- a rounded, not angular, profile
- an open rather than dense profile
- particles of abrasive material
- dust and detritus
- crystalline salts

As the coating of the pipe in the plant was not witnessed, only plant records were available. These confirmed that neither phosphoric acid treatment nor chromate pre-treatment had been used, even though included in one of the 'many editions' of the Quality Plan.
The abrasive blast cleaning profiles were recorded to be in the required range, but the roundness/angularity/denseness of profile were not recorded.

It is known that LDPE has a considerably higher rate of moisture vapour transmission than MDPE and HDPE. The combination of poor surface preparation, and water vapour transmission through the LDPE coating system were the main contributory causes to the failure of the coating system. It is probable that the FBE layer had been applied at too low a temperature, thus not flowing and wetting the surface accurately.
Where similarly coated pipe had been stored above ground, under tarpaulins, the adhesion of the coating to the substrate was adequate, over 3 years after coating.
Pipe stored above ground, in the open, exhibited adequate adhesion of the 3-layer coating on the body of the pipe, but a lack of adhesion next to the cut-back areas.

Mastic heat shrink wrap-around sleeves were used as a field joint coating. All the sleeves examined exhibited wrinkling where the ground conditions had "grabbed" the sleeves causing the mastic to creep. Mastic type heat shrinks were totally inadequate for this diameter of pipe, and ground conditions.
All patch repairs had been undertaken with heat shrink patches. Many below ground patches had lost adhesion to the pipe/coating and all those viewed above ground were loosing adhesion.
In one area examined, cathodic disbonding of the coating was visible, where the pipe was resting on a large pointed rock which had damaged the full coating system.

A lack of surface preparation and poor heating techniques were contributory causes to the failure of the heat shrink patches.

Case Study 3 – Scandinavia

Pipe diameter:	750mm
Bare pipe storage:	by sea for a short time
Coating system:	3LPP
Coating specification:	national specification with addenda
Surface preparation:	reasonably good
Years in ground:	new onshore and offshore project
Operation:	new project
CP system:	new project

The pipe was 'successfully' coated with a 3LPP system and shipped to Scandinavia, where it was stored for a number of months. During storage it was noticed that the adhesion, to the substrate, at the ends of the coating was problematical on some pipes.
During pipe cutting and welding procedures it was apparent that the residual heat from the welding process was 'lifting' the total 3-layer coating from the substrate.

On induction heating for the joint coating process, it was found that the full coating system lost adhesion from the substrate. Trying to cut back to obtain a fully bonded coating was usually unsuccessful.
On-site, laboratory, and coating plant investigations proved that the FBE first layer had been applied at too low a temperature. The FBE had not flowed and wetted the substrate correctly. When examined under high magnification (x200) in the laboratory it was found that there was a micro-void between the prepared substrate and the FBE layer of the coating system, together with possible contamination.
Stresses in the coating were also considered to have contributed to the adhesion problems.

PROJECT MANAGEMENT

Before any part of a pipe coating, or pipe laying contract is undertaken, a great deal of work is needed to ensure fitness for purpose. If there is conflict, incompatibility, unsuitability and a lack of information in the project documentation/procedure, the required results cannot be achieved.

Effective communication/liaison

It is essential that all parties are in liaison with one another, via the project coordination body (end user). One of the main failings in modern pipeline corrosion control work is the lack of liaison between all parties concerned, from an early stage.
The coating and the CP system are an integral part of a pipeline project, and should be treated as such.

Construction and ROW issues

Modern 3LPO and FBE coatings are designed to provide unrivalled performance and durability on pipe in buried or sub-sea service. They are not, however, best suited to the atmospheric and environmental conditions above ground, especially at the pipe ends, before field jointing. The two cutback areas on each pipe joint expose the edge of the coating system that is, in effect, a large continuous circular "holiday" or "damage site", to the mercy of the prevailing conditions at the ROW or the coated pipe stockyard. Over time, this will result in a number of potential problems.

Site conditions that will cause problems may include: cycles of significant day/night temperature variation and dry/wet conditions, direct sunlight producing high surface temperatures of the coating, weathering effects (e.g., sandstorms), handling, storage, etc. Add the impact of the field joint welding and coating operation (preheating effects) and the integrity of this cutback edge of the coating system will be seriously questioned as the ROW or pipe stockyard is turned into one giant laboratory testing the adhesion (dry and wet), moisture penetration and flexibility of the coating.
As time goes on, the effect of moisture absorption by the FBE layer, drying out and rewetting cycles, expansion and contraction of the PE or PP top layer, and the effect of direct sunlight , etc, will likely result in "coating lift" at this cutback edge. This situation is made worse with the very high hoop stresses present in the modern high density coating systems
It may take several months of construction delays or unplanned storage of coated pipe above ground for these effects to develop this problem, but it has been seen within a few weeks of coating. In cases of poor coating application and/or inadequate surface preparation, this problem has been seen within a few days of coating, even before the pipe has left the coating plant storage!
Over the last few years, coating lift at the cutback has become much more prevalent in a wide range of countries, some unexpected. In many cases, the problem may well point to coating application problems and/or inadequate surface preparation but not always. To some, this problem is a nuisance, manageable or repairable as part of the field joint coating procedure; to others it is treated as a major problem that means unexpected and costly surveys, dispute and delay, and special repair procedures, etc.

This is an important and time-consuming issue that undermines confidence and is not properly addressed in either specifications, contractual responsibilities and liaison, repair needs and method (and by whom), or its implications. Preparing for all the possible effects and eventualities of this part of the project may not be realistic or practical but being aware of and being able to act cost-effectively on the potential problems that may arise needs to be addressed.
Within the plant and field joint coating specifications, a more comprehensive approach to pipe end preparation and to include (temporary) protection of the cutback area would seem to be needed and that is suitable for and manageable by both contractors. Preventing these above ground environmental conditions from actually acting on the cutback edge of the coating would go a long way to eliminating this coating lift issue.

Plant and Field Joint Coating (FJC) Specifications, Quality Plans and Inspection & Test Plans(ITP's)

Although company, national or international specifications may be utilised, all documentation including the plant and FJC specifications, should be project specific. Specifications should avoid detailed or too-specific procedure as each coating plant or contractor is different from the next. They should focus on tasks and goals, quality and performance, measurable consistency and its achievement, and allow some degree of flexibility in how best to meet the client/project needs and expectations from the chosen coating system
Similarly, quality plans and ITPs must be written to reflect the actual requirements of a project (and the coating plant employed), not generalised.
As an example, opinions continue to differ but, for today's high performance 3LPO technology, a 1st FBE layer thickness of 50-80µm is no longer considered suitable, especially with the latest high density polyolefins and grafted adhesives. Although lower thicknesses may wet out a profiled surface more easily, the ability to fully "cover" a well-prepared, densely angular profile of up to 100µm is suspect and thus its anti-corrosion and bonding

properties to the adhesive layer would be significantly impaired. For today's performance requirements and best practice, an FBE film thickness of at least 60µm *more* than the average specified (and measured) profile height is now usually considered the necessary minimum. Depending on the requirements of the specification, 1st layer FBE thicknesses of 125-200µm, and sometimes up to 450µm, are now being specified.

THE PROTECTIVE COATING SYSTEM

Individual protective coating systems should be chosen to meet the specific requirements of each pipeline project. Once a system has been chosen then all the components of that system, the full coating system, and the applicator (and his coating line) must be procedurally qualified, against the requirements of the project-specific specification, prior to the start of any pipelining project.

Equipment and material application

Plant and field application equipment must always be run and maintained in an efficient manner in order to achieve the required end product.
PQT approval data must be used throughout any coating contract, unless otherwise agreed with the end user.

Inspection and testing procedures

In order to obtain the required quality of work all inspection and testing should be undertaken by qualified and trained personnel. Instrumentation should be calibrated regularly, and records maintained. All inspection and test results should be diligently recorded.

Management, testing and control

As coating technology has advanced, the types, duration and relevance of the tests used to measure their applied capability and performance needs to keep pace. In some cases, testing methodology and pass/fail criteria designed originally for older coating technology may not provide a true representation of what is likely to happen in service with a much more capable coating system. This applies particularly to any test method that bears little relation to the reality of coated pipe in the ground.
Peel testing of 3LPO coatings will assess very well the relationship between the 3 coating layers, their correct application and the way they work together, as well as the overall adhesion performance of the coating system - if done and interpreted correctly. Failure of the FBE layer may point to deficiencies in the surface preparation but is also a possible indicator of any problems in its application e.g. application at too low a temperature thus preventing correct flow, wetting, cure and adhesion.
The duration of testing, for both performance capability (periodic long term testing and qualification) and as a quality assurance procedure during production (continuous short term testing), may also need to be reviewed for assessing or comparing more capable coating systems.

In corrosion testing and the increasing need to assess coated pipe performance under hot, wet operating conditions, the importance, correct methodology, duration and interpretation of CD resistance and HW soak testing may need remodelling.
For mono-layer FBE's, the importance and relevance of these tests are well known and fully accepted as they go directly to the relationship between the FBE capability, its correct application and the surface preparation. But, even here, method and interpretation are critical.

The CD test should be done with an artificial holiday of not less than 6mm dia. to aid correct visual assessment and to ensure no possible electrochemical shielding or calcareous deposit effects, especially if it is short duration. If the test temperature is above 50^{o}C and the test duration is more than 72hrs, the test cell or method must also be designed and set up correctly. At the very least, the anolyte and catholyte solutions need to be kept physically separate (but still electrically connected) so that the impact of the mixing of their electrochemical reaction products will not invalidate the test.
The HW soak test and its interpretation could also be used more to assess the effect of moisture uptake and transport through an FBE film and its impact on the adhesion - and its correct application. Visual assessment for blistering or lessening of adhesion and a full destructive adhesion test after allowing to cool (with a well-established method and rating system) will tell a great deal about the durability of the FBE's adhesion performance, and its correct application and/or effective surface preparation. Additionally, a simple visual assessment of the *underside* of any disbonded coating to assess whether there is any residual contamination from the steel surface and whether the FBE has wetted out the profile fully will point to any potential problems with surface preparation, FBE application and cure.

For 3LPO coatings, these 2 tests are more difficult to carry out and interpret, mainly because of the thickness and complexity of the coating. In the case of CD testing, the current methodology is also wrong. If the CD test is carried out on the complete coating system, electrochemical rules say that the diameter of holiday must be at least 3 times the thickness of the coating to ensure there is no electrical shielding and reduction in current draw. For 3-Layer total coating thicknesses of 3+mm (more on critical large diameter heavy wall pipe), a holiday of at least 10mm dia. is more correctly needed.
For such thick film coatings with holidays of 6mm dia. or less, a 24hr hot CD test is almost ineffectual as the initiation of the disbondment process would be difficult to see or measure. Even at 48hrs, the disbondment process and its inevitably slow progression would make it difficult to differentiate between good and bad.
For the 3LPO coatings the HW soak test is an important means of assessing the coating system's adhesion to the substrate. This test has been included in the new, draft ISO 3LPO coating specification.
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Of these 2 tests, it is also now suggested that an effective HW soak test is the fundamentally more important test as it assesses the critical adhesion performance, initial and long term, of the coating system.

THE SURFACE PREPARATION (SP)

It is well to repeat the old adage that "a coating is only as good as the surface to which it is applied". With the latest high performance coating systems now being used and the experience of the last few years, this statement probably now needs amending somewhat. It is probably fair to say that "the more capable and demanding the coating quality and performance is expected, the more demanding and capable the surface preparation will need to be".
What is certainly true is that relying too much on the expected capability of such coating systems and not addressing all their SP implications is an unnecessary and potentially costly risk.

As coating technology improves, the latest systems may seem to have greater tolerance to less

effective SP. In product testing, this may appear to be the case and it can be argued that a more tolerant coating system can "even out" some inconsistencies in the coating and SP procedures. But, during an actual coating contract, the contractor will likely be under pressure to get the job done and, perhaps, be struggling with his plant and equipment and the application of the coating system. Taking risks with the likely variability, inconsistency or plain ineffectiveness of a traditionally prepared surface could quickly destroy any benefit that such tolerance may seem to provide, making it a potentially unreliable tool.
Not surprisingly the client's and the coater's carefully built confidence in the quality and performance of the coating system would be badly shaken.In reality, as we have seen with the latest high performance coating systems in use, the SP requirements are usually even more demanding and critical if the required quality, performance and durability of the coating are to be achieved and expected.
There are many suitable surface preparation "tools" and techniques available to today's pipe coating specifiers and contractors. All may be used to provide the surface finish required and some or all may be needed, even demanded, depending on many different situations and expert opinions.
Preparing the coating operation, and its specification, to be able to handle all eventualities may seem to be too complicated and costly but will, through best practice, be able to guarantee expected best quality and performance. But, to limit the operation and/or the specification and risk the (too) often seen issues of variable quality and performance because of surface condition problems only results in costly and contract-delaying concession, rejection, procedure change and re-approval needs.
Investment in best practice from the start will very quickly be returned in the benefits from a cost efficient and trouble-free coating contract.

Appendix 1 summarises the key elements of best practice surface preparation for FBE and/or 3LPO coating application. In several regions of the international pipecoating marketplace, this is now considered and operated as standard procedure, not as special needs or for specification requirement only. Incorporation of all these elements in local, national or client specifications is now regularly seen, as well as approval or acceptance of their use and benefit under existing, less defining specifications.

Surface quality and consistency
For FBE coatings in particular [whether as mono-layer thick film (250+µm) or as the specially formulated 1^{st}, thin film (50-200µm) layer of the 3-Layer PE/PP coating systems], the suitability, condition and consistency of the surface to which they will adhere is critical and fundamental to their expected performance.
Applied correctly, FBE's will wet out and adhere very well to a cleaned, contaminant-free and (visible) oxide-free steel surface of the right profile height and density. But, with such techniques, their relative inflexibility in operation and the variability already present in the procedure and the steel itself, it is impossible to guarantee coating quality and performance on every pipe coated.
Even with best practice abrasive blast cleaning and any chemical cleaning ("Acid Washing"), such a surface is very fragile, unstable and, most importantly, considerably variable which translates into this inconsistency or reduction in the expected performance, quality and durability of the FBE layer.
Make this surface more robust and tolerant of the variability of the coating and SP procedures, and provided with an adhesion-promoting and corrosion resistant oxide layer better suited to such FBE's, then these expectations can be achieved *all the time on every pipe*.

For many years, this has been achievable with the use of the specialised Chromate treatment processes that modify or convert this unstable and inconsistent surface (to an inert complex Cr/Si/Fe oxide layer) and are now widely used in many parts of the world.
For a long time, the measurable and significant improvement in Cathodic Disbondment (CD) and Hot Water (HW) soak resistance was seen as the main reason for using this Chromate treatment, especially with earlier FBE technology. Even then, this tended to mask the real benefit of such surface treatment and its ability to provide true and reproducible coating consistency and performance all the time - from coatings expected to be capable of providing such. But, a coating material of poor quality or inherently poor performance cannot be made to perform beyond its capabilities by even the best form of surface preparation, especially if it has poor basic adhesion, flexibility or corrosion resistance and a particular sensitivity to, for example, hot, wet conditions, etc.
The latest generation of FBE's are seen to have very good inherent performance capabilities which, if they are to be consistently obtained and optimised, benefit even more from the best SP practice. If one is, therefore, investing in high performance, high quality coating technology it is logical and ultimately cost effective to invest also in best practice, both in SP and coating application, to obtain the expected (and paid for) finish quality, performance and durability - its consistency and best fitness for purpose. The proof of the advantages of such investments can be seen from in-ground comparison studies that confirm these benefits translate into significant improvements in long term adhesion performance, lower corrosion management costs and better durability of such coated pipe after many years in the ground.

Eliminating all contamination
Having produced the ideal surface profile, angular and dense, it is often unfortunate that it can be ruined by the presence of contamination that will be detrimental, often severely, to the effective adhesion and durability of the protective coating system. The most damaging contaminants are the "salts", such as chlorides, sulphates, etc., present in both soluble (as, e.g., the dissociated Cl^- ion) and "bound" form (as ferritic salts, e.g., $FeCl_3$). If such salts present were in soluble form only and had not penetrated the original oxide/scale layer on the pipe surface, simple washing before Abrasive Blast Cleaning the surface ('blast clean') should remove them. Unfortunately, the true extent of most of this kind of salts contamination is often only revealed after the blast clean operation has removed the rust and scale. It is not unusual to find that the measured level of chloride contamination before blast cleaning actually increases after blast cleaning.

It is now almost universally accepted that a surface measurable Chloride contamination level *after* blast cleaning of more than 2μg/cm^2 (20mg/m^2) is likely to lead to adhesion problems, especially under wet condition testing (HW soak tests). Increasingly, coating specifications are now requiring the measurement of and the ability to ensure final Chloride contamination at no more than this level or even less. In fact, this is quite a high figure, even potentially risky, and some recent specifications have been seen to require the achievement of levels of 1μg/cm^2 or less.
[Whatever method of measurement of this contamination is chosen (e.g. ISO 8502, parts 5-12), it should be acceptable to all parties and be able (in the hands of suitably trained personnel) of providing reproducible and meaningful results. Where possible, calibration of any equipment used, and/or its method of use, should be carried out, at the required frequency, against a definitive standard and with proven methodology. As this is known to be an area of concern at the moment, this may need to be addressed further in relevant standards committees].
The coating contractor, therefore, not only needs to be able to measure the Chloride

contamination level on the pipe surface after blast cleaning, but also have a means to reduce/eliminate it if it is present. As such contamination will always vary considerably throughout any coating contract and be dependent on so many different factors concerning the pipe steel, the storage and environmental conditions and even the prevailing atmospheric conditions, it will be impossible to predict the expected chloride level after blast cleaning. This effectively means that, if such a level is set and must be monitored, a method for its removal or control must be in place and in use all the time. If no such facility is in place, chloride contamination on the pipe after blast clean that exceeds the maximum limit would inevitably result in rejection of the pipe and its return to the start of the SP procedure - a costly exercise that also reduces production efficiency.

Today, the only really effective and industry approved method of removing such contamination is by chemical cleaning, known generally as "Acid Washing"(AW), using specially formulated acid-based (usually phosphoric acid) cleaning processes. These processes include special additives for fast and powerful wetting and penetration (into the profile) and controllability of their reaction with the steel surface. The process method includes the need to use pure water -from Deioniser(DI) or Reverse Osmosis(RO) generation- in its operation and for the rinsing afterwards.
Using the proven processes, operated correctly, AW will remove all the measurable damaging chloride contamination - both the soluble form and the more dangerous "bound" form. It will also thoroughly clean the profiled surface of dust (from blast cleaning or from the shop environment), bound or magnetic particulates, and all trace residuals (organic and inorganic) not removed completely by the blast cleaning operation

Recently, however, the use of locally available commodity grade phosphoric acid solutions has been reported in some countries. Problems of the inability to control the process and the damaging presence of unwanted and severe contamination in the low quality materials sourced has, not surprisingly, been seen, even to the point of increased chloride contamination after supposed cleaning than before.
It has also been suggested that, with a well-prepared blast cleaned profiled surface, surely only a wash with pure (DI or RO) water is needed to remove chlorides? Such an action may remove some of the soluble salts on the surface but will also tend to "spread them around". The more damaging and difficult to remove "bound" salts will not readily be removed by water washing, even at high pressures and volumes. At worst, they will be "released", slowly becoming soluble and more "active", increasing their potential impact on adhesion and coating quality.
It is not surprising then to hear of cases also where such pure water washing has been tried and the level of chloride contamination has increased rather than decreased!

Although dust is also removed by the AW operation, the degree of dusting after blast clean should be monitored and not allowed to exceed the permitted level. Excess dust after blast cleaning is an important pointer to any equipment or abrasive problems within the blast clean machines which should be resolved even though the AW process will be able to remove it - but with increased consumption of the AW materials. Prevention is always better than cure.

This thorough cleaning of the well prepared profiled steel surface will minimise or eliminate any risks associated with contamination, both from what was on the steel surface in the first place or that couldn't be fully removed by the blast clean operation or was (re)contaminated by it. The resultant, lightly oxidised clean surface will, in fact, be more beneficial to FBE adhesion that is sometimes seen in slight improvements in coating performance. But, it remains highly variable and unstable and quickly deteriorates or is easily damaged during the subsequent operations on the way to coating if it is not treated and stabilised (as above).

The right surface profile?

Arguably the most important step in the surface preparation of the pipe steel before coating, achievement of the right surface profile is the foundation on which the expected coating performance is built.

The traditional techniques of Abrasive Blast Cleaning ('blast clean') using powerful Shot/Grit blast cleaning machines is ideally suited to the mass and shape of the pipe. 2 such machines are preferred, especially for high production rates, but this task can readily be completed by 1 machine with good management and control.

The blast clean operation has 2 key functional strengths: to remove all the oxide (scale and rust) from the pipe surface and to provide the correct surface roughness (profile) demanded of the coating specification and for the coating system being applied. For today's high performance FBE and 3LPO coating systems, this means a dense and evenly distributed, angular profile ("anchor pattern"), of the required depth and correctly measured, consistently achieved and reproducible. Rounded or dished profiles, residual oxide in the base of the profile or largely uneven distribution or sparse numbers of peaks per unit area are unacceptable. Such problems will significantly affect the wetting out and flow of the FBE on/into this surface and the ability of the epoxy to bond with and adhere effectively to it.

The type and possible mixture, size, quality, and hardness of the chosen abrasive(s) is critical to this procedure and is affected by many variables, not least the steel grade and hardness, its surface condition, and the capacity and required production rates from the blast clean machines. Managing all this, and the contamination impact on and efficient use of the abrasive(s) is fundamental to achieving the right surface finish. With the inherently high variability of the received steel surface and what is actually present on it, this is no easy task, especially in terms of contamination build up and transfer in the blast clean machines. Lately, and in some way exacerbated by the current rising prices and shortages in the steel market, problems with low quality abrasives with supposedly suitable hardness have been more evident with insufficient profile depth, density or angularity, excessive dust and poor visual cleanliness.

Additionally, pipe steel grades and surface hardness have been increasing putting further strain on this traditional surface treatment technique and greater thought and care is needed in this area if the right result is to be achieved consistently.

But, the assessment of surface cleanliness after blast cleaning is a visual one that, even at its highest level, takes no account of the non-visible and chemically active contamination. Expecting this mechanical, albeit powerful, technique to truly and consistently clean the steel surface is, at best, risky and, fundamentally, a false premise; nor is it a procedure that can be easily or quickly adjusted to meet changing surface conditions or problems.

As a relatively fixed procedure, it is best to rely only and heavily on the "sledgehammer" effect of its 2 key functional strengths. Then use the specialised procedures that follow as the "scalpel" approach to the consistent and maximum quality achievement of a surface truly fit for the purpose of coating with today's modern pipe coating systems.

Cleaning first

The received pipe surface and its condition will vary greatly depending on its source, age and storage and, particularly the environment in which it was manufactured, transported and stacked. All loose contamination must be removed before the blast cleaning procedure to prevent its contamination of the abrasive and the blast clean machines if allowed to build up.

Simple non-abrading brushing or pressure washing with water may be all that is needed but to remove those contaminants that have absorbed into the oxide layer as the scale breaks down may require a more aggressive approach
Even freshly made mill pipe can be heavily contaminated with manufacturing residues and difficult to remove organics such as hydraulic fluids, expander lubricants or other oils or greases from manufacture or movement.
Flame cleaning can remove such combustible materials but may also leave combustion residues behind or, worse, "bake" these materials onto the surface or into the oxide/scale layers and make them more difficult to remove and more contaminating to the blast cleaning operation.
Solvent cleaning is a logical approach but needs to be done with care and preferably with solvents that evaporate readily and are residue free. Solvent cleaning will also tend to "spread" oils and grease residues around before they are fully washed off.

The ability to effectively clean and degrease the oxidised/scaled steel surface and prevent any unwanted contamination being carried through to the blast cleaning operation will ensure that it *only* has to remove this (clean) oxidation layer. This will improve its efficiency, achieved quality and protect the blast cleaning machines and the abrasive mix from uncertain and varying levels of contamination, thereby reduce the strain on (and cost of) management of the blast cleaning operation.

The latest high pressure, high detergency alkali cleaning and water rinsing procedures, together with dedicated purpose-designed application equipment, now provide this ability. This specialised and effective surface cleaning of the oxide layer not only ensures little or no contamination residues being carried through and improved abrasive blast cleaning efficiency but can also help to accelerate the breakdown of the millscale and make the removal of all the oxides easier.

Know what you're dealing with! - the steel itself
As we have seen, many of the variability and contamination problems of surface preparation before coating pipe can be traced back to the steel itself, its condition and its provenance. If we don't know what we are dealing with right from the start, and the variability and impact it can have on the SP procedures and operations, it is impossible to expect that the job will be done properly all the time, unless we prepare for it.

Even with full knowledge of and a reasonable degree of control over the starting condition of the surface we want to prepare and coat, the standard SP procedures and operations are unlikely to be enough to ensure consistent quality and performance. It only takes a couple of "rogue" or difficult pipes per shift in a coating operation to reduce production efficiency by a significant percentage but also add excessive cost. This could be avoided by planning for and establishing the additional procedures available, as standard rather than special needs practice, to handle any such eventuality.

The removal problem of long term temporary protective coatings such as the shellac or bitumen materials is one that may require additional or special procedures. Ideally, such materials should not be permitted and any pipe received with such coatings present should be rejected, where possible.
If not possible, the only way to remove these coatings sufficiently well requires a separate often costly and unbudgeted pre-cleaning operation before the pipe enters the coating plant. Alternative temporary protectives, more suitable and readily removeable (by available coating

line surface preparation procedures) for both stock pipe and, when required, the prepared cut-back pipe ends when storage or delay at the ROW is expected, are available and should be considered.

As current best practice, all these dedicated, separate, but closely interconnected SP procedures, will collectively ensure the best available and expected performance from and durability of today's latest FBE and 3LPO pipe coating technology. Clean the incoming pipe properly, remove all oxidation and produce the required profile, clean this profile of all contamination and then treat the surface so that it is ideally suited to the coating being applied and it will ALWAYS be the same, *regardless of what you started with.* And, by eliminating virtually all this inconsistency and variability, performance and quality doubts and most of the described past problem issues, and thus increasing production efficiency, the unit cost for coating will reduce!

OPERATIONS MANAGEMENT

Experience and learning

Experience is hard earned and considered to be worth more than knowledge, but learning never stops. The coating of pipe involves many interested parties, differing opinions, and a complex and extensive set of procedures and operations that must each be done and managed correctly and in a close inter-relationship to each other. Mistakes or shortcomings in one area can destroy benefits from or even the ability to correctly undertake the procedure in another area.

There are no shortcuts to glory in the pipe coating business and the impact of bad or inadequate practice only results in the disappointment of missed expectations, dispute, delay and inevitable cost penalty.

Overconfidence in or too much reliance on past experience and operating means and method is not going to ensure the expected results unless all aspects of the job are identical to the previous ones.

It is also evident that the wide ranging variation in the steel, its condition, the coating materials, application needs, specifications, expert opinion of all parties involved, performance and quality demands, even international expectations and differences, etc., seems to be increasing.

The need, therefore, to be prepared for all eventualities *and* to be able to handle them all before they become a problem or a cost issue is, more than ever, the surest way of achieving problem-free and cost-effective coated pipe fit for purpose.

All the technology, materials and methodology is available to achieve this. In the end, it is up to all the parties involved in any pipe coating project to utilise all that they will need to meet all their project, contract and operational requirements with ease, certainty and risk-free.

Flexibility of approach

Specifications or standards cannot cover all eventualities. They should, where possible be project-specific and define the minimum requirements of quality and performance expected. Where procedural, they must not limit or prevent the contractor from actually being able to achieve these requirements and should allow interpretation and flexibility that will ensure this.

Specifications and the coating plans derived from them should also encourage the achievement of better than these minimum requirements, including the use of any proven procedure or technique that will aid this, whether actually specified or not. Aiming just to meet the minimum specified requirements will inevitably mean that issues of borderline or sub-standard condition will occur, sadly, sometimes too frequently, causing dispute, delay and added cost. Aiming higher means that the minimum requirements can be assured at the start and an efficient, problem-free and cost-effective operation should be attainable.

Materials selection, application, and the impact of safety and environmental legislation
The modern pipe coating systems and the specialist chemical surface preparation processes, such as the Chromate treatment and "Acid Washing" materials, are purpose-designed complex formulations utilising special grades of raw materials. This is a critical aspect of their correct function as processes that are poorly formulated or made from the wrong grades of raw materials may not actually work properly or, more dangerously, contain levels of unwanted contaminants that can actually destroy their benefits. Their appropriate selection, including the level of expertise and support available for their correct operation, will be the key to risk-free and complete satisfaction in best practice and overall protective coating quality and performance expectations.
As with any process or technique, correct application or operating method, using the right equipment, is essential. Correctly applied, these chemical surface treatment processes will provide significant, even disproportionate benefits compared to their minimal cost. Get it wrong, though, and these benefits are lost, costs will rise and problems and doubts will replace confidence and success. New designs of application equipment, with full or partial automation of process management and control, materials handling and safety, and fully automated waste treatment and disposal, are now available making the use of these technologies very much easier, safer and more cost effective.

The dedicated and approved material supplier will have this requisite knowledge and expertise and his specialist advice, support, training and practical experience should be sought and relied on to achieve best practice and the results expected - safely and cost effectively. This is particularly relevant in the area of occupational and environmental safety where important user concerns and the requirements of national or international legislation must be met.
All chemical processes are hazardous. Some, like the Chromate treatments, have a particularly severe potential hazard in a particular form (not specifically relevant to the pipecoating industry) and the legislation concerning them makes them difficult to use but does not prohibit their use. Understanding these hazards and the risks implied and how best to manage and minimise or eliminate them should also be available from the experienced supplier.
As this legislation and client concern is a major driver of product development, the availablity of "safer" surface treatment processes (e.g., Chromium-free surface treatments) that are sufficiently beneficial and cost-effective will not be too far away.

Advice and support
The key parties involved in any pipe coating contract cannot be expected to be experts in all matters, especially surface preparation, coating systems, procedural interaction, and the impact of variability. That expertise - technical, advisory, product and process support, operational development, even training, etc. - rests with the many suppliers, consultants, specialists and others who have an extensive knowledge of their technology and its operating options and capability from many different operating situations and cultures.
For the newer, perhaps less experienced coating contractor, this expertise can (and has so proven in certain cases) be invaluable and allow rapid progress along the learning and continuous improvement curves. For the long-established and usually experienced coater

already well along the learning curve, the natural reluctance to ask for advice or support for a particular product or procedure may mean the inability to obtain the real or full benefit from it. In the words of the old saying of "not being able to see the wood for the trees", the ability of a fresh pair of eyes or ears to be able to, perhaps, quickly solve a persistent or trying problem or improve an operation or procedure could be worth every penny it costs and more!

COSTS

For FBE and 3LPO coating, the direct cost of employing best practice and all the available SP technology described, heating, QA/QC, inspection, and general procedural needs will increase the total applied coating cost by less than 5%, typically around 3-4%. Recent corrosion (coating) cost surveys on a typical 100kms x 610mm pipeline project confirmed the cost of these key stages in surface preparation, ensuring appropriate surface cleanliness, correct profile and optimum application temperatures (FBE) to be an average of 3% of the total coating application cost.
The coating materials and the heating requirements are the major cost contributors (60-75%) to the coating project and the material cost of all the additional SP cleaning and treatment process chemicals will be less than 2% of the coating material costs, even less for 3LPO coating systems.

But, in terms of true unit cost (operating cost per pipe joint coated), the cost of error, concession, rejection and delay has to be factored in. By using best practice and all the available technology and procedures described, such transient but potentially inevitable extra costs, whether low or high and budgeted for or not, can be reduced or even virtually eliminated.
In reality, if even only 1 or 2 pipe joints per shift are "saved" from rejection, reprocessing or quarantine, all the cost of additional procedures and processes of best practice will be more than paid for. The indirect effect on the unit cost, over time, can be dramatic. If a coating plant can coat 100 pipe joints per shift but has to reprocess a couple every shift, the production efficiency and, therefore, unit cost suffers accordingly. Further, if production line speed has to then be slowed a little to help overcome any SP, coating application, or quality/performance issues causing this potential rejection, unit cost increases more.
If such described best practice and available technology can allow a coating contractor to achieve this kind of reject-free production efficiency he would expect on his plant with ease and without problems, his unit costs will reduce very considerably.
More significantly, it has been reported by a number of contractors in various parts of the world that, by employing all available SP technology and best practice in SP, coating application and plant operation, production efficiency can get much closer to actual maximum plant coating capacity.
With the ability to operate more efficiently, potentially faster and error- and reject-free, it is not difficult to imagine the benefit (and significant reduction in unit cost) of being able to coat a couple more pipe joints every shift.

For the hard-pressed pipeline Operations Director or local Corrosion Engineer, the point-of-view is very different. The beneficial impact of this best coating practice, and the achieved expected quality and performance (on which their integrity management plan would be based), can have a far more significant effect on their pipeline's through-life inspection and integrity management costs and budget.
With in-line inspection costs currently quoted at $3,200 - $5,300 per Km for gas lines and

$4,600 - $6,100 per Km for oil lines [cf. CC Technology Cost Survey], any change to a typical inspection strategy requiring additional inspection adds significant cost. This doesn't include the costs of any excavation, investigation and repair or additional CP needs.
Assuming there are no CP shielding problems and minimal repair requirements, through-life inspection and integrity management costs of a new pipeline with a 3LPO coating showing adhesion problems could increase by 70-90% of a budgeted cost that is already nearly half the total applied cost of the coating system.
If corrosion and possible SCC due to CP shielding is assumed, the through-life costs increase even more significantly from selective excavation, repairs to the pipe and re-coating to eliminate the CP shielding problem
On this basis, a compromise in the coating process, its control and, especially, the surface preparation in the pipe coating plant may show a short term benefit but create the risk of significantly greater through-life monitoring, inspection and management costs

CONCLUSIONS

1. It is recognised that correctly applied FBE coating systems, when used in conjunction with well engineered CP systems, are effective in protecting pipelines and in providing fitness for purpose pipelines.

2. 3LPO coating systems can have 'system weak points' such as problems in their adhesion to a steel substrate.

3. Poor application controls, incorrect application temperatures and unacceptable/incomplete coverage of the steel substrate and poor surface preparation contribute to the adhesion problem

4. Thermal cycling can accelerate the loss of adhesion of a 3LPO system to a steel substrate

5. The long term performance of some FJCs may be questionable, particularly with respect to the adhesion of the FJC to the outer PO layer.

6. The right surface preparation is essential if the integrity of a pipeline coating is to be achieved. Expected quality and performance can only be assured consistently by use of correctly chosen materials, all available "tools" and best practice.

7. Pipeline integrity and protection from corrosion can be achieved with project specific specifications, approved products and processes, trained personnel and good procedures.

8. The achievement of 'fit for purpose' pipeline corrosion protection systems costs money. The money, personnel and procedures can be directed at expensive in-service repairs and intelligent pigging, or at obtaining, inexpensively, a product that is 'fit for purpose' from the outset.

Appendix 1: Standard Requirements for the Surface Preparation of Pipes Prior to the Application of an FBE and/or 3LPO Anti-corrosion Protective Coating

- All operations to be carried out to the requirements of the relevant coating specification and procedurally qualified (plant and materials) prior to contract start.
- Remove all detritus, grease, oil etc. by the relevant means - which may be by use of a specialised cleaner and water washing – prior to pipe entering the plant.
- Heat pipe to remove moisture/condensation, prior to abrasive blast cleaning.
- Two abrasive units are preferable to just one unit. (Contamination is kept to a minimum, and management of the profile is usually better).
- The type, size and hardness of abrasive to use (possibly a mix) will depend on the type and hardness of the pipe steel, its provenance, the degree and type of corrosion products present (mill-scale etc), and the capacity and efficiency of the abrasive blast cleaning unit etc.
- Blast Cleaning and the (metallic) abrasives used are characterised in:
  ISO 8504 - Part 2: Surface Preparation Methods - Abrasive Blast Cleaning
  ISO 11124 - Parts 1-4: Specifications for Metallic Abrasives.
  ISO 11125 - Parts 1-7: Testing of Metallic Abrasives
  (and other standards in this ISO range).
- The types of abrasives used, where two in-line abrasive blast cleaning units are employed, could be different.
- Preferably in between the two units, or possibly after the second unit, soluble salts should be removed to less than the measurable specified maximum level ($<2\ \mu g/cm^2 \equiv 20 mg/m^2$). This is undertaken with a proven and approved Acid Wash process (usually phosphoric acid-based), followed by a thorough pure water wash (DI or RO generated water of <100µS conductivity).
- The required surface cleanliness, minimum Sa 2½ or better, should be visually assessed in accordance with the requirements of ISO 8501 Part A1
- An angular and dense profile ("anchor pattern") is required in order to obtain the greatest, cleaned surface area, and the maximum adhesion of the coating to the substrate. (A rounded, dished profile or one that is uneven or sparse in angularity is not acceptable.)
- The profile (peak to trough height) should be governed by the thickness of the coating e.g. for 180 microns of FBE in a 3-layer coating the peak-to-trough height should usually be within the range 75 – 100 microns.
  Methods of profile measurement are contained within the ISO 8503 series of standards. The stylus method is usually considered to be the preferred method.
- The degree of dust on the surface after abrasive blast cleaning operations should be assessed in accordance with the requirements of ISO 8502-3. The maximum allowable level is usually 3. Dust levels should be checked before and after Acid Wash treatment (the Acid Wash process should not be required to remove excessive amounts of surface dust/residuals)
- Dust can be removed by vacuum cleaning and/or a lance of clean, dry air.
- Finally, a proven and approved Chromate surface treatment process should be employed. This treatment modifies the surface chemistry of the pipe, ensures total surface consistency, and provides a greater adhesion for and durability of the coating system.

All materials and special application equipment for surface preparation and treatment should be sourced from experienced and approved suppliers. Their expert advice and support for safe, effective and best practice should be requested and taken.