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DEVELOPMENT OF A NEW SOLVENT-FREE FLOW EFFICIENCY COATING FOR NATURAL GAS PIPELINES

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Introduction

Pipeline design engineers have traditionally considered external anti-corrosion coatings for the protection of gas transmission pipelines, with less consideration given to the benefits of internal flow efficiency coatings. This paper reviews the benefits of using a traditional solvent-based flow efficiency coating, and the relationship between the internal surface roughness of a pipe, the pressure drop across the pipeline, and the maximum flow rate of gas through the pipeline.

To improve upon existing solvent-based flow efficiency coatings, a research program was undertaken to develop a solvent-free coating. The stages in the development of this coating are discussed, resulting in the plant application of the coating and final qualification to API RP 5L2.

Background

The Benefits of Using a Flow Efficiency Coating (FEC)

There are a number of benefits in using a flow efficiency coating for a natural gas pipeline. Below are three different ways in which these benefits can be recognized:

1. A reduction in the pressure drop in the pipeline and thus an increase in the flow rate of natural gas through the pipeline;
2. A decrease in the pipeline outer diameter in the design phase of the project to achieve the same flow capacity as reported by Tobin et al (2005);
3. A reduction in power consumption for compression of the gas to achieve the same flow capacity, with a subsequent reduction in greenhouse gas emissions for the transportation of natural gas as reported by Westcoast Energy (2003).

Other benefits that can be realized during installation and operation of the pipeline include:

4. Mitigate the corrosion of the internal surface of the pipe during storage and transportation.
5. Provide a clean smooth surface for ease of pipe inspection.
6. Reduce the effort and cost of cleaning the pipeline after hydrostatic testing, and subsequent ease of disposal of water used in hydrostatic testing.
7. Decreased line maintenance through minimizing fouling and damage to valves.

The effect of surface roughness of the FEC on the reduction of the friction coefficient at the pipe wall / fluid interface will be discussed in the following sections.

Frictional Resistances affecting Fluid Flow in Pipes

Fluids in motion in a pipeline are subjected to various frictional resistances. Friction occurs between the fluid and the pipe wall, but also occurs within the fluid. Some of the main factors affecting fluid flow in pipes include:

i) The length, internal diameter, and ***internal roughness*** of the pipe.
ii) The viscosity, density and velocity of the fluid.
iii) Changes in fluid temperature, which will affect the viscosity and density of the fluid.
iv) The geometry of the pipeline, including bends, risers, valves and other fittings.

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How Surface Roughness dictates Laminar or Turbulent Flow

Fluid flow in a pipeline can either be laminar flow or turbulent flow. Transportation of natural gas in pipelines at high flow rates exhibit turbulent flow. In a turbulent flow condition a laminar film can be formed at the pipe wall / fluid interface, which will reduce the friction between the fluid and pipe wall with subsequent reduction in the pressure drop through the pipeline and increased flow capacity. Creation of this laminar film is dependent upon the surface roughness at the pipe wall / fluid interface, and to a lesser degree the extent of the turbulent flow and the fluid velocity.

The laminar film created at the pipe wall is very thin. The maximum peak height of the profile of the pipe wall surface may, depending upon its height, be able to protrude through the laminar film created. This protrusion results in disrupting the flow pattern of the laminar film and effectively creating a turbulent flow pattern adjacent to the pipe wall, increasing the friction coefficient at the pipe wall / fluid interface, with subsequent increased pressure drop across the pipeline and reduced flow capacity.

Surface Roughness

Surface roughness is usually expressed as Ra or R_{ZD} parameters. Ra is commonly referred to as the arithmetic average of all deviations from the predetermined baseline for the surface. R_{ZD} is the arithmetic average of the maximum peak to valley heights of five defined consecutive sampling lengths. R_{ZD} is also called a ten-point height average, which is the average height difference between the five highest peaks and the five lowest valleys according to the Deutsche Institut fuer Normung c.v. Specification, DIN 4768/1.

For pipe internal surfaces, relative roughness is often referred to. Relative roughness is the average height of surface regularities divided by the pipe diameter according to equation 1:

$$\text{Relative roughness, } k = \frac{R}{D} \qquad (1)$$

Relative roughness is used to calculate the friction factor. The pressure drop due to friction can then be calculated for a pipe segment. One consideration is whether to use Ra or R_{ZD} to calculate the relative roughness. Farshad et al (1999) suggested that the ability of R_{ZD} to ignore intermediate height data and focus on extreme height data that would be the most likely to affect turbulent flow made it the more useful parameter compared to Ra. It is also important to specify the instrument parameters used to measure the surface roughness, such as cut-off value, stylus OD and filter type. The cut-off value can be especially significant in influencing the results.

Steel pipe delivered to the coating yard has a relative roughness in the order of 20μm. However, once in production this relative roughness may exceed 50μm, depending upon corrosion products formed on the surface due to the amount of time and conditions the pipe was stored in prior to installation, hydrostatic testing, and the corrosive nature of the fluid being transported. Using hydraulic pipe flow software, the pipe roughness versus maximum achievable flow rate can be plotted, for a constant discharge and arrival pressure.

The following example is taken from an engineering specification for a sub-sea gas export line. The pipe length is 145km, 24” OD, with a compressor discharge pressure of 194 barg and an arrival pressure of 119 barg. The specification for the line was to coat with an internal FEC to obtain a relative roughness of 12μm and a flow rate of 328 MMscf/d – see figure 1.

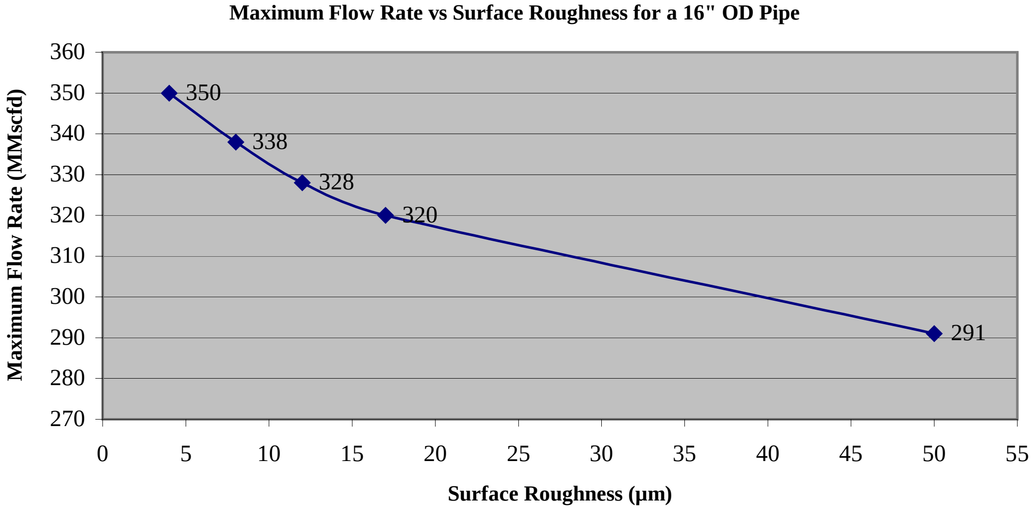

Figure 1: Pipe Roughness versus Maximum Flow Rate

Figure 1 shows that the difference in maximum flow rate for a surface roughness of 4µm compared to 50µm is 60MMscf/d

Economic Analysis

Nelson et al (2000) reported that flow efficiency coatings may reduce the friction coefficient across a carbon steel surface by up to 50%, allowing transmission increases of 15 to 25%. A number of companies have conducted more in-depth studies and reported the economic analysis of using internal flow efficiency coatings. A selected few will be reported here.

GasAtacama Pipeline

A study was conducted by Zamorano (2002) on the economic benefits of using a flow efficiency coating. The study was based upon internally coated pipe on the Argentine side of the GasAtacama pipeline system. GasAtacama is a 1,200km pipeline system running from northern Argentina to the pacific coast of Chile. The Argentine section is 530km of 20” OD pipe, and was coated with a solvent-based epoxy flow efficiency coating; the Chilean section was left bare due to project CAPEX restraints. The economic analysis in the study was based upon the existing capacity of the pipeline and two capacity expansion scenarios. A conclusion of the study was that the economic benefits of using internal flow efficiency coatings were more substantial at higher gas flow rates – see figure 2.

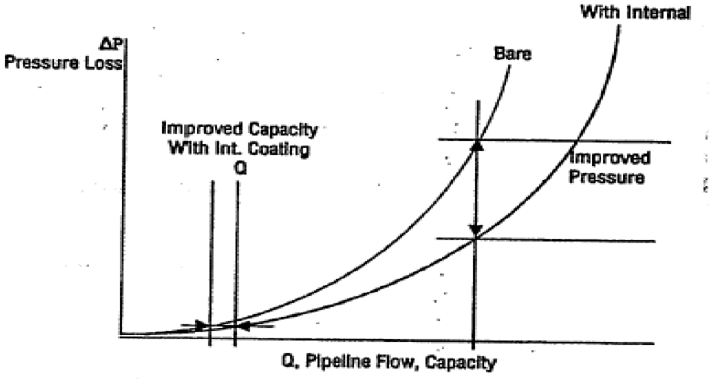

Figure 2: Pipeline Flow Capacity for Bare and Internally Coated Pipe

The economic analysis also considered fuel gas costs for the compressor stations, CAPEX and OPEX expenditure. Based upon a capacity of 5.6MMscm/d, the cost savings are reported in table 1:

Table 1: Cost Savings using a FEC

Incremental Compression Service Cost	**With internal coating in Argentina**	**Bare Pipe**	**Savings**
Fuel gas (US$ millions)	6.5	8.9	2.4
CAPEX (US$ millions)	17.7	26.6	8.9
OPEX (US$ millions)	18.1	27.2	9.1
Total cost (US$ millions)	**42.3**	**62.7**	**20.4**

Shell Global Solutions

Tobin et al (2005) of Shell Global Solutions recently reported data to support Shell's positive experiences with using flow efficiency coatings, and the associated CAPEX savings. The example reported was for a 250 km long pipeline, with a requirement to transport 330 MMscf/d at an inlet pressure of 70 bar and a minimum delivery pressure of 20 bar. For bare pipe with an assumed roughness of 50μm a pipe size of 26" OD is required, whereas with an internal coating of roughness 10μm a 24" OD pipe is sufficient. The reduction of the pipe diameter results in a cost saving of 5% (assuming a typical API X65 pipe, 12mm wall-thickness, and a coating cost of 2-3% of pipe material), which implies a saving of some 2-3% on total pipeline CAPEX.

The Institut Francais du Petrole (IFP)

Charron et al (2003) of IFP reported an economic analysis for the use of flow efficiency coatings, which was based upon the cost of the steel line pipe, compressor requirements, fuel gas, pipeline internal coating costs, and the natural gas sale price. The conclusions of this study were there were for a smooth internal coating at 150 bar there were cost savings of 7-14% relative to a steel pipe with little corrosion (20μm) and cost savings of 15-25% relative to a highly corroded pipe (50μm). Consistent with GasAtacama Pipeline study, the cost savings were smaller for lower operating pressures and greater for higher operating pressures. There was also a cost variation of up to 10% due to coating type and application, which is reported in the next section.

In conclusion, there are a number of factors that should be considered in the economic justification for using a flow efficiency coating.

Developing New FEC Technology

Improving upon Existing Solvent-based Epoxy Flow Efficiency Coatings

Traditionally, solvent-based epoxy coatings have been used for flow efficiency coatings. Solvated coatings cure by the release of the solvent in the drying process followed by cross-linking of the chemical components. This process lends itself well to thin film coatings such as required for flow efficiency coatings.

It is generally recognized that solvents classified as VOC's (volatile organic compounds) contribute to the depletion of the ozone layer when released into the atmosphere. Environmental legislation around the world is continually becoming more stringent concerning the type and quantity of solvents released in coating processes.

A development program was undertaken to improve the performance of flow efficiency coatings in 3 key areas:

1. A reduction in the surface roughness of the coating to reduce pressure loss and thus increase flow capacity
2. A reduction in solvent emissions during application to meet increasingly stringent environmental regulations and customer requirements regarding the release of volatile organic compounds (VOC's) and hazardous air pollutants (HAP's).
3. A resistance to more aggressive service environments other than non-corrosive natural gas.

A number of alternative technologies to solvent-based coatings were investigated to meet these key requirements, in addition to being competitively priced and the ability to apply using existing standard application equipment. The different coating technologies and their ability to meet the required performance criteria is summarized in table 2:

Table 2: Coating Technology versus Required Performance Criteria

	Cost[A]	**VOC / HAPs Reduction**	**Friction Reduction**	**Existing Application Equipment**	**Aggressive Service Environment**
Solvent-free (SF)	✓	✓	✓	✓	✓
Water-based	**X**	✓	**X**	**X**	**X**
Powder	**X**	✓	✓	**X**	✓
High-solids	✓	**X**	**X**	✓	✓

[A]: Cost considerations included cost of materials, plant CAPEX requirements and plant operating costs.

The Institut Francais du Petrole (IFP) and Norwegian University of Science and Technology (NTNU) undertook a joint venture research program to study how the pressure loss in natural gas pipelines can be reduced, to increase the capacity of the pipelines and distribution networks. A progress report issued by Charron et al (2003) from this study concluded that both solvent-based and water-based coatings gave a relatively large roughness and friction factor, while solvent-free and powder coatings gave a relatively small roughness and friction factor.

Based upon the performance criteria requirements reported in table 1 and reported research data such as IFP, it was decided to pursue solvent-free (SF) epoxy coating technology for a new class of flow efficiency coatings. Solvent-free epoxy coatings have been in use in other industries for a number of years, as coatings for tanks, clarifiers, pump stations, and pipelines as anti-corrosion coatings. Solvent-free coatings cure via a thermoset reaction with a catalyst that eliminates the solvent evaporative process. However, the challenge has always been to formulate a solvent-free coating that can be applied at a dry film thickness (DFT) of 50 - 100µm / 2.0 - 4.0mils, as required for a flow efficiency coating.

Development Process

Laboratory Screening of Candidate Materials

A solvent-free (SF) 2-part epoxy was formulated to meet the performance requirements of the American Petroleum Institute Recommended Practice 5L2 Standard “Internal Coating of Line Pipe for Non-Corrosive Gas Transmission Service” (API RP 5L2-2002). API RP 5L2 is intended for low solids (<38%) coating materials, so the material specification requirements did not directly apply to the solvent-free epoxy formulation.

In addition to passing the API RP 5L2 performance requirements, the new solvent-free epoxy was also required to meet minimum plant production requirements reported in table 3.

Table 3: Plant Production Requirements for an Solvent-free Flow Efficiency Coating

Property	**Minimum criteria**
Application Equipment	Plural component
Steel Application Temperature	10 - 50°C/ 50 – 122°F
Spray Characteristics	Consistent, with short interruptions of up to 10 minutes
Pot Life	>10 minutes
Applied Film Thickness	50 – 100µm/2.0 – 4.0 mils
Cure Requirements	< 18 hrs at 20°C/68°F
Applied Appearance	Uniformly smooth and even
Air Entrainment	None

Plant Application Trial Evaluation

Once the solvent-free epoxy had met the API and plant production requirements, a full-scale plant application trial was conducted. The objectives of the trial were:

1. To confirm the equipment settings, material and pipe conditions for application.
2. To demonstrate compatibility of the liquid epoxy with plant operations.
3. To determine the coating performance in plant applied pipe.

Two different scenarios were considered for the plant application trial:

i. To simulate routine production line speeds. This part of the trial established that the coating could be easily used in everyday production.
ii. To simulate upset conditions. Upset conditions may occur when minor equipment malfunctions occur, or when adjustments are made to the production line. Though upsets in the plants are typically rare, fast curing coatings such as the solvent-free epoxy will require extra attention to be paid to the coating and equipment when these conditions occur, due to the limited pot life of the plural component epoxy once it is mixed.

The plant application trial included all steps required with most customer specified pre-qualification trials, such as pre-qualification to the client's specifications, incoming quality control of the liquid coating material, plant application and production quality control testing, and quality control testing of the applied coating as per API RP 5L2.

The solvent-free coating passed the plant application trial requirements – see table 4. However, close inspection of the coating revealed microscopic entrained air within the coating and a slight orange peel appearance.

Table 4: Plant Trial Quality Control Tests

Test	**Test Condition**	**Pass Criteria**	**Result**
Pinhole	Glass slide	Minimal (3/slide)	Pass
Cure	4 hrs immersion, flush solvent	No softening, wrinkling, or delamination	Pass
Adhesion	Cross-Hatch/Tape	No lifting other than cuttings	Pass
Water Immersion	4 hrs in fresh water	No loss of adhesion, softening, wrinkling, or blistering	Pass
Bend	Conical Mandrel	≥ 13mm no flaking, loss of adhesion, or cracking per unaided observation	Pass
Stripping	Knife	No delaminating in strips, crumbles to powdery particles when crushed between thumb and forefinger	Pass

Coating Manufacture and Formulation Adjustments

Upon further investigation, microscopic air bubbles were detected in the base component as received at the plant. The air was not removed during mixing of the base and hardener, and showed up in the API pinhole test after application. Note, the air did not cause pinholes, but there is little visual difference between entrained air and pinholes in that test. Some of the effects of air entrainment are the same as the effects of pinholes, as reported in table 5.

Table 5: Differences between Pinholes and Entrained Air

Effect	**Pinholes**	**Entrained Air**
Direct pathway for corrosive species from surface to substrate	✓	**X**
Weaken coating film to physical stresses	✓	✓
Create roughness by distorting coating surface	✓	✓

To ensure that entrained air was removed from the base component before shipment to the application plants, the manufacturing procedure for the base component was changed. The solvent-free base component is now manufactured under vacuum, which pulls the microscopic air bubbles out of the liquid before it is placed in the container and shipped to the plants.

A coating formulation adjustment was required to eliminate the orange peel appearance. This slight formulation change allowed the applied coating to smooth within a couple of minutes of application. The applied coating was then completely retested to the API performance criteria, to ensure the adjustments did not alter the resulting coating film properties.

After the formulation adjustments were made, a follow-up plant trial was required to ensure that the changes did not affect either the plant operation or the finished product. The requirements of the first plant trial were duplicated in the follow-up plant trial.

Final Qualification Testing of Plant Applied Coating

Final qualification test results to API RP 5L2 are reported in table 6.

Table 6: Qualification test results to API RP 5L2

Test	Test Condition	Pass Criteria	Results
Salt Spray	500 hrs	No blisters, <3.2mm removal from scribe	Pass
Water Immersion	500 hrs in saturated $CaCO_3$	No blistering over 6.3mm from edge	Pass
Methanol/Water Immersion	1:1 mixture for 120hrs	No blistering over 6.3mm from edge	Pass
Stripping	Knife	No delaminating in strips, crumbles when crushed between thumb and forefinger	Pass
Bend	Conical Mandrel	≥ 13mm no flaking, loss of adhesion, or cracking per unaided observation	Pass
Adhesion	Cross-Hatch/Tape	No lifting other than cuttings	Pass
Hardness	Buchholtz	94 minimum	Pass
Abrasion	Falling abrasive	Minimum 23 COA	Pass
Gas Blistering	1200psi, N2, 24hrs	No blisters	Pass
Hydraulic Blistering	2400psi, saturated CaCO3, 24 hrs	No blisters	Pass

In addition to the API qualification testing, a major oil and gas company requested that additional testing be conducted on laboratory-coated samples after the samples had been stretched over a mandrel to 3% elongation. The stressed coating samples were then tested to API specifications as reported in table 7.

Table 7: Qualification Testing to Client Specifications – Samples stretched to 3% Elongation

Test	Test Condition	Pass Criteria	Results
Salt Spray	500 hrs	No blisters, <3.2mm removal from scribe	Pass

Water Immersion	500 hrs in saturated $CaCO_3$	No blistering over 6.3mm from edge	Pass
Methanol/Water Immersion	1:1 mixture for 120hrs	No blistering over 6.3mm from edge	Pass
Methanol Immersion	7 days	No blistering over 6.3mm from edge	Pass
Triethylene Glycol Immersion	7 days	No blistering over 6.3mm from edge	Pass
Stripping	Knife	No delaminating in strips, crumbles to powdery particles when crushed between thumb and forefinger	Pass
Bend	Conical Mandrel	≥ 13mm no flaking, loss of adhesion, or cracking per unaided observation	Pass
Adhesion	Cross-Hatch/Tape	No lifting other than cuttings	Pass
Abrasion	Falling abrasive	Minimum 23 COA	Pass

The solvent-free coating has also been tested by gas chromatography to establish that they are free of chemicals identified by a major client as potential contaminants of natural gas.

Roughness Testing of Solvent-Free Flow Efficiency Coating

Roughness measurements were made using a Mitutoyo Surftest profilometer using the following parameters: Cut-off = 0.8mm, Filter = 2-CR, and Tip OD = 5µm. Comparable results for both a solvent-based and new solvent-free flow efficiency coatings are summarized in table 8.

Table 8: Comparison of Roughness for a Solvent-based and Solvent-free Flow Efficiency Coating

Coating Product	**Dry Film Thickness, µm**	**R_{ZD} Roughness,µm**
Solvent-based FEC	61	18.7
	84	11.2
	140	6.8
SF FEC	65	3.8

The traditional solvent-based FEC shows a generally accepted trend that as the coating thickness is increased the surface roughness is reduced. For the solvent-free flow efficiency coating, there is only one dry film thickness measurement available as this was the thickness of the coating in the plant trial.

Conclusion

1. There is sufficient data reported in the technical literature to substantiate that the use of flow efficiency coatings can substantially reduce both the CAPEX and OPEX for gas transmission pipelines.

2. Product development testing and supporting technical literature confirm that solvent-free flow efficiency coatings are smoother than solvent-based flow efficiency coatings, providing further reductions in the friction coefficient between the pipe wall / fluid interface, with a subsequent increase in the flow rate.

3. The solvent-free flow efficiency coating developed by Bredero Shaw can be applied at the required thin film thickness for flow efficiency coatings.

4. The solvent-free flow efficiency coating developed by Bredero Shaw passed the API 5L2 ‘Recommended Practice for Internal Coating of Line Pipe for Gas Transmission Service’ and additional ‘more stringent’ test requirements

specified by a major oil and gas company.

Further testing is still to be conducted, including determining if the solvent-free flow efficiency coating is more resistant to aggressive environments.

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