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PRECOMMISSIONING OF OIL&GAS PIPELINE

Overview of all Pre-commissioning phases, in-depth analysis of involved physical phenomena and investigation on current calculation methods with introduction and proposal of new representative models

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Abstract

This thesis has been developed in Sicim spa, a construction company that offers services related to the installation of pipelines and relevant ancillary facilities for the transmission and distribution of oil and gas on an international basis. After a brief introduction related to all construction phases of a pipeline, the thesis focused on all steps related to pre-commissioning: the emptying of the pipeline from the water used for pressure test, the swabbing with foam pigs to absorb most of the residual water, the drying in order to achieve a satisfactory dryness of the pipe to avoid corrosion phenomena and possibility of hydrate formation in case of a gas pipeline, the detection of possible presence of gouges or dents using inspection tools, and lastly inertization using nitrogen prior to gassing-up. Each of these phases is addressed with an explanation of the procedure, a portray of some adopted technical specifications, a description of tools and equipment involved. The main scope of the work is primarily analyzing the phases and when necessary developing a deterministic model. The models are not only capable of analyzing and explaining the phenomena from a scientific point of view but also effective tools to calculate and predict parameters involved. They have been successfully applied in the GB 022 project in Scotland.

Summary

Pipeline are the most efficient, safe and economic way to transport fuels from refinery to various delivery points; this work is developed in Sicim spa, one of the main Italian construction companies involved in the pipeline industry, and it begins with an overview of all construction phases of a pipeline, highlighting the grouping of them in three main categories: mechanical completion, Pre-commissioning and commissioning, where the second one is the topic of the thesis. The thesis deal with it theoretically with descriptions and explanations and practically by working on a real project, Scotland GB 022 project.
The structure is divided in chapters, where each chapter is roughly dedicated to a specific phase of the pre-commissioning and contains a detailed description of the procedure, a deep investigation and explanation of the involved physical phenomena and the supplement of some technical specifications related to the GB 022 project. Careful consideration has been taken to the equipment related to each phase by introducing measuring-instruments and tools widely used in the pipeline industry for inspection, called pigs.
Though reported in a separate chapter, a relevant effort in the study has been devoted to build mathematical models capable of predicting some parameters of each phase of the pre-commissioning, such as their duration. The models are aimed at not only time prediction but also enrichment of the physical explanation of the phenomena for example by means of the qualitative attached plots, that show the spatial and temporal behavior of a pipeline system. The models result from manipulation of specific principles and laws of physics and are indeed deterministic. Nevertheless, many of the hypothesis and initial assumptions are empirical (coming from experience).
Additional chapters are added as appendices in order to provide some insights about non-properly relevant for the thesis but related topics, such as the corrosion of a pipeline, the trenching methods, the main contract types used in the pipeline industry and the description of additional devices used in pre-commissioning of pipeline, such as pig traps, used every time a pig needs to be loaded or unloaded.

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Definitions

A

Absorption drying: A method by which the thin layer of water left on the pipe surface is removed by absorbing it into the foam pigs.
Acceptability criteria: it's needed as a reference to which compare the result coming from a test; it indicates whether the result are satisfactory and the requirements are met or no.
Air lock: is a restriction of, or complete stoppage of liquid flow caused by vapour trapped in a high point of a liquid-filled pipe system.
Anode: terminal of an electrolytic cell where oxidation occurs: is the point that corrodes and metal is lost.

B

Backpressure: refers to pressure opposed to the desired flow of fluids in confined places such as a pipe.
Barrel: the major diameter section of a pig trap into which the pig is loaded and to which the closure is fitted.
Bi-directional: term describing pigs capable of moving both forwards and backwards.
Boom: Pipe layer also known as a side boom tractor, very significant to pipeline construction and maintenance
Brushes: are commonly fitted to cleaning pigs; made from steel or nylon.
Buckle/buckling: A condition in which the pipeline has undergone sufficient plastic deformation to cause permanent wrinkling or deformation of the pipe wall or the pipe's cross-section: possible abrupt change in curvature; it differs from a dent because it's not caused by an indenter but usually derives from overbending during laying process or result of ground movements
Burst pressure: the pressure that makes something to fail
Bypass: controlled flow of pressure (and fluid) past the sealing face of the pig: this reduces the differential pressure acting on the pig and is done to control pig speed and cleaning efficiency.

C

Calibration Dig: An exploratory excavation to compare findings of an in-line inspection system to actual conditions with the purpose of improving data analysis. See also Verification Dig.
Caliper Pig: A configuration pig designed to record conditions such as buckles, dents, wrinkles, ovality, bend radius and angle, and occasionally, indications of significant internal corrosion by sensing the shape of the internal surface of the pipe (also referred to as geometry pig).
Cathode: terminal in the electrolytic cell where the reduction reaction occurs, it attracts positively charged particles.
Chainage: Cumulative pipeline distance usually measured on the surface from a specific point of origin.
Check Valve: Valve that prevents reverse flow. Can cause damage to ILI tools if not fully opened.
Caliper tools: examples of geometry tools.
Cleaning Pig: A utility pig that uses cups, discs, scrapers, or brushes to remove dirt, rust, mill scale, corrosion products, and other debris from the pipeline. Cleaning pigs are utilized to increase the operating efficiency of a pipeline or to facilitate inspection of the pipeline.
Combination Tool: An instrumented in-line inspection tool designed to perform both geometry (deformation) inspections as well as metal loss inspections with a single tool chassis.
Commissioning: it follows pre-commissioning and begins with the introduction of the product into the pipeline, followed by packing (raising the pipeline to operating pressure in readiness for production)
Component: Any physical part of the pipeline, other than line pipe, including but not limited to valves, welds, tees, flanges, fittings, taps, branch connections, outlets, supports, and anchors.

Corrosion: The deterioration of a material, usually a metal, that results from a chemical or electrochemical reaction with its environment.
Crack, Cracking: A fracture type of discontinuity characterized by a sharp tip and high ratio of length to width to opening displacement.
Cups: elastomeric fittings that allow a pig to form a seal in the pipeline; they can be standard or conical. Pigs fitted with cups are unidirectional only, irrespective of the type of cup fitted.

D

Data Analysis: The evaluation process through which indications are classified and characterized.
Defect: A physically examined anomaly with dimensions or characteristics that exceed acceptable limits. See also Imperfection.
Deformation Tool: An instrumented in-line inspection tool designed to record geometric conditions such as buckles, dents, wrinkles, ovality, and bend radius and angle. See Caliper Pig and Geometry Tool.
Deformation: A change in shape, such as a bend, buckle, dent, ovality, ripple, wrinkle, or any other change that affects the roundness of the pipe's cross-section or straightness of the pipe.
Dent: A local change in piping surface contour caused by an external force such as mechanical impact or rock impact. It's a depression that produces a gross disturbance in the curvature of the pipe wall caused by contact with a foreign body resulting in plastic deformation of the pipe wall.
Detect: To sense or obtain a measurable indication from a feature.
Dew point: The temperature below which the water vapor of humid air at a constant barometric pressure will condense into liquid water. Condensed water is called dew when it forms on a solid surface.
Differential pressure: the pressure difference across the sealing elements of any tool operating a seal in a pipeline; it must be high enough to overcome the frictional resistance of the pig seals on the pipe walls.
Disc: elastomeric fittings that allow the pig to form a seal with the pipeline wall and to provide a scraping action; they are needed when the pigs must be bi-directional.
Dual-diameter pig: pig capable of passing through two or more nominal pipe diameters in the same piping system.

E

Electric Resistance Weld (ERW): A weld seam formed by resistance heating of the two edges of a pipe and then forcing them together.
Equipment: all temporary fittings, piping, pumps, compressors, pigs, materials, equipment and consumables used for Pre-commissioning of the pipeline.
Evaluation: A review, following the characterization and examination of an anomaly to determine whether the anomaly meets specified acceptance or rejection criteria.
Evaporative drying: A method by which the thin layer of water left on the pipe surface is removed by super dry air or nitrogen.

F

Fatigue: The process of progressive localized permanent structural change occurring in a material subjected to fluctuating stresses less than the ultimate tensile strength of the material that may culminate in cracks or complete fracture after a sufficient number of fluctuations.
Feature: Any physical object detected by an in-line inspection system. Features may be anomalies, components, nearby metallic objects, welds, appurtenances, or some other item.
Fitness-for-purpose: word with different meaning and field of applicability; in the pipeline defect assessment, it means to consider a particular structure that is adequate for its purpose, provided the conditions to reach failure are not reached. It's a detailed technical assessment.
Foam pig: pig made entirely from open cell polyurethane foam.

G

Galvanic corrosion: is an electrochemical process in which one metal corrodes preferentially when it is in electrical contact with another, in the presence of an electrolyte.
Gassing-up: introduction of product into the pipeline
Gauging Pig: A utility pig mounted with a flexible metal plate or plates to gauge the internal diameter of the pipeline. Pipe bore restrictions less than the plate diameter or short radius bends will permanently deflect the plate material.
Geographical Information System (GIS): A computer system capable of assembling, storing, manipulating, and displaying geographically-referenced information.
Geometry Tool: An instrumented in-line inspection tool that records data about the geometric condition of the pipeline or pipe wall.
Girth Weld: A complete circumferential butt weld joining pipe or components.
Golden Weld: a weld that is usually the final weld connecting tested pipe section to other tested pipe section. Since this weld is not submitted to the pressure test, several NDT are performed on it in order to guarantee its safety. Golden Welds, differently from other welding between pipes, are performed in the trench, and don't have external protective coating, indeed the weld is then wrapped in a thermo-shrinkable band made of quartz or granulated slag.
Global Positioning System (GPS): The navigational system utilizing satellite technology to provide a user an exact position on the earth's surface.
Gouge: Elongated grooves or cavities usually caused by mechanical removal of metal.
Groove: hole in the shape of a elongated cut
Guide disk: disk on the pig with the specific purpose of guide the pig along its passage in the pipeline

H

Hydrate: In chemistry, an hydrate is a substance that contains water or its constituent elements.
In this context we call hydrate what should be correctly called **clathrate hydrate**: it is crystalline water-based solid physically resembling ice, in which small non-polar molecules (typically gases) or polar molecules with large hydrophobic moieties are trapped inside "cages" of hydrogen bonded, frozen water molecules. They are naturally present on earth, but thermodynamic conditions may favour hydrate formation that's why they are often found in pipelines. This is highly undesirable, because the clathrate crystals might agglomerate and plug the line and cause flow assurance failure and damage valves and instrumentation. The results can range from flow reduction to equipment damage.
Hydrostatic head: The vertical height of a fluid column, regardless of the length or other dimensions of that fluid column: it means a pressure exerted on the bottom of the column
Hydrostatic Test: A pressure test of a pipeline in which the pipeline is filled with water and pressurized to ensure it meets the design conditions and is free of leaks.

I

Imperfection: An anomaly with characteristics that do not exceed acceptable limits. See also Defect.
Indication: A signal from an in-line inspection system. An indication may be further classified or characterized as an anomaly, imperfection, or component.
Induction Coil: A type of sensor that measures the time rate of change in magnetic flux density. Induction coils do not require power to operate, but have a minimum inspection speed requirement.
In-Line Inspection (ILI): An inspection of a pipeline from the interior of the pipe using an in-line inspection tool, it's also called intelligent or smart pigging.
In-Line Inspection Tool (ILI Tool): The device or vehicle that uses a nondestructive testing (NDT) technique to inspect the pipeline from the inside. Also known as intelligent or smart pig.
Interaction Rules: A spacing criterion among anomalies that establishes when closely spaced anomalies should be treated as a single, larger anomaly.

J

Joint: A short piece of pipe, typically 3 m (10 ft) or less in length. SP0102-2010 NACE International 5

K

Kicker Line: Piping and valving that connects the pressurizing pipeline to the launcher or receiver.
Kinked dent: damage on the pipeline in the shape of a dent with sharp change in curvature; it has low burst pressure and short fatigue life. Approximate definition of kinked dent is that the sharpest part of it is less than five times the wall thickness (Roovers, et al., 2000)

L

Lamination: An internal metal separation creating layers generally parallel to the surface.
Launcher: A device used to insert an in-line inspection tool into a pressurized pipeline. It may be referred to as pig trap or scraper trap.
Line Pipe: describes the pipe before it is welded into a pipeline.
Liquefied Petroleum Gas (LPG): Petroleum gases (butane, propane, etc.) liquefied by refrigeration or pressure to facilitate storage or transport. SP0102-2010 4 NACE International

M

Magnetic Flux Leakage (MFL): A type of in-line inspection technology in which a magnetic field is induced in the pipe wall between two poles of a magnet. Anomalies affect the distribution of the magnetic flux in the wall. The magnetic flux leakage pattern is used to detect and characterize anomalies.
Magnetic Particle Inspection (MPI): A non-destructive examination (NDE) technique for locating surface flaws in steel using fine magnetic particles and magnetic fields.
Measurement Threshold: A dimension or dimensions above which an anomaly measurement can be made.
Mechanical completion: phase of construction activity that verifies the completeness of the plant: every component is fabricated, installed and tested in accordance with the project specifications.
Metal Loss: Any pipe anomaly in which metal has been removed. Metal loss is usually the result of corrosion, but gouging, manufacturing defects, or mechanical damaging can also cause metal loss.
Micro tunnelling: no-dig technology used for new pipeline construction: it doesn't require trench digging. The technology is similar to raise boring, but the diameters involved are smaller.

N

Neckpipe: the minor diameter section of a pig trap
Non-destructive Examination (NDE): The evaluation of results from nondestructive testing methods or nondestructive testing techniques to detect, locate, measure, and evaluate anomalies.
Non-destructive Testing (NDT): A process that involves the inspection, testing, or evaluation of materials, components, and assemblies for materials' discontinuities, properties, and machine problems without further impairing or destroying the part's serviceability.
Non-destructive Testing Method (NDT Method): A particular method of NDT, such as radiography, ultrasonic, magnetic testing, liquid penetrant, visual, leak testing, eddy current, and acoustic emission.
Non-destructive Testing Technique (NDT Technique): A specific way of utilizing a particular NDT method that distinguishes it from other ways of applying the same NDT method. For example, magnetic testing is a NDT method, while magnetic flux leakage and magnetic particle inspection are NDT techniques. Similarly, ultrasonic is a NDT method, while contact shear-wave ultrasonic, and contact compression-wave ultrasonic are NDT techniques.

O

Open-cut: term used to describe an activity involved with soil were everything is done from thesurface of the ground rather than from passages dug under it
Operator: A person or organization that owns or operates pipeline facilities as an owner or as an agent for an owner.
Ovality: Out of roundness, i.e., egg shaped or broadly elliptical.

P

Packing : pressurize the product in the pipeline up to operating pressure
Pig Signal: Usually a mechanical sensor on the pipe activated by the passage of a pig.
Pig Trap: A pig trap is a pipeline facility used for launching or receiving a pig. It usually becomes an integral part of the pipeline system. In some cases, the pig traps must be removed or isolated during a hydrotest because of pressure limitations. Pipeline blinds might be installed to provide the necessary pressure integrity. Some traps are crude in design with nothing but a basket to catch an exiting pig during drying operations. Complex traps provide all of the pig launching and receiving capabilities needed for the pipeline. Most of the trap designs have an internal diameter larger than the pipeline to aid in placement and retrieval of the pig from the pig trap and to allow fluids to bypass around the pig after the pig is received in the pig trap.
Pig: A pig is a device that is propelled through a pipeline to perform one of several functions. In some cases, several pigs are necessary to perform multiple functions in the same pass. A pig requires fluid or gas movement in the line to propel it down the pipeline and to perform its function. The pig discs, cups, or foam body makes contact with the wall of the pipeline to provide a seal. This seal prevents fluid from bypassing the pig as it moves down the pipeline. Pigs are used to separate fluids, gauge lines, provide magnetic pickup, caliper the pipeline, provide a temporary barrier, and provide brushes for cleaning. Foam pigs are used to dry the pipeline. Most pigs are unidirectional. Some pigs are bidirectional, which means they can be moved in either direction.
Pinhole failure: perforation of a tube as a result of pitting corrosion initiated on the interior surface.
Pipeline Coordinates: Location coordinates of the course that a pipeline follows as given in a standard geographic coordinate system.
Pipeline System: All portions of the physical facilities through which gas, oil, or product moves during transportation. This includes pipe, valves, and other appurtenances attached to the pipe, compressor units, pumping units, metering stations, regulator stations, delivery stations, tanks, holders, and other fabricated assemblies.
Pipeline: A continuous part of a pipe system used to transport a hazardous liquid or gas. Includes pipe, valves, and other appurtenances attached to the pipe.
Pit: type of hole, see Pitting corrosion.
Pitting corrosion: form of extremely localized corrosion that leads to the creation of small holes in the metals; the corrosion penetrates the mass of the metal.
Plain dent: a smooth dent without any presence of metal loss; burst strength is not significantly reduced and the the fatigue life is not significantly affected if the plain dent is constrained.
Plough: polyurethane fittings, often used as an alternative to brushes and scrapers. Suitable for soft waxes.
Pressure: Level of force per unit area exerted on the inside of a pipe or vessel.
Probability of Detection (POD): The probability of a feature being detected by an in-line inspection tool.

R

Raise borer: machine used in underground mining or pipeline engineering, to excavate a circular hole between two levels without the use of explosives
Receiver: A pipeline facility used for removing a pig from a pressurized pipeline. It may be referred to as trap, pig trap, or scraper trap.

Reducer: a point of transition built into a pig trap that compresses the pig seals from the freely loadable into the travelling state which corresponds to the bore of the pipeline.
Remaining strength: the strength of a material affected by a dent; it's lower with respect to the same and perfect material strength.
Rerounding: behaviour that occurs when the element that keeps a dent stable within a pipe is removed and the pipe bend back towards the position where the object was.
Rupture: The instantaneous tearing or fracturing of pipe material causing large-scale product or water loss.
Rust: reddish-brown substance that forms on the surface of iron and steel as a result of reacting with air and water

S

Scope of work: the part of the contract which states the overall scope for Pre-commissioning operations
Scraper: polyurethane or metal fittings often used as an alternative to brushes and ploughs. Well applicable to remove waxes.
Seal disk: disk adhering on the pig with the specific purpose of being an active seal
Seam Weld: The longitudinal or spiral weld in pipe, which is made in the pipe mill.
Section: part in which the pipeline project has been divided; in the thesis we considered sections the ones used for hydrostatic test.
Segment: a small discretization of the pipeline, used in this thesis usually as 10m of pipeline length.
Sensors: Devices that receive a response to a stimulus, (e.g., an ultrasonic sensor detects ultrasound).
Settling tank (sedimentation pond): tank for purification of water for hydrotest; water is purified from heavier particles
Shear Wave: Pertaining to pipe inspection, shear waves are generated in the pipe wall by transmitting ultrasonic pulses through a liquid medium. The same transducer is used for both sending and receiving ultrasound (so-called pulse echo technique). The angle of incidence is adjusted in such a way that a propagation angle of approximately 45° is obtained in the pipe wall. By using 45° shear waves, it is possible to detect radial-oriented, surface-breaking cracks at both sides of the pipe wall with high sensitivity, because the ultrasound pulse undergoes a strong angular reflection at the crack edge (so-called corner reflection).
Sideboom: construction equipment with a boom on the side.
Signaller: device installed on a point along the pipeline that generate a visible or electric signal to the operator when it detects the passage of a pig in that point
Sizing Accuracy: The accuracy with which an anomaly dimension or characteristic is reported. Typically, accuracy is expressed by tolerance and a certainty. As an example, depth sizing accuracy for metal loss is commonly expressed as +/-10% of the wall thickness (the tolerance), 80% of the time (the certainty).
Slackline: The flow of product fails to completely fill the pipeline.
Smart Pig: See In-Line Inspection Tool (ILI Tool).
Slot: elongated holes in a material
Smart pig: smart pig is an inspection device that records information about the internal conditions of a pipeline. It is used to detect and measure corrosion and metal loss internally and externally on the pipe wall. Smart pigs can also detect curvatures in the pipeline. When referring to using a smart pig for a pipeline some may refer to the process as "pigging the pipeline." A smart pig is also known as a pipe pig, pipeline pig, pipeline inspection gauge, pipeline inline inspection tool, natural gas pipeline inspection tool or corrosion detection pipe
Spread: term used to call each step in which a big project can be divided.
Strain: Increase in length of a material expressed on a unit length basis (e.g., millimeters per millimeter or inches per inch).
Survey: Measurements, inspections, or observations intended to discover and identify events or conditions that indicate a departure from normal operation of the pipeline.

T

Test head: device welded to the pipe section that is going to be hydrotested. After the hydrotest it will be cut away
Transducer: A device for converting energy from one form to another. For example, in ultrasonic testing, conversion of electrical pulses to acoustic waves, and vice versa.
Transmission Line: A pipeline, other than a gathering or distribution line, that transports gas from a gathering or storage facility to a distribution centre or storage facility; operates at a hoop stress of 20% or more of the specified minimum yield strength of the pipe; or transports gas within a storage field.
Trap: A pipeline facility for launching or receiving tools and pigs. See Launcher and Receiver.

U

Ultrasonic Testing (UT): A type of inspection technology that uses ultrasound for inspecting pipe.
Unidirectional: term for pigs that can move only in one direction within the pipeline.

V

Verification Dig: An excavation made to verify the reported results of an in-line inspection. See Calibration Dig.

W

Wrinkle: A smooth and localized bulge visible on the outside wall of the pipe. The term wrinkle is sometimes restricted to bulges that are greater in height than one wall thickness. See Buckle.

Y

Yield Strength: The stress at which a material exhibits a specified deviation from the proportionality of stress to strain. The deviation is expressed in terms of strain by either the offset method (usually at a strain of 0.2 percent) or the total-extension-under-load method (usually at a strain of 0.5 percent).

List of symbols and abbreviations

a, b, ω, β = *constants*
A= *cross-section area*
AGI = *above ground installation*
APB = *acid-producing bacteria*
ASME = *american society of mechanical engineers*

BV = *block valve*
C = *concentration*
$_c$ *or* *= *critical*
CMC = critical moisture content
d = *depth* or *diameter*
D = *mass diffusion coefficient*
EMC = *equilibrium moisture content*
FAD = *free air delivery, flow rate*
g = *acceleration gravity*
h = *height (altitude)*
ILI = *in-line inspection*
Kc = *mass transfer coefficient (m/s)*
Ky = *mass transfer coefficient (kg/s m2)*
L = *length*
M = *mass*
MAOP = *maximum allowable operaiting pressure*
MIC = *microbacterial induced corrosion*
EPC = *Engineering, Procurement and Construction*
ERF = *estimated repair factor*
MFL = *magnetic flux leakage*
MOP = *maximum operating pressure*
N = *flux rate*
n = *number of cycle or number of moles*
NACE = *National Association of Corrosion Engineers*
NDT = *non-destructive test*
ODE = *ordinary differential equation*
P = *pressure*
PHMSA = *Pipeline and Hazardous Materials Safety Administration*
POF = *pipeline operator forum*
Q = *flow rate*
R = *gas constant*
r = *radius*
RDX = *road crossing*
Re = *Reynold number*
ROW = *right of way*
RVX = *river crossing*
S = *internal surface*
Sc = *Schmidt number*
Sh = *Sherwood number*
SMYS = *specified minimum yield strength*
SRB = *sulfate-reducing bacteria*
T = *temperature*
t = *thickness or time*
UT = *ultrasonic test*
v = *velocity*
V = *volume*
W = *width*
X or Y = *molar fraction*
Δ = *difference*
µ = *dynamic viscosity*
ν = *kynematic viscosity*
ρ = *density*
σ = *stress*

Introduction

Natural fossil fuels like crude oil and natural gases are the raw material that provide energy to the world and are extracted in locations different from where they are eventually processed or refined into fuels for our lives and then delivered and consumed. Many forms of transportation are used to move these products to marketplaces: pipelines remain one of the safest, most efficient and economical ways to move these natural resources.
The construction of a pipeline involves big location and qualified crews of workers: being a large project it's usually divided in different phases that are called "spreads". Together with specialized workers and engineers with different responsibilities, most of the phases involve large equipment such as engines, compressors, trucks and pipe layers, and specific devices such as *pigs*: pigs are tools widely used in the pipeline industry because capable of running inside the pipeline, propelled by a fluid, and performing several actions according to the gadgets mounted on them: displacing water, cleaning, detection of internal damages.. Whenever a pig is used, pig traps are employed as the most efficient way to load and unload the pig. The steps for a pipeline construction are many: after all surveys, planning and installation, the line is filled with water and pressurized in order to verify its strength and absence of leaks; with this set of phases, the *Mechanical Completion* is accomplished. Then the line has to be emptied from water, swabbed (residual water is removed by using slightly-dry air and foam pig capable to absorb water), dried and then filled with nitrogen to keep inert (not flammable) the atmosphere within the tube: this second set of procedures is what is commonly defined *Pre-commissioning*. After this phase it's time for the introduction of the fuel in the pipeline and the pressurization up to the design pressure: this is what is called *Commissioning.*
Lot of papers and chapters on the topic of hydrotest are available (Kiefner, et al., 1973), (Kiefner & Haines, 2012) (Kiefner & Maxey, 2013) (Cosham & Hopkins, 2004) (McAllister, 2005): some explain the procedure and show calculation, some other investigate more deeply in what lies behind the hydrotest, why pressurization is fundamental for the detection of leaks, entering in the field of fracture mechanics.
The available papers and studies in literature related to the modelling of *Pre-commissioning* steps instead are few and in the firms the design calculations are usually based both on basic equations and approximations and on past experience in shipyards, hence the need to provide a deep explanation of each phenomena from a physic point of view and to model it with a mathematical approach. As regards *dewatering* for instance, only a basic approach is available in literature: it's based on the simple evaluation of the hydrostatic pressure head and the rate of the compressor used. (Ravi Shankar, et al., 2013). More technical papers and proposals are available for *drying* calculation, the simplest are even accompanied by application to case studies (Ravi Shankar, et al., 2013), (Al Farayedhi, 1999) whereas the most complicated models (Ahmed, et al., 1997) (Cengel, 2002) are usually only theoretically presented and results of application are eventually shown. For *inertization* the quite known purging equation (Crowl & Louvar, 2002) is the reference model and no new equations are presented in the thesis.
The thesis is dedicated to a detailed analysis of all steps that are part of the *Pre-commissioning* and has been developed in ***Sicim*** *spa*, a construction company that offers all types of services related to the installation of pipelines and relevant ancillary facilities for the transmission and distribution of oil and gas on an international basis. After a comprehensive overview about all construction phases of a pipeline from the installation and mechanical completion up to the introduction of the fuel, the work is organized in the description of all specific steps of the pre-commissioning with the aim of providing an elucidation of the procedure and of some related aspects, the physical laws behind it and the illustration of the employed equipment. Then, where possible, a deterministic model has been set up in order to estimate those functional parameters such as time required and to enrich the description and explanation of the physical phenomena. Models are discussed, and a note related to the relationship between the swabbing and the drying is present: it aims to debate on the effectiveness of the swabbing procedure, if prior to drying, in reducing of time and cost to completely dry the pipeline. All models have been applied to a real current project of the firm for a pipeline in Scotland, the *GB 022* project currently in progress.

1 Construction phases of a pipeline

Pipelines are an economical and eco-friendly way to transport liquid and gaseous fuels from the extraction site to the refinery and from the refinery to various delivery and consumption points. Storage areas, storage zones and yards are strategically located along the planned *right-of-way (ROW)* in order to comply with all construction phases required to build a pipeline according to the client requirements and in accordance with the international rules. Pipeline companies indeed usually tend to use existing roads to provide access to the construction ROW that is the area available for working and laying the pipeline. The access roads are temporarily available to transport material, equipment, trucks, personnel to project work areas. The pipeline rights-of-way are recognizable as corridors that are cleared of trees, buildings or other structures except for pipeline markers. Here below are listed all phases of the pipeline construction:

1.1 Construction and mechanical completion

1.1.1 Survey

The working area is highlighted with sticks and terrestrial surveys are made. Notes related to river crossing, existing pipeline crossing, characteristics of soil and environment are taken. It's necessary to define possible point of water uptake and delivery. Environmentally sensitive areas are fenced for protection, possible trees present on the ROW may be explanted.

1.1.2 Clearing and grading

Once surveying is complete the caterpillar and other machineries remove trees, rocks and the top layer of soil, clearing the ROW: they will be replaced at the end of the work. The grader is then used to make the soil tight for the subsequent safe passage of machinery on the work surface.

1.1.3 Trenching

Trenching machines, backhoe or drilling machines are used to dig the soil: the excavation proceeds until the depth is enough to provide to the future pipeline a sufficient thickness of coverage, depending on the pipe diameter and classification of the location (the coverage increases in sensitive zones as river crossing or road crossing). When rocky zones are encountered, as in *Figure 74 pipeline route in a hostile and rocky soil,* rock trenchers are used to fracture the rocks prior to excavation; where equipment can't break the rocks, blasting may be necessary. Fine fractured rock cuttings or sand are usually employed to create a protective bed on which the pipeline will be laid. Typically, the removed soil is temporary stored in the non-working side of the rows: it will be replaced in the trench at the end of the construction. Main types of trenching methods are listed below:

- To minimize cost, the "open-cut" method to lay down pipe is adopted. Pipeline installation using open-cut method involves the digging of an open trench in the soil material with a slope that depends on the cohesion of the soil particles, the mobilization of material, labour, and machinery to obtain, assemble, install, inspect, and test the pipeline system.

FIGURE 1 OPEN TRENCH METHOD

- When it's not possible to perform the common open-cut method, for example in presence of railway or river crossing, the "Horizontal Directional Drilling" method is adopted: a small borehole is drilled horizontally under the critical area and the pipe will be then inserted protected by a casing tube.

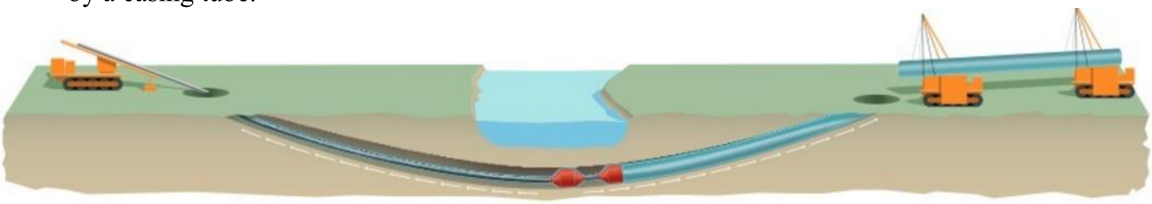

FIGURE 2 HORIZONTAL DIRECTIONAL DRILLING AT A RIVER CROSSING

- In places with relevant slopes, especially where the place that will guest the pipe is mainly made of rocks, the "raise boring" method is used: a raise borer is a machine used in underground mining, to excavate a circular hole between two levels of a mine without the use of explosive and it's employed in pipeline installation when crossing sub-vertical slope or sensitive environmental areas.

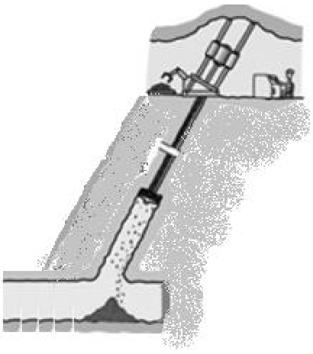

FIGURE 3 RAISE BORING METHODOLOGY

1.1.4 Stringing and bending

Pipes are transported to the ROW by trucks along the public roads and authorize paths; the chain of tubes is laid parallel to the excavation: each segment has usually a length of 12 m. *Figure 75 pipe segment, still disconnected, are laid parallel to the future route* represents this phase. Stringing is the method by which workers assemble the pieces: every piece of pipe is marked to indicate where it belongs along the line, with information about the thickness and the coating used on it. In case of difference in altimetry, a hydraulic cold-bending machine (see *Figure 76 cold bending machine is bending a pipeline segment*) will be used to bend the tube up to well defined angle/m. (see *Appendix E - Bending of a* pipe*)*. For greater bending prefabricated elbows are employed.

1.1.5 Welding, weld inspection and coating

The different sections of the pipe are joined together thanks to welding (see *Figure 77 welding procedure to join tubes*); welding is usually performed outside the trench: non-destructive tests (NDT) are then performed to verify the effectiveness and absence of leak in the welding procedure: UT, MFL are common way of detection. Once the welds between sections are completed, a protective epoxy coating or mastic is applied; with other types of external coatings they provide a protection against corrosion. Also, internal coating is performed, with for the purpose of reducing the roughness (facilitating the flow inside it) and preventing corrosion phenomena.

1.1.6 Lowering in and backfilling

Pipeline is laid in the excavation space on a bed made of soft and grinded material to avoid indentations during the phase. Inspectors verify the absence of animals, free rocks or debris in the trench. The lowering-in of pipeline is performed by sideboom (see *Figure 78 Lowering-in of the pipe by sidebooms* and *Figure 79 Lowering-in of the pipe by sidebooms along a steep slope*) that are all aligned parallel to the excavation line: during this phase the pipe and its coating are protected by non-metallic slings or coated rollers. In *Figure 4 scheme for distances and layout of sideboom during lowering-in* is reported a scheme for the lowering-in: distances between sidebooms, layout and height are advised according to calculation of allowable elastic bend for the pipeline.

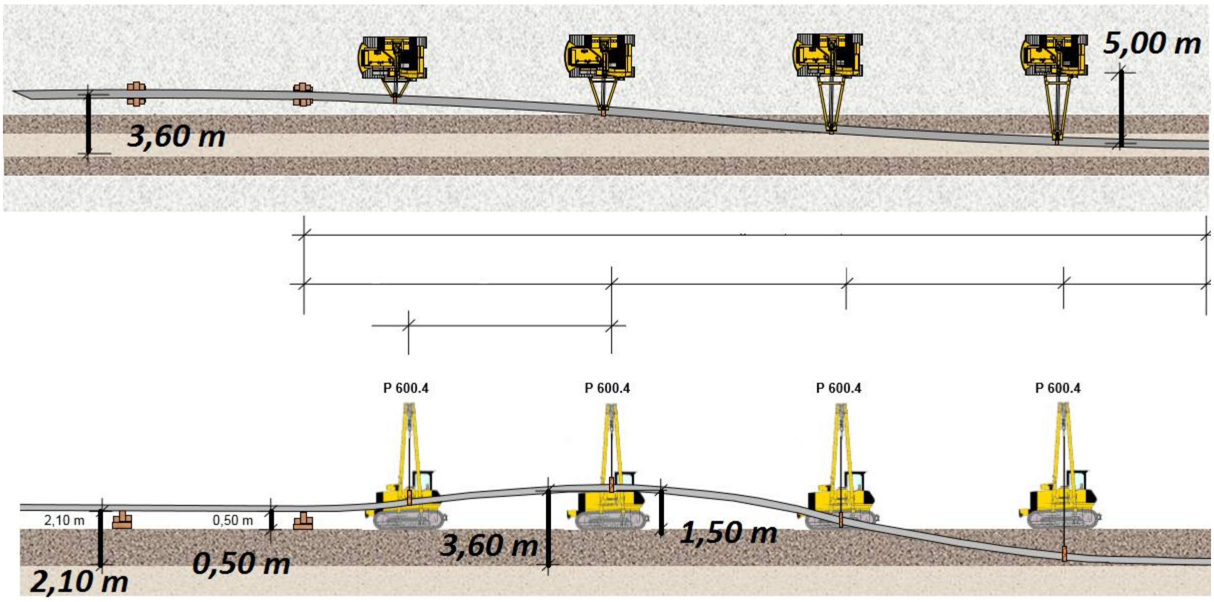

FIGURE 4 SCHEME FOR DISTANCES AND LAYOUT OF SIDEBOOM DURING LOWERING-IN

The backfilling is then performed by strata of different granulometry, as during lowering-in, in this phase also particular attention is required to avoid damage to the pipe (rock fallings on it); a safety plastic strip is then laid above the pipe along its route to warn possible excavations about the presence of the pipeline; it is concluded with a compaction performed by a road roller.

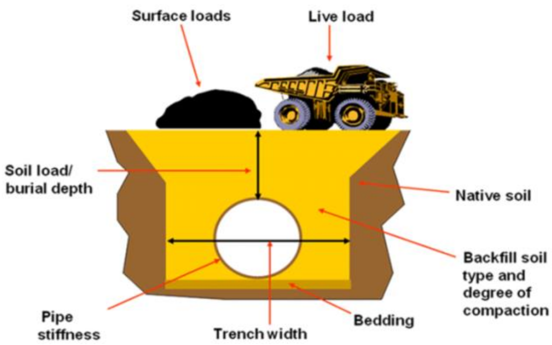

FIGURE 5 DESCRIPTION OF LOCATION FOR THE BURYING OF THE PIPELINE

In the *Figure 5 description of location for the burying of the pipeline*, are reported some important features for a construction of a pipeline: the presence of a bedding made of small particle to avoid indentation by rocks during the lowering-in, the trench, the backfilling with the soil, the presence of a safety burial depth that depends on the place.

1.1.7 Filling of the line with water

In order to perform hydro test, the line is flooded with water: the process is made using a pig and it has to be controlled in order to maintain the velocity of the pig within a specified range (usually around 0,2 m/s ÷ 1,6 m/s, depending on the internal diameter of the pipeline), avoiding damages to the pipeline due to impact. The filling must be done with a specific procedure in order to avoid the entrance of air in the section that would both require greater amount of water to reach the desired pressure and it would lead to misrepresenting values: it's for this reason that the procedure involves the use of pigs propelled by the filling medium, and pigs are launched and received in pig traps in a way that during the motion of the pig water is already present both ahead and on the rear of it. (see *Appendix C*). Depending on the location, the water used in hydrostatic test is drawn from a local river, lake, tank or taken from municipal supply through specific agreement with those responsible for it.

1.1.8 Hydrotest

After the installation of the pipeline and the welding of the main parts, the line needs to be tested to verify its effective capability to work at the predicted pressure in safety conditions. To perform this kind of check the line, now filled with a fluid (water or air), is pressurized for a certain number of hours in order to assess the presence of leaks, verify the effective resistance of the pipe under pressure and reduce residual stresses present in the material. Those defects that can be assessed with hydrotest are mainly present due to negligence during construction (detection not effective), fabrication defects (due to the firm that produced the tube: usually tubes are already tested in the firm that has produced them, but the pressures applied and the holding time are very low!), laying defects (due to impacts of the pipe with rocks or mechanical equipment). If leaks are found they will be found and repaired and the line will be tested again.

1.2 Precommissioning

Pipeline Pre-commissioning is the set of phases that aims to guarantee the ability of a pipeline and piping systems to contain product without leaking. This product may be liquid, gaseous or multiphase hydrocarbons, water, steam, CO_2, N_2, petrol, aviation fuel etc.
This series of processes is carried out on the pipeline before the introduction of the fuel: they comprise all activities from the emptying after the hydro test until the inertization.
The planning of such operations involves a number of analyses that can be undertaken to determine the duration to perform each of these tasks. Different meanings of Pre-commissioning are available in the industry: in the following chapter some of the main interpretations will be presented; however, we are going to intend it as the phase in the pipeline industries that includes dewatering, cleaning, drying and preservation of the pipeline (Shell, 1994): as according to the Shell definition, hydrostatic test is not included in Pre-commissioning.
Main mechanical equipment necessary to perform Pre-commissioning are pigs and pig traps (see *Appendix C - Pigs and related devices*) capable to safely launch and receive pigs with no interruption of the flow. Pigs are used, see *Figure 80 pig with set of sealing disks and guide disks* and *Figure 81 pig during transport*: sealing disks are more flexible and larger than guide disk due to their duty of providing an effective seal with the pipe internal wall avoiding flow passage between the front and the rear of the pig and also a scraping action for cleaning purposes. The guiding discs instead provide mechanical support to the pig.

1.2.1 Dewatering

Once the line has been successfully tested, it can be emptied: bulk dewatering is the removal of water which has been used for hydro test; generally, the dewatering has to be performed in a controlled way using of pigs, compressors and opening or closure of valves, without letting the water to flow out by gravity. If the water was taken from a lake or a river it will be stored for enough time in a settling tank after dewatering and when particles are settled, and the purity of water returns to a satisfactory values, it can be poured again in the lake/river.

1.2.2 Swabbing

This phase consists in the passage of foam pig to absorb and spread the residual water left on internal surface of the pipe wall.

1.2.3 Passage of Caliper pig

The passage of a special tool, called geometry pig, has the scope to identify within the internal wall of a pipeline the possible presence of indentations, gouges, ovalizations, change in diameters. The tool is a device that runs along the pipe propelled by air and by means of scrapers or radial feelers it detects and record on a memory all deviations from the standard diameter.

1.2.4 Drying

Due to the incomplete effectiveness of the swabbing phase, drying with compressed dry air is performed to strip out residual water molecules still present on the internal surface, reaching a good condition of internal environment to avoid: risks of corrosion, subsequent dangerous hydrate formation and contamination of the product that is going to run in the pipeline.

1.2.5 Inerting

Prior to complete the project, the line has to be closed with a safe environment inside, especially in case the product that will be distributed with the pipeline is methane or similar: that means the maintaining of an atmosphere within the pipe with no risk of corrosion, flammability or hydrate formation; oxygen is indeed substituted with nitrogen ensuring that the pipe is not filled with a flammable atmosphere.

1.3 Commissioning

After the Pre-commissioning, the line is ready for the introduction of the fuel (*gassing-up*) and the pressurization *(packing*) of the line up to the predetermined pressure.
In the following figure is reported a schematic representation of the steps in sequence; the blue zone is the main topic of this thesis.

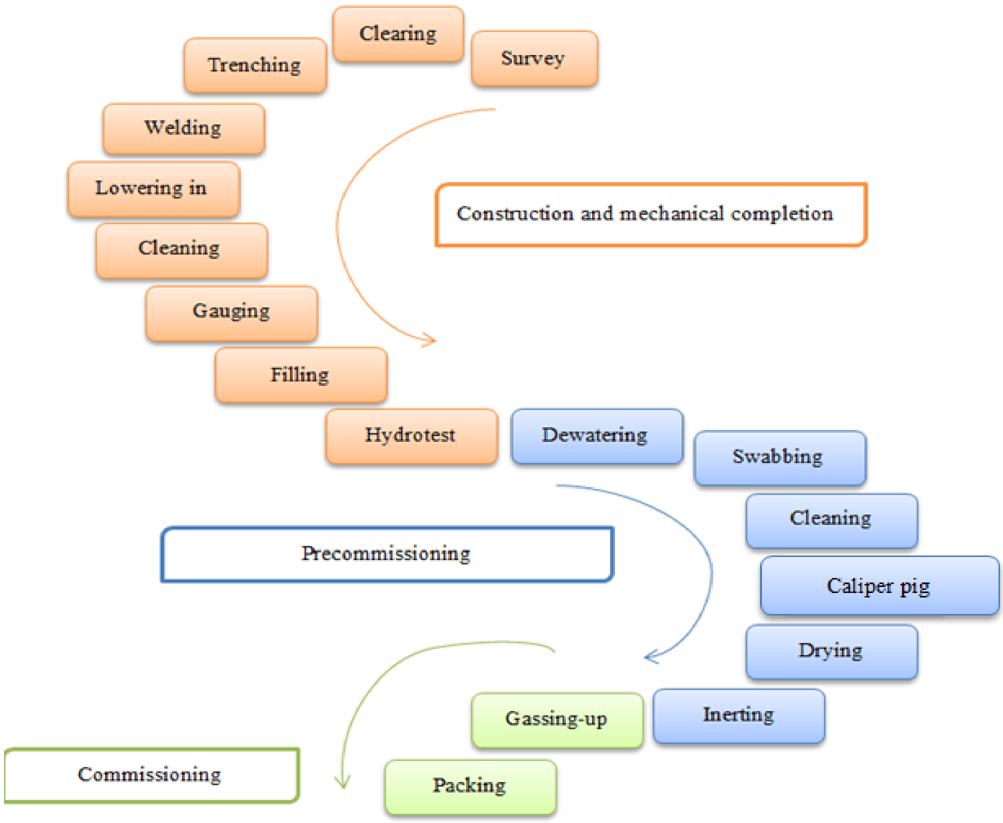

FIGURE 6 SCHEMATIC REPRESENTATION OF ALL STEPS IN THE CONSTRUCTION OF A PIPELINE

2 Scotland GB-022 project

The project consists in the construction of a 50 km (approximately) welded steel gas pipeline and of two new Block Valves (BV's) in the southwest of Scotland. In 2002 the authorization for the construction of a new pipeline between *Beattock* and *Brighouse*, *Dumfries* in Scotland was granted: phase 1 of the project was constructed in those years, which included 29,6 km pipeline (blue line). It's now time for phase 2 of the project consisting of the remaining 50 km of the pipeline including a re-route, between *Cluden* and *Lochfoot* (7,2 km). In *Figure 7 southwest Scotland pipeline: 50 km line between Cluden and Lochfoot* the pipeline route is highlighted in red .

FIGURE 7 SOUTHWEST SCOTLAND PIPELINE: 50 KM LINE BETWEEN CLUDEN AND LOCHFOOT

- The pipeline route originates at *Cluden Block Valve* near *Holywood* (northwest of *Dumfries*) and runs generally in a southwesterly direction keeping south of *Castle Douglas* and north of *Kirkcudbright*.
- The pipeline terminates at *Brighouse Bay Compressor Station*
- The nominal diameter is 900 mm
- The wall thickness is 14.27 mm and 19.1 mm depending on the locations.
- The *design pressure* is 90.1 bar.
- The depth will generally be approximately 1.2 meters below subsoil level to the top of the pipe, but it will be deeper at some locations including road, river, ditch crossings and for crossings of existing services and at other locations.
- The nominal working width shall be between 36 m and 42 m.

The pipeline is routed through farmland and crosses 32 roads which includes a primary trunk road, the A75(T) which links *Gretna / Dumfries* with *Stranrae*r and the ferry ports at *Cairnryan*. In *Table 1 road crossings with related crossing methods* they are all listed and the choice of the methodology to deal with them, the normal open cut or the tunneling without trenching (see *1.1.3*) is also shown. The road crossing numbers commence at RDX 20 as the Project is a continuation of the *Beattock* to *Cluden* pipeline which was constructed in 2002. Due to a re-route RDX 27 does not exist.

Crossing Id	Road Name or Number	Crossing Method
RDX 20	B729	Trenchless
RDX 21	C112n	Trenchless
RDX 22	C14n	Trenchless
RDX 23	U232n	Open cut
RDX 24	U232n	Open cut
RDX 25	C56n	Open cut
RDX 26	A75T	Trenchless
RDX 28	C1s	Trenchless
RDX 29	Private Road	Open cut
RDX 30	C5s	Trenchless
RDX 31	U124s	Trenchless
RDX 32	C33s	Open cut
RDX 33	B794	Trenchless
RDX 34	U99s	Open cut
RDX 35	U97s	Open cut
RDX 36	A745	Trenchless
RDX 37	C38s	Open cut
RDX 38	B736	Trenchless
RDX 39	C15s	Open cut
RDX 40	U55s	Trenchless
RDX 41	U57s	Open cut
RDX 42	C2s	Trenchless
RDX 43	A711	Trenchless
RDX 44	U43s	Open cut
RDX 45	A762	Trenchless
RDX 46	U31s	Open cut
RDX 47	C4s	Open cut
RDX 48	U32s	Trenchless
RDX 49	A755	Trenchless
RDX 50	C32s	Open cut
RDX 51	B727	Trenchless
RDX 52	U42s	Trenchless
TTX01	BHB Access road	Trenchless

TABLE 1 ROAD CROSSINGS WITH RELATED CROSSING METHODS

The Block Valves are located at *Cluden* (existing), *Culmain* (BV7) and *Arkland* (BV8). The Sites at BV7 and BV8 have been fenced off after some preparatory landscaping was carried out in 2002.
Utility crossing are listed below:

- GNI (UK) – IC 1 – Crossing of existing Ireland Interconnector at 3 locations
- SGN – Crossing of existing pipelines at various locations including a number located at road crossing
- Scottish Water – Crossing water services and working within 2 km of existing aquifer
- HV and LV power lines – buried and overhead, numerous crossing and parallel sections

Major river crossing are:

- RVX 4 – *Cluden Water*
- RDX 5 – *Urr Water*
- RVX 6 – *River Dee*

Steepest slope locations are the following:

- Section 22 (approximately KP 3 - 3+500)
- Collachan Bank (RDX 23 –ve)
- RDX 33 –ve
- RDX 43 +ve & -ve sides

In order to make a big installation like a pipeline more manageable for calculation, it has been divided in different parts:

- *sections* are those parts of the line each one with its own (consistent) length that usually comes from the partition used for hydrostatic test
- *segment* is a discretization of the whole line in small pieces all with the same length, that in our calculations is usually equal to an horizontally projected length of 10 m.

Altimetric profiles of all pipeline sections are attached.

3 Bulk Dewatering with compressed air

The first phase of Pre-commissioning is the removal of as much water as possible after the successful completion of hydrostatic test and before the drying.
Dewatering is achieved by propelling a train of pigs with air or nitrogen as propellant to displace the water present in the pipeline (see *Figure 8 bulk dewatering: removal of water using pigs propelled by air)*: as a general rule of thumb it's forbidden the emptying of the line only by gravity (the uncontrolled emptying leads to stresses on the steel). The distance between pigs is critical: if the distance is too short a pig may collide with the pig in front of it. (Halliburton, 1997)
The efficiency of dewatering determines the time required to dry the pipeline: it's indeed easier and less expensive to remove water during dewatering than it is to remove it by any of the drying techniques. (Halliburton, 1997).

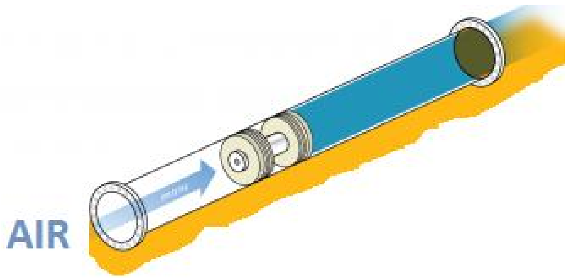

FIGURE 8 BULK DEWATERING: REMOVAL OF WATER USING PIGS PROPELLED BY AIR

Pigs used in dewatering (see *Figure 80 pig with set of sealing disks and guide disks* and *Figure 81 pig during transport*) are run in front of the air column evacuating water from the pipeline that is released at the receiver. The most important characteristic required for a pig that is pushed through the pipeline using compressed air is the ability to maintain an effective seal against the pipe wall in order to minimize leakage and possible mixture between the displaced water and the displacing air. Care must be taken in the dewatering operation to make sure that no air is introduced into the test section, thus minimizing the possibility of air locks. An air lock is probably the most severe problem involved in dewatering. Air locks are caused by air accumulating into the uphill leg that creates a manometer in the pipeline: extremely high pressures may be required to overcome the manometer, it may also be necessary to tap the line and vent air at the high points (McAllister, 2005).

3.1 Documents and technical specifications related to Scotland project

3.1.1 Scope of work (Gas Network Ireland, 2016)

Dewatering of the Pipeline shall be carried out using suitable pigs propelled by air. Sufficient runs of the swabbing pigs shall be carried out to ensure that the pipeline is sufficiently dry to commence drying operations. All pig runs shall be carried out with sufficient back pressure to prevent excessive pig speeds in the pipeline.

3.1.2 IS328 CODE OF PRACTICE FOR GAS TRANSMISSION PIPELINES AND PIPELINE INSTALLATONS 2003 (National Standards Authority of Ireland, 2003)

Before purging and gassing up a pipeline as much residual water as possible shall be removed by repeatedly running a suitable swabbing pig. A considerable amount of water may still remain however on the wall of the pipe and it can be estimated with the following expression:

Residual water (litres / km) = 0,37 x the internal diameter of the pipeline in mm.

3.2 Equipment

The required equipment for the bulk dewatering is:

- **Air motor-compressor** to push the sealing pig in order to displace water; air is usually the most used propellant. In *Figure 84 air compressor: ATLAS COPCO, 20 bar. Free Air Delivery 23,5 m3/ min* is represented a diesel-engine compressor with an intake of air at atmospheric pressure equal to 23,5 m^3/min (~ 396 l/s): it can reach operating pressure of 20 bar.
- **Pig**: the pig in *Figure 80 pig with set of sealing disks and guide disks* has to provide an effective seal between the air and the displaced water (Pipeline Engineering & Supply Co. Ltd, 1999). Foam pigs may also be used in order to absorb some moisture.
- **Settling tank (sedimentation pond):** after the removal of the water used for hydrotest from the pipeline, it is sent to a settling tank in order to restore its initial condition prior to pour it back in the river or sea from which it was pumped: in the sedimentation tank water is stored for enough time in order to let heavier particles (debris or metal particles) to settle down. It's characterized by its three dimensions and their product (volume).
- **Test heads:** For the purpose of dewatering of the line (but already used for water filling), test heads are used to optimize the processes:
  1) Test heads are welded to pipeline sections at both edges and with bypass connections the water filling of all section can be performed continuously, being them all connected. Here below are shown two test heads and their configuration during filling.

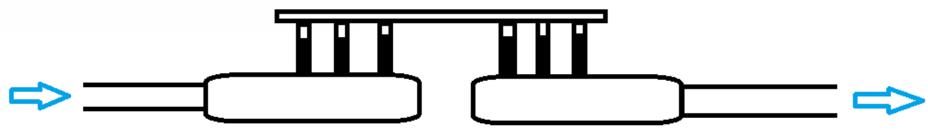

FIGURE 9 BYPASS CONFIGURATION FOR WATER FILLING

  2) After Filling the line, all valves are closed thus all sections are hydraulically separated and each section will be in turn pressurized: bypass cannot be submitted to test pressure due to their different admissible pressurization level.

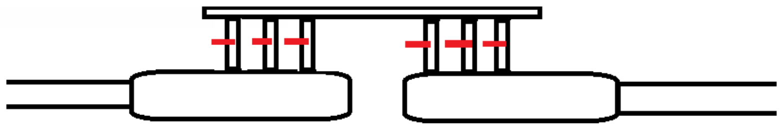

FIGURE 10 CLOSED CONFIGURATION DURING PRESSURIZATION

  3) After the pressurization, bypass is still used for the emptying of the line if in accordance with the designed passage of pigs;
  4) At the end all heads are cut.

  Pictures of test heads are attached, see *Figure 96 test heads for hydrotest* and *Figure 97 test heads.*

3.3 Calculation method and discussion of results

Basic linear laws of hydraulics have been used in order to evaluate the time required to entirely dewater the pipeline by means of pigs: the approach consists in the calculation of the required pressure to move the pig, and from it the evaluation of the rate by means of the gas law (air is used to propel the pig) and thus the time.

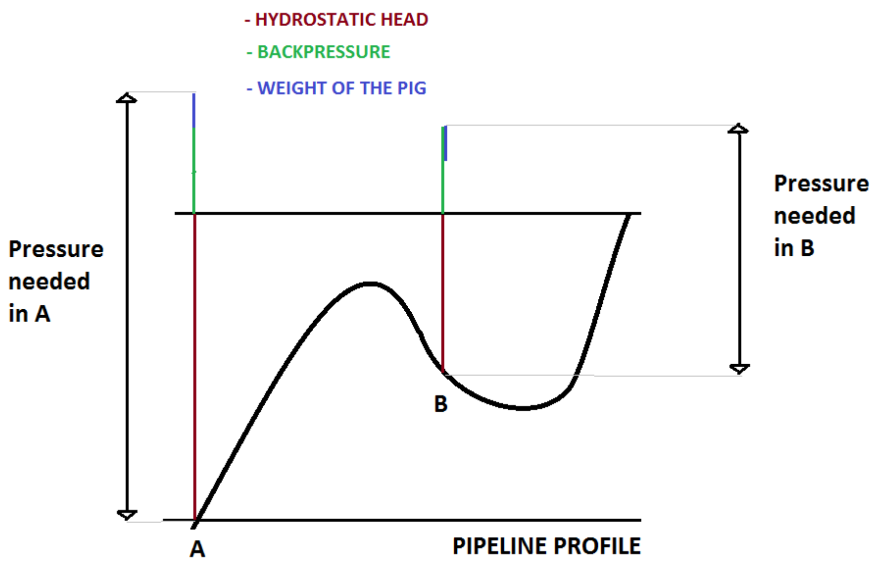

FIGURE 11 EVALUATION OF PRESSURE FOR DEWATERING

As shown in the illustrative figure, the parameters considered to calculate the pressure are:

- Hydrostatic head
- Backpressure ensured to control the pig motion
- Weight of the pig (positive or negative according to the slope of the point)

Two methods have been adopted to relate the required pressure with the pressure at compressor: the first method simply put them equal, in the second method instead the pressure at compressor comes out from an equation of weighted average pressures. With pressure at compressor is then possible to estimate the time value for the dewatering of each section, summarized below in *Table 2 time output for dewatering; comparison of two calculation methods*

Section	Length	Flow rate	Time (1^ method)	Time (2^ method)
	km	m^3 / h	hours	hours
1	*4,17*	*3060*	*9,3*	*8,7*
2	11,56	3060	10,2	10,3
3	5,44	1530	6,7	7,3
4	11,61	3060	9,7	11,7
5	17,14	3060	22,4	25,8

TABLE 2 TIME OUTPUT FOR DEWATERING; COMPARISON OF TWO CALCULATION METHODS

The whole explanation and computation of result can be found in *11.1* .

4 The theory behind residual dewatering of a surface

The drying of a pipeline relies on both the absorption of water by pig during drying and on the mass transfer of water vapour due to a difference in the concentration between the injected air and the air in the pipe. When a system contains two or more species (components) whose concentrations vary from point to point there is a natural tendency for mass to be transferred to minimize the concentration difference within the system. The mechanism of mass transfer can be classified in three categories:

- *Diffusion*: result of a concentration gradient, governed by the mass diffusion coefficient D
- *Convection*: mass transfer between a surface and a moving fluid. Fluid motion enhances mass transfer considerably by removing the high-concentration fluid near the surface and replacing it by the lower concentration fluid further away.
- *Change of phase*: combination of diffusion and convection (what occurs in the pipe)

The physical laws that govern the transport of mass, energy, and momentum, as well as that of electricity, are based on the notion that the flow of these entities is induced by a driving potential. This driving force can be expressed in two ways (Basmadjian, 2005):

- *the gradient or derivative* of that potential in the direction of flow (Diffusion *Fick's Law*, Conduction *Fourier's Law*, ..)
- the gradient is taken to be constant: the driving force then becomes simply the *difference in potential* over the distance covered (electricity *Ohm's Law*, Convective mass transfer, Convective heat transfer..).

Convective mass transfer is the transfer of mass between a surface and a moving fluid due to both mass diffusion and bulk fluid motion (Cengel, 2002). Mass convection is complicated because of the complications associated with fluid flow such as the surface geometry, flow regime, flow velocity, and the variation of the fluid properties and composition. Therefore, we will have to rely on experimental relations to determine mass transfer. Also, mass convection is usually analysed on a mass basis rather than on a molar basis. Consider the flow of air over the free surface of a water body such as thin film in the pipe under isothermal conditions: if the air is not saturated, the concentration of water vapour will vary from a maximum at the water surface where the air is always saturated to the free steam value far from the surface: in mass convection, we define the region of the fluid in which concentration gradients exist as the concentration boundary layer.

4.1 Where: the boundary layer

Mass transfer in the pipe takes place initially through a *boundary layer*, which is located immediately adjacent to the interface between water and air and it's saturated with water molecules. Transfer through this region (also known as an *"unstirred layer*") is relatively slow and constitutes the preponderant portion of the resistance to mass transport (Basmadjian, 2005). This layer is followed by a *transition zone* where the flow gradually changes to the turbulent conditions prevailing in the bulk of the air that is flowing in the pipe.

Considering a cross-section of the pipe, the concentration trend along the radius cannot be easily quantified, that's why is usually postulated the existence of an equivalent linear concentration profile that extends from the boundary above the water till the bulk of the flowing fluid. This postulate is enshrined in the concept known as *film theory.* Basically, we are supposing not a continuous change in concentration over distance (radial) but a defined separation between the two regions at different concentrations.

In the *Figure 12 concentration of water vapour at the film layer: the real radial variation of concentration is curved and continuous, however according to the film theory it is discretized in a linear part and a constant part* and *Figure 13 water partial pressure at the film layer: the real radial variation is curved and continuous, however according to the film theory it is discretized in a linear part and a constant part* below is depicted the concept of the film of water that has vaporized from a water layer on a solid surface and that is in contact with a gaseous stream.

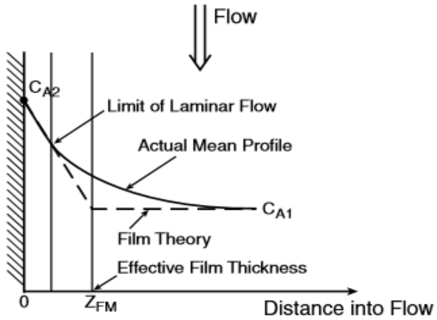

FIGURE 12 CONCENTRATION OF WATER VAPOUR AT THE FILM LAYER: THE REAL RADIAL VARIATION OF CONCENTRATION IS CURVED AND CONTINUOUS, HOWEVER ACCORDING TO THE FILM THEORY IT IS DISCRETIZED IN A LINEAR PART AND A CONSTANT PART

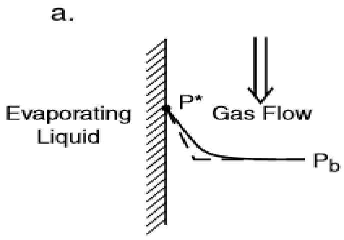

FIGURE 13 WATER PARTIAL PRESSURE AT THE FILM LAYER: THE REAL RADIAL VARIATION IS CURVED AND CONTINUOUS, HOWEVER ACCORDING TO THE FILM THEORY IT IS DISCRETIZED IN A LINEAR PART AND A CONSTANT PART

When molecules in this *film* move in the bulk of the surrounding air driven by a gradient of concentration, other water molecules vaporize from the liquid water replacing those which moved away, keeping constant the pressure at the wall (equal to saturation pressure), until there is no more enough water on surface able to provide a continuous “recharge”.
In the main body of the fluid we see macroscopic packets of fluid or eddies moving rapidly from one position to another, including the direction toward and away from the boundary (Basmadjian, 2005). One notes in addition that with an increase in fluid velocity there is an attendant increase in the degree of turbulence and the eddies are able to penetrate deeper into the transition and boundary layers. The latter consequently diminishes in thickness and the transport rate experiences a corresponding increase in magnitude. Thus, high flow rates mean more turbulence, high Reynolds number and hence more rapid mass transfer. (Basmadjian, 2005)

4.2 Why: the water partial pressure difference

The case we are analysing is the mass transfer of water vapour molecules due to a difference in the humidity (expressed as partial pressure of water in air) between two volumes of air; the amount of humidity can be identified by the measure of dew point: dew point, by definition is the temperature at which water vapour begins to condense out of a gas at atmospheric pressure, the temperature at which the content of vapour saturates the mixture.
Given a gas mixture identified by its percentage of water vapour and dry air, both will exert a pressure that is equal to the partial pressure of the compound and if summed together it will give the total pressure of the mixture. Reducing the surrounding temperature, the water vapour that can be hold in the mixture decreases till, when the dew point is reached, water will condense out of the mixture; increasing the pressure will create a similar effect, reaching at a certain level the condensation of the vapour.

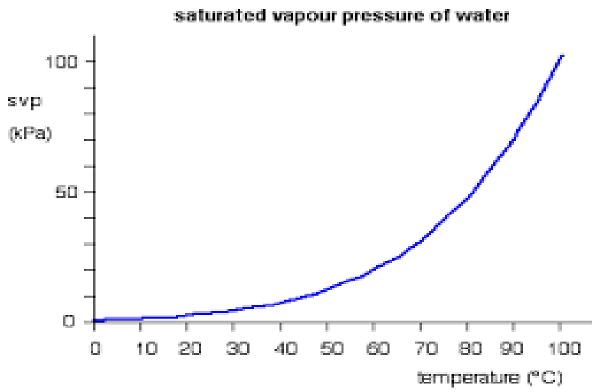

FIGURE 14 SATURATION VAPOUR PRESSURE CHANGE WITH TEMPERATURE. INCREASING TEMPERATURE THE LEVEL OF MOISTURE THAT CAN BE HELD BY WATER ALSO INCREASES

From the *Figure 14 saturation vapour pressure change with temperature. increasing temperature the level of moisture that can be held by water also increases* it's possible to verify the exponential dependence of the saturated vapour pressure of water in air with the temperature.
As in almost all physical phenomenon, even drying require a difference to "naturally" happen: if two kinds of air with different moisture level are put in touch, the difference in the partial pressure of the water between them will create a driving-force that will lead vapour water molecules from the more moisture air to the other one until equilibrium is reached: the more is the difference the greater will be the rate of transfer. This is the phenomena exploited by drying with low dew point air and it simply consists in water absorption from the dry air during the transit of the pipeline.
When air in the pipe is dried according to this phenomenon, the equilibrium of the system water-pipe-air has changed due to a change in relative humidity thus changing the equilibrium moisture content: to reach a new equilibrium-state, a corresponding amount of water has to evaporate from the film on the surface of the wall to counterbalance the water absorbed by the flowing air. This phenomena of absorption and evaporation will continue until almost all the water in the pipe has vaporized: the time efficiency of this motion will depend on the length, the temperature of the pipeline, the difference between the two dew points, the flow rate of dry air and the water film thickness.

4.3 When: the time required

The residual water present after dewatering can be imagined as a thin water film adhering on the internal surface: this film is said to be in *equilibrium* with the surrounding environment (interaction with air and solid surface) if the tendency of the molecules of the water film to escape and vaporize is counterbalanced by the molecules of water vapour in the air (humidity) that collide within the film and by the capillarity suction exerted by the solid surface. The amount of moisture corresponding to an equilibrium state is called "*equilibrium moisture content*" if referred to water in the bulk of a solid (or "*surface moisture at equilibrium*" if, as in our case, is about the quantity of moisture laying on a material surface).
It depends on:

- Temperature of the environment
- Water vapour pressure (relative humidity, dew point temperature)
- Type of substrate (material, wettability, roughness..)

If a hygroscopic material is maintained in contact with air at constant temperature and humidity it will reach equilibrium and the material will attain a definite moisture content; as the relative humidity increases, represented in *Figure 15 saturation curve at a solid surface: reducing the external humidity the equilibrium is broken and water escape from the solid. main regions are highlighted*, more layers will adhere on the surface (the moisture range involved represents the level of moisture of a surface that depends on the relative humidity of air): the first few layers are more strongly attached , until in C, as depicted in the figure below, the layers grow to such a size that they begin to interact and interconnect and the surface tension of water causes meniscuses to form within the smallest pores. This is the capillary regime (Straube, 2006) and it starts at the critical moisture content *Wcr* where it is presumed that a continuous liquid phase forms : this water comes from *capillary condensation* that is the process by which a surface adsorb the vapour into its porous surface even though the air is not at the the saturation vapour pressure, Psat, of the pure liquid (it's the water adsorbed by *capillary suction*). Finally, increasing the water adsorbed, the supersaturated state may happen when relative humidity is always 100% and no more water will wick into a material because external forces (like gravity and air) must force it in (region E) (Straube, 2006).

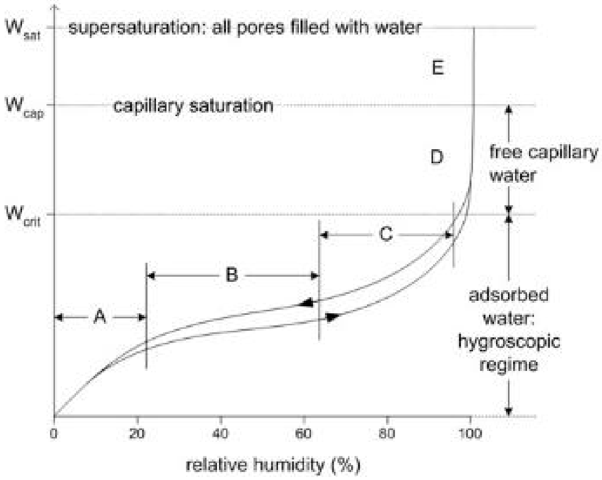

FIGURE 15 SATURATION CURVE AT A SOLID SURFACE: REDUCING THE EXTERNAL HUMIDITY THE EQUILIBRIUM IS BROKEN AND WATER ESCAPE FROM THE SOLID. MAIN REGIONS ARE HIGHLIGHTED

According to this explanation of the moisture level on solid surface it's now necessary to analyse how this reflects on the swabbing and drying phase. When a solid is dried, the drying rate is subjected to variation with time: it means that moisture content decreases over time during the drying with different trends as depicted in *Figure 16 moisture content and drying rate changes over time. moisture content decrease steadily till point C (constant drying rate) then the drying progressively reduces (decreasing drying rate).*

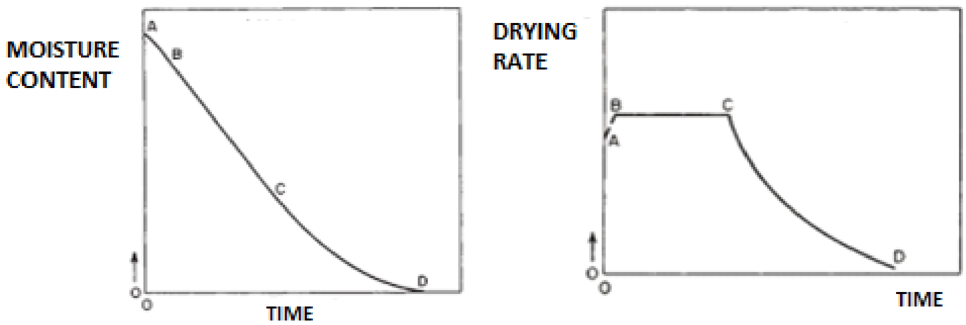

FIGURE 16 MOISTURE CONTENT AND DRYING RATE CHANGES OVER TIME. MOISTURE CONTENT DECREASE STEADILY TILL POINT C (CONSTANT DRYING RATE) THEN THE DRYING PROGRESSIVELY REDUCES (DECREASING DRYING RATE)

The section BC represents the *constant-rate period* of residual dewatering: moisture movement is rapid enough to maintain the saturated layer at the surface, drying proceeds by diffusion of vapour from this saturated layer above water surface to the air of the environment, the moisture content of the pipe surface linearly decrease with time (Moyers & Baldwin, 1999) : the particles of vapour water that escape with air are easily replaced by continuing evaporating water. In C the constant rate ends, and the drying rate begins to fall: C is the point where the critical moisture content *Wcr* is reached, water becomes difficult to be removed due to the attraction to the solid surface (in the interstices, due to capillary attraction), the moisture content of the surface continues to decrease but a slower and slower pace. The CD period is usually divided into two zones: the unsaturated surface drying and the zone where internal moisture movement controls; in the first zone the first layer of air above the water film gradually becomes no more fully saturated and then the point of the evaporation thus moves into the roughness of the solid surface

leading to the second zone where the drying is governed by the internal moisture movement. A lengthy drying period results as the moisture becomes increasingly inaccessible in the region CD (Basmadjian, 2005), BC section corresponds to the swabbing phase of the pipeline, whereas the other is the drying phase, where the slightly dry air of the swabbing and the mechanical absorption of foam pig is no more effective to strip water from surface.
It's useful to relate a given EMC (or SM) with a thickness of the film of water left in the pipeline: when there is a relative humidity lower than 100%, the film is present but formed only by the thickness of some molecules of water, whereas when relative humidity is 100% or there is rain or condensation or water still present (as in our case after the mechanical dewatering), the moisture film is thick enough even to be seen by the naked eye. (Baker, et al., 1990)
In our calculation we fixed a starting value of thickness for the water film prior to swabbing and also fixed the target value of 50 μm (Shell, 1994) as admissible value after swabbing that corresponds to the critical moisture content of our coated pipeline (100 μm is instead for not coated pipes, where greater roughness means tighter curvatures that leads to greater amount of water retention on the pipe wall): the swabbing phase is represented by the constant drying rate period BC and a steady-state model can thus be applied in calculations, with a linearly decrease of moisture in time, period in which water can be (easily) mechanically extracted. CD represents instead the drying phase (that will be explained in the next chapter) tough it starts after the attainment of critical moisture content.

4.4 Assumptions adopted for Swabbing and Drying

Several assumptions have been followed for calculations:

- The air behaves like an ideal gas, that is we can assume that air containing water vapour obeys all the laws of ideal gas
- Wall temperature is assumed to be equal to the ambient temperature
- Film thickness on the pipeline wall is assumed to be spatially uniform
- Kinetic energy and gravity are neglected

The following chapters will present an explanation of the swabbing phase and the drying phase with calculations related to the Scotland project. An additional chapter has been added to theoretically deal with the other type of drying that is Vacuum drying, not performed on Scotland pipeline project.

5 Swabbing

After the successful dewatering, all sections of the line are tied-in using approved welding procedures with 100% radiography, 100% ultrasonic inspection and magnetic particle inspection (*Golden Welds*).

The swabbing phase is performed with the aim of reducing the level of residual water left in the pipeline prior to drying and it couples the vantages of using foam pig with air to reduce the residual water left in the pipeline:

- Foam pigs propelled by air, are light devices made of polyurethane foam that absorb in their bulk the water left in the pipeline, remove pools of water at low points and spread the residual moisture all along the internal surfaces during their passage, thus increasing the exposed area for evaporation. It's common practice to consider their absorption capacity between 75% and 85 % of their volume.
- Compressed air with a dew point slightly lower than the dew point present in the line enhances the moisture transfer away from the internal surface.

Foam pigs become saturated quite soon, that's why many of them, according to what is required in technical specifications, will usually be run until it appears that the swabs are not effectively removing any remaining water because they look dry.
An usual method to identify the amount of water absorbed by the foam pig relies on the wet frontal thickness (expressed as % of the pig volume) of the pig at the outlet of the line: common practice is to stop swabbing when the wet thickness of the pig is < 2 cm.

5.1 Documents and technical specifications

5.1.1 Scope of work (Gas Network Ireland, 2016)

Dewatering of the pipeline shall be carried out using suitable air propelled swabbing pigs. Sufficient runs of the swabbing pigs shall be carried out to ensure that the pipeline is sufficiently dry to commence drying operations. All pig runs shall be carried out with sufficient back pressure to prevent excessive pig speeds in the pipeline. The Contractor shall be responsible for pigging, swabbing and gauging of the pipe line both before and following testing.

5.1.2 General pipelining specification - AO/SP/007 (Gas Networks Ireland, 2015)

Contractor shall pass swabbing pigs through the entire pipeline until the Engineer is satisfied that all water has been removed. Finally, the Contractor shall pass a gauging pig fitted with an aluminum sizing plate through the entire length of the pipeline. The Contractor shall demonstrate to the satisfaction of the Engineer that the sizing plate is undamaged when the gauging pig emerges at the receiving end. The diameter of the sizing plate shall be in accordance with IS 328

5.1.3 Steel pipeline for high gas pressure transmission (The Institution of Gas ENgineers, 2001)

The number of swabbing pigs that run in the pipeline depends on the internal roughness and on the length of the pipeline:

- Coated: 0,5 pigs / km
- Uncoated: 1,3 – 1 pigs / km

5.1.4 Code of Practice for Gas Transmission Pipelines and Pipeline Installations (National Standards Authority of Ireland, 2003)

Sufficient runs of the swabbing pigs should be carried out to ensure that the pipeline is clear of water. During the course of the final swabbing run, a suitable pressure recorder should be used to record continuously the pressure required to propel the pig. Before purging and gassing up a pipeline as much residual water as possible shall be removed by repeatedly running a suitable swabbing pig. A considerable amount of water may still remain however on the wall of the pipe, an estimate of the amount is given by the following expression:

$$Residual\ water\left(\frac{litres}{km}\right) = 0{,}37\ times\ the\ internal\ diameter\ of\ the\ pipeline\ (mm).$$

5.2 Equipment

- **Foam pigs**: light pig made of polyurethane foam, highly flexible; in order to remove water, a series of pig are propelled by compressed air through the pipeline; the most important characteristic is the ability to provide an effective seal (Pipeline Engineering & Supply Co. Ltd, 1999). Foam pigs are usually involved in the procedure in order to absorb some moisture and spread it along the wall internal surfaces.
  Foam pig can have different density (Pipeline Engineering & Supply Co. Ltd, 1999) according to the purpose and specific situation in which it will be used:
  - Soft: 2 lb/ft^3 ˜ 30 kg/m^3
  - Medium: 5 lb/ft^3 ~ 80 kg/m^3
  - Hard: 8 lb/ft^3 ~ 130 kg/m^3
- **Compressor** with after cooler
- **Dew point meter**: for swabbing is usually used a hygrometer without strict requirements on its sensitivity (differently from the dew point meter tool used for drying, that will be described in that chapter).

5.3 Calculation methods and discussion of result

According to what explained in the chapter related to mechanism behind drying, the rate when moisture is above the critical moisture content should be constant over time, and the moisture content should decrease linearly. With the approaches adopted this is what it is supposed to happen: the properties of the system are time invariant (constant rate), but they vary with distance in the direction of flow: the system is said to be at *steady state* and distributed in one spatial coordinate (the profile of the pipeline).
Two methods have been used to calculate the parameters for swabbing:

- with the first approach a simple mass balance has been applied on the overall pipeline considering the amount of water that air can take up during its passage

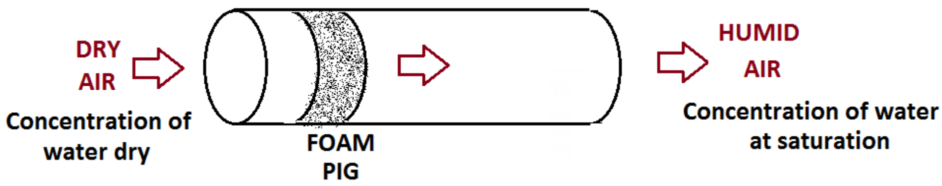

FIGURE 17 REPRESENTATIVE IMAGE OF THE SWABBING PROCESS

$$mass\ of\ water\ removable = (\ C\ water_{saturated\ air} - \ C\ water_{dry\ air}\ ) * Vair$$

To this mass of removable water, we must add the water absorbed by foam pigs; then, by knowing flow rate, mass of water that needs to be removed and volume of air it's possible to calculate the time required. The methods is presented in chapter *11.2.3,* and it's linearly dependent on time, that means the rate is constant over time because we assume that during swabbing we always work with a pipeline with a moisture content that is greater than the critical one.

- in the second method the mass balance has been done *differentially*; the concept is the same as for a large mass balance, but it is taken over an incremental space element, dx, dr, or dV. The mass balance equation is then divided by these quantities and implemented with a mass transfer law. We speak in this case of a "difference" or "differential" balance, or alternatively of a "microscopic" or "shell" balance. For the purpose of the application of mass transfer laws, additional parameters related to mass transfer phenomena were computed (for instance *Sherwood number, Schmidt number*..).
  Due to the complexity of the subject, its analysis is left in chapter *11.2.4*
  Such balances arise whenever a variable such as concentration undergoes changes in space, as in our case. They occur in all systems that fall in the category of the device we termed a *1-D pipe*, schematized in *Figure 18 1-D pipe*. When the system does not vary with time, i.e., is at *steady state*, we obtain an ODE (ordinary differential equation).

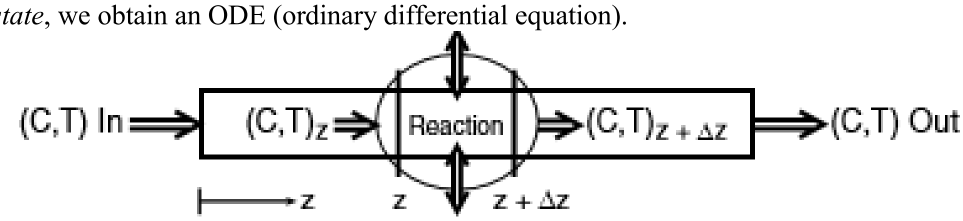

FIGURE 18 1-D PIPE

The two methods provide as expected exactly the same results: with a number of pig equal to 7, that corresponds to a time of nearly **55 hours**, a successful swabbing of the line is ensured.
This output is a good result that confirms the correspondence between a simple mass balance equation and a calculation process that involves several empirical coefficient and numbers; the second method is more comprehensive: it includes a representation of the swabbing phenomena in the space, that is how the rate varies along the pipeline profile.
Furthermore, an additional evidence of the reliability of the result obtained comes from the past experience in shipyard: after dewatering 36 inches of diameter, 80 km long pipeline, 2 foam pigs passed and came out of it fully wet, then other 15 pigs are passed in a coated pipe propelled by slightly dry air to achieve the desired dew point prior to drying. Comparing this data with our pipeline (same diameter, almost half-length), the result of half of the pig used results to be reasonable.

6 Cleaning

Cleaning of the pipe is performed to at different stages of the pipeline construction:

- Post installation, before tie-in operation
- In Pre-commissioning
- Prior to commissioning

This step means the cleaning of the pipe during the Pre-commissioning and it's usually not necessary but sometimes it's specifically required by the client. The reasons to remove impurities is because they can damage the valves, retain water and increase the resistance to flow of the product

6.1 Documents and technical specifications

6.1.1 Steel pipeline for high gas pressure transmission (The Institution of Gas ENgineers, 2001)

Remove pipeline debris from the pipeline using a "cleaning pig". Magnets may be fitted to the cleaning pig in order to remove ferrous material (see *Figure 86 brush pig: sealing and guiding discs are shown, together with a set of metallic brush all around the pig central surface*). Repeat the operation until the pipeline is judged to be clean. Depending on the type of cleaning pig, it may be necessary to pass the profile pig through the pipeline prior to the use of the cleaning pig.

6.2 Equipment

Cleaning is performed with passage of **special pigs** (see *Figure 85 detail of nylon brushes in a pig, Figure 86 brush pig,* and *Figure 87 detail on metallic brush*) propelled by air in order to remove debris, rust and mill scale. Special fittings are attached to pig: pig with nylon brushes is adopted if the internal surface of the pipe is coated, or in metal if not; magnet boxes can be found in pigs used for tracking or cleaning of ferrous debris inside the pipeline whereas foam pig is also applicable for swabbing if the unwanted substance can be removed by absorption (Pipeline Engineering & Supply Co. Ltd, 1999).
No rule exists for calculating a safe distance between pigs: as a guideline allow 1% of the pipeline length between pigs to ensure that the pigs won't collide. For short pipeline keep it more than 200 m. (Halliburton, 1997)

7 Gauging with Geometry Pig (Caliper)

The laying of the line, the backfilling and the pressurization are phases in which the steel of the pipe may be deformed: sharp rocks or roots may have indented it, the lowering machine may have hit the pipe during the installation, rocks in the backfilling soil may have caused deformations, during transport and installation the pipe may shows grooving…
The deformation of the pipe can then cause an immediate or delayed failure due to a loss in strength, leading to possible failure and subsequent damage to people and environment: the presence of this risk makes necessary the inspection of the line prior to start the drying: this can be performed with different aims and different tools.

7.1 Classification of defects

Main damages to the pipeline can be classified according to two main categories, *geometry damage* and *metal loss*.

- Geometry damage:
    - *Depression*: a depression in the profile of the pipe
        - *Denting:* indentation or distortion of the pipe caused by external force (American Society of Mechanical Engineers, 2003)
            - *Smoothed* (smooth change in the curvature) or *kinked* (abrupt change in the curvature)
            - With or without metal loss (gouge)
            - *Unconstrained* (free to spring back elastically) or *constrained* (i.e. by a rock): unrestrained dents will typically rebound almost completely with the internal pressure of the fluid in the pipe. Restrained dents usually have a fatigue life at least an order of magnitude greater than unrestrained dents. (Baker, 2004)
            - Smooth with no metal loss (*plain dent*) (American Society of Mechanical Engineers, 2003)
            - *Rock dents,* represented in *Figure 19 Rock dent* (usually found in the bottom side due to rock in the soil bed , it's smooth: it's usually better not to remove the object to avoid rerounding) or *impact dents* (dent caused by impact with excavating equipment, with abrupt configuration, usually found in the top half of the pipe; usually rerounding occurs leading to consider this a dangerous dent).

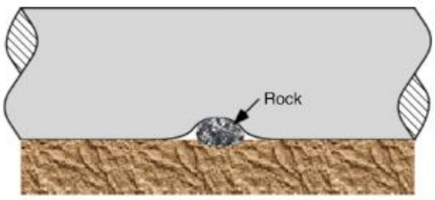

FIGURE 19 ROCK DENT

        - *Buckling*: due to overburden weight during pipelaying

- *Ovality*: flattening of the pipe. Usually not dangerous except if the two radii of curvature are very different. It typically occurs in large diameter, thin wall thickness pipeline due to the weight of the pipe and the overburden, as shown in *Figure 20 ovality due to overburden load*; it could even cause disbonding of the external coating

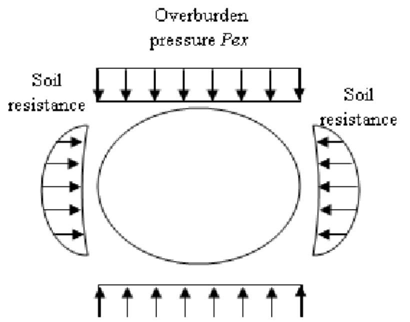

FIGURE 20 OVALITY DUE TO OVERBURDEN LOAD

  - First method *(out of roundness)*

$$\%\ ovality = \frac{Dmax - Dmin}{Dn} * 100$$

  - Second method (the one adopted in Scotland)

$$\%\ ovality = 2 * \frac{Dmax - Dmin}{Dmax + Dmin} * 100$$

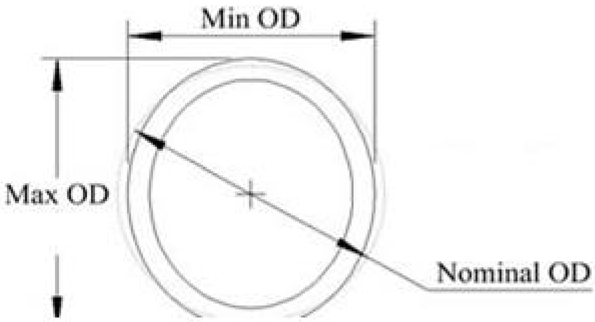

FIGURE 21 REPRESENTATION OF OVALITY

- Metal loss damages:
  - *Gouge*: metal loss defect due to impact: reduction in thickness of the pipe
    - Grooving
    - Slotting
    - Hole
  - *Corrosion* (see
  - *Appendix D - Corrosion of steel,* Rusting process): on seamed or welded pipe, the high failure rate and vulnerability is well-known by specialists nowadays. Today, it is not common to find seamless pipe installed because seamed is cheaper, but its drawback is the high vulnerability to corrosion at the seam due to many causes, such as incomplete seam, that may become a favourable location for rust and microorganisms to establish and promote corrosion of the steel, often leading to *pinhole failure*. Another threat is the difference in electrical potential between the pipe and weld filler. Last example, the lack

of zinc protective coating at the weld for seamed pipe, initiating a very premature line of galvanic attack. (Anon., 2014)

- Internal corrosion: it usually happens at the pipe bottom
- External corrosion: damage to the coating and cathodic protection

The main difficult data to obtain when assessing corrosion is usually the *expected growth rate*: corrosion is a time dependent failure mechanism

According to the U.S. Department of Transportation's *Pipeline and Hazardous Materials Safety Administration (PHMSA*), excavation damage has accounted for one-fifth of all significant pipeline incidents on transmission pipelines (both onshore and offshore) over the past 20 years (Baker, 2009). On gas distribution systems, excavation damage as accounted for more than 36 percent of all significant pipeline incidents, far greater than any other cause of pipeline failure. Excavation damage was listed as the cause of more than one-third of all serious pipeline incidents (those involving a fatality or injury requiring hospitalization of injured people.) Most excavation damage results in immediate failure of the line; whereas only few incidents in the 1990s resulted from mechanical damage inflicted on the pipeline prior excavation damage. As was evidenced in the famous incidents in Edison, New Jersey, and Bellingham, Washington, unreported mechanical damages can have serious consequences (Baker, 2009) that's why nowadays many efforts are put in detecting them.

7.2 Problems related to mechanical damages

The problem of mechanical damages that still have not caused leaks detected with the hydrostatic test, is that they may cause *delayed pipeline failure* (though the majority of failures occurring at the time of impact). The initial indentation of a pipe leads to generation of tensile stress in the pipe's internal surface and compression of its external surface: the material is said to "*yields"* locally, causing an irreversible strain on both surfaces. (Hopkins & Leis, 2003)

7.2.1 Mechanical damage

A mechanical damage defect can fail as a leak or a rupture. In a *leak*, the full-penetration crack length is similar to that of the initial damage feature, and the release is controlled or limited by the opening size. In a *rupture*, once the initial opening is generated, it grows rapidly along the pipe axis due to crack propagation at one or both edges. (Baker, 2009)

The deformation associated with mechanical damage can overload (up to *Ultimate Tensile Strength*) and significantly affect the properties of the pipe material. When a gouge is formed, the area immediately beneath the indenter is highly deformed and its *crack-initiation* resistance significantly reduced. This type of damage extends into the pipe material to a shallow depth. The deformed layer is usually harder than the base metal and may contain transformed microstructures resulting from rapid heating and cooling during its formation. In addition, the denting process may strain-harden the material away from the location that was hit by the indenter. Strain-hardening or cold work during plastic deformation can increase hardness and decrease toughness, but to a lesser extent than under the indenter.

7.2.2 Unrestrained dents

Failures from dents alone are relatively uncommon: *plain dents* are generally not an immediate threat to pipeline integrity but they can create a longer-term issue due to development of other problems (coating damage, corrosion, hydrogen cracking..)_(Baker, 2004); In case of *restrained* dent, when the indenter is removed and the pipe re-rounds, the external surface experiences residual tension: if the residual tension is severe enough, cracking may initiate. In many cases, cracking may also lead to immediate failure of the pipe during the re-rounding process. (Baker, 2009) It happens indeed that the pressure in the pipe after the removal of the restrain can make the dent spring back, leading to the possibility of failure: this "*rerounding*" is also a cycle dependent behaviour (fatigue for the steel). This is the reason why usually restrained dents have a *fatigue life* (resistance to pressure cycles) 10 times greater than the unrestrained dents: for this reason, excavating rock that caused a dent should be avoided, indeed if left unrestrained, the pipe can begin to flex under cyclic loading much like a diaphragm in a pump (Baker, 2004), except if there are two closely spaced restrained dents (the flattening between them may be susceptible to big pressure cycle and in this case is better to remove it). If we have closely spaced restrained dents, the saddle-shape area between them is actually a unrestrained zone and thus may be susceptible of pressure cycle fatigue though dents themselves are restrained. (Baker, 2004)

7.2.3 Dents with mechanical damage

A dent containing a gouge is a severe form of damage (Penspen Integrity, 2001) : dents with *mechanical damage (metal loss*) result in immediate failure 80% of the time (Rosenfeld, 2001). In the remaining 20% of third-party damage incidents, damage is not sufficiently severe to cause immediate failure, but if it is not repaired, failure may occur later due to an increase in the internal pressure, corrosion of the damaged material or pressure cycle fatigue caused by the cyclically rerounding under internal pressure fluctuation (Baker, 2004) : the presence of gouges on a dent or on weld is very dangerous because it reduces the burst pressure of the material, promote crack initiation and ductile tearing._(Penspen Integrity, 2000). The presence of a gouge on a dent also reduces its fatigue strength because of the additional stress concentration due to the gouge and the possibility of local cracking at the base of the gouge. (Penspen Integrity, 2001)

7.2.4 Economic loss

Another problem related to the presence of dents or deformations is the increased friction when the fluid flows along the pipe due to presence of these ovalities, dents and gouges that leads to economical end energy losses.

7.3 Remaining strength assessment

There are basic equations to evaluate the *remaining strength* (*failure stress*) of a pipe with defect according to the characteristics of the defect (depth, length…): this parameter can be useful to determine whether a damaged pipeline is still safe or not; many empirical methods are available in the literature to assess the remaining strength of pipeline with gouges, dents and gouges, plain dent, corrosion defects…
In this chapter some of them will be described; the main scope of calculating the remaining strength is indeed to build the defect assessment curve from which we can understand whether a defect is acceptable or not. The curve is presented at the end of this sub-chapter.

7.3.1 Remaining strength evaluation and general defect assessment

7.3.1.1 Remaining strength of plain dents

Tests indicate that plain dents do not significantly reduce the burst strength of a pipeline (Bjørnøy, et al., 2000): when pressurized indeed, the dent attempts to move outward, allowing the pipe to regain its original circular shape. (Penspen Integrity, 2000).

7.3.1.2 Remaining strength of kinked dents

There are no published methods for predicting the behaviour of kinked dents; therefore, a kinked dent should always be repaired. (Penspen Integrity, 2003)

7.3.1.3 Remaining strength of metal loss defects (axial gouges)

In ductile line pipe, the failure stress of an axially orientated gouge subject to internal pressure loading can be described and evaluated with the following equation:

- **NG-18 equation:** for axially oriented gouges (Kiefner, et al., 1973)

$$\sigma_{hoop} = 1{,}15\ \sigma_y * \frac{1 - \frac{depth}{t}}{1 - \left(\frac{depth}{t} * M^{-1}\right)}$$

$$where\ M = \sqrt{1 + 0{,}26\ (\frac{2\ c}{r\ t})^2} \qquad or \qquad M = \sqrt{1 + 0{,}40\ (\frac{2\ c}{r\ t})^2}$$

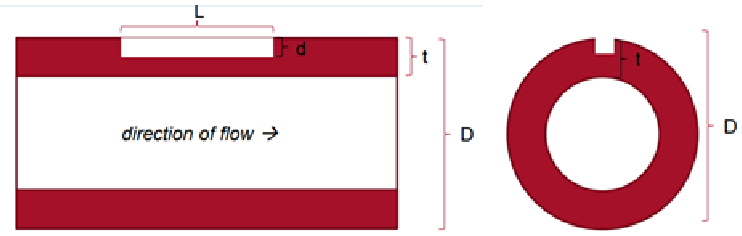

FIGURE 22 ELEMNTS OF THE PIPE TO BE INSERTED IN THE FORMULA FOR THE CALCULATION OF DEFECTS

Where r is the radius and c is *half maximum axial length of defect*. The first formulation of M is an approximation of the one that appears in B31 G modified and RSTRENG , the second one appears in ASME B 31 G (American Society of Mechanical Engineers, s.d.) and it's the most conservative. $1{,}15\ \sigma_y$ is the *flow stress*, usually close to the intermediate value between SMYS and SMTS: flow stress is an empirical concept intended to represent the stress at which unconstrained plastic flow occurs in a strain hardening elastic-plastic material via a single parameter. (Penspen Integrity, 2002)

7.3.1.4 Remaining strength of corrosion defects

- **ASME B31G** : Remaining strength of pipelines with smooth corrosion with the following formula; In this method is used a parabolic approximation of the corroded area; it's the most pessimistic approach.

$$\sigma_{hoop} = 1{,}15\ \sigma_y * \frac{1 - \frac{2\ depth}{3\ t}}{1 - \frac{2\ depth}{3\ t * M}} \qquad \text{with } M = \sqrt{1 + 0{,}8 * (\frac{L}{d\ t})^2}$$

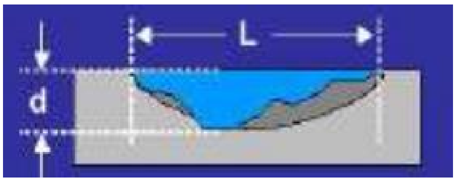

FIGURE 23 ASME B31G APPROXIMATION AREA

It refers to a corrosion geometry that is a parabola if the shape is projected. In the B31G is reported that this last equation should be applied only to corrosion which has a maximum depth less than 80% of wall thickness. Parabolic shape furthermore doesn't fit long corrosion: the limit of defect length corresponds to M≤ 4,12, or $B = \sqrt{M^2 - 1} \leq 4$.
$1{,}15\ \sigma_y$ is what is called *flow stress* (σ_y is yielding stress, SMYS)

- **Modified B31G / Rstreng 0,85:** (Kiefner & Vieth, 1989) . It uses 0,85 as coefficient instead of 2/3, the flow stress is increased and the *Folias factor M* has changed also. Still a pessimistic (conservative) method in the evaluation of actual failure pressure. It's considered to have a more accurate definition for the *flow stress* (Penspen Integrity, 2000), that is $SMYS + 68{,}95\ MPa$ that is a very close value to the conventional fracture mechanism definition of the flow stress: the average of the yield and ultimate strength (Szary, 2006). The corrosion profile is assumed arbitrarily.

$$\sigma_{hoop} = (SMYS + 68{,}95\ MPa) * \left(\frac{1 - 0{,}85 \frac{d}{t}}{1 - 0{,}85 \frac{d}{t * M}} \right)$$

$$M = \sqrt{1 + 0{,}06275 \frac{L^2}{D * t} - 0{,}003375 \frac{L^4}{(D * t)^2}} \quad if \ \frac{L^2}{D * t} \leq 50$$

$$or \ \ M = 0{,}032 \frac{L^2}{D * t} + 3{,}3 \quad if \ \frac{L^2}{D * t} > 50$$

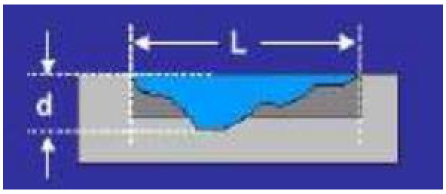

FIGURE 24 RSTRENG APPROXIMATION AREA OF THE DEFECT

- **RSTRENG** : simultaneously to Modified B31G another method has been developed: it's very similar to that one apart from the geometry description: RSTRENG takes into account the actual profile of the defect (it doesn't approximate it with 0,85).

FIGURE 25 DETAILED RSTRENG APPROXIMATION AREA OF THE DEFECT

- **DNV recommended practice RP-F101** (Det Norske Veritas, 2010) incorporates methods for assessment of corrosion defects developed through a *Group Sponsored Project* undertaken by *BG* (formerly *British Gas) Technology* that are reported here below and guidelines for the assessment of corrosion defect produced by a *Joint Industry Project* undertaken by *Det Norske Veritas (DNV)* (Penspen Integrity, 2000). The BG method has the same frame as the original part-wall failure criterion used in the previous two methods, but the geometry correction has been modified (Penspen Integrity, 2000); shape of the defect is indeed assumed rectangular (Cosham & Hopkins, 2004). The flow stress is *SMTS* (the ultimate tensile strength) and *Folias factor M* has been replaced by the *Length correction factor Q*:

$$\sigma_{hoop} = 1{,}1 * SMTS * \left(\frac{1 - \frac{d}{t}}{1 - \frac{d}{t * Q}} \right) \quad where \ \ Q = \sqrt{1 + 0{,}31 \frac{L^2}{D * t}}$$

7.3.1.5 *Remaining strength in a dent containing a gouge*

Dents containing a gouge have complex behaviour (Penspen Integrity, 2002), many equations can be found in literature in order to estimate the remaining strength; the most famous and adopted methods are the

Empirical Q factor model and the *Dent-Gouge fracture model* developed by British Gas and adopted by the EPRG. However, it won't be treated in this thesis because it's not the intent.

- **Empirical Q factor model**: in this method a relationship is presented between (Penspen Integrity, 2002):
  - Failure stress normalized by the flow stress
  - Empirical parameter Q, that is function of
    - the upper shelf Charpy impact energy
    - dent depth
    - gouge length
    - gouge depth

$$\frac{\sigma_f}{\bar{\sigma}} = \frac{(\,Q - 300\,)^{0,6}}{90}$$

$$\text{Where } Q = \frac{C_v}{\frac{H}{2R} * 2 * c * \frac{d}{t}} \quad \text{and} \quad \bar{\sigma} = \sigma_y + 10'000\ psi$$

- **Dent-Gouge fracture model:** for its complexity it's not reported in the thesis but just cited;

7.3.1.6 *Assessment of buckling*

Pipeline codes do not provide acceptance criteria for buckles, but they recommend to avoid it. (Yablonskikh, et al., 2007) . The strain-based method described in ASME B31.8 could be used in an assessment of buckle criticality in terms of an immediate static integrity of the pipeline. (Yablonskikh, et al., 2007)

7.3.2 *Defect Assessment Curve*

With the methods listed above, the calculation of the remaining strength of a damaged pipeline is provided. Then substituting σ_{hoop} with a defined value of stress it's possible to build and represent the defect-assessment curve for a defect:

$$\sigma_{hoop} = MAOP \rightarrow \text{ red curve}$$

$$\sigma_{hoop} = Hydrotest\ stress \rightarrow \text{green curve}$$

(both only identifying combinations of depth and length of the defect leading to failure respectively at MAOP and HYDROTEST pressure).

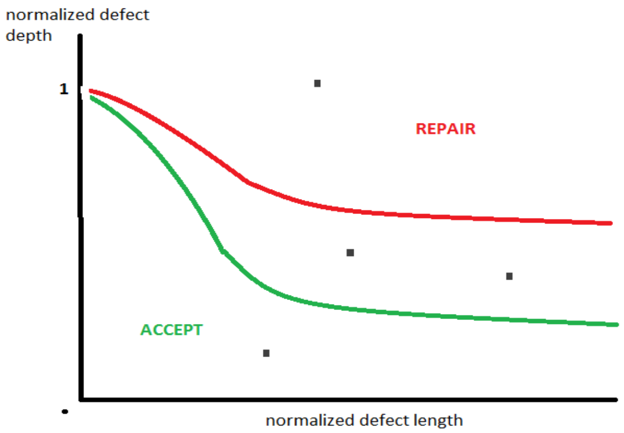

FIGURE 26 DEFECT ASSESSMENT CURVE: THE DEFECT WILL FALL IN ONE OF THE THREE POSSIBLE ZONE, SEPARATED BY THE CURVE OF MAOP-FAILING-DEFECT AND HYDROTEST PRESSURE-FAILING-DEFECT

The scheme that comes out in *Figure 26 Defect assessment curve: the defect will fall in one of the three possible zone, separated by the curve of MAOP-failing-defect and HYDROTEST pressure-failing-defect* is the Defect Assessment Curve*:* it can be used as a reference model where the position in the plot of each defect (real, on a pipeline) provides whether the defect needs to be repaired or not (Penspen Integrity, 2000). Defects above the red line are predicted to fail at a pressure below the *MAOP* and will need to be repaired immediately; those intermediate defects should be reassessed using more sophisticated methods or straightly repaired. (Penspen Integrity, 2000) Defects that lie below the green line can fail only at a pressure above the hydrostatic pressure applied at the hydro-test and can indeed considered acceptable. This plot is used to *prioritize* the repair of defects. (Penspen Integrity, 2000) With the point 1 is represented the condition of failure of a defect with no length and no depth, that means the failure of a pipe without defect that is the *burst pressure*.

7.4 Documents and technical specification

The acceptance criterion of a tool inspection depends on the client and its requirements. Here below are attached main reference document for the passage of the Caliper pig in the Scotland project.

7.4.1 Scope of work (Gas Network Ireland, 2016)

The scope of work recommends to follow the POF document 2009 "specifications and requirements for intelligent pig inspection of pipelines" (Pipeline Operator Forum, 2009) ; it advises that gauging shall be performed both prior and after hydrotest; The Contractor shall be responsible for pigging, swabbing and gauging of the pipe line both before and following testing.

7.4.2 Inspection guidelines for timely response to geometry defects (Baker, 2004)

This kind of document provide a classification into different types of repairing-requiring conditions of some possible defects:
Following conditions must be treated as **immediate repair conditions**:

- A calculation of the remaining strength of the pipe shows a predicted failure pressure less than or equal to 1,1 times the MAOP (methods to calculate the remaining strength are available in ASME B31 G)
- Dents with metal losses, cracking or stress riser
- Person designated by the operator to evaluate damages indicate a requirement of immediate reapair.

One year repair conditions: any of the followings must be repaired within one year of discovery

- Smooth dent located between 8 o'clock and 4 o'clock , above, with a depth greater than 6% of the pipe diameter
- A dent with depth greater than 2% of the pipe diameter that affects curvature at a girth weld or seam weld

Monitored condition*:*

- Dent with depth more than 6% between 4 o'clock and 8 o'clock downward
- Dent between 8 and 4 located above with a depth more than 6%
- Dent with depth more than 2% of diameter that affects pipe curvature at girth weld or longitudinal seam weld.

7.4.3 Best practice in pipeline defect assessment (Penspen Integrity, 2000)

The main concept is that failure modes in the pipeline world usually are not due to a single and independent aspect but due to combination of factors: that's why an "holistic" approach to pipeline defect assessment and integrity is necessary. Just to make an example: if the coating is ageing, the environment is aggressive, and the corrosion growth happens at a fast rate, the pipeline may fail not due to a simple "*corrosion*" failure but a "*corrosion control system*" failure.

The paper provides a process for reviewing any set of inspection data, it's about how to organize and proceed in the analysis of data obtained by an internal inspection of the line.

1. Inspection
2. Preliminary analysis
    a. Ensure successful inspection
    b. To confirm no ambiguity between client and contractor about definition of defects
    c. Credibility of results
    d. Qualitative general assessment
    e. Presence of severe defects
3. *Level 1 integrity assessment* if the condition of the line confirms the requirements
4. *Level 2 integrity assessment* if there are potential problems: recommendation for future repair, potential growth of the defect… *Fitness for purpose* approach is adopted: calculation of the failure condition of a structural defect and comparison with the operating condition of the pipeline
5. *Level 3 integrity assessment* for all those defect that require urgent action

A fitness for purpose assessment usually involve a deterministic assessment of the defect without entailing a risk analysis, in order to determine whether the defect is acceptable or not. Probabilistic methods are useful when dealing with uncertainty over the data used in the assessment on future conditions, such as corrosion rates. Safety factor are not given: it's the responsibility of the engineer to select them.

7.4.4 API 1160 – 2001

Repair is needed for the followings within 6 months:

- Dents with metal loss on weld
- Dents at the top of the line pipe between 4 and 8 o'clock if depth greater than 2% (for NPS 12 and greater than 0,25 inches)
- Dents greater than 6%

7.4.5 ASME B 31 8 (American Society of Mechanical Engineers, 2003)or 2016

Immediate response is required if it's found:

- Plain dent > 6% *Dn*; plain dent of any depth are acceptable provided strain levels associated with deformation do not exceed 6% strain: this strain can be calculated in accordance with *Non-mandatory appendix R: estimating strain in dents* below.
- Dent + corrosion > 6% *Dn*
- Dent on weld > 2% *Dn*, except those with strain level associated with the deformation less than 4% strain. If a gouge on dent is found it needs further assessment.

7.4.5.1 Non-mandatory appendix R: estimating strain in dents (American Society of Mechanical Engineers, s.d.)

This additional chapter taken from ASME standards provides a method to calculate the maximum strain in a dent:

Given the following data taken from the pipe:

R_0 = initial pipe surface radius = ½ outer diameter OD nominal diameter

R_1 = curvature radius of the dent in a transverse plane through the dent: if in the same direction as normal curvature of the pipe $R_1 > 0$, otherwise $R_1 < 0$ (re-entrant dent).

R_2 = curvature of the dent in a longitudinal plane through the dent, usually $R_2 < 0$.

t = wall thickness

d = depth

L = length of dent

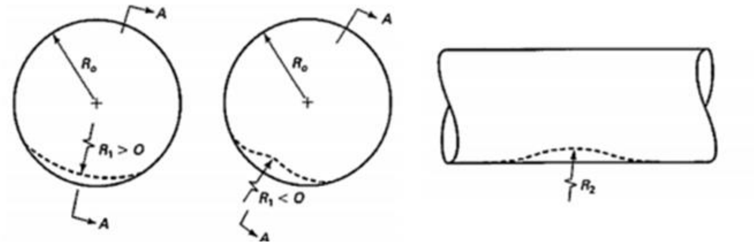

FIGURE 27 DENT CURVATURES

The estimation of the maximum strain in a dent is performed in the following steps:

- Each strain component is evaluated separately: *ε1 ε2* and *ε3* are respectively the *bending strain in the circumferential direction and longitudinal direction* and the *extensional strain in the longitudinal direction*; they can be evaluated according to the formulas below:

$$\varepsilon_1 = \frac{1}{2} t\,(\frac{1}{R_0} - \frac{1}{R_1})$$
$$\varepsilon_2 = -\frac{1}{2} t\,(\frac{1}{R_2})$$
$$\varepsilon_3 = \frac{1}{2}\,(\frac{d}{L})^2$$

- Assuming that each component occurs coincidently at the dent apex, the components are accordingly combined to determine the total strain. The strain on the inside and outside pipe surface are respectively:

$$\varepsilon_i = \sqrt{[\,\varepsilon_1{}^2 - \varepsilon_1(\varepsilon_2 + \varepsilon_3) + (\varepsilon_2 + \varepsilon_3)^2]}$$

$$\varepsilon_o = \sqrt{[\,\varepsilon_1{}^2 + \varepsilon_1(-\varepsilon_2 + \varepsilon_3) + (-\varepsilon_2 + \varepsilon_3)^2]}$$

The strain provides an indication of the *sharpness* of the dent, that can aid in determining whether the dent is mechanical damaged and can assist in judging the severity of the dent without excavation. The limitation is that there are no industry standards for acceptance criteria for maximum allowable strain. ASME code allows 3% strain as the lower bound and 12% from experiment could be the upper bound.
However, these equations were derived considering incorrect plane strain assumptions, and therefore their use can lead to inaccurate result (Ramezani & Neitzert, 2013). More appropriate expressions to the equivalent strain were presented later (Ramezani & Neitzert, 2013) (Noronha, et al., 2010):

$$\varepsilon_i = \frac{2}{\sqrt{3}}\sqrt{[\,\varepsilon_1{}^2 + \varepsilon_1(\varepsilon_2 + \varepsilon_3) + (\varepsilon_2 + \varepsilon_3)^2]}$$

$$\varepsilon_o = \frac{2}{\sqrt{3}}\sqrt{[\,\varepsilon_1{}^2 - \varepsilon_1(-\varepsilon_2 + \varepsilon_3) + (-\varepsilon_2 + \varepsilon_3)^2]}$$

7.4.6 Specification and requirements for intelligent pig inspection of pipelines POF

This source provides information related to the **identification**, **assessment** and **classification** of metal losses and it's reported as reference document in the Scope of work. According to the POF, to allow the Client to rank **(classification)** the anomalies in the pipeline on the basis of a first screening of severity, the *Estimated Repair Factor (ERF)* shall be calculated. The ERF is defined as:

$$\frac{MOP}{P\;safe} = ERF$$

where *P safe* is the safe operating pressure as calculated by the latest version of an anomaly assessment method **(assessment)** as agreed between Client and Contractor. P safe is evaluated after the identification and characterization of the defect (**identification**).

7.4.6.1 Identification of a defect and its features

Geometrical parameters of anomalies are length "*L*", width "*W*", depth "*d*" and wall thickness "*t*". The parameter *A* is used for the geometrical classification of the anomalies detected by a tool: this parameter is needed for pipes with $t < 10$ mm then $A = 10$ mm If $t \geq 10$ mm then $A = t$.
The measurement threshold as displayed in *Figure 28 Identification of length and width of a damage, Figure 29 Thickness of damage,* and *Figure 30 Standardization for description of damages* determine the start and end point of an anomaly. Its projected length on the longitudinal axis of the pipe gives the length, "*L*". The projected length of *L* between *S* (starting point) and *E* (ending point) shall be considered in the pigging direction; the width, "*W*" is given by its projected length on the circumference of the pipe. The projected length of *W* between *S* (starting point) and *E* (ending point) shall be considered in the clockwise direction, looking downstream.

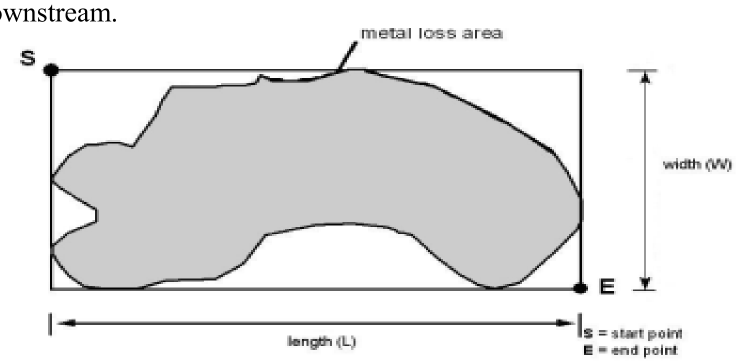

FIGURE 28 IDENTIFICATION OF LENGTH AND WIDTH OF A DAMAGE

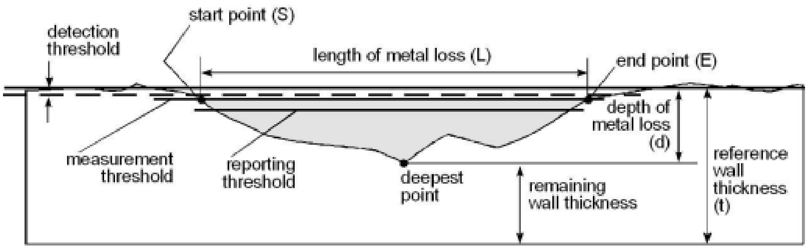

FIGURE 29 THICKNESS OF DAMAGE

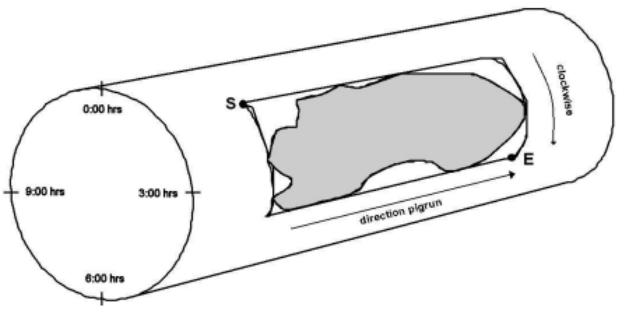

FIGURE 30 STANDARDIZATION FOR DESCRIPTION OF DAMAGES

The measurement capabilities of non-destructive examination techniques depend on the geometry of the metal loss anomalies. These metal loss anomaly classes have been defined as shown in the figure below, according to their normalized W (projected length on the circumference) and normalized L (axial projection length).

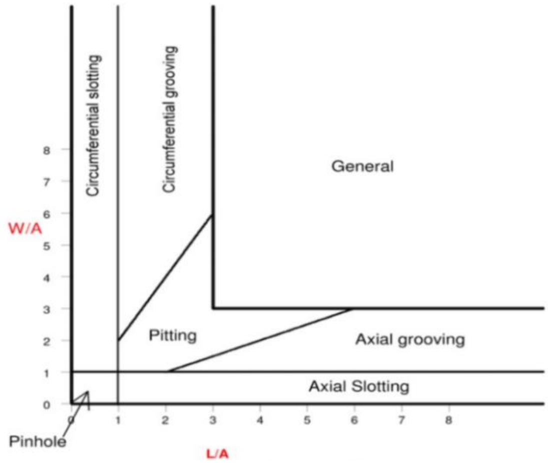

FIGURE 31 CLASSIFICATION OF METAL LOSSES

Where
slot: elongated circular cut-out

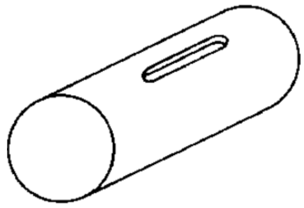

FIGURE 32 REPRESENTATION OF A SLOT

Groove: Groove is a long cut.
Pit: hole or group of holes that coalesce
Hole: circular cut-out
If no value is specified, then the measurement threshold shall be taken at 5% for MFL tools and 0.5 mm for UT tools with respect to the reference wall thickness. The depth of the metal loss “d” is determined by the maximum wall loss in an anomaly and can be given as a depth from or percentage of the reference wall thickness. Unless the Client specifies otherwise, the following interaction rule (both steps) shall be applied:

- Step 1: An anomaly (individual or part of a cluster) shall never be clustered with another adjacent anomaly (individual or part of a cluster) if the distance is ≥ 6 t. This is applicable for the axial and circumferential direction.
- Step 2: Individual anomalies shall be clustered when the axial spacing between the anomalies is less than the smallest anomaly length and the circumferential spacing is less than the smallest anomaly width.

7.4.6.2 Assessment of defects

If not specified otherwise by the Client, *method B31 G* shall be used. We remind that the simple relationship existing between the pressure (in this case P_{safe}, the safe pressure) and the internal stress (in this case hoop stress σ_{hoop}) is given by the *Barlow equation*: this means that the following equations are obtained by previous different ways of evaluating the remaining strength and then by multiplying it by the other elements present in the Barlow’s equation.

$$Pf = \frac{2 * t}{D - t} * \sigma$$

• **ASME B31 G.** (American Society of Mechanical Engineers, s.d.).

$$Pf = 1{,}11\,\frac{2 * SMYS * t}{D} * \left(\frac{1-\dfrac{2d}{3t}}{1-\dfrac{2d}{3t * M}}\right) \quad if \quad \frac{L}{\sqrt{D * t}} \leq 4{,}479$$

$$Pf = 1{,}11\,\frac{2 * SMYS * t}{D} * \left(1-\frac{d}{t}\right) \quad if \quad \frac{L}{\sqrt{D * t}} > 4{,}479$$

$$where \quad M = \sqrt{1+0{,}893 * \frac{L}{D * t}}$$

Possible alternative assessment methods are, but not limited to:

• **Rstreng-5 (Modified ASME B31 G**).

$$Pf = \frac{2 * (SMYS + 68{,}95\ MPa) * t}{D} * \left(\frac{1-0{,}85\dfrac{d}{t}}{1-0{,}85\dfrac{d}{t * M}}\right)$$

$$\text{Where } M = \sqrt{1+0{,}06275\frac{L^2}{D*t}-0{,}003375\frac{L^4}{(D*t)^2}} \quad if \quad \frac{L^2}{D*t} \leq 50$$

$$or \quad M = 0{,}032\,\frac{L^2}{D * t}+3{,}3 \quad if \quad \frac{L^2}{D * t} > 50$$

• **DNV recommended practice RP-F101** (Det Norske Veritas, 2010)

$$Pf = 1{,}1\frac{2\ SMTS * t}{D} * \left(\frac{1-\dfrac{d}{t}}{1-\dfrac{d}{t * M}}\right) \quad where \quad M = \sqrt{1+0{,}31\frac{L^2}{D * t}}$$

• **Shell 92** (Ritchie & Last, 1995)**:** The shape of the defect is assumed rectangular (Cosham & Hopkins, 2004) and $SMTS$ is the flow stress

$$Pf = \frac{1{,}8\ SMTS * t}{D} * \left(\frac{1-\dfrac{d}{t}}{1-\dfrac{d}{t * M}}\right) \quad where \quad M = \sqrt{1+0{,}805\frac{L^2}{D * t}}$$

• **BS 7910.**

Typical reporting threshold are 2% for dents and 5% for ovalities as stated in *POF* though this value will be contested by Sicim spa. Over years it has been proved that the burst strength of a gouge is affected also by *toughness* of the pipe steel: as the toughness increases the burst strength tends to be toughness-independent, and flow stress dependent (all equations above are valid above at a well-defined toughness and are only *flow stress* dependent).

7.4.6.3 Classification of defect, acceptance criteria

In order to verify if the parameter that characterize the defect makes it acceptable or not, the Estimated Repair Factor is evaluated with the equation at the beginning of the chapter; if the ERF is less than 1 the defect is acceptable, whereas if the ERF is greater than 1 the defect is considered not acceptable.

7.4.6.4 Defect report: how to do it

The *Final Inspection Report* (hard & electronic copy) of either a single or combined ILI tool run shall contain the following information and be available within 8 weeks of the ILI run unless agreed otherwise:

- Field report
- Tool operational data
- Tool calibration
- Pipe tally
- List of anomalies:
- Summary report of metal loss tools shall contain a listing of:
    - Total number of anomalies;
    - Number of internal anomalies;
    - Number of external anomalies;
    - Number of general anomalies;
    - Number of pits;
    - Number of axial and circumferential grooves;
- Summary report of geometry tool shall contain a listing of:
    - Number of dents with depth 2 – <6% ID;
    - Number of dents with depth ≥ 6% ID;
    - Number of ovalities* 0.10 > ratio < 0.05;
    - Number of ovalities* with ratio ≥ 0.10;

7.4.7 General Pipelining Specification - AO SP 007 (Gas Networks Ireland, 2015)

Swabbing and Gauging have to be performed prior to hydrostatic testing, as many swabbing and gauging runs as required must be carried out to ensure that the line is clear of all debris and extraneous matter to the satisfaction of the Engineer. The final cleaning runs shall be carried out with rubber pigs. All swabbing and gauging runs shall be carried out in the direction of the gas flow and shall be completed before hydrotesting commences.

7.4.8 Pressure Testing of Transmission Pipelines - AO SP 006 (Gas Networks Ireland, 2015)

On completion of tie-in and before commissioning, a gauge pig shall be run; at the stage before testing, a suitable gauging or geometric pig shall be passed through the pipeline to prove the bore to the specified acceptance procedure.
Where a geometric pig is used, all local reductions in diameter equal to or greater than 1.5% of the diameter shall be investigated, assessed and, where necessary, remedial action shall be taken.
Note: For larger diameter high strength pipelines, the use of a geometric pig run prior to commissioning may identify any dents caused as a result of construction activity. Where a gauge plate is used, its diameter shall be compliant with *IS 328*. Only rubber nosed pigs shall be used, pigs with exposed steel at either end shall not be used. On completion of the final tie-ins of all the sections and before commissioning, a gauge pig shall be run from the start of the pipeline to the end in the direction of flow.

7.4.9 Code of practice for gas transmission pipeline and gas installations (National Standards Authority of Ireland, 2003)

Steps shall be taken to ensure that the pipeline is free from internal obstruction. At some stage prior to testing and again before commissioning a suitable gauging pig shall be passed through the pipeline. Where a gauge plate is used, its diameter should be 95% of the least nominal bore of a pipeline or fitting having a diameter more than 500 mm. For pipelines and fittings having a diameter of 500 mm or less the gauge plate should have a diameter 25 mm less than the nominal bore. Further pigging operations should be carried out during testing and commissioning

7.5 Equipment: classification of inspection tools

Different inspection tools and technologies are available in the market to assess the integrity of the pipeline. Note: in this section it's not included the classical gauging pig, a pig equipped with a gauging plate (see *Figure 100 gauging plate*) that permits to identify the presence or absence of dents by visual inspection, because it's used prior to Pre-commissioning.

7.5.1 Caliper pig

More refined measurements are made by **calliper pig** which carries a number of radial feelers (see *Figure 89 Kaliper pig, RAS, scrapers in the foreground*): a dent elastically deflects the feelers and their deflections at different points around the circumference are recorded as a measure of the cross section.
Kaliper pig, shown in *Figure 88 Kaliper pig, RAS,* is usually propelled with air that doesn't need extreme dry conditions because is done before drying; the velocity is an important parameter that needs to be controlled during the pigging, usually it has to be less than 3 km/h. A slowdown and subsequent acceleration may happen when it contacts some obstacles along the pipe or when it has to follow the uphill and downhill of the profile of the line. The common way to control the velocity in order both to preserve the tool and to leave to it enough time to detect and record possible defects, is obtained by imposing *backpressure*. Kaliper pig is usually propelled by oil-free compressed air. In *Figure 90 insertion of a caliper pig into the pipeline* it is represented the insertion of the Kaliper pig into the installed pipeline.
The inspection tool can be *single-channel* if diameter reduction and dents or ovalities are identified along the length of the pipeline; if the caliper is also able to provide the circumferential location of the defects is called *multi-channel* caliper. The firm that supplies the kaliper pig should provide information about the bending (see *Appendix E - Bending of* a pipe) that the tool is able to pass, the reduction in diameter expressed as percentage that it's able to overcome, and all other sensor with which it's equipped.

7.5.1.1 How the caliper works: interpretation of output

Here below is reported an interpretation of output of data; the main output can be represented in 2-dimension plot if the caliper pig is for instance *single-channel*, with the length of the pipe on the abscissa and the indicative parameter on the ordinate. This parameter is the minimum length of the scrapers of the inspection tools, revolved vertically, represented by the red line in the plot: when scrapers pass through a restriction in cross section, the smallest diameter is noted and it will be depicted in the plot as a peak in height.

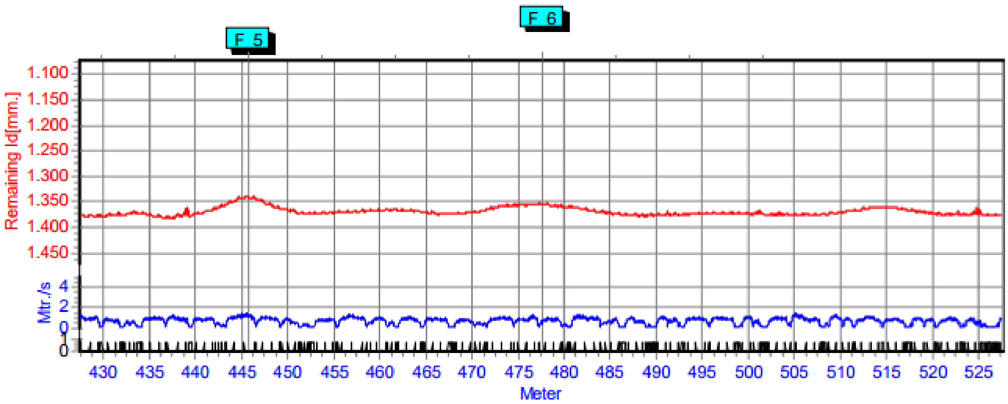

FIGURE 33 2D PLOT OUTPUT OF CALIPER PIG

As can be appreciated in *Figure 33 2D plot output of caliper pig*, in the first meters of the pipeline 2 main peaks are detected. Usually the more the spike in the red line of the 2d plot is sharp, the more it's likely to be a dent, the more it's smooth the more it's likely to be an ovality.
A first row-cut of defect types can be made looking at the 2D plot of the thickness internal changes of the pipe; in *Figure 34 feature identification* are shown main features:
A) dent in ovality
B) dent
G,H) T piece
I) Valve
C) ovality
D) change of thickness
E) regularly-spaced girth welds

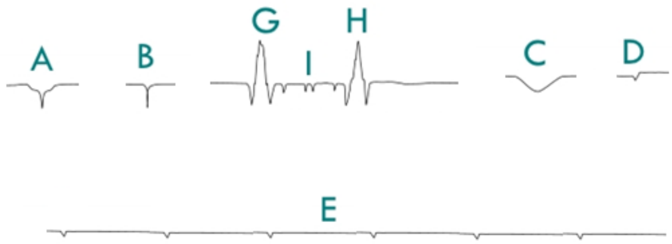

FIGURE 34 FEATURE IDENTIFICATION

If the tool is *multi-channel*, it can then provide a development of this output plot into three dimensions: at a given cross section the effective diameter is displayed at all angles (the third added parameter is the angle). In *Figure 35 3D output plot of kaliper pig, critical zone* is attached an example of the 3D plot in which on the third dimension is represented the degree of angle, for the critical point named F6 (feature 6) in the neighbourhood of 477 meters:

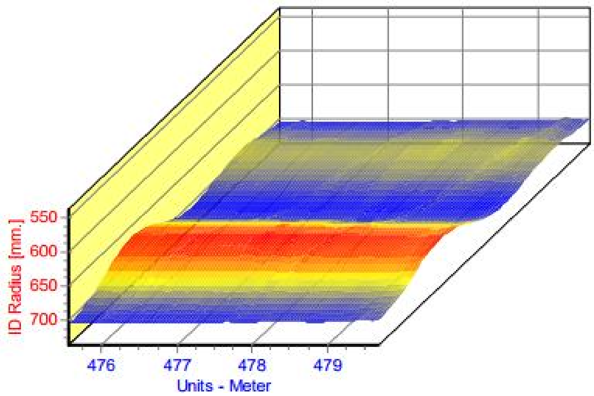

FIGURE 35 3D OUTPUT PLOT OF KALIPER PIG, CRITICAL ZONE

Blue zones represent an increase in the diameter, whereas red zones represent a reduction in diameter (possible location of dents). This 3D plot can then be transformed graphically into a cross-section representation of the pipeline:

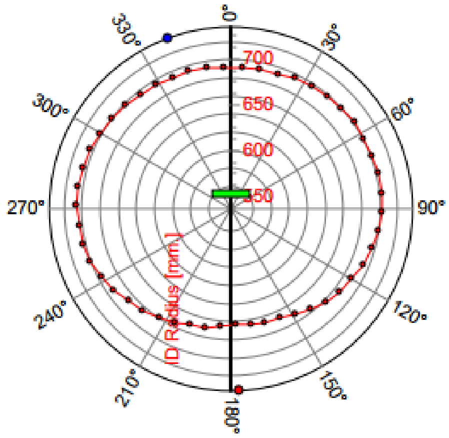

FIGURE 36 CROSS SECTION OF THE PIPELINE IN A CRITICAL POINT

It's shown in *Figure 36 Cross section of the pipeline in a critical point* where the reduction is located (red zone, thus red point), and where the opposite enlargement is (blue zone, blue point). Most of the critical features are located in the down side of the cross-section of the pipe and this is one example, usually due to gravity and possible rocks on the ground. On this it's usually performed a brief assessment: evaluation of % reduction, % ovality, assessment whether it is a dent or an ovality and the comparison with *acceptability criteria* in order to decide whether to take an action (removal of the land and visual inspection of the defect, possibility of substitution of the damaged section of the line) or to accept it and leave it proving its safety.

7.5.2 Other tools (for metal loss)

Damages that instead involve a metal loss (part of the material has been lost, removed, ruined from the pipe surface) need **metal loss detection tools** and techniques: among those it's worth to mention *MFL (magnetic flux leakage),* and *UT (ultrasonic test*). Those devices can be used to confirm the presence and orientation of significant deformation, but they cannot be reliably used to evaluate deformation size or depth. When a rock dent is very deep, the probability of loss detection reduces: UT device is even worse than the MFL. *(Baker, 2004)*

8 Drying with dry air

Most of the water left in the pipeline after the hydrotest, has been removed by passing foam pigs through the line; however, with that operation, a very thin layer of water (usually 50 µm) still remains on the internal surface of the pipeline thus requiring another dedicated phase to completely dry the line and to avoid phenomena of corrosion, impurity of the delivered product, formation of hydrates with the consequent probability of occlusion, obstruction and damage of the line and fittings.
Drying has the purpose to remove this residual water and make the pipeline ready to be intertied; it can be performed in different method, this chapter is dedicated to the one often used in *Sicim* spa (and in the Scotland GB 022 project), that is the blowing of dry air in the pipeline: this process relies on the mass transfer phenomena explained in the chapter 4. Another effective method is the vacuum drying, briefly outlined in the next chapter for information.
In drying with dry air, some pigs propelled by dry air are employed; in this chapter is also added an explanation of the parameters that influence the process, such as temperature and pressure.

8.1 Temperature and Pressure influence on humidity content

The higher the air temperature and lower the pressure, the higher is the water content that air can uptake, the better is the absorption of water into air. This is a milestone for the drying procedures and can be explained with the following small dissertation about humidity of air.
When water is exposed with air, part of the molecules will start to escape (evaporation) and form a layer of vapour water immediately above the water surface, but the more the evaporated molecules of water the more will be their collision with the surface, that is a recondensation; the pressure of water in this layer is called partial pressure of water, P_w, and will increase until $P_w = P_{sat}$: this is the equilibrium situation at which condensation and evaporation occurr at the same rate, and can be reached only if the box of water is closed. P_{sat} is the maximum saturation pressure of air that only depends on temperature (see *Figure 14*). The humidity content of air can thus be expressed as ${}^{P_w}/{}_{P_{sat}}$, and it reaches 100%, as stated before, when $P_w = P_{sat}$.

- The number of molecules that escape increases with temperature (and the same does P_{sat}) because an increase in temperature corresponds to an increase in the kinetic energy of molecules (Rototronic Instrument Corp., 2005): the air can uptake more moisture

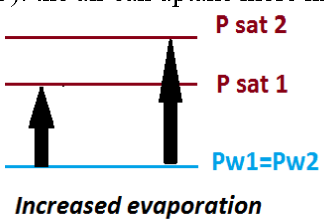

FIGURE 37 CHANGE IN MOISTURE CONTENT OF AIR DUE TO AN INCREASE IN TEMPERATURE

- Increasing pressure won't lead to an increase in the P_{sat} (that only depends on temperature), but will lead to a proportional increase in the partial pressures of the humid air components, that is also P_w ; this means that the numerator of ${}^{P_w}/{}_{P_{sat}}$, will increase and the relative humidity too: air can absorb fewer moisture.

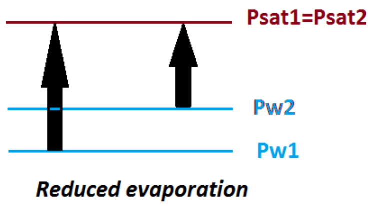

FIGURE 38 CHANGE IN MOISTURE CONTENT OF AIR DUE TO AN INCREASE IN THE TOTAL PRESSURE

This is reflected in the efficiency with which a pipeline can be dried: at the pipe inlet the temperature is higher (very good) and the pressure higher (bad); proceeding along the pipeline, the pressure continuously reduces a bit due to frictional losses (good) and the temperature quite reducing (bad) (Shell, 1994). This can be represented in the *Figure 39 maximum saturability of air in drying with dry air depending on the position along the pipe.* The trend of the violet line represents qualitatively the maximum saturation of air that is an indicator of the effectiveness of the drying (because it represents the quantity of moisture that air can uptake).

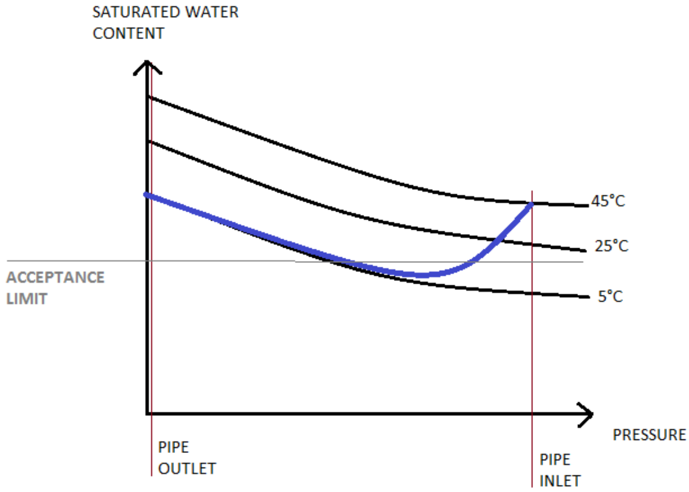

FIGURE 39 MAXIMUM SATURABILITY OF AIR IN DRYING WITH DRY AIR DEPENDING ON THE POSITION ALONG THE PIPE

8.2 How moisture can affect the pipeline state

As stated before, if moisture is left within the pipeline the consequences may be severe; here below are described some of the main possible drawbacks.

8.2.1 Hydrate formation

Hydrates are particular problems for flow assurance of the pipeline and related equipment and form when hydrocarbon are in contact with water at specific thermodynamic conditions shown in the *Figure 40 qualitative representation of hydrate formation regions*

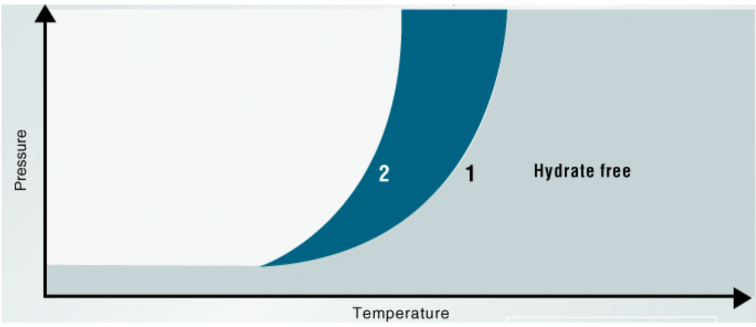

FIGURE 40 QUALITATIVE REPRESENTATION OF HYDRATE FORMATION REGIONS ACCORDING TO TEMPERATURE AND PRESSURE: ON THE LEFT SIDE, THE HYDRATE-FORMATION ZONE; ON THE BLUE REGION, THE TRANSITION-ZONE, ON THE RIGTH SIDE, THE HYDRATE-FREE ZONE

The white zone represents qualitatively the zone of formation of hydrates; the zone 2 represents a potential risk of hydrate formation; the zone 1 represent the safe operating zone, hydrate free. The curve is only qualitative because each hydrocarbon (with a tendency to form hydrates) has its own quantitative curve (that varies according to the percentages of the two). The risky situation for the possible hydrate formation is in winter or cold climate at high pressure. Hydrate formation is a dangerous phenomenon that can lead to damages on fittings and valves and can obstruct the line.

8.2.2 Corrosion

At present, for natural gas containing H_2S the generally accepted moisture limit is 56 kg per million standard cubic meters which corresponds to a dew point of -45°C at atmospheric pressure; however, this specification could also include lines with a significant CO2 content unless corrosion inhibitors are used, but it's not our cases: furthermore, experience has shown that for practical purposes a dew point of -20°C is attainable, further drying is not economically viable except for short lines or special cases. (Shell, 1994)
(see
Appendix D - Corrosion of steel)

8.2.3 Impurity of the product

Moisture present on the pipeline wall can affect and change the purity of the product that will run within the pipeline, this occurs only at the very first stages of production, that's why it is the less severe problem (usually neglected).

8.3 Documents and technical specifications

8.3.1 Scope of work (Gas Network Ireland, 2016)

Supply and operation of equipment and resources to bring dryness levels of the pipeline to a dew point at or below -20°C. Drying shall be completed in accordance with *AO/SP/007.*

8.3.2 General Pipelining Specification - AO SP 007 (Gas Networks Ireland, 2015)

Drying Acceptance Criteria - Pipeline and AGI Following adequate pigging, desiccant dry air shall be purged through the chosen section of pipeline. A dew point measurement will be taken at the outlet from the dryer to establish its performance. All measurements shall be taken using a certified calibrated dew point meter. Dry Air will be purged until the contractor is satisfied the pipeline section is sufficiently dry to meet the following criteria:

- With the drying unit shut off and following a *stabilisation period of 1 hour* a dew point measurement at or below –20º C must be achieved at injection and receiving end (and any other available points agreed) of the section. The actual Dew point measurement shall be recorded at all points.
- A positive air pressure of 2 barg minimum will be locked into the section
- Air shall be vented at the measurement point for a minimum period of 5 minutes before measurement is taken. Following a *soak period of 24 hours* minimum dew point measurements will be taken from the same locations and the Dew point shall remain at or below –20º C but shall not have increased by more than 5º C from the initial measurement.
- Desiccant dry air, the equivalent of 2 volumes of the pipeline section shall be passed through the section. Measurements shall be taken, and the Dew point shall remain at or below –20º C but shall not have increased by more than 5º C or 20% of the original value whichever is the greater from the previous measurement

8.3.3 Steel pipeline for high pressure gas transmission (The Institution of Gas ENgineers, 2001)

Shortly before drying is concluded, the block valve cavities should be purged with dry air/nitrogen by closing partially the mainline valve and venting to atmosphere. The pipeline can be considered to be dry along its whole length when the required dew point has been reached at the receiving end. The line should then be closed off and the air-drying equipment removed.

It is considered that at dew points at or below -20° C no corrosion will occur. This degree of dryness is attainable with more or less standard desiccant dryers, which will output air at -40° C dew point at atmospheric pressure. The optimum length for drying by this method is approximately 30 km. Normally, lengths greater than this are avoided to prevent abrasion of the pig material.

This method utilizes an air-drying unit and compressors to produce dry, oil-free air or a dry inert gas which is used to propel foam pigs through the pipeline. These pigs absorb water, remove pools of water at low points and distribute any residual water as a thin film on the internal pipe wall to facilitate faster evaporation. On completion of the drying/purging operation, the pipeline can be gassed up immediately or sealed off for gassing up at a later date. Alternatively, a pipeline can be simply dried by passing super dry air or gas through the pipeline after the free water has been removed by multiple pigging runs.

In order to minimise the time required for an air-drying operation, it has to be recognised that a given mass of air can take up only a *limited amount of water vapour*, the precise amount being calculable from the initial dryness and the temperature with reference to saturation tables. Thereafter, the larger the throughput, the shorter will be the drying time. However, the rate at which water molecules are transferred from the pipe wall to the free stream is, in part, dependent on a coefficient which is proportional to pressure and temperature. The pressure in the drying medium needs to be kept low.

In order to determine the dryness of the pipeline, the moisture content of the air at the discharge end of the section is measured by recording the dew point temperature. The moisture content of the discharged air can be obtained by reference to the dew point temperature in standard saturation vapour pressure tables. The air drying/super dry air equipment should be located at the launching end of the pipeline and connected to allow the repeated dispatch of foam pigs during the operation. The air-drying unit should have sufficient capacity to suit the pipeline size and be able to achieve a dew point temperature below that specified. The unit should have two absorption vessels with fully automatic change over facilities for regeneration to allow for continuous working. Dew point temperature measuring instrumentation should be installed at both the pig launching and receiving stations to allow continuous monitoring to take place. This should be calibrated and checked in accordance with an agreed procedure and check list. As soon as the first pig has been despatched, the instrumentation at the launching end should be checked to ensure the air-drying unit is attaining the required dew point temperature. Pigs should be discharged at regular agreed intervals, established from calculations based on the length and internal condition of the pipeline, as well as the ambient temperature of the ground and dew point temperature to be achieved.

Instrument readings at the receiving end should commence when there are no further signs of moisture being expelled or when the pipe begins to discharge dust. Shortly before drying is concluded, the block valve cavities should be purged with dry air/nitrogen by closing partially the mainline valve and venting to atmosphere. The pipeline can be considered to be dry along its whole length when the required dewpoint has been reached at the receiving end. The line should then be closed off and the air drying equipment removed. Air drying consist in the removal of the thin layer of water that has not been removed with the bulk dewatering. The dryness level to be reached depends on the contractor choices and mainly on the kind of purity the material transported requires.

8.3.4 Code of practice for gas transmission pipeline IS328 (National Standards Authority of Ireland, 2003)

*Residual water (litres/km) = 0,37 * the internal diameter of the pipeline in mm.*

8.4 Equipment

Equipment required for drying:

- a **Desiccant Unit** is required, the one planned to be used in this operation has the following characteristics: The equipment should be located at launching station whereas dew-point meters should be located both at the receiving and launching station and eventually even along the line.
- At the entrance of the dry air flow, a **Compressor** and desiccant unit must be provided to deliver air into the line; at the outlet of the pipe air is then discharged into the atmosphere.
  The air compressor must have sufficient capacity to ensure turbulent flow within the pipe length, note that, the lower the pressure the greater will bethe absorption (Shell).
- In the drying phase**, Pigs** are also used with the purpose of displacing the humid air in the line and replacing it with dry air enhancing the transfer of humidity from the pipe towards the air. In the calculations, the presence of the pig should be taken into account taking the volume required in the pipe with a correction factor of 1,1 for each pig used.
- **Dew Point Meter**, shown in *Figure 91 dew point meter probe – vaisala* , is used to verify the attainment of the desired dew point within the line. Dew point, hygrometer and humidity meters are used after a procedure that aims to remove moisture in order to check the effectiveness of the procedure and to verify that the targeted level of dryness has been reached. Those tools are involved after the phases of dewatering, swabbing and drying.
  - Impedance sensors:
    Ceramic sensor absorbs in a first porous layer the water vapour from air: the presence of moisture changes its electrical impedance (resistance or capacitance).
  - Chilled Mirror hygrometer:
    In order to evaluate the humidity level in a gas: the *golden coated mirror* M in contact with gas is automatically (electrically) cooled and the temperature at which condensation occurs is detected by an optical system (*led light source* E and *photodetector* R). It is thus capable of provide the dew point temperature. That is an effective indication of the moisture content of air. It is a precise tool with small sensitivity and indeed high cost.

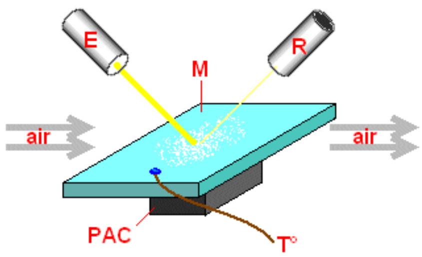

FIGURE 41 SCHEMATIC REPRESENTATION OF HOW A CHILLED MIRROR HYGROMETER WORKS

  - Capacitive hygrometer:
    In this modern humidity sensor, a *dielectric* material like plastic or a polymer is placed between a pair of electrodes. The *capacitance* is determined by the sensor geometry and

the dielectric constant of this material. The dielectric constant changes as the vapour water concentration changes: at normal room temperature, the dielectric constant of water vapor has a value of about 80, a value much larger than the constant of the sensor dielectric material. Therefore, absorption of moisture by the sensor results in an increase in sensor capacitance. Capacitive hygrometer, differently from chilled mirrors, can tolerate dusty environment, however, their poor long-term stability means there is a need for frequent calibration (Paasimaa, 2000), and also, too moist environment may damage the sensor.

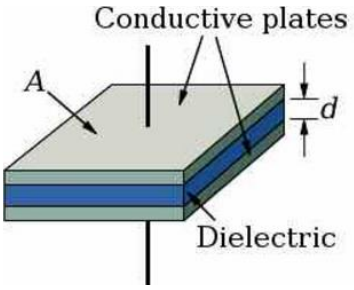

FIGURE 42 REPRESENTATION OF A CAPACITIVE HYGROMETER

- Dark spot technology (only for hydrocarbon):
  It allows to identify almost invisible films of condensate. The film condenses on a particular surface made of a mirror with a central conical depression that is focused by a beam of *red visible light*. The parameter studied is the reflection that the light produces after passing the curve: if it has the shape of a ring it means that something has condensed on the surface. It's an high precision method.

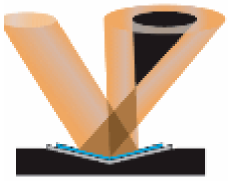

FIGURE 43 SCHEMATIC REPRESENTATION OF DARK SPOT TECHNOLOGY FOR MOISTURE DETECTION

As almost all other instruments, hygrometers also can suffer from *bias* and *long-term drift* (gradual and undesired change in a device); therefore, calibration is essential for accurate measurement. Calibration is the comparison of an instrument against a reference value, that may be a calibrated reference hygrometer: the reference tool can be calibrated in laboratory and must have a calibration certificate; or the calibration of the reference hygrometer can also be done "In the field" by using salt solution to generate known values of relative humidity.

8.4.1 The production of dry air

For the production of dry air, a compressed-air production-and-treatment plant is necessary; all steps are listed and explained below with the annex scheme of the plant in *Figure 44 low dew point air production plant.*

8.4.1.1 Equipment and steps

- Air is drawn from the external atmosphere and it's filtered to remove some particulate matter through the *filter* (A)
- Air is driven into a *compressor* (B) thus reducing the moisture content present
- Air is passed through a *cooling coil* (C): the moisture is removed by condensation; the cooling temperature should not be below 4°C in order to avoid ice formation and damages to the process

but the dehumidification can only happen if the air is cooled below the dew point temperature of the air so that the moisture will drop out of the air in the form of condensate.

- Air can be stored into a *pressurized tank* (D)
- Air is passed into an *oil-removal unit* (E)
- Air is driven into a *desiccant unit* (F) (it can be liquid spry desiccant or adsorbent: the adsorbent is usually regenerated by *heat treatment* (Evaporation of adsorbed water). Most used water *adsorbent* are SiO2, Al2O3 as solid and solutions of organic salts or inorganic compounds like ethylene, glycol for liquid.
- Air is again filtered (G) and it's ready to be delivered

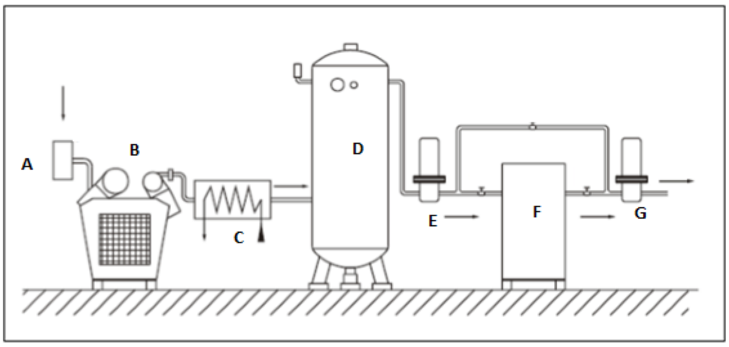

FIGURE 44 LOW DEW POINT AIR PRODUCTION PLANT

8.4.1.2 *Psychrometry of dehumidification to obtain dry air*

All psychrometrical transformations presented above will be schematized using all those reference transformations shown in *Figure 45 possible transformations in psychrometric chart;*

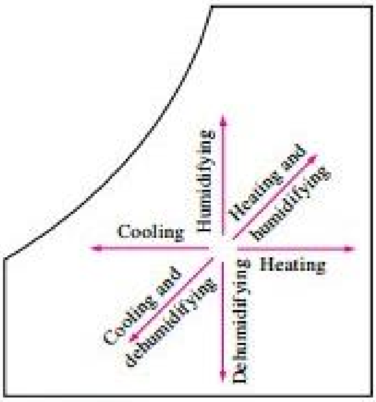

FIGURE 45 POSSIBLE TRANSFORMATIONS IN PSYCHROMETRIC CHART

The path to produce low dew point air is then described below and depicted in *Figure 46 cooling of air :*

- In the stage C (*cooling*), water vapour present in the humid air is condensed and drop out. This can be shown on a psychrometric chart as air is sensibly cooled until dew point temperature is reached (point 1 to 2);
- It's then further cooled to a lower temperature along the saturation curve down (point 2 to 3) where moisture is removed by *condensation* (Ahmed, et al., 1997). Point 3 is called *apparatus dew point* (ADP) of the cooling coil (Zajac, 1997). In the ideal condition, the temperature of the air coming out of the cooling coil will be T3, however, no cooling coil is 100 % efficient so the condition of air coming out of coil be represented by point 4.

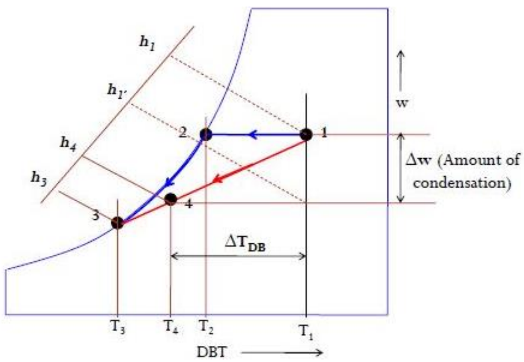

FIGURE 46 COOLING OF AIR

- If then air, at stage F, is passed over a solid absorbent surface or liquid absorbent spray, *heating* and *dehumidification* occur. Water vapour will be taken by the adsorbent material thus reducing the vapour content of the air (dehumidification) from point 4 to point 5 and it will condense out of the air. That means that the latent heat of condensation is liberated which causes the heating of air and therefore the total heat of the air remains constant: air follows a path along a constant enthalpy line as shown in the psychrometric chart below.

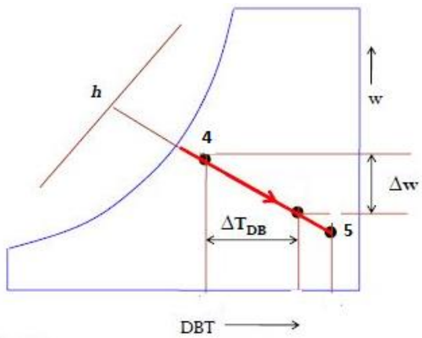

FIGURE 47 DEHUMIDIFICATION BY DESICCANT

8.5 Calculation methods and discussion of results

The constant drying rate has been used in the swabbing phase and also at the beginning of the drying phase: the driving force is the difference in partial pressure of water vapour between the air and the water vapour in the pipe film. This rate of drying will remain constant as long as this inner surface of the "stationary" air film remains saturated.

As evaporation proceeds, the water surface recedes between the valleys of the pipe roughness (made of peaks and valleys), and an increasing suction potential is developed in the liquid: this increased suction potential acts against the evaporation phenomena thus slowing down the drying rate and this is reflected in a falling-rate period of drying.

The phenomena of *swabbing* and *drying* can be qualitatively represented as in series. The swabbing and the drying happens at a constant rate, different one from the other due to different parameters of flow rate and humidity of injected air; at a certain point during the drying, the tendency of water to be absorbed is reduced and thus the drying rate too. This theory subsists according to what stated above in the chapter related to the drying and the time required for the process.

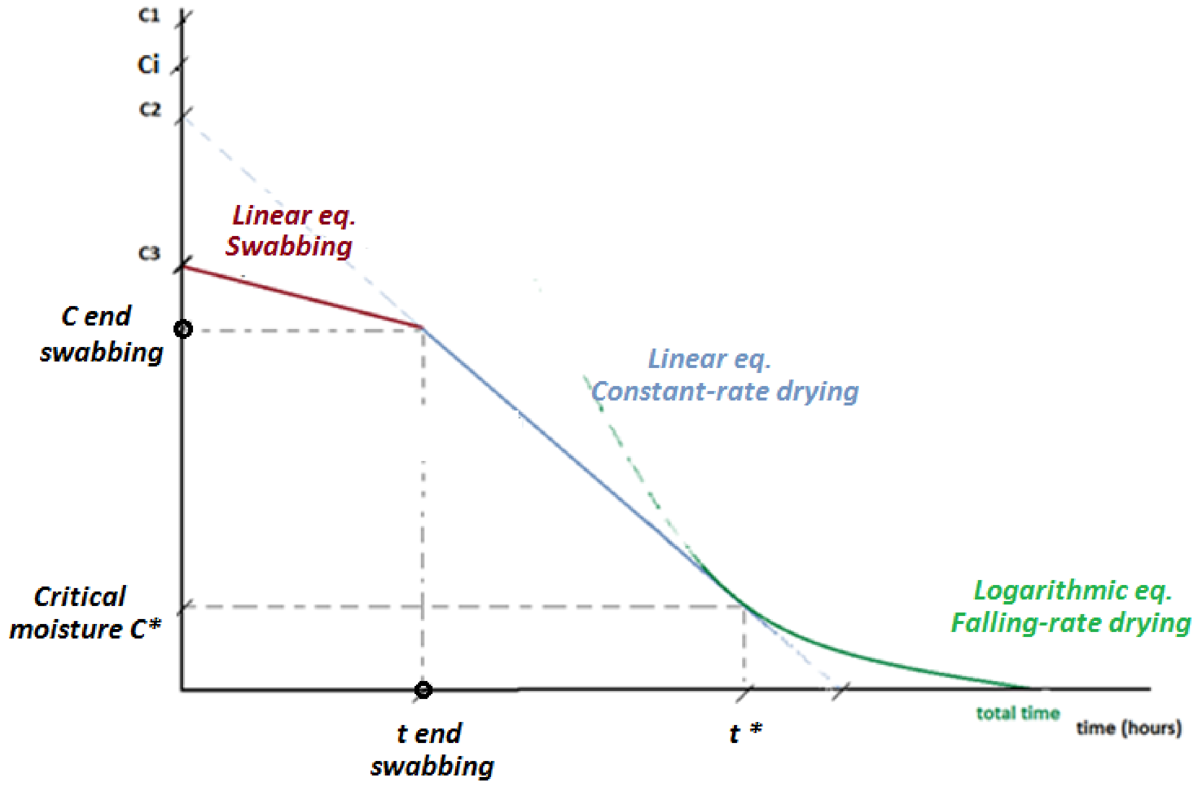

FIGURE 48 QUALITATIVE PLOT RELATED TO THE SWABBING AND DRYING PHASE

A linear equation has been used in combination with a logarithmic equation and an evaluation of the time has been made; the linear equation is taken as for swabbing, but with different parameters. Logarithmic equation is retrieved by integration in *11.3.3*, however, due to a missing data, it's not applicable and another equation coming from purging (Crowl & Louvar, 2002) is instead employed. The two are then used in combination and provide two results very close one with the other.

The total time for swabbing and drying required to dry out the line consists of:

- **54 hours** for swabbing with 7 pigs that is 2,2 days that translated in working days is near 7
- 202-54 hours for drying that is **148 hours**, divided into a linear part (**103 hours**) and a logarithmic part (**45 hours**)

9 Vacuum Drying (alternative of drying with dry air)

Vacuum drying is an *alternative* of drying with dry air to remove all the residual water of the pipeline, and it won't be used in the Scotland GB 022 project; it's usually more energy-consumer and more expensive but very effective. It's the removal of water from a pipeline by reducing the pressure inside it under controlled conditions: by reducing the total pressure until it reaches the value that at the ambient temperature will make the water to vaporize will effectively dry the pipeline (saturated vapour pressure) .
The vacumm drying basically consists of three separated phases plus the soak end test:

- **Pump-down / evacuation:** the pressure in the pipeline is reduced till it induces at the ambient temperature the free water to boil and change into water vapour. If drawdown is performed too rapidly, localized ice patches may form in the pipeline in bottom sections, where water is pooled. (Halliburton, 1997) . The phase takes several hours to end.
- **Evaporation:** As long as the water vaporizes, the evacuation of the air is maintained in order to remove the steam and allowing the vaporization to continue: the rate of vapour evolution will increase resulting in a reduction ìin the rate of pressure decrease (trend nearly horizontal). This phase can take several days to end. After all the free water has evaporated and has been drawn from the pipeline, the rate of pressure reduction start to increase again.
- **Final drying:** when all the water has evaporated, if the evacuation continue the pressure will have no more the rechange from evaporating air: pressure will decrease sharply again.

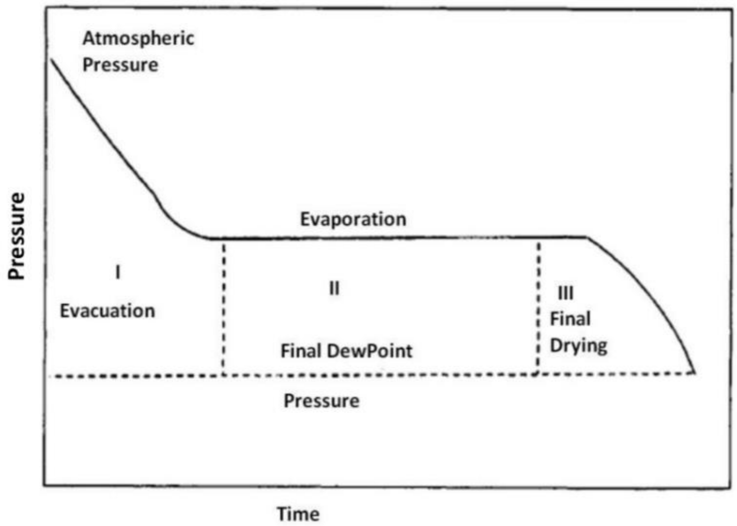

FIGURE 49 VACUUM DRYING PHASES

- **Soak test:** Once the pipeline has been drawn down to lowest practical pressure with a maximum dew point of -20°C, the vacuum plant and instrument spools will be isolated from the pipeline. Accurate pressure monitoring instruments in the required pressure sensibility (0-10 mbar) will be installed at both ends of the line, and all valves will be closed: pressure will be monitored for a period of at least 12 hours. After an initial stabilization there should be no, or very little pressure increase due to possible in-leak; otherwise it means that water is vaporizing in the pipe, thus leading to understand that the pipe has not completely dried. The soak test provides thus proof that vacuum drying is complete.

10 Preservation and inertization

If the product to which is reserved the pipeline is gas, last step required prior to commissioning is the inertization: the atmosphere within the tube has to be with a concentration of oxygen below a well-defined value. One way to create an inert atmosphere inside the pipeline is via pressure purging using Nitrogen at a pressure slightly greater than the atmospheric pressure: the purpose of doing this is the creation of an inert environment with a low concentration of oxygen in order to avoid the generation of a flammable atmosphere within the pipe (it can be a risk at the gassing-up of the line). For liquid product is not necessary the filling of the line with nitrogen but it's sufficient to fill it with dry air at a pressure (defined by technical specifications or scope of work) again above the atmospheric pressure in order to avoid the entrance of humid air from the environment. The main parameters that govern this are the pressure at which the client required the completion of the line and the purity.

10.1 Flammability and the use of inert gases

Noble gases could be used to make inert an environment however they are usually too expensive to be used for inerting and do not perform as effectively as nitrogen; other more common inert gases are *Nitrogen*, *Carbon dioxide, Helium* and *Argon*. Tough CO_2 provides a more effective inerting-effect due to its greater number of atoms, it is capable of reacting with a much larger number of substances than other inerting gases, it's soluble in aqueous products and corrosive in the presence of moisture; furthermore if the pressure drops sharply, carbon dioxide can solidify and finally, CO_2 emission into the atmosphere are linked with environmental issues: that's why nitrogen is usually more used.
One of the main reasons for inerting is to prevent explosions. The following factors are needed for an explosion to occur:

- a flammable substance
- oxygen
- source of ignition.

The risk of explosion can be averted by avoiding the formation of an explosive atmosphere: it can be visualized in the following tertiary diagram (see *Figure 50 flammable region in a system fuel-oxidant-inert*) that shows how reducing oxygen concentration through the use of inert gas and excluding ignition sources can make our environment to fall outside the flammable region of the diagram (Wells, 1997).

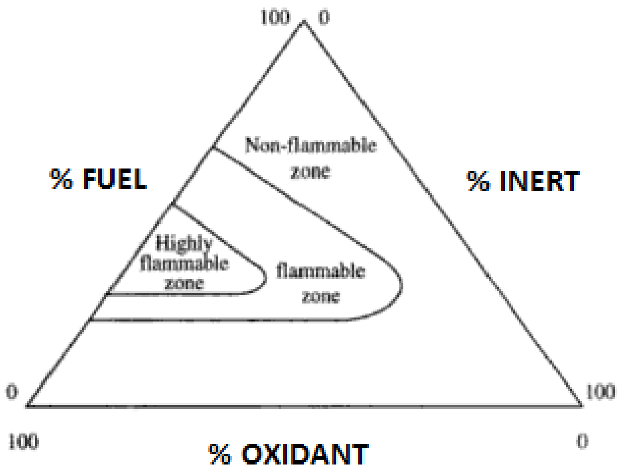

FIGURE 50 FLAMMABLE REGION IN A SYSTEM FUEL-OXIDANT-INERT

10.2 Documents and technical specification

10.2.1 IGE/TD/1 Edition 4 ; Steel pipeline for high pressure gas transmission (The Institution of Gas ENgineers, 2001)

The gas may be supplied in a gaseous form from bottles or be a direct supply pipeline or be in liquid form in tankers, in which case a vaporiser will be required of sufficient capacity to suit the speed of supply.
If gassing up is to take place sometime in the future, the pipeline should be secured in dry air or an inert gas. When gassing up is due to take place, the dewpoint should be re-checked prior to introduction of the gas behind pigs and an inert gas slug. Where it is not practicable to fill a large diameter pipeline section with grout, charge with an inert gas and seal permanently the vent and fill points. Leakage tests should be carried out and pressures checked periodically and re-charged as necessary.

10.2.2 IS 328 Code of Practice for Gas Transmission Pipelines (National Standards Authority of Ireland, 2003)

Every pipeline or section of pipeline to be abandoned shall be totally isolated, be purged of gas and other hydrocarbons and left in an "inert" condition and sealed. The oxygen content of the nitrogen fill shall not exceed 2% at atmospheric pressure after purging. The operating pressure for the nitrogen should be approximately 1,5 bar or the maximum water table pressure plus 0,5 bar whichever is the greater. Purge connections, constructed to the same standard as the sleeve pipe, and incorporating a suitable valve, shall be fitted at each end of the sleeve. They shall be located to enable air and/or water to be removed from the annulus by a nitrogen purge, and may be incorporated into the vent and/or drain connections. The diameter shall not be less than 50 mm at the point of attachment. A sampling system incorporating safeguards against the possibility of high pressure in the annulus shall be provided to permit monitoring of the annulus content

10.3 Equipment

- **Oxygen measurement device**: the device works with an electrochemical galvanic cell (cell where electrical energy is naturally generated by spontaneous redox) that employs an high temperature *ceramic sensor* containing stabilized zirconium oxide. Two electrodes are attached to either side of a solid electrolyte tube: the tube is made of zirconium oxide and filled by gas: it conducts electricity by means of oxygen ions.
- **Nitrogen unit:** Nitrogen may be stored in a tank and then purged in the pipeline for inertization; the purity of the used Nitrogen depends on the level of inertization that has to be achieved in order to leave the pipeline with a safe internal environment and it's usually specified in the client requirement. It's obvious that the impurity of the Nitrogen has to be lower than the impurity (everything apart from Nitrogen) that can be left in the pipeline

10.4 Calculation methods and discussion of results

The method adopted for inerting is the *pressure purging,* shown in *11.4.1* : the nitrogen is introduced under pressure and after its diffusion in the pipeline with the present atmosphere, it's vented out from the enclosure to the open air. More than one pressure cycle is usually necessary (as in our case) in order to decrease the oxygen content down to the safe limit value that ensure a non-flammable and non-corrosive environment. The method is then compared with equations for *sweep-through purging*, presented in *11.4.2* that is the continuous injection of nitrogen in the pipeline and the simultaneous venting of the flow from the opposite site. Both the approaches are taken from literature (Crowl & Louvar, 2002)

11 Calculations and Modelling

All phases of Pre-commissioning have been modelled in different ways according to different methodologies and output will be compared; in the following figure an extreme synthesis of all methods implemented is shown in order to provide to the reader a well-defined path to follow.

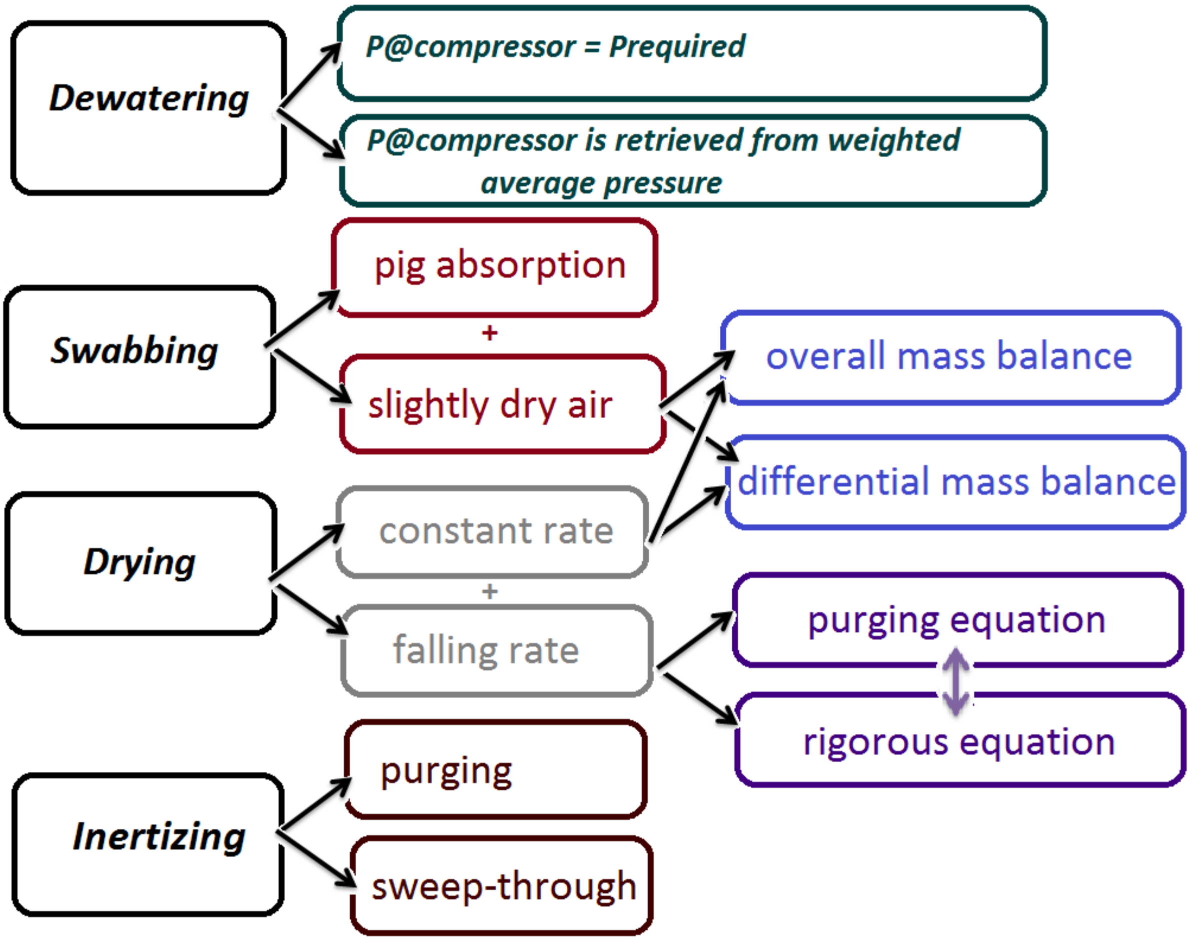

FIGURE 51 SCHEMATIC SYNTHESIS OF MAIN CALCULATION METHODS FOR PRECOMMISSIONING PHASES

On the left are summarized the phases; when the sign "+" is present it means both phenomena are involved in that step and so both require analysis, otherwise, if no sign is present it means that the possible paths of analysis are alternatives one for the other.

11.1 Bulk dewatering

Calculations for bulk dewatering have been made considering section by section, maintaining the same division used for the hydrostatic testing of the line. The compressed air for the process is provided by the compressor mentioned above. Known parameters are the flow rate of the compressor and the volumes of pipeline involved, whereas the unknown that is possible to estimate with the analysis is the time required for the process.
The time-governing feature is the flow rate of air provided by the compressor which will be inversely proportional to the pressure that it provides: pressure and flow rate are related one to the other by the ideal gas law equation; this pressure is somehow related to the pressure required to move the pig, which is given by the sum of the hydrostatic head of the water column plus the atmospheric pressure plus the drop of pressure due to the weight of the pig (only going uphill, assumed equal to 0,5 bar, and negative if going

downhill) plus the backpressure needed to be guaranteed at the outlet (2 bara in our case). Frictional losses of the fluid motion along the pipe are not considered in this estimation.

Pressure required	=	Hydrostatic head (n) +	
		200 000 Pa (2 bar) +	
		50 000 Pa (0,5 barg) +	if going uphill OR
		- 50 000 Pa (0,5 barg)	if going downhill

Where:

$$Hydrostatic\ head\ (n) = \left(h_{\max\ ahead} - h(n)\right) * \rho * g$$

because hydrostatic head at each point (each segment) is obtained by calculating the elevation difference between the point and the highest segment of the line ahead of the point and then shifting it into a pressure value (the higher the column of fluid the greater the pressure at the bottom). In first section for example the highest point coincides with the end, as can be appreciated in the altimetric profile displayed below.
In *Figure 52 Altimetric profile of the section 1 in violet: some hydrostatic heads are shown in red: they refers to the highest point ahead with respect of the direction of the pig, that is at the end* is presented the elevation profile of the first section of the line as an example: in four random points the elevation difference for the attainment/retrieval of the head pressure is shown.

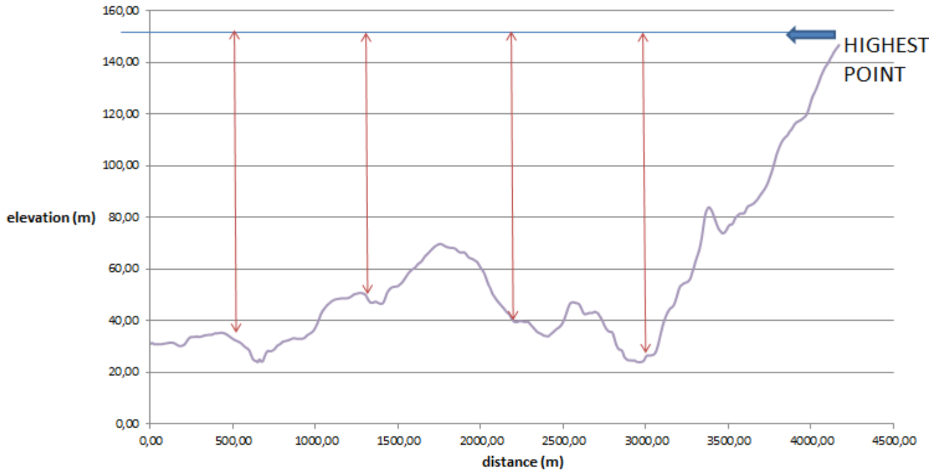

FIGURE 52 ALTIMETRIC PROFILE OF THE SECTION 1 IN VIOLET: SOME HYDROSTATIC HEADS ARE SHOWN IN RED: THEY REFERS TO THE HIGHEST POINT AHEAD WITH RESPECT OF THE DIRECTION OF THE PIG, THAT IS AT THE END

In the following two calculation methods, two different relationships between pressure@compressor and pressure required to move the pig (and the water head) are presented.

11.1.1 Specific pressure calculation

With this first method, the pressure required, obtained as stated before, is applied directly per each 10 meters at the compressed air entrance, so the required pressure to move the pig at a given point is considered as the pressure value that the compressor has to provide.
The pressure required at the compressor is simply set equal at the pressure required to move the pig step by step and the greater is this value to move it further of ΔV, the more is the time required for the compressor to reach that pressure: the state equation of gas is then applied.

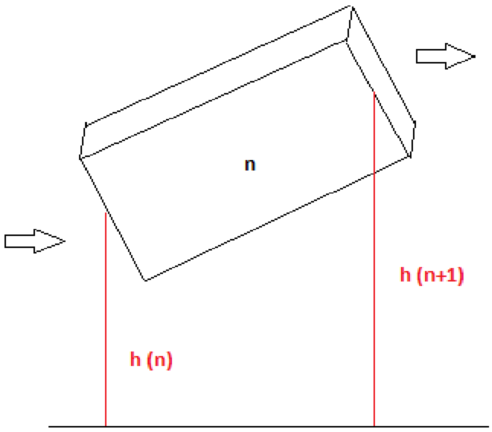

FIGURE 53: REPRESENTATION OF A SEGMENT FOR DEWATERING: THE LINE IS DIVIDED IN THESE SMALL SEGMENTS AND A MASS BALANCE IS APPLIED TO THEM

$$\frac{P_{required}(n) * \Delta V(n)}{Q_{FAD} * P\ atm} = Time\ to\ move\ on\ \Delta V(n)$$

$$Total\ time\ for\ dewatering = \sum_{n=1}^{i} time\ for\ each\ segment$$

Where $\Delta V\ (n)$ is the volume of water in the segment n, whereas Q_{FAD} represent the free air delivery of the compressor that is the flow rate of air taken by the compressor at standard conditions: the compressor will then compress air thus the flow rate effectively delivered will decrease proportionally to the increase in pressure provided (required). The end result gives as output the time required for the emptying of each section which will be proportional to the length of the section and the extent of the water column. For the section 1, 2, 4, 5 it came out that the introduction of another compressor in a parallel-configuration would be necessary to reduce the time to a satisfactory value. Taking $Q_{FAD} = 3060\ m^3 / h$, is it possible to calculate the time in each segment that depends on the pressure required in each segment; results are presented in the left column of *Table 2 time output for dewatering; comparison of two calculation methods*. Diagrams for each section are also attached below.

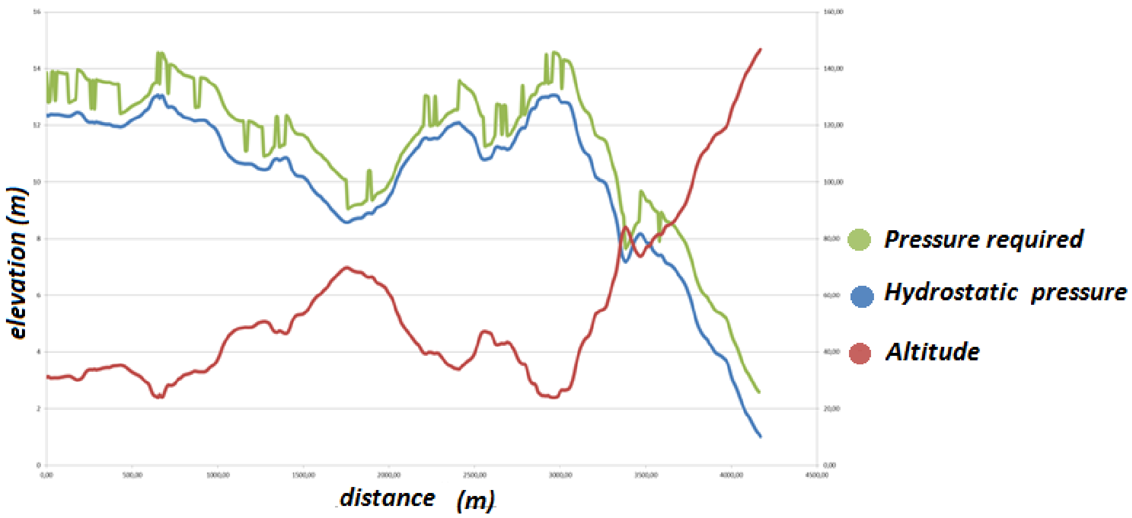

FIGURE 54 BULK DEWATERING, SECTION 1 : COMPARISON AMONG HYDROSTATIC WATER PRESSURE IN BLUE AND REQUIRED PRESSURE OF AIR IN GREEN TO KEEPS THE PIG IN MOTION. RED LINE REPRESENTS THE ALTIMETRIC PROFILE

In the *Figure 54 bulk dewatering, section 1 : comparison among hydrostatic water pressure in blue and required pressure of air in green to keeps the pig in motion. red line represents the altimetric profile* is shown the hydrostatic pressure in blue (inversely proportional to the elevation) and the pressure required to push the pig and displace the water in green: it's possible to see how in the uphill the pressure required is high compared to the hydrostatic pressure (it has to sustains also the weight of the pig) , whereas in the downhill the pressure required is closer to the hydrostatic pressure (obviously lower). Another section analysis is presented:

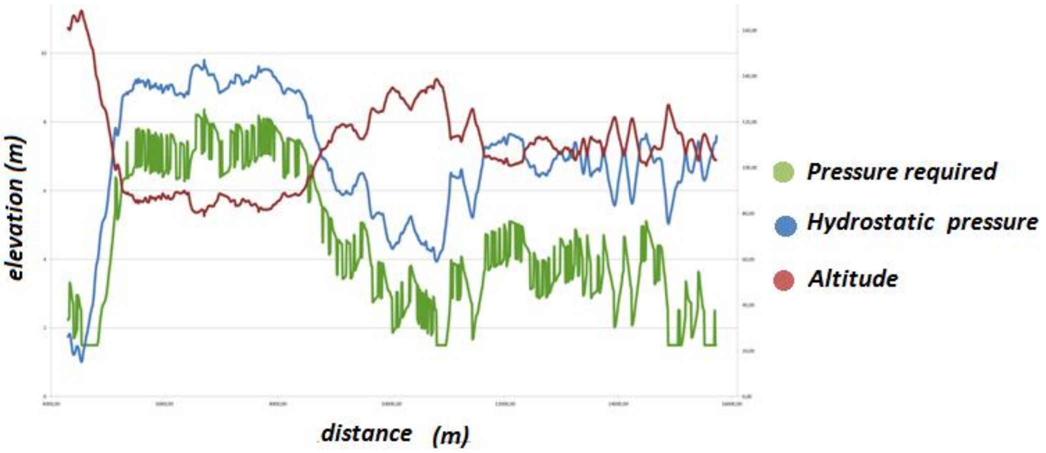

FIGURE 55 BULK DEWATERING, SECTION 2 : COMPARISON AMONG HYDROSTATIC WATER PRESSURE IN BLUE AND REQUIRED PRESSURE OF AIR IN GREEN TO KEEPS THE PIG IN MOTION. RED LINE REPRESENTS THE ALTIMETRIC PROFILE

The section 2 is represented in *the Figure 55 bulk dewatering, section 2 : comparison among hydrostatic water pressure in blue and required pressure of air in green to keeps the pig in motion. red line represents the altimetric profile* : in the plot is shown how the pressure required decreases where the point approaches the highest point (right side and beginning) and increases when the altitude of the point is lower compared to the highest point ahead (left side).
Here below all plots for remaining sections are shown.

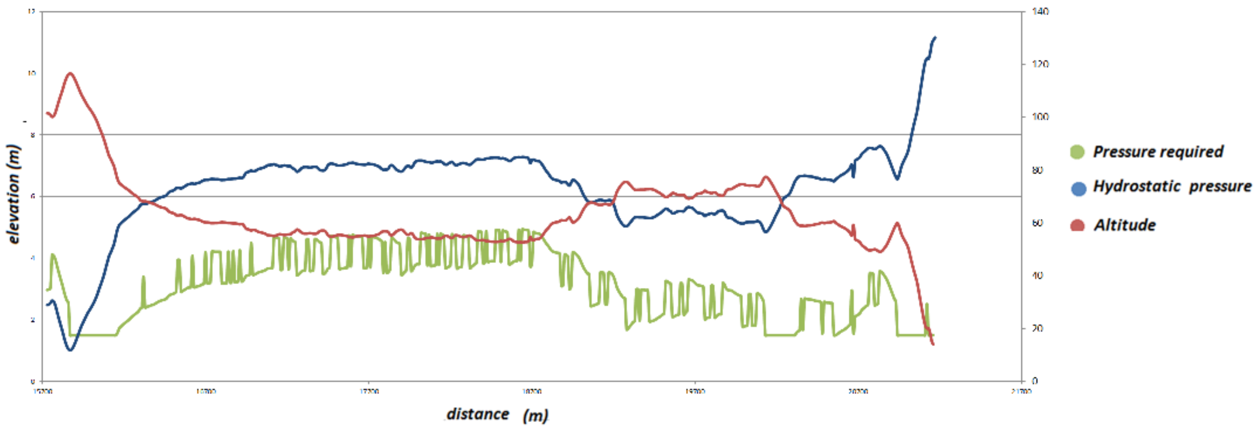

FIGURE 56 BULK DEWATERING, SECTION 3 : COMPARISON AMONG HYDROSTATIC WATER PRESSURE IN BLUE AND REQUIRED PRESSURE OF AIR IN GREEN TO KEEPS THE PIG IN MOTION. RED LINE REPRESENTS THE ALTIMETRIC PROFILE

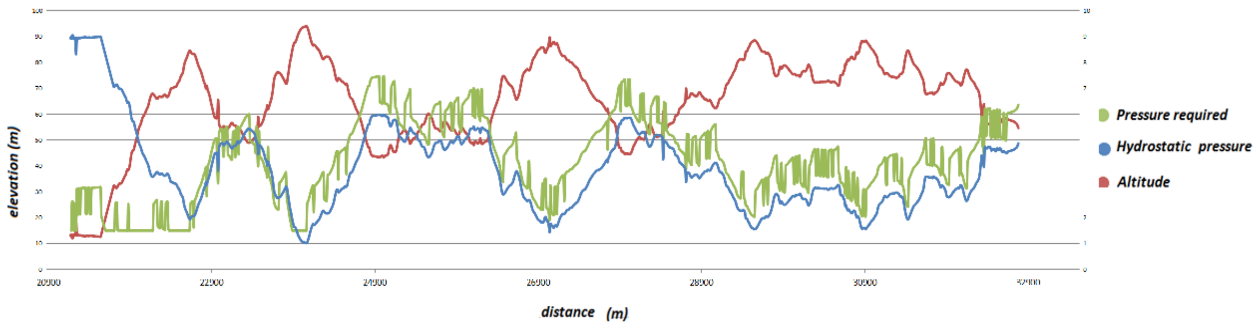

FIGURE 57 BULK DEWATERING, SECTION 4: COMPARISON AMONG HYDROSTATIC WATER PRESSURE IN BLUE AND REQUIRED PRESSURE OF AIR IN GREEN TO KEEPS THE PIG IN MOTION. RED LINE REPRESENTS THE ALTIMETRIC PROFILE

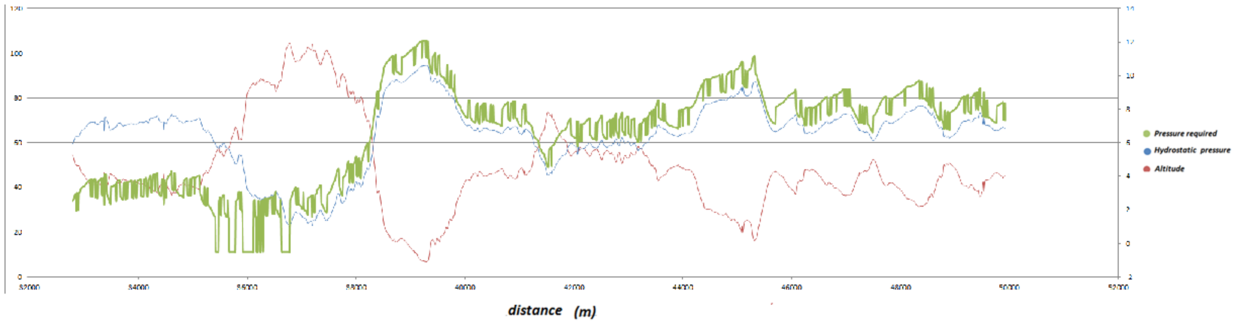

FIGURE 58 BULK DEWATERING, SECTION 5 : COMPARISON AMONG HYDROSTATIC WATER PRESSURE IN BLUE AND REQUIRED PRESSURE OF AIR IN GREEN TO KEEPS THE PIG IN MOTION. RED LINE REPRESENTS THE ALTIMETRIC PROFILE MOISTURE CONTENT OF AIR: TABLES AND CALCULATION

11.1.2 Average pressure required

With this following method a more specific approach is applied, where the required pressure is considered resulting from the weighted average of the new air at the entrance, which will be used to estimate the time, and the already pressurized air injected at the previous step.
When the already present compressed air expands and turns out to provide enough pressure to keep moving the pig, the pressure introduced by the new block of air is assumed as 0 (and same will be the time). By applying the following equation (where P required is the same as per previous method) it's possible to evaluate $P_{\,new\,introduced}$.

$$P_{present} * \sum_{1}^{n} V \; + \; P_{new\,introduced} * V_{n+1} \; = \; new\; P_{required} * \sum_{1}^{n+1} V$$

Then the time for each segment can be obtained by the same previous equation; the total time again can be found by the sum of all segment times:

$$\frac{P_{new\,introduced}(n) * V(n)}{Q_{FAD} * P\;atm} \;=\; Time\;to\;move\;on\;\Delta V(n)$$

$$Total\;time\;for\;dewatering \;=\; \sum_{n=1}^{i} time\;for\;each\;segment$$

Here below are attached plot of pressure required at compressor along the pipeline profile for some section

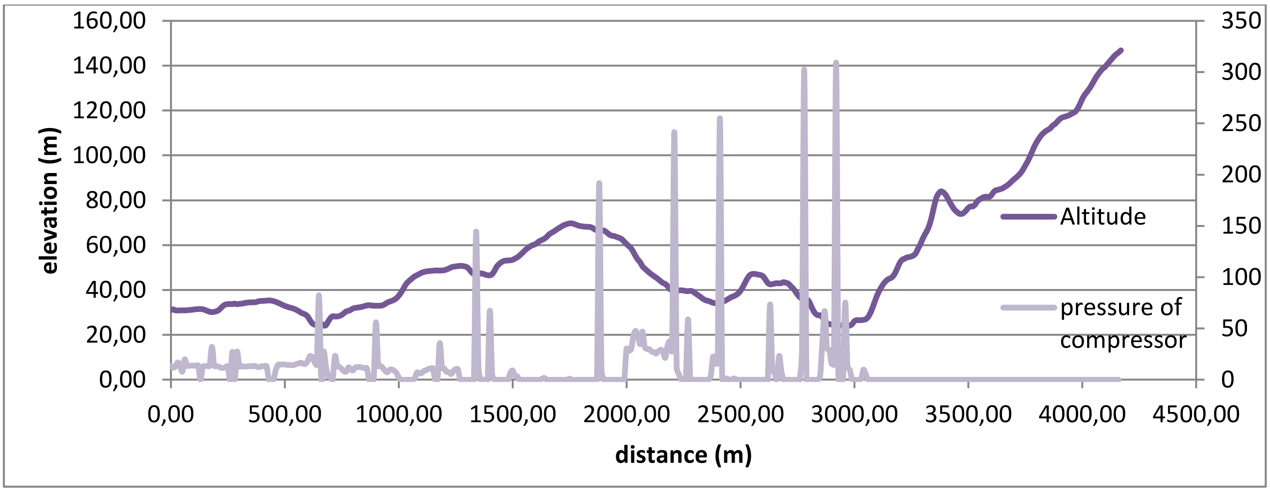

FIGURE 59 SECTION 1 : PRESSURE @ COMPRESSOR REQUIRED FOR DEWATERING

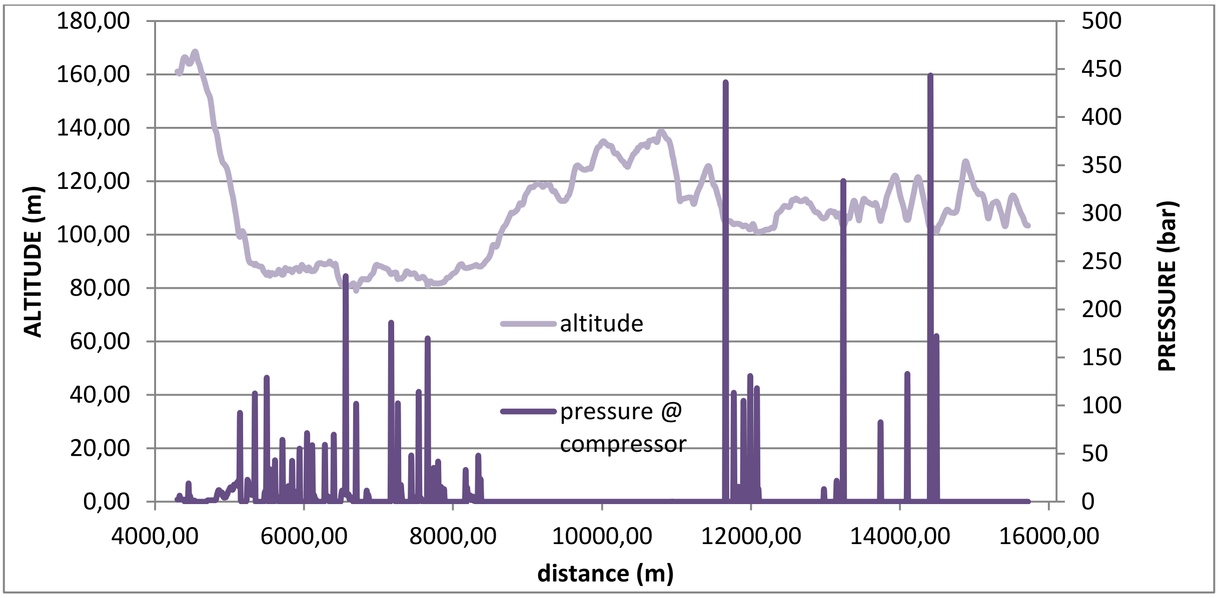

FIGURE 60 SECTION 2 : PRESSURE @ COMPRESSOR REQUIRED FOR DEWATERING

11.1.3 Comparison of two method outputs

As suggested, the time outputs of the two methods turned out to be in the same order of magnitude. In *Table 2 time output for dewatering; comparison of two calculation methods* are shown result.
Apart from the first pipeline section, where the steep uphill slope indicates that a method that takes into account previous pressurization provide favourable results in terms of time, all other section show a slight increase in the time required for their dewatering when calculated with the second method: this is because instead of considering the pressure required applied only at a segment, all the air-filled section behind the pig has been considered in the pressure estimation.

11.2 Swabbing

Calculation adopted for swabbing has the scope to identify the number of foam pigs required to ensure a good level of dryness to better prepare the line for the drying phase; it's also necessary to estimate the time spent for the operation.

The starting point for the calculation of humidity data is the value of partial pressure @ saturation of water in air found in *Table 3 saturation pressure of water VS temperature* available on the books; "*X*" stands for both components, dry air and water.

$$\frac{partial\ pressure\ x}{total\ pressure} = molar\ fraction\ x$$

$$molar\ fraction\ X * total\ moles\ in\ 1m^3 \ = moles\ of\ x\ in\ 1m^3$$

Taking 1000 g of air : $\frac{mass\ of\ air}{molecular\ weight\ of\ air} = moles\ of\ air\ in\ 1\ kg\ of\ air$

$$\frac{moles\ of\ air\ in\ 1\ kg\ of\ air}{moles\ of\ water\ with\ 1\ kg\ of\ air} = \frac{moles\ of\ air\ in\ 1m^3}{moles\ of\ water\ in\ 1m^3}$$

➔ $moles\ of\ water\ with\ 1\ kg\ of\ air * molecular\ weigth\ of\ water = \frac{mass\ of\ water}{mass\ of\ dry\ air}\ \left[\frac{g}{kg}\right]$

➔ $moles\ of\ water\ in\ 1\ m^3 * molecular\ weigth\ of\ water = \frac{mass\ of\ water}{volume\ of\ humid\ air}\ \left[\frac{g}{m^3}\right]$

Temp. (°C)	Pressure (kPa)	Temp. (°C)	Pressure (kPa)
−20	0.10	30	4.24
−10	0.26	40	7.38
−8	0.31	50	12.33
−6	0.37	60	19.92
−4	0.44	70	31.16
−2	0.52	80	47.36
0	0.61	90	70.11
1	0.66	95	84.53
2	0.71	96	87.67
3	0.76	97	90.94
4	0.81	98	94.3
5	0.87	98.5	96.00
6	0.93	99.0	97.75
7	1.00	99.2	98.45
8	1.07	99.4	99.16
9	1.15	99.6	99.88
10	1.23	99.8	100.60
11	1.31	100.0	101.32
12	1.40	100.2	102.04
13	1.50	100.4	102.78
14	1.60	100.6	103.52
15	1.71	100.8	104.26
16	1.82	101	105.00
17	1.94	102	108.78
18	2.06	103	112.67
19	2.20	104	116.67
20	2.34	105	120.8
21	2.49	110	143.2
22	2.64	120	198.5
23	2.81	130	270.1
24	2.98	140	361.4
25	3.17	150	476.0
26	3.36	170	792.0
27	3.56	200	1555
28	3.78	250	3978
29	4.00	300	8592

TABLE 3 SATURATION PRESSURE OF WATER VS TEMPERATURE

It’s worthy to remind the reader that for calculations where pressure is *n* times the atmospheric pressure (1 atm), the *partial water vapour pressure* is increased *n* times as well, whereas the *saturation pressure* remains the same.

11.2.1 Data set and assumptions

Calculus are based on the final target of a dew point in the line of 10°C (in order to reduce as much as possible, the following phase of drying) that, according to documents and empirical data, correspond to a residual thickness of the water film of 50 µm for coated pipe (100 µm in uncoated pipe, where greater roughness makes more difficult for the foam pigs to access to all water “stored” in pores). As the Scotland pipeline is made of coated tubes, the target for swabbing is 50 µm (Shell, 1994) and the initial value is estimated to be the double, 100 µm.

11.2.1.1 Humidity data

Hereafter, are reported in tables all results of calculation used to estimate the moisture content of air in the pipe and in the air injected to propel the pigs, at different pressures and dew point temperature. These data are fundamental for further calculations; the air present in the pipe before swabbing is considered to have a dew point equal to the ambient temperature.

- *Table 4 Air in the pipe before swabbing , if considered at 101325 Pa (atmospheric)* refers to the air in the pipe present before swabbing at atmospheric pressure: in the second table are reported the different portions of dry air and water at a saturation level in different unit measure (volume, partial pressures..) in a specific amount of humid air

Pressure	Dew point Temperature	Volume reference	Total moles in reference volume
Pa	°C	m^3	Moles / m^3
101325	20	1	41.59

	Saturation pressure	Molecular weight	% pressure or moles	Moles tot	Moles in reference vol.	mass	Moles in 1kg
	Pa	g/mol			Moles / m3	g	Moles / kg
Dry air	98988	28,96	0,9769	40,63	40,633	1000	34,53
Water	2337	18,015	0,0230	0,95	0,9593	14,68	0,815

Massic water content on massic dry basis	Massic water content on massic humid basis	Density dry air	Massic water content on volumetric dry basis	Density humid air
g h20/kg dry air	g h20/m3 humid air	g dry air/m3	g h20/ m3 dry air	g humid air / m3
14,68628	17,2818	1204,51	**17,6898**	1,194

TABLE 4 AIR IN THE PIPE BEFORE SWABBING , IF CONSIDERED AT 101325 PA (ATMOSPHERIC)

- *Table 5 Air in the pipe before swabbing, if considered at 202650 Pa (swabbing pressure)* refers to the air in the pipe present before swabbing at 202650 Pa: in the second table are reported the different portions of dry air and water at a saturation level in different unit measure (volume, partial pressures..) in a specific amount of humid air

Pressure	Dew point Temperature	Volume reference	Total moles in reference volume
Pa	°C	m^3	Moles / m^3
202650	20	1	83.18

	Saturation pressure	Corrected pressure	Molecular weight	% pressure or moles	Moles tot	Moles in my reference vol.	mass	Moles in 1kg
	Pa		g/mol			Moles / m3	g	Moles / kg
Dry air	197.976,0	200.313	28,96	0,9885	82,23	82,225	1000	34,530
Water	4.674,00	2.337	18,02	0,0115	0,959	0,959	7,257	0,4028

Massic water content on massic dry basis	Massic water content on massic humid basis	Density dry air	Massic water content on volumetric dry basis	Density humid air
g h20/kg dry air	g h20/m3 humid air	g dry air/m3	g h20/ m3 dry air	g humid air / m3
7,25747	17,2818	2409,03	**17,483**	2,398

TABLE 5 AIR IN THE PIPE BEFORE SWABBING, IF CONSIDERED AT 202650 PA (SWABBING PRESSURE)

- *Table 6 Air used for swabbing, dew point = 10°C, at atmospheric condition* refers to the air used for swabbing at atmospheric condition: in the second table are reported the different portions of dry air and water at a saturation level in different unit measure (volume, partial pressures..) in a specific amount of humid air

Pressure	Dew point Temperature	Volume reference	Total moles in reference volume
Pa	°C	m^3	Moles / m^3
101325	10	1	41.59

	Saturation pressure	Molecular weight	% pressure or moles	Moles tot	Moles in my reference vol.	mass	Moles in 1kg
	Pa	g/mol			Moles / m3	g	Moles / kg
Dry air	100098	28,96	0,987890	41,08877	41,088766	1000	34,53038
Water	1227	18,015	0,012109	0,503666	0,5036655	7,625	0,423273

Massic water content on massic dry basis	Massic water content on massic humid basis	Density dry air	Massic water content on volumetric dry basis	Density humid air
g h20/kg dry air	g h20/m3 humid air	g dry air/m3	g h20/ m3 dry air	g humid air / m3
7,6252637	9,073535312	1204,5168	**9,184**	1,1990

TABLE 6 AIR USED FOR SWABBING, DEW POINT = 10°C, AT ATMOSPHERIC CONDITION

- *Table 7 air used for swabbing, dew point = 10°C, at pressure of injection (202650 Pa)* refers to the air used for swabbing at the pressure of injection: in the second table are reported the different portions of dry air and water at a saturation level in different unit measure volume, partial pressures..) in a specific amount of humid air

Pressure	Dew point Temperature	Volume reference	Total moles in reference volume
Pa	°C	m^3	Moles / m^3
202650	10	1	83.18

	Saturation pressure	Molecular weight	% pressure or moles	Moles tot	Moles in my reference vol.	mass	Moles in 1kg
	Pa	g/mol			Moles / m3	g	Moles / kg
Dry air	201423	28,96	0,9939	82,68	82,68	1.000,00	34,5303
water	1227	18,02	0,00605	0,50	0,50	3,79	0,2103

Massic water content on massic dry basis	Massic water content on massic humid basis	Density dry air	Massic water content on volumetric dry basis	Density humid air
g h20/kg dry air	g h20/m3 humid air	g dry air/m3	g h20/ m3 dry air	g humid air / m3
3,7894066	9,0735353	2409,0336	**9,1288**	2,4035210

TABLE 7 AIR USED FOR SWABBING, DEW POINT = 10°C, AT PRESSURE OF INJECTION (202650 PA)

11.2.2 Mass of water to remove and mass of water uptaken by foam pigs

First, it's necessary to assess of the amount of water up taken by pig, according to the number of pigs used and their absorption capacity, the amount of water present in the pipe, and the difference between the two. Considering 1 barg the backpressure to be maintained during the swabbing we can get the effective flow rate provided by the compressor and the corresponding average effective velocity:

$$Q_{provided} = \frac{Patm * Q_{FAD}}{P_{required}}$$

$$velocity = v_{effective} = \frac{Q\ provided}{Area}$$

$$V_{air} * P_{atm} = V_{effective} * P_{required}$$

Selecting a number of foam pig (by trial) and with the velocity above it's possible to get the time to run the whole line by the last pig, and imposing a distance between pigs (taken from laws) it's also possible to calculate the time between other pigs ahead.

$$time\ for\ last\ pig = \frac{length\ of\ the\ pipe}{v_{effective}} \quad ; \quad time\ between\ pigs = \frac{distance\ between\ pigs}{v_{effective}}$$

Using the formula here below it's estimated the total time for swabbing, during which the compressors run, from which we can estimate the amount of compressed air injected during the whole phase

$$total\ time = (n_{pig} - 1) * (time\ between\ two\ pigs) + time\ for\ last\ pig$$

$$Total\ volume\ of\ compressed\ air = Q\ effective * total\ time$$

The amount of water that needs to be removed by swabbing can be evaluated supposing an initial thickness of the film equal to 100 µm and a final target thickness of 50 µm

$$Volume_{\ water} = V\left[\pi * \left(\frac{d-(2t)-(2t_{w\ after\ swabbing})}{2}\right)^2 - \pi * \left(\frac{d-(2t)-(2t_{w\ initial})}{2}\right)^2\right] * L$$

$$Mass\ of\ water = M_{line} = V * \rho\ water$$

$t_{w\ after\ swabbing}$ = *total thickness of water left after swabbing (target)*
$t_{w\ initial}$ = *total thickness of water present at initial conditions, prior to swabbing*
L = length of the pipe
t = thickness of the pipe
d = diameter

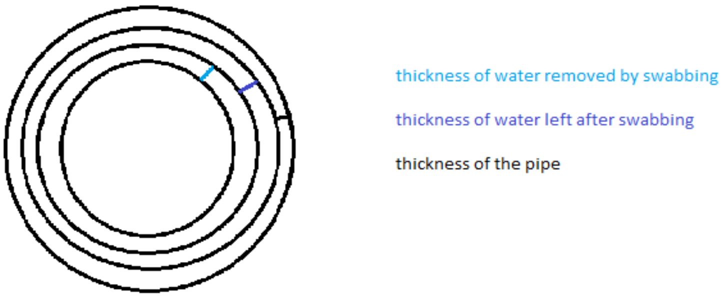

FIGURE 61 GRAPHICAL REPRESENTATION OF THE WETNESS OF THE PIPE

The total amount to remove is given by this value plus humidity present in the pipe minus the humidity that we can leave in; however, the initial amount in air is displaced by the passage of the pipe: only the liquid water minus the humidity in the air we can leave in has to be considered.

$$total\ mass\ of\ water\ to\ remove = M_{tot} = M_{line} + \left(\frac{g}{m^3}\bigg|_{@\ T\ dew\ 20°C} - \frac{g}{m^3}\bigg|_{@Tdew\ =\ 10°C}\right) * V\ pipe$$
$$\cong M_{line} - \left(\frac{g}{m^3}\bigg|_{@Tdew\ =\ 10°C}\right) * V\ pipe$$

Most of the water will be absorbed by the foam pigs as explained above, according to the number used and their absorption capacity (considered equal to 85% in volume of the pig, chosen similar to the one suggested in (Pipeline Engineering & Supply Co. Ltd, 1999), 75%) :

$$Mass\ of\ water\ removed\ by\ pig = M_{pig} = (mass\ absorbable\ by\ 1\ pig) * n_{pig}$$

$$Mass\ of\ water\ left\ that\ needs\ to\ be\ removed = M_r = M_{tot} - M_{pig}$$

11.2.3 Mass balance equation (overall pipeline)

This approach comes from the well-known mass balance equations applied to water in the pipeline system; the rate of water that evaporates from the line is equal to the change in the moisture of the air : the initial water content of air is known whereas the final content is assumed to be equal to the maximum content that air at that temperature can contain (*saturation content*). This method is based on the assumption of a steady-state that can be considered in accordance with reality because the first drying period above the critical moisture saturation happens at a constant rate. The water left (not taken up by pigs) will be absorbed in the bulk of air driven by a difference level in humidity between the compressed air and the air at the first immediate layer above the water. The equation used comes from a mass balance applied at the water vapour and imposing steady-state condition $\frac{dm_{water}}{dt} = 0$).

$$\frac{dm_{water}}{dt} = C_{water\ in} * Q_{\ air\ in} - C_{water\ out} * Q_{\ air\ out} = 0$$

The time required to swab pigs and the flow rate is known: we can arrange the previous equation in the following way (the values in brackets represents the maximum value to which air can be saturated at the temperature of the pipe minus the actual water content of the injected air expressed in term of humidity) :

$$mass\ of\ water\ removable = \left(\frac{g}{m^3}\Big|_{Tdew\ sat=20°C} - \frac{g}{m^3}\Big|_{Tdew=10°C}\right) * Vair$$

The swabbing is considered successful if the amount removable with drying process corresponds to (or overcomes) the value of water left, in other words if the contribution of absorption by foam pigs plus the absorption by drying reach the water removal target value, that means

$$mass\ removable > M_r$$

$$Mass\ not\ removed = Mr - mass\ removable$$

The tables hereafter report the output of evaporation with 7 and 8 pigs. With ten pigs the swabbing phase is proven to be successful because the combined action of the foam pig and the air is capable of removing the unwanted water.

M	M line	Capacity	water	number	M tot	M pig	Mr
Mass liquid	Mass line	Of a pig	absorbed	Foam pig		Removed	residual
Kg	g	%	g / pig		g	g	g
6915.966	6915966	85	850000	7	6637288	5950000	687288
Distance	Q effective	v effective	v effective	Last round time	Added time	Total time	Volume air @ p atm
m	m^3/h	m /h	m /s	h	h	**h**	m^3
14000	1530	2487	0.69	20	5.63	**53.8**	166447

TABLE 8 DATA SET: SWABBING WITH 7 PIG @ 14 KM DISTANCE

Mass removed	Mass not removed	
g	g	NO
676363	10925	

TABLE 9 OUTPUT FOR SWABBING WITH 7 PIG @ 14 KM DISTANCE

M	M line	Capacity	Water	number	M tot	M pig	Mr
Mass liquid	Mass line	Of a pig	absorbed	Foam pig		Removed	residual
Kg	g	%	g / pig		g	g	g
6915.966	6915966	85	850000	7	6637288	5950000	687288
Distance	Q effective	v effective	v effective	Last round time	Added time	Total time	Volume air @ p atm
m	m^3/h	m /h	m /s	h	h	**h**	m^3
15000	1530	2487	0.69	20	6	**56.3**	173902

TABLE 10 DATA SET: SWABBING WITH 7 PIG @ 15 KM DISTANCE

Mass removed	Mass not removed	YES
g	g	
706657.2	-19368.6	

TABLE 11 OUTPUT FOR SWABBING WITH 7 PIG @ 15 KM DISTANCE

As can be seen by comparing the two outputs, the use of 7 pig at a great enough distance is enough to effectively swab the line: the time required is precisely **54,75 hours** (translated into working days is less than 7 days, 8 hours per day). Basically we can rewrite the equation by imposing that the water that can be removed over time (left side) has to be equal to the water that needs to be removed (right hand side):

$$\left(\left.\frac{g}{m^3}\right|_{Tdew\ sat=20°C} - \left.\frac{g}{m^3}\right|_{Tdew=10°C}\right) * Q * time = \left(\left.\frac{g}{m^3}\right|_{INITIAL} - \left.\frac{g}{m^3}\right|_{FINAL}\right) * V_{pipe}$$

$$\left.\frac{g}{m^3}\right|_{FINAL} = \left.\frac{g}{m^3}\right|_{INITIAL} - \frac{\left(\left.\frac{g}{m^3}\right|_{Tdew\ sat=20°C} - \left.\frac{g}{m^3}\right|_{Tdew=10°C}\right) * Q * time}{V_{pipe}}$$

This last equations (application of Boyle's ideal gas law) shows the linear relationship between time and water moisture of the pipe, graphically represented in this way:

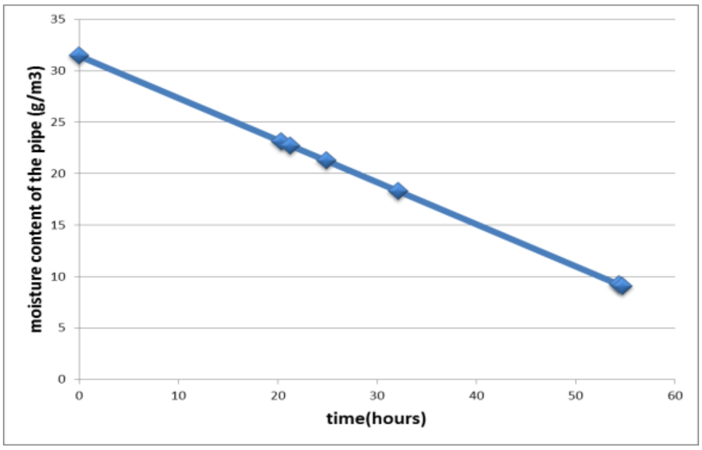

FIGURE 62 MOISTURE CONTENT DECREASES LINEARLY OVER TIME IN SWABBING

Where C initial is $\left.\frac{g}{m^3}\right|_{INITIAL}$ and the slope of the line is $-\frac{\left(\left.\frac{g}{m^3}\right|_{Tdew\ sat=20°C} - \left.\frac{g}{m^3}\right|_{Tdew=10°C}\right) * Q}{V_{pipe}}$. This linear trend fits with the drying explanation of the BC period where the rate in BC remains constant.

11.2.4 Film theory, differential mass balance equations

The main scope of this approach based on the *film theory* is firstly to verify the behaviour of first drying period in the pipeline found with the mass balance equation and secondly to show the spatial behaviour of drying that is, how the rate and the moisture concentration of air changes according to the cross section considered. With *Fick's law* the concept of film theory explained in the previous chapter (it postulates the existence of an equivalent linear concentration profile that extends from the boundary into the bulk fluid) can be quantified into a rate law:

$$N = S * D * \frac{dC}{dz}$$

Where N is the flow, D is the diffusivity coefficient and the derivative refer to the concentration of moisture. By implementing in it the constant gradient of film theory we obtain the flow rate

$$N = S * D * \frac{(C_{film} - C_{bulk})}{z} = S * k_c * (C_{film} - C_{bulk}) \qquad [\text{moles / m}^3]$$

Where D is a diffusivity coefficient, S the exposed surface and k_c is the new term called *mass transfer coefficient* (Basmadjian, 2005). According to the case (and in particular to the driving potential of the transfer), in the table here down are provided different measure units of coefficients and corresponding expression of *flux* (i.e. *rate* per unit surface) (Basmadjian, 2005). The C_{bulk} is the moisture in the air, it is assumed to change along the pipe, increasing up to the saturation level, whereas the C_{film} is constant and equal to the saturation content.

Flux (mol/m² s)	Driving Potential	Mass Transfer Coefficient
Gases		
$N_A/A = k_G \Delta p_A$	p_A (Pa)	k_G (mol/m² s Pa)
$N_A/A = k_y \Delta y_A$	y_A (mole fraction)	k_y (mol/m² s mole fraction)
$N_A/A = k_C \Delta C_A$	C_A (mol/m³)	k_C (m/s)
$W_A/A = k_Y \Delta Y_A$ (kg/m²/s)	Y_A (kg A/kg B)	k_Y (mol/m² s ΔY_A)
Liquids		
$N_A/A = k_L \Delta C_A$	C_A (mol/m³)	k_L (m/s)
$N_A/A = k_x \Delta x_A$	x_A (mole fraction)	k_x (mol/m² s mole fraction)
Conversion Factors		
Gases	$k_G = k_y/P_T = k_C/RT = k_Y/Mp_{BM}$	
Liquids	$k_L C = k_x$	

TABLE 12 RATE LAWS AND MASS TRANSFER COEFFICIENT FOR DIFFUSION

This mass transfer coefficient can be defined as the ratio between the actual mass (or molar) flux of a species into or out of a flowing fluid and can be calculated with the following:

$$k_c = \frac{Sh * D}{d} \qquad [\frac{m}{s}]$$

Our case is the third one in the list shown above in *Table 12 rate laws and mass transfer coefficient for diffusion*; it's important to note that *mass transfer coefficient Kc* is not a material property though it depends also on geometry and flow condition. *D* instead depends on temperature, pressure and nature of system components and has been evaluated using the formula below (temperature expressed in Kelvin, pressure in atm) (Marrero & Mason, 1972):

$$D = 1,87 * 10^{-10} * \frac{T^{2,072}}{P}$$

If we consider the mass transfer from the walls of a circular tube to a fluid, it is the result of the concentration gradient: during the evaporation of water by moving air over the water surface, the energy associated with the phase change is the latent heat of vaporization of the water, and this energy must come from water by lowering its temperature: however, under steady-state conditions, the latent heat supplied by water during its evaporation is equal to the heat supplied to water by surrounding air, which in turn also gets cooled.
Sh in the previous equation represents the *Sherwood number*, that is dimensionless way to express the mass transfer flux: two formula are available according to the condition.

$$Sh = 0{,}023 * Re^{0{,}83} * Sc^{0{,}44} \qquad \text{(Gilliland \& Sherwood, 1934)}$$
$$\text{if } 2000 < Re < 3500 \quad and \quad 0{,}6 < Sc < 2{,}5$$

$$Sh = 0{,}023 * Re^{0{,}83} * Sc^{0{,}33} \qquad \text{(Linton \& Sherwood, 1950)}$$
$$\text{if } 4000 < Re < 70000 \quad and \quad 0{,}6 < Sc < 3000$$

- *Reynold number Re* defines the type of air flow in the pipeline: if greater than 4000, the flow is considered turbulent, if lower is laminar or of transition between the two.

$$Re = \frac{\rho * u * d}{\mu}$$

- *Sc* in the formula for the Sherwood number is instead the *Schmidt number*:

$$Sc = \frac{\mu}{\rho * D_{ab}} = \frac{ability\ of\ the\ fluid\ to\ transport\ momentum\ by\ molecular\ means}{ability\ of\ the\ fluid\ to\ transport\ species\ by\ molecular\ means}$$

In gases, molecular transport of momentum and species occur by similar means, namely, by the random movement of molecules moving from one place to another. While some momentum is transmitted through molecular interactions when two molecules come close to each other, the major contribution is from the movement of molecules themselves, which is the only mechanism for species transport by molecular means. Therefore, Schmidt numbers in gases are typically of the order unity (Coulson & Richardson, 2002). In contrast, in a liquid, molecules are packed closely together, and diffusion is slow, as we know from the order of magnitude of diffusivities in liquids when compared with the order of magnitude of diffusivities in gases. On the other hand, momentum is efficiently transmitted in liquids through molecular interactions with each other. Therefore, Schmidt numbers in liquids are typically three orders of magnitude larger than those in gases.
A scheme of the coefficients used in this approach is depicted in the figure below, with relationship indicated with an arrow.

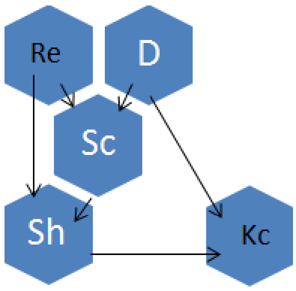

FIGURE 63 : SCHEMATIC RELATIONSHIP AMONG DIFFUSION-TRANSFER COEFFICIENTS

In *Table 13 Calculation for mass transfer coefficients : swabbing* values and coefficients are tabulated.

Length	Width pool	Pressure air	Partial pressure in air	Kynematic viscosity
m	m	Pa	Pa	m^2/s

49959	2.78	202650	1227	0.000015
Density air	Convection mass transfer *D*	Internal surface	Dynamic viscosity	*Reynold number*
kg / m^3	m^2 /s	m^2	kg / m s	
2.4	0.000024	138862.9	0.000036	40504
Diameter	Convection *D* @ 2 bar	*Kc*	*Schmidt number*	*Sherwood number*
m	m^2 /s	m/s		
0.89	0.000012	0.002241	1.26	165.66

TABLE 13 CALCULATION FOR MASS TRANSFER COEFFICIENTS : SWABBING

Analysing the formula (third row of the first table of this subchapter), concentrations have to be expressed in moles/m^3 : C_{film} is the concentration in the layer and is assumed constant and equal to the saturation value, whereas C_{bulk} is known at the entrance and increases along the pipe until it asymptotically reach the saturation value.
The gradient is constant over time in each point along the line because the water in this beginning phase is supposed to be enough to continue to substitute the escaped vapour molecules, but it is different point by point and its maximum is where the difference is greater, e.g. at the inlet : it's a steady-state analysis.
To evaluate the rate, the line has been discretized as it was done for the dewatering calculation, and for each segment it has been imposed a mass balance in order to evaluate the concentration of moisture at the output of each segment and thus retrieve the rate in each segment. Here below is reported a segment of the line and relative calculation.

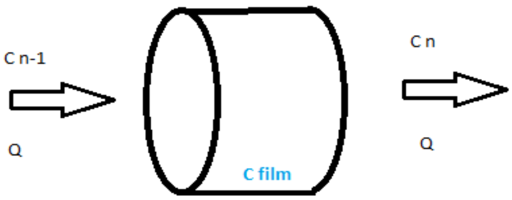

FIGURE 64 : MASS BALANCE IN A REFERENCE VOLUME ΔV OF THE PIPE, SEGMENT : EVAPORATION

$$N_{n-1} = k_c * A * \left(C_{film} - C_{bulk\ n-1}\right) = Q * C_n - Q * C_{bulk\, n-1}$$

The scope is to evaluate Ci that will become the input value for the calculation of C of the next section ;

$$C_n = C_{bulk\, n-1} + \frac{k_c * A * \left(C_{film} - C_{\ bulk\, n-1}\right)}{Q}$$

The last formula has been applied starting from the first piece of the line where $C_{bulk\, n-1}$ was the moisture content of air injected in the pipe and then repeated iteratively on all following sections.
Then it has been possible to evaluate the rates of evaporation for each segment with the formula and multiplying it by the time of swabbing and the molecular weight of water the output is the total water mass amount that can be extracted in that time in that section: the values are then summed.

$$N_{n-1} = \left(k_c * A * \left(C_{film} - C_{bulk\ n-1}\right) \right) * \ Mw_{water}$$

$$mass\ removed = \sum_{n=1}^{m} (N_n * time) \ = \sum_{n=1}^{m} ((A * k_c * \left(C_{film} \ - \ C_{bulk_n}\right)) * \ Mw_{water} * time)$$

As before this mass is compared with the mass required to remove: in *Table 14 mass left in the pipe with 7 pigs after swabbing, 53,8 hours* and *Table 15 mass left in the pipe with 7 pigs after swabbing, 56,2 hours* are reported the estimation of mass removed with 7 pigs, that is then subtracted from Mr, the mass to be removed in order to obtain the grams left in the pipe.

Mass removed	Mass not removed	NO
g	g	
676363	10925	

TABLE 14 MASS LEFT IN THE PIPE WITH 7 PIGS AFTER SWABBING, 53,8 HOURS

Mass removed	Mass not removed	YES
g	g	
706657.2	-19368.6	

TABLE 15 MASS LEFT IN THE PIPE WITH 7 PIGS AFTER SWABBING, 56,2 HOURS

The results obtained perfectly fits with those found with the mass balance equation, the time value to fully swabbing the line perfectly corresponds to the one found before **(54,7 hours).** The other reason to apply this approach was to evaluate how the moisture content of air in the line changes during the path: as expected, the general trend of mass transfer rate decreases along the pipe due to a reduction in the driving difference of the transfer, air becomes more and more wet as it flows through the pipe and absorbs water: this can be visualized in *Figure 65 mass transfer rate (grams / second) along the pipe*

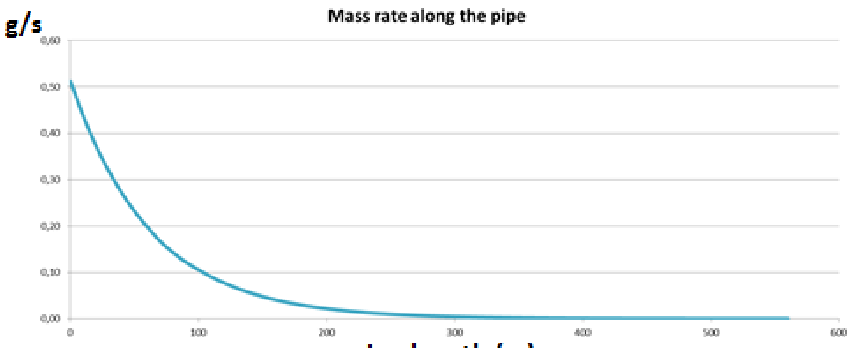

FIGURE 65 MASS TRANSFER RATE (GRAMS / SECOND) ALONG THE PIPE

Displaying how the moisture content in the injected air varies along the pipeline, it's possible to verify the asymptotic behaviour (moisture trend qualitatively remains the same though number of pigs changes) in *Figure 66 : Moisture content of air along the pipe during swabbing:*

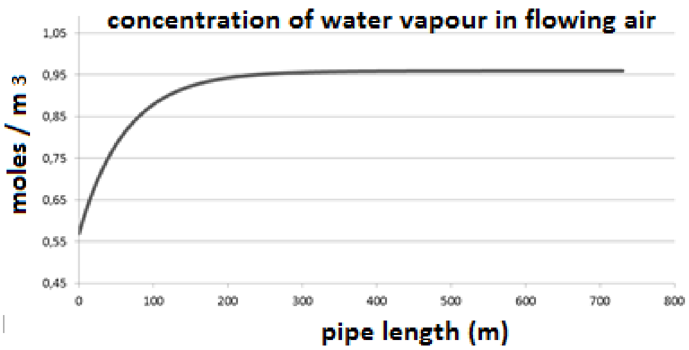

FIGURE 66 : MOISTURE CONTENT OF AIR ALONG THE PIPE DURING SWABBING

The air tends to a moisture content corresponding to the *saturation moisture content* at that temperature: the zone where effectively mass transfer happens is the first half kilometre of the line due to a greater driving

difference, and due to continuous evaporation (regeneration of the film) from water surface, this trend can be considered constant with time.
The result of mass of water removed with this approach confirmed the result obtained with the simple mass balance, that is 54 hours swabbing time with 7 foam pigs is good to remove the predicted water.

11.3 Drying

The steady analysis discussed earlier (in the swabbing phase) is useful when determining the leakage rate of a species through a *stationary layer*. (Cengel, 2002) The steady state analysis can be used as model even in this phase but only until the *critical moisture content* is reached: at this point water becomes more and more difficult to be stripped from the surface, thus leading to a trend in time different from the linear one seen in the swabbing: the approach won't be the same. The moment in which the dynamic changes and the transfer rate of water start to decrease needs also to be determined: this transition point has been determined by setting a law for the falling rate period and defining some conditions at that point: it has been possible then apply the law and calculate the time to successfully complete the drying. Then another law for falling rate period has been mathematically retrieved by integration and the point has been set equal as previously as an input, allowing for the calculation of time required for drying. The two times value coincide.

11.3.1 Data set and assumption

Here below are reported the tables with respectively of characteristic of air present in the pipeline and air injected by compressor: the air at the beginning is assumed to have a dew point of 10°C as obtained with swabbing, the dry air injected has a dew point of -40°C and the targeted dew point is -20°C.

- *Table 16 moisture data expressed in different units for air in the pipe before drying at 101325 Pa* refers to the air present in the pipe at atmospheric condition: in the second table are reported the different portions of dry air and water at a dew point level of 10°C in different unit measure (volume, partial pressures..) in a specific amount of humid air

Pressure	Dew point Temperature	Volume reference	Total moles in reference volume
Pa	°C	m^3	Moles / m^3
101325	10	1	41.59

	Saturation pressure	Molecular weight	% pressure or moles	Moles tot	Moles in my reference vol.	mass	Moles in 1kg
	Pa	g/mol			Moles / m3	g	Moles / kg
Dry air	100098	28,96	0,9879	41,09	41,09	1000	34,53
Water	1227	18,015	0,0121	0,50	0,50	7,62	0,42

Massic water content on massic dry basis	Massic water content on massic humid basis	Density dry air	Massic water content on volumetric dry basis	Density humid air
g h20/kg dry air	g h20/m3 humid air	g dry air/m3	g h20/ m3 dry air	g humid air / m3
7,63	9,07	1204,52	9,18	1,20

TABLE 16 MOISTURE DATA EXPRESSED IN DIFFERENT UNITS FOR AIR IN THE PIPE BEFORE DRYING AT 101325 PA

- *Table 17 moisture data expressed in different units for air in the pipe before drying at 202650 Pa* refers to the air present in the pipe at 202650 Pa: in the second table are reported the different portions of dry air and water at a dew point level of 10°C in different unit measure (volume, partial pressures..) in a specific amount of humid air

Pressure	Dew point Temperature	Volume reference	Total moles in reference volume
Pa	°C	m^3	Moles / m^3
202650	10	1	83.18

	Saturation pressure	Corrected pressure	Molecular weight	% pressure	Moles tot	Moles in reference vol.	mass	Moles in 1kg
	Pa		g/mol			Moles / m3	g	Moles / kg
Dry air	200196	201423	28,96	0,994	82,681	82,681	1000	34,53
Water	2454	1227	18,015	0,01	0,50	0,50	3,789	0,21

Massic water content on massic dry basis	Massic water content on massic humid basis	Density dry air	Massic water content on volumetric dry basis	Density humid air
g h20/kg dry air	g h20/m3 humid air	g dry air/m3	g h20/ m3 dry air	g humid air / m3
3,79	9,07	2409,03	9,12881	2,40352

TABLE 17 MOISTURE DATA EXPRESSED IN DIFFERENT UNITS FOR AIR IN THE PIPE BEFORE DRYING AT 202650 PA

- *Table 18 moisture data of dry air at 101325 Pa* refers to the air used to dry the pipeline at atmospheric condition: in the second table are reported the different portions of dry air and water at a dew point level of -40°C in different unit measure (volume, partial pressures..) in a specific amount of humid air

Pressure	Dew point Temperature	Volume reference	Total moles in reference volume
Pa	°C	m^3	Moles / m^3
101325	-40	1	41.59

	Saturation pressure	Molecular weight	% pressure or moles	Moles tot	Moles in my reference vol.	mass	Moles in 1kg
	Pa	g/mol			Moles / m3	g	Moles / kg
Dry air	101306	28,96	0,9998	41,584	41,5846	1000	34,530
Water	19	18,015	0,00018	0,0077	0,00779	0,11666	0,0064

Massic water content on massic dry basis	Massic water content on massic humid basis	Density dry air	Massic water content on volumetric dry basis	Density humid air
g h20/kg dry air	g h20/m3 humid air	g dry air/m3	g h20/ m3 dry air	g humid air / m3
0,116668	0,140502	1204,5168	0,14052	1,20443

TABLE 18 MOISTURE DATA OF DRY AIR AT 101325 PA

- *Table 19 Maximum saturability of dry air at 101325 Pa* refers to the maximum saturability of air used to dry the pipeline at atmospheric condition: in the second table are reported the different portions of dry air and water (at saturation level) in different unit measure (volume, partial pressures..) in a specific amount of humid air

Pressure	Volume reference	Total moles in reference volume	Dew point Temperature
Pa	m^3	Moles / m^3	°C
101325	1	41.59	20

Saturation pressure	Molecular weight	% pressure or moles	Moles tot	Moles in reference vol.	mass	Moles in 1kg
Pa	g/mol			Moles / m3	g	Moles / kg
2337	18.015	0.023	0.959	0.959	14.52	0.806

Massic water content on massic dry basis	Massic water content on massic humid basis	Density dry air	Massic water content on volumetric dry basis
g h20/kg dry air	g h20/m3 humid air	g dry air/m3	g h20/ m3 dry air
14.523	17.28	1204.52	17.494

TABLE 19 MAXIMUM SATURABILITY OF DRY AIR AT 101325 PA

- *Table 20 Moisture data of dry air at 202650 Pa* refers to the air used to dry the pipeline at 202650 Pa: in the second table are reported the different portions of dry air and water at a dew point level of -40°C in different unit measure (volume, partial pressures..) in a specific amount of humid air

Pressure	Dew point Temperature	Volume reference	Total moles in reference volume
Pa	°C	m^3	Moles / m^3
202650	-40	1	83.18

	Saturation pressure	Correct pressure	Molecular weight	% pressure or moles	Moles tot	Moles in reference vol.	mass	Moles in 1kg
	Pa	Pa	g/mol			Moles / m3	g	Moles / kg
Dry air	202612	202631	28.96	0.9999	83.177	83.1771	1000	34.5304
Water	38	19	18.015	$9.4*10^{-5}$	0.008	0.00779	0.0583	0.003238

Massic water content on massic dry basis	Massic water content on massic humid basis	Density dry air	Massic water content on volumetric dry basis	Density humid air
g h20/kg dry air	g h20/m3 humid air	g dry air/m3	g h20/ m3 dry air	g humid air / m3
0,0583288	0,140502	2409,0336	0,140516	2,40894

TABLE 20 MOISTURE DATA OF DRY AIR AT 202650 PA

- *Table 21 Maximum saturability of dry air at 202650 Pa* refers to the maximum saturability of air used to dry the pipeline at 202650 Pa: in the second table are reported the different portions of dry air and water (at saturation level) in different unit measure (volume, partial pressures..) in a specific amount of humid air

Pressure	Volume reference	Total moles in reference volume	Dew point Temperature
Pa	m^3	Moles / m^3	°C
202650	1	83.18	20

Saturation pressure	Molecular weight	% pressure or moles	Moles tot	Moles in reference vol.	mass	Moles in 1kg
Pa	g/mol			Moles / m3	g	Moles / kg
2337	18.015	0.01153	0.959	0.959	7.217	0.4006

Massic water content on massic dry basis	Massic water content on massic humid basis	Density dry air	Massic water content on volumetric dry basis
g h20/kg dry air	g h20/m3 humid air	g dry air/m3	g h20/ m3 dry air
7.2174	17.2818	2409.034	17.387

TABLE 21 MAXIMUM SATURABILITY OF DRY AIR AT 202650 PA

Considering what is stated in the Shell technical specification, and as explained in the swabbing dedicated chapter, the water film thickness that is assumed to be left in a coated pipe after a good swabbing is 50 µm (0,05 mm) and this value has been used in the equation below to compute the volume and mass of water left in a pipe, starting from this value of thickness:

$$Volume\ of\ water = \left[\pi * \left(\frac{d-(2t)}{2}\right)^2 - \pi * \left(\frac{d-(2t)-(2t_w)}{2}\right)^2\right] * L$$

$$Mass\ of\ water\ M_{line} = volume * \ \rho\ water$$

To this value we should sum the water content present in the air and remove the moisture that can be left in order to find the mass that must be removed; as done before, the initial moisture content can be neglected because pigs will provide to displace it.

$$M_{tot} = M_{line} + \ V * \left(\left.\frac{g}{m^3}\right|_{@T\ dew=\ 10°C} - \left.\frac{g}{m^3}\right|_{@Tdew\ =\ -20°C} \right) \cong M_{line} - \ V * \left(\left.\frac{g}{m^3}\right|_{@Tdew\ =\ -20°C} \right)$$

Those calculations are reported in the table below: the quantity $\left.\frac{g}{m^3}\right|_{@Tdew\ =\ -20°C}$ corresponds to the value of 0,77 g/m^3. Considering 0,5 barg the backpressure to be maintained during the drying, as stated in (Shell, 1994), 0,5 bar the pressure due to the weight of pig and the hydrostatic column of air to sustains, the dry air compressor has to guarantee an operating pressure of 2 bar (sum of previous values). Using this pressure, we can get the effective flow rate provided by the desiccant unit:

$$Q_{effective} \ = \frac{P_{required}}{Patm * Q_{FAD}}$$

Q_{FAD}	Pressure	Q effective	Pressure effective
m^3 / h	bar	m^3 / h	bar
7000	1.01325	3500	2.02650

TABLE 22 FLOW RATE PROVIDED BY THE DESICCANT UNIT

Now we can use as input the number of pig and the distance between pigs in order to obtain the time necessary to propell them; 1,1 is the coefficient used to take into account the presence of pig during the calculation of the volume required.

$$total\ time = \left(n_{pig} - 1\right) * (time\ between\ two\ pigs * 1{,}1) + time\ for\ last\ pig * 1{,}1$$

$$Total\ volume\ of\ air\ V = Q\ effective * total\ time$$

It's worthy to emphasize that all our calculation are based on the selection of the moisture value at which the swabbing is stopped and the drying starts, chosen according to the empirical data of residual water thickness of 0,00005 m that corresponds to a water concentration of 225 g/m^3; this limit is explainable considering that :

- a reducing effectiveness of the sorption due to the too small difference in humidity level between the air in the pipe and the injected air at the end of swabbing
- a limited capability of the foam pig to mechanically strip water off the roughness present in the internal pipe wall.

11.3.2 Purging equation for falling-rate period

The drying phase is supposed to continue from the swabbing phase as a linear process until it reaches a critical point where the tendency for water to be removed by air reduces more and more and the drying rate starts to decrease.
According to what depicted in *Figure 48 Qualitative plot related to the swabbing and drying phase* , *C1* is the intercept of the general logarithmic equation with the Yaxis, *C3* is instead the intercept of the swabbing line with the *Y* axis: it represents the residual water that has not been absorbed by pig. *Ci* represents the total water present in the pipeline. So, the segment $\overline{C_\iota C_3}$ represents the amount of water concentration absorbed in the foam pigs.

- For the **constant-rate drying** we used the equation coming from both the overall mass balance and the differential mass balance, that means assuming that all the air that enters in the pipeline comes out saturated;

$$\left.\frac{g}{m^3}\right|_{FINAL} = \left.\frac{g}{m^3}\right|_{INITIAL} - \frac{\left(\left.\frac{g}{m^3}\right|_{Tdew\ sat=20°C} - \left.\frac{g}{m^3}\right|_{Tdew=-20°C}\right) * Q * time}{V_{pipe}}$$

For the differential mass balance we obtained the following data that rule the mass transfer :

Length		Pressure air	Partial pressure in air	Kynematic viscosity
m		Pa	Pa	m^2 /s
49959		202650	19	0.000015
Density air	Convection mass transfer *D*	Internal surface	Dynamic viscosity	*Reynold number*
kg / m^3	m^2 /s	m^2	kg / m s	
2.4	0.000012	138862.9	0.000036	92646

Diameter	Convection *D* @ 2 bar	*Kc*	*Schmidt number*	*Sherwood number*
m	m^2/s	m/s		
0.89	0.000012	0.00446	1.26	328,95

TABLE 23 CALCULATION FOR MASS TRANSFER COEFFICIENTS : CONSTANT-RATE DRYING

The plot below shows how the dry air injected gradually becomes saturated; the end value of moisture removed, and time required is shown later because it's linked with falling rate period.

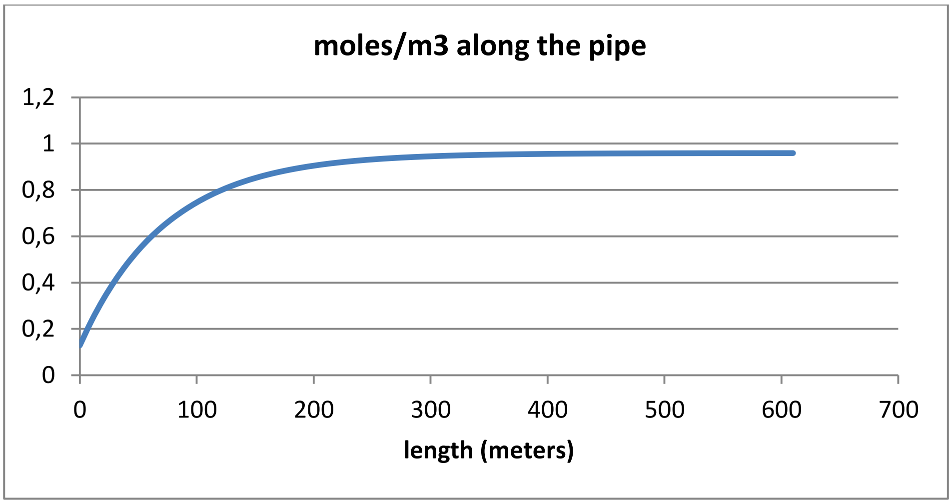

FIGURE 67 MOISTURE INCREASE IN THE INJECTED AIR ALONG THE PATH

- For the **falling-rate drying,** tough there is an analytic procedure to analyse it (see *11.3.3*), we firstly adopted a logarithmic equation used in the nitrogen purging of the line during the inertization phase, where the nitrogen is pressurized in the line displacing the oxygen present; in this case water vapour is the element that needs to be displaced and the time required is the time to fill a given volume V at the fixed pressure, where this volume V is equal to the Volume of the line multiplied by the following coefficient *n*, that express the number of cycles.

$$n_{cycles} = \frac{\ln\left(\frac{y_f}{y_i}\right)}{\ln\left(\frac{P_l}{P_h}\right)}$$

Pl and *Ph* are respectively the Low and High pressure inside the pipe. *Yf* and *Yi* represent respectively the molar ratio of water in the air left after swabbing and present before swabbing (corresponding to partial pressures of water in both case) : the initial value is calculated by supposing that the water to be removed is all at the gaseous state plus the water effectively present in the air (this term can be deleted because again it will be displaced by the pig), whereas the final value is the water left in the air. Formula are stated below:

$$C_i = \frac{M_{line\ to\ be\ removed}}{V} + \left.\frac{g}{m^3}\right|_{Tdew=10°C} \cong \frac{M_{line\ to\ be\ removed}}{V} \quad \rightarrow \ y_i$$

$$C_f = \left.\frac{g}{m^3}\right|_{Tdew=-20°C} \quad \rightarrow \ y_f$$

By applying the Ideal gas law and introducing the n factor it's possible to calculate the time

$$n * V_{line} * P_{in} = Patm * V_{air\ required\ @\ P\ atm}$$

$$time = \frac{V_{air\ required\ @\ P\ atm}}{Q_{atm}} = \frac{\ln\left(\frac{y_f}{y_i}\right) * V_{line} * P_{in}}{Patm * \ln\left(\frac{P_l}{P_h}\right) * Q_{atm}};$$

$$\ln\left(\frac{y_f}{y_i}\right) = \frac{Patm * \ln\left(\frac{P_l}{P_h}\right) * Q_{atm} * time}{V_{line} * P_{in}} \rightarrow \frac{y_f}{y_i} = e^{\frac{Patm * \ln\left(\frac{P_l}{P_h}\right) * Q_{atm} * time}{V_{line} * P_{in}}}$$

$$\rightarrow y_f = y_i * e^{\frac{Patm * \ln\left(\frac{P_l}{P_h}\right) * Q_{atm}}{V_{line} * P_{in}} * time}$$

At the critical point (expressed by asterisk, or pedis letter C in the figures) where the drying rate changes, two conditions have to be imposed:

- At that time (point C) the concentration according to the linear equation is equal to the concentration according to the logarithmic equation

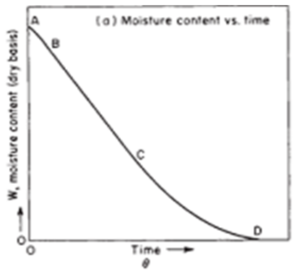

FIGURE 68 DECREASE IN CONCENTRATION OVER TIME

- At that time (point C) the rate of drying in the linear equation has to be equal to the rate in the logarithmic equation (after that time, the rate will decrease)

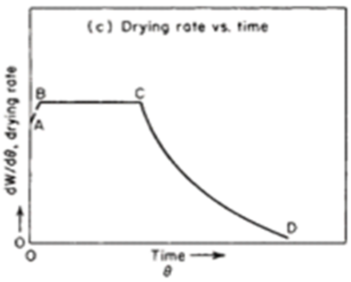

FIGURE 69 RATE OF MASS TRANSFER OVER TIME

The two conditions can be expressed with the systems below:

- $$\begin{cases} C^* = C_1 * e^{\ln\left(\frac{1}{2}\right) * \frac{Q_{drying}}{V} * t^*} \\ C^* = C_{end\ swabbing} - \frac{\Delta C_{drying} * Q_{drying}}{V} * \left(t^* - t_{end\ swabbing}\right) \end{cases}$$

- $$\begin{cases} \left.\frac{dC}{dt}\right|_{t=t^*} for\ linear\ eq. = -\frac{\Delta C_{drying} * Q_{drying}}{V} \\ \left.\frac{dC}{dt}\right|_{t=t^*} for\ logarithmic\ eq. = C_1 * e^{\ln\left(\frac{1}{2}\right) * \frac{Q_{drying}}{V} * t^*} * \ln\left(\frac{1}{2}\right) * \frac{Q_{drying}}{V} \end{cases}$$

Where ΔC_{drying} is the difference in humidity content of air between injected air and air and saturated air at ambient conditions: it acts like a gradient for moisture motion. Solving systems, we obtain:

- $$C^* = -\frac{\Delta C\ _{drying} *\ Q\ _{drying}}{V} * \frac{1}{\ln\left(\frac{1}{2}\right) * \frac{Q_{drying}}{V}} = 25\ \frac{g}{m^3}$$
- $$(\ C_1 = f(\ C^*\ ) \cong 7*10^6 \frac{g}{m^3}\ )$$

Having the value of C* we can represent the linear trend of drying, that follow the linear equation from the initial concentration of 225 $\frac{\mathrm{g}}{\mathrm{m}^3}$ to the final 25 $\frac{\mathrm{g}}{\mathrm{m}^3}$; and then applying the logarithmic concentration from 25 $\frac{\mathrm{g}}{\mathrm{m}^3}$ to the end target concentration 0,77 $\frac{\mathrm{g}}{\mathrm{m}^3}$. From both it's possibile to retrive the time.

- *Total time (h)* to reach the target $\cong$ **54 (swabbing)** + **[103 (linear drying) + 45 (log drying)]** **= 54 + (103 + 45) = 202 hours**

The number of passages of pigs can be chosen according to the time for drying (148 hours).
With the red, blue and green plots, are reported in *Figure 70 complete swabbing and drying compared with drying only. initial water thickness 0,00005 meters* respectively the swabbing phase, drying phase and the nonlinear period of the drying.

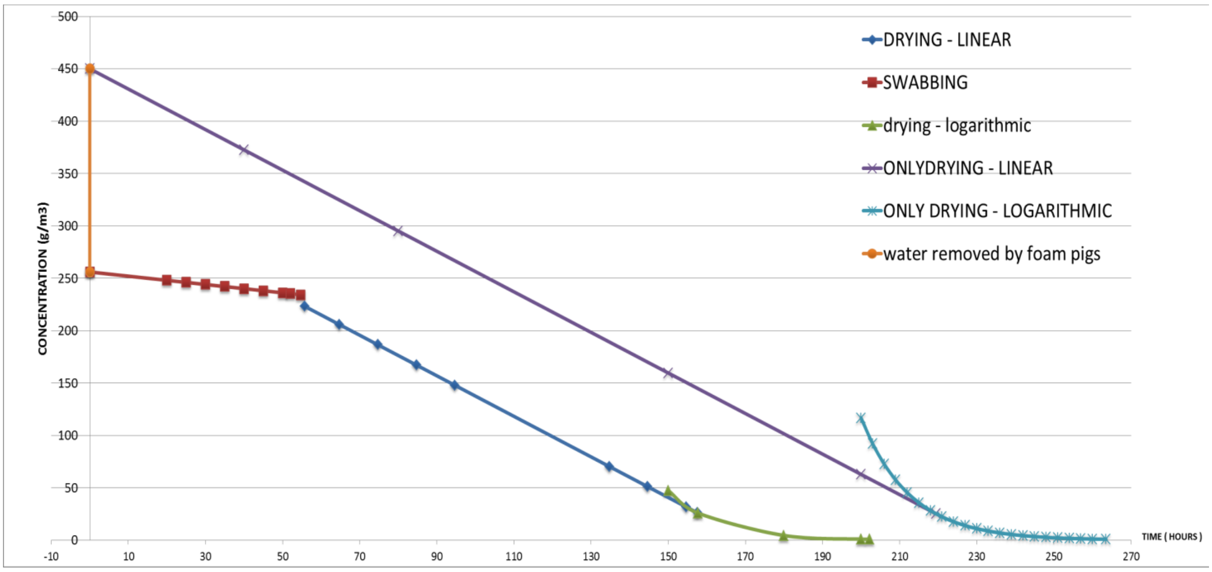

FIGURE 70 COMPLETE SWABBING AND DRYING COMPARED WITH DRYING ONLY. INITIAL WATER THICKNESS 0,00005 METERS

The vertical amount in orange represents the water absorbed by foam pigs during swabbing. The violet and ligth blue lines on the upper-rigth side represents the drying as if it was done alone without swabbing: as it can be appreciated by the figure, the time required in this case is greater and the energy required to run those compressors with higher flow rate and the cost to produce air with that low dew point is highly greater than the energy consumption involved in the splitted procedure.
As can be appreciated from figure, the passage from linear trend to logarithmic trend is smooth, as presented in the figure before (*Figure 68 decrease in concentration over time*); here down in *Figure 71 drying rate change over time according to the "two drying period"* is also attached the rate change according to the calculation with partial pressure values: it is similar to the one found in theoretical books (*Figure 69 rate of mass transfer over time*).

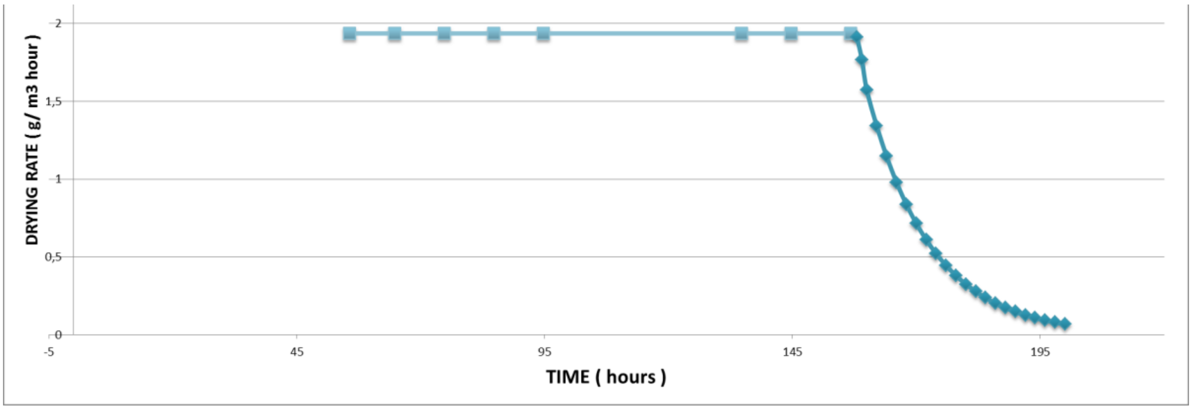

FIGURE 71 DRYING RATE CHANGE OVER TIME ACCORDING TO THE “TWO DRYING PERIOD”

11.3.3 Alternative Rigorous method for falling-rate period modelling

In this short chapter is presented the rigorous analytic way to estimate the passage from the constant rate drying to the falling rate drying; it’s a mathematical study that is not employed in the thesis because of a lack of a data, that is the *critical moisture content* of the steel surface. However, in case of future findings, the following approach can be adopted. In this chapter the subscript *c* stands for *critical*, though in some previous chapter it was indicated with an asterisk.
In *Figure 72 three main plots used to represent the behaviour of drying in the two period: constant rate and falling rate* are represented the three main plots that qualitatively explain the drying in its two main phases; the cross-disposition of the three is functional for the comprehension because parameters on the axis too are criss-crossed.

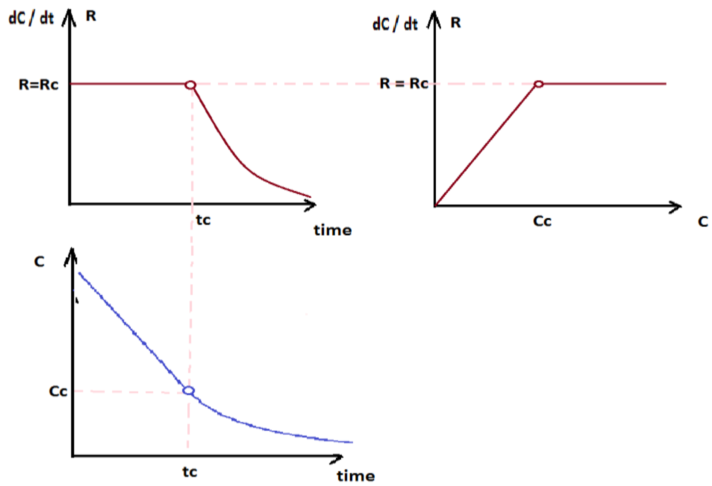

FIGURE 72 THREE MAIN PLOTS USED TO REPRESENT THE BEHAVIOUR OF DRYING IN THE TWO PERIOD: CONSTANT RATE AND FALLING RATE

The diagrams on the left have already been presented at the beginning of the chapter, the third one is introduced only now and taken from literature. (Moyers & Baldwin, 1999)
The starting point for the mathematical analysis is the **constant-rate period**: the rate is given by the following equation and, being constant, it will be also equal to the rate at the last point of the constant-rate period, that is the rate at the critical moisture level, *Rc.*

$$R = \frac{dC}{dt} = Rc$$

From this equation we can perform integration within a general interval in the constant-rate period:

$$\rightarrow\ dt = \frac{dC}{R} \quad \rightarrow \quad \int_1^2 dt = \int_1^2 \frac{dC}{R} \quad \rightarrow \quad \int_1^2 dt = \frac{1}{R}\int_1^2 dC \quad \rightarrow \quad t_2 - t_1 = \frac{C_2 - C_1}{R}$$

Then is possible to analyse the **falling-rate period**: from the second plot on the right, we can retrieve this linear- equation: $R = m * C$ where m is the slope and it's equal to $m = \frac{Rc}{Cc}$; from that we can estimate the following derivatives that will be used in the further integration.

$$dR = m * dC \quad \rightarrow \quad dC = \frac{dR}{m}$$

Now we can integrate and apply the substitution because of the no-more-constant R :

$$\int_1^c dt = \int_1^c \frac{dC}{R} \quad \rightarrow \quad time = \int_1^c \frac{dR}{m * R} = \frac{1}{m} * ln\,\frac{Rc}{R_1} = \frac{Cc}{Rc} * ln\,\frac{Rc}{R_1}$$

Then, to calculate the total time to reach a dry condition 1 in the falling rate period we also have to add the time of constant rate (*tc*)

$$total\ time\ to\ reach\ state\ 1 = tc + \frac{Cc}{Rc} * ln\,\frac{Rc}{R_1}$$

Expanding the concept to a general dry condition after the critical moisture content Cc, we have:

$$total\ time = tc + \frac{Cc}{Rc} * ln\,\frac{Rc}{R}$$

Where $R = C * \frac{Rc}{Cc}$, so it can also be expressed as

$$total\ time = tc + \frac{Cc}{Rc} * ln\,\frac{Rc}{C * \frac{Rc}{Cc}} = tc + \frac{Cc}{Rc} * ln\,\frac{Cc}{C}$$

From this equation we can explicit C:

$$(total\ time - tc) * \frac{Rc}{Cc} = ln\frac{Cc}{C} \quad \rightarrow \quad C = Cc * e^{-(total\ time - tc) * \frac{Rc}{Cc}}$$

By combining the equation of C = f (t) and R = f(C) we can retrieve the equation of R = f(t) that is

$$R = C * \frac{Rc}{Cc} = Cc * e^{-(total\ time - tc) * \frac{Rc}{Cc}} * \frac{Rc}{Cc} = Rc * e^{-(total\ time - tc) * \frac{Rc}{Cc}}$$

We can plot the three equations in a 3d space: they can be considered the projections on the three-orthogonal plane of the *tri-dimensional drying path* (line), as represented in *Figure 73 3D representation of the total drying path with all projections on the three orthogonal plans.*

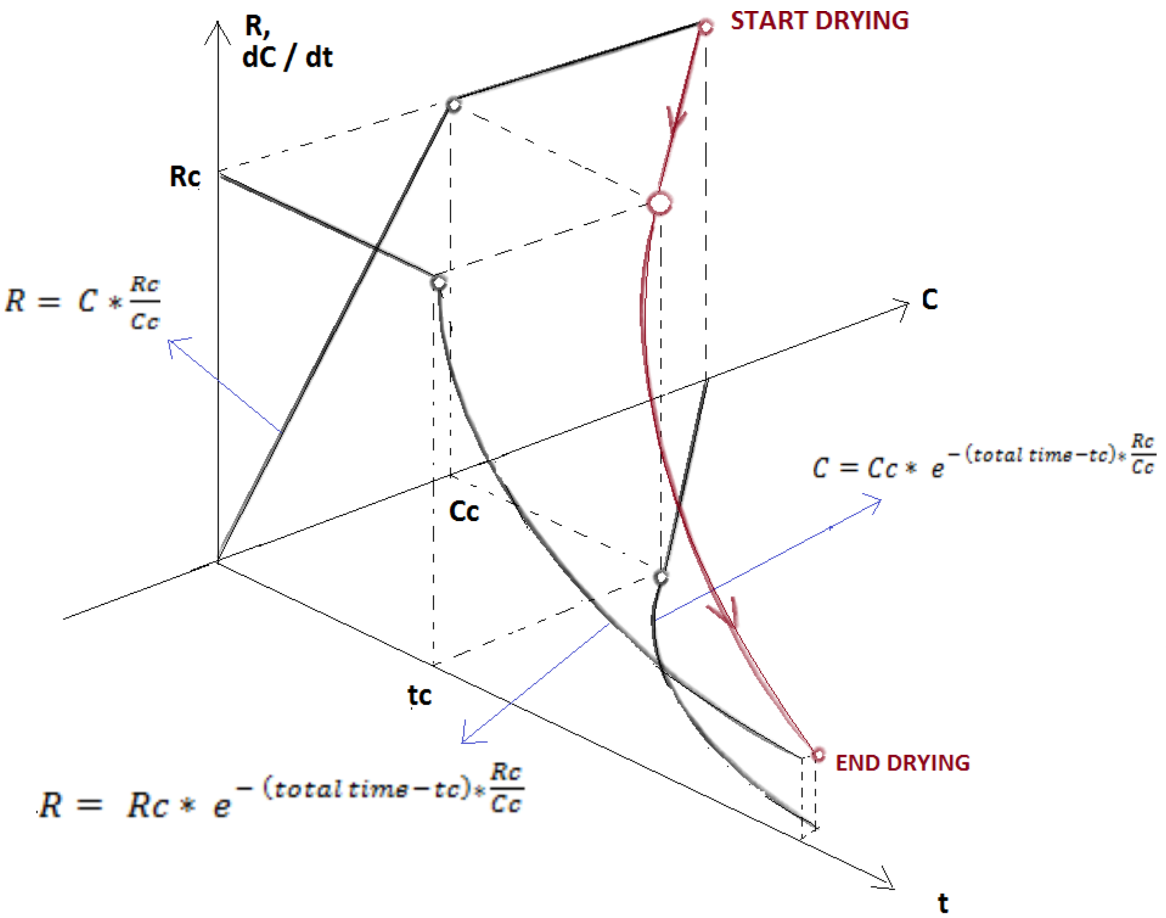

FIGURE 73 3D REPRESENTATION OF THE TOTAL DRYING PATH WITH ALL PROJECTIONS ON THE THREE ORTHOGONAL PLANS

Only one information is missing in order to complete this work and that's why it is employed in the calculations only now: Cc or tc (one is in function of the other according to the second to last equation). Knowing this value for steel at the pipeline condition we could estimate the falling rate period with this sequence of calculation:

Cc → constant-rate eq. $C = f(t)$ to find tc
→ falling-rate eq. $C = f(t)$ to find time according to the target C
(→ eventually falling-rate eq. $R = f(t)$ to find the rate at which I stop drying)

The following question arises: would the time be different if the critical moisture value for concentration is put equal to the one adopted in the previous calculation? And how the time changes according to a change in the critical moisture value of concentration? For sure due to a different trend, if the critical moisture content is higher, the constant-rate of drying will be shorter, and the total drying time will be increased; the opposite is true for a smaller critical moisture content. Let's see in the table the summarization of this.

Critical Moisture Content *Cc*	Critical time *tc*	TOTAL TIME *(swabbing + both drying periods)*
g / m3	h	h
10	165	178.7
20	160	194.1
25	***157.6***	***202.9***
30	155	212.1
40	149	232

TABLE 24 APPLICATION OF THE ALTERNATIVE METHOD FOR THE FALLING RATE DRYING PERIOD: TIME RESULTS ARE SHOWN ACCORDING TO DIFFERENT CRITICAL MOISTURE VALUES

From the *Table 24 application of the alternative method for the falling rate drying period: time results are shown according to different critical moisture values* we can also compare the result of this method that can be inferred by the bold-type row in the table above with the end result of the previous calculation method: the error between them is completely negligible (202,1 VS 202,9 hours). From the other rows of the table we can appreciate how the time value varies according to a different critical moisture content *Cc*.
It's fair to consider results of this evaluation quite satisfactory.

11.4 Inertization

Here below are applied from the manipulation of gas equations different formula (Crowl & Louvar, 2002) to estimate the time for inertization, according to two different procedures: the pressure purging and the sweep-through purging.

11.4.1 Pressure purging

The methods adopted for inerting is called *pressure purging*: the purge gas is introduced under pressure and after its diffusion inside, it's vented out from the enclosure to the atmosphere. More than one pressure cycle *n* is usually necessary (as in our case) in order to decrease the oxygen content down to the safe limit value that ensure a non-flammable and non-corrosive environment.
Here below is described the procedure taken from manipulation of gas laws

- component A in the vessel, *Xa*
- component B in the vessel, *Xb* (it needs to be displaced)
- component A in the purging gas,
- component B in the purging gas (it will be in very low quantities)

$$n_{tot}\, before\ purging = \frac{P_{low} * V}{RT}$$

$$n_{A\,present} = X_{A\,purge\,gas} * \frac{P_{low} * V}{RT} \qquad and \qquad n_{B\,present} = X_B * \frac{P_{low} * V}{RT}$$

$$n_{tot}{}'after\ purging = \frac{P_{high} * V}{RT}$$

$$n_{added}\, with\ purging = \frac{(P_{high}-P_{low})*V}{RT} \quad \text{made of :}$$

$$\rightarrow\ n_{A\,added}\, with\ purging = n_{added} * X_{A\,purge\,gas}$$

$$\rightarrow\ n_{B\,added}\, with\ purging = n_{added} * X_{B\,purge\,gas} \cong 0$$

$$X_{B\,end} = \frac{n_{B\,added}\, with\ purging + n_{B\,present}}{n_{tot}} \cong \frac{n_{B\,present}}{n_{tot}{}'}$$

$$\text{That is} \quad = \frac{X_B V \frac{P_{high}-P_{low}}{RT} + X_B V \frac{P_{low}}{RT}}{\frac{V * P_{high}}{RT}} = X_B \left(\frac{P_{high}-P_{low}}{P_{high}}\right) + X_B \frac{Plow}{P_{high}}$$

And when the purge gas has a negligible concentration, it becames $$X_{B\ end} = X_B \frac{P_{low}}{P_{high}}$$

And $$X_{B*}\left(\frac{P_{initial}}{P_{final}}\right)^n = X_{B\ end}$$

$$\ln\left(\left(\frac{P_{initial}}{P_{final}}\right)^n\right) = \ln\left(\frac{X_{B\ end}}{X_B}\right)$$

$$n * \ln\frac{P_{low}}{P_{high}} = \ln\left(\frac{X_{B\ end}}{X_B}\right)$$

$$n = \frac{\ln\left(\frac{X_{B\ end}}{X_B}\right)}{\ln\left(\frac{P_{low}}{P_{high}}\right)}$$

Where *n* in the *number of cycles* (immission of volume) in the pipeline. $V\ required = n * \frac{P_{atm} * V_{pipe}}{P}$

Here below in *Table 25 data and time output of the inertization* are tabulated the calculations:

Final O_2 concentration	Pressure initial	Pressurization value	Initial oxygen volume	Total volume O_2
%	Bar	Bar	%	m^3 @ atm
2	1	2	20	613815
Ln (P/p')	Ln (c/c')	Number of cycles (excess approximation)	Volume nitrogen	Q_{FAD} compressor
			m^3 @ atm	m^3 / h
-0.69	-2.3	4	245526	4000
Time required				
hours		days		
61.4		2.6		

TABLE 25 DATA AND TIME OUTPUT OF THE INERTIZATION – PRESSURE PURGING

11.4.2 Sweep-through purging

In this different type of procedure, the purge gas is injected continuously through the pipeline and running inside it is capable to progressively displace the internal atmosphere;

$$\frac{P * V}{R * T} = n\ ; \ \frac{dn}{dt} = 0 \quad \rightarrow \quad \dot{n}_{flow\ in} - \dot{n}_{flow\ out} = 0$$

$$\dot{n}_{flow\ in} = \frac{P * \dot{V}_{flow\ in}}{R * T} = \dot{n}_{flow\ out}\frac{P * \dot{V}_{flow\ out}}{R * T} \quad \rightarrow \quad \dot{V}_{flow\ in} = \dot{V}_{flow\ out}$$

By introducing the mole fraction of the species that needs to be diluted (oxygen):

$$\frac{d\,(n * Xb)}{dt} = X_{flow\ in,\ b} * \dot{n}_{flow\ in} - X_{flow\ out\ ,\ b} * \dot{n}_{flow\ out}$$

$$= X_{flow\ in,\ b} * \frac{P * \dot{V}}{R * T} - X_{flow\ out,\ b} * \frac{P * \dot{V}}{R * T} \quad \rightarrow \quad V * \frac{dX}{dt} = \dot{V} * (X_{flow\ in,\ b} - X_{flow\ out,\ b})$$

There's then the need of introducing a factor to take into account of the non-ideal mixing between gases, f, it varies from 1 to 1/10 in the worst mixing case.

$$\dot{n}_{flow\ out,\ b} = X_{flow\ out,\ b} * \dot{n}_{flow\ out} = f * Xb * \dot{n}_{flow\ in} + (1-f) * X_{flow\ in,\ b} * \dot{n}_{flow\ in}$$

$$\rightarrow X_{flow\ out,\ b} = f * Xb + (1-f) * X_{flow\ in,\ b}$$

I can use it to perform a substitution in the previous formula

$$\rightarrow \quad V * \frac{dXb}{dt} = \dot{V} * [X_{flow\ in,\ b} - (f * Xb + (1-f) * X_{flow\ in,\ b})]$$

$$\frac{dXb}{dt} = -\frac{f * \dot{V}}{V} * \left(Xb - X_{flow\ in,\ b}\right)$$

Integrating the two members of eq, we get $\ln\left(\frac{Xb(t1) - X_{flow\ in,\ b}}{Xb(t2) - X_{flow\ in,\ b}}\right) = -\frac{f * \dot{V}}{V} * (t1 - t2)$

$$\boldsymbol{time} = -\frac{\mathrm{V}}{f * \dot{V}} * \ln\left(\frac{Xb(t1) - X_{flow\ in,\ b}}{Xb(t2) - X_{flow\ in,\ b}}\right)$$

By performing calculation with this procedure, we get different time values according to the chosen f, but the order of magnitude is the same as the one of the value obtained for pressure purging (64 hours)

Conc. % O_2 in N_2		Conc. % O_2 initial		Conc. % O_2 final target		
0,01		20		2		
f	/	1	1/2	1/3	1/4	1/5
time	*hours*	17,2	35,4	53,1	70,8	88,5

TABLE 26 END RESULTS FOR INERTIZATION – SWEEP-THROUGH PURGING

12 Appendix A - Main Reference Company (technical) Specifications

In this chapter is presented a review of how the Pre-commissioning should be intended and performed in most of its phases according to major Oil&Gas companies. The chapter has been divided according to these companies: *Shell, Halliburton, Eni, Snam*, and for each one the main specification for relevant phases of the Pre-commissioning are reported.

12.1 Shell (Shell, 1994), (Shell, 1994)

12.1.1 Pre-commissioning

Pre-commissioning is defined as the phase in the pipeline industries that includes dewatering, cleaning, drying and preservation of the pipeline; *Pre-commissioning* should commence either immediately after completion of hydrostatic test or immediately prior to commissioning as specified in the scope of work pipeline elevation, density of the fluid, back-pressure at the receiving end shall be taken into account when calculating the required inlet flows and pressures for the driving medium. The control of the pig speed shall be assisted by maintaining a back-pressure of 1 barg for liquids and 3 barg for gases: this pressure shall be increased when necessary to avoid acceleration of the pig in downhill sections.

12.1.2 Dewatering

Dewatering by gravity is not permitted. All pipelines should be dewatered by at least two high sealing pigs, with at least two guiding and four sealing discs: if the drying medium is nitrogen glycol or methanol one run is required, if the propelling medium is air the number of required runs is two.

- First dewatering run: The travelling speed of the pig shall be between 0.5 and 1 m/s whereas the backpressure should always and everywhere along the pipe be kept at least 1 barg above the ambient pressure.
- Second dewatering run (what we defined swabbing): the speed should be in the same range as stated above; the dew point of the air for pigging shall be at least 5° C below the minimum ambient temperature along the pipeline measured at 1 barg. Foam pigs are involved after the passage of one high sealing pig and dewatering should continue until pigs come out completely dry.

12.1.3 Swabbing

The number of foam pigs suggested depends on the length of the pipeline that require swabbing and on the presence or absence of coating:

- 0,8 pig/km coated
- 1,2 pig/km if uncoated

Backpressure during pigging should be 0.5 barg; after the swabbing, the dew point of the line shall be at least 5°C below the minimum ambient temperature along the line measured at 1 bar g.
Velocity of the foam pig shall be less than 1,2 m/s and density of the foam pig has to be between 30 and 50 kg/m3.

12.1.4 Cleaning

Final water cleaning shall be carried out in combination or before the first dewatering run. Pigging shall continue until two consecutive pigs, the last brush and the high sealing disc pig of a train arrive without debris and no debris has been sampled at the discharge end during run. Final cleaning of carbon steel pipelines shall be concluded by a run with a magnetic cleaning pig.

- Low velocity water cleaning (between 0.5-1 m/s) shall be carried out by pigging the pipeline with pig trains consisting of a series of brush cleaning pigs followed by a high sealing disc pig;

- High velocity water cleaning shall be carried out by continuously pumping water at a minimum of 3 m/s of velocity till no debris is sampled at the discharge end; cleaning shall be considered complete when no debris is sampled at the discharge end whilst replacing the line content at the specified velocity.
- Low velocity air cleaning shall be carried in combination with dry air pigging: pig trains consisting of a series of brush cleaning pigs following by a high sealing disk pig at a speed between 0.5-1 m/s, with a air with the same dew point as the one used for drying.
- High velocity air cleaning shall be carried out after dry air drying: dry air shall be purged continuously through the pipeline at a minimum velocity of 10 m/s in a quantity sufficient to replace the volume of the pipeline three time at the purging pressure.

12.1.5 Drying

Experience has shown that for practical purpose, a dew point of -20°C is attainable but further drying is not economically viable except for short lines or special cases. At the beginning of the line though the pressure is very high, even the temperature and the dryness of air is high thus improving the level of the absorption; going on with the drying, the efficiency is reduced due to a decrease in temperature and dryness of air, except at the outlet of the pipe where the pressure is very low due to pressure drop leading again to a good efficiency (this will be further explained with the representation of *Figure 39 maximum saturability of air in drying with dry air depending on the position along the pipe*) . Not all moisture can be removed, only the free one can be dried: the equilibrium moisture is the limit to which a pipeline can be dried under specific conditions. This bound-to-pipe water may exist under several conditions (it can penetrate fine capillaries where it will exert an abnormally low vapour pressure due to high concave curvature of the surface): the greater the pipe roughness the higher the level of moisture retention in the pipe.

- Air or nitrogen drying: air introduced into the pipeline should have a *dew point* of at least 15°C below the final dew point of the pipeline as specified in the scope of work. If nitrogen is used for drying, it shall have a dew point below -50°C at atmospheric pressure. The pipe should be pigged at a *velocity* below 1.2 m/s, keeping a *backpressure* of at least 0.5 barg; the pigging for drying shall be performed by high sealing disk pigs in combination with foam pigs: pigging shall continue until the dew point of the drying medium at the receiving end remains below the dewpoint specified in the scope of work and does not fluctuate by more than 3°C whilst replacing the content of the line by a pig. The air compressor must have sufficient capacity to ensure that turbulent flow is maintained throughout the pipe length, note that, the lower the pressure the greater the absorption. After pigging the pipe should be purged with the drying medium with a minimum velocity of 3 m/s, till the dew point measured at the discharge remains below the desired one. Upon completion, the pipeline shall be blocked-in for at least 12 hours at 0.5 barg all along the line: if the measure after this period provides a dew point below the desired, the process is considered successfully completed.

  The sizing and calculation of drying equipment shall be based on a film thickness of the residual water of not less than 0,1 mm for uncoated pipe and 0,05 mm for coated pipe.
- Vacuum drying: the final dew point of the dry pipeline shall be -20°C, which is equivalent ot a pressure of 1 mbar (abs), unless otherwise specified in the scope of work.

12.1.6 Inerting

The final pipeline pressure to be achieved at the end of operation of air filling shall be 0.5 barg; pipeline can be filled with super dry air or nitrogen.

12.2 Halliburton (Halliburton, 1997)

12.2.1 Pre-commissioning

Halliburton defines *Pre-commissioning* as a wider set of phases involving cleaning, gauging, removing weld spheres, filling, pressure testing, dewatering and drying. Pre-commissioning begins after completion of construction activities. *Commissioning* follows *Pre-commissioning* and begins with the introduction of the product into the pipeline, followed by packing (raising the pipeline to operating pressure).

12.2.2 Dewatering

It's good to perform dewatering in order to save expenditures in the whole Pre-commissioning phase. This is because it's easier and less expensive to remove water during dewatering than it is to remove it by any of the drying techniques. The less water left as a film after dewatering and swabbing, the less the rime required to vaporize out that film in the drying phase.
It's recommended to always maintain a *backpressure* during dewatering operation in order to prevent water in the pipeline from moving ahead of the pig and creating accumulated head: those heads are several different water columns due to on-going of water along downhill that represent gaps in the continuity of the fluid and increase the energy required for the dewatering.
In Halliburton it's made a distinction between two main dewatering phases:

- Bulk dewatering: train of pigs propelled by air, it's the removal of the main body of water left in the pipeline after hydrotesting
- Residual dewatering (swabbing): another train of pigs propelled by air; the train contains some foam pigs which help in water removal

As a guideline, 1% of the pipeline *length between pigs* is enough to ensure that the pigs will not collide; however, if the internal surface of the pipe is abnormally rough and could produce excessive wear on the pig discs, the distance should be increased up to 1,5% of the whole length. For short pipeline the minimum distance between pigs is 200m.
Unless specified otherwise, the most suitable *velocity* for a dewatering pig train is 0,6 m/s.
The formula proposed for dewatering calculation by the Halliburton manual is:

Dewatering pressure = $pig\ differential + water\ friction + hydrostatic\ head + backpressure$

It's easier and less expensive to remove water during dewatering than it is to remove it by any of the drying techniques. The efficiency of dewatering determines the time required to dry the pipeline. The less water left in the pipeline after dewatering, the shorter the time required to reach the specified level of dryness.

12.2.3 Drying

Drying to a specified moisture content is required for pipelines designed to carry the following products: dry gas, sour gas or crude oil, gas or oil containing CO_2, fuel. It is also required for the following pipeline:

- pipelines fed into other lines or systems with specified moisture content
- pipelines with end facilities with molecular sieves
- pipelines requiring liquid knock-out in service

Drying to a specified moisture content is normally accomplished through one of the following methods:

- Dry air: super dry air is passed through the pipeline, possibly in conjunction with foam pigs; super dry air absorbs water that remains after dewatering. Compressors must have sufficient capacity to ensure that turbulent flow is maintained along the pipeline length to keep water-saturated boundaries away from the walls of the pipe and keep dry air in continual flow. However, the lower the pressure in the pipeline, the greater the absorption of water.
- Nitrogen drying: the mass of water that can be absorbed by a gas is a direct function of the partial pressure of water at system temperatures
- Vacuum drying: it removes all free water from the pipeline, including water in low points and dead legs, film of water and water trapped in interstices. It's performed by reducing the pressure in the pipeline in relation to the temperature: water vaporizes and produces steam (water vapor) when the pressure is reduced sufficiently.

12.2.4 Inerting

After dry-air conditioning and before gas-up, operators inert pipelines by running nitrogen through them: this because mixing gas and air may create an explosive mixture.

12.3 Eni (ENI spa, 2012)

12.3.1 Pre-commissioning

The Eni specifications follows the philosophy of Shell, stating that *Pre-commissioning* involves activities of dewatering, swabbing and possible drying and inerting prior to pipeline *commissioning.*

12.3.2 Dewatering

Dewatering pigs shall be propelled by oil-free compressed air, keeping velocity and pressure in control: speed shall be in the range of 0,5 – 1,5 m/s and dewatering by gravity is not permitted.

12.3.3 Swabbing (residual dewatering)

Swabbing is a sequence of operations carried out in order to eliminate or reduce the residual water into the pipeline after the completion of dewatering, in order to achieve maximum benefit for subsequent drying operation. Swabbing shall be carried out by running pigs propelled by compressed air and their velocity shall be maintained in the range 0.5-1.5 m/s. Pig trains shall contains foam pigs and prior to launching they shall be weighted and measured: each foam pig of 32 kg/m^3 shall be followed by a foam pig of 160 kg/m^3. Swabbing shall be continued till the received pigs do not show any additional pick up water on repeated basis. Prior to start drying operations, water coming out of the pig receiver during final swabbing shall be tested for presence of bacteria: if the presence of bacteria is proven, executor shall run a slug of undiluted biocide to treat the pipeline.

12.3.4 Drying

Drying operations shall commence as soon as possible after residual dewatering and swabbing operation. for the drying with low dew point air, the air shall be passed through the pipe till the dew point is achieved throughout the pipe. For final acceptance the specified dew point in the pipeline shall be maintained for a minimum period of 48h (soak test).

- Drying with dry air: Air introduced shall have a dew point of at least 15°C below the final dew point of the line. Pigging shall continue until the dew point of the drying medium at the receiving end remains below the dew point specified in the scope of work and does not fluctuate by more than 3°C whilst replacing the content of the line by a pig.
- Nitrogen: purity of nitrogen has to be at least 99%, dew point has to be -50°C and oil inside it absent.
- Vacuum drying: all pressure or vacuum retaining Pre-commissioning equipment shall be designed, fabricated, tested and marked, in accordance with recognized standards, for a safe operating pressure of not less than the maximum/minimum pressure predicted during the pre-commissioning.

12.3.5 Inerting

When the pipeline commissioning doesn’t follow immediately the pipeline drying activity, the corrosion risk should be assessed and, if necessary, the pipeline shall be purged and pressurized with dry nitrogen for preservation (when commissioning activities are delayed for more than three months). The section is considered purged if the oxygen content at the remote end is below 2% in volume.

12.4 Snam (SNAM, 2005), (SNAM, 1998), (SNAM, 2005)

12.4.1 Gauging with Kaliper pig

The operator shall excavate in the following points after the caliper run:

- all sections indicated by the caliper tool operator
- all section where ovalities > 4%
- all sections where reduction > 3%
- all other section that committent requires

The committent will then provide to control those points and define whether repair is necessary or not.

12.4.2 Drying

At the beginning of the drying air should be addressed in at the maximum velocity in order to drive out water by lamination; the drying must proceed slowly, paying attention to let air pass through all valves and fitting and bypass in order to flush them out, keeping the dew point measurement controlled at the final head. When a dew point of -20°C is recorded, all valves must be closed and the drying stopped, keeping the line at a pressure of at least 1,2 bar: dew point is then measured every 30 minutes for 8 hours. The successful completion of the drying process is achieved if the dew point for 8 hours hasn't changed.

- Dry air: The drying will be executed with compressed dry air at a dew point lower than -30°C, oil-free. Hygrometers used for the measurement should have precision of ±2°C.
- Nitrogen: when performed with Nitrogen, it has to be 97% pure (at least) and with a dew point not greater than -60°C.
- Vacuum: for Vacuum drying instead, the pumps have to provide a depressurization at a pressure equal to half of the saturation vapour pressure (1,03 mbara). The pipeline will be depressurized until 100 or 200 mbara is reached; then there will be a test to verify the maintainment of the pressure. If the pressure won't increase for 2 hours, the result will be satisfactory, and the depressurization will continue down to 20 mbara.

For coated pipeline, after swabbing and dewatering, the residual water left on the internal surface has a thickness lower than 0,1 mm.

12.4.3 Inerting

Nitrogen will be inserted from the opposite side to the side where the drying has been performed; the quantity of nitrogen inserted has to be at least 1,5 times the volume of the pipeline referred at 20 mbara.

13 Appendix B - Figures

FIGURE 74 PIPELINE ROUTE IN A HOSTILE AND ROCKY SOIL

FIGURE 75 PIPE SEGMENT, STILL DISCONNECTED, ARE LAID PARALLEL TO THE FUTURE ROUTE

FIGURE 76 COLD BENDING MACHINE IS BENDING A PIPELINE SEGMENT

FIGURE 77 WELDING PROCEDURE TO JOIN TUBES

FIGURE 78 LOWERING-IN OF THE PIPE BY SIDEBOOMS

FIGURE 79 LOWERING-IN OF THE PIPE BY SIDEBOOMS ALONG A STEEP SLOPE

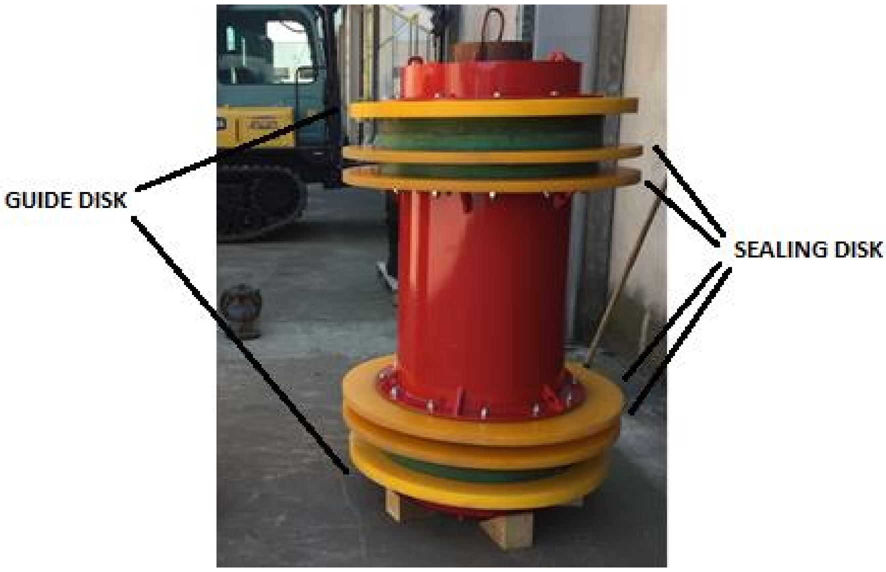

FIGURE 80 PIG WITH SET OF SEALING DISKS AND GUIDE DISKS

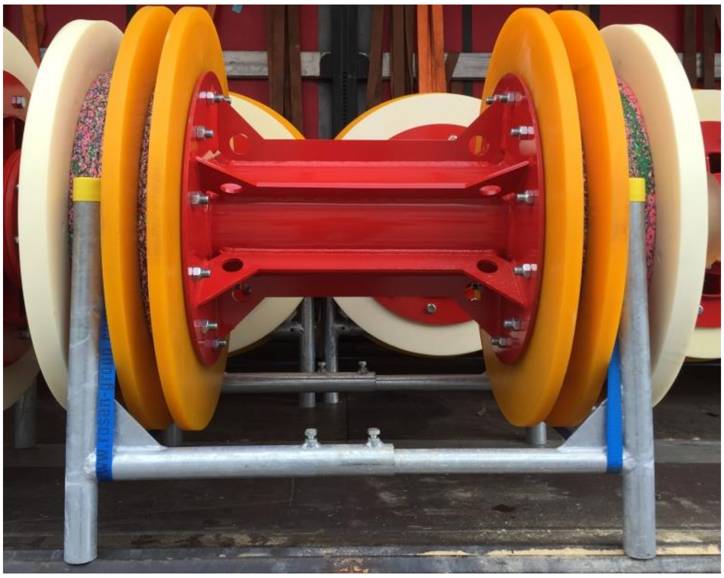

FIGURE 81 PIG DURING TRANSPORT

FIGURE 82 BIDIRECTIONAL PIGS

FIGURE 83 FOAM PIG FOR WATER ABSORPTION DURING SWABBING

FIGURE 84 AIR COMPRESSOR: ATLAS COPCO, 20 BAR. FREE AIR DELIVERY 23,5 M^3/ MIN

FIGURE 85 DETAIL OF NYLON BRUSHES IN A PIG

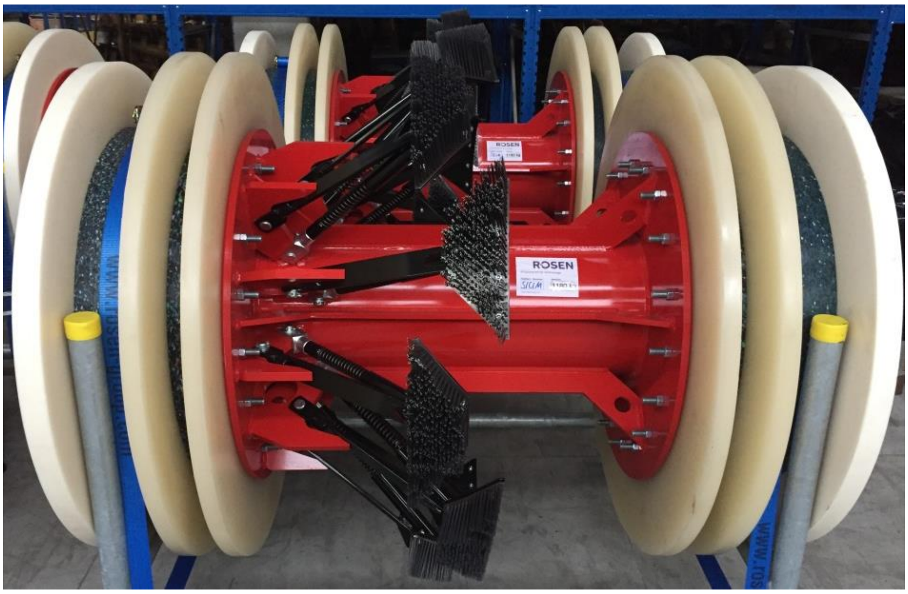

FIGURE 86 BRUSH PIG: SEALING AND GUIDING DISCS ARE SHOWN, TOGETHER WITH A SET OF METALLIC BRUSH ALL AROUND THE PIG CENTRAL SURFACE

FIGURE 87 DETAIL ON METALLIC BRUSH

FIGURE 88 KALIPER PIG, RAS

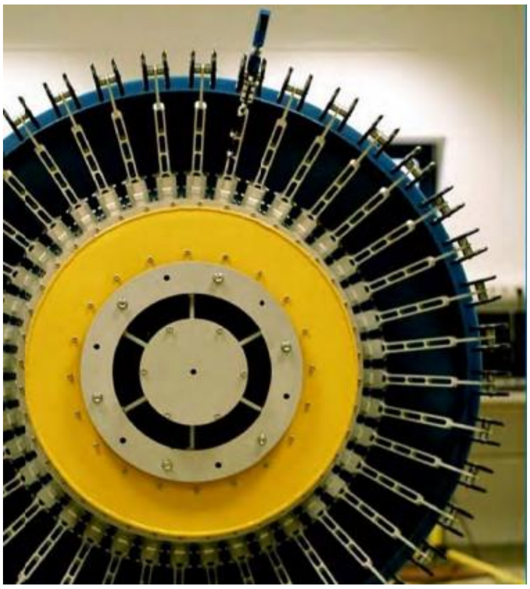

FIGURE 89 KALIPER PIG, RAS, SCRAPERS IN THE FOREGROUND

FIGURE 90 INSERTION OF A CALIPER PIG INTO THE PIPELINE FOR THE GEOMETRIC INSPECTION

FIGURE 91 DEW POINT METER PROBE – VAISALA – USED IN DRYING OPERATIONS

FIGURE 92 PIG TRAP WITH AUTOMATED OPENING

FIGURE 93 DETAIL ON AUTOMATED OPENING ON A PIG TRAP FOR PIG INSERTION

FIGURE 94 PIG TRAP WITH SOFT OPENING

FIGURE 95 DETAIL ON BLIND FLANGE OF THE PIG TRAP : SOFT OPENING

FIGURE 96 TEST HEADS FOR HYDROTEST

FIGURE 97 TEST HEADS USED FOR WATER FILLING AND DEWATERING IN THE PHASE OF HYDROTEST

14 Appendix C - Pigs and related devices

14.1 Pigs

A pig is a device that is propelled through a pipeline to perform one of several functions, in some cases, several pigs are necessary to perform multiple functions in the same pass. A pig requires fluid or gas movement in the line to propel it down the pipeline and to perform its function. Pigs may have different functions according to the process in which they are launched: sealing, cleaning, gauging, absorption or retention of products, separation, so they are used to separate fluids, clean, gauge lines, provide magnetic pickup, provide a temporary barrier, absorb moisture or debris.
Pig discs, cups, or foam makes contact with the wall of the pipeline to provide a seal; foam pigs are used to dry the pipeline and the seal prevents fluid from bypassing the pig as it moves down the pipeline. Most pigs are unidirectional, some are bidirectional which means they can be moved in either direction.
General classification divide them into two main categories (Pipeline Engineering & Supply Co. Ltd, 1999):

- ILI (in line inspection tools): complex pigs with special functions
- Utility : they include all categories apart from intelligent pigs; they are employed for the common functions of gauging, absorption…

14.1.1 Components of the pig and indication

There are three elements to be considered with regard to pig construction (Pipeline Engineering & Supply Co. Ltd, 1999):

- The pig body: it is usually made from carbon steel or elastomers like polyurethane or rubber; resistance to temperature is a limitating feature for elastomers, especially for polyurethanes that can operate effectively in a temperature range with a low upper limit. However rubbers (Nitrile, Silicon, Neoprene, Viton) have inferior physical characteristics (strength).
- The type of seal: the pig has seal mounted on it in order to run adherent to the wall surface of the pipeline avoiding contact between fluid in the front of the pig and fluid behind; the seal can have different shape: disc, standards cup, conical cup (see *Figure 98 standard caps: they are fitted on the pig* and *Figure 99 conical cups: they can be fitted on the pig*). Between polyurethane and rubber, the former is the best material for a effective seal. Cup disc, both standard and conical, are uni-directional pigs, whereas disc pigs are bi-directional. If a pig stops providing an effective seal and the fluids behind it starts to bypass it, the pig will get stuck: a foam pig can then be sent there in order to isolate and push onward the pig (Halliburton, 1997); discs are lighter and can be reversed, however they are more prone to damage and are less able to pass obstructions and reductions in the pipeline than conical cups. (Pipeline Engineering & Supply Co. Ltd, 1999)
- The fittings: fittings are other types of item than can be attached and removed from the pig: brushes, blades, scrapers, gauging plates, magnets (see *Figure 85 detail of nylon brushes in a pig*)…

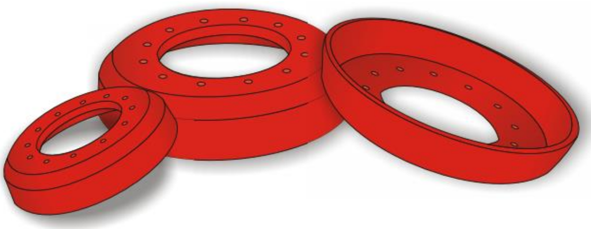

FIGURE 98 STANDARD CAPS: THEY ARE FITTED ON THE PIG (THE PIG IS UNIDIRECTIONAL)

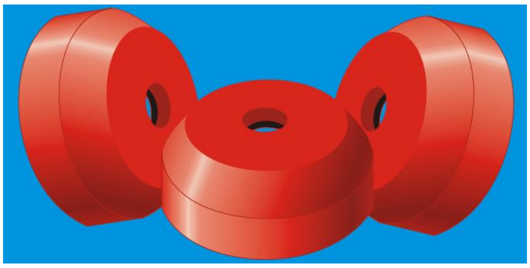

FIGURE 99 CONICAL CUPS: THEY CAN BE FITTED ON THE PIG

The recommended dimension for a pig depends on the pipeline dimensions: the following formula is an example of relationship:

$$length\ of\ the\ pig = Dn * X$$

where Dn is the nominal diameter of the pipe and X is a coefficient in the range = 1,4 ÷ 2 (Pipeline Engineering & Supply Co. Ltd, 1999).
In case the pipeline system includes two or more nominal diameters, dual-diameter pigs are available: they are usually designed to cope with two changes in pipe diameter. In this case pigging should be carried out from large diameter to small diameter pipe: to assist the pig, the transition from diameter to diameter should be smooth and gradual, with concentric reducer with a taper no steeper than 1:5.
If two features of the pipeline features, in particular valves, offtakes (tees and laterals) and bends, are located too close one to the other,they might influence the efficiency of a pig, that may get become stuck. The general rule is that a minimum distance should be allowed between any two features (Pipeline Engineering & Supply Co. Ltd, 1999):

$$minimum\ distance\ between\ two\ features = 3 * Dn$$

14.1.2 Pigs used prior to Pre-commissioning

14.1.2.1 Pigs for debris removal

It involves the clearance from the pipeline from waste, rocks, sand, dead animals. this task requires a robust, well specified pig. Bi-directional pigs are required as it may be necessary to reverse them if the get stuck (Pipeline Engineering & Supply Co. Ltd, 1999).
In this phase the pig is usually propelled with compressed air: pigging occurs in a series of high speed excursions between localized restrictions: the pig stops and pressure behind it builds up until there is sufficient energy to launch the pig past the obstacle. As the pig moves forward rapidly the pressure is dissipated until the pig reaches the next restriction, causing the process to be repeated

14.1.2.2 Pigs for cleaning

For the purpose of cleaning two requirements are fundamental (Pipeline Engineering & Supply Co. Ltd, 1999):

- pigs must be fitted with cleaning devices: foam pigs to absorb water or condensate, brushes for removal of rust, circular scrapers for hard waxes, ploughs for soft waxes. See *Figure 86 brush pig* and *Figure 85 detail of nylon brushes in a pig.*
- “by-pass” must be introduced across the pig and, in particular, the brushes.

Pig can be propelled with air or water; Aggressive pigs are required to remove scale (mill scale, coke, calcium), whereas coated lines requires nylon brushes to avoid damage to the coating.

14.1.2.3 Pigs for gauging

Gauging is performed for two main reasons:

- Ensure absence of dents
- Ensure ovality is not above a certain maximum limit

Gauging is usually performed with the fitting on the pig of a gauging plate, a soft aluminium plate which is mounted on the front end of a hard pig: if the pig runs past a dent, the edge of the gauging plate bends back when it comes out at the downstream end and visual inspection then gives the depth of the largest dent (subsea pipeline engineering). Most common use of gauging pig today is simply to determine whether or not ("go" or "not to go") a full geometry survey is necessary (Stewart, 2015)

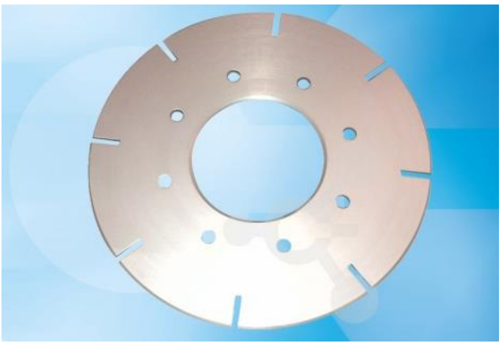

FIGURE 100 GAUGING PLATE

14.1.2.4 Pigs for filling

The line is filled with water for hydrotest: the pig has to provide the ability of maintaining an effective seal (Pipeline Engineering & Supply Co. Ltd, 1999) between the water behind it and the air above it: multiple sealing disks are used.

14.1.3 Pigs used for Pre-commissioning

In each chapter of the thesis has been included a description of the most suitable pig for the described operation.

14.1.4 Pigs used in commissioning

14.1.4.1 Pigs for filling (gassing-up)

For the *commissioning* phase, pigs are also used to bring the pipeline to the point of operation, filling it with the product: in this case several pigs are required (train pig) (Pipeline Engineering & Supply Co. Ltd, 1999) involving slugs of methanol or glycol between one and another, in order to vent air and introduce the fuel.

14.2 Pig traps

Pig traps are equipment that allows the loading and unloading of a pig in/from pipeline to avoid the interruption of the flow in the line. Pig traps are actually pressure vessel and the design pressure of a trap should never be less than that of the pipeline; each time they are used they are welded to the pipe section and then unwelded. Pig traps are used for launching and receiving pig during cleaning and gauging and are necessary every time that a line has to be pigged (Pipeline Engineering & Supply Co. Ltd, 1999).

14.2.1 Design and manufacture of the trap

Pig traps are designed and manufactured within limits that may be requirement or codes:

- National and International standards

- Client specification about temperature and pressure (client requirement)
- Possible indication from the client about material
- Design code related to welding
- Performance of hydrotest at a pressure of 1,25 times the design pressure (less than 1,5)
- All certificates, examinations and inspection reports

14.2.2 Structure of the trap

The structure of a trap, either launcher or receiver is similar and always comprises:

- a short minor diameter pipe section, often referred to as *neck pipe* and only between 500 and 1000 mm in length (with exception of intelligent pig receivers where it may be very longer)
- a *reducer*
- a longer major diameter pipe section, called *barrel:* it's designed to be oversize so that the pig can be easily loaded and unloaded. For conventional pigs, the diameter of the barrel is generally 2'' larger than the diameter of the line pipe, whereas for intelligent pig it's recommended that the diameter of the barrel is at least 4'' larger than that of the line pipe. (Pipeline Engineering & Supply Co. Ltd, 1999)
- a *end closure* (quick opening) or a blanked, removable flange
- *nozzles, supports* and *lifting lugs.* Nozzle is the collective term for the connections from the trap to its associated piping system. Three main and only *nozzles* are:
    - *kicker*: it should not be more than 125% the main line pipe diameter (Pipeline Engineering & Supply Co. Ltd, 1999)
    - *drain:* used to allow flow of liquid
    - *vent:* located at the highest point, it allows venting of air

  lifting lugs are designed to facilitate the lifting of the complete trap during installation stage; *supports* should permanently support and restrain the pig trap.

14.2.2.1 Pig launcher

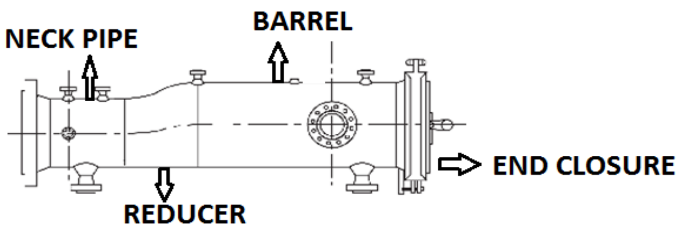

FIGURE 101 SCHEMATIC REPRESENTATION OF A PIG LAUNCHER TRAP

The major barrel is eccentric with respect to the axis of the pipeline; usually its length is 1,5 times the length of the pig, measured from the kicker connection to the reducer weld (Pipeline Engineering & Supply Co. Ltd, 1999).
The opening *(end closure)* for the insertion of the pig can be automated, or manual with a blind flange; The *kicker* is located near the closure end; *Drain* too should be near the *end closure*

14.2.2.2 Pig receiver

In pig receiver usually the major barrel is concentric as shown in the profile below.

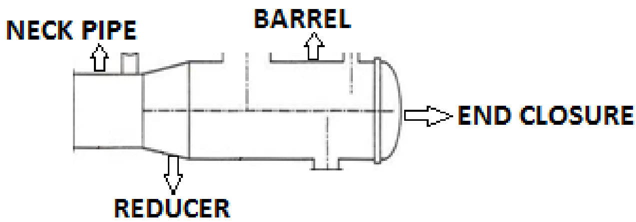

FIGURE 102 SCHEMATIC REPRESENTATION OF A PIG RECEIVER TRAP

The *kicker* is usually near the reducer end; drain should be near the *trap valve* (ahead of the neck pipe). For receivers the recommended barrel length is again 1,5 times the pig length; however, this dimension is measured from the kicker connection to the closure weld.

14.2.3 Operation of pig traps

14.2.3.1 Pig launcher

The presence of the *neck pipe* between the *mainline valve A* and the *reducer* R is a safe space that during pressurization represents a space to avoid contact between the head of the pig and the valve A.
The *kicker* is the supply point of the stream that will drive the pig and should not be installed, as it could be imagined, at 6 o'clock position but from a perpendicular direction, because it's proved to be a safest design not to damage the pig during the filling of the major barrel.
Two *vents* are present, one D in the trap and one in the neck to ensure the possibility of depressurize in case the pig becomes stuck in the neck pipe.

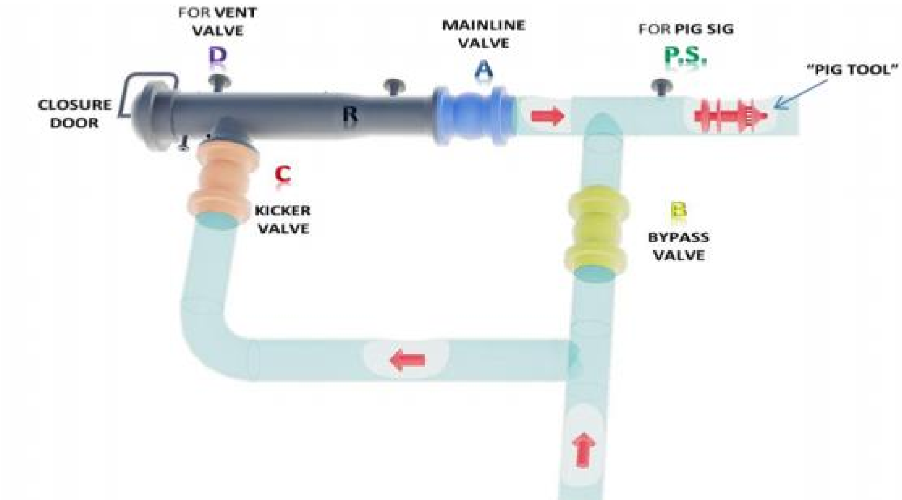

FIGURE 103 PIG LAUNCHER STATION – TRAP

Here down is reported the sequence of operation to safely introduce the pig in the line by the launcher trap:

- Close *mainline trap valve A* and *kicker* valve C.
- Open *vent valve D* to vent the launch trap to atmospheric pressure.
- When the trap is completely vented (zero manometric) with *vent valve D* still opened, open the closure door and insert the "PIG tool", adjusting itself into *reduction (R)* previous to *A valve* with the first cup of the tool.
- Close and secure the *closure* door. Purge the air from the trap through *vent valve D* by slowly opening *kicker valve C*. When the purge is done, close *vent valve D* to allow pressure equalization between trap and pipeline, then close *kicker valve C.*

- Open *mainline valve A*, then *kicker valve C*. The “PIG tool” is ready to be launched.
- Close partially *bypass valve B*. This will increase the gas flowrate through *kicker valve C* and behind the “PIG tool”. Continue closing *B valve* until the tool goes out of the trap inserting itself into the pipe current indicated by the "PIG-SIG“passage indicator.
- When the “PIG tool” is launched from the trap and comes into the mainline, open *bypass valve B* completely. (during launching both *kicker valve C* and *bypass valve B* are open).

14.2.3.2 Pig receiver

In the *neck* is installed a pig signaller P.S. to detect the arrival of the pig

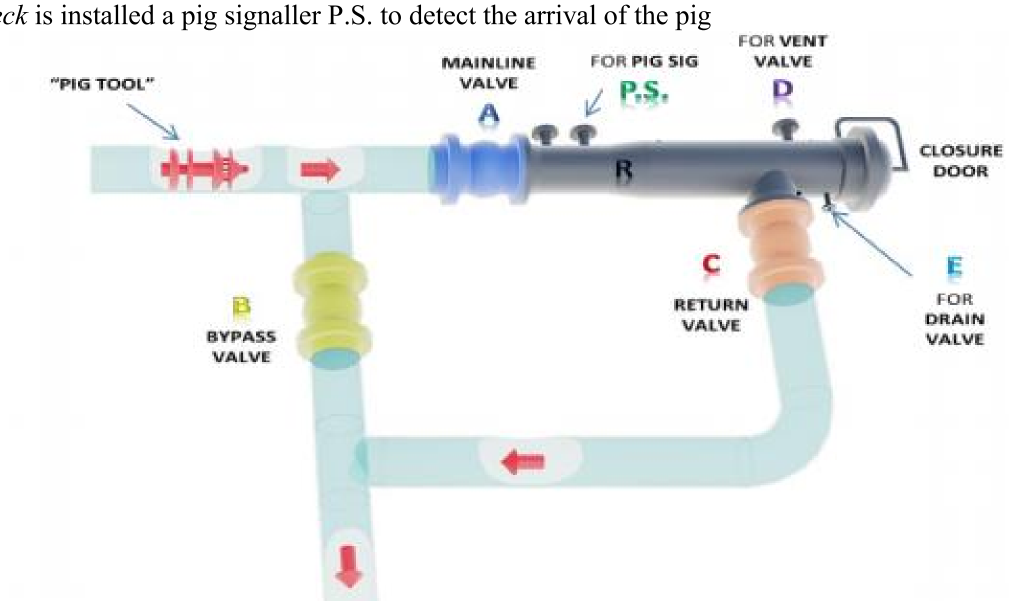

FIGURE 104 PIG RECEIVER STATION - TRAP

- Drain the trap, close *drain valve E* and open slowly *return valve C.*
- Once it is drained, start equalizing the pressure in the trap closing *vent valve D* with the *kicker valve C* opened.
- With return *valve C* still opened, open *mainline valve A*. The trap is now ready to receive the “PIG tool”.
- When the “PIG tool” arrives, this will stop between *mainline valve A* and the entrance tee piece (R) of the trap so close *partially bypass valve B*. This will force the “PIG tool” to introduce itself into the trap increasing the gas flow through *return valve C*.
- After the “PIG tool” is in the trap, shown by the "PIG-SIG“ passage indicator, open *bypass valve B* and *close A and C valves*.
- Open *vent valve D* and *drain valve E* to vent the trap to atmospheric pressure.
- After the trap is *vented and drained with D and E valves* opened, open the *closure door* and remove the “PIG tool” manually or with a winch.
- Close and secure the *closure door.*

14.3 Pig alert

Pig alert or Pig signallers are used to provide confirmation of the movement of pipeline pigs through a pipeline: when a pig signaller detect the passage of a pig it communicates it to the operator through an electric signal or visually:

- Visually: spring loaded high visibility flag flips up when internal magnet is withdrawn
- Electric signal: electric output to the controller

They are normally positioned at the pig launching and pig receiving stations and at key points along a pipeline. *In Figure 105 petrosystem pig signaller, mounted on valves* is represented how a pig signaller appears;

FIGURE 105 PETROSYSTEM PIG SIGNALLER, MOUNTED ON VALVES

14.3.1 Types of pig signallers

In *Figure 106 types of pig signallers, respectively: welding boss mounted, flanged mounted, ball valve mounted on nipolet* different types of pig signallers according to the kind of temporary joint that links them to the pipeline are shown: welding boss mounted, flange mounted, ball valve mounted.

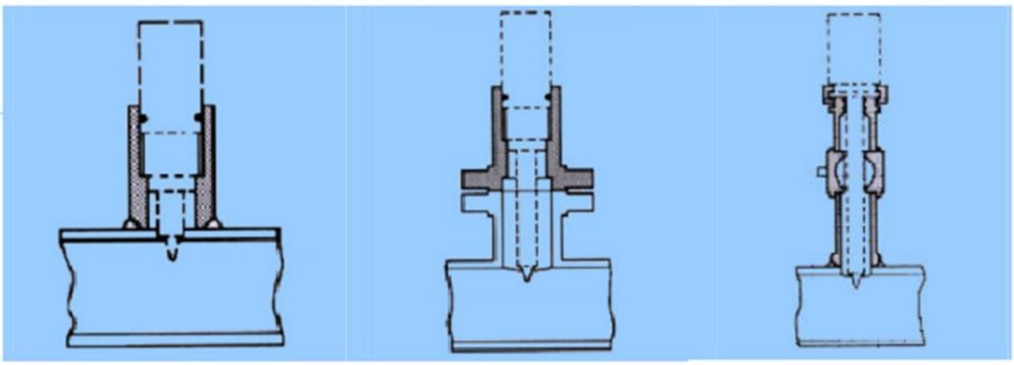

FIGURE 106 TYPES OF PIG SIGNALLERS, RESPECTIVELY: WELDING BOSS MOUNTED, FLANGED MOUNTED, BALL VALVE MOUNTED ON NIPOLET

- *Boss mounted signaller*: it can be installed even when the pipeline is under pressure (hot tapping).
- *Flange mounted signaller*: it's installed at the construction stage or when there is no internal line pressure
- *Valve mounted signaller*: it's installed at the construction stage or when there is no internal line pressure

14.3.2 How does a pig signaller work?

When a pig passes beneath a correctly installed signaller, the pig disk pushes the protruding bi-directional trigger forward in the direction of the pig travel. The trigger is hinged at two points which convert the angular motion gained from contact with the pig axial motion withdrawing a spring-loaded, permanent magnet holder down through the 'cap'. At rest, the proximity of the magnet at the top of the cap retains the mechanical, spring-loaded "flag" (visual communication) and/or the contacts of an externally mounted proximity switch (electric communication).

15 Appendix D - Corrosion of steel, Rusting process

Corrosion (from Latin "*corrodere*" that means "cat away") is defined as the *deterioration of a material, usually a metal, that results from a reaction with its environment* (NACE (National Association of Corrosion Engineers), the primary support organization in the corrosion industry, 2007).
Most metals exist in nature in their most stable form (oxidized), as stable ores of oxides, carbonates or sulphides: then they are extracted and refined using energy that brings them to a reduced state: corrosion is nature's tendency to bring them back to a lower energy state for the *principle of entropy* (all-natural phenomena in a system occur in order to the increase the total entropy of the system).

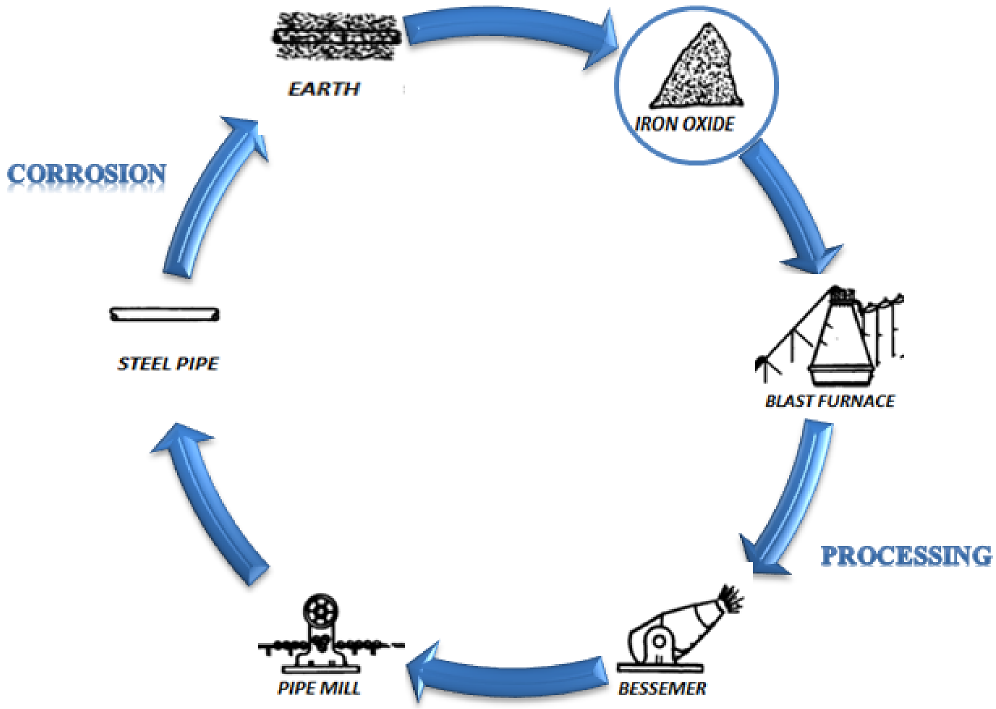

FIGURE 107 EARTH CYCLE OF A METAL: FROM OXIDE TO REDUCED THROUGH PROCESSING, AND FROM REDUCED TO OXIDIZED THROUGH CORROSION

That's why all metals have a tendency to dissolve or corrode (Brondel, et al., 1994) and their life is like a *cycle,* as represented in *Figure 107 earth cycle of a metal: from oxide to reduced through processing, and from reduced to oxidized through corrosion.* Corrosion can be initiated for different reason and in different environments: the purpose of the chapter is to list the main ones.

15.1 Galvanic Corrosion

The required elements for an electrolytic or galvanic corrosion to happen are four:

- Anode
- Cathode
- Electrolyte
- Electrical connection between Anode and Cathode.

15.1.1 Rusting process

Let's suppose that metals are immersed in an electrolyte:

- The metal with the greater tendency to corrode (for instance the metal zone that has more stored up energy due to the productive process than the other metal) forms the negative pole and is called the *anode*: it loses positive metal ions, Fe^{++} into the electrolyte causing the release of some electrons (*oxidation* of iron into iron(II)) that can run through the conductor in the form of electric current towards the cathode.

$$(oxidation) \quad Fe(s) \rightarrow Fe^{++}(aq) + 2e^-$$

- Free electrons are taken up: *reduction* of oxygen into hydroxide ions, OH^-. No metal is lost at the *cathode;*

$$(reduction) \quad O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

$$\text{or} \quad 2H^+ + \tfrac{1}{2}O_2 + 2e^- \rightarrow H_2O$$

$$\text{or} \quad 2H^+ + 2e^- \rightarrow H_2 \quad \text{in deaerated environment}$$

If nothing happens to the positive iron ions they will travel through the electrolyte towards the cathode and react with other compound:

$$2Fe^{++}(aq) + 4OH^- \rightarrow 4Fe(OH)_2(s)$$

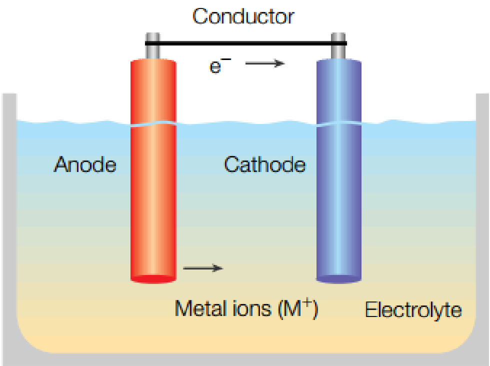

FIGURE 108 GALVANIC CELL REPRESENTATION, SEMPLIFICATION OF HOW THE CORROSION WORKS

These products of corrosion will accumulate on or near the corroded surface: the buildup of them can even slowdown or stop the corrosion process by sealing off the corroded area and preventing migration of iron ions into the electrolyte (American Water Works Association, 2002) (**passivation**) or it can proceed and give rise to rust:

$$4Fe(OH)_2(s) + O_2 + xH_2O \rightarrow 2Fe_2O_3\bullet(x+4)H_2O(s) \quad : \quad \textbf{rust}$$

In the *Figure 108 galvanic cell representation, semplification of how the corrosion works* is shown a schematic representation of the corrosion system. If the conductor was disconnected from the terminals the current would be interrupted and the ions released at the surface of the anode would have nowhere to go and accumulate in such number that corrosion is virtually stopped. (Watson, s.d.) The flow of electrons goes from anode to cathode through the conductor and back from the cathode to the anode through the electrolyte solution.
From a **thermodynamic** point of view the reaction will take place (there is a potential that drives it into a specific direction), however the **kinetic** (velocity in doing it**)** depends on many factors and is controlled by the slowest step, which is the *reduction,* and depends on environment parameters*:*

- in de-aerated solutions the rate is very low due to low H+ ions (apart from acidic environment), when instead oxygen is dissolved the first reduction type can occurr faster. Important is te possibility for the oxygen to reach the metal surface and this is accomplished by diffusion through the solution, and the diffusion is proportional to the oxygen content.

- pH effect on iron corrosion is important: in acid range corrosion rate increase rapidly through hydrogen availability
- increase in temperature acts on greater diffusion of hydrogen (see point 1), however its increase means low solubility of oxygen. The net contribute is that an increase in temperature leads to an increase in the corrosion rate.
- Microorganisms, high velocity fluid also enhance corrosion

15.1.2 Possible mechanism of galvanic corrosion in a pipeline

Anode and *cathode* can form on a single piece of metal made up of small crystals of slightly different compositions: on the same pipeline separated by some kilometers, for instance if a new pipe is coupled with an old pipe, the new one will act as anode

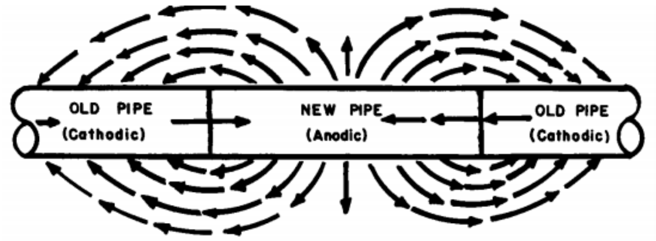

FIGURE 109 GENERATION OF A GALVANIC CELL (CORROSION) WITHIN A PIPELINE DUE TO DIFFERENT CHARACTERISTIC OF THE STEEL IN TWO ADJACENT ZONES

Another possible situation is when a metal pipe that is in contact with different types of soil, as depicted in *Figure 110 generation of a galvanic cell (corrosion) within a pipeline due to contact with different type of soil,* Figure 110 generation of a galvanic cell (corrosion) within a pipeline due to contact with different type of soil: anode and catode are both the same continuous metallic structure, meaning that there is a conductor between them ; the electrolyte may be simply water and the surrounding soil.

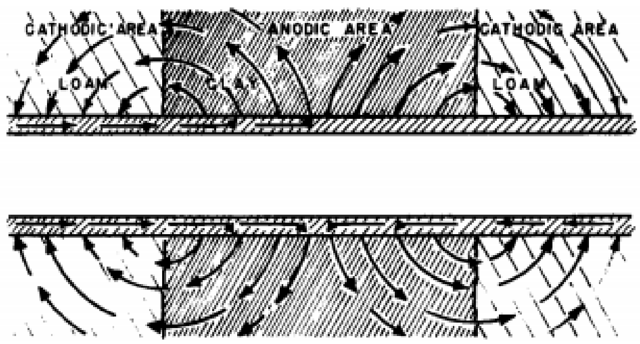

FIGURE 110 GENERATION OF A GALVANIC CELL (CORROSION) WITHIN A PIPELINE DUE TO CONTACT WITH DIFFERENT TYPE OF SOIL

It may happen also that if one surface of the pipe is more exposed to oxygen (greater aeration) than another surface: for example the top surface of the pipe exposed to bigger amount of oxygen becomes the cathode of the pipeline while the other part becomes the anode, as shown in *Figure 111 generation of a galvanic cell (corrosion) within a pipeline due to different oxygen availability*

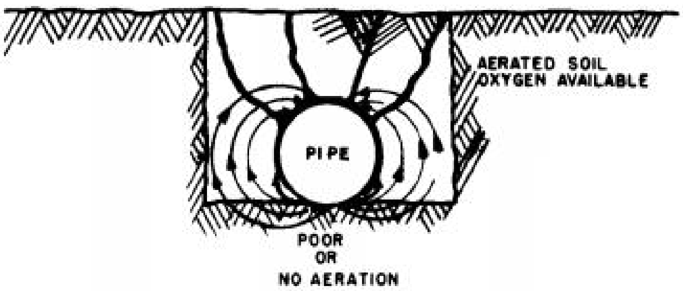

FIGURE 111 GENERATION OF A GALVANIC CELL (CORROSION) WITHIN A PIPELINE DUE TO DIFFERENT OXYGEN AVAILABILITY

The **Pourbaix diagram** is useful to explain the corrosion chemistry: it shows the state of a metal according to the pH of the electrolyte solution and the redox potential; it has been drawn from Nernst equation and solubility data of metals. The three states possible for a metal are identified by regions in the Pourbaix diagram and are represented in *Figure 112 three regions identify the possible state of a metal in an aqueous solution, according to pH of the solution and redox potential*:

- Corrosion (active state)
- Passivation (formation of a layer that inhibits corrosion)
- Immunity (metal is stable)

These three regions are separated by lines:

- vertical lines mean that a pH-dependent reaction has to occur in order to change state
- horizontal lines mean that a electron transfer reaction has to occur in order to change state
- sloping lines means that a reaction with both type of phenomena has to occur

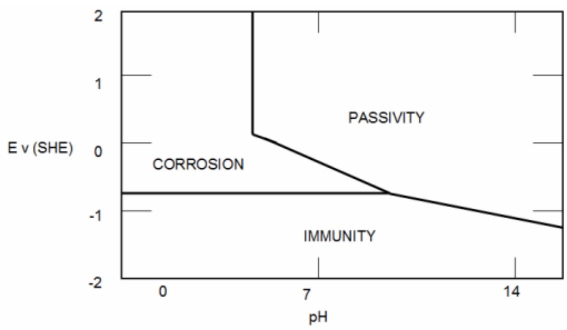

FIGURE 112 THREE REGIONS IDENTIFY THE POSSIBLE STATE OF A METAL IN AN AQUEOUS SOLUTION, ACCORDING TO PH OF THE SOLUTION AND REDOX POTENTIAL

In the Pourbaix diagram is also presented a subdivision in three regions for water, divided by three sloping lines and represented in *Figure 113 three region of possible state of water are shown in the Pourbaix diagram:*

- the first upper region is the liberation of oxygen (above O_2 line) : $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
- the stable zone of water is the intermediate region
- the hydrogen release zone (below H_2 line) : $2H^+ + 2e^- \rightarrow H_2$

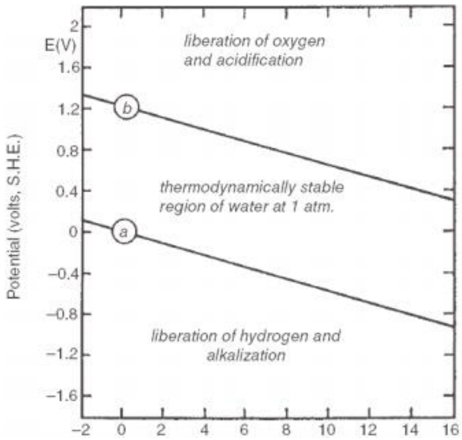

FIGURE 113 THREE REGION OF POSSIBLE STATE OF WATER ARE SHOWN IN THE POURBAIX DIAGRAM

It is useful to explain the reason because in the case od different aeration for example:

- the part of the pipeline not exposed to air (thus to oxygen) has potential of the solution close to the H_2 line in the Pourbaix diagram, where Fe can corrode to Fe^{2+} (aq), losing electrons: this is the *anode*
- the upper part of the pipe in contact with well oxygenated water is well oxygenated experiences instead the reduction of oxygen into water, $O_2 + 4H^+ + 4e^- = 2\ H_2O$, being close to the O_2 line. The conductive pipe completes the circuit, carrying electrons from the anode (where Fe is oxidized and releases electrons) to the cathode (where O_2 is reduced).

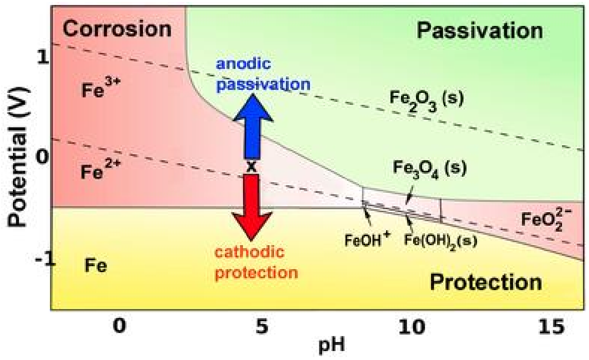

FIGURE 114 POURBAIX DIAGRAM FOR IRON: TENDENCY OF IRON TO CORRODE OR NOT DEPENDS ON THE PH AND ON REDOX STATE

The complete Pourboix diagram is shown, made up from the overlapping of the two previous regions diagrams related one to water and the other to metal.

15.2 Chemical corrosion

The water used for hydrotest may contain dissolved salts and minerals which make the water a good electrolyte (Halliburton, 1997), catalysing the corrosion reaction of electrolytic oxidation and reduction.
If water itself contains dissolved gases such as CO_2 or H_2S or if are present elements that can form acidic products (such as H^+) that enlow the pH, the corrosion process will be accelerated (as shown in the red region of corrosion at low pH in *Figure 114 pourbaix diagram for iron: tendency of iron to corrode or not depends on the pH)* .

$$2Fe + 2H_2S + O_2 \rightarrow 2\ FeS + 2H_2O$$

Or $\quad CO_2 + H_2O \rightarrow H_2CO_3. \quad$ and $\quad H_2CO_3 + Fe \rightarrow FeCO_3 + H_2$

15.3 Bacterial corrosion

Microbiologically influenced corrosion (MIC) is caused by microbes whose actions initiate the corrosion cycle. There are several types of microbes that, while producing different effects, have been found to promote either external or internal corrosion.

- The main types are *sulfate-reducing bacteria **(SRB)***, that consume hydrogen from cathodic regions thereby accelerating the cathodic reaction and corrosion by eliminating hydrogen as it is formed, they metabolize sulfate ions and produce H_2S

$$\text{Bacteria} + \text{oxidized Sulphur (sulphate, sulphite..)} \rightarrow H_2S$$

- *acid-producing bacteria (APB)* which generate as their metabolic by-product and concentrate acids (like acetic acid, nitric acid, sulphuric acid..) that enlow the pH and corrodes the pipe, and aerobic bacteria that can for example cause the depletion of oxygen and formation of sulfuric acid.
- Oxygen dissolved in the water: oxygen induces oxidation of the steel, producing a range of corrosive ferrous and ferric oxides.

15.4 Erosion - corrosion

Erosion is the abrasion of the internal diameter of the pipe (Antaki, 2003) and it can be caused by:

- the contact with suspended solid in a flowing fluid
- high velocities or turbolencies
- cavitation, that is the formation of vapor bubbles at the center of turbulence vortices in liquid lines and the subsequent collapse of those bubbles. Cavitation tends to form where the liquid pressure drops below vapor pressure such es downstream of an orifice or high-altitude zone;

If corrosion is present, erosion will accelerate it, eroding the corrosion layer and exposing new material for further corrosion.

16 Appendix E - Bending of a pipe

The bending of a pipe can be performed in the shipyard with a cold bending machine or the pipe can be already bent when they are acquired:

- Cold bends can be performed to obtain small curvatures in the shipyard with a cold bending machine, shown in *Figure 76 cold bending machine is bending a pipeline segment*; the pipe is bent plastically in the field usually to a radius of 40D and angle <15 degrees. Usually after the bending, the cross section of the pipe results to be slightly deformed toward an oval shape. First cold bent pipe section 36 can be defined by a bend angle (α), a bend radius (r), and a length (l) where $2\pi r : 360° = l : \alpha°$

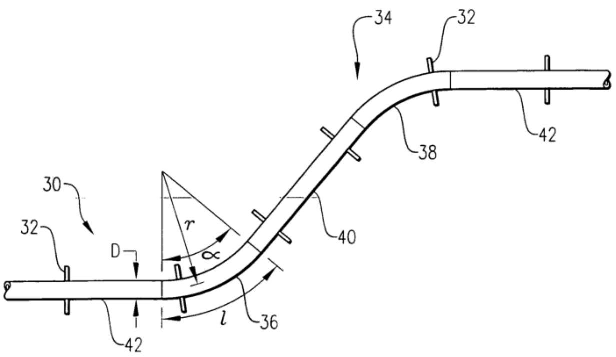

FIGURE 115 SMALL ANGLES PIPE BENDING

In *Figure 115 small angles pipe bending* above is shown half of the bending of a pipeline for the crossing of a river of a street. If the space under the crossing is enough pipes are usually cold bended.

- For great curvatures, elbows are already ready and stored in the shipyard in case of need; the way of catalogue a 90° bending of a pipe basing on the radius of curvature is explained in the following figure; a bend is named “nD” if the radius of curvature taken from the center of the circle till the axis of the pipe is equal to n time the Diameter of the pipe.

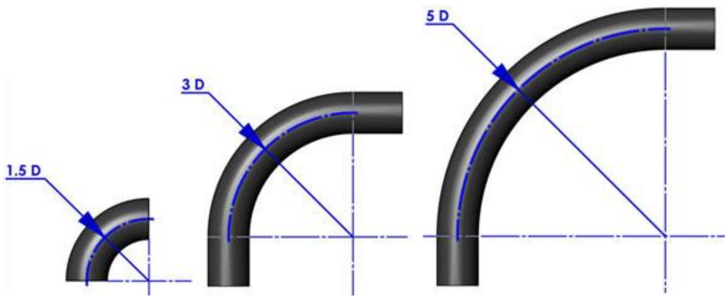

FIGURE 116 CATHEGORIES OF PIPE ELBOWS

17 Appendix F – Pipelayer

Thanks to the new automatic quick release of the tracks which is directly controlled by the driving position, the *Pipelayer Performer GPL 980* can be transported with normal open top containers which allows a great saving in terms of shipping costs and time. It has been designed by Sicim workers in 2015 and then realized in collaboration with Euro Pipeline Equipment S.p.a.

FIGURE 117 GPL PERFORMER 980 DISASSEMBLED

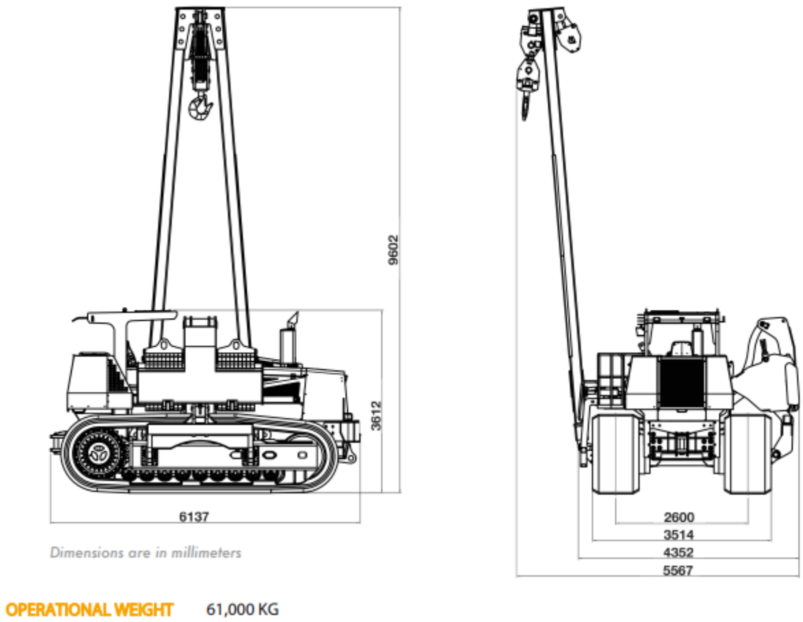

FIGURE 118 PERFORMER GPL 980 DIMENSIONS

18 Appendix G – EPC contracts

Prior the *Pre-commissioning* the firm has to show by excavation that in a random location chosen by the client all rules have been followed; after the completion of the project there is usually a *1-year guarantee*: if in that period something happens to the pipeline the firm has the duty to provide a repair solution.

18.1 Types of contract

There are two common approaches to the contractual framework for the engineering, procurement and construction of a pipeline.

1) The project company can contract all the required services through the *EPC contractor alone* which will then be responsible, under the terms of the contract with the project company, for procuring all necessary services, by itself subcontracting with other companies (i.e. the pipe supplier).
2) Alternatively, the project company can *contract separately with each contractor*: this gives rise to an enhanced interface risk, although this would not necessarily make it impossible to obtain project financing as there are established mitigants to interface risk. That said, where the sponsors are seeking to obtain project financing, then this contractual structure becomes subject to additional scrutiny as lenders will wish to ensure that the contract(s) required to build the pipeline are as time and cost certain as possible.

During the construction of a pipeline system there will be a team of *construction inspectors* and *managers* in charge of verifying that various aspect of the construction are completed according to the technical specifications, drawings and documents. (pipeline planning and construction).

18.2 Documents

Documents involved in the planning and performance of all phases from mechanical completion, Pre-commissioning, commissioning and start-up are:

- *Technical specification (construction, hydrotest, Pre-commissioning, …)*
- *Scope of work* : it is intended to be used to describe the specific project and any additions or modifications to the clauses used in Technical Specifications.
- *Reference regulations, Standards and Code* : will be used depending on the location of the plant which will define the laws, rules and regulations to be used

In the event of conflicts between this specification and other documents, the most stringent code or standard shall apply. (Anon., 2006) The terminology used in the specification must be selected with care since words can be interpreted in different ways. Some specifications have sections that provide definitions for words used in the specification to avoid misinterpretations and confusion. Specifications provide a means of communicating the purchaser's requirements for a piece of equipment. Terms such as 'shall', 'should' and 'may' must be used appropriately to avoid confusion as to what requirements are mandatory, recommended or optional. The usual definition of these terms are as follows: Shall indicates requirements that are mandatory, Should indicates requirements that are recommended but not mandatory, May indicates requirements that are optional and, consequently, are at the discretion of the designer.

Parties involved in a contract are:

- *Contractor*: party which carries out all or part of the design, engineering, procurement, installation and commissioning or management of a project or operation of a facility. (Shell, 1994)
- *Manufacturer / Supplier*: party which manufactures or supplies equipment and services to perform the duties specified by the Contractor. (Shell, 1994)
- *Principal*: party which initiates the project and ultimately pays for its design and construction. The principal will generally specify the technical requirements. The principal may also include an agent or consultant, authorized to act for, and on behalf of, the principal. (Shell, 1994)

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