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Pipeline Integrity Design, Maintenance and Diagnosis – The overall strategy

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Abstract
Pipeline Integrity is a simple expression, the maintenance of pipeline integrity is something a little more complex and costly to be ensured during the entire lifetime of pipelines, tanks or other buried gas-oil-water facilities.
It is firstly a matter of culture, then a matter of human and financial resources, strict rules and regulations being the forcing guide. In our long-term experience, we have learned the lesson: first of all the prevention, then a careful maintenance to ensure the integrity of buried metallic structures. The technical organisation, which must be devoted to the design, the follow up and the implementation of Pipeline Integrity is unavoidably made by well-prepared technicians and engineers.
The paper aims to show the importance of the Organisation, the expertise and competence of the personnel devoted to pipeline integrity. The knowledge of the entire network, the correct and up-dated documentation are also fundamental in order to attain and maintain a sufficient level of safety along the entire network. Various techniques for evaluating and safeguard Pipeline Integrity are then illustrated, bearing in mind which method is considered the most effective under given conditions. Not always the techniques can be adopted in the same way on a structure and/or when the surrounding conditions change. Starting from the very beginning of pipeline laying phase, the installation of a correct Cathodic Protection System and its careful monitoring during time, allows the observation of possible changes of surrounding environment and to make the relevant interventions “on condition”. This can make it easier and less costly the routine scheduled maintenance but, above all, to prevent incidents and the associated damages.

1 – Pipeline Integrity

The integrity of a buried pipeline during its operating lifetime is mainly referred to:

- its coating quality and integrity;
- the follow-up of the efficiency of the Cathodic Protection System during its lifetime
- its mechanical integrity overtime, which can be hindered by events such as mechanical damages due to operating machines or by soil movements (earthquakes, landslides, floodings etc.)

1.1. – The prevention phase

1.1.1. – Coating quality and integrity

Pipelines are built by joining over the ditch many pipe spools. These can be either bare or already coated in the factory. If a pipeline is coated on line, many factors can influence its quality and integrity. When a pipeline is built by using spools that are already coated in the factory, it has usually two weak points: the coating of the spools can be damaged during the transport, their storage or during the installation and the welded sections, which are coated on line. Further damages can occur to the coating integrity due to laying and backfilling phases (stones falling in the ditch, stones under the pipe if the bedding is not proper.

Usually Gas Companies adopt an overall strategy which allows to maintain the integrity of a pipeline at the best conditions. This is achieved by applying strict specifications for the coating, its material, its application, careful attention during the laying phases and verifications and controls once the pipeline is in operation.

In Snam, the Italian Company owner of the entire methane network Pipelines in Italy, presently around 33.000 km, since the 80th it is obligatory to verify the coating conditions after the soil has settled around the pipeline (usually 1 year). Any damage or imperfection found on the coating is to be repaired at the expenses of the Contractor who built the pipeline. This is a very strong way to force the Company to do their job at the best possible level, as later on it would be quite expensive to excavate and repair the coating where this was found faulty (coating faults, coating disbondment, contacts with foreign objects or structures etc.).

1.1.2. – Cathodic protection

According to National and International Standards and sometimes to the more stringent internal Company Specifications, a buried pipeline must be cathodically protected immediately (i.e. as soon as possible) after its laying and burying phases. The installation of Insulating Joints is quite always necessary to separate concentrated works (i.e. Pumping or Compressor Stations, Terminals etc.) from the main line and, in stray current areas, to limit and control the influence of electrical interferences. A careful initial test is then performed to make a picture of the baseline conditions of the pipeline in terms of coating (insulation values) and electrical parameters that are carefully monitored and recorded.

1.2. – Pipeline Integrity – The follow up during pipeline operation at SNAM

1.2.1.– Monitoring of Cathodic Protection effectiveness

During the operating life of a pipeline, Cathodic Protection effectiveness is verified by means of measurements, 24h recordings at the CP Stations, Drainages, at in the Characteristic Test Points. Once a year, the CP level at all the Test Points are also verified.

1.2.2. – Monitoring of Pipeline Integrity during its operation

Apart the verification of Cathodic Protection Effectiveness and possible anomalies which can be consequently detected (e.g. short circuits with casings or other buried structures, variation of the external electric fields, possible mechanical damages), many types of controls are performed over and along the pipeline during its operating life.

The most common are the following:

- Coating Fault Surveys in suspect areas;
- Installation and monitoring of strain gauges on areas where landslides or soil movements have been discovered;
- Excavations for relaxing the pipeline from mechanical stresses; consequent repairs of the coating.

Since 1994 a SIPE (**Computerised Information System for Cathodic Protection**) was completed; it consisted on a Data Base developed in Fortran & GDDM Language (IBM). This Computerised System allowed to store a series of Data for each CP Station, including delivered Currents, Potentials, Ground-bed characteristics and their conditions and consistence.

These Data, uploaded by each Maintenance Centre (76 Maintenance Centres all over the territory existed at the time) were available for each relevant Zone (12 Zones – each Zone had the supervision of a certain number of Maintenance Centres) and at the Central Office in Milan, where all the Data were available.

A **Computerised Remote Control System** for the all the CP Stations, Drainages and Characteristic Test Points (CTP) was completed and in full operation in 2000. At the time, the CP Stations and Drainages for D.C. interferences were around 4.500. All the Cathodic Protection Feeders were replaced with Digital, 50V – 8A Remotely Controlled Feeders, each of them equipped with a so called AEMT apparatus (where AEMT stands for Acquisition, Elaboration, Memorisation, and Transmission of electrical parameters).

In order to develop such Remote Control System, preliminary surveys were performed over all the CP stations, Drainages and Characteristic Test Points (CTP) to verify the presence and the quality of Telecommunication Signals. Only 93 positions over the whole territory were found not covered by a WIFI signal. During the study, also a satellite communication system was taken into consideration (2 Satellite Systems were available at that time: a Geo-stationary and a non-Geo-stationary). Their cost was too high in order to justify their use.

In the positions where no telecommunication signals were available, a telephonic line was installed. All the CP Stations, Drainages and CTP were covered by two main Italian operators which were available by that time: TIM and OMNITEL.

1.2.2.1. – Coating fault Surveys

As quoted in the previous par. 1.1.1., within 1 year after their burying, the pipeline's coating was subject to a strict verification. Various specialised external Companies where qualified for this service being also third parties between the Pipeline Contractor and the Company owner of the pipeline network. Any faults in the coating was to be repaired at the expenses of the pipeline Contractor. In this case the quality control was a two senses direction (the Contractor and the Specialised Company performing the Coating Surveys, Snam being the impartial judge.

1.2.2.2. – Control of the right of way

This activity is performed either by men walking along the pipelines, and visually inspecting the right of way to verify that no mechanical works or other activities such as perforations, construction of roads, buildings etc. is happening around the pipeline. For large diameters / high pressure pipelines a weekly control by helicopter is foreseen. The personnel is charged to take a film of the area along the pipeline. This film will later on automatically compared to the next film etc.

1.2.2.3. – Control of Landslides and Soil movements

Geologists were displaced in every "Zone" and were devoted to verify the stability of soils all along their pertinent pipelines. These geologists were later on embedded in the central Organisation under the Soil Movement Control Office. In case of ascertained landslides or soil movements, they studied the most appropriate actions and possible installation of devices.

1.2.2.4. – Control of the Mechanical Stress over critical Sections

Where soil observation show its instability and the possibility of inducing mechanical stress on the pipeline, the so-called Strain-Gauges have been installed. These are continuously monitored by using a local registration apparatus and automatically transmits alarm signals by a telecommunication system (SMS) so that when the stress overcomes a pre-set limit, the personnel makes the necessary works to release this mechanical stress (excavations, change of pipe spools etc.).
In case of known mechanical stress sections, some specialised surveys were performed, finding in some occasion some active Stress Corrosion Crackings. This type of surveys were accompanied by curate preliminary geological studies, knowledge of pipe spools, type of coating, type of weldings, period of laying etc..
A case history has been previously reported and is very useful to clarify the way how to proceed in these cases.

1.2.2.5. – Monitoring of Mechanical Impacts on the pipeline

A patented system was developed in the 90applied over a real pipeline in order to verify in real time any possible accident, which could be able to reduce the pipeline insulation resistance. The system was able to detect, in real time, the following type of accidents:

- Any mechanical impact on the pipeline;
- Short circuits of insulating joints (upstream to downstream the pipe) or contact between casings with the carrier pipeline;
- Mechanical/electrical contact with any buried metallic structure extraneous to the CP System;
- Floodings along the pipeline;

The patented system and its relevant device were the result of laboratory studies followed by real-field tests made in collaboration with Eniricerche, the Research Company of ENI Group. A section of real 16" gas pipeline was tested for the trials, demonstrating the capability of the system to detect a simulated mechanical impact which happened at 14 km distance. The interesting fact to notice is the capability of the system to detect both mechanical wheels machines that rubber wheels machines. Short as well as long impacts were easily distinguished from the Remote Acquisition Centre.
This system was asked for application in Nigeria, in order to monitor and discover the thieves when they were connecting extraneous output on oil pipelines.
In the Gas Company, however, the system was in operation only for experimental scopes and did not enter into exercise on real pipelines.

1.2.2.6. – Control of the Coating and Cathodic Protection Condition of Offshore Pipelines

The import Offshore Pipeline crossing the Mediterranean sea from Tunisia to Italy is cathodically with a mixed system: Sacrificial Anodes and a CP System for the parts nearby the coastal. In order to verify the CP effectiveness and the conditions of the coating along the pipeline, additionally to the periodical Intelligent Pig inspections an external survey was also made to verify the pipeline for the external corrosion point of view.
The British Company SUBSPECTION was chosen and duly qualified to perform these surveys which allowed to:

- Verify Cathodic Protection effectiveness all along the sealine (down to 620 m u.s.l.);
- Discover the presence of any extraneous objects in contact with the pipeline.

The System consisted on a ROV (Remote Operated Vehicle), connected to the Computerised System installed on the Main Ship. The ROV was connected with a Hydraulic and Electrical System via a pipe whose length was up to 2.000 m. The pipe, transported oil and energy to operate a mechanical arm and 3 cameras. The mechanical arm mainly served to "stab" the electrical contact realised on the Sacrificial Anodes. A near the pipe Reference Electrode served to measure the Potential along the pipeline, while a "Remote Reference Electrode" was used to measure the IR drops across the water and then calculate the CP current distributed along the Pipeline and correct the potential values accordingly. The method, patented by Subspection, produced a plot with accurate pipe-to-soil potential measurements along the pipeline, together with the relevant “Transverse Gradient Technique” results, while the cameras realised the corresponding video along the pipeline.

2 – Intelligent Pig Inspections and results

Intelligent Pig Inspections are essential to verify the present integrity of operating, buried pipelines. Pig Inspections of pipelines are programmed according to technical, economic and strategic factors, such as:

- Year and Standards of construction;
- Conception and operating pressure;
- Possibility of interference by third parties;
- Evidences or doubts about the presence of corrosions;
- Diameter and thickness;
- Cost to allow the passage of the pig in the pipeline;
- Development program of the pipeline network.

The MFL (Magnetic Flux Leakage) PIG (the most used one) is able to detect:

- Corrosions (it can distinguish between internal and external corrosion)
- Material defects or construction defects not detected by the hydraulic tests.
- Metallic objects nearby or in contact with the pipeline.
-

Then excavations, inspections and analyses of coating/metal defects are evaluated according to Internal Specifications, whose criteria are based in ASME last revision. The type of damages and the relevant repair methods are applied according to the severity of damage: superficial, moderate or severe.

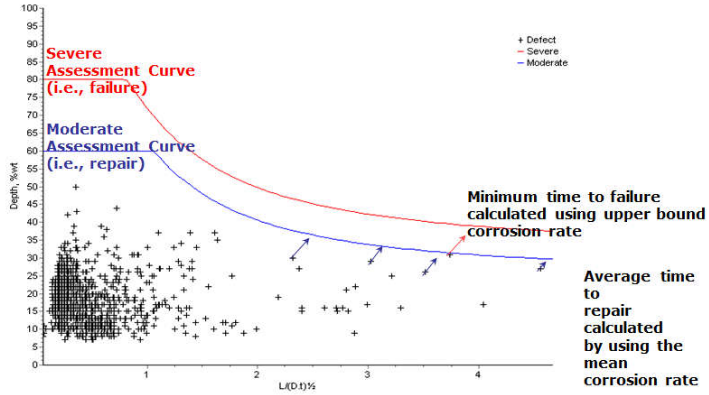
2.1. – Pig Inspection Interval Optimization

As there is a large number of pipelines to be inspected, the need of optimization of Pig Inspection Intervals is quite evident. A methodology and a database to compare different parameters used to evaluate the integrity has been then developed containing:

- Basic data of pipelines;
- Class Location information;
- Condition monitoring data,

and many other data allowed to develop the complex algorithm “**Pig Inspection Interval Optimization”** which was later on integrated with a new approach:

- Obtain Corrosion Rates from previous, repeated Pig Inspections
- Apply this Corrosion Rate to the population of remaining Corrosions and evaluate their growth over time
- Estimate the minimum time to failure and the Average Time for executing a certain number of X Repairs.



Intelligent PIG Inspection – Typical elaboration of the results

2.2. – Non-Piggable Pipelines

The majority of modern pipelines are certainly piggable. Nevertheless, about 10.000 Km out of the total of 31.000 Km of gas pipelines were not piggable. Non-Piggable Pipelines which had been installed in the period 1950 – 1989, whose operating gas pressure was > 24 to 100 Bars were taken into consideration in order:

a - to make them piggable;
b - to perform specialised surveys along them;
c - to localise critical sections in terms of various possible corrosion or damages in order to perform excavations and relevant repairs.

In detail, the main critical conditions on operating gas pipelines from the corrosion point of view are the following:

- Corrosion due to d.c. or a.c. interferences
- Stress Corrosion Cracking
- Corrosion under disbonded coatings (shielding effect towards CP current)

According to laboratory researches and field measurements, the characterization of coating faults can lead to localize corrosions, even under disbonded coatings, by above ground surveys. An important study was performed to electrochemically characterise the various possible types of coating faults. The measurements were performed by using a series of modulated square waves, and recording the responses at different frequencies by measuring, contemporaneously, the following parameters:

- the Rp (Polarisation Resistance);
- the Cdl (the Double Layer Capacitance);
- IR Drop.

The result of this study was the following:

Comparative Electrochemical Characterisation of different types of Coating Faults				
N.	FAULT FEATURE	COMPARISON		
		Rp (Ohm)	Cdl (microFarads)	IR drop (Ohm)
1	Slightly permeeable Coating	Very High	Very Low	Very High
2	Open fault (Cathodically Protected)	High	Low	Low
3	Open Fault (in corrosion conditions)	Low/very Low	High	Low
4	Open, small Fault - High a.c. Density	Medium/Low	Medium/Low	Low/very Low
5 and 6	Coating Fault + Mechanical damage	High	Low	Low
7	Shielding fault (corrosion under disb. Coating)	Low	Medium/High	High
8	Open Fault + Disbonded Coating	Medium/Low	Medium/High	Low

In order do decide which section of which pipeline should be made piggable, a series of considerations were made. Various types of Specialised Electrical Surveys were performed.

3 – Specialised Surveys

On gas pipelines which cannot be inspected by intelligent Pig, typically the following surveys were performed:

3.1. – ECA – Electromagnetic Current Attenuation

Poor quality coatings such as bitumen, pipelines absorbing high amount of current densities for being cathodically protected, low/very low resistivity & flooding soils.

3.2. – DCVG – Direct Current Voltage Gradient (specifically the Transverse Gradient Technique)

According to the results of ECA Surveys, some sections whose attenuation values were lower than the LIMIT VALUE, were surveyed by using the Transverse Gradient Technique.

3.3. – Detection of Rp values along the Pipeline

This type of survey was only used as an experimental technique, on a few pipelines chosen among those which suffered from corrosion under disbonded coatings. In particular, this type of corrosion is known to happen on pipelines laid in the 70ies, whose coating was constituted by Field Applied Tapes, and in more recently laid pipelines whose main coating is PE (2 or three layers Polyethylene) applied in the factory, but whose repairs in the field were performed by using thermo-shrinkable sleeves. These sleeves were often site of wrinkles and then corrosion under disbonded coating (shielding effect).
According to their age, their strategical function in terms of Gas Service to the Clients, and the results of the above said surveys, the Pipelines were prioritised in order to make some Sections of them or the entire Pipeline piggable.

4. – The Technical structure of the Company

In order to obtain the objectives quoted above, a careful, devoted Organisation is necessary. The structure of the Company dealing with Corrosion, Cathodic Protection and Pipeline Integrity in general was spread within 2 main Divisions:

STUDY & RESEARCH DIVISION

METALLURGICAL LABORATORY
Metallography
Weldings
Non Destructive Techniques
Corrosion & Cathodic Protection
Corrosion & Stress Corrosion
Polyethilene Pipes
Plastic materials
Landslides - Finite Elements Calculations
Fracture Mechanics
Materials

TECHNICAL DIVISION

PIPELINE INTEGRITY
Cathodic Protection
Coatings
Intelligent Pig Inspections
Landslides - Tunnels - Crossings
Geological Controls

While the Technical Division was dealing with the normal operating life of Pipelines, the Study & Research Division was mainly devoted to study corrosion and integrity problems found on the pipelines, in order to better understand their origin and causes and then study remedial actions.

It is very meaningful that one of the main task which was assumed in order to study the risk associated with corrosion under disbonded coatings was the subject of a MBO (Management by Objective) Study performed in the following steps:

- Find out the causes which determine wrinkles in the coating;
- Study of the formation of anaerobic environment;
- Verify where Corrosions can take place;
- Verify the Corrosion rate at the sites where they have been found.

5 – Pipeline Integrity Data Sheet

Well before the ECDA was adopted in the USA, within our Company was developed a methodology to verify the integrity of pipelines, the **Scheda Integrità Metanodotti (Pipeline Integrity Data Sheet)**. Its content recorded the Data of interest obtained by various origin:

A – CP System, CP Station/s
B – Intelligent Pig Inspections
C – Geologically controlled Areas
D – River Crossings and Tunnels
E – Characteristics of Cathodic Protection Systems

The typical **Pipeline Integrity Data Sheet** appeared as follows:

SCHEDA INTEGRITA' METANODOTTI

1. ANAGRAFICA

Denominazione	: **Ravenna - Chieti**	
Tratto	: **Recanati - San Benedetto**	
Famiglia	: Dorsale driatica	
Commessa	: 45.650 (4.500.070)	
Lunghezza (km)	: 69,8	
Distretto	: Centro Orientale	
Centro	: Civitanova	
Pressione CPI (bar)	: 68,6	
Pressione MAOP (bar)	: 68,6	
Rete	: Primaria	
DN	: 650 (26")	
Anno di costruzione	: 1970	
Spessori (mm)	: 11,13 - 14,2	
Coeff. di sicurezza	: 2	
Grado acciaio	: API 5L X60	
Tipo di rivestimento	: Linea	NAL
	Giunto	NAI

NOTE :

ICS: 3

Data

2. ISPEZIONI CON PIG INTELLIGENTE

Denominazione piggabile	: Recanati - San Benedetto	
Lunghezza piggabile (km)	: 69,8	
Anno ispezioni	: 1994	1998
N° di ML esterni al km	: 7,18	18,67
N° di ML esterni al m² (x 1000)	: 3,48	9,00
N° di ML esterni giunti sald.	: 104	191
Tasso medio di crescita delle corrosioni (mm/anno)	: 0,04	
Anno prossima ispezione	:	

NOTE :

ICS: 4

Data

3. AREE A CONTROLLO GEOLOGICO

N° tratti soggetti ad instabilità	: 72	Lungh.tot. (km):	28,647
N° tratti soggetti a frane	: 23	Lungh.tot. (km):	10,665
N° tratti soggetti a frane ed erosioni	: 3	Lungh.tot. (km):	1,250
N° tratti soggetti a erosioni	: 4	Lungh.tot. (km):	1,065
N° località con estensimetri	: 15		
N° località con inclinometri	: 11		
Data ultima survey geologica	: 1998		

NOTE :

ICS: 3

Data

LEGENDA:
ICS - INDICE CRITICITA' SPECIFICO
IGIM - INDICE GLOBALE INTEGRITA' METANODOTTO
(Media aritmetica ICS)

VALORE INDICI
1 - OTTIMO
2 - BUONO
3 - SCARSO
4 - MOLTO SCARSO

4. ATTRAVERSAMENTI FLUVIALI E GALLERIE

N° attrav. fluviali subalveo	: 6	Lungh. tot (m):	104
N° attrav. fluviali aerei	: 9	Lungh. tot (m):	941
N° gallerie	: 0	Lungh. tot (m):	0

NOTE :

ICS: 4

Data

5. CARATTERISTICHE PROTEZIONE CATODICA

Densità corrente di protez. media (μA/m²)	: alta	120,00			
Valori d'isolamento medio (Ω*m²)	: scarsa	5.750			
Variabilità correnti disp.	: bassa				
Resistività media del terreno (Ωm)	: media	35			
Corrosività media del terreno	: media				
N° attraversamenti FS	: 1	di cui elettrif.	1		
N° parallelismi FS	: 0	di cui elettrif.	0	Lungh. tot. (km)	0,0
N° parallelismi AT	: 0			Lungh. tot. (km)	0,0
Anno stato elettrico	: 97-98				

NOTE :

ICS: 4

Data

6. RILIEVI ELETTRICI

Attenuazione media	: 2,50	Anno rilievi:	1998		
Valore di rif. - 3.7 (mdB/m²)		km :	68,8	% : 100	
Gradienti trasversali	: 0,00	Anno rilievi:			
km		% :	0	N° falle/km	0
Gradienti longitudinali	: 0,00	Anno rilievi:			
km		% :	0	N° falle/km	0

NOTE :

ICS: 3

Data

7. INTERVENTI SULLA CONDOTTA

Riparazioni a seguito passaggio Pig

n° ripristini	: 27
n° corazze	: 8
n° sostituzioni	: 13
n° clock spring	: 0
n° f.o.r.t.e.	: 0
n° in attesa risultati	: 27

Interventi in aree a controllo geologico

n° delle località	: 0
lungh. totale scavi (m)	: 0

Interventi a seguito controllo stato elettrico

n° scavi per verifica rivest.	: 0
n° scavi per verifica effetti interf.	: 0

NOTE :

ICS: 4

Data

VALUTAZIONE		*Max*
IGIM :	3,6	4,0

where:

ICS : Indice di Criticità Specifica (**Specific Criticity Index**);
IGIM: Indice Globale Integrità Metanodotto (**Pipeline Global Integrity Index - the arithmetic mean value of various ICS**).

The Classification of the Indexes being the following:

1 – Great
2 – Good
3 – Poor
4 – Very poor

The calculated Pipeline Global Integrity Index in this case was:

EVALUATION		Max
IGIM :	3,6	4,0

Which means that the Mean Global Index all over the pipeline is 3,6 (poor), with a Maximum value of 4,00. This means that one of the indexes (the results of Intelligent Pig Inspection in this case) showed a very poor value.

6 – The Guided Waves Technique

Wherever an operating pipeline cannot be accessed for a Pig Inspection, the use of the Guided Waves Technique can be a very helpful alternative. The application of Guided Waves as NDT Technique started 30-40 years ago. The initial ddevelopment started in 1987 by Alleyne & Cawley. The first generation of the present technology was licensed in 1997-1998. Various updated have been made since then.

This methodology is especially cost effective and useful in those cases where the pipe is difficult to be inspected such as:

- Pipe racks
- Corrosion under insulation
- Road crossings
- Tunnels
- Wall penetrations

The method is able to reliably detect cracks and general metal loss along a short section of pipe. The method is very useful in Compressor Stations or Pumping Stations, where many pipes cannot be inspected with other techniques.
The use of the Guided Waves Technique is not simple. Very highly qualified and Specialised Technicians are needed. Experience is fundamental when using this Technique.

a – Guided Ultrasonics solid transducer system

b – Flexible, pneumatically clamped system for larger diameter pipes

7 – Conclusion

According to our large field experience and the use of the various techniques described in this paper, we can conclude that a devoted organisation within the Company is necessary in order to reach fundamental results, which are surely very useful to design, build, and then maintain Pipeline Integrity, especially when the network is quite large and involves the whole country. It is important that the Third Party Personnel involved in the surveys is very highly qualified; the supervision from the Company Technicians is essential.
In order to achieve this task, the Company Personnel must be prepared, expert in the relevant fields, and mainly should know very deeply the characteristics of their pipelines in order to be able to help the Specialist of the Surveys (which are usually by a third party Company). This means that the Technical staff within the Company must have two main Characteristics:

- They must know in a very detailed way the network and the pipelines under control;
- They must be deeply expert in the techniques which are being used.

But, mainly, they must be accompanied by a careful organisation within its Company which allows him to reach the due level of knowledge in Pipeline Integrity.