Meeting

Condition-Based Maintenance for Highly Engineered Systems
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LIFE ASSESSMENT OF PIPELINES BY ADVANCED IN-SERVICE INSPECTION

1. SUMMARY

Enel S.p.A has approximately 240 km of oil pipelines available, to transport the fuel required to feed its Thermoelectric power plants. They play, therefore, a particularly important strategic role.
This is the reason why they are periodically inspected for their State of Maintenance, in compliance with the legal provisions in force, and for Mechanical Stability, according to long-standing international procedures.
The inspections for Mechanical Stability and the resulting Residual Life Evaluations are based on the results of the defect status provided by highly engineered control systems. These notes report a brief description of the above instruments and describe a practical example of their use and data processing methods.

2. LEGAL PROVISIONS AND APPLICABLE REGULATIONS

For the inspection of the general State of Maintenance, coastal oil pipelines are subject to the provisions of the DPR (Presidential Decree) no. 328 of 15.02.92, which establishes that oil pipelines must undergo a general inspection by a “Testing Committee”, which can show the need to conduct “extraordinary inspections”.
Since the mentioned Presidential Decree does not tell which type of inspections should be conducted, Enel S.p.A, consistently with international practice and in particular with the European Pipeline Operator Forum **,** periodically inspects the Integrity status of the pipe steel composing their oil pipeline network. (provided they are constructively fit), using the so-called “ In Line Intelligent Pigs” (PIGs), and, for the External Integrity Status of Sea Lines, using the Remotely Operated Vehicles (ROVs).
The results of the in-line inspection measurement performed by the PIGs are processed according to the ASME B31G regulation **[1],** as will be described later in more detail.

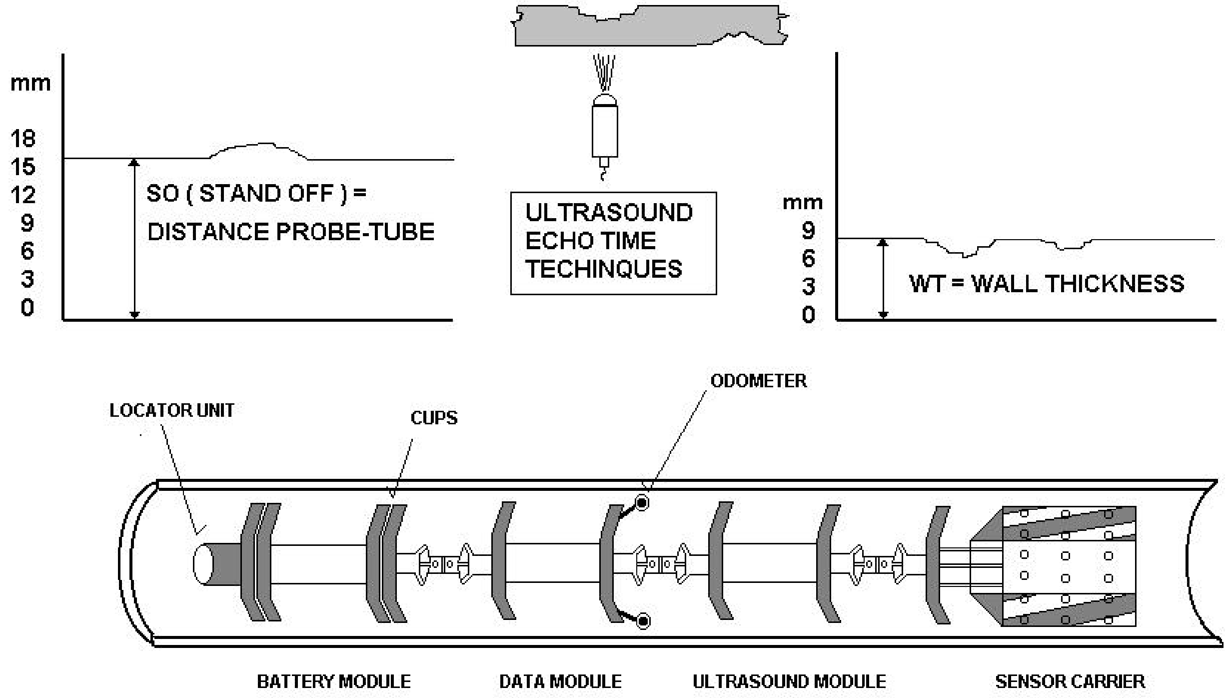
3. DESCRIPTION OF SELF-CONTAINED INSPECTION EQUIPMENT

It describes the main features of the latest-generation Intelligent PIGs, which are ordinarily used to inspect pipelines structural defects, as well as the (ROVs), which are used for the external inspection of Sea Lines.

3.1 Intelligent PIGs

High-Resolution Ultrasound Pigs (PIG/UT/HR)

The Wall Thickness Measurement inspection principle of this PIG, shown in **Fig. 1,** is based on the ultrasonic time-of-flight immersion technique, using a low-density oil (e.g. a flushing oil) or water (raw or sea water) as a coupling fluid.
Ultrasonic transducers are installed on a flexible sensor carrier, which keeps them properly aligned to the pipe wall.



PIPETRONIX ULTRASCAN SYSTEM

(COURTESY OF SOC. TECMA-MI)

Fig. 1

The remaining wall thickness is quantified as an absolute value based on the measurement of the echo-signal interfaces between the "fluid- internal pipewall" and "external pipewall -air", after calibration of the ultrasonic speed based on a fluid sample and a nominal wall thickness pipe steel section.
The data, which are displayed on a PC monitor, are shown in a special template.
The upper part shows the C-scan map of the feature, and provides the opportunity to read the "stand-off" value, the distance between transducer and internal wall (SO) and the absolute thickness of the wall (WT).The lower part shows the B-scan signals, which supply the defect cross-sectional profile of each probe.
Selecting the sensor which detects the deepest corrosion will provide the reading of the corresponding value.**Fig.2** shows an example of B-C Scan presentation respect a real picture of corroded area.

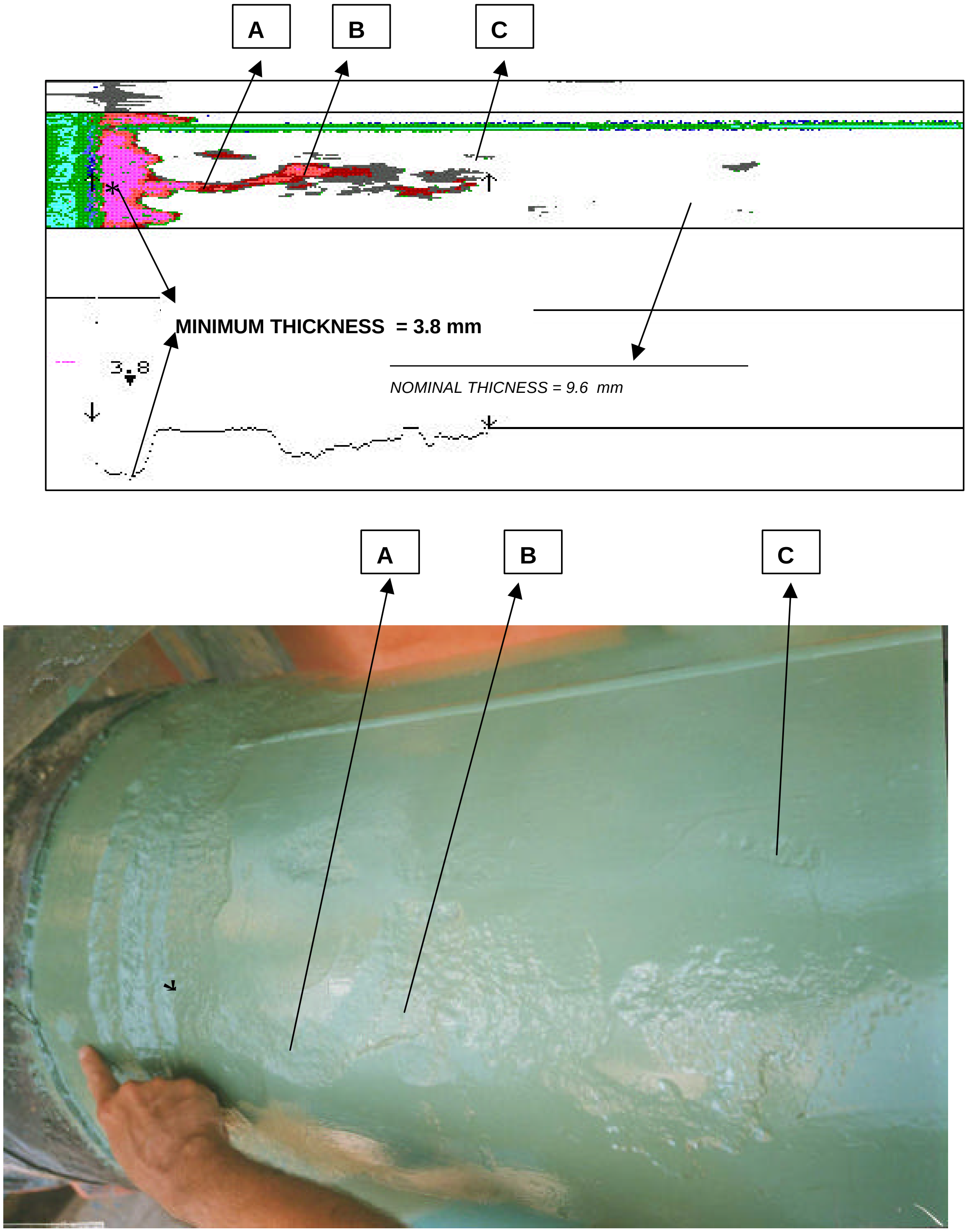


Fig.2

Tab.1 reports the performance reference of a PIG/UT/HR

Key Specifications of Wall thickness Measurement Ultrasonic Pig (*)	
Available nominal diameter	6”60”
Transducer frequency	5 MHz
Pulse generator frequency	330 Hz
Inspection range	100-1000 km (depending on diameter and settings)
Nominal speed	0,2-2 m/sec
Operating temperature	4-50°C (up to 70° optional)
Minimum negotiable bending radius	R = 1.5 D
Thickness measurement resolution	+/- 0.2 mm
Accuracy of corrosion depth evaluation	+/- 0.5 mm (mean value)
Circumferential resolution	≈ 8 mm
Longitudinal resolution	≈ 3.3 mm at 1m/sec and 330 Hz
Location accuracy	+/-0.2 m from nearest weld
Maximum pressure	120 bar

Tab.1

(*) : PII-Pipetronix UT/WM Pig specifications (courtesy of TECMA-MI)

High-Resolution Magnetic Flux Leakage Pig (PIG/MT/HR)

The inspection principle of this Pig, shown in **Fig. 3 ,** is based on the magnetic flux leakage principle.
As the tool travels trough the pipeline, powerful permanent magnets magnetise the surrounding metal via wire brushes, that contact the internal wall. Flux density is driven to the point of saturation.
Any change in the thickness of the metal in the pipe wall – a fitting, a weld or a patch of corrosion – causes disturbances in the magnetic field. Sensors surrounding the circumference of the tool read these disturbances and record the data on-board.
The characteristic patterns of flux leakage can be interpreted to establish the dimensions of each anomaly. Since flux leaks on both sides of the pipe wall it is possible, by means of secondary tool-mounted sensors, to discriminate between internal and external metal loss.
Other data is recorded as the tool progresses, odometer wheels log the distance travelled, and an internal pendulum records the orientation of the tool within the pipeline.
A time based marker system is deployed along the pipeline right of way to log the time of passage of the tool. When combined with the tool’s on board reference, the system aids in the location of anomaly when intervention become necessary.
High resolution magnetic tools are available in standard and custom dual-diameter versions, and with by-pass speed control which enables optimum tool speed without restricting product flow. They can also be equipped with the latest ring laser technology to provide for inertial mapping data for precise geographical information.
Fig.4 shows a commercial Magnetic Flux Leakage Pig commonly used in pipeline inspections.

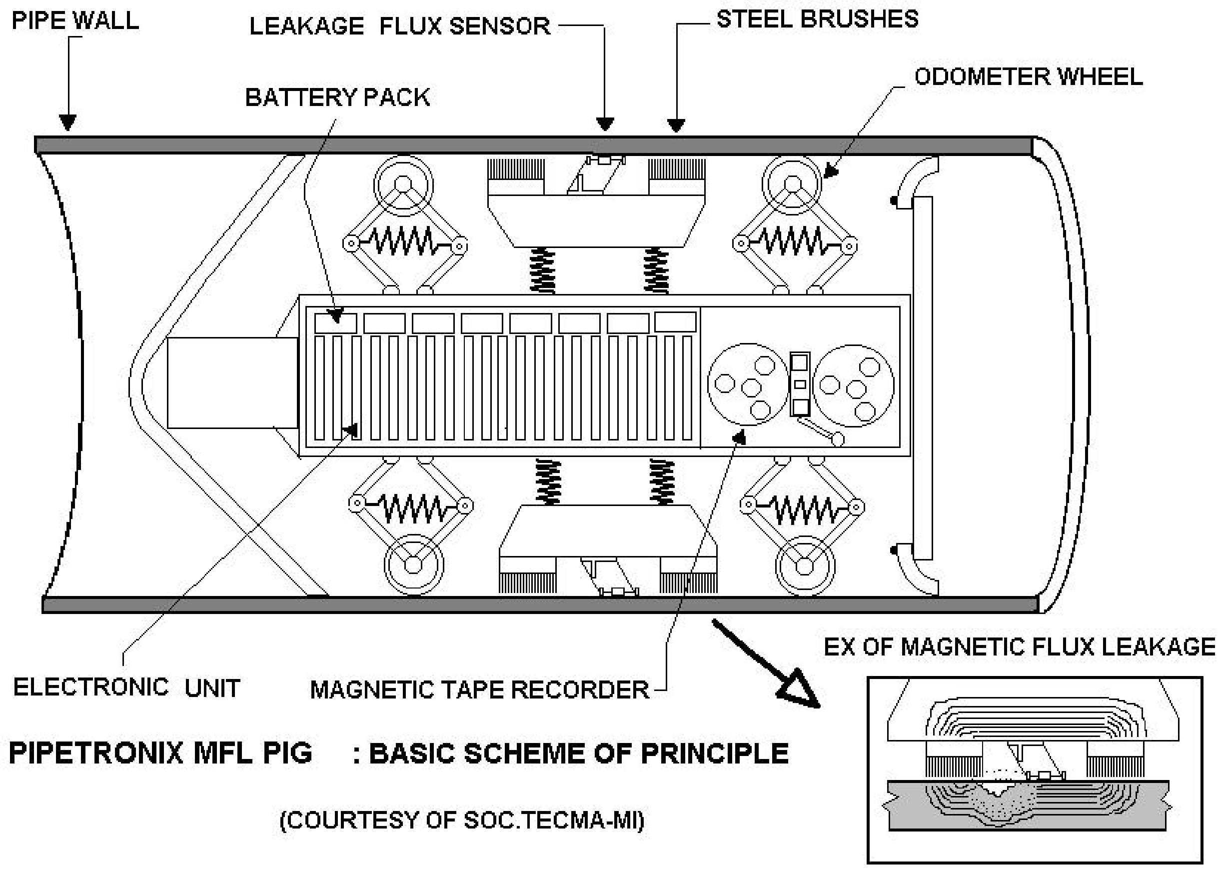


Fig.3

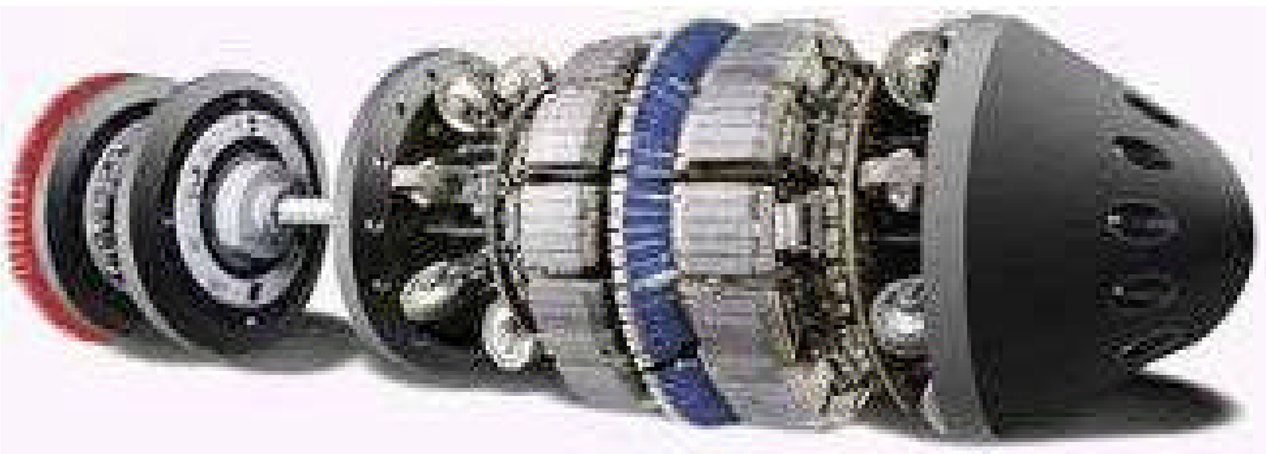


Fig.4

(PIPETRONIX MAGNESCAN HR PIG : COURTESY OF. SOC. TECMA-MI)

Tab.2 reports the performance reference of a PIG/MT/HR

Key Specification of High Resolution Magnetic Pig (**)	
Available nominal diameter	6-56”
Maximum wall thickness	Up to 38 mm (depending on size)
Product	Liquid and gas
Inspection range	100-1000 km (depending on diameter)
Rated speed	0.5-4 m/sec
Operating temperature	0 - 40°C (higher temperature optional)
Minimum negotiable bending radius	R = 3 D (1.5 D optional)
Minimum measurable corrosion depth	10% wall thickness
Minimum measurable corrosion area	(7mm)x(7mm) or (0.4t x 0.4t) (t = pipe wall thickness)
Sizing - detected features Length > 3t Length < 3t	Depth accuracy +/- 0.10t Length accuracy +/- 20mm Length accuracy +/- 10mm
Location accuracy	+/-0.5 m from reference weld
Maximum pressure	220 bar

Tab.2
(**) :PII-Pipetronix Magnescan HR Pig specifications (courtesy of Soc.TECMA-MI)

Although high resolution metal-loss detection tools such as the above presented magnetic and ultrasonic vehicle are capable of identifying a wide range of corrosion defects, they cannot be relied upon to detect all of them. If special problems should arise, then special inspection PIGs, such as the following are ready on the market:

Crack Detection PIGs
MFL transverse field: A revolutionary high resolution magnetic intelligent pig designed to detect seam weld and other axial defects.

Ultrasonic Crack Detection:
An ultrasonic tool optimized for the detection of cracks such as stress corrosion cracking.

Caliper PIG
It is provided with articulated sensors, with double-contour wheels, which perform a continuous control survey of the pipeline, along several generating lines, to detect any deformation caused by:
- Earth movements;
- Manufacturing deformations;
- Interference caused by third party (e.g. excavators, etc.)
- Yielding of supports.

The Caliper Pig is generally used after pipeline construction to validate the job quality or prior to inspections to check if the pipe is geometrically fit for the passage of the inspection Pig.

Leak Scan PIG
It is a sound-detector Pig which picks up the ultrasonic waves generated by leaks of carried fluid, while locating the source.

Remote Operated Vehicle (ROV)

The ROV is used for the external inspection of the maintenance condition and eventual spanning of the Sea-Line.

It consists of an underwater automated system, provided with special instruments on board.

It is fed and controlled, through an “umbilical cable”, from a control console located on a Support Ship which drives it along the sea line using GPS systems, as outlined in **Fig.5.**

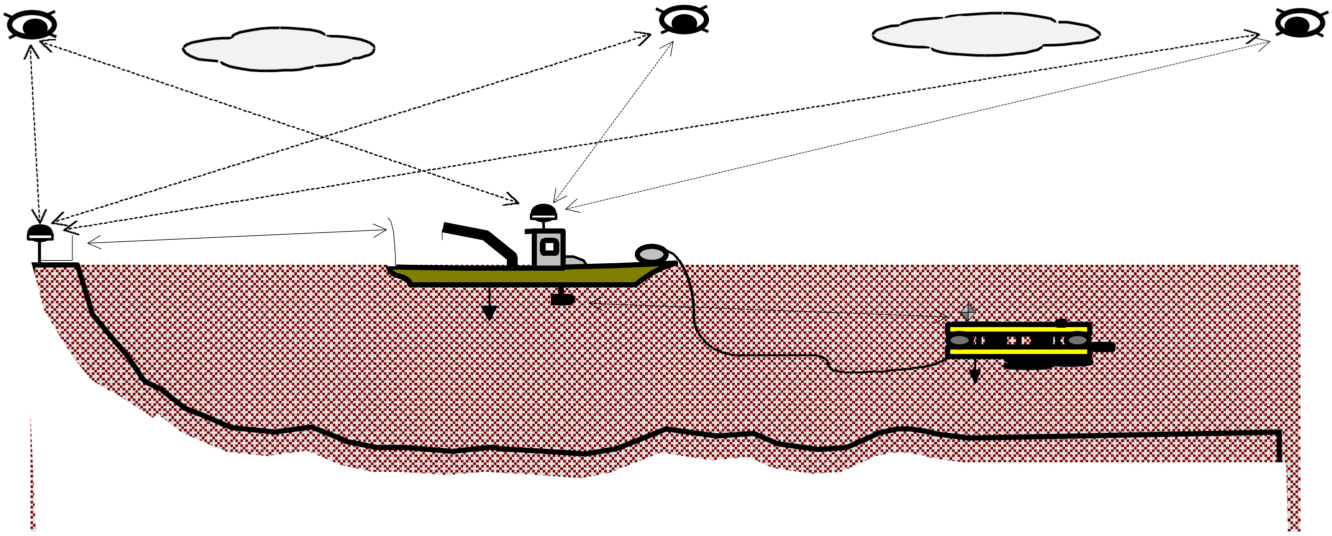


Fig.5.

The ROV is equipped with motors to drive it vertically/laterally as well to along the pipeline.

The ROV normally used by Enel S.p.A, is manufactured by CESI S.p.A and shown in **Fig.6.**

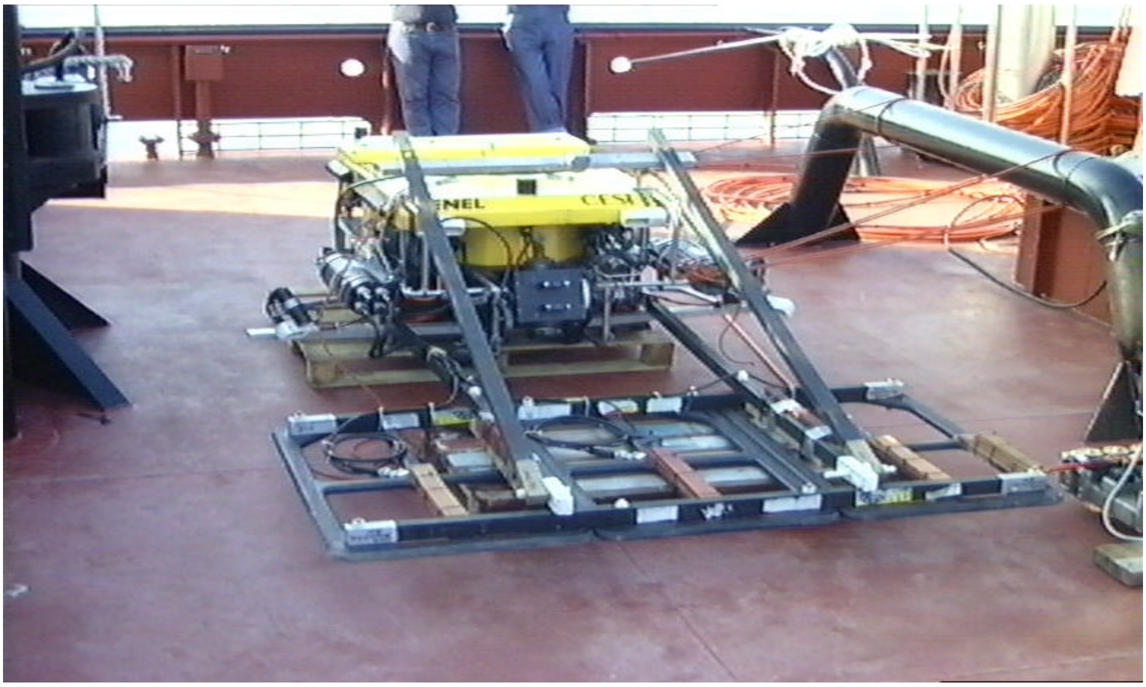


Fig.6

The ROV is provided with the following main instruments:

- GPS (Global Positioning System)
- Sonar Profiler to survey transversal sections of pipes
- Sonar Wide Range to detect any object or obstacle
- Precision altimeter;
- Hydro-acoustic position reference system;
- General-purpose television camera and low light level television camera;
- Pipe tracker to survey pipe where filled in;
- Multi-electrode probe for continuos measurements of cathodic protection.

During ROV inspection will be acquired both visual and instrumental data using appropriate HW and SW.
All apparatus will be interfaced with navigation system in order to simultaneously store ROV position and data supplied by measure instruments.
In **Fig.7** is simplified a typical Data Processing of a Sea Line Survey.

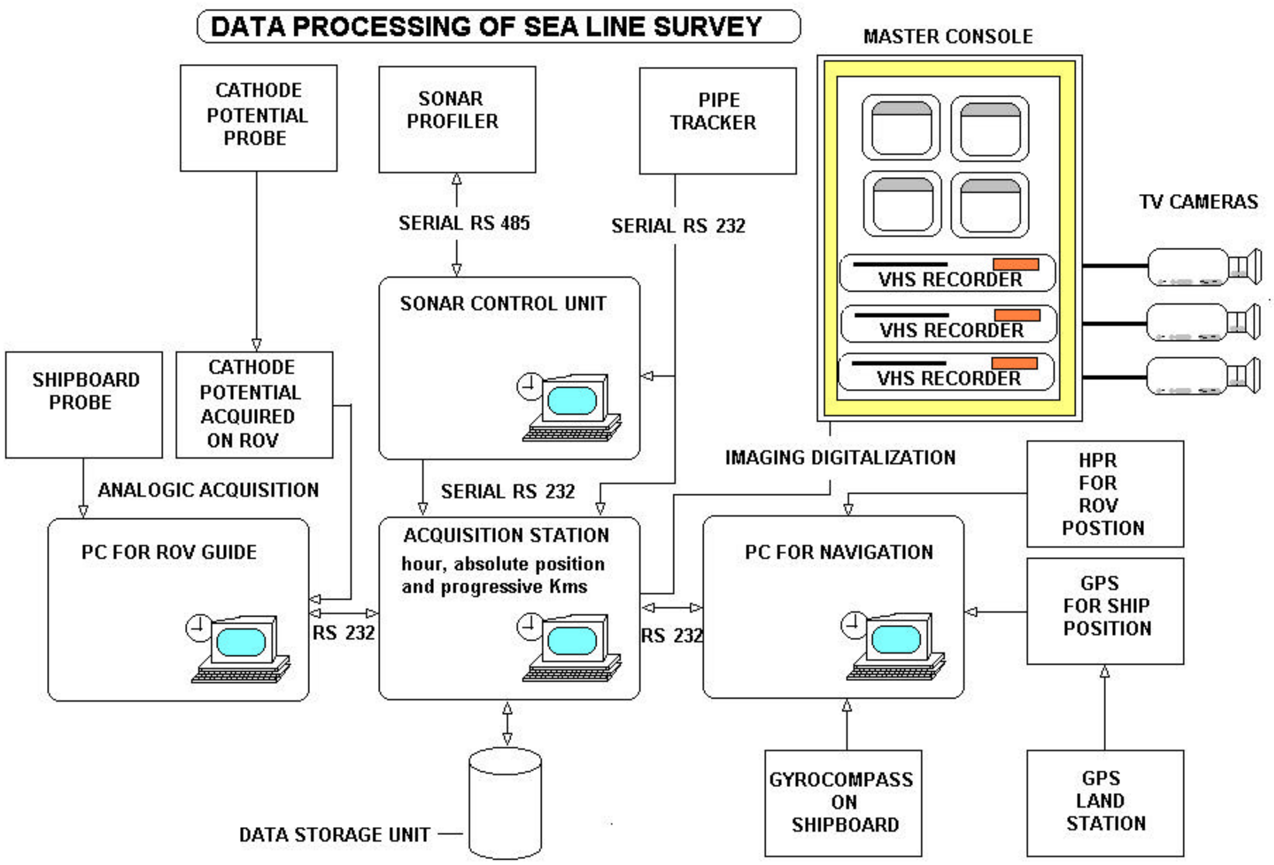


Fig.7

4. PURPOSE OF INSPECTIONS

The purpose of internal inspections through the use of Intelligent Pigs is to detect the presence of anomalies and potential defects, in order to follow up with strategic integrity maintenance and rehabilitation programs (Condition-Based Maintenance services).
The following are the most significant anomalies:

1. Corrosion phenomena;
2. Manufacturing cracks;
3. Fatigue cracks;
4. Stress corrosion cracks or cracks induced by sour service (sulphide compounds) ;
5. Hydrogen induced cracks;
6. Mechanical or metallurgic damages (gouges, hardspots etc.)
7. Geometric deformations (ovalization, indentations, etc)
8. Laminations;
9. Non-metal inclusions;
10. Repairs.

5. CONDITION-BASED MAINTENANCE

The detected anomalies are assessed both in terms of quality and engineering criteria, when practicable, in order to determine the need for **Condition-Based Maintenance** (CBM) services.
Regarding the thickness profile revealed, the metal losses are evaluated according **ASME B31G** regulation, in order to determine the MECHANICAL INSTABILITY RISK, that is the most significant parameter for any CBM decisions.
ASME B31G establishes criteria for the calculation of the **PCP** (**Plastic Collapse Pressure**), beyond which the “contour” of the metal loss area might originate a local plastic collapse, that could result in in the rupture of a pipe and leak of fluid .
The following condition must occur at any point along the line:

$$\textbf{RF (Risk Factor)} = \frac{\textbf{MAOP}}{\textbf{PCP}} \leq 1$$

where MAOP (Maximum Allowable Pressure) it is the maximum pressure, specified by the “Customer”, which the pipe can undergo as a function of the design value, operating parameters and safety coefficient.
CBM services are to be planned in the areas where **RF** values >1, and their “urgency” depends on the parameter value and other ambiental factors (type of defect, location of section, type of fluid etc).

As far as non-structural aspects are concerned, experience suggests that CBM services may be also required under the following circumstances:

- Significant ground movement deviations;
- Significant deformations;
- Damages to external coating/insulation;
- Damages underneath support, anchor, expansion joints;
- Faulty operation of cathodic protection.[2]

Typical CBM services related to Structural Integrity inspections are the following:

Internal lining
Applying a multi-layer epoxy barrier in several coats will “stop” internal corrosive phenomena (e.g. by the carried fluid).

Clock Spring
Coil of high strength composite material that wraps tightly around the defect area. All interfaces are filled with high strength adhesive. It forms a monolithic support 8 layer thick that restores the original yeld stress capacity (SMYS) of the steel pipe.

Epoxy sleeve repair
Two oversize steel half sleeves joined by welding or bolting, the annular gap filled with high stiffness epoxy grout, it provide support for defects and restores the original yeld stress capacity (SMYS) of the steel pipe.

Snug fitting welded sleeve
Closely fitted around the defect area, two halves joined by welding. Designed to provide support and pressure containment.

Replacement of piping section
The faulty pipe section will be completely replaced with a new one.

Above ground (CIPS, DCVG) surveys
Will pinpoint and asses the need of uprating the cathodic protection system

Fitness for purpouse
FFP assessments provide a comprehensive strategy for determination of pipeline condition and preservation of safe and profitable operation.

Risk assessment
This service calculates the probabilities and consequences of pipeline failure, allowing the operator to focus maintenance resources on the right priority areas.

Where, in the short time, it is not possible to realize any of the above CBM services, one must reduce the operating pressure (derating criteria), in order to obtain a **RF** value <1

6. EXAMPLE OF A SEA LINE INSPECTION

The oil pipeline submitted to in service inspection consists of a 16” sea-line pipeline, having the following main specifications

- Mean flow rate = 400 m^3/h;
- Total length: = approximately 35.8 km;
- Design pressure: 60 bar
- Design temperature: 90 °C;
- Carried fluid: heavy fuel oil, having density of 730-970 kg/m

The underwater section, called SEA-LINE, consists of a bi-tubular pipe, total length approximately 33 km, laid at a maximum depth of approximately 50 m, the technical features of which may be briefly summarized as follows:

- internal pipe: nominal diameter: 406,4 mm (16”); thickness: 10,3 mm; material: API 5L X60 with external protection.
- external pipe: nominal diameter: 508 mm (20”); thickness: 7,9 mm; material: API 5L X 60.
- Cavity filling material: polyurethane foam.
- Corrosion protection external coating: three-layered extruded polyethylene, total thickness: 3 mm.
- Concrete external protection.

External inspection using the ROV

The main activities of such inspection using the ROV concerned:

a) Planimetrical location of the pipe;

b) Determination of the pipe-bottom contour

c) Inspection of external conditions of the pipe;

d) Inspection of the extent of pipe covering or underground laying, if provided;

e) Inspection of cathodic protection potential and current density.

Results of inspection [3]

- Moderate alterations of the altimetric pipe-bottom contour due to sea current effects;
- Moderate scratches to the external concrete coating, caused by the collision of foreign bodies due to local navigation.
- No significant deviation of the planimetrical location of the pipe.
- Proper operation of cathodic protection.

The data acquired did not suggest any CBM condition.

7. EXAMPLE OF AN ON SHORE PIPELINE INSPECTION

The oil pipeline submitted to in service inspection is located on shore, mainly underground, and has the following features:

- Year of construction: 1982, commissioned in 1985.
- Pipes : no. 2 x 24”, w.t.. 9,52 mm, in API 5 LX steel.
- Type of fluid: fuel oil, maximum temperature: 85°C.
- Flow rate: 1,500 t/h.
- Design pressure: 21 bar.

Results of inspection:
The oil pipeline was inspected in 1992 using a PIG/UT/WM and in 1997 using a PIG/MT/HR.

The 1997 inspection found the following:

- 4,133 defects on the internal surface;
- 603 defects on the external surface;
- 26 defects with depth> 50% ;
- **5** defects with unacceptable **Risk Factor .**

Such results determined a CBM condition, which was corrected by snug-fitting welded sleeve.

8. LIFE ASSESSMENT AND IMPACT ON MAINTENANCE POLICY

As described, since the CBM is related to the results of the inspection, it becomes extremely important to be able to plan the following in-line inspection; in order to qualify the development of the most severe defects and their impact on the mechanical stability of the component, keeping in consideration the Risk Based Criterion.(**RBC**) :

RBC = Probability of Failure x Conseguence of Failure

Fig. 8 shows a probability failure diagram developed by a world wide company **[5]** specialized on "Total Integrity Assessment" of pipelines, based on 30 years of experience.

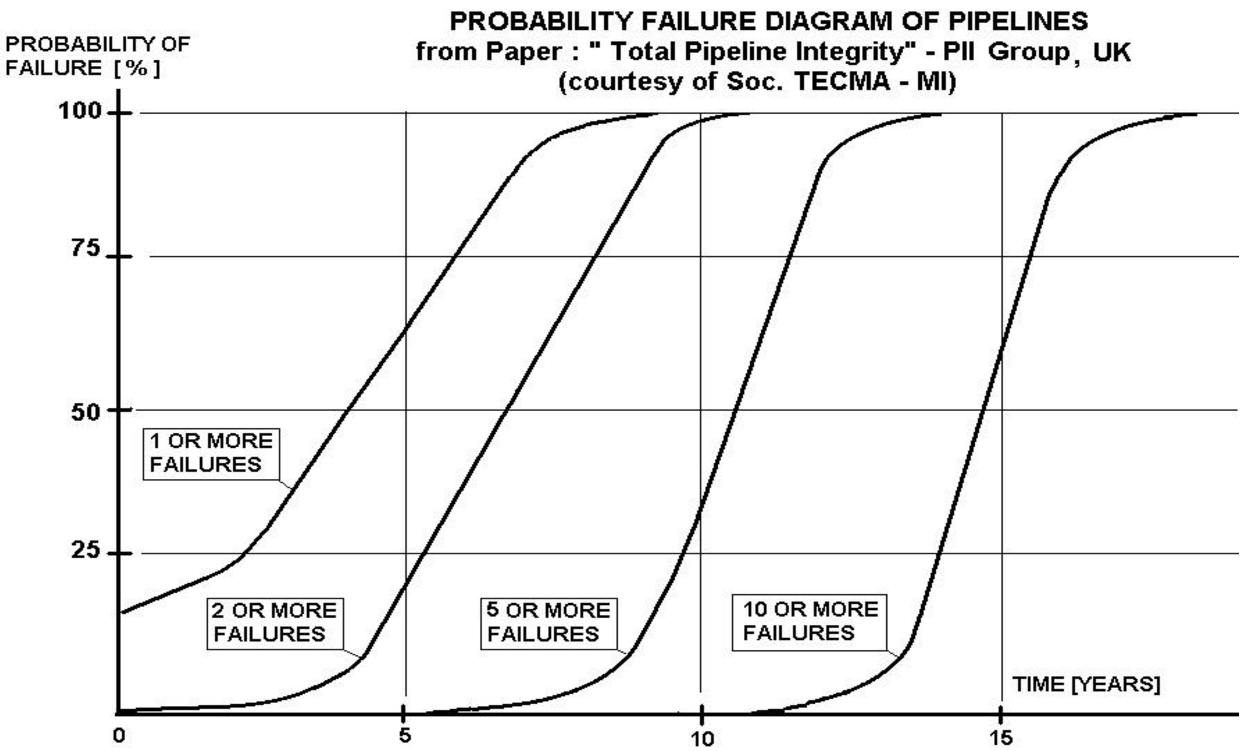


Fig.8

This approach means a long-term description of the development of the most serious defects and their impact on the mechanical stability of the component.
This information immediately affects the decision-making process about maintenance, since it allows to suddenly start repairing those defects which are not yet considered dangerous on the basis of ASME analysis and to plan the following inspection at sufficiently distant intervals (optimization of cost control impact), while ensuring a reasonable level of safety for the component (risk management).
The occurrence and growth of defects show both fortuitous and deterministic aspects.
A defects is to be considered as a probabilistic event; once it has been initiated, it will tend to grow over time in proportion to a specific growth law (deterministic aspect).
One of the several growth laws applied is the “Crews’ law”, given by:

$$d = k1*t^{k2} \qquad \text{where:}$$

- **t** is the time elapsed from the defect trigger-off time;
- **k1** and **k2** are experimental constants available in literature, which are “calibrated” on the basis of observations resulting from the two or more inspection campaigns.

Such projection law was applied to the defects found on the oil pipeline on shore described at **Par.7**, which had a typical depth equal to or higher than 50% of thickness, though still acceptable at the time of inspection (no. 26 defects).
Such survey showed that the data which would reach a non-acceptability condition (**RF>1**) by the end of 2001 would be no. 11 defects (42%), as shown in **Fig. 9.**
Such results suggested that some of these defects should be repaired earlier than planned and that new targeted inspections should be anticipated by the end of 2000.

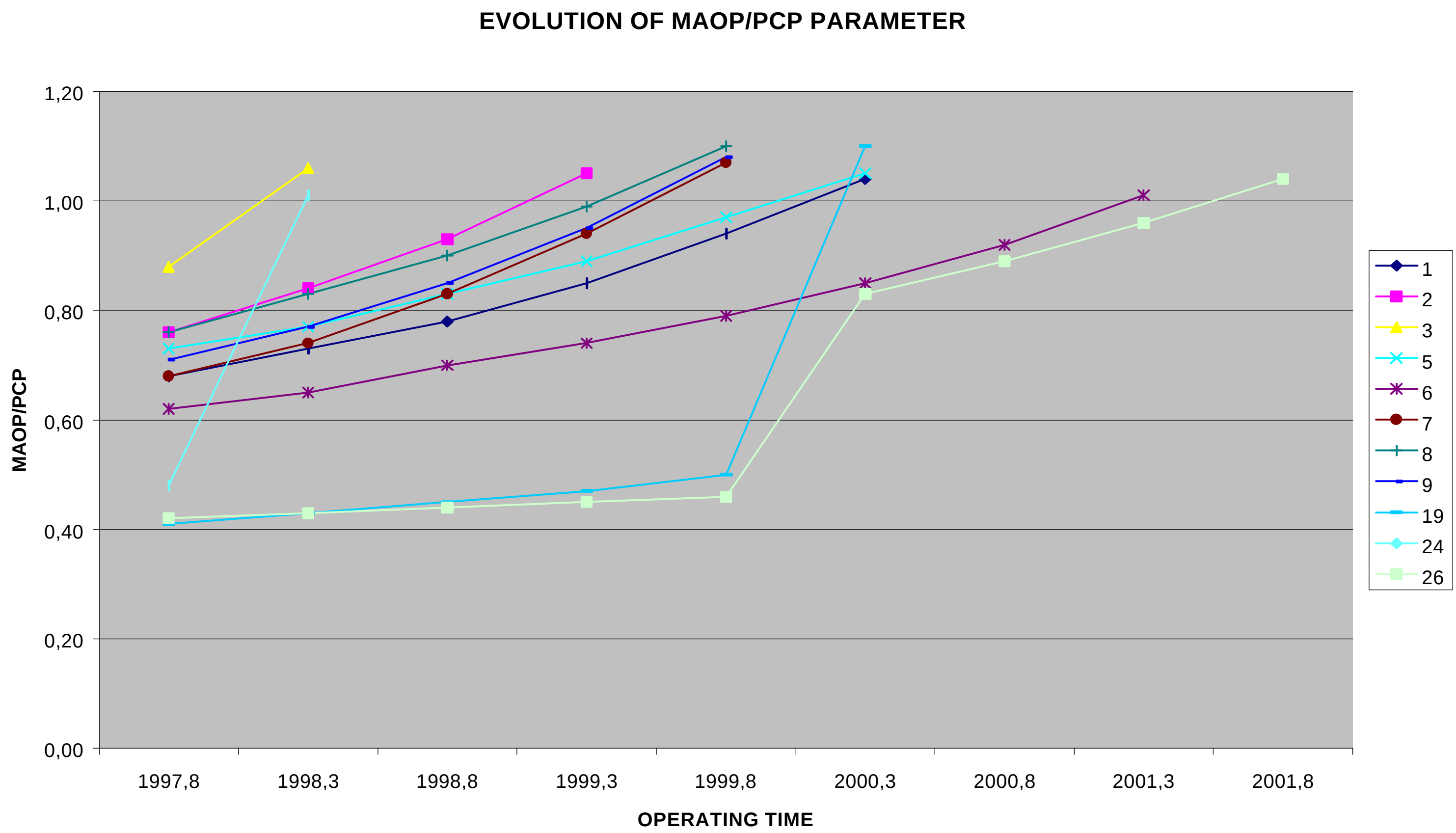


Fig. 9

9. CONCLUSIONS

The experience described of an internal inspection of an oil pipeline on-shore and the external inspection of a sea-line showed that the Condition-Based Maintenance policy must be supported by objective and documentable inspections of the conditions of the component.

Nevertheless, whenever experience suggests that damaging processes are **highly time- and environmental dependent ,** the CBM must be supported by forecasting instruments (Fitness for Purpose and Risk Assessment), which can sometimes suggest that some maintenance service should be performed earlier than planned, or may, however, help to plan the following inspections more efficiently.

R. Crudeli

Pisa, September 2000

GENERAL INFORMATIONS

- **CESI S.p.A** (Via R.Rubattino,54 - 20134-Milano, Italy) is a Company of Enel S.p.A Group
- **TECMA S.p.A** (Via A.Milesi, 5-7- 20133-Milano, Italy) Represents Pipetronix on Italian market
- **PIPETRONIX Ltd** is a Service Company, now merged with PII in the **PII Group Ltd**

REFERENCES

[1] : “Manual for Determining the Remaining Strenght of Corroded pipelines”

[2] : “Role of Chatodic Protection in Mechanical and Residual Life Evaluations o Pipelines” by : R.Crudeli et alii. APCE Congress, Rome 1996

[3] : Technical Report Enel SRI n° AG-UAD-99-6

[4] : Technical Report CISE n° SME-98-11

[5] : “Total Pipeline Integrity” by D.G Jones et alii-PII Group Ltd, Ateley, Cramlington Northumverland NE 23 1 WW (UK)