
# Acoustic Emission data fractal analysis for structural integrity assessment of pressure equipment

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# ACOUSTIC EMISSION

**Acoustic Emission (AE) → Elastic Waves**

Static or Fatigue loads → A change occurs inside a structure (deformation, dislocation motion, crack initiation or propagation)

The elastic waves are in the range 20kHz – 1 MHz.
The AE can be captured by piezoelectric sensors.

In seismology there is a direct correspondence between the AE and the law of Gutemberg -Richter that describes the process of fracture of the earth's crust.

This fact originated all the research efforts to apply this technique to the study of damage and fracture of the engineering materials.

# ACOUSTIC EMISSION

Since many years, the AE methods are currently used in several structural fields as: deformation and damaging of materials, fracture mechanics, composite materials, concrete and rock mechanics, fatigue of metals, life assessment and corrosion monitoring.

The analysis of AE signal is under the application of several rules in different countries.

The most popular applications regard the life assessment of
- Tank
- Crane
- Bridge
- Concrete structure

# ACOUSTIC EMISSION

At University of Tor Vergata we study innovative applications of the AE analysis


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# FRACTALS

**In this paper we applied the AE through a particular type of mathematical treatment of the discrete signals originated during the damaging process of small LPG underground tanks.**

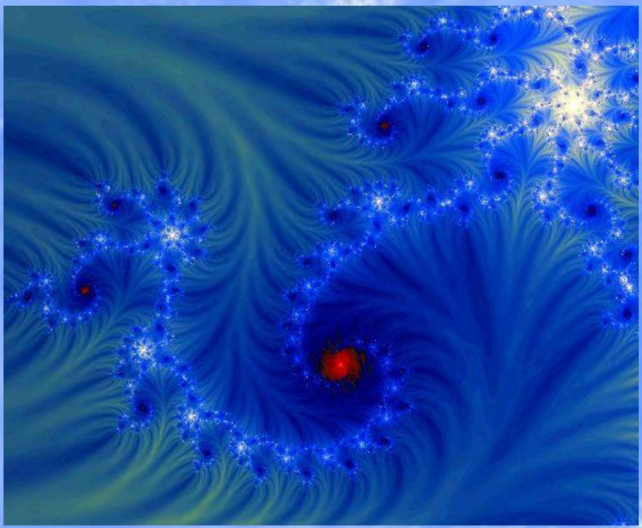
**In particular, the method used is based on the fractal analysis.**

**For this we introduce a brief description of the mathematical approach using fractal analysis**

# FRACTALS

The term «fractal» was introduced by Benoît Mandelbrot (1975), and derives from latin *fractus* (broken, fractured):  the fractals are considered in mathematics objects with a fractional dimension

Computer graphics



Signal analysis

Physical phenomena that can be represented by fractals repeat their structure at different scales

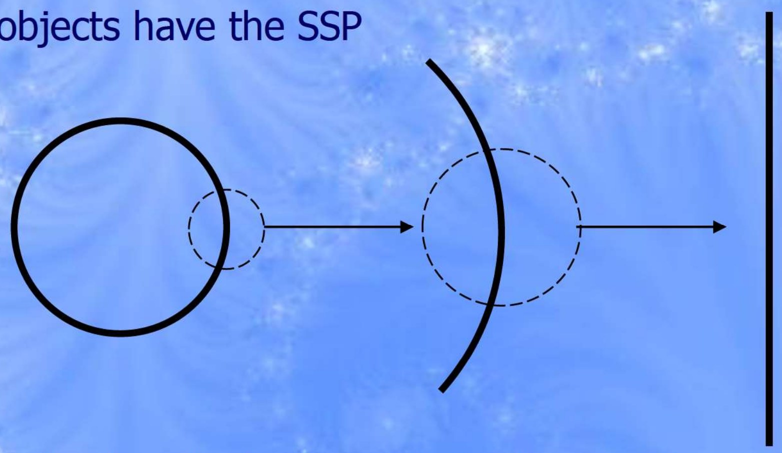
Curva di Koch

# FRACTALS

A FUNDAMENTAL PROPERTY IS SELF-SIMILARITY **SSP**

Not all the natural objects have the SSP

Example 1



Enlarging the image a circle degenerates into a straight line

**The circle has not the SSP**

# FRACTALS

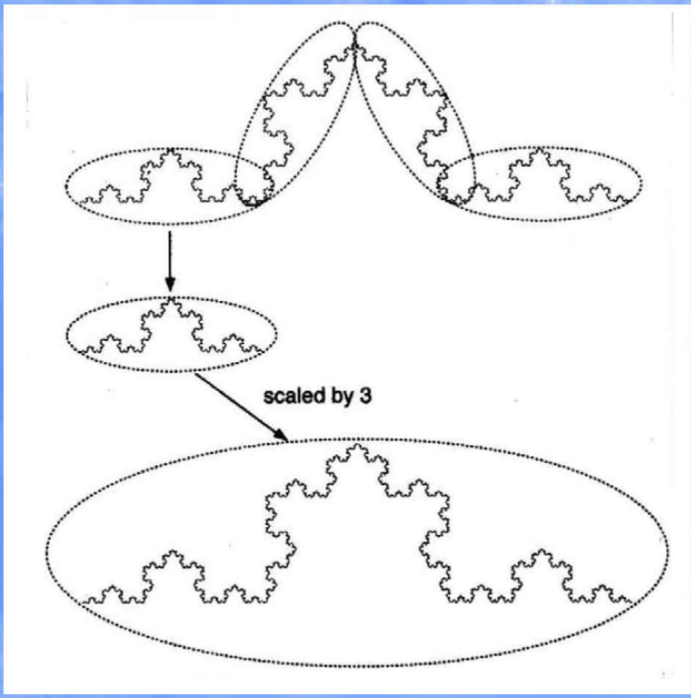
Example 2
Consider the Koch's curve

Dividing the curve we obtain always another Koch's curve

The Koch's curve has the SSP

Several physical objects have the SSP as:
- Cauliflower
- Sea coast generated by erosion
- Etc.

By means of SSP it is possible to introduce the dimension of a fractals



# FRACTALS

The dimension of a fractal shape can be defined by several different formulation.

One of the most popular is the Box Counting Method (BCM) that is due to Mandelbrot and allows to measure the dimension of elements where a self-similar structure is superimposed to a not self-similar one: that is the case of EA signals.

For example if we consider the Acoustic Emission signals as a fractal when its BCM dimension is large we have a perfectly disordered emission: the sources have a random distribution

On the contrary if the fractal dimension is small the emission is ordered that is there is a source or a cluster of sources that release energy at an highest level compared to the others

# BOX COUNTING METHOD

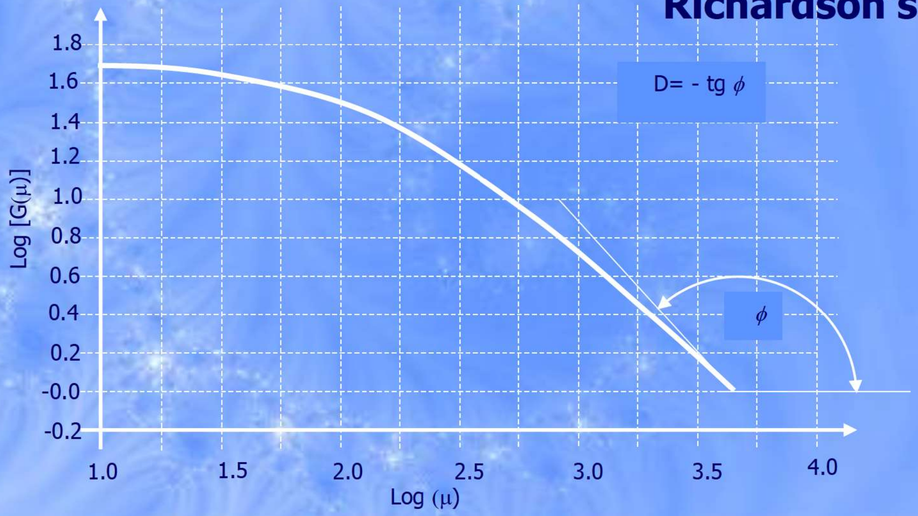
| | |
|---|---|
| If we have a discrete time signal | S |
| In the time interval | $0<t<T_0$ |
| Divide interval $T_0$without superposition in n time lag | $\mu$ "ruler". |
| Define a threshold for the intensity of the signal | $S_0$ |
| Define a counter | $G(\mu)$ |
| When we have at least a signal above the threshold $S_0$ | ADD +1 |
| To the counter $G(\mu)$ | |

# BOX COUNTING METHOD

Plot $G(\mu)$ versus $\mu$ in a log–log graph
Define the interpolating curve C
The slope $H = tg\ \varphi$ of the interpolating curve and this is the fractal dimension changed in sign

$$\Delta_t = -H$$

**Richardson's diagram**



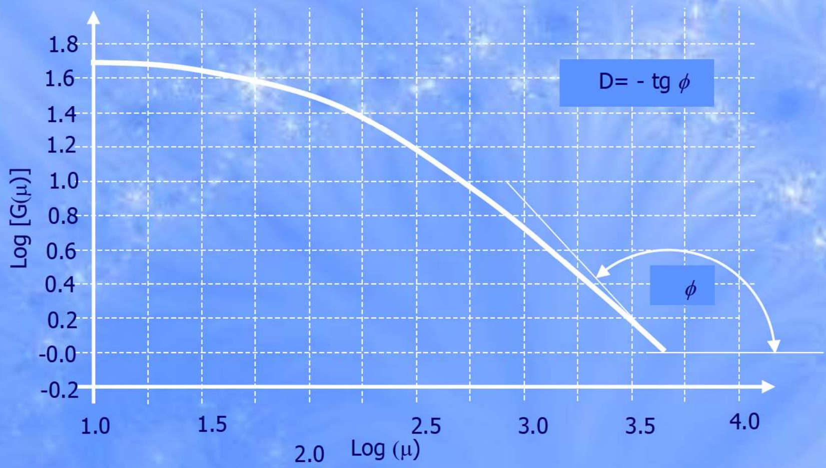
# BOX COUNTING METHOD

As the Richardson's diagram shows
$\Delta_t$ changes with the evolution of the process.

If $\Delta_t \to 1$ there is no correlation between the events

The system has a completely disordered pattern of sources

If $\Delta_t \to 0$ the system evolves towards a better-organized structure




This means that there is a distribution of sources emitting at the highest energy confined in a small region

↓

**The material is approaching to the collapse**

# BOX COUNTING METHOD

Several authors verified this result experimentally studying the AE in loaded structures

Paparo & Gregori et al. (2003) analyzed the sources distribution

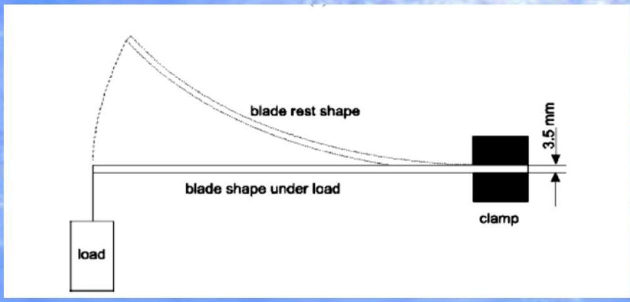
Braccini et al. (2002) experimented that the $D_t$ decreases during a static damaging process

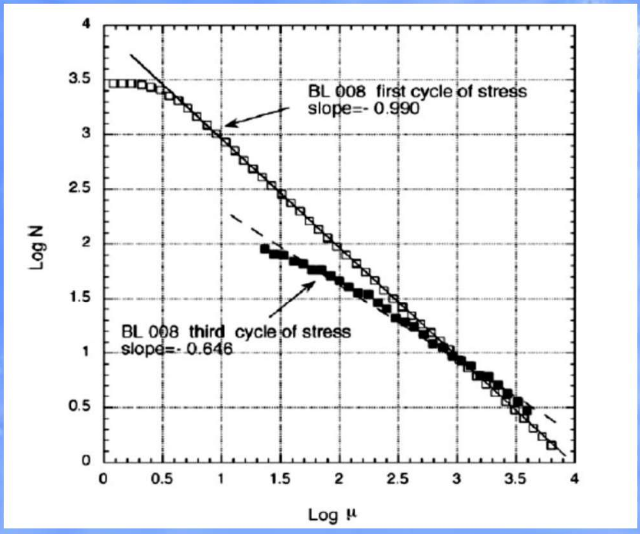
Biancolini et al. (2006) applied thr BCM and the fractal dimension to fatigue growth of cracks in specimens under rotating bending up to collapse

**ALL THESE AUTHORS SHOWED THAT THE FRACTAL DIMENSION $D_t$ DECREASES $\rightarrow$ 0 APPROACHING TO THE COLLAPSE OF THE STRUCTURE**

# BOX COUNTING METHOD

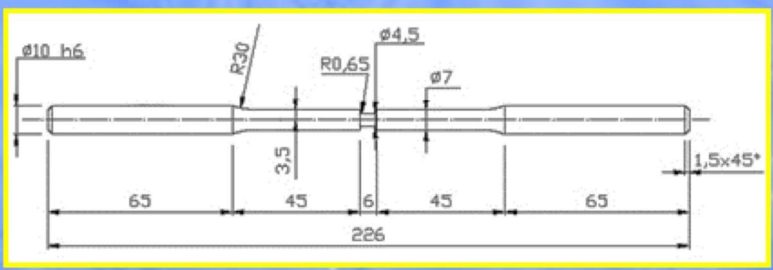
Paparo & Gregori et al. (2003) achieved a distinction between AE sources in a 3D space distribution and a 2D space distribution, proving that this technique based on fractal dimension is able to analyze the AE sources.
Braccini et al. (2002) applied the method to study the behavior of maraging steel blades used in a gravitational antenna named VIRGO, The authors studied the movements of dislocations and the Kaiser effect, using two narrow-band p.e. sensors and applying several bending loads.
At each bending cycle, the fractal dimension decreases starting from a value near to 1 (disordered pattern of sources) progressively to values near 0 (ordered pattern of source).

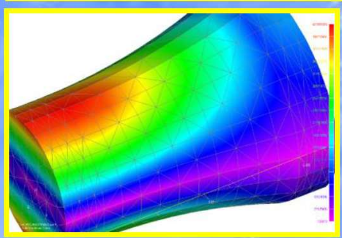


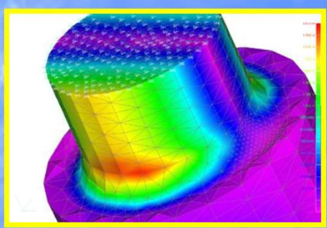



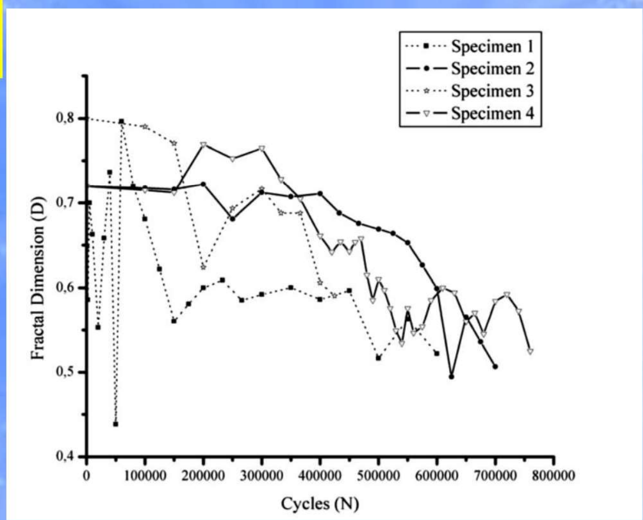
# BOX COUNTING METHOD

Biancolini et al. (2006) applied the BCM and the fractal dimension to fatigue growth of cracks in specimens under rotating bending up to collapse







# BOX COUNTING METHOD

**We can conclude that the physical meaning of fractal dimension is**

**<u>No damage in the structure</u>**

$\Downarrow$

**EA sources randomly distributed**

$\Downarrow$

$$\Delta_t = 1$$

**<u>Damage in the structure</u>**

$\Downarrow$

**EA is more regular**

$\Downarrow$

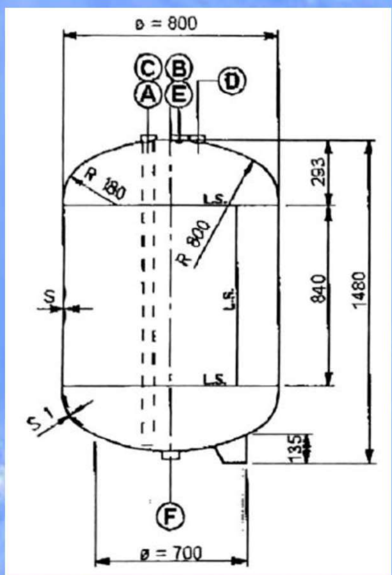
**Few sources prevail over the others in the damaged zone**

$\Downarrow$

$$\Delta_t \to 0$$

# BOX COUNTING METHOD

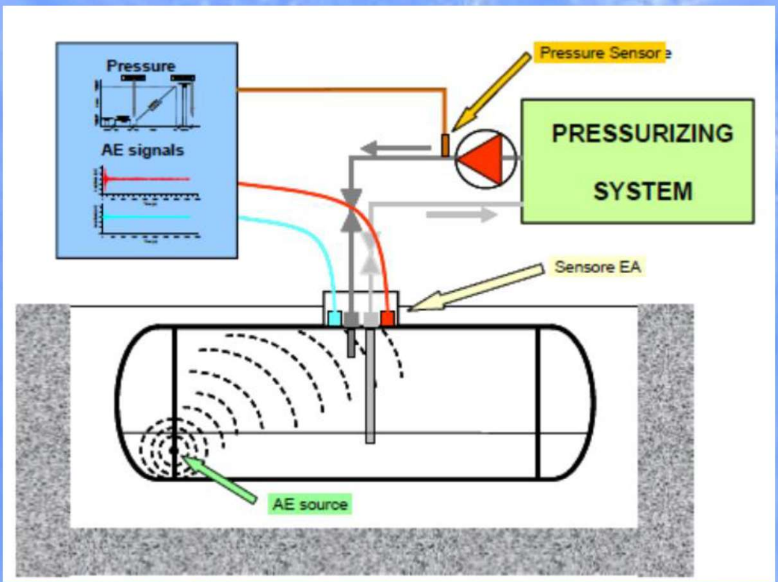
In this paper we used AE through the fractal analysis and the BC method to study the damaging process of underground pressurized tanks in order to check if this approach and  the usual AE based procedure are in agreement




# INAIL-ISPESL procedure for underground LPG vessels

Since about 15 years, the requalification of small underground tanks is based on the INAIL-ISPESL procedure

The tank pressurization must take place linearly with a gradient of 0.2 ± 0.05 bar / min up to reaching 16 bars at which the test will be complete
During the test the AE signals are recorded and then analyzed



# INAIL-ISPESL procedure for underground LPG vessels

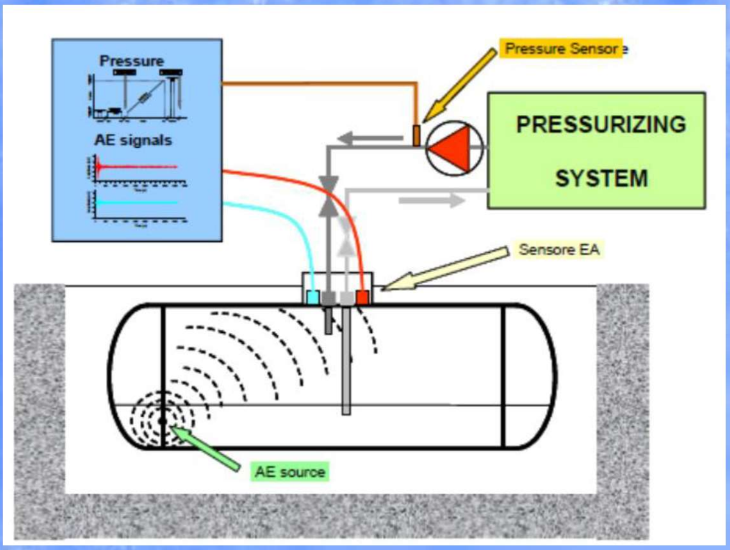
The EA signals recorded by the pair of EA channels must be processed in order to extract information that allows to assess the structural integrity of the tank examined.
The following indexes are elaborated through a patented algorithm:

- *synthetic quality index ICSE*

$$ICSE = f\left(HC, K, \frac{EC}{\Delta p}, AC\right)$$

- *time-history index* ISRE

$$ISRE = \frac{\sum_1 E_j}{\sum_2 E_j}$$



EPERC-AISBL
European Pressure Equipment Research Council

# INAIL-ISPESL procedure for underground LPG vessels

ICSE and ISRE are combined to form a synthetic unique index

$$\gamma = f(ICSE, ISRE)$$

Classification of vessels takes place as follows:

CLASS 1: Vessels for which a no-significant AE activity detected. These vessels can continue to operate for a period set according to Italian rules (usually 10 years).

CLASS 2: Vessels for which a significant AE activity detected that is:

1. $\gamma_{max}$ >0.95 or
2. N1 ≥ 30 hits with amplitude above A1 ≥ 75 dB, or
3. N2 ≥ 15 hits with amplitude above A2 ≥ 85 dB or
4. N3 ≥ 1500 hits with amplitude above A3 ≥ 40 dB

**Class 2 vessels cannot longer be operated**

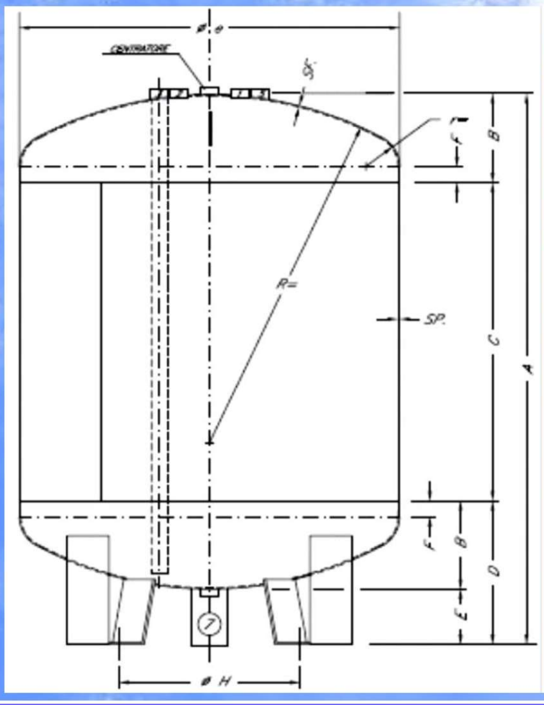
EPERC-AISBL

European Pressure Equipment Research Council

# LPG SMALL TANKS TESTED

We tested three underground tanks. We pressurized the tanks according to the INAIL-ISPESL procedure in order to execute the comparison of the results obtained with the two methods.

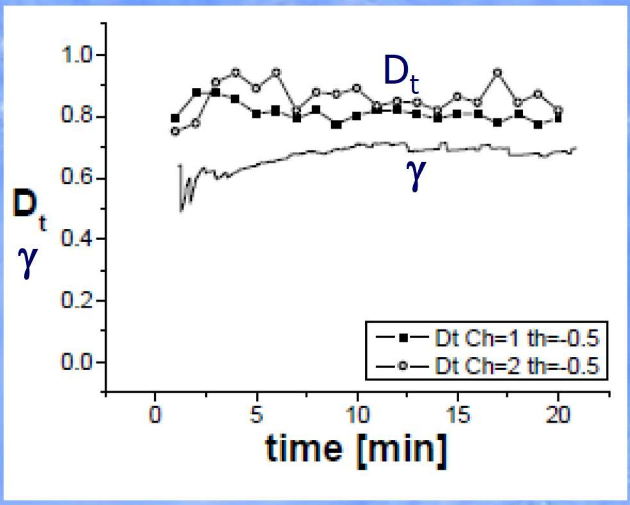
Material P355NH
Young Modulus ≈206 MPa
Yield stress ≥ 355 MPa
Ultimate stress 490÷630 MPa
Ultimate strain ≥ 22%

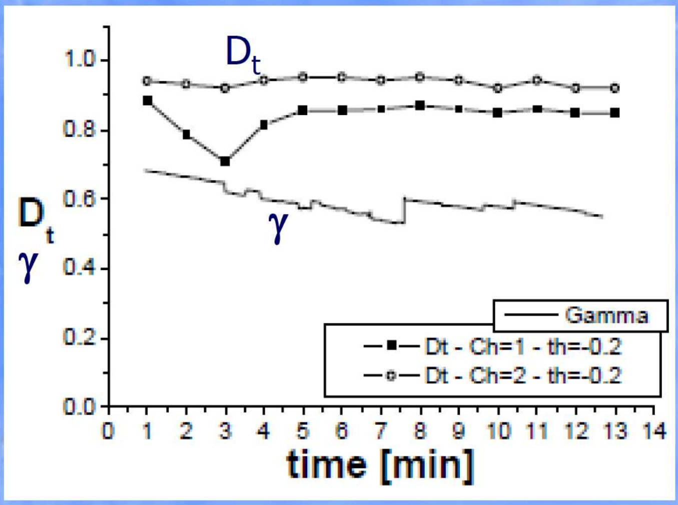



| | DIMENSIONS (mm) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| V (l) | A | B | C | D | E | F | Ø H | Øe | L | R | r | t |
| 1000 | 1500 | 315 | 800 | 385 | 70 | 60 | 700 | 1000 | 830 | 800 | 168 | 5,4 |

# LPG SMALL TANKS TESTED

The results of the test of the tanks n.1 and 2 are in the following figures
In the graph the $D_t$ vs time and $\gamma$ vs. time are reported.
The tanks n. 1 and 2 passed the check as $\gamma < 0,95$. During the test the Fractal dimension is between 0,75 and 1.0: no damage is detected



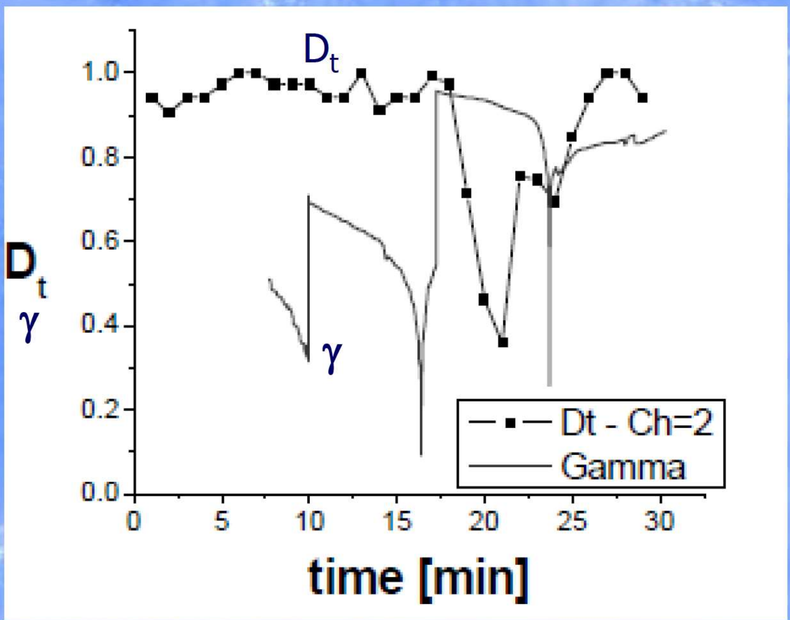



# LPG SMALL TANKS TESTED

The tank n.3 did not pass the check as $\gamma > 0{,}95$.
During the test the Fractal Dimension suddenly decreases after about 20-25 min to a value 0.35.

This is an undoubtable sign of a relevant structural damaging process. However, after a valley, $D_t$ grows back towards the unit.
Though a damaging process is active, the material is still able to sustain the applied pressure.

**As the damage is irreversible, further increments of pressure originate an increase of the damaging rate and a decrease of the fractal dimension up to the collapse.**



# CONCLUSIONS

1. The fractal analysis of EA signal by means of box-counting method is particularly effective for the monitoring of structures as already reported in the references available in bibliography.
2. By this technique, it is possible to get a lot of information on the damage of structures both under static and dynamic loading.
3. The fractal dimension $D_t$ is a measuring tool of the random disorder of the AE. It is able to show when a local damaging process is active and how it evolves both in static and fatigue load conditions.
4. A sudden decrease of $D_t$ shows that there is a zone with important AE events, this is a method to identify and to monitor a defect from the nucleation through the growth and final collapse.

# CONCLUSIONS

The results of the test on three underground tanks revealed the agreement between the ISPESL-INAIL procedure and the Fractal analysis of AE through the BCM.

**We can conclude that this technique gives encouraging results**

For an extended use, it is necessary to know better the meaning of the decrease of $D_t$ during the growth of a crack. In particular, topics of further investigation could be, for example:

- if there is a limit of $D_t$ that divides the range of safety condition from the critical one, equivalent to the value of $\gamma_{max}$ in the ISPESL-INAIL procedure;
- if this limit is universal or depends on material, load and crack type (from stress concentration, from corrosion, from plastic zone etc.).