A.C. CORROSION ON BURIED PIPELINES: A PROBABILISTIC APPROACH

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1. INTRODUCTION

Within the community of experts in A.C. corrosion of pipelines, the idea that the current density flowing through a holiday in the insulating coating is a meaningful parameter able to assess the risk of corrosion is commonly accepted; in particular the value of 30 A/m^2 is considered a threshold value that, if exceeded, leads, for sure, to corrosive effects for any type of soil [1].
On the other side, the assessment of corrosion conditions is only possible when the pipeline has already been laid down in the trench and the current density can be really measured on simulated holidays (usually having 1 mm^2 bare surface). These measurements in the field are affected by a possible wide variation of the spread resistance of these simulated holidays, which is connected to complex and not yet completely understood electrochemical reactions deriving from d.c. and a.c. current effects and the chemical composition of the soil contacting the bare steel. It has been demonstrated by laboratory tests that this spread resistance may, during time, increase by as much as 100 times or decrease by as much 60 times (formation of particular layers at the phase boundary).

From this point of view, at the design stage of new plants (pipelines from one side and power or railway lines on the other) the only possible approach to the problem is represented by simulation tools able to assess the level of current density exchanged between pipe and soil through the insulating coating holidays.
The algorithms on which such simulation tools are based, are essentially the same used to predict the electromagnetic interference (i.e. induced voltages and currents) on pipelines and telecommunication lines by A.C. power and electrified railway lines [2], [3]; thus, from this point of view, the A.C. corrosion can be considered as a particular problem inside the wider set of the power frequency Electromagnetic Compatibility problems.

2. DETERMINISTIC APPROACH VERSUS PROBABILISTIC APPROACH

In [4] some examples of calculations of current density, based on real situations, are presented; the approach there followed is purely deterministic, i.e. it is based on specific assumptions concerning the holiday size and location. Such an approach, focused on the worst case study, is, without any doubt, useful from the cautionary point of view but, in our opinion, it should be completed by a probabilistic approach which takes into account of the random nature of some significant parameters like the holidays size and location.
Therefore, the main purpose of this work, is to describe an algorithm for the assessment of the probability associated to the exceeding of a certain current density value in a generic section of pipeline; the advantage of such an approach is the possibility to individuate those pipeline sections which are more exposed to the A.C. corrosion risk.
Strictly speaking, we have to mention that the algorithm object of this work is still deterministic as far as the calculation of electric quantities (voltage, current, current density) is concerned while it is statistic as far as the holidays data are concerned; the consequence of such an approach is that the results of the algorithm are given in terms of probability of exceeding a certain value of current density for a generic section, of given length, along the pipeline. Here we shall describe only the probabilistic aspects and we refer to [2], [3] and [4] for all the other aspects.

3. LIMIT VALUE FOR THE HOLIDAY AREA

Before entering into details of the algorithm, it is necessary to recall some concepts relevant to the resistance R_h with respect to remote earth of an holiday in the pipeline coating; Fig.1 may help in illustrating such concepts.

Let us consider a buried pipeline covered by a coating having thickness d; moreover, let us suppose that a single holiday is present on the coating at a given location of the pipeline. The holiday is represented by a small cylindrical vacancy of the coating, filled with soil, and having cross section A and same height d as the coating thickness. Moreover, due to the electrochemical reactions occurring at the holiday location between the steel of the pipe and soil, the value of the soil resistivity measured in points very close to the holidays is very different with respect to the value of the soil resistivity measured at a certain distance from the pipeline; this is also confirmed by field measurements [5]. For such a reason, we shall consider two different values of resistivity: ρ_h for points inside the holiday and ρ_s in all the other points[1].

[1] On the basis of the results in [5] we have in first approximation that $\rho_h \approx \rho_s /10$.

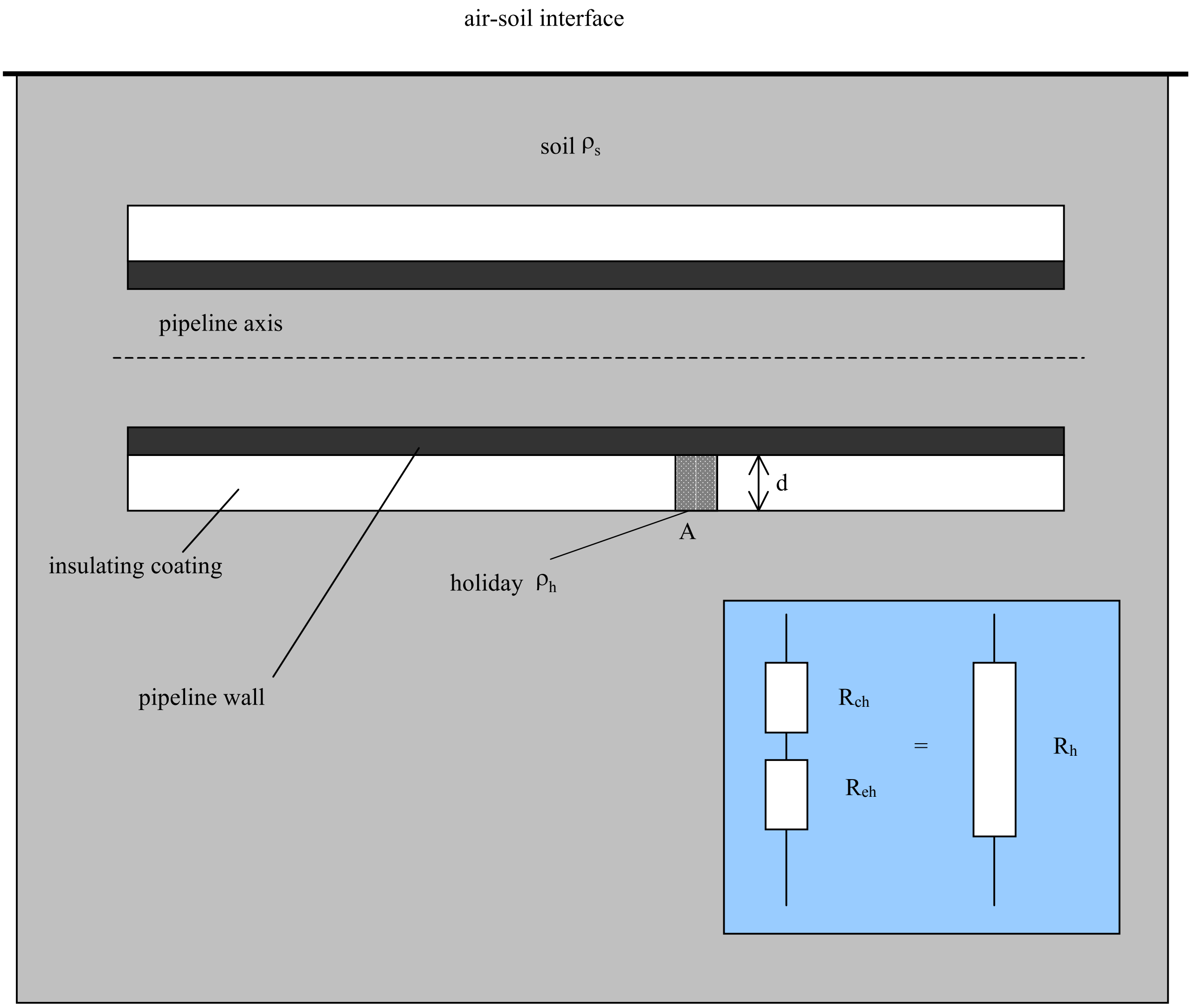

Fig.1: Holiday resistance to remote earth

The resistance to remote earth R_h of the pipeline through the holiday is given by the sum of two contributions; the first one, indicated by R_{ch} , and representing the resistance relevant to the small cylinder inside the coating, is given by:

$$R_{ch} = \frac{\rho_h d}{A} \tag{1}$$

The second one, indicated by R_{eh} , represents the earth resistance (with respect to the remote earth) of the holiday; it can be evaluated as the earth resistance of a disk of area A, placed on the soil surface [2], that is:

$$R_{eh} = \frac{\rho_s}{4}\sqrt{\frac{\pi}{A}} \tag{2}$$

Therefore, by adopting the term *holiday resistance* to indicate the quantity R_h, we have:

$$R_h = \frac{\rho_h d}{A} + \frac{\rho_s}{4}\sqrt{\frac{\pi}{A}} \qquad (3)$$

It is useful to remark that in corrosion books and papers, R_h is generally named *spread resistance*.
Thus, if the pipe under the electromagnetic influence of a power or of an electrified railway line assumes a voltage[2] V at the holiday location, the current density J exchanged between pipe and soil through the holiday itself is given by:

$$J = \frac{V}{R_h A} = \frac{V}{\rho_h d + \frac{\rho_s}{4}\sqrt{\pi A}} \qquad (4)$$

Let J^* be the limit value for the current density adopted to quantify the A.C. corrosion risk (e.g. $J^*=30A/m^2$); from (4) we can get, for a given voltage V, the maximum value of the holiday area $A^*=A^*(V)$ for which we may have a current density $J \geq J^*$; in fact the following inequality must hold:

$$\sqrt{\pi A} \leq \frac{4}{\rho_s}\left(\frac{V}{J^*} - \rho_h d\right) \qquad (5)$$

At the same time, in order that formula (5) has physical meaning, it must be:

$$V > J^* \rho_h d \qquad (6)$$

Formula (6) means that in all the pipeline route regions satisfying the inequality $V \leq J^* \rho_h d$, the limit value J^* for the current density can never be exceeded independently on the value of the holiday area A.
On the contrary, provided that formula (6) is verified, from (5) we can deduce that:

$$A^*(V) \leq \frac{16}{\pi \rho_s^2}\left(\frac{V}{J^*} - \rho_h d\right)^2 \qquad (7)$$

So formula (7) establishes an upper limit (in function of the pipe voltage V) for the holiday area A in order to have the exceeding of the limit value J^* for the current density through the holiday itself. We shall name $A^*(V)$ limit area.

4. PROBABILISTIC APPROACH

4.1 Random characteristics of holidays coating

[2] Here and in the following, the voltage V is always considered in modulus.

The main purpose of this paragraph is to describe the random characteristics of the holidays by means of suitable random variables and their relevant probability distributions.
As already remarked, the random characteristics of the holiday are inherent to:

- their location[3] along the pipeline route;
- their size.

As far as the holidays location is concerned, it is reasonable to assume that, for homogeneous kinds of soil and of pipeline (i.e. having the same diameter and the same type of coating), the holidays are uniformly distributed along the pipeline; from this point of view the main parameter which has to be known is the number of holidays per unit length n_h.
As far as the holidays size is concerned, we have verified, on the basis of data collected from field measurements, that its distribution is sufficiently well fitted by a log-normal distribution characterized by parameters μ and σ deduced from the population $\{A_i\}$ of the holidays area composed by N_A elements (A_i $i=1,2,\ldots N_A$). Such parameters are calculated according to the formulas:

$$\mu = \frac{1}{N_A} \sum_{i=1}^{N_A} \ln(A_i) \tag{8}$$

$$\sigma = \sqrt{\frac{1}{N_A} \sum_{i=1}^{N_A} \left(\ln(A_i) - \mu\right)^2} \tag{9}$$

Some information about the log-normal distribution and the numerical values for the parameters n_h , μ and σ which have been deduced from field data are reported in the Appendix.
By using these information, we shall deduce in the following the probability that the generic section [s', s''] along the pipeline route, characterized by a mean voltage V, contains **at least one** holiday with area $A \leq A^*(V)$ so that the current density J exceeds the limit J^*.

4.2 Probability of having k out of N holidays in the section [s', s'']

[3] The location of a generic point along the pipeline route is identified by means of a coordinate s with $0 \leq s \leq L$ being L the pipeline length.

Let us consider a pipeline having a number of holidays per unit length n_h and length L. The total number of holidays N_h relevant to its coating is given by:

$$N_h = round(n_h L) \tag{10}$$

being *round* the function approximating the numeric value $n_h L$ to its nearest integer.
Starting from the hypothesis that the holidays are uniformly distributed along the pipeline route, we have that the probability p(s', s'') of having one holiday in the section [s', s''] is given by:

$$p(s', s'') = \frac{s'' - s'}{L} \tag{11}$$

while the probability q(s', s'') of having no holidays inside the same section is:

$$q(s', s'') = 1 - q(s', s'') \tag{12}$$

By considering that the total number of holidays relevant to the whole plant is N_h we have to consider all the possible events represented in Table I.

Table I: Partitioning of N_h holidays inside and outside a generic section [s', s''] along the pipeline route.

number of holidays inside section [s', s'']	number of holidays outside section [s', s'']
0	N_h
1	N_h-1
2	N_h-2
⋮	⋮
N_h-1	1
N_h	0

So, by the help of Table I and remembering the definition of binomial distribution [6], we have that the probability P(k, N_h, [s', s'']) of having k out of N_h holidays in the section [s', s''] is:

$$P(k, N_h, [s', s'']) = \binom{N_h}{k} p(s', s'')^k q(s', s'')^{N_h - k} \tag{13}$$

4.3 Probability of having m out of k holidays inside the section [s', s''] with A≤A*(V)

As before mentioned, let us assume that the random variable A is distributed according to the log-normal distribution characterized by the parameters μ and σ; let us consider a section [s', s''] along the pipeline route characterized by mean value V for the induced voltage. Under such a condition, we can calculate the probabilities $p_A(V)$ and $q_A(V)$ defined as:

$$p_A(V) = P(A \le A^*(V)) = \begin{cases} \int_0^{A^*(V)} \frac{1}{A\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\frac{(\ln A-\mu)^2}{\sigma^2}} dA & \text{if} \quad V > J^* \rho_h d \\ 0 & \text{if} \quad V \le J^* \rho_h d \end{cases} \tag{14}$$

The complementary quantity $q_A(V)$ is given by:

$$q_A(V) = 1 - p_A(V) \tag{15}$$

If in the section [s', s''] are present k holidays, we are interested in determining the probability that m out of k holidays have area $A \le A^*(V)$.
All the possible events are shown in Table II.

Table II: Partitioning of k holidays inside a generic section [s', s''] along the pipeline route with $A \le A^*(V)$.

number of holidays inside section [s', s''] having $A \le A^*(V)$	number of holidays inside section [s', s''] having $A \ge A^*(V)$
0	k
1	k-1
2	k-2
⋮	⋮
k-1	1
k	0

Also in this case by the aid of Table II and by remembering the binomial distribution, we have that the probability $P_A(m, k, A^*(V))$ of having m out of k holidays, inside [s', s''], with area $A \le A^*(V)$ is given by:

$$P_A(m,k,A^*(V)) = \binom{k}{m} p_A(V)^m q_A(V)^{k-m} \tag{16}$$

4.4 Probability of having at least one holiday with $A \le A^*(V)$

If we make the reasonable assumption that the random quantities represented by the number of holidays inside [s', s''] and by the holidays area A are independent, we can calculate the probability P([s', s''], V) of having at least one holiday, with A≤A*(V), inside the section [s', s''], characterized by a mean voltage V; in such a way, for at least one holiday, the current density J exceeds the limit J*. By taking into account of formulas (6), (13) and (16), the probability P([s', s''], V) is given by:

$$P([s',s''],V)=\begin{cases}\sum_{k=1}^{N_h}\binom{N_h}{k}\left(p(s',s'')\right)^k\left(q(s',s'')\right)^{N_h-k}\sum_{m=1}^{k}\binom{k}{m}\left(p_A(V)\right)^m\left(q_A(V)\right)^{k-m} & \text{if } V>J^*\rho_h d\\ 0 & \text{if } V\le J^*\rho_h d\end{cases} \tag{17}$$

From the computational point of view, it is much faster to calculate the complementary quantity Q([s', s''], V) which is the probability of having no holidays inside [s', s''] with A≤A*(V).
Q([s', s''], V) is calculated by means of the following expression:

$$Q([s',s''],V)=\begin{cases}\sum_{k=0}^{N_h}\binom{N_h}{k}\left(p(s',s'')\right)^k\left(q(s',s'')\right)^{N_h-k}q_A(V)^k & \text{if } V>J^*\rho_h d\\ 1 & \text{if } V\le J^*\rho_h d\end{cases} \tag{18}$$

Thus, P([s', s''], V) can also be evaluated through the relation:

$$P([s',s''],V)=1-Q([s',s''],V) \tag{19}$$

We would like to remark that such formulas are based on the mean value V of the induced voltage inside the section [s', s'']; from this point of view, when the voltage presents large variation with respect to the abscissa s along the pipeline, it is necessary to subdivide it by using sections of suitable length so that the mean value V is not too much different from the minimum and maximum values assumed by the voltage in the same section.

5. EXAMPLE OF APPLICATION OF THE ALGORITHM

5.1 Data and results of the calculation

From the previous paragraphs it is clear that the probability of exceeding a certain value for the current density is mainly related to two important quantities:

- the length of the pipeline section considered (i.e. the longer is the section, the higher is the probability);
- the mean value of the voltage assumed by the pipeline in the same section (i. e. the higher is the mean voltage the higher is the probability).

On the basis of these considerations, it is useful, from the practical point of view, to have at disposal a certain set of curves relating the probability of exceeding the limit value of current density J^* versus the pipeline section length Λ for a given value of the mean voltage V.
In Fig.2 an example is shown by considering a limit value of J^*=30A/m^2.

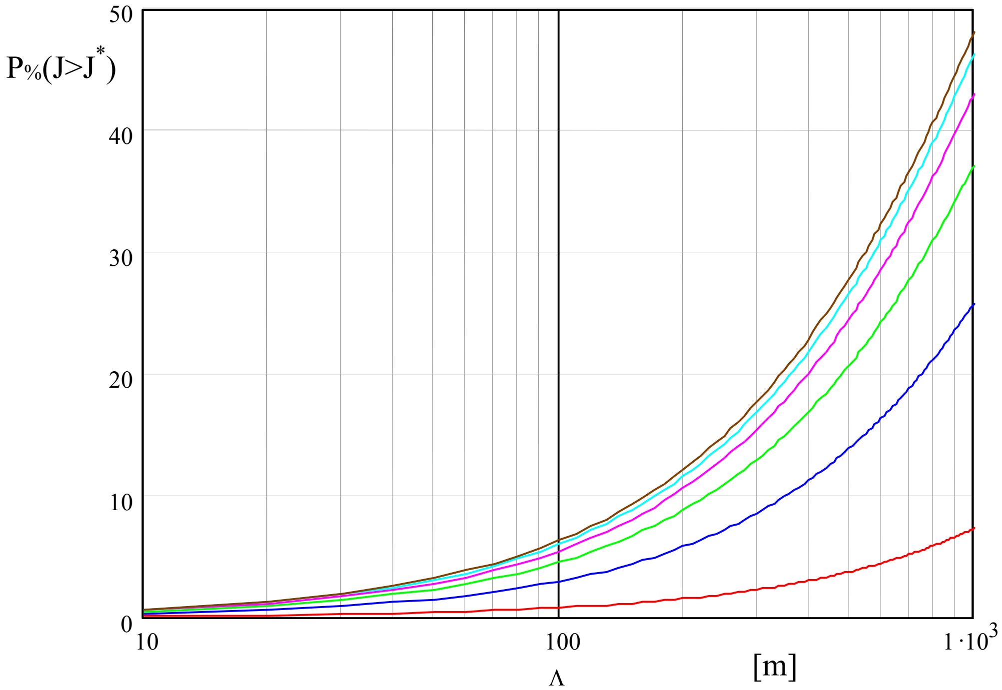

Fig.2: Per cent probability of exceeding the current density limit J^*=30A/m^2 versus the pipeline section length Λ for different values of the mean voltage; the curves from top to bottom correspond to V= 60, 50, 40, 30, 20, 10V respectively; n_h=0.7 holidays/km.

Other data relevant to this example are: n_h=0.7 holidays/km, ρ_h=10Ωm, ρ=100Ωm L=28.5km, d=3mm; from these data, one can also derive from formula (6) that the minimum value of V able to produce the exceeding of the limit J^*= 30A/m^2 is 0.9V. Moreover, from formula (10), we have that the total number of holidays present on the pipeline coating is N=20.
In Fig.3, the same probability curves as in Fig.2 are shown with the only difference that n_h=1.4 holydays/km so that N_h=40 number of holydays.

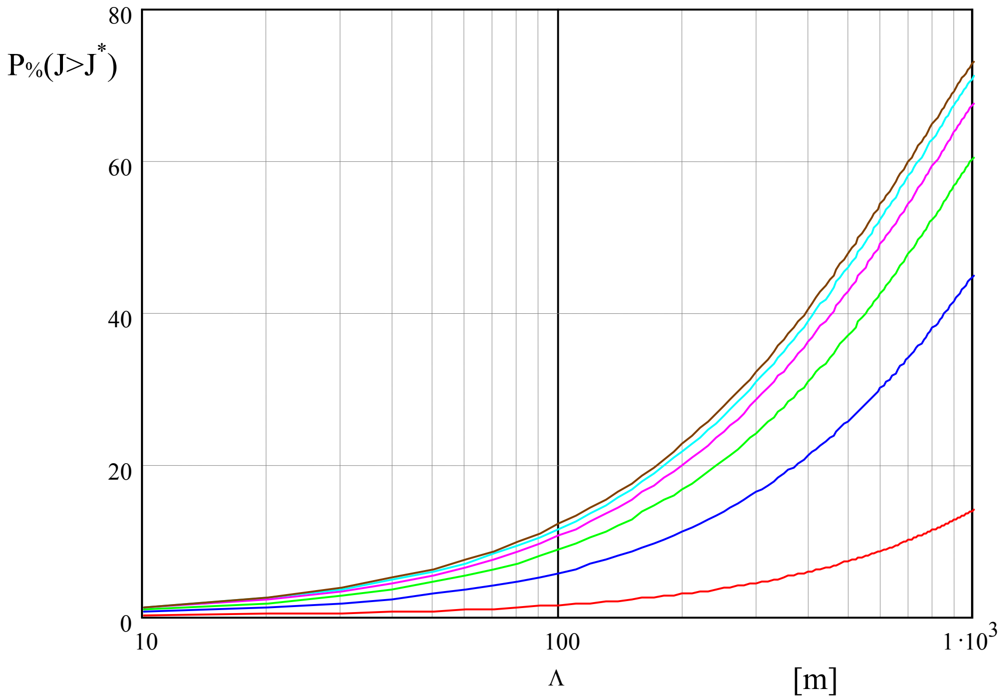

Fig.3: Per cent probability of exceeding the current density limit J^*=30A/m^2 versus the pipeline section length Λ for different values of the mean voltage; the curves from top to bottom correspond V= 60, 50, 40, 30, 20, 10V respectively; n_h=1.4 holidays/km.

5.2 Practical use of the probabilistic graphs

How can the information contained in a graphic similar to the ones shown in Fig.2 and Fig.3 be used ?
The following procedure shows the main steps:

1. calculation of the interference voltage values: i.e. determination of the voltage profile V=V(s) along the pipeline;

2. individuation of the section(s) of interest along the pipeline (e.g. the section(s) characterized by the highest level of induced voltage);

3. determination of the mean voltage(s) relevant to that (those) section(s);

4. determination of the probability of exceeding the limit J^* inside the section by means of graphics similar to Fig.2; alternatively formulas (17) or (19) can be directly used for a more precise calculation.

In Fig.4 an example of voltage profile induced along a pipeline by a 380kV-50Hz power line carrying balanced currents of 630A is shown.

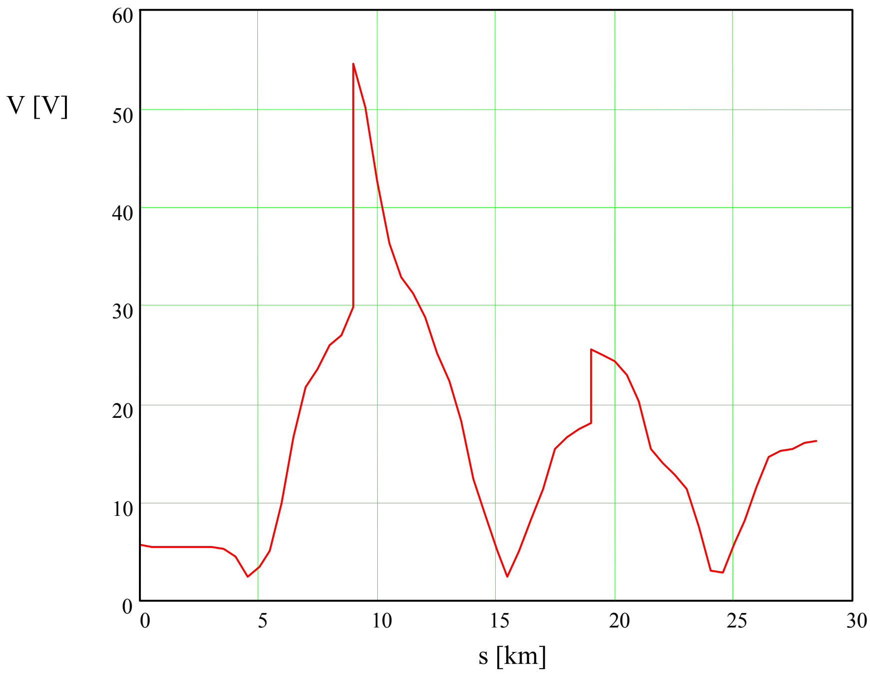

Fig.4 Example of voltage profile induced along a pipeline by a nearby 380kV-50Hz power line.

Let us suppose we are interested in calculating the probability of exceeding the limit $J^*=30A/m^2$ in the section [9km, 10km](the region containing the highest peak) along the pipeline route which is characterized by a mean value of voltage V of nearly 50V. From the graphic in Fig.2 and Fig.3 we can estimate a probability of about 46% and 71% respectively. Similarly, if we consider the section [19km, 20km](the region containing the second peak) characterized by a mean voltage of nearly 25V we obtain a probability of about 32% and 53% respectively.

6. CONCLUSIONS

In the frame of the A.C. corrosion problem produced on buried pipelines under the electromagnetic influence of power or electrified railway lines, we have presented a method for estimating the probability of exceeding a certain threshold J^* for the induced current density for *at least one* holiday in the insulating coating and located in a generic region of the pipeline between the abscissas s' and s''.
The method consists in the integration of deterministic calculations, necessary for the determination of the induced voltage profile along the pipeline route, with probabilistic calculations necessary for the determination of the holidays size and consequently of the current density.
The parameters and the characteristics relevant to the random quantities (i.e. the holidays area distribution, the number of holidays per unit length) have been inferred starting from experimental data coming from the field.
As one could expect the probability levels are directly related to:

- the levels of induced voltage on the pipeline;
- the number of holidays per unit length besides the other statistical characteristics of the holidays distribution;
- the length of the pipeline section considered.

In our opinion such a calculation method can be used as previsional tool able to quantify the risk of A.C. corrosion pipelines exposed to the electromagnetic influence of a power/electrified railway line both at the design stage and at the normal operating stage; we emphasize that at the design stage, when measurements are of course not possible, this is the only tool at our disposal in order to assess the A.C. corrosion risk.

APPENDIX: STATISTICAL CHARACTERISTICS OF COATING HOLIDAYS

A.1 INTRODUCTION

This Appendix is devoted to the statistical description of the holidays characteristics coming from the field thanks to the pluri-annual experience of SNAM RETE GAS.
No coating exists without holidays. These are often due to backfilling operation during the pipe-laying phase.
For this reason, after the pipe-laying phase, a coating fault location is performed over the entire pipeline.
According to Italy's and most of the European Gas Companies practice, any coating fault detected is repaired at the Contractor's expences.
Two are the main aspects that, according to the model previously described, are necessary to be focused:

- the number of holidays per unit length;
- the statistical distribution of the holidays area.

It is important to notice that, due to the fact when holidays are detected they are almost always repaired, the data herebelow reported are in principle, only valid at the stage just after the pipeline laying phase installation; nevertheless not all the holidays can generally be detected; thus the data and the product of their processing can be still used so obtaining results which can be considered cautionary.

A.2 NUMBER OF HOLIDAYS PER UNIT LENGTH

In Table A1, the total number of holidays detected on various pipelines having different diameter are shown; from the knowledge of the total length it is possible to calculate the global number of holidays per unit length n_h.

Table A1: number of holidays detected on pipelines having different diameters

diameter [mm]	M: number of holidays	L: total length [km]	n_h=M/L: number of holidays per km
100	37	66	0.561
150	92	74.8	1.23
200	115	160.5	0.717
250	107	185.4	0.577
300	199	165.1	1.205
400	145	267.1	0.543

500	143	129.3	1.106
600	94	108.9	0.863
750	33	150.6	0.219
850	7	14.2	0.493
900	39	178	0.219
1000	7	47	0.149
1200	455	376.6	1.208
Total	**1473**	**1923**	**0.766**

The last row of Table A1 contains the values referred to the whole population with no relation to the pipe diameter.

A.3 STATISTICAL DISTRIBUTION OF THE HOLIDAYS SIZE

A.3.1 Determination of the probability density

As far as the holidays size is concerned, we have at disposal a population $\{A_i\}$ composed by N_A=100 elements (A_i i=1,2,…N_A) being each element contained in the interval [0.1cm^2, 320cm^2]. For the detailed distribution see Table A2.

Table A2: Detailed distribution of holidays size

holiday area size [cm^2]	number of holidays
0.1	1
0.5	3
0.8	2
1	21
1.5	3
2	17
2.5	2
3	10
4	3
4.3	1
5	4
6	2
7	3
8	4
9	1
10	3
12	2
15	6
20	1
24	1
30	2
40	2
50	1
60	1
100	1

120	1
300	1
320	1
total	100

On the basis of data reported in Table A2, the following histogram of the relative frequencies applies [4]:

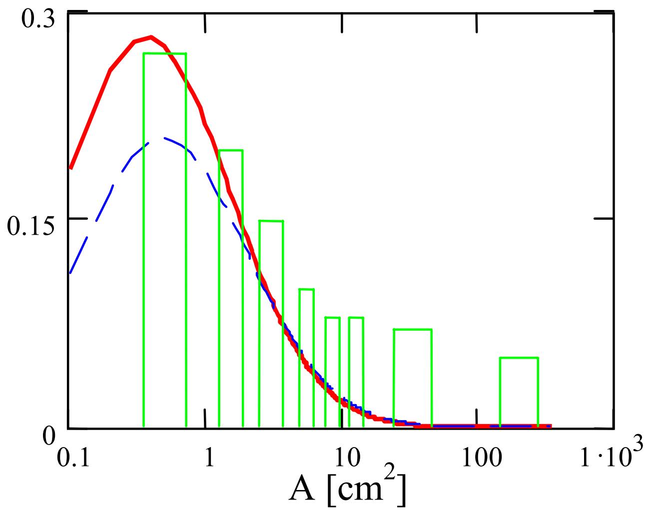

Fig.A1: Histogram of the relative frequencies and conjectured log-normal distribution

Our purpose is to infer an analytical density distribution able to fit, sufficiently well, the histogram of the relative frequencies.
A possible conjecture is the log-normal distribution whose probability density is given by:

$$y(A) = \frac{1}{A\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\frac{(\ln A-\mu)^2}{\sigma^2}} \qquad \text{(A.1)}$$

being A the random variable representing the holiday area while μ and σ^2 are the mean value and variance of the random variable ln(A) respectively. In practice we have the log-normal distribution for the random variable A when its natural logarithm is distributed according the normal law.
The next step is the determination of the parameters μ and σ^2 characterizing the log-normal distribution of formula (A.1).
They can be calculated by using the so called *maximum likelihood method* (see [6], [7]); according to it we obtain for μ and σ^2 the following expressions:

[4] In order to obtain the histogram shown in Fig. A.1, the following partition of the interval [0.1, 320] has been choosen: [0, 1.001, 2.001, 4.001, 7.001, 10.001, 15.001, 50.001, 320.001]

$$\mu = \frac{1}{N_A}\sum_{i=1}^{N_A} \ln A_i \tag{A.2}$$

$$\sigma^2 = \frac{1}{N_A}\sum_{i=1}^{N_A} (\ln A_i - \mu)^2 \tag{A.3}$$

From formulas (A.2) and (A.3) and by using the values of the population $\{A_i\}$, we obtain the following values μ=-7.907 and σ=1.419 yielding the dashed curve in Fig.A.1; nevertheless a better fit can be achieved is we use the guessed value μ=-8.207 obtaining the continuous line curve in Fig.A.1. Thus, in our work, we refer to this latter value.

A.3.2 Goodness of fit tests

In previous paragraph we have made a conjecture concerning the probability density distributions of the holidays area size; nevertheless, in order to decide if our hypothesis is good or not we have to make a statistical test of goodness of fit in order to reject or not this conjecture.
To this purpose, we used two different tests:

- the χ^2 test;
- the Kolmogorov-Smirnov test.

We again refer to [6] and [7] for some information about these two tests. We only report here, that according to the results of both tests (considering a level of significance[5] α=0.05), it is not possible to reject the hypothesis that the probability density distribution of the holidays area size is sufficiently well described by a log-normal curve.

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[5] If α is the level of significance of the test, it means that we have a probability of 100α% of making an error by rejecting the hypothesis

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[6] The English version of such a paper can be found in [1] (in Annex 2).