Classification of hazardous areas produced by maintenance interventions on n.g. distribution networks and in presence of open surface of flammable liquid

CLASSIFICATION OF HAZARDOUS AREAS PRODUCED BY MAINTENANCE INTERVENTIONS ON N.G. DISTRIBUTION NETWORKS AND IN PRESENCE OF OPEN SURFACE OF FLAMMABLE LIQUID

Riccardo Tommasini
Department of Electrical Engineering
Politecnico di Torino
C.so Duca degli Abruzzi, 24
Torino, TO 10125
ITALY
riccardo.tommasini@polito.it

Enrico Pons
Department of Electrical Engineering
Politecnico di Torino
C.so Duca degli Abruzzi, 24
Torino, TO 10125
ITALY
enrico.pons@polito.it

Abstract – The safety and protection of workers is a duty of their employer. In case of presence of hazardous areas due to the risk of explosion, an area classification has to be performed to identify the shape and size of the locations where an explosion may happen. Two typical cases that can produce hazardous areas are gas emissions from a containment system, because of normal operation or because of a failure, and vapors emissions from an open surface pool of flammable liquid. In this paper two studies are presented: the first deals with the problem of natural gas releases during maintenance work on the gas distribution network, the second with vapors emissions from a pool of flammable liquid. In the first case experimental measures have been performed to easily calculate the size of the hazardous area; in the second case computer simulations are used to derive a simplified model to determine it. The results of the two studies presented are examined and commented in the light of the International and national Standards.

Index Terms — Hazardous Areas Classification, Natural Gas, Inflammable Liquid.

I. INTRODUCTION

For many years the risk of explosion and the consequent requirement for the classification of areas has been a concern worldwide [1] and in the beginning industry codes were mainly used [2]. In 1994 and 1999 the two ATEX directives were published by the European Parliament, respectively Directive 94/9/EC [3] and Directive 99/92/EC [4]. The first deals with equipment and protective systems intended for use in potentially explosive atmospheres; the latter with the safety and health protection of workers potentially at risk from explosive atmospheres. In particular, Directive 99/92/EC provides that the employer adopts adequate measures in order to prevent the formation of explosive atmospheres, avoid their ignition and mitigate the detrimental effects of an explosion. Among these measures is the classification of the places where explosive atmospheres may occur which is particularly important.

The regulations provided by the second ATEX Directive have been adopted in the International and European Standard IEC EN 60079-10-1 [5]; in Italy, moreover, in February 2007 a new edition of the Guide CEI 31-35, “Guide for classification of hazardous areas” [6] has been published.

Meanwhile in the United States other Standards, with similar methods, are used for the classification of hazardous areas [7].

The two main different sets of standards, NEC and IEC have also been compared for what concerns the protection methodologies [8].

This paper briefly outlines the area classification procedure, describes the approach adopted by the international standard [5], illustrates some experimental measures and simulations and illustrates some general equations and assessment methods developed by the authors and introduced in the new Italian national guide [6].

II. AREA CLASSIFICATION PROCEDURE BASED ON IEC EN 60079-10 METHODOLOGY

Whenever dangerous quantities and concentrations of flammable gas or vapour may arise, one of the standards used to classify the area is IEC EN 60079-10 [5].

Hazardous areas (in which an explosive gas atmosphere is present, or may be expected to be present) shall be classified in zones on the basis of the frequency of occurrence and persistence of the dangerous atmosphere, as reported in Table I.

TABLE I
ZONE TYPES

ZONE 0	An explosive atmosphere is present continuously or for long periods or frequently
ZONE 1	An explosive atmosphere is likely to occur in normal operation occasionally
ZONE 2	An explosive atmosphere is not likely to occur in normal operation but, if it does occur, will persist for a short period only

In accordance with Table B.1 of Standard IEC EN 60079-10-1 [5] (Table II below) the type of zone can be evaluated, knowing three parameters: the grade of release, the degree and availability of the ventilation.

TABLE II

INFLUENCE OF VENTILATION AND GRADE OF RELEASE ON TYPE OF ZONE

Grade of release	Ventilation – Degree: High			Medium			Low
	Availability: Good	Fair	Poor	Good	Fair	Poor	Good, fair or poor
Continuous	(Zone 0 NE) Non-hazardous[a]	(Zone 0 NE) Zone 2 [a]	(Zone 0 NE) Zone 1 [a]	Zone 0	Zone 0 + Zone 2	Zone 0 + Zone 1	Zone 0
Primary	(Zone 1 NE) Non-hazardous[a]	(Zone 1 NE) Zone 2 [a]	(Zone 1 NE) Zone 2 [a]	Zone 1	Zone 1 + Zone 2	Zone 1 + Zone 2	Zone 1 or Zone 0 [c]
Secondary [b]	(Zone 2 NE) Non-hazardous[a]	(Zone 2 NE) Non-hazardous [a]	Zone 2	Zone 2	Zone 2	Zone 2	Zone 1 and even Zone 0 [c]

NOTE 1 '+' signifies 'surrounded by'.

[a] Zone 0 NE, 1 NE or 2 NE indicates a theoretical zone which would be of negligible extent under normal conditions.

[b] The zone 2 area created by a secondary grade of release may exceed that attributable to a primary or continuous grade of release; in this case, the greater distance should be taken.

[c] Will be zone 0 if the ventilation is so weak and the release is such that in practice an explosive gas atmosphere exists virtually continuously (i.e. approaching a 'no ventilation' condition).

Sources of release are classified in the following three grades of release:

- **continuous grade** of release when the release is continuous or is expected to occur frequently or for long periods;
- **primary grade** of release when the release can be expected to occur periodically or occasionally during normal operation;
- **secondary grade** of release when the release is not expected to occur in normal operation and, if it does occur, is likely to do so infrequently and for short periods.

Two aspects of ventilation are considered in controlling dispersion and persistence of the explosive atmosphere: the degree of ventilation and its availability; and the effectiveness of the ventilation.

Three degrees of ventilation are identified:

- **high ventilation (HV)** can reduce the concentration at the source of release virtually instantaneously, resulting in a concentration below the lower explosive limit. A zone of negligible extent may result (depending on the availability of the ventilation);
- **medium ventilation (MV)** can control the concentration, resulting in a stable zone boundary while the release is in progress and in the elimination of the explosive atmosphere after the release has stopped;
- **low ventilation (LV)** cannot control the concentration while release is in progress and/or cannot prevent the persistence of an explosive atmosphere after release has stopped.

Three levels of availability of the ventilation are considered:

- **good** if ventilation is present virtually continuously;
- **fair** if ventilation is expected to be present during normal operation. Discontinuities are permitted provided they occur infrequently and for short periods;
- **poor** if ventilation does not meet the standards of fair or good, but discontinuities are not expected to occur for long periods.

For example if we have a primary grade of release (which means that the release can be expected to occur periodically or occasionally during normal operation) the degree of ventilation is medium (which means that the ventilation can control the concentration, resulting in a stable zone boundary while the release is in progress and in the elimination of the explosive atmosphere after the release has stopped) but the availability is just fair or poor (which means that discontinuities in the ventilation can be present) normally the hazardous area is confined in the Zone 1 but when the ventilation is missing, occasionally, a bigger area can be involved (Zone 2).

Once the type of zone has been defined, its dimensions have to be determined, choosing an appropriate geometric shape; for this purpose the Italian Guide CEI 31-35 [6] uses the dangerous distance d_z and a certain number of standardized shapes.

III. THE HAZARDOUS DISTANCE FOR GAS RELEASES ACCORDING TO THE ITALIAN GUIDE

The equation for the evaluation of d_z (computed hazardous distance) in the case of a flammable gas jet is presented, as illustrated in the Italian Guide CEI 31-35 [6]. It was worked out by the authors in previous works [11],[12],[13]:

$$\mathbf{d_z = k_z \cdot \frac{1650}{k_{dz} \cdot LEL_v} \cdot \left(P \cdot 10^{-5}\right)^{0,5} \cdot M^{-0,4} \cdot A^{0,5}} \qquad (1)$$

where:

- A is the cross section of the source of release [m^2];
- P is the absolute pressure inside the containment system [Pa];
- M is the flammable substance molar mass;
- LELv is the substance lower explosive limit, expressed in volume per cent;
- k_z is a correction coefficient to account for the gas or vapour concentration in the far field (far away from the source of release, where the gas or vapour is completely mixed with air); in the case of open space release k_z = 1;
- k_{dz} is the safety coefficient applied to the LEL for the calculation of d_z; assumes values between 0.25 and 0.5 for releases of continuous and first grade and values between 0.5 and 0.75 for second grade releases.

Equation (1) is used to calculate the hazardous distance d_z for gas releases, when release velocity u0 ≥ 10 m/s.

Experimental measures have been carried out in the case of a natural gas release and have been compared with the calculations suggested by the Italian Guide CEI 31-35 [6].

As sometimes the cross section of the source of release is not known, the Italian Guide provides with typical values for this parameter.

IV. HAZARDOUS AREAS PRODUCED BY MAINTENANCE INTERVENTIONS ON N.G. DISTRIBUTION NETWORKS

A. The Natural Gas distribution network

The natural gas distribution to domestic and tertiary users is performed in Italy by an interconnected network with operating pressure of about 20 mbar. This network pipes are usually buried, except for some ends, and are usually made of cast iron, steel or polyethylene; the pipes cross section ranges from 50 to 600 mm^2.

The gas network requires repair and maintenance work in ordinary conditions, due to users needs (new connections, changes of the supply, etc.) and for routine modernization (cast iron pipes are gradually being substituted by polyethylene pipes, which have lower structural losses and are more versatile during repairs and modifications).

All these operations on the network must be performed with as little effect on end users as possible while guaranteeing the highest service continuity as required by Gas and Electrical Power Authority (AEEG) provisions [10].

In order to fulfill these requirements, all the interventions for pipe modification must be performed without interrupting the gas flow to the users, and this is achieved due to the interconnection and redundancy of the network, by sectioning the pipe on both sides of the work location.

This procedure involves boring the pipe and inserting rubber balloons that are then inflated to stop the gas flow, producing therefore natural gas releases. Such releases give rise to explosive atmospheres with variable dimensions and shapes, depending on the work procedure and on the proper execution of the procedure itself (malfunctions or unexpected events are always possible).

Experimental measures have been conducted to determine the duration of the work operations and the extension of the hazardous zones produced by the gas release and are described in this section.

B. Description of the maintenance intervention

A typical intervention on a gas pipe is made of the following five phases:

- work preparation;
- interruption of the gas flow;
- inerting of the sectioned pipe
- execution of the required maintenance work;
- purging the pipe to remove air.

1) *Work preparation*: A trench is opened to reach the pipe on which the following operations are to be carried on. An electrical bonding connection is made for metallic pipings, in order to connect different metallic parts and prevent the formation of sparks when the pipe sections are separated from each other.

2) *Interruption of the gas flow*: On both sides of the work location, the gas pipe is bored on its center-line, using a manual or pneumatic pipe-boring machine equipped with a hole saw. The hole diameters depend on the pipe cross section and range from 1 inch to a maximum of 4 inches. The pipe-boring machine is connected tightly to the pipe due to a threaded sleeve or collar depending on the piping material (Fig. 1). The boring phase, which may require several minutes, does not produce significant releases, since the pipe-boring machine is connected to the sleeve using a sealing o-ring. The gas concentration in the sleeve is therefore largely above the UEL (upper explosive limit). When the pipe has been bored, the machine is removed and the gas flow is stopped with the insertion of a blocking balloon (Fig. 2).

Fig. 1 of the pipe-boring machine and of the collar on a steel pipe

As the pipe-boring machine is removed, the hole behaves like a source of release, approximately of the same cross section of the entire hole. The release lasts for the time required to insert the balloon and stop the hole with the frustum of cone plug. Since the gas flow has to be interrupted in two points (marked with the letters A and B in Fig. 3), the same procedure, with the same characteristics and releases, is repeated twice.

Fig. 2 Blocking balloons with frustum of cone plugs to stop the pipe holes; the deflated balloon is strengthened by an aluminium sheet which constitutes a protection against sparks originated by welding operations.

When maintenance work is carried out on steel pipes, and therefore welding is necessary, even a very small leak through the interruption points could be extremely dangerous. For this reason two rubber balloons instead of one are inserted into the pipe and the volume between them is filled with water, forming a wet seal. The situation at this stage is illustrated in Fig. 3.

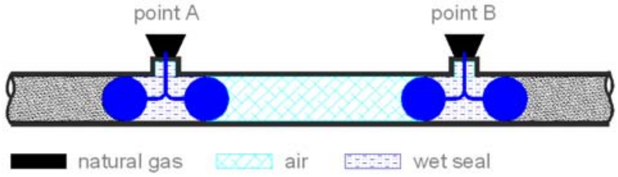

Fig. 3 Interruption of the gas flow inserting two balloons in each hole opened in the gas pipe to create a wet seal.

3) *Inerting of the sectioned pipe:* After the gas flow has been stopped by inserting the rubber balloons at both sides of the work location, before the insertion of the third and fourth balloons and the formation of the wet seal, the gas which is still contained in the pipe must be discharged. This is obtained by injecting an inert gas into the pipe through one of the holes previously bored in it: the natural gas is therefore forced out through the other hole. This constitutes a release which is regulated by the inert gas injection; the natural gas emitted is mixed with the inert gas.

4) *Execution of the required maintenance work:* The pipe is then cut using a manual pipe cutter which, in case of metallic piping, does not produce sparks. The following assembly is carried out by welding in case of steel pipes, by using flange couplings in case of cast iron pipes and by electrofusion in case of polyethylene pipes.

5) *Purging the pipe to remove air:* The final phase of the intervention consists in the removal of the rubber balloons and wet seal, if present. However, before this phase can be carried out, the pipe has to be purged in order to remove the air that has entered it. This is performed by removing completely one of the two sectioning points, which produces a gas release from the hole bored in the pipe (the cross section of the source of release, however, is not the full cross section of the hole, because the rubber balloons being extracted limit the gas flow and because the operator partially plugs the opening). As soon as the first sectioning point is removed, the plug of the second sectioning hole is removed: the air-gas mixture contained in the pipe is ejected. The gas concentration in the ejected mixture is measured and when it reaches nearly the 100% (which means that all the air/nitrogen has been expelled, the operation finishes: the last balloon is removed and the hole is closed.

C. Anomalous events during the intervention

During the typical intervention previously described, unexpected events may arise increasing the releases duration, and influencing the extent of the hazardous zones.

The most critical phase from this point of view is the interruption of the gas flow using the rubber balloons.

These devices are tested before the intervention being inflated and deflated. However damage to a rubber balloon may occur during its insertion through the hole bored in the pipe. The damage would appear while trying to inflate the balloon itself, thus requiring its extraction and substitution. During these operations the release would be much longer than that in standard operations.

The modeling chosen for this event is a 10 s release through the full hole cross section. This outflow duration is sufficient to reach a steady state gas concentration condition.

D. System modeling

The object of this work is the evaluation of the extension of the hazardous zones produced by the gas releases previously described. Two situations are modeled: the normal situation, in which the releases last a few seconds and are characterized by a strong transient, and the abnormal situation, in which the releases last a longer time and are characterized by reaching a steady state gas concentration condition.

However, the presence of the workers can limit and deflect the outflow introducing a random factor which is not repeatable.

Practically, the two different situations can be characterized as follows:

Normal situation:

- Short and small outflows
- Gas outflows reduced and diverted by presence of workers
- Gas outflows do not reach steady state gas concentration levels.
- Hazardous area is not clearly identified because of workers' presence and operation.

Abnormal situation:

- Long and consistent outflows
- Workers' normally leave the area and therefore do not interfere with gas outflow behavior.
- Gas outflows reach a steady state gas concentration condition.
- Hazardous area contours can be identified.

Therefore, normal situations modeling is actually impossible, because events are characterized by key transients that are not repeatable. On the other hand, abnormal situations modeling is feasible, under the following conditions:

- No workers' presence during gas outflows
- Gas outflows reach steady state gas concentration levels
- Ventilation based on calm wind conditions
- Hazardous area contours can be identified with a cone whose maximum angle can be 40 to 60°.

E. Experimental tests

Tests have been performed in an area, property of the major Italian gas distribution company, which has been set up with a trench and some pipes that reproduce a portion of the distribution network. The pipe used for the tests described in this paper has a cross section of 150 mm and is fed with natural gas on both sides, thanks to a by-pass, with a pressure of 20 mbar, to better simulate a portion of urban interconnected distribution network (see Fig. 4).

Fig. 4 Trench and pipe in test area.

Tests have been performed in order to define a model representing gas outflow under the abnormal conditions described in the previous paragraph. An outflow hole with a 1 inch diameter has been chosen.

Natural gas concentrations have been measured with eight gas detectors. These detectors are able to measure natural gas concentrations in the range between 0% and 5% (percentages of volume), with an accuracy of 0.5‰ and a sampling rate of 10 s. At each measurement step, the instrument detects the maximum and the minimum value of the gas concentration. When the concentration exceeds the 5% an “Overflow” message is reported and no values are stored.

Each test has been performed using 8 gas sensors, whose clocks had been previously synchronized.

Three different gas sensors configurations have been used to determine the extension of the hazardous zone, which was assumed conic:

1. Gas sensors placed along the outflow axis. The first one has been positioned at 2.56 m from the hole; the other 7 sensors have been placed at 30 cm from each other.
2. Gas sensors placed along the outflow axis. The first one has been positioned at 2.86 m from the hole; the other 7 sensors have been placed at 30 cm from each other.
3. Radial arrangement of the gas sensors, on two different levels: on a plane orthogonal to the outflow axis, at a height of 75 cm from the source of release and on a plane orthogonal to the outflow axis, at a height of 150 cm from the source of release.

The sensors are quite small and so the deflection of the gas stream can be neglected.

The positioning schemes of Fig. 5 and Fig. 6 have been used in order to evaluate the natural gas concentration trend along the outflow direction, as a function of different distances from the hole, and the width of the hazardous zone (assumed conic). The initial hypothesis about shape and dimensions of the hazardous zone was confirmed also due to the support given by an infrared camera sensitive to methane.

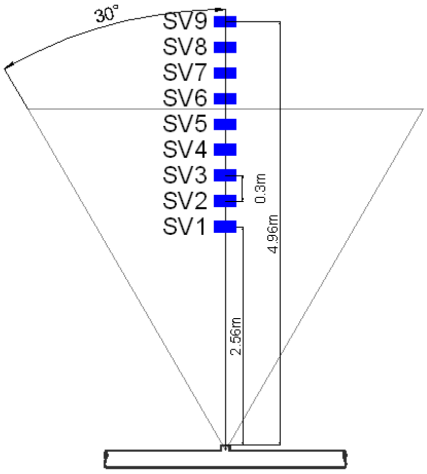

Fig. 5 Gas sensors placed along the outflow axis.

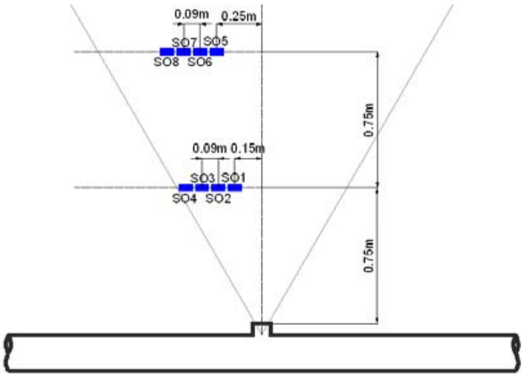

Fig. 6 Radial arrangement of the gas sensors

The IR camera, which senses the different thermal behavior of the gas and air molecules, was used to identify the height and width of the release cone (Fig. 7).

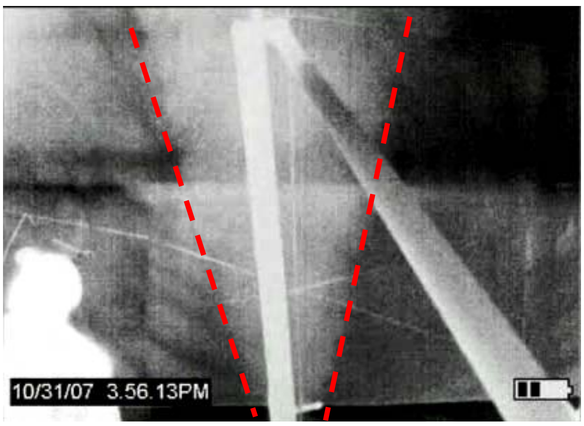

Fig. 7. Frame from the film recorded by the IR camera during a gas release.

In order to improve contrast in the shooting, two sides of the area have been covered with a 4 m high sheet. Such a choice certainly influenced the tests, slightly modifying the ventilation conditions. However this effect is considered negligible since the tests were performed in calm wind conditions. Moreover the error committed improves safety as wind tends to dilute the flammable atmosphere

F. Tests results

The gas detectors provided, both on the outflow axis and on the two horizontal planes, the trend of the concentration peaks reached in each 10 s time interval, for every measurement point (shown in Fig. 5 and Fig. 6). From these values the overall peaks registered during the whole test are extracted. The detectors which produced an "overflow" message are discarded. The mean values of the peaks registered (C_P) in the different tests are reported in Table III for the outflow axis disposition and in Table IV for the radial arrangement.

TABLE III
MEAN OF THE PEAK VALUES REGISTERED IN THE DIFFERENT TESTS ON THE OUTFLOW AXIS

Detector	Height [m]	C_P [%]
SV1	2.56	>5
SV2	2.86	>5
SV3	3.16	3.450
SV4	3.46	2.675
SV5	3.76	2.575
SV6	4.06	2.175
SV7	4.36	1.650
SV8	4.66	1.625
SV9	4.96	0.900

TABLE IV
MEAN OF THE PEAK VALUES REGISTERED IN THE DIFFERENT TESTS ON THE HORIZONTAL PLANES

Detector	Height [m]	Horizontal distance [m]	C_P [%]
SO1	0.75	0.15	>5
SO2	0.75	0.24	2.300
SO3	0.75	0.33	0.450
SO4	0.75	0.42	0.125
SO5	1.5	0.25	>5
SO6	1.5	0.34	>5
SO7	1.5	0.43	3.500
SO8	1.5	0.52	1.725

G. Experimental data processing

The aim of this work is the definition of the distribution of the natural gas concentration near the source of release. On the basis of the previously advanced hypothesis of conic shape with vertex on the source of release, the concentration values measured by the vertical and horizontal sensors have been used to determine height and width of the cone itself.

In particular, to determine the vertex angle of the cone, the sensors located at 150 cm above the source of release have been used, leading to more conservative results (i.e. a wider angle).

1) Concentration along the release axis: The concentration trend along the outflow axis (which is vertical) is determined by the superposition of two different effects:

- a momentum effect, due to the pressure of the gas inside the pipe;
- a buoyancy effect, due to the different density between natural gas and air ($\rho_{gas} = 0.6\ \rho_{air}$).

In order to evaluate the two effects, the models suggested in the TNO Yellow Book [14] have been chosen. The adopted simplification is based on the separation of the two effects: in the first part of the outflow, only the momentum effect, which is predominant, has been considered, and the buoyancy effect has been neglected; in the second part of the outflow only the buoyancy effect has been taken into account, while the momentum effect, considered to be already finished, has been neglected. A concentration decay in inverse relation to the distance from the source of release was used for the momentum effect:

$$C(y) = \frac{k_1}{y - t_1} \tag{2}$$

where:

- $C(y)$ is the natural gas concentration along the outflow axis;
- k_1 and t_1 are two constants which were determined to best approximate the experimental data.

A concentration decay in inverse relation to the distance raised to 5/3 was used for the buoyancy effect:

$$C(y) = \frac{k_2}{(y - t_2)^{5/3}} \tag{3}$$

where:

- $C(y)$ is the natural gas concentration along the outflow axis;
- k_2 and t_2 are two constants which were determined to best approximate the experimental data.

The first decay law appears to be a good approximation of the concentration measured by the gas sensors up to 3.5 m from the source of release, while the second decay law appears to be a good approximation above 4.3 m from it. The concentration trend in the interval between 3.5 and 4.3 m has been assumed linear, to connect the two curves. In Fig. 8 the measured data and the approximation curves following the two decay laws previously presented are reported.

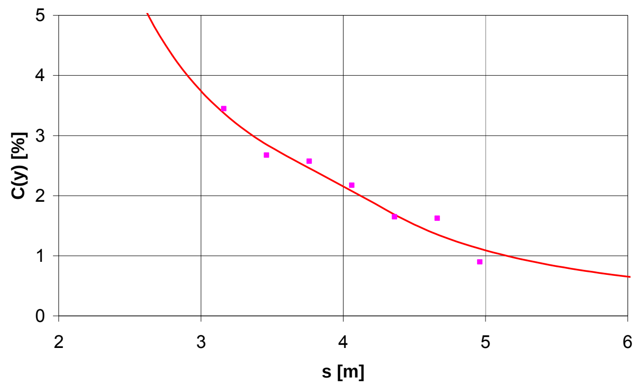

Fig. 8 Gas concentration trend along the outflow axis.

2) *Concentration on a plane perpendicular to the outflow axes:* The concentration trend on a plane perpendicular to the outflow axis has been measured at two different heights, as

previously described. Of the two sets of measures, the most conservative one has been chosen (with sensors located at 150 cm from the source of release). Assumed that the outflow is axisimmetric (i.e. the wind effect has been neglected), the radial concentration trend has been modeled with an exponential law [14]. From the experimental data, concentration values were available only in two points (see Table IV), since the two innermost sensors reached the overflow (concentration above 5%). The coefficients used to define the exponential law have been determined forcing the intersection with the outflow axis at the concentration value obtained through the model described in the previous paragraph, and optimizing the interpolation of the available experimental data.

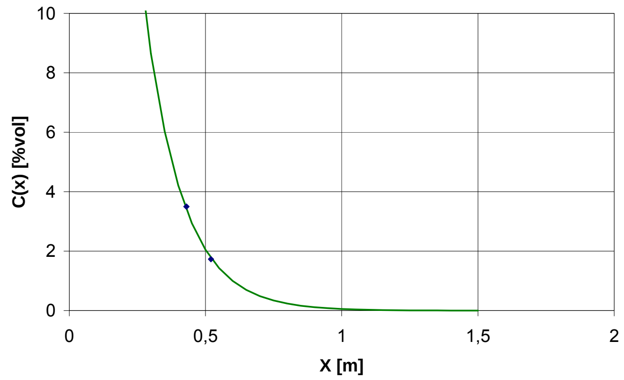

Fig. 9 Gas concentration trend on a plane perpendicular to the outflow axis.

The obtained model is described through equation (4):

$$C(x) = k_3 \cdot e^{-k_4 \cdot x} \qquad (4)$$

where:

- $C(x)$ is the natural gas concentration on the horizontal plane;
- k_3 and k_4 are two constants which has been determined to force the intersection with the y axis as previously described and to best approximate the experimental data.

In Fig. 9 the measured data and the approximation curve are reported. The values determined for the coefficients of equations (2), (3) and (4) are reported in Table V.

TABLE V
COEFFICIENTS

Coefficient	k_1	t_1	k_2	t_2	k_3	k_4
Value	5.5	1.5	6	2.2	75	0.072

H. Definition of the hazardous zone on the basis of the experimental tests

The release produced for the experimental tests is comparable to that caused by unexpected events during the maintenance intervention, so that the phenomenon reaches a steady state condition. Such a situation is the worst possible and, according to Standard IEC EN 60079-10 [5], can be classified as a secondary grade of release.

Since the release takes place outside in calm wind conditions, the availability of the ventilation is considered good, while its degree is considered medium. The hazardous zone is therefore Zone 2 (see Table II).

The hazardous volume has been determined through the experimental data and their subsequent elaboration (see § IV. G.); similarly to what is suggested in the Italian Guide CEI 31-35 [6], the volume in which the flammable gas concentration is higher then k_{dz} • LEL_v (with k_{dz} =0.5) is defined “Zone 2”.

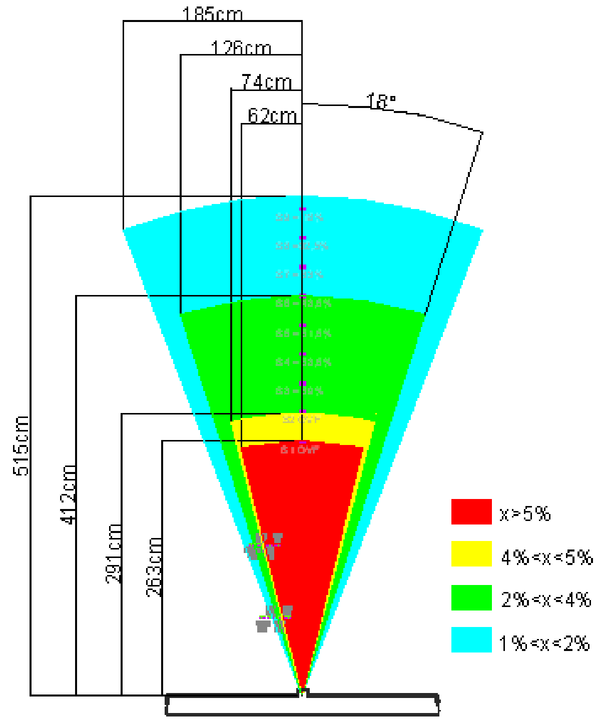

Fig. 10 Gas concentration near the source of release, as determined through experimental data.

The situation is summarized in Fig. 10, where it can be seen that Zone 2 (volume in which the gas concentration is higher then k_{dz} • LEL_v = 2%) is a cone 4.12 m high with a vertex angle of 36°.

I. Comparison with the Italian Guide calculation

For the release on which the experimental tests have been carried out, on the basis of equation (1), having set k_{dz} = 0.5, the computed hazardous distance d_z is:

$$\mathbf{d_z} = \frac{\mathbf{1650}}{\mathbf{0.5 \cdot 3.93}} \cdot \left(\mathbf{0.02 \cdot 1.01325}\right)^{\mathbf{0.5}} \cdot \mathbf{16.34^{-0.4}} \cdot \mathbf{(5.07 \cdot 10^{-4})^{0.5}}$$

$$\mathbf{d_z} = \mathbf{6.3m}$$

The hazardous zone determined following the guidelines of the Italian Guide CEI 31-35 [6] is therefore a conic volume, with vertex on the source of release, vertex angle of 90° and height of 6.3 m.

V. HAZARDOUS AREA PRODUCED BY A POOL OF FLAMMABLE LIQUID

As previously stated, a hazardous area is produced when a pool of flammable liquid is in contact with the atmosphere.

After an assessment of the size of the explosive cloud has been made using a simulation software, a number of approximate relations are obtained for determining the hazardous zone.

A. Theoretical basis

In this paragraph the potentially explosive volume produced by a pool of flammable liquid is described. The examined pool was located on the ground, in the open, and the flammable liquid was assumed as being at ambient temperature, with a boiling point higher than the ambient temperature.

In this situation, a certain amount of vapours, with an evaporation rate *g,* are released from the pool, the release being a function of the characteristics of the substance and the intensity of the wind. For the determination of the dispersion in the atmosphere of vapours issuing from the flammable substance, it is possible to apply approximate analytical models. The model most widely used, which is valid within the limits of certain simplified hypotheses, is a point source with evaporated gases dispersed vertically and horizontally according to a Gaussian curve, the standard deviation σ of which varies according to the direction considered.

In Fig. 11 an example is provided: the source of release is located in the axes origin and the wind direction is along the x axis. The Gaussian curves represent the concentration of the vapour in the y and z directions at different distances from the source of release.

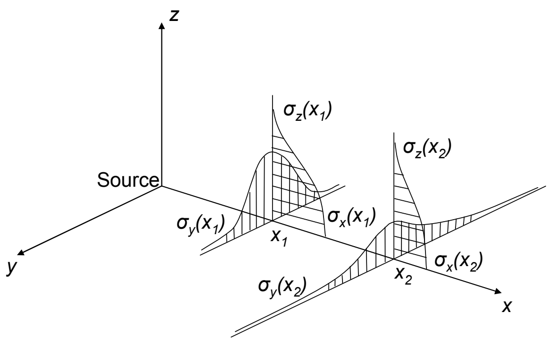

Fig. 11 Gaussian model of release

The distribution of gas in the atmosphere is influenced by numerous factors, among which are the weather conditions, the characteristics of the ground around the pool (e.g. the presence of trees, buildings, etc.), wind speed and so forth. For the calculation of the distribution in the various points of space, it is possible to use approximate formulas obtained from experimental findings [9].

In the case where the source of emission is of large dimensions, as in the case of vaporization from a pool of flammable liquid, the area of release cannot be assimilated to a point source and it is necessary to make further approximations.

If an assessment is made of concentrations at a sufficiently large distance from the source assuming that the surface of the source itself is quite extensive, it is possible to substitute for the actual source a virtual point source located at an appropriate distance upwind of the real source. In other words, the distant virtual source is assumed to produce, in the area of the actual source, an emission having the same characteristics and dimensions as the actual source itself. For this purpose, the two sources must release the same amount of substance, and the cloud discharged by the virtual source must "cover" the entire real source.

The computation procedures and the above mentioned relations were applied to the case of a pool of gasoline. Fig. 12 shows the distance to which the lower explosion limit (LEL) extends in the direction of the wind (x axes) as a function of the area of the pool (wind speed 5 m/s).

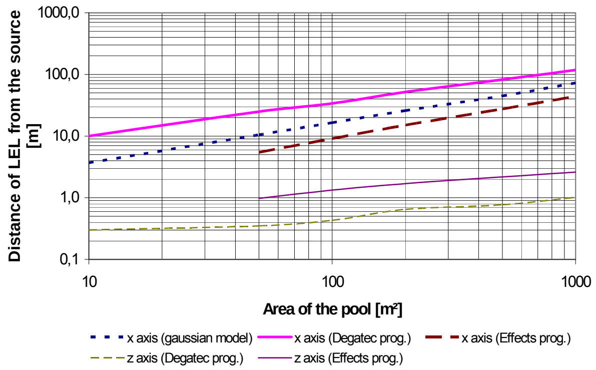

Fig. 12 Maximum distance from source, in downwind direction (x axis) and in vertical direction (z axis), at which the LEL concentration is reached. Wind speed 5 m/s

In the same figure are shown the distances of LEL in the direction of the wind (x axes) and in the vertical direction (z axes) estimated using two of the most widely used simulation software devised for evaluating hazardous emissions [15]. An example of the results of the simulation is presented in Fig. 13.

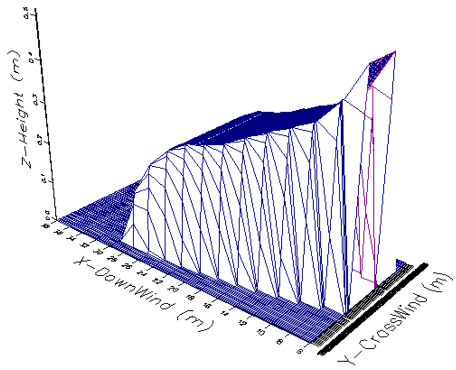

Fig. 13 Simulation results

B. Simplified computational procedure

Taking as a reference the simulation model and approximating with an exponential function the variations in the distances at which the LEL concentration is reached in the direction of the wind (X) and upwards (Z), it is possible to simply relate the size of the cloud to the wind speed and the pool area. The following relations have been obtained:

$$X = 5.5 \cdot w^{-1} \cdot A^{0.6} \qquad \text{for } w < 2 \text{ m/s}$$
$$X = 3.5 \cdot w^{-0.3} \cdot A^{0.6} \qquad \text{for } w > 2 \text{ m/s} \qquad (5)$$
$$Z = 0.03 \cdot w^{0.8} \cdot A^{0.3}$$

where:
w is the wind speed in m/s;
A is the area of the pool in m^2.

Fig. 14 shows a comparison, for the x axes, of the distances indicated by simulations (polygons) with those obtained from the above relations (solid lines).

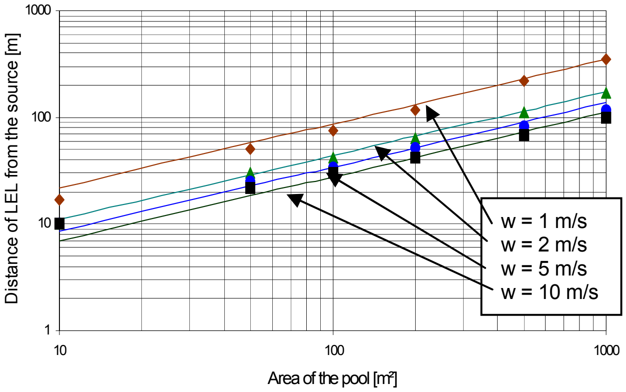

Fig. 14 Maximum distance from source, in downwind direction (x axis), at which the LEL concentration is reached, obtained from relations (5) (solid lines) and using the simulation model (Polygons)

The size of the area with risk of explosion around the pool may be determined on the basis of the considerations and calculations presented in the foregoing sections. In general, the area extends symmetrically around the pool (Fig. 15), starting from its edge for a distance *d*, and upwards for a height *h*. The dimensions *d* and *h* may be calculated through equations (5) using an appropriate safety factor *k* > 1.

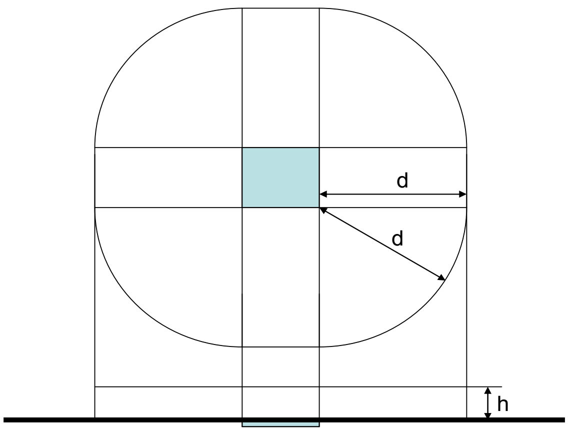

Fig. 15 Extent of the dangerous area around a pool of flammable liquid at ground level.

The relations obtained make it possible to calculate, simply but with good approximation, the main dimensions of the explosive cloud for this type of hydrocarbon pool.

The coefficients indicated in the relations are valid only for gasoline and in the environmental conditions previously described. However, within certain limits, the variations in the size of the cloud, as temperature varies, or in the case of flammable substances other than gasoline, may be derived on a percentage basis, from the Gaussian model and applied, using appropriate corrective coefficients, to the relations (5).

VI. CONCLUSIONS

This paper presents two typical cases of releases of flammable substances (gases or vapours), which produce hazardous areas due to the risk of explosion. For both cases, a model (physical in the first case, numerical in the second) is built and used to evaluate the size of the hazardous area. The experimental data of the gas release fits quite well the theoretical model suggested by the Italian Guide [6] for the calculation of the hazardous area boundary distance. Actually, the theoretical model is more conservative than the experimental, leading to a bigger distance d_z which has in the presented case an extra margin (or safety factor) of around 30% above the experimental one.

The size of the hazardous area defined in this way can therefore be applied by the workers who perform maintenance intervention on the natural gas distribution network.

In the case of a pool of flammable liquid, it is shown that the simplified equations can be used to determine the extent of the hazardous area instead of having to run simulations.

VII. ACKNOWLEDGEMENT

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G. VITA

Riccardo Tommasini received the master degree and the Ph.D. in electrical engineering. He is currently assistant professor at Politecnico di Torino, Italy. His research activities include power systems and electrical safety. He is member of CEI, the Italian Electrotechnical Committee where he is working in the 31 Committee, dealing with the evaluation of hazards due to the risk caused by explosive atmospheres and in committee 81, dealing with the Protection against lightning.

Enrico Pons received the master degree in electrical engineering and the Ph.D. degree in Industrial safety and risk analysis from Politecnico di Torino, Torino, Italy. He is currently a postdoctoral research fellow there. His research activities include power systems and electrical safety.