

EVALUATION REPORT

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**ASSESSMENT OF EARLY STREAMER
EMISSION TECHNOLOGIES¹**

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English version

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ASSESSMENT OF EARLY STREAMER EMISSION (ESE) TECHNOLOGIES

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1. INTRODUCTION: CONTEXT AND METHODOLOGY

INERIS, a public industrial and commercial establishment supervised by the French Ministry of the Environment is assigned with helping to prevent the risks triggered by economic activities for the health and safety of individuals and the integrity of assets, and clearly, the environment. INERIS carries out research programs aiming to improve the understanding of the phenomena likely to lead to at-risk situations or downgrade the environment and health, and to develop its expertise in terms of prevention. Its scientific and technical skills are at the disposal of public authorities, companies and local authorities in order to assist the former in reaching the most appropriate decisions in order to improve environmental safety.

INERIS was entrusted by the French Ministry of the Environment (MEEM) with revising the report "Etude des Paratonnerres à Dispositif d'Amorçage" (Study of Early Streamer Emission], 2001 version (reference: DCE-2000-25265f), in order to incorporate changes to standards and technological developments in relation to early streamer emission (ESE).

This report repeals and supersedes the former report from 2001 (reference DCE-2000-25265f).

This report has been fully redrafted, and incorporates changes to standard NF C 17102 (September 2011), and the information provided by manufacturers, standardisation bodies and recent scientific publications. This report exclusively covers the performances of ESE, and does not attempt to compare this technology with other technologies such as lightning rods (LR), meshed conductors or catenary wires.

A questionnaire was forwarded to manufacturers in order to obtain information on the latest technical developments and incorporate the progress achieved over the last 15 years, to better characterise these terminals. Most of the manufacturers consulted generally replied to this questionnaire by enclosing technical documentation, test reports and scientific publications.

INERIS did not test the performance of this equipment.

9 out of the 12 French and European manufacturers consulted provided information.

The ESE manufacturers on the following list provided technical information to INERIS.

Manufacturer	Country of the manufacturer
ABB France	France
ADEE ELECTRONIC	France
DUVAL MESSIEN	France
ERICO (PENTAIR)	USA/France
France PARATONNERRE	France
FRANKLIN France	France
INDELEC	France
ORWELS / PIORTEH	Poland/France
SAP	France

INERIS will not issue opinions on products by ESE manufacturers which failed to respond to the request for information.

2. EARLY STREAMER EMISSION – ESE (OVER 30 YEARS): HISTORY AND OPERATING PRINCIPLES

Early stream emission (ESE) lighting protection air terminals appeared in 1984, initially in France, and later in Spain, which were also the first countries to adopt specific standards (NF C 17 102 in France, UNE 12 186 in Spain). This type of air terminal is currently sold by foreign manufacturers (European, American, Chinese, Australian, Argentine, Turkish, etc.).

They are still known as ESE (Early Streamer Emission) air terminals. In recent years, various devices designed to improve the efficiency of Franklin-type rod lightning protection terminals have appeared, particularly to replace prohibited radioactive devices. France has been extensively involved in this research, alongside other countries such as Spain. Research results have now been validated with laboratory tests, and even site testing. The industrial products developed based on this research improve the efficiency of capturing an upward connecting leader compared with a lightning rod air terminal.

All discussions on efficiency aim to determine how the upward connecting leader can be activated as early as possible (at the best possible time) with the best possible initial speed. The principle² is therefore to adjust and/or drive the corona discharge.

Two physical principles are applied for this concept:

- Using high voltage pulses: repetitive high voltage pulses are applied to the end of the air terminal, the basic idea is to control the initial corona discharge and benefit from the "memory" effect left by previous discharges.
- Using a spark near to the tip: a spark is triggered near to the tip in order to ensure the presence of initial electrons in correlation with the increase in electric field. In practice, an ESE with the same size as a Franklin rod leads to a faster initiation of the upward connecting leader, which may, according to some authors, lead to a larger radius for the protected area or, with an identical radius of the protected area, to significantly higher reliability (probability of capture) compared with a rod terminal. However, the efficiency of such a terminal must be validated with specific tests.

In 2001, INERIS listed ESE-related technologies: technologies with electronic or piezoelectric activation, or with special profiles.

In 2016, only ESE technologies with electric/electronic activation and special profiles exist, and many manufacturers have combined both a profile and an activation mode. Piezoelectric terminals are no longer sold in France.

In 2001, INERIS listed 100,000 ESE air terminals manufactured after 1985 (source: APF), GIMELEC³ currently lists 440,000 for French members alone, i.e. $\frac{1}{4}$ of production occurred over the first half of the 30-year period and $\frac{3}{4}$ over the second half. This demonstrates the strong growth recorded in the market availability of these products.

² For more details, see the OMEGA 3 guide, which can be downloaded from the INERIS site, www.qualifoudre.org

³ GIMELEC: A group representing companies providing electrical and automation solutions and associated services

How does an ESE air terminal operate?

- if a lightning protection terminal generates an upward connecting leader before a nearby object, it will naturally win any competition with upward connecting leaders. This is the basic principle behind ESE. ESE air terminals must demonstrate early triggering ΔT compared with a lightning rod (LR) air terminal.
- if a terminal benefits from early triggering ΔT , the upward connecting leader or leader generated will cover a distance D , greater than for an LR air terminal, to meet the downward leader. The terminal will capture the lightning at a larger distance, its range is therefore increased. The increase in range is therefore obtained from the propagation speed of the upward connecting leader as $\Delta L = v \Delta T$.

In terms of standards, standard NF C 17102 defines the Early Streamer Emission air terminal as a lightning protection terminal with an earlier streamer emission than a lightning rod air terminal in identical conditions. No information on the technology used is given.

An ESE air terminal comprises a capture lightning rod, an attachment device, a fixation and a connection to the downward conductors.

The area protected by an ESE air terminal is determined depending on its efficiency, as defined in § 5.2.2. of the standard. The ESE air terminal must be installed on the highest part of the structure. The terminal must represent the highest point in the area to be protected. The standard defines efficiency by measuring ΔT (see Appendix C of standard NF C 17102).

The maximum allowable value of ΔT is 60 μs , including when the results of performance tests exceed this value. The value of ΔT corresponds to the difference expressed in μs between the emission times of an ESE and an LR air terminal, measured in a laboratory in the conditions defined in standard NF C 17102.

The minimum permissible value of ΔT is 10 μs if the terminal is to be considered as an ESE air terminal.

Statistical processing of test results must give a ratio of less than 0.8 between the standard errors of an ESE and an LR air terminal.

2.1 DATA COLLECTED

The following table lists the main characteristics of these terminals on the basis of the information provided by the manufacturers. Some of this data is confidential, therefore all information is anonymous.

Ref	No. of patents	Physical principle behind the technologies	Components	Quality (Post-manufacturing and on-site tests)	Qualification tests (1)
A	2	<ul style="list-style-type: none"> - Use of the ambient electric field - Creation of an ionised space around the tip using voltage pulses generated cyclically at a variable frequency 	<ul style="list-style-type: none"> - passive components only - non-polarised capacitors - autotransformer - gas discharge tube - stainless steel tip and body 	<ul style="list-style-type: none"> - no active component is used, ensuring the very-long-term reliability of the lightning protection terminal. - the steel ESE body containing electronics is filled with resin, eliminating any risk of oxidation for electronic parts and contacts in internal parts. - high voltage testing of internal electronics in each product prior to assembly - test due operation using the test kit - permanent embedded visual test system - communicating system equipped with an electronic monitoring system 	<ul style="list-style-type: none"> - tests in several independent laboratories - multiple tests at a natural outdoor site (on-site)
B	3	<ul style="list-style-type: none"> - energy source from the ambient field via the lower electrode, - neutralisation of the space charge, then the ESE air terminal activates a pulse-based electronic system (threshold based on variation in dE/dt) with synchronised ionisation, which significantly raises the potential of the upper electrodes, - regardless of the location where the ESE air terminal is installed (height) with respect to dE/dt 	<ul style="list-style-type: none"> - passive and active components - continuous central tip carrying the lightning current directly to the earthing network - electrodes with variable geometry (sharp tip or rounded end) - mechanical surge arrester - adaptation of circuits according to the polarity of the storm cloud 	<ul style="list-style-type: none"> - factory testing of each ESE air terminal (passive and active components) - on-site testing with a test kit connected via a cable or compatible with remote testing (depending on the model) 	<ul style="list-style-type: none"> - tests in several internal and external laboratories - multiple tests at a natural site and on a full scale experimental set-up (on-site)
C	1	<ul style="list-style-type: none"> - storage of energy (from the ambient field) in a capacitor. - if the field is strong (near the downward leader), the stored charges are released by a surge arrester and the process recovers at 	<ul style="list-style-type: none"> - passive components only - inductor coil, capacitor, internal surge arrester, resistor - rod with external surge arrester 	<ul style="list-style-type: none"> - the shape of the rod alone (with vanes) increases ΔT - checks of parameters R, L, C using a portable device, of 100% of products leaving the production chain, 	<ul style="list-style-type: none"> - independent laboratory

		increasing speed, depending on the arrival of the downward leader.		- on-site checks using the same portable device (small impedance meter) directly or via a rod	
D	1	- storage of energy (from the ambient field) in a capacitor. - if the field is strong (near the downward leader), the stored charges are released by a surge arrester and the process recovers at increasing speed, depending on the arrival of the downward leader.	- passive components only - inductor coil, capacitor, internal surge arrester, resistor - rod with external surge arrester	- the shape of the rod alone (with vanes) increases ΔT - checks of parameters R, L, C using a portable device, of 100% of products leaving the production chain, - on-site checks using the same portable device (small impedance meter) directly or via a rod	- independent laboratory - on-site tests
E	3	- energy supplied by the ambient electric field of the cloud and the downward leader, - application of current when the surge arrester short circuits, - the electric current passing through the coil increases as the distance between the upward connecting and downward leaders reduces	- passive components only - inductor coil, - internal surge arrester - resistor	- testing of 100% of products manufactured using a pulse generator, - checking of the characteristics of the set-up on-site using a mobile test device (rod) or via hard-wired remote testing (test kit).	- in several independent external laboratories - on-site tests
F	2	- energy supplied by the increase in the Earth's electric field, - accumulation of electric charges at the tip (spherical part with a range of optimised rounded geometric shapes) and upward connecting leader activated when the downward leader comes near	- passive components only - inductor coil, capacitor, internal surge arrester, resistor - stainless steel tip and body - continuous central tip carrying the lightning current directly to the earthing network - rounded tip promoting a repetitive response	- standalone device, ensuring long-term reliability - systematic manufacturing checks based on defined protocols, - on-site test with a test bench including a HV generator - testing with a test kit using a hard wired system - test device in a remote unit (able to communicate with a smartphone)	- in several independent external laboratories - multiple tests at a natural site (on-site)
G	1	- storage of the electrostatic energy in the atmosphere, accumulation of electric charges at the tip and activation of the upward connecting leader	- passive and active components - The capture point tip (head of the terminal) is electrically insulated from the earth	- permanent checks during manufacturing and at the end of manufacturing - on-site checks with various testers (which can be connected to the ESE	in several independent laboratories Multiple on-site tests

		<ul style="list-style-type: none"> - control with an initial built-in sensor measuring the value of the ambient electric field E and then a polarity reversal, - storage of the solar energy in power capacitors to support the propagation of the leader, - control of the activation of the leader from the power capacitors with a 2nd built-in sensor, measuring the intensity of the current (using a threshold current I) forming on the tip. 		terminals, used remotely, or integrated into the software in real time)	
H	2	<ul style="list-style-type: none"> - storage of the electrostatic energy in the atmosphere - electrostatic sensor for the E field with determination of the polarity of the tip - signal processing module with application of a charge to the tip (polarisation and increase in the local field) - various technologies: depending on the models, addition of functions: magnetic detection, E-meter, tip ionisation energy increased using a power capacitor charged by photovoltaic panels 	<ul style="list-style-type: none"> - basic technology: Passive components - advanced technology: passive and active components 	<ul style="list-style-type: none"> - permanent checks during manufacturing and at the end of manufacturing On-site after installation: <ul style="list-style-type: none"> - remote tester - tester, which can be connected to the ESE terminals, - tester integrated in the software (signal processing module) fed by accumulators recharged by photovoltaic panels 	tests in external laboratories
I	1	<ul style="list-style-type: none"> - trigger a corona current at the tip - no spark control at the tip - the process involves minimising the corona current at the tip when no lightning impact is imminent and allowing this current to form just before the impact. The point in time when the corona current is allowed to form is determined by the exponential growth of the ambient electrostatic field. - rings can be fitted to tips 	<ul style="list-style-type: none"> - passive components only - inductance - capacitor, with a secondary surge arrester fitted in parallel to protect the capacitor from voltage surges - main surge arrester comprising the tip and the tube separated by an insulating ring 	checking of the values of internal components using direct measurements	tests in an external laboratory

(1) laboratory and on-site tests (external site at full scale) are described in detail in paragraphs 5 & 6.

Table summarising the main elements

Summary		No. manufactured	No. of patents	Physical principle	Components	Quality	Qualification tests (1)
Common elements		a total of 440,000 for French manufacturers (GIMELEC data)	Approximately 15 patents	A wide range of physical principles over the period 1985-2000, tending to harmonise over the period 2000-2015	Passive components, sometimes combined with active electronic components, for pulse control purposes	All assessed at 100% after manufacturing or can be checked on-site (testing due operation)	All tested in internal laboratories (by the manufacturer with external supervision) or in independent external laboratories in accordance with standard NF 17-102, version 2011

(1) laboratory and on-site tests (external site at full scale) are described in detail in paragraphs 5 & 6.

2.2 BASIC PRINCIPLES

2 main ESE groups can be identified in the summary table:

- **air terminals** with special profiles including **passive** components (L, R, C: coil, resistor, capacitor),
- **air terminals with electronic activation** including one or more **active** electronic circuits for managing the activation of the upward connecting leader at a specific point in time.

Most of the ESE systems of the manufacturers operate whether the ambient electric field is negative or positive, which is compatible with a downward negative or positive lightning strike.

No early triggering is required for an upward connecting lightning strike (positive or negative), the terminal will emit at the highest point connected to the earth and the ESE air terminal, if installed at the highest point as required by standard NFC 17 102, will represent the preferred starting point for this type of lightning strike.

2.2.1 PARTICULARITIES OF ESE AIR TERMINALS WITH PASSIVE COMPONENTS ALONE

This type of ESE air terminal operates with passive components, without a battery and without a controlled electronic activation system.

The electric circuit comprising passive components (such as inductor coils, capacitors and surge arresters fitted differently depending on the patented technologies of the manufacturers) built into the head of the ESE air terminal, acts as a generator and will use the energy of the existing natural ambient electric field to activate a precursor.

The ambient electric field charges a capacitor, which will discharge into the circuit at a given point in time, and create a voltage pulse and a current, which will ionise the tip(s) at the head of the ESE air terminal depending on the tip shape. The tip shape (rounded, sharp, grooved, depending on the manufacturer) will have a significant effect on the activation of the upward connecting leader.

The upward connecting leader emitted by the ESE air terminal (which has higher energy levels than other upward connecting leaders due to uneven ground) is thereby promoted by this ionisation, and will connect to the downward leader to form an ionised channel.

2.2.2 PARTICULARITIES OF ESE AIR TERMINALS WITH ACTIVE COMPONENTS

This type of ESE air terminal operates with active components which can be used with a controlled electronic activation system.

Energy is provided at the best possible point in time thanks to electronic activation systems, which vary depending on the manufacturer:

- either the activation system consists of an electronic circuit, which will activate at a threshold for variation in the electric field, dE/dt , to ionise the tips at the best possible point in time, and another electronic circuit, which will neutralise the space charges,
- or the activation system consists of an electronic circuit (initial sensor) measuring the value of ambient electric field E , which activates the pulse device with a polarity reversal and another electronic circuit (2nd sensor measuring the intensity of the current), which activates the leader (if $I > I_{\text{threshold}}$) from the power capacitors (charged with solar energy via a battery) forming on the tip (ionisation).

3. REMINDER OF THE RECOMMENDATIONS OF THE 2001 REPORT

We confirm the main observations and results of the previous study and subsequently analyse the improvements to these products in order to optimise characterisation and provide data proving their efficiency.

These observations, taken from the 2001 report, are written in italics. The following extracts in italics from the 2001 report are no longer accurate, as this 2016 report repeals and supersedes the 2001 report in full (final conclusions are given in paragraph 8 of this 2016 report).

A wide range of products exists under the name "ESE air terminals". Standard NF C 17-102 (1995 version) fails to determine the behaviour of some products. The name "ESE air terminals" refers to products with very different operating principles and technical solutions. Users of ESE air terminals do not hold adequate information to appraise the efficiency of the different models.

ESE air terminals are designed to generate an upward connecting leader early compared with a traditional lightning rod air terminal. This early triggering is the main characteristic of the efficiency of these products according to French standard NF C 17-102; this lead can be easily measured in a High Voltage laboratory.

Subsequent to the study carried out in 2001 by INERIS, it appears that:

- 1. some ESE air terminals cannot be tested in laboratories, despite announcing conformity with standard NF C 17-102,*
- 2. some models have never been tested to check that they are able to absorb a lightning current,*
- 3. the radii of the protected areas announced by some manufacturers, with reference to standard NF C-17-102, have never been verified on protected facilities,*
- 4. the ability of ESE air terminals to absorb lightning is confirmed, however the superior radius of the protected area compared with a lightning rod air terminal has not been shown,*
- 5. the early triggering parameter, even if measured subject to specific conditions, is not sufficient to justify the radii of the protected area announced in the standard, as the validation conditions for the formula used are based on unverified assumptions, particularly in terms of the propagation speed of the upward connecting leader and the minimum energy contributed by the downward leader. The criticism in terms of ESE air terminals relates to the excess confidence shown for the size of the protected area and not to physical inadequacies.*

For an ESE air terminal with zero early triggering (i.e. an LR air terminal), the radii calculated as per standard NF C 17-102 (1995) are approximately 40% larger than those obtained using the protection angle as per table 3 of standard NF C 17-100⁴.

We suggest two lines of research in order to demonstrate the efficiency of ESE air terminals:

- use the high number of terminals installed and user feedback to estimate the effective protection provided by ESE air terminals,*
- validate the performance qualification tests of ESE air terminals in terms of protection using a study in order to check that the parameter measured during tests is representative of the efficiency of a protection system.*

INERIS detected specific points in standard NF C 17-102, which would be worth revising. The proposals raised for UTE by GIMELEC in April 2001 relate to the following points:

- remove all aspects in the standard, which relate to the set-up and already exist in NF C 17-100.*
- improve installation rules for ESE air terminals,*
- homogenise protection ratings (4 for NF C 17-100 and 3 for NF C 17-102),*
- add electric tests to determine the resistance of the product to lightning strikes,*
- corrosion tests: on the basis of EN 50164-1,*
- changes to the protection model to determine the revision of efficiency tests for ESE air terminals.*

⁴ This standard was replaced by IEC 62305-3.

4. IMPROVEMENTS OVER THE PERIOD 2001-2015

The analysis of improvements and changes is covered to answer the following questions:

1. What has changed in terms of the technical aspects mentioned in the previous report?
2. What works have lightning professionals launched to ensure the credibility of these terminals?
3. How have regulations changed and taken these terminals into account?

4.1 CHANGES TO STANDARDS WITH STRICTER TESTING

Manufacturers of ESE air terminals must ensure that these terminals comply with the NF C 17102 standard, applicable since 2011, and stricter than the 1995 version.

Products have therefore been developed to meet the requirements of the 2011 standard, which has improved credibility in terms of product operation and life.

Some technical publications (e.g. [11]) report on changes to standard NF C 17102.

To summarise, changes to standard NF C17102 (2011) relate to the following points:

- variation in parameters for efficiency tests was reduced in standard NF C 17102 (2011). Other criteria have been introduced (standard error, min.-max. values of ΔT), and a reference rod has been launched,
- harmonisation with the content of standards NF EN 62305-2 and NF EN 62305-3,
- harmonisation with the content of the series of standards NF EN 50164-x,
- consideration of EMC-related risks,
- addition of a requirement on inspection of the ESE air terminal.

Several details have been added in relation to the efficiency of the ESE air terminal (ΔT). The first resides in the range of the early triggering, which must be between 10 μs and 60 μs . If ΔT is less than 10 μs , the terminal is not considered as an ESE air terminal.

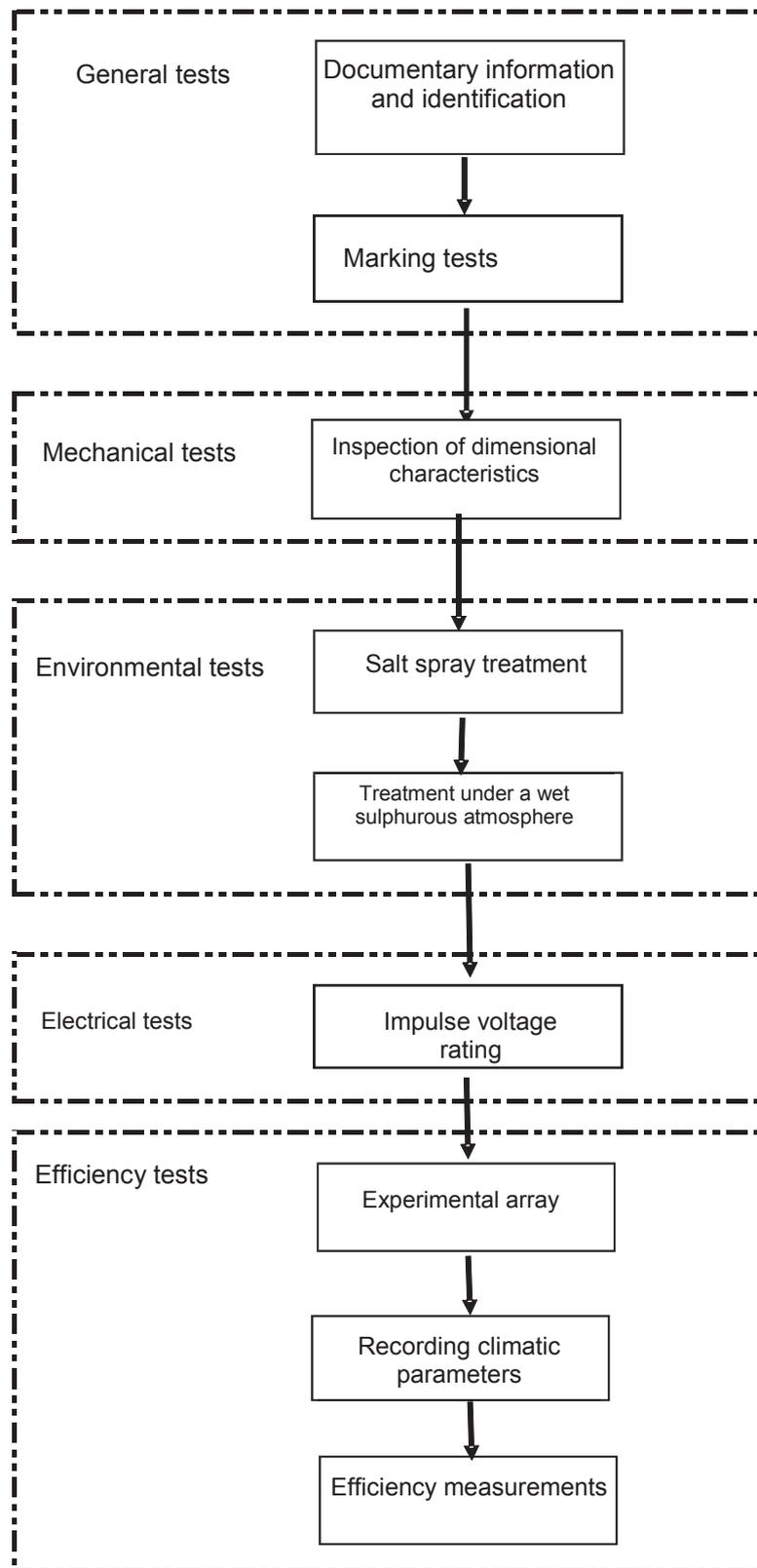
The criterion adopted to assess the efficiency of an ESE air terminal corresponds to its ability to emit an upward connecting leader before an LR air terminal placed in the same conditions, on a repetitive basis. The value T^5 at the point in time when the upward connecting leader is triggered is measured for each valid strike on the LR air terminal, and subsequently on the ESE air terminal.

Efforts by manufacturers of ESE air terminals have also focused on adding performance tests based on the series of standards, NF EN 50164-x (maximum current, corrosion, etc.), and on the significant changes to standard NF C 17-102 (2011 version), which includes details of the test procedure and introduces requirements (appendix C) by specifying, for example, tests with a lightning strike of 100 kA.

The following diagram shows the different tests required.

These tests meet the requirements of the European standard NF EN 62305-3 in application of the series of standards NF EN 50164-x (and, recently, the series NF EN 62561-x), which are also mentioned in standard NF C17102 (September 2011).

⁵ Mean emission times T_{mean}^{LR} and T_{mean}^{ESE} are calculated based on valid strikes, using the measurements of the points in time when the upward connecting leaders are emitted from an LR air terminal and an ESE air terminal, in compliance with parameters. In the same way, standard errors are calculated for the two distributions (σ_{LR} and σ_{ESE})



Furthermore, close attention was paid to EMC-related risks.

This new version requires ESE air terminals incorporating electronic circuits to comply with the standard on emissions, NF EN 61000-6-3 and NF EN 61000-6-2, in terms of immunity requirements for industrial environments.

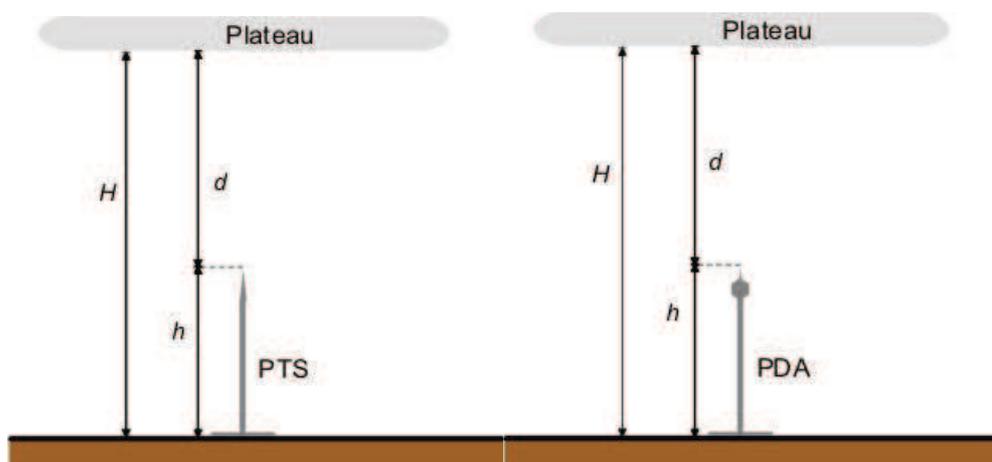
For ESE air terminals which satisfy these conditions, but comprise radio modules, all of the requirements described in directive RED 2014/53/EU, must be satisfied.

Periodic checks of ESE air terminals depend on the technology used, therefore, refer to the information provided by the manufacturer. A chapter has been added to appendix C (C5) of the standard on inspecting ESE air terminals. In fact, in order to check the due operation of the ESE air terminals, the manufacturer must describe the devices required for product maintenance and servicing in a maintenance and testing manual.

4.2 THE IMPORTANCE OF EFFICIENCY TESTS

The efficiency of an ESE air terminal is assessed by comparing the point in time when the upward connecting leader is emitted with that of an LR air terminal in a high voltage laboratory.

In this context, the LR and ESE air terminals are assessed one after the other in identical electrical, geometric and climatic conditions as part of laboratory tests simulating the "natural" conditions activating an emission (upward connecting positive leader).



See above figure	Translation
Plateau	Plate
PTS	LR air terminal
PDA	ESE air terminal

(see Appendix C of NFC 17-102: 2011)

A recent technical publication [3] highlights the efficiency of an ESE air terminal, compared with an LR air terminal, based on experimental laboratory qualification. This article describes a new experimental technique for demonstrating the efficiency of an ESE air terminal compared with an LR air terminal. On the theoretical base of an ESE model (modelled in an equivalent circuit), it has been demonstrated that the intensity of the dynamic electric field of an active ESE air terminal is higher (twice as high in theory) than the intensity of a static field for a conventional LR tip. Subsequently, experimental testing by the SIAME laboratory of Pau University in France demonstrated the efficiency of an ESE air terminal compared with a conventional Franklin rod terminal. This method involves installing both ESE and LR air terminals (where the LR air terminal is an ESE air terminal with an inactive/short-circuited head) in the same set-up. During the tests, all leaders are recorded using the ESE air terminal with an active head.

To complement standard NF C 17102, some manufacturers of ESE air terminals have mandated efficiency tests in laboratories with vertical clearance of 7 to 10 m and outside (particularly at the WHVRI laboratory).

5. LABORATORY TESTING TO MEASURE PERFORMANCE

ESE manufacturer	External or internal laboratory	Type of test	Independent third party
A	SIAME (Pau, France)	Efficiency measurements	general certificate APAVE
	Ilmenau university (Germany)	Current (100 kA)	APAVE certificate
B	Internal	Efficiency measurements	supervised by BV and UL
	CITEL (Reims, France)	Current (100 kA)	supervised by BV and UL
	LCIE (Fontenay aux Roses, France)	Environmental (corrosion, etc.)	supervised by BV and UL
	Internal	General, mechanical	supervised by BV and UL
	SOCOTEC	EMC	supervised by SOCOTEC
C	UNICAMP (Brazil)	Current (230kA)	
	EDP Labelec (Portugal)	Efficiency measurements	supervised by ISQ
	ELEMKO (Greece)	Current (100 kA) - Environmental (corrosion, etc.)	
D	EDP Labelec (Portugal)	Efficiency measurements	supervised by ISQ
	ELEMKO (Greece)	Current (100 kA) - Environmental (corrosion, etc.)	
E	SIAME (Pau, France)	Efficiency measurements	
	Instytut Fizyki Plazmy I Laserowej Mikrosyntezy (Warsaw - Poland)	Current (100 kA)	
	Building Research Institute (Poland)	Environmental (corrosion, etc.)	
F	CNRS AMPERE LAB in LYON (France)	Efficiency measurements	Supervised by BV
	LCIE laboratory	Environmental (corrosion, etc.)	Supervised by BV

	GERAC laboratory in Limoges (France)	Current (100 kA)	Supervised by BV
	Shanghai Grand Top Lightning Technology laboratory	Current (100 kA) Current (200 kA)	
	Shanghai Lightning Protection Center laboratory	Efficiency measurements	
	Internal	General, mechanical	Supervised by BV
G	HV LABORATORY IN BAZET (France)	Efficiency measurements (High voltage tests)	Global conformity certified by BV
	CITEL 2CP	Current (100 kA)	Global conformity certified by BV
	LABEP	Environmental (corrosion, etc.)	Global conformity certified by BV
H	HV LABORATORY IN BAZET (France) High Voltage test laboratory of PEKIN WHVRI (China)	Efficiency measurements (High voltage tests) High voltage tests, high vertical clearance	Global conformity certified by BV
	CITEL 2CP	Current (100 kA)	
	LABEP	Environmental (corrosion, etc.)	
I	SIAME (Pau, France)	Efficiency measurements	

Table summarising internal and external test laboratories

6. ON-SITE TESTS CARRIED OUT BY SOME MANUFACTURERS

6.1 GIMELEC-UTE PROTOCOL IN PROGRESS SINCE 2003

Two types of on-site tests are defined below:

- natural lightning tests, where it is necessary to await until lightning hits the object undergoing testing (long-term tests),
- triggered lightning tests, where lightning is triggered using rockets (testing over one or two stormy seasons).

A protocol was developed between GIMELEC and UTE [1] at end-2003 in order to obtain preliminary experience of at least 3 years on around a dozen sites. The test method used was easy to set up at an existing site and is currently used as a base for the draft "pure performance standard" prEN 50622. The aim was to install ESE air terminals at potentially exposed sites in order to confirm the protection model used in NFC 17-102 in normal conditions of use, particularly with components competing with the ESE air terminal (antennas, stack, etc.).

6.2 TABLE SUMMARISING ON-SITE TESTS

ESE manufacturer	Location	Type of test
A	Pic du Midi (France)	On-site (GIMELEC protocol)
B	Saint-Privat-d'Allier (France), Douai (France), Japan, USA, Brazil, Indonesia	On-site (GIMELEC protocol)
C	New Mexico	On-site (to define the best tip shape)
D	Johannesburg university (South Africa)	On-site (GIMELEC protocol)
E	Poland	On-site (protocol with IEN Warsaw)
F	3 on-site locations: - Super Besse (France) - Church with 2 bell towers at Satu Maru (Romania) - Arequipa airport (Peru)	On-site (GIMELEC protocol)
G	Manilla university in the Philippines	On-site (GIMELEC protocol)
H	Manilla university in the Philippines	On-site (GIMELEC protocol)
I	Not disclosed	

Some manufacturers have drafted technical publications to define on-site tests in more detail ([12]-[15]-[16]-[17]).

7. CHANGES TO REGULATIONS, GUIDES AND STANDARDS ON ESE AIR TERMINALS

The amended law of 4/10/2010 [5] specifies the application of the French and European standards in force.

Article 19 of this order specifies that the lightning protection systems provided for in the technical study comply with French standards and any other equivalent standard in force in an EU member state.

Furthermore, the circular of 24 April 2008 [6] relating to this order refers to standard NF C 17102.

A complementary report [7] by the ministry of 22 February 2016 specifies the different installation options for ESE air terminals (environmentally classified sites (ICPE), sites open to the public (ERP), high-rise buildings (IGH)). To date, no text excludes the use of ESE air terminals for protection purposes.

Reference text	Sites in question	comments
Order of 4/10/2010 amended by the order of 19/07/2011 Circular of 2008 relating to the order of 2010	Environmentally classified sites (ICPE/SEVESO) requiring authorisation	For some sections mentioned in the law
Summary report on ESE air terminals of 22 February 2016 (joint report between the French Ministry of the Environment and the French Ministry of the Interior)	Environmentally classified sites (ICPE), sites open to the public (ERP) and high-rise buildings (IGH)	

Standards and guides	Title	Country of issue
NF C17102 (2011)	Early streamer emission air lightning protection terminals	FRANCE
GESIP guide no. 2013/01 (2013)	Protecting industrial sites against lightning	FRANCE
INERIS Omega 3 guide (2011)	Protecting environmentally classified sites against lightning	FRANCE
UNE 21186		SPAIN
NP 4426		PORTUGAL
I-20		ROMANIA
MKS N.B4 810		MACEDONIA
STN 34 1391		SLOVAKIA
JUS N.B4.810		YUGOSLAVIA
IRAM 2426		ARGENTINA
NA 332014		ANGOLA
TS 13709		TURKEY
UL	UL (Underwriters Laboratories) certificate of conformity for products and systems with standard NF C 17102	USA

8. FINAL CONCLUSIONS ON IMPROVEMENTS FOR ESE AIR TERMINALS

Reminder of INERIS recommendations 2001	Observations on integration in 2016	Comments
Some ESE air terminals cannot be tested in laboratories, despite announcing conformity with standard NF C 17-102,	All manufacturers propose ESE air terminals, which comply with testing for standard NF C 17102 (2011).	Piezoelectric terminals are no longer sold in France to date.
Some models have never been tested to check that they are able to absorb a lightning current,	Impulse current tests (100 kA) are now mandatory according to standard NF C 17102 (2011)	
<ul style="list-style-type: none"> - The radii of the protected areas announced by some manufacturers, with reference to standard NF C17-102, have never been verified on protected facilities, - The ability of ESE air terminals to absorb lightning is confirmed, however the superior radius of the protected area compared with a lightning rodair terminal has not been shown 	On-site tests are in progress (as per GIMELEC protocol)	Feedback on on-site tests in progress should include the validation of the theoretical model for the radius of the protected area, based on experimental results
<p>The early triggering parameter, even if measured subject to specific conditions, is not sufficient to justify the radii of the protected area announced in the standard, as the validation conditions for the formula used are based on unverified assumptions, particularly in terms of the propagation speed of the upward connecting leader and the minimum energy contributed by the downward leader. The criticism in terms of ESE air terminals relates to the excess confidence shown for the size of the protected area and not to physical inadequacies</p> <p>For an ESE air terminal with zero early triggering (i.e. an LR air terminal), the radii calculated as per standard NF C 17-102 (1995) are approximately 40% larger than those obtained using the protection angle as per table 3 of standard NF C 17-100</p>	The circular of 2008 and a Qualifoudre report from 13/12/2011 require the application of a 40% reduction to the value obtained by calculating Rp as per standard NF C 17102 (application for classified sites requiring authorisation pursuant to the order of 4 October 2010 amended)	Future publications based on on-site measurements with ultrarapid 2D or 3D videos will probably provide more precise values for the speed of upward connecting leaders
<p>Remove all aspects in the standard, which relate to the set-up and already exist in NF C 17-100.</p> <ul style="list-style-type: none"> - improve installation rules for ESE air terminals, - homogenise protection ratings (4 for NF C 17-100 and 3 for NF C 17-102), - add electric tests to determine the resistance of the product to lightning strikes, - corrosion tests: on the basis of EN 50164-1, - changes to the protection model to determine the revision of efficiency tests for ESE air terminals. 	<p>Standard NF C17102 (2011) has been updated to integrate all of these observations</p> <p>Tests are stricter (impulse current tests at 100 kA, corrosion tests, etc.)</p>	In addition to these more-restrictive laboratory tests (recognised), many manufacturers carry out on-site tests (as per the GIMELEC protocol) with current levels which can exceed 100 kA in real climatic conditions
<p>We suggest two lines of research in order to demonstrate the efficiency of ESE air terminals:</p> <ul style="list-style-type: none"> - use the high number of terminals installed and user feedback to estimate the effective protection provided by ESE air terminals, - validate the performance qualification tests of ESE air terminals using a study in order to check that the parameter measured during tests is representative of the efficiency of a protection system. 	<p>Recent scientific publications demonstrate the efficiency (ΔT) of ESE air terminals (in laboratories)</p> <p>The preliminary report of the GIMELEC shows satisfactory feedback</p>	

9. ITEMS TO BE DEMONSTRATED

Standard NF C 17102 from 2011 has changed in terms of how the radius of the protected area, R_p , is calculated, with:

- The addition of the protection rating IV in the formula,
- The value of ΔL in the formula without using the speed, v , of the upward connecting leader (measured value).

The radius of the protected area, R_p , from standard NF C 17-102 (2011 version) is determined using the formula:

$$R_p(h) = \sqrt{2rh - h^2 + \Delta(2r + \Delta)} \quad \text{for } h \geq 5 \text{ m}$$

and

$$R_p = h \times R_p(5) / 5 \quad \text{for } 2 \text{ m} \leq h \leq 5 \text{ m}$$

With

$R_p(h)$ (m)	corresponds to the radius of the protected area at a given height h ;
H (m)	corresponds to the height from the end of the ESE in the horizontal plane to the farthest point of the object to protect;
r (m)	20 m for protection rating I; 30 m for protection rating II; 45 m for protection rating III; 60 m for protection rating IV;
Δ (m)	$\Delta = \Delta T \times 10^6$ Field experience has shown that Δ is equal to the efficiency obtained during the ESE assessment tests.

The value of 10^{+6} used in the formula is no longer related to a speed of the upward connecting leader, but is based on trials carried out in the field (with a high speed video camera).

In the 2011 version of standard NC 17102, the calculation formula for the radii of protected areas, R_p , remains the same, however parameter D (from 1995) becomes parameter r and the protection level IV is added in order to match the 4 levels in standard NF EN 62305-3.

The formula used to calculate the radius of the protected area, R_p , is based on the rolling sphere method ⁶ (also known as the electro-geometric model) by adding the extent of the early triggering ΔL .

In order to verify the consistency of the formula based on a comparison, calculate the radius of the protected area of an LR air terminal (using the rolling sphere method) and an ESE air terminal (where $\Delta L=0$).

For example, let us calculate the radius of the protected area for a protection level I of a simple building (parallelepiped) with a lightning protection device at a height of 5 m on the roof of the building.

For the LR air terminal, the radius of the protected area is determined using the rolling sphere method defined in standard NF EN 62305-3. This gives a radius of 14 m for the protected area (R_p).

If the device is an ESE air terminal, for which we consider, on a random basis, that zero early triggering applies (i.e. $\Delta T=0$), the radius of the protected area, R_p , with the above formula, is equal to 14 m.

⁶ The rolling sphere method is described in standard NF EN 62305-3 and in the OMEGA 3 guide

An ESE air terminal with $\Delta T=0$ therefore behaves in the same way as an LR air terminal with an equivalent radius of the protected area (based on the rolling sphere method); the formula is therefore consistent.

In addition, INERIS, in its 2001 report, had recommended the application of a 40% reduction coefficient to the radius of the protected area in order to maintain a safety margin for uncertainty with models.

On this basis, since 2011, the 40% reduction coefficient must be systematically applied to classified sites in application of the order of 4 October 2010 amended and in application of the Qualifoudre report of 13 December 2011.

This reduction coefficient is also mentioned in GESIP guide no.2013-01 and is applied for the protection rating I++ mentioned in standard NF C 17102 (2011).

In order to incorporate current scientific developments, the theoretical model for lightning attachment is currently being revised at international level. The following scientific articles could be mentioned in particular.

A scientific article [9] reports on the influence of corona discharge space charges on the interception of a downward lightning strike on high single rods. Using a simulation model known as SLIM (Self consistent Leader Inception and propagation Model), it has been demonstrated that the reduction in the vertical interception distance (I_D) when capturing the lightning strike due to corona discharge space charges is approximately 20%, and the reduction in the lateral interception distance (I_D) is approximately 10%. It was also demonstrated in the conclusion to this article that the theoretical attachment model must be modified in order to integrate the propagation of upward connecting leaders under the influence of downward leaders.

Various lightning attachment models have been described in recent years [8] (effect of space charges and tip shapes), [13] and [14] (connection model between upward connecting positive leaders and downward negative leaders).

In addition, a recent publication [10] (on the attachment process) proved that existing lightning protection models (Electro Geometric Mode: EGM, Rolling Sphere Model: RSM, Leader Progression Model: LPM) must be upgraded to a new model, in which upward connecting leaders (UCL) are replaced by FLF (Faintly Luminous Formations), which would describe the creation of upward connecting leaders from ESE air terminals more precisely.

Once the new model has been validated at international level for standard NF EN 62305-3, it will be necessary to apply this model for ESE air terminals.

10. CONCLUSION

Since 2001, the manufacturing of ESE air terminals has changed to integrate improvements to the electronic components used in these terminals and, above all, to meet the new requirements of standards, and the more-exhaustive performances tests required by NF C 17102 (September 2011).

This study identified several positive points for the actions taken by manufacturers, particularly with the launch of on-site tests (which go beyond the requirements of standards) and the harmonisation of operating principles.

The requirements of standard NF C 17102 (2011):

- demonstrate the early triggering of ESE air terminals (measuring efficiency ΔT) by laboratory testing,
- guarantee the long-term operation of products thanks to current tests (100 kA) and environmental tests (corrosion, etc.), which simulate real conditions.

The manufacturers of the ESE air terminals covered by this study all propose terminals which meet the requirements of the applicable standard NF C 17102 (September 2011), which was harmonised with European standards.

11. REFERENCES AND PUBLICATIONS

ref.	Titles of references and publications	Number of pages
1	Preliminary GIMELEC report on French "ESE" (Early Streamer Emission) technology - version from September 2015 By GIMELEC: A group representing companies providing electrical and automation solutions and associated services	53
2	Article on engineering techniques "Foudre et protection des bâtiments" [Lightning and building protection] Ref. C3307 – May 2000 By Alain Rousseau, Claude Gary and Gérard Berger	21
3	Experimental Demonstration of the Effectiveness of an Early Streamer Emission Air Terminal Versus a Franklin Rod – April 2015 By L. Pecastaing, T. Reess, A. De Ferron, S. Souakri, E. Smycz, A. Skopec and C. Stec	10
4	New high-speed video observations of natural lightning at the Lightning Observatory in Gainesville, Florida – October 2015 By V. A. Rakov, M. D. Tran, Y. Zhu and S. Mallick	6
5	Order of 4 October 2010 amended on the prevention of accidental risks within environmentally classified sites requiring authorisation (section III)	17
6	Circular of 24 April 2008 on the lightning protection of some classified sites	4
7	Report dated 22/02/2016 on the regulations applicable to ESE air terminals in the context of lightning protection	2
8	Investigations and studies on lightning air terminal shapes in relationship with the efficiency of a simple rod - 2014 By Sylvain Fauveaux and Olivier Alconchel	7
9	Corona discharges and their effect on lightning attachment revisited: upward leader initiation and downward leader interception - 2014 By Marley Becerra	8
10	New progress in the process of lightning attachment to grounded structures -2016 By Gérard Berger	4
11	Focus on the new range of tests for Early Streamer Emission air terminal technology - 2014 By Michael Troubat	3
12	The Reliability and the Efficiency of the Early Streamer Emission Concept - 2014 By Elysabeth Benali, Michael Troubat and Fabien Barriere	3
13	A 3-D numerical model of negative lightning leader inception - 2004 By Sonia Ait-Amar and G. Berger	22
14	Occurrence of new upward positive leaders triggered by negative downward CG lightning - 2010 By Gérard Berger, Louis-Jonardan Gallin and Sonia Ait-Amar	4
15	New lightning experiments at Pic du Midi - 2010 By Gérard Berger, Guy Lafon, Gérard Serrie and Stéphane Pedeboy	4
16	Installation And Implementation Of A Rocket Triggered Lightning Test Facility - 2016 By Sylvain Fauveaux, Thomas Nowicki, Bernard Thirion, Reynaldo Zoro and Tulus Leo	8
17	An experimental study of leaders initiated by single and advanced (ESE) lightning rods - 2004 By A.Eybert-Bérard, B. Thirion, P. Boilloz, M. Saba and N. Solorzano	7

12. GLOSSARY

Terms	Definitions
ESE	Early Streamer Emission
LR	Lightning Rod
GIMELEC	A group representing companies providing electrical and automation solutions and associated services
APF	Association de Protection contre la Foudre (Association for lightning protection)
ICPE	Environmentally classified sites
Rp	Radius of the protected area
MEEM	Ministère de l'Environnement, de l'Energie et de la Mer (Ministry of the Environment, Energy and Sea)