

Recommended Practice for Lightning Protection of Aboveground Storage Tanks for Flammable or Combustible Liquids

API RECOMMENDED PRACTICE 545
FIRST EDITION, OCTOBER 2009



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Recommended Practice for Lightning Protection of Aboveground Storage Tanks for Flammable or Combustible Liquids

Downstream Segment

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Foreword

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Contents

| | Page |
|-------------------------------------------------------------------------------------------------------------------------|-----------|
| 1 Scope | 1 |
| 1.1 Applicability | 1 |
| 1.2 Application of Requirements to New and Existing Tanks | 1 |
| 2 Normative References | 1 |
| 3 Terms and Definitions | 2 |
| 4 Protection of Specific Types of Tanks | 3 |
| 4.1 Fixed-roof Tanks (Metallic) and Tanks with Internal Floating Roofs | 3 |
| 4.2 External Floating Roof Tanks | 3 |
| 5 Metal Thickness | 4 |
| 6 Inspection and Maintenance Requirements | 4 |
| Annex A (informative) General | 5 |
| Annex B (informative) Understanding Lightning Discharge and its Secondary Effects | 11 |
| Annex C (informative) Different Seal Types | 12 |
| Figures | |
| A.1 The Process of Attachment from Lightning Cloud to a Tank | 6 |
| A.2 Components of Typical Negative Cloud-to-ground Lightning Stroke | 7 |
| A.3 Current Routes for Flash to a) Top of Shell, b) Floating Roof, c) Ground Near a Floating-roof Tank | 9 |
| Table | |
| A.1 Lightning Parameters | 8 |

Recommended Practice for Lightning Protection of Aboveground Storage Tanks for Flammable or Combustible Liquids

1 Scope

API RP 545, First Edition, *Recommended Practice for Lightning Protection of Aboveground Storage Tanks for Flammable or Combustible Liquids*, replaces the requirements of API 2003 regarding lightning protection for preventing fires in storage tanks with flammable or combustible contents. This recommended practice (RP) provides guidance and information to assist owners/operators with lightning protection for tanks. This RP does not provide complete protection for all possible lightning stroke occurrences.

1.1 Applicability

This RP is applicable to tanks as described in API 650.

1.2 Application of Requirements to New and Existing Tanks

The requirements of this RP shall apply to new or reconstructed tanks. The requirements may be applied to existing tanks at the discretion of the owner/operator.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API/EI Technical Report 545-A, *Verification of lightning protection requirements for above ground hydrocarbon storage tanks*

API Standard 650, *Welded Tanks for Oil Storage*

API Standard 653, *Tank Inspection, Repair, Alteration, and Reconstruction*

API Standard 2003, *Protection Against Ignitions Arising Out of Static, Lightning, and Stray Currents*

ASTM D3453 ¹, *Standard Specification for Flexible Cellular Materials*

BS EN 14015 ², *Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperature and above*

EMMUA 159 ³, *Users' Guide to the Inspection, Maintenance and Repair of Aboveground Vertical Cylindrical Steel Storage Tanks*

NFPA 780 ⁴, *Standard for the Installation of Lightning Protection Systems*

SAE ARP 5412 ⁵, *Aircraft Lightning Environment and Related Test Waveforms*

¹ ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org.

² European Committee for Standardization, Avenue Marnix 17, B-1000, Brussels, Belgium, www.cen.eu.

³ The Engineering Equipment and Material Users' Association, 10-12 Lovat Lane, London, EC3R 8DN, United Kingdom, www.eemua.org.

⁴ National Fire Protection Association, 1 Batterymarch Park, Quincy, Massachusetts 02169-7471, www.nfpa.org.

⁵ Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, Pennsylvania 15096-0001, www.sae.org.

Lightning: Physics and Effects, Vladimir A. Rakov and Martin A. Uman, 2003

All About Lightning, Martin A. Uman, 1986

The Lightning Discharge, Martin A. Uman, 1987

3 Terms and Definitions

For the purposes of this document, the following definitions apply.

3.1

action integral

The joule or ohmic heating energy dissipated per unit resistance at the lightning attachment point. The action integral is measured in A^2s (amperes-squared seconds), which is the same as $J\Omega^{-1}$ (joules per ohm) (Rakov and Uman, *Lightning: Physics and Effects*, p. 277).

3.2

bonding

An electrical connection between two electrically conductive objects that is intended to significantly reduce potential differences.

3.3

bypass conductor

A conductive cable that provides a direct electrical connection between the tank shell and the tank floating roof.

3.4

external floating roof tank

EFRT

An aboveground tank with a floating roof, which has no fixed roof and has an open top.

3.5

flash

A complete discharge of the cell between the thundercloud and ground (as it applies to cloud-to-ground lightning) (Uman, *The Lightning Discharge*, p. 10).

3.6

grounded (grounding)

Connected (connecting) to ground or to a conductive body that extends the ground connection (NFPA 780).

3.7

internal floating-roof tank

IFRT

An aboveground fixed roof tank with a floating roof inside the tank.

3.8

release prevention barrier

A release prevention barrier includes steel bottoms, synthetic materials, clay liners, and all other barriers or combination of barriers placed in the bottom of or under an aboveground storage tank, which have the following functions:

- a) preventing the escape of contaminated material, and
- b) containing or channeling released material for leak detection.

3.9

shunt

A short conductor that is electrically connected to the tank floating roof and contacts the tank shell.

3.10

striking distance

The distance over which the final breakdown of the initial lightning stroke occurs.

3.11

stroke

One current component of a lightning flash. The number of strokes per flash is typically three to four, but may be as low as one or as high as 30 (Uman, *All About Lightning*, p. 41).

4 Protection of Specific Types of Tanks

4.1 Fixed-roof Tanks (Metallic) and Tanks with Internal Floating Roofs

For fixed roof tanks (metallic cone or dome) and internal floating-roof tanks (IFRTs), there is a possibility of flammable vapors being present at atmospheric vents. If present, flammable vapors can be ignited by a lightning flash.

Shunts or bypass conductors are not required for lightning protection. Bonding techniques to prevent static discharge between the floating roof and shell are addressed in API 650, Appendix H.

Tanks handling low vapor pressures or in-service with properly maintained floating roofs with tight-fitting seals are not likely to have flammable vapors at atmospheric vents unless it is being refilled from empty. In these cases, no further lightning protection is required (see Annex B).

4.2 External Floating Roof Tanks

4.2.1 Bonding Between Floating Roof and Shell

4.2.1.1 Shunts for Conduction

4.2.1.1.1 General

Shunts are used for conduction of fast and intermediate duration components of lightning-stroke current.

4.2.1.1.2 Number and Placement

The shunt to shell contact point shall be submerged at least 0.3 m (1 ft) below the surface of the liquid product. The shunt shall have as short and direct a path as possible from the conductive floating roof to the tank shell. The shunts shall be spaced at intervals no greater than 3 m (10 ft) around the perimeter of the floating roof. When retrofitting existing tanks with submerged shunts, the abovedeck shunts shall be removed.

4.2.1.1.3 Cross-sectional Area—Minimum Width and Material

The shunts shall consist of an austenitic stainless steel conductor of at least 20 mm² (0.031 in.²) cross-sectional area, or of other material conductors of equivalent current-carrying capacity and corrosion resistance. The minimum width of the shunt shall be 51 mm (2 in.). The shunts shall be of the minimum length necessary to permit the function of the floating-roof seal assembly. The shunts shall be of the minimum length necessary to remain in contact with the shell during the full horizontal and vertical design movement of the floating roof.

4.2.1.1.4 Durability

The shunts and termination connections shall be of sufficient flexibility, cross-sectional area, and corrosion resistance to have a minimum service life of 30 years.

4.2.1.2 Bypass Conductors

4.2.1.2.1 General

Bypass conductors are used for conduction of the intermediate and long duration component of lightning-stroke current.

4.2.1.2.2 Number, Length and Electrical Resistance

The tank floating roof shall be bonded to the tank shell by direct electrical connection through an appropriate number of bypass conductors. Each conductor, including connections, shall have a maximum end-to-end electrical resistance of 0.03 Ω . The bypass conductors shall be of the minimum length necessary to permit full movement of the floating roof. Bypass conductors should be evenly spaced not more than every 30 m (100 ft) around the tank circumference with a minimum of two.

4.2.1.2.3 Durability

The bypass conductors and termination connections shall be positioned and of sufficient flexibility, cross-sectional area, and corrosion resistance to have a minimum service life of 30 years.

4.2.2 Parallel Conducting Paths (Seal Assembly from the Floating-roof Tank)

Any non-fully submerged conductive seal assembly components including springs, scissor assemblies, seal membranes, etc. shall be electrically insulated from the tank roof. The insulation level shall be rated 1 kV or greater.

NOTE This allows any lightning discharge current from the floating roof to the tank shell to take the preferential path through the shunts and bypass conductors.

4.2.3 Insulation of Gauge or Guide Poles

Any gauge or guide pole components or assemblies that penetrate the tank floating roof shall be electrically insulated from the tank floating roof. The insulation level shall be rated 1 kV or greater.

NOTE This allows any lightning discharge current from the floating roof to the tank shell to take the preferential path through the shunts and bypass conductors.

5 Metal Thickness

Minimum metal thicknesses for tanks are provided in API 650 and API 653.

Additional information is presented in EI/API 545-A, *Verification of lightning protection requirements for above ground hydrocarbon storage tanks*.

6 Inspection and Maintenance Requirements

All bonding and grounding appurtenances shall be maintained and inspected in accordance with API 653. Below-deck inspections shall coincide with API 653 out-of-service inspections.

Annex A⁶ (informative)

General

A.1 Phenomenon of Lightning and Secondary Effects on Tanks

A.1.1 Introduction

This section summarizes the present knowledge on the lightning flash process and attachment mechanism.

A.1.2 Lightning Principles

Under fair weather conditions, there is normally a steady but weak vertical electric field at the earth's surface with virtually no ground currents and a small distributed charge on the ground. Horizontal flat surfaces will have a very uniform charge distribution, (i.e. a similar surface charge density everywhere). The highest surface charge occurs on thin pointed objects such as church spires, tops of aerials, tips of lightning rods, etc. Where the surface charge is highest, the local electric field is the highest. Sharp-pointed, upward-facing items will tend to discharge a small current into the air, such as aerials and lightning air terminals. This will often be a silent, invisible discharge in the order of a micro amp.

Electrical storms involve the relatively slow movement of heavily charged clouds. Charging mechanisms in the storm build up an electrostatic field over a large area across the base of the storm cloud. This field induces an opposite charge on the surface of the earth beneath it. This induced ground charge flows along the surface of the earth beneath the storm cloud at a relatively slow rate. The charging current flows are relatively small and cause no damage. This charge differential is periodically neutralized almost instantaneously by a lightning stroke that collapses the field. At that time, a heavy ground current flows toward the lightning attachment point, equalizing local ground charge distribution.

The lightning process starts in the clouds, with a stepped leader descending to earth. The stepped leader often exhibits branching on its path to the ground as it attempts to find the best route to the ground. The path of the stepped leader is very irregular because of random variations in the local air conditions and other factors. When the stepped leader is within about 100 m (334 ft) or less from the tank (or ground), the electric field at ground level rises sharply, and the electric field on the highest items becomes great enough to launch an upward streamer towards the down-coming leader. In fact, two or more streamers may rise almost simultaneously from ground objects (tanks, vents, trees, etc.) but only one usually is successful in making the connection to the downward leader (see Figure A.1). This is the usual mechanism by which a lightning stroke completes its path to the ground.

A.1.3 Lightning Electrical Parameters

A complete lightning discharge is called a flash. Each cloud-to-ground flash is composed of one or more lightning strokes. Over 90 % of cloud-to-ground flashes are of negative polarity (Uman, *The Lightning Discharge*, p. 8). A typical negative cloud-to-ground flash contains three to four strokes, but may have as many as 30 (Uman, *All About Lightning*, p. 41). The currents in any one stroke can range from just a few kilo amperes (kA) to over 200 kA.

The current in a typical negative cloud-to-ground stroke has several components, as listed below and as illustrated in Figure A.2.

- Component A—First return stroke.
- Component B—Intermediate current.
- Component C—Continuing current.
- Component D—Subsequent return stroke, if present, followed by additional B and C components, etc., until the completion of the discharge.

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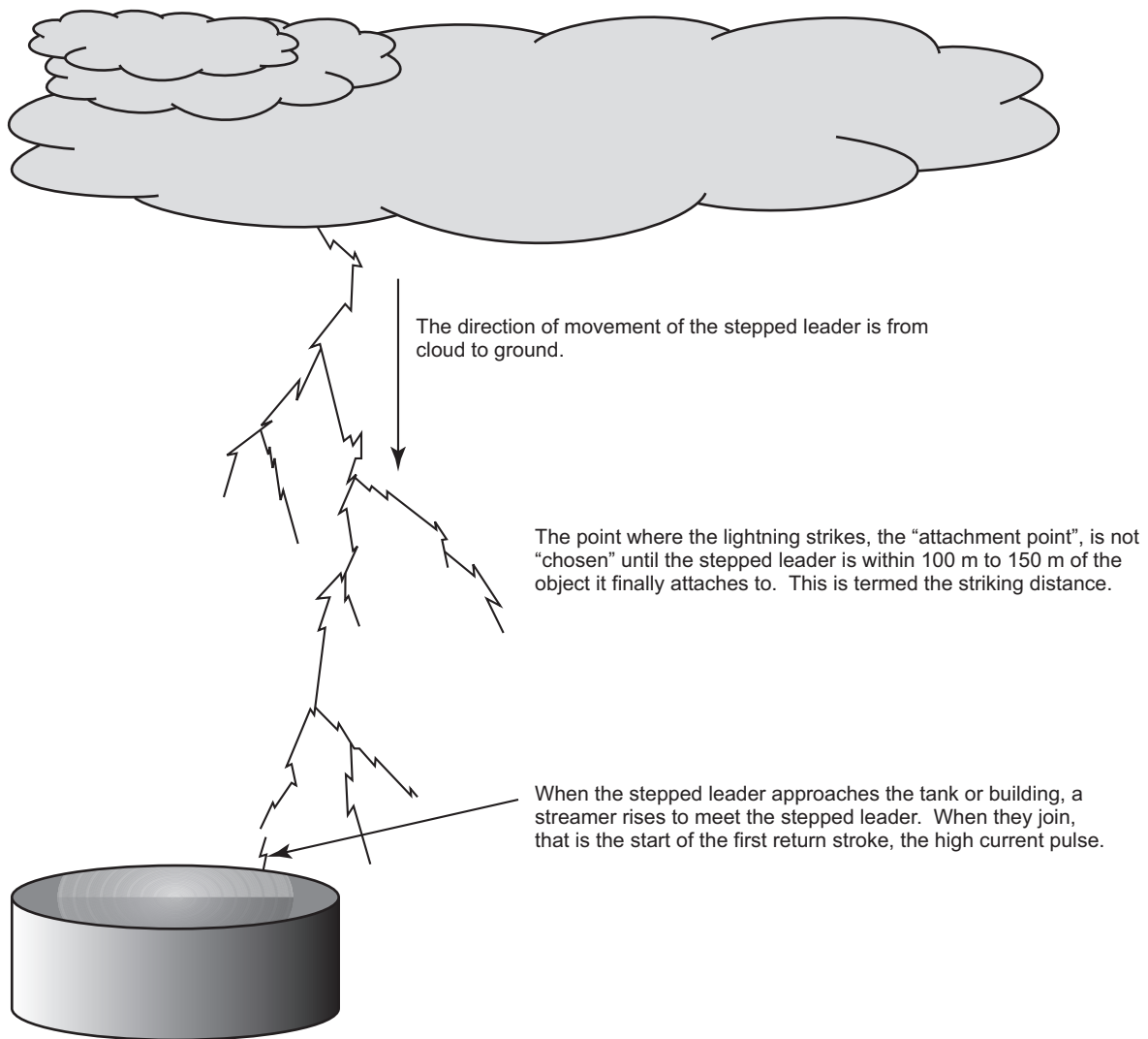
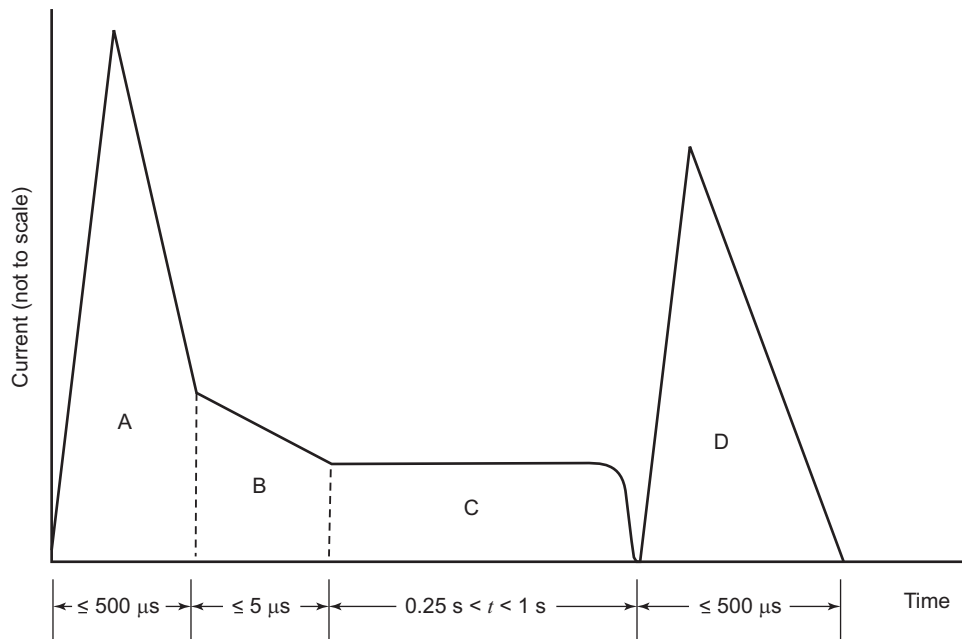


Figure A.1—The Process of Attachment from Lightning Cloud to a Tank

These stroke components have varying current characteristics, as follows (SAE ARP 5412):

| Component A (First Return Stroke) | | Component C (Continuing Current) | |
|------------------------------------|----------------------------------------------------------------------------------|----------------------------------------|-------------------------------------------------------------------------------------|
| Peak amplitude | 200 kA (+10 %) | Amplitude | 200 A to 800 A |
| Action integral | $2 \times 10^6 \text{ A}^2 \text{ s}$ ($\pm 20 \%$) (in 500 μs) | Charge transfer | 200 C ($\pm 20 \%$) |
| Duration | $\leq 500 \mu\text{s}$ | Duration | 0.25 s to 1 s |
| Component B (Intermediate Current) | | Component D (Subsequent Return Stroke) | |
| Max. charge transfer | 10 C ($\pm 20 \%$) | Peak amplitude | 100 kA ($\pm 10 \%$) |
| Average amplitude | 2 kA ($\pm 20 \%$) | Action integral | $0.25 \times 10^6 \text{ A}^2 \text{ s}$ ($\pm 20 \%$) (in 500 μs) |
| Duration | $\leq 5 \mu\text{s}$ | Duration | $\leq 500 \mu\text{s}$ |

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Reprinted with permission from the Cambridge University Press. Rakov and Uman, *Lightning Physics and Effects*, p. 363.

Figure A.2—Components of Typical Negative Cloud-to-ground Lightning Stroke

Additional lightning parameters are shown in Table A.1. The upper limit parameters usually employed for typical lightning strokes are:

- current = 200 kA,
- action integral = $2.25 \times 10^6 \text{ A}^2\text{s}$,
- total charge = 200 C (coulombs),
- rate of change of current (di/dt) = 140 kA/ μs .

A.1.4 Effects of Lightning

A.1.4.1 General

Tanks can be affected by both direct and in-direct lightning strokes.

A.1.4.2 Effects of Direct Lightning Strokes

It is standard nomenclature to name the point at which the lightning flash connects with the ground or structure as the “attachment point.” The attachment point for tanks will be at the highest vertical electric field regions which would include the tank rim, vents, hand rails, gauge poles, lights and other objects on the top of the shell or, for large diameter tanks, the fixed or floating roof itself. Lightning will not follow a single path down to ground. The stroke current will divide in proportion to the surge impedance of each available path. From the point of attachment, the current will flow as a sheet over all conducting paths. As the current spreads out over a large area, the surface charge is neutralized (see Figures A.3 a and A.3 b). Any discontinuities in the current paths may result in arcing across the gaps.

A.1.4.3 Effects of Indirect Lightning Strokes

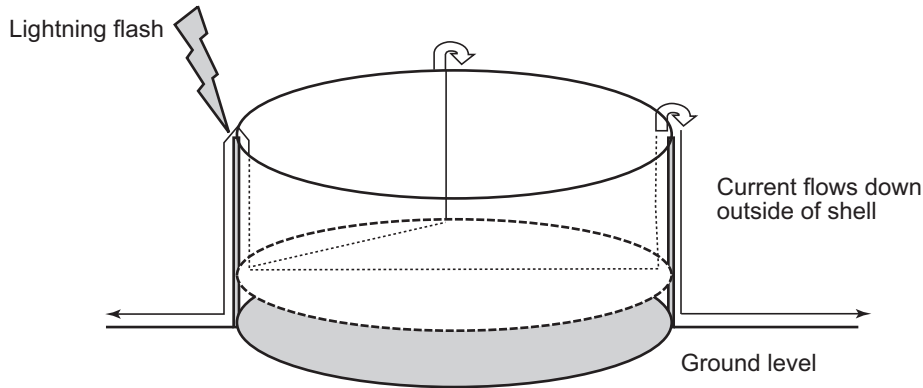
For a stroke adjacent to a tank, some current will flow over the outer skin of the shell across the fixed or floating roof and down to the ground on the other side of the shell (see Figure A.3 c). There would be much less energy in the discharge currents moving across the tank as compared to a tank directly struck. As with direct strokes, any discontinuities in the current paths may result in arcing across the gaps.

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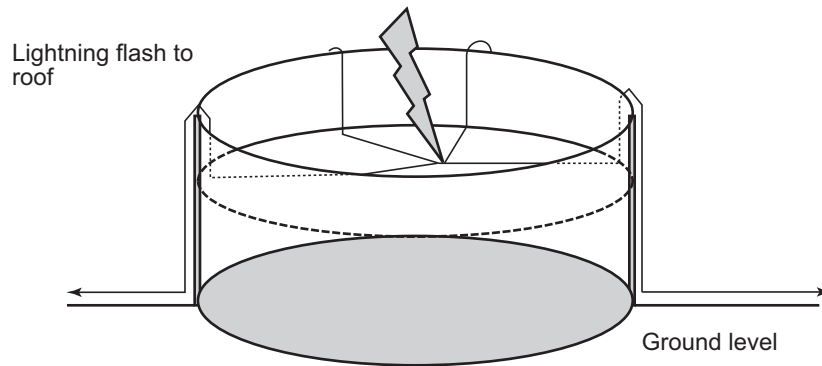
Table A.1—Lightning Parameters

| Number of Events ^a | Parameters | Unit | Percentage of Cases Exceeding Tabulated Value | | |
|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------|------------------|-----------------------------------------------|-------------------|-------------------|
| | | | 95 % | 50 % | 5 % |
| Peak current (minimum 2 kA) | | | | | |
| 101 | Negative first strokes | kA | 14 | 30 | 80 |
| 135 | Negative subsequent strokes | kA | 4.6 | 12 | 30 |
| 20 | Positive first strokes (no positive subsequent strokes recorded) | kA | 4.6 | 35 | 250 |
| Charge | | | | | |
| 93 | Negative first strokes | C | 1.1 | 5.2 | 24 |
| 122 | Negative subsequent strokes | C | 0.2 | 1.4 | 11 |
| 94 | Negative flashes | C | 1.3 | 7.5 | 40 |
| 26 | Positive flashes | C | 20 | 80 | 350 |
| Impulsive charge | | | | | |
| 90 | Negative first strokes | C | 1.1 | 4.5 | 20 |
| 117 | Negative subsequent strokes | C | 0.22 | 0.95 | 4.0 |
| 25 | Positive first strokes | C | 2.0 | 16 | 150 |
| Front duration (2 kA to peak) | | | | | |
| 89 | Negative first strokes | μs | 1.8 | 5.5 | 18 |
| 118 | Negative subsequent strokes | μs | 0.22 | 1.1 | 4.5 |
| 19 | Positive first strokes | μs | 3.5 | 22 | 200 |
| Maximum di/dt | | | | | |
| 92 | Negative first strokes | kA/μs | 5.5 | 12 | 32 |
| 122 | Negative subsequent strokes | kA/μs | 12 | 40 | 120 |
| 21 | Positive first strokes | kA/μs | 0.20 | 2.4 | 32 |
| Stroke duration (2 kA to half-value) | | | | | |
| 90 | Negative first strokes | μs | 30 | 75 | 200 |
| 115 | Negative subsequent strokes | μs | 6.5 | 32 | 140 |
| 16 | Positive first strokes | μs | 25 | 230 | 2000 |
| Integral (i^2dt) | | | | | |
| 91 | Negative first strokes | A ² s | 6.0×10^3 | 5.5×10^4 | 5.5×10^5 |
| 88 | Negative subsequent strokes | A ² s | 5.5×10^2 | 6.0×10^3 | 5.2×10^4 |
| 26 | Positive first strokes | A ² s | 2.5×10^4 | 6.5×10^3 | 1.5×10^7 |
| Time interval | | | | | |
| 133 | Between negative strokes | ms | 7 | 33 | 150 |
| Flash duration | | | | | |
| 94 | Negative (including single-stroke flashes) | ms | 0.15 | 13 | 1100 |
| 39 | Negative (excluding single-stroke flashes) | ms | 31 | 180 | 900 |
| 24 | Positive (only single flashes) | ms | 14 | 85 | 500 |
| ^a Number of events is actual sample size. | | | | | |
| (Uman, <i>The Lightning Discharge</i> , p. 124, Reprinted with permission from Martin A. Uman.) | | | | | |

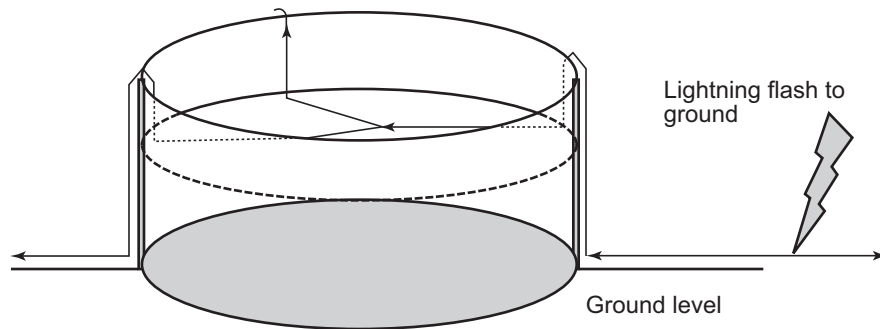
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a) Current routes for flash to top of shell. Note that the fast high current pulse flows down the inside of the shell and via the rim seals, and across the top of the floating roof. (Only two routes are shown; in practice, current flows all over the top of the roof and crosses the rim seal all around the perimeter of the roof.)



b) Current routes for flash to floating roof. Note that the fast high current pulse flows across the floating roof in all directions to the rim seals and shunts, and then up and over the shell to ground. (Only if the roof is high is this a likely strike point.)



c) Current routes for flash to ground near a floating roof tank. The current spreads all around from the strike attachment point, including to the tank, up and over the tank, and down the far side as shown by the typical current flow lines and arrows. This current flow plan would only apply to the fast high current pulse. The continuing current would flow along the ground and the tank floor only.

**Figure A.3—Current Routes for Flash to
a) Top of Shell, b) Floating Roof, c) Ground Near a Floating-roof Tank**

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A.1.5 Sparking

Sparking is the most likely cause of tank fires from lightning in external floating roof tanks (EFRTs) owing to the tendency for current from any stroke on the tank or closely nearby to drive the current across the floating roof, via the shunts or via any other metal making intentional or unintentional contact between the floating roof and the shell.

Thermal and air-gap sparks should be considered as follows.

- a) A thermal spark is defined as a minute piece of incandescent material which has been ejected from some sparking site, usually a place where tens or hundreds of amps or more are passing through a very poor joint, such as the contact point from a shunt on to the inner shell wall of an open floating roof tank, or from a poorly bolted flange joint, etc. The white-hot metal sparks falling from welding operation are examples of thermal sparks, which are actually very small particles of metal, burning as they fly through the air. Usually, they are less effective as incendiary sources than air-gap sparks.
- b) An air-gap spark occurs in a location with a small gap between conducting items where the lightning creates a voltage large enough to cause electrical breakdown of the air or vapor/air mixture in the gap.
- c) Air gap sparks with energy above 0.2 mJ are sufficient to ignite product vapor/air mixtures if they are within the flammable mixture range. For mixtures that are not optimum, the energy requirement is higher, however, the energy in lightning induced sparks is likely to be many orders of magnitude higher.

A poorly contacting rim-seal shunt on an EFRT is an example of where sparks might occur under lightning conditions. The small contact area and the presence of surface treatments or contaminants are conducive to sparking. If there is a nonconducting layer on the shell or the shunt, the spark will initially be an air-gap spark to break down the insulation, followed by current flow in a poorly contacting area resulting in thermal sparks.

A.2 Grounding

A.2.1 Flat-bottom tanks resting on the ground need not be grounded by the use of external grounding rods for the purpose of lightning protection. Grounding for other purposes is not addressed by this document.

A.2.2 The occurrences of incendiary sparks, rim-seal fires, etc., are not dependent on tank grounding resistance or tank dimensions. This is because the tank will inevitably have ground conductivity through its massive steel structure in contact with the ground. There will also be additional grounding through the many pipes and cables that connect to each tank. A tank is considered adequately grounded if the tank bottom is resting on the ground or foundation. This applies whether or not there is an elastomeric liner in or under the tank bottom.

A.2.3 There is no known occurrence of lightning induced fires around the base of tanks, or underneath tanks, which are the only places where inadequate grounding of the tank would result in sparking or other sources of ignition. The initial attachment process of a lightning stroke would be unaffected by tank ground resistance, since it will be sufficiently low to permit the lightning leader attachment process to occur, even if the resistance to ground of the tank were many tens of ohms. Lightning safety for tanks is not dependent on tank grounding.

A.2.4 Tank grounding associated with the power frequency supply should conform to local electrical codes.

A.3 Effect of Release Prevention Barrier Membrane on Grounding

Tank grounding is not an important contributing factor to the prevention of incendiary sparks or rim-seal fires, or explosions in tanks. A release prevention barrier would be expected to have the effect of reducing the conductivity between the tank floor and the ground. However, the existence or absence of a membrane is not relevant to the prevention of lightning induced fires or explosions.

⁶ The examples in Annex A are merely examples for illustration purposes only. [Each company should develop its own approach.] They are not to be considered exclusive or exhaustive in nature. API makes no warranties, express or implied for reliance on or any omissions from the information contained in this document. Users of instructions should not rely exclusively on the information contained in this document. Sound business, scientific, engineering, and safety judgment should be used in employing the information contained herein.

Annex B (informative)

Understanding Lightning Discharge and its Secondary Effects

Presence of Flammable Vapors

Ignition cannot occur unless flammable vapors are present together with an oxygen concentration that places those vapors within the flammable range. The Faraday Cage Effect serves to protect an internal floating roof from exposure. IFRTs have a good fire safety history, with four areas of fire vulnerability being:

- a) a landed floating roof (includes initial fill) exposes flammable vapors which are normally controlled by the floating roof;
- b) improper operating practices such as an overfill situation (includes filling to the point where floating-roofs seals are near the overflow vents) or storing product with a vapor pressure exceeding the limit and approaching atmospheric pressure (resulting in boiling) can expose flammable vapors normally contained by the seals;
- c) mechanical failure (failing seals, lack of buoyancy, and other damage to the floating deck) can expose vapors above the deck;
- d) improper venting, which is venting other than as required by API 650, Appendix H.

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Annex C **(informative)**

Different Seal Types

Primary seals may be mechanical shoe seals, liquid-mounted rim-seals, or vapor-mounted rim-seals. Secondary seals are vapor-mounted wipers mounted above any type of primary seal.

- 1) A mechanical shoe is a peripheral seal that utilizes a light-gauge metallic band as the sliding contact with the shell and a fabric seal to close the annular space between the metallic band and the rim of the floating roof deck. The band is typically formed as a series of sheets (shoes) that are overlapped or joined together to form a ring and held against the shell by a series of mechanical devices. Mini-shoe seals may be necessary for aluminum floating roofs.
- 2) A liquid-mounted rim-seal is a resilient foam-filled or liquid-filled primary rim-seal mounted in a position resulting in the bottom of the seal being normally in contact with the stored liquid surface. This seal may be a flexible foam (such as polyurethane foam in accordance with ASTM D3453) or liquid contained in a coated fabric envelope.
- 3) A vapor-mounted rim-seal is a peripheral seal positioned such that it does not normally contact the surface of the stored liquid. Vapor-mounted peripheral seals may include, but are not limited to, resilient-filled seals (similar in design to liquid-mounted rim-seals), and flexible-wiper seals. Flexible-wiper seal means a rim-seal utilizing a blade or tip of a flexible material (such as extruded rubber or synthetic rubber) with or without a reinforcing cloth or mesh.

The sources of these definitions and descriptions are from API 650.



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