Residential Lightning Fires in the USA: An Overview

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***Abstract*—Lightning ignites some 6,000 fires each year in residences in the USA, where very few are equipped with a lightning protection system. Many of these fires cause serious damage to or destruction of the structure and cause both injury and loss of life. Although the incidence of residential fires in the USA from all other causes has fallen dramatically over the past thirty years, lightning fires have increased in number. This paper presents an overview of the incidence of residential lightning fires in the USA from published sources of fire data and from the author's review of insurance claims. The likely causes of residential lightning fires are briefly discussed. It is concluded that these fires occur both from direct lightning strikes to the structure and from nearby indirect strikes. It is further suggested that lightning overvoltage damage to electrical power conductors and appliances is a major cause of residential fires. Additions to existing Codes of practice are recommended to address this problem.**

***Index Terms*—Electric breakdown, fires, grounding, insulation, lightning,**

I. Introduction

THE incidence of fires in residences in the United States, while significantly reduced over the past three decades, continues at a rate higher than in many other developed countries [1] [2] [3] This higher incidence is reflected in the rate of fires, property loss and fatalities [4](Fig. 1).

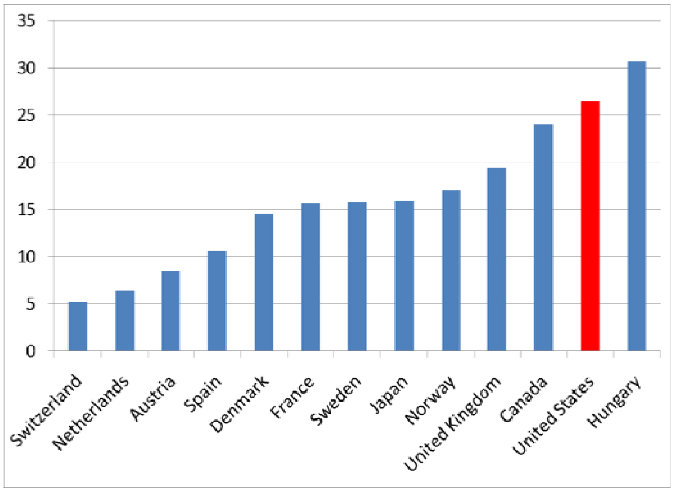

Fig. 1. Fire deaths per million population by country (1979-1992)

Residential fires comprise about 25% of all fires reported in the USA, but account for 56% of the dollar loss and over 75% of the deaths and injuries [5]. The recent reduction in fires has likely resulted from a combination of improvement to construction codes, greater fire education, the widespread adoption of smoke detectors, and, to a lesser extent, the installation of automatic sprinklers.

Unlike fires from other causes, which have shown a large drop over the past thirty years, lightning fires have continued to increase. They now represent approximately 1.5% to 2% of residential fires at an annual cost of more than $100 million. Residential lightning fires in the USA occur at rates five to ten times higher than in many European countries [2]. This may be attributed to a combination of the different construction methods as well as the higher incidence of lightning in most parts of the USA compared to Europe. Some European countries also are more likely to require lightning protection of residences, which is voluntary in the USA.

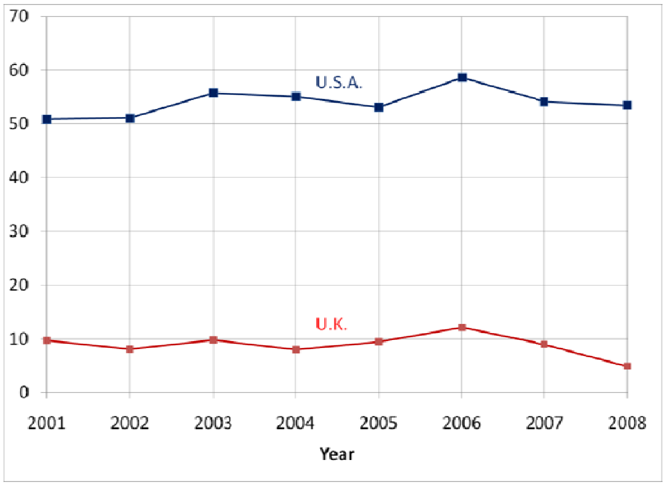

Fig. 2. Number of lightning fires in the USA and UK per million residences (2001-2008)

The paper examines data on residential fires from all causes and from lightning and considers the mechanisms by which lightning may ignite fires. Examination of these data shows that the commonly-held idea that lightning fires result mainly from ignition of the structure from the electrical energy of lightning may not be true [1]. It is suggested that a major cause of residential lightning fires in the USA is damage to electrical systems or appliances as a result of lightning overvoltages. Mitigation methods are briefly discussed.

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II. RESIDENTIAL FIRE DATA

Fire data in the USA are collected in two main ways. The first is the National Fire Incident Reporting System (NFIRS), which acquires standardized voluntary reports from fire departments across the country and is administered by the U.S Fire Administration under the auspices of the Federal Emergency Management Association. (FEMA). The second is an annual survey done by the non-government National Fire Protection Association (NFPA), using similar methodology, but a smaller representative sample. Published estimates for national fire statistics are based on NFIRS and NFPA data samples, using statistical methods to correct for sampling [6] [7] [8] [9] [10] [5] [11].

The incidence of annual residential fires for the period 1977 to 2009 is shown in Fig. 3 and the incidence of lightning fires for the period from 1980 to 2008 is shown in Fig. 4.

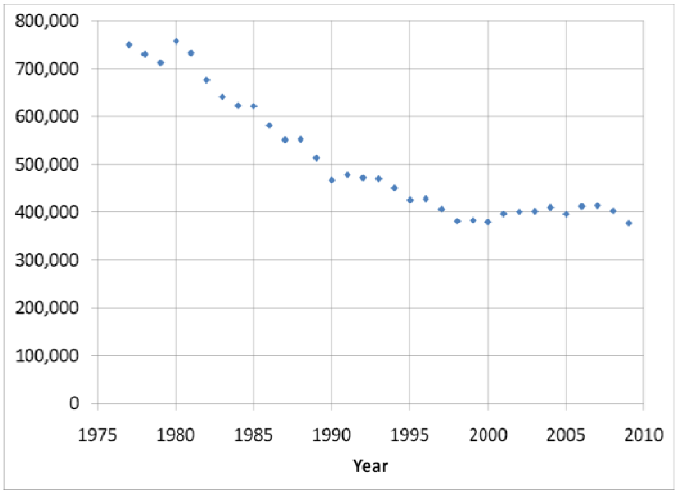

Fig. 3. Annual number of residential fires in the USA

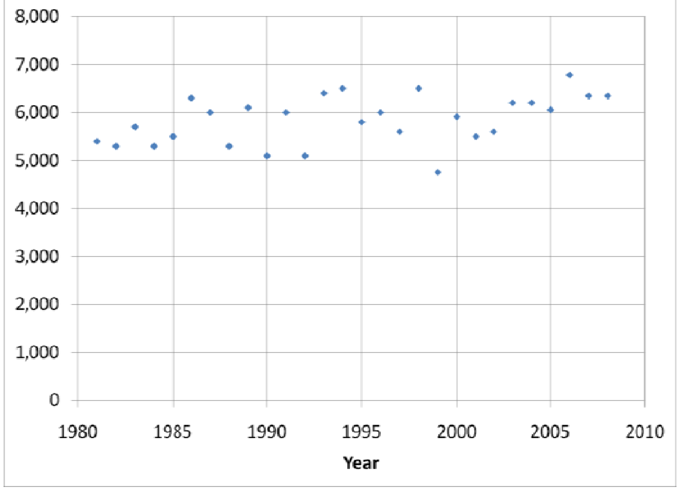

Fig. 4. Annual number of residential lightning fires in the USA

Fire data were also normalized on the basis of incidents per million residences. The number of residences for this normalization procedure was taken from the US Census Bureau data for all residences, excepting mobile homes. These show an increase in the number of residences from 82 million in 1980 to nearly 94 million in 1990 and to 107 million in 2000. The author estimates that the number of residences peaked in 2008 and is now constant at just below 120 million.

The normalized annual incidence of residential fires for 1997 to 2009 is shown in Fig. 5 and the normalized lightning fire incidence for the 1980 to 2008 is shown in Fig. 6. US residential fires incidence is approximately constant at a level of approximately 2,800 per million homes. This compares with a reported rate of about 2,500 in the UK.

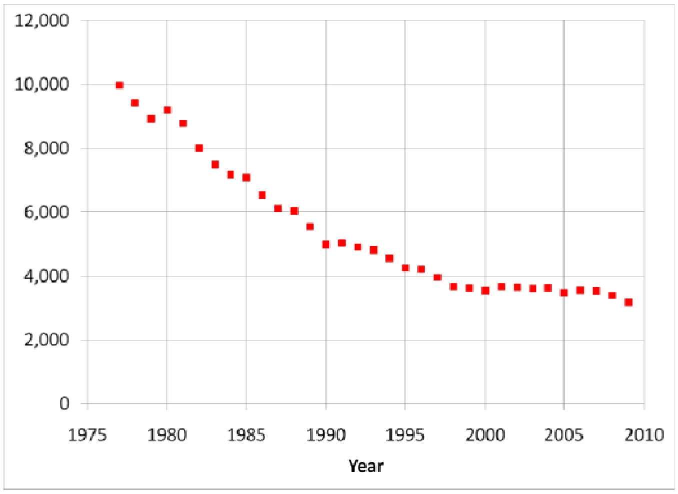

Fig. 5. Normalized annual number of residential fires in the USA

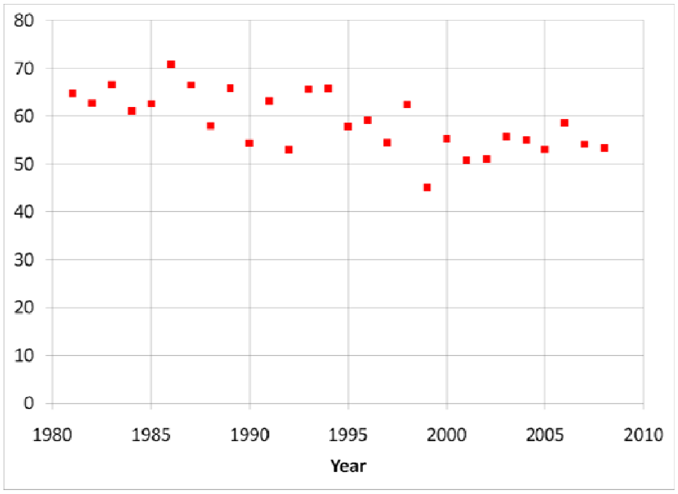

Fig. 6. Normalized annual number of residential lightning fires in the USA

The normalized data show a slight drop in annual residential lightning fire incidence from about 65 per million in the early 1980's to a low of around 50 in 2000 and a gradual rise in the past decade to a present-day level of around 55 per million. Lightning, however, represents a rapidly increasing fraction of residential fires (Fig. 7). At the start of the survey period, lightning caused approximately 0.7% of residential fires and this has more than doubled to a present-day level of 1.6%.

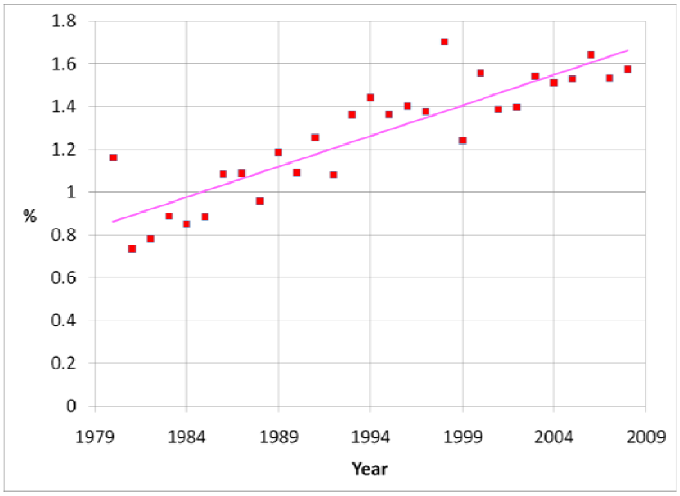

Fig. 7. Percentage of residential fires caused by lightning in the USA

III. DIRECT AND INDIRECT LIGHTNING STRIKES

A lightning discharge to ground consists of two main stages, the leader and return stroke. The leader stage is the process by which an electric discharge, usually heavily branched, progresses from the thundercloud towards the earth. As it approaches the earth, the charge carried on the various leader branches rapidly increases the electric field at the earth's surface, to the point that shorter upward discharges, or connecting leaders, are triggered from points on the earth. When one or more of these connecting leaders meets the downward leaders, the charge on the leaders rapidly travels into the earth, producing the high-current return stroke stage [12] [13].

Direct lightning strikes result when one or more strokes of a ground flash terminate on a structure, injecting both leader and return stroke currents into it.

Indirect lightning strikes result when one or more strokes of a ground flash terminate on the ground or another object close to the structure. Such indirect strikes will nevertheless inject currents into the building by mechanisms discussed below in Section V.

Lightning fires are reported to occur as the result of both direct and indirect lightning strikes.

IV. CAUSE OF IGNITION BY DIRECT LIGHTNING STRIKES

Ignition of flammable material by lightning requires that the lightning current pass through or close to the material and that the current has sufficient duration and energy transfer to initiate combustion. High current but short duration lightning strokes may not result in ignition, whereas lower current but longer duration events may do so [14].

Lightning flashes most often transport negative charge from cloud to earth, but the rarer positive flashes are characterized by higher return stroke currents, longer durations and the transfer of more electrical charge than negative flashes. Continuing current in negative flashes is generally associated with multi-stroke events having two or more strokes. Such negative lightning flashes consist of several successive leaders and return strokes, often (but not always) following the initial channel to earth. Some lightning flashes also have longer duration continuing currents that flow between the strokes of a multi-stroke flash or after the final stroke. These continuing currents are much lower amplitude than the return stroke, but because of their long duration can impart a significant charge transfer. Continuing current is characterized by low amplitude (100 amp magnitude) events having relatively long durations (hundreds of milliseconds). Such continuing currents are implicated in ignition of fires and increased likelihood of creating damage because of the larger energy transfer.

Leaders have average currents that are in the 1 to 1,000 amp range, while return strokes have been observed with peak currents between about 2 kA and 600 kA. The distribution of peak currents in lightning return strokes is approximately log-normal, with a median value of 30 to 40 kA for negative first strokes and 10 to 15 kA for subsequent negative strokes. Current waveforms have risetimes from 1 to 10 microseconds, with decay to half-value of from 50 to 500 microseconds.

The distribution of electrical current and energy in individual paths in unprotected structures struck by lightning is not known. It is reasonable to assume that the voltages involved are so large that flashover will occur between any service struck and any conductors that are reasonably close (from a few inches to a few feet). Lightning damage to electrical power systems, telephone, computer, low voltage control wiring and electrical power systems is common in buildings, suggesting that lightning current takes many paths to earth. Only a fraction of the current and energy will therefore flow on any individually affected conductors. Nevertheless, in direct strike events, sufficient current, voltage and energy is available to damage most services in unprotected buildings, including electricity supply conductors and equipment, telephone lines and equipment, TV service equipment and receivers, and gas supply lines and equipment [15].

V. CAUSE OF IGNITION BY INDIRECT LIGHTNING STRIKES

Although indirect lightning strikes are frequently blamed for damage to buildings or their contents, including the ignition of fires, there is no industry-standard definition of what constitutes an indirect strike event or how electrical charges are transferred in the absence of a direct strike to the structure. However, an indirect strike may generally be regarded as occurring through secondary effects of lightning when a lightning flash strikes the ground or another object nearby.

The three major ways that electrical current is injected into buildings by indirect lightning are:

1. The triggering of a non-connecting upward leader from the structure, particularly from antennas, chimneys and ungrounded metalwork.

2. The induction of electric currents and voltages onto conductors in the building due to electric and magnetic coupling from the nearby lightning channel [16] [17].

3. Entry into the building of lightning currents on the overhead or buried conductors of services (electric supply lines, cable TV, telephone lines or gas lines).

The first two of these indirect effects result in moderately high voltages on any metalwork involved, but relatively low current levels of short duration [13]. For example, voltages from both indirect effects may exceed several hundred thousand volts, quite sufficient to result in flashover between adjacent conductors that are not effectively electrically bonded together. However, the currents from such indirect effects rarely exceed a few hundred amps and duration of the current pulses is typically only several tens of microseconds, or even shorter. A non-connecting upward leader may be expected to carry a total electric charge of about 0.01 coulombs. The induced surge on a 10 m long conductor will be in the order of 10 to 100 amps with durations of from a few microseconds to no longer than 50 microseconds [12]. The electrical energy involved in both of these two indirect events is orders of magnitude too small to directly ignite flammable materials.

Indirect lightning events frequently cause tripped electrical circuit breakers on the power systems of the residence, This is indicative of the flow of fault current that is likely caused by lightning-induced overvoltages. Ignition of fire from indirect lightning events seems most likely to be the result of damage to electrical supply systems caused by flashover between energized conductors or between conductors and grounded metalwork. The latter includes water and gas pipes, and the chassis of equipment, such as TVs, water heaters and air handlers. Such flashover results in the flow of electrical power system fault currents that can provide sufficient energy to ignite flammable materials if these lie in the flashover path. Interruption of fault currents by automatic circuit breakers may not be fast enough to interrupt these currents, especially when a high-resistance path is involved. Damage to gas piping systems from electrical fault currents has also been reported [18]. Lack of a low-resistance connection between a gas pipe and the power-system ground will hinder the operation of circuit breakers and protective devices and may result in the flow of low magnitude long duration fault current. Failure of joints in rigid gas piping, to gas valves in appliances and arc damage to thin-walled gas pipes are the occasional result of these events.

The third indirect effect may generally be discounted if all services entering a building are electrically bonded to the building and electric service ground. In the USA, the National Electrical Codes (NFPA 70 and 70A) require such bonding for all incoming metallic conductors with the exception of gas pipes. In the absence of such bonding, significant transient electrical currents may enter the building on all unprotected services. These may include overhead and buried electrical, telephone and other service conductors and buried gas pipes. The most common problem arising from the entry of lightning currents on such service conductors is transient overvoltage damage to electrical systems, which may lead to fire as described above. It should be emphasized that, although metallic water pipes entering a residence are required to be electrically bonded to the power system ground, metallic gas pipes which enter the building and are similarly distributed throughout it are not required to be bonded.

VI. MATERIAL IGNITED IN LIGHTNING FIRES

In addition to the publicly-available data, the author has reviewed data on fire insurance claims from several lightning-prone areas of the U.S.A. Perhaps surprisingly, a large number of direct strikes to residences caused little damage.

Examination of lightning claims that resulted in severe damage, which, for the purposes of this study, was defined as losses over $10,000, showed that about 25% involved structural damage without fire. Detailed analysis of the 75% severe losses that involved fire was also carried out by the author, using all reports that were made available as part of the insurance claims.

NFIRS reports that the majority (75%) of lightning fires are caused by direct ignition of structural materials (roofing, cladding, siding and framing), with the second largest cause (20%) being damage to electrical systems, with damage to gas systems resulting in about 5% of fires. The author's smaller survey from insurance claims identified 76 lightning fires, of which 41 (54%) were identified as likely resulting from electrical damage, 29 (38%) were identified as direct ignition of structure and 6 (8%) were attributed to damage to gas piping or appliances. From this analysis, the author concludes that NFIRS reports likely underestimate the fraction of electrical fires that result from lightning strikes and that these could comprise as much as half of the incidents. This suggestion is supported by a recent report on residential attic fires, which finds that, although the material first ignited closely mirrors that in lightning strikes, the primary cause is electrical faults including arcing. It is likely that electrical faults ignite structural materials without the original cause being easily identified. Melting of electrical insulation during fires, resulting in arcing of the conductors, is a widespread occurrence. The fire itself frequently damages wiring and appliances to such an extent that determining whether or not the electrical damage preceded the fire or resulted from it is not straightforward.

Where investigations of lightning fire are carried out, determination of whether or not the structure was directly struck is also not always easy. In events where a lightning strike carrying substantial current and energy terminates on a metallic object, localized melting of the metal may be good evidence of a strike. The author is aware of a significant number of direct strike incidents where lightning terminated on ungrounded roof penetrations. These include antennas, chimney flues and caps, and vent pipes from plumbing systems and gas heaters. Of these metallic roof penetrations, only antennas are required to be grounded and bonded under the current U.S. National Electrical Codes (NFPA 70 and 70A). However, such grounding is often neglected, especially in installations done by the home owner.

VII. DISCUSSION

The fire data show that there was a dramatic drop in the overall number of residential fires over the past thirty years. This is especially notable when viewed in normalized format; annual fires from all causes dropped from 10,000 down to 3,000 per million residences over this period. This improvement in fire safety is largely attributed to a combination of improved codes of practice for building construction and the installation of services, widespread adoption of smoke detectors and enhanced public safety education.

On the other hand, residential fires ignited by lightning increased during the same period. The increase was modest and, when normalized to take account of the increase in number of residences, the incidence of lightning fires showed a modest drop from around 65 per million residences in 1980 to 50 in 2000. The past decade has seen a slight increase in residential lightning fire incidence to 55 per million residences.

The data suggest that the changes that succeeded in dramatically reducing fires in residences over the past three decades had little effect on fires ignited by lightning.

VIII. MITIGATION OF RESIDENTIAL LIGHTNING FIRES

There are a number of methods of reducing the incidence of residential lightning fires. The installation of a lightning protection system would seem an obvious solution. However, the large majority of residences (>95%) in the USA are not equipped with lightning protection systems. Application of the applicable code (NFPA 780) is voluntary and rarely invoked, leaving the majority of structures unprotected. These unprotected residences often have vulnerable ungrounded metallic roof penetrations, such as chimney flues and vents that act as a conduit for these lightning currents. In these buildings, direct lightning strikes and the more severe indirect strikes may cause damage, especially to electrical conductors and, less frequently, gas lines [19].

Grounding and bonding of these vulnerable conductors is not required by the National Electrical Code (NFPA 70) or the equivalent code for residences (NFPA 70A). NFPA Committees have ruled that these National Electrical Codes are intended to provide guidance on electrical safety and not to address lightning protection issues. These codes therefore have no requirements for bonding or grounding ungrounded metallic roof penetrations or gas piping systems.

The evidence suggests that a significant fraction of lightning fires, possibly the majority, result from electrical faults. The circuit breakers designed to interrupt these faults may not do so sufficiently quickly to avoid ignition where the fault occurs through flammable material. Electrical faults that occur through a high-resistance path, for example to unbonded metalwork or pipes, may be particularly prone to start fires. One example of this is the lightning-caused insulation failure of TVs having an ungrounded chassis and double-insulated power supplies. Such failures result in the flow of fault current from the chassis to any connected TV signal cable, which is not designed or intended to carry such currents. The electrical codes of some countries mandate ground-fault leakage relays that do appear effective in minimizing at least some of these fires, especially those involving high-resistance paths that would otherwise not trip a conventional breaker.

The author is also surprised that there is no requirement for the grounding and bonding of gas systems in the US National Electrical Code, except where these are connected to equipment that also has electrical power. The absence of such bonding results in the development of high voltages and arcing when power fault and lightning currents flow on gas pipes in residences. Lack of a low-resistance connection between a gas pipe and the power-system ground will hinder the operation of circuit breakers and protective devices and may result in the flow of low magnitude long duration fault current. Failure of joints in rigid gas piping, to gas valves in appliances and arc damage to thin-walled gas pipes are the occasional result of these events.

IX. CONCLUSIONS

Lightning fires ignited by direct lightning strikes to the structure may be substantially eliminated by the installation of a properly designed and installed lightning protection system. Since these are installed on few residences in the USA, lightning fires from direct strikes will continue to occur at an increasing rate. However, structures equipped with a lightning protection system will still experience some indirect lightning effects.

The electrical energy entering residences from indirect strikes is insufficient to directly ignite fires. The evidence points to the majority of fires triggered by indirect lightning to be the result of damage to the electrical power system in the residence. Damage to other services, such as water and gas lines, is likely the result of the electrical fault currents and not caused by the indirect lightning energy itself.

Mitigation of damage from both direct and indirect lightning strikes may be achieved by a number of techniques, including:

1. Grounding and bonding of metallic roof penetrations, such as vents and chimney flues
2. Equipotential bonding of all services close to the entry point in the building (including gas lines)
3. Use of ground-fault leakage relays on equipment that may provide other paths for fault current.

It is strongly recommended that the appropriate US Code Committees address the gap in grounding and bonding by ensuring that both:

1. Residences exposed to and vulnerable to lightning damage are provided with at least a minimal lightning protection system.
2. Equipotential bonding is applied to all metallic services entering or leaving a structure.

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