Fire Safety of Grounded Corrugating Stainless Steel Tubing in a Structure Energized by Lightning

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Authors:

Bryan Haslam
Massachusetts Institute of Technology
77 Massachusetts Ave
Cambridge MA 02139
bhaslam@mit.edu
858-717-6279

Donald Galler
Massachusetts Institute of Technology
77 Massachusetts Ave
Cambridge MA 02139

Thomas W. Eagar
Massachusetts Institute of Technology
77 Massachusetts Ave
Cambridge MA 02139

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Abstract Corrugated Stainless Steel Tubing (CSST) has been used for more than 20 years as a replacement for conventional black iron gas piping. CSST has a thinner tubing wall and is susceptible to damage from lightning activity when discharges enter a structure, potentially resulting in perforation of the CSST wall and fire ignition. Grounding has been promoted by CSST manufacturers as a solution to this problem. We use modeling and simulation of voltage potentials and arc currents to evaluate the effects of grounding on the voltage potential across CSST, which can result in arc initiation, and charge through the arc, which can result in melting and perforation of the CSST wall. Our results show multiple scenarios where a 10kA 10x350 μs current waveform with 1 Ω grounding of the CSST still results in voltages greater than the arc initiation threshold of 25kV and charge through the arc greater than 1.2 C, the perforation threshold we measured. For the case where lightning enters the structure through an outdoor light fixture or chimney, the presence of a grounding wire increases the charge through the arc from 0.13 C to 2.22 C. These results indicate that good grounding of CSST will not necessarily prevent arc initiation nor perforation of the CSST wall by lightning. Good grounding may in fact exacerbate the problem of lightning damage to CSST depending on where lightning enters the building and the electrical parameters of the path to ground.

Keywords Lightning · Corrugated stainless steel tubing · Ignition · Gas piping

1 Introduction

Corrugated Stainless Steel Tubing (CSST) is a semi-flexible gas tubing that received ANSI LC1 approval in January 1991 [1]. It is favored over traditional black iron pipe because it reduces installation time and requires fewer fittings. However, the thickness of CSST is approximately 0.25 mm compared to black iron pipe with a thickness of approximately 2.5 mm. The thinner wall makes CSST more susceptible to perforation when assaulted by lightning [2]. Over the past decade there has been concern over the fire safety of CSST when exposed to lightning. Some local fire marshals have banned the use of CSST in their jurisdictions. By 2005 manufacturers began to market a black plastic jacketed CSST product to improve the lightning perforation resistance over the yellow jacketed CSST product [3], though field failures have continued. A further enhancement was then produced using a perforated aluminum sheet underneath the black jacket. Penetration capability is measured in Coulombs of charge and Figure 1 shows the three types of CSST and their Coulomb ratings.

In 2006 manufacturers added an installation requirement to connect CSST to the electrical ground system with a single bond wire where the gas piping enters the structure, in an effort to prevent damage from lightning. In 2009, this grounding or bonding requirement was adopted into the National Fire Protection Association (NFPA) 54 Fuel Gas code [4, 5]. There continued to be damage from lightning and some researchers believe grounding only to be effective if it occurs every 20 ft [2]. The NFPA Standards Division Council issued decision D#10-2 on 3 March 2010 to obtain more information concerning bonding of the CSST with respect to assault by lightning. With grounding still thought to be the best way to prevent damage to CSST from lightning, the National Association of State Fire Marshals launched the CSST Safety Campaign in 2012 to encourage the use of grounding [6]. The United States Senate passed a resolution commending the NASFM for the campaign [7]. It was cited that at least 6,000,000 homes have a combined

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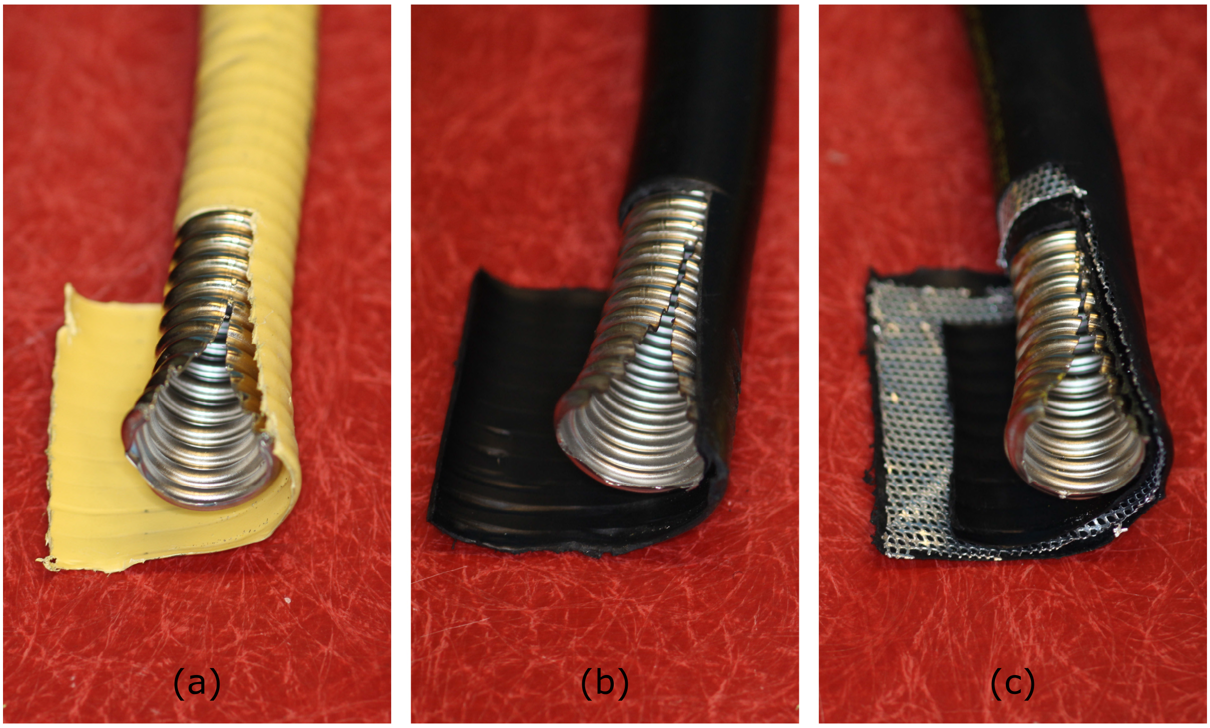

Fig. 1: Three types of CSST products with varying Coulomb ratings: (a) 0.12 C. (b) 6.0 C. (c) 80 C.

total of more than 1,000,000,000 ft of yellow CSST installed. It is still believed widely that the best way to protect those 6,000,000 homes is with grounding and that black CSST needs no protection.

In response to concerns about grounding, the manufacturers of CSST commissioned simulated lightning testing. The testing results released in 2013 reported that bonding prevents initiation of arcs and prevents arcs from melting holes in CSST [8, 9]. Only simplified lightning voltages and currents were possible with the limited voltage and current available from the waveform generators, so electrical circuit simulations were used to extend the conclusions of the manufacturer's tests to practical installations.

In this paper we replicate the simulations from the cited reports and obtain the same resulting values in order to validate our methodology. We then challenge several of the assumptions used in the reports [8, 9] and modify the simulations to include a wider range of likely parameter values and test scenarios. From these expanded simulations, we do not find that grounding with a single bond wire will resolve the problem of perforation of the CSST by lightning. In particular, while more bonding and grounding is often beneficial, in some cases excellent grounding of the CSST within the structure can attract an arc to the CSST since the CSST is the most favorable path to ground once lightning enters the structure. Our results indicate that good grounding of CSST will not necessarily prevent perforation of the CSST by lightning; good grounding may exacerbate the problem of lightning damage to CSST depending on where lightning enters the building.

In the next section we present an overview of the basic physics of electricity and lightning to illustrate the rationale for our simulations. We then describe our simulations for analyzing arc initiation and perforation of the CSST by melting. We conclude discussing the parameters we found most influential in causing damage.

2 Mechanisms Involved in Lightning-Induced Ignition of Gas from CSST

2.1 Lightning Strike

A lightning strike is an electrical discharge between a cloud and the earth. Positive and negative charges separate and accumulate in the cloud. Negative or positive charge may accumulate on the ground. When the potential difference between part of the the cloud and the ground becomes sufficiently large the air breaks down and charge moves. Roughly 90% of cloud to ground flashes transfer negative charge to ground [10].

The negative charge leader is met by an upward positive leader a few hundred meters above the ground. A plasma channel is formed allowing for rapid transfer of charge along the channel.

2.2 Lightning Parameters

Three parameters useful in determining damage from lightning are peak current, maximum rate of change of current and charge transferred [10]. The peak current (i_{max}) is the highest transient value of the current. This is the maximum rate of change of charge (measured in Coulombs/second or equivalently Amps) flowing through a material at an instant in time. The maximum rate of change of current ($(di/dt)_{max}$) measures how quickly the current changes. Charge is the integral of current over time. Damage from lightning to metals occurs from the heat generated when electrical energy passes through the conductor. If the heat is generated more quickly than it can be dissipated, melting can occur. Lightning events take place on such a short time scale, heat cannot significantly dissipate and therefore total charge transferred (measured in Coulombs) is the most useful predictor of melting.

Many researchers have attempted to quantify these and other parameters of lightning. In 1980, the International Electrotechnical Commission began working on parameters for lightning protection standards. Their work was mainly based on measurements published a few years earlier by Berger and colleagues [11, 12]. IEC published standard 62305 “Protection Against Lightning” outlining possible simulation waveforms and parameters for different applications. Table 1 shows the electrical current parameters of interest for the first stroke and subsequent strokes within a lightning strike [13, 14]. All of the values are for lightning protection level (LPL) I, which is the highest rating [14]. Much of this work is more than three decades old [15].

Table 1: Lightning Parameters from IEC 62305 [14].

Current parameter	Suggested values
Maximum current	200 kA
Average di/dt	200 kA/μs
Total charge	300 C

A more recent study from 2013 has somewhat modified values as shown in Table 2 [16]. Another study from 2013 challenged some of the traditional parameters used. For example, they estimated that more than 80% of negative cloud-to-ground lightning flashes are composed of two or more strokes with the average being 3-5 strokes [17]. They also found that even though the first stroke has 2 to 3 times the peak current on average, about 1/3 of flashes have at least one subsequent stroke that exceeds the peak current of the first stroke. More flashes with more current results in more total charge. The data indicate that max current, max di/dt and total charge are higher than previously thought.

Table 2: Recent parameters for the top 1% of measured lightning strikes [16].

Current parameter	Measured Values
Maximum current	500 kA
Maximum di/dt	400 kA/μs
Total charge	700 C

2.3 Lightning Current Entering a Structure

Lightning is sometimes classified into direct and indirect strikes. A direct strike is one where the current enters the structure directly from the atmosphere. The definition of an indirect strike varies, so for the purposes of this paper, an indirect strike encompasses any other way current could enter a structure, which could happen through electromagnetic induction, electrostatic induction or current on a conductor that enters the structure. These are illustrated in Figure 2.

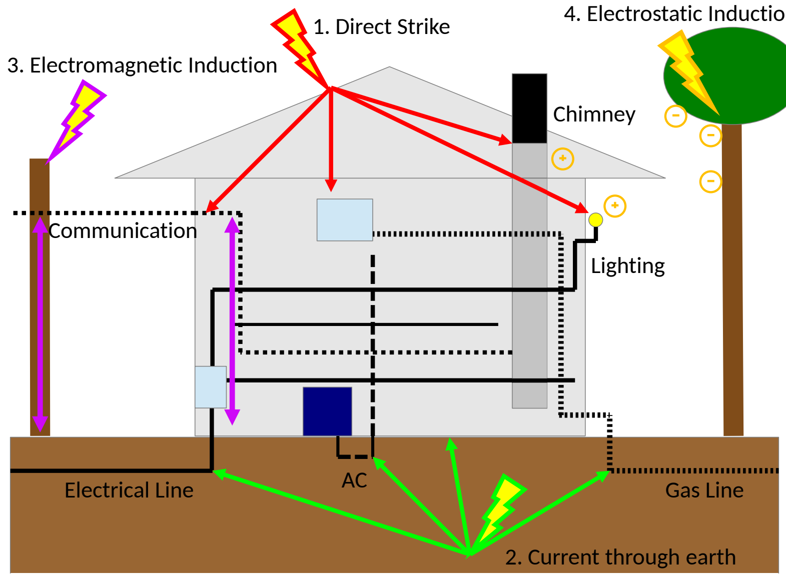

Fig. 2: Four ways lightning can affect structure conductors. Black lines are possible discharge paths.

2.3.1 Direct Strike

A direct strike is when the plasma channel is established between the structure (or conductors within it) and the downward leader from the thunderstorm overhead. This is case 1 of the figure. The voltage can be approximately 100 MV and the current according to the parameters presented in Table 2. Black iron pipe is thick enough to resist even the strongest of these electrical currents. The most effective way to protect a structure from lightning is with a lightning protection system [15].

2.3.2 Current through earth

Lightning can strike nearby a structure and electrical current can run through the ground or through conductors above or below ground. Such conductors could be a telephone line, power line or a gas line. Lightning may travel 100-200 meters through high resistivity soil, but much longer distances through a conductor [18]. The magnitude of the current will likely be smaller than in the direct strike case, but the frequency may be similar. Step voltage is a specific term describing the voltage gradient caused when current travels through the ground. Fisher & Schnetzer measured this to be 2 kV/m at 20 meters away and 4 kV/m at 10 meters away from a triggered lightning event with a current of 15 kA [19]. These voltage gradients can drive current through a conductor, which is the reason people or farm animals with their feet apart are electrocuted when lightning strikes the ground nearby.

2.3.3 Electromagnetic Induction

Lightning current does not have to enter a conductor directly to induce voltage on a conductor. The high frequency nature of lightning current can induce a current on nearby conductors. For example, lightning could strike a tree nearby a structure or a drain pipe connected to the house and the current running down the tree or pipe could result in a voltage on parallel conductors inside the structure. The same thing could happen for two parallel conductors once current is inside a structure. The induced electric field is proportional to the rate of change of current and falls off the further from the location of the changing current [18].

2.3.4 Electrostatic Induction

A lightning strike is a massive electrostatic discharge, meaning there is a build up in charge difference between the ground and the cloud it comes from. The charge moves from the cloud to the ground resulting in a large voltage (approximately 100MV) between the tip of the leader and the ground. The electric field induced by this charge could be very large but may be a short horizontal distance from the lightning leader. Fisher & Schnetzer measured a vertical gradient of 100-150 kV/m at 10 meters away from where lightning was triggered [19]. Current will flow along a conductor in such a gradient and will be more pronounced if the conductor is grounded. It is also possible that lightning strikes an object such as a tall tree and charge builds up on the tree, resulting in another discharge from the object to a conductor such as the light on the side of a house. Current would then flow directly into the house.

2.4 Current Flow within a Structure

Current flow through conductors within a structure will depend on the relative impedances of the conductors. It is important to include inductance and resistance because the high frequency nature of lightning can make the inductive component of impedance significant relative to the resistive component. A current divider occurs when a single conductor branches into two paths (represented by Z_1 and Z_2), with the amount of current in one branch given by

$$i_1 = \frac{Z_2}{Z_1 + Z_2} i_{in} \tag{1}$$

where i is the current and Z is the impedance. How much current goes through CSST then depends on how much current enters the structure and the relative impedances of the conductors. It is important to include the earth grounding impedances or the effective impedance from a conductor to the earth in this analysis.

2.5 Arc Initiation

An arc is initiated by a very high voltage which decomposes air into a plasma allowing electrons to flow easily. The energy which damages CSST focuses the charge into a small area. Such an arc can form between CSST and another conductor if there is a large voltage between them. Such a voltage will occur from voltage gradients or from current flowing through a conductor with resistance and inductance, having a maximum voltage according to the following equation

$$V_{max} = i_{max} \cdot R + (di/dt)_{max} \cdot L \tag{2}$$

where i is the current through a conductor with resistance R and inductance L. This provides a theoretical maximum voltage since it is not possible for the i_{max} and $(di/dt)_{max}$ to occur at the same point in time.

Arc initiation depends on the breakdown voltage of the dielectric between two conductors. In the case of CSST the dielectric is the polyethylene jacket as well as air. The dielectric breakdown voltage of air is well documented, but the breakdown voltage of the jacket is less well defined. Tests of the jacket in mineral oil suggest the breakdown voltage to be around 25-30 kV [8].

2.6 Melting and Ignition

The voltage of a sustained arc is approximately 10 V plus 10 V per cm of arc length, while the current is not limited by the arc, but by the external circuit. An enormous amount of current (hundreds of thousands of Amperes) can then flow through the arc. Stainless steel melts in the temperature range 1325-1510 C [20]. The temperature of metal caused by an arc depends on (1) the amount of energy transferred, (2) time interval, (3) heat conduction of solid and (4) thickness of solid[21].

The anode voltage in an arc remains relatively constant at 5 to 10 V. Therefore $P \propto i$ and $Energy \propto \int idt = Q$ where Q is charge. We use the charge transferred through the arc as a proxy for energy since voltage is relatively constant. The time interval can be important because heat will flow away from the arc site over time, but with time on the order of microseconds and the thermal conduction of stainless steel, there is insufficient time for a significant amount of heat to flow away from the arc site. The material properties of CSST, namely the thickness and heat conduction, are relatively uniform. Given bare stainless steel, charge transfer is the important variable between lightning strikes that will determine if a perforation occurs by melting.

Interestingly, the dieletric jacket around the CSST lowers the charge necessary to melt a hole. Hagenguth [22] showed that the size of holes in metal caused by lightning was proportional to the charge transferred, so smaller holes required less charge. It has also been shown that arcs to aircraft with painted panels have more concentrated arcs with higher temperatures than unpainted panels because the non-uniform thickness of the paint acts as an insulator [23, 24]. Thus an insulator can act to focus the arc to a location of lower dielectric strength (such as a void in the jacket), requiring less charge to melt a hole. We conducted our own testing at Lightning Technologies Inc in Pittsfield, MA and found that CSST without a jacket required 10 Coulombs to melt a hole, while CSST with a pinprick in the jacket required only 1.2 Coulombs to melt a hole [25]. We therefore conclude that melting depends on charge and the size of the hole in the CSST dielectric jacket. It is highly likely that during manufacturing, shipping or installation, small holes are introduced into the CSST jacket.

Once a hole is melted in the CSST wall, gas can escape from the pipe and ignite. To confirm this, we used an electrical arc to melt a hole in CSST filled with gas and observed ignition and sustained burning of the gas. Using high speed video at 960 frames per second we recorded the ignition and observed spatter leaving igniting at the site of the arc followed by ignition of the leaking gas. Figure 3 shows frames from the high speed video demonstrating ignition and burning of the gas escaping from the CSST. Similar testing at Lightning Technologies Inc also showed ignition of gas leaking from CSST and agrees with field experience.

3 Simulation Scenarios

Arc initiation depends on voltage and melting depends on charge transferred through the arc. Voltage and current/charge in turn depend on how strong the lightning current is, where it enters the structure and the configuration of conductors in and around the structure. There are many conductors in a structure such as power and communication wiring, HVAC equipment and ducts, appliances, gas tubing, plumbing pipes and fixtures, satellites and antennas, hardware such as nails and braces, chimneys, railing and more. Many of these are connected and there is no standard configuration, resulting in numerous possible scenarios. We choose two configurations from previous reports for the purpose of comparison [8, 9]. We expand these scenarios to include different locations the lightning current will enter the structure and vary the parameters to include a broad range that could be encountered in practice.

Configuration A shown in Figure 4 is the original scenario in [8] with some additions to include other possible locations lightning could enter the structure. In addition to the CSST, there are two other conductors in the structure modeled - one that is grounded, electrical wiring, and one that is ungrounded, a chimney. These could represent any grounded and ungrounded conductors. There are five locations lightning could enter the house: the gas line, the electrical line, the ground rod, the outdoor light fixture and the chimney. A bonding wire is shown with a dashed line connecting the CSST where it enters the house with a grounding rod at another location. Simulations were conducted with and without the bond wire to determine how bonding affects initiation and melting.

Configuration A has an electrical line which enters the house at the electrical meter (left) and distributes electricity to the house with one such wire shown in blue. The electrical line has a grounding rod. The gas line enters the house at the gas meter (right) and distributes gas through CSST, one branch of which is shown in yellow. An ungrounded conductor, a metal chimney, is also shown which passes close to the electrical wire and the CSST. Numbered are some locations where lightning current could enter the house.

Configuration B shown in Figure 5 is taken from [9] with the addition of an ungrounded conductor, namely the chimney. This scenario is different from Configuration A in that the CSST is connected to an appliance that is grounded at the opposite end of the structure where the lightning current entered. There are also additional HVAC equipment and ducts. Details of the components are (a) 100 CSST 3/4 (b) 75 AWG #6 wire (c) 100 AC Power Line AWG #14, (d) 20 AC Power Line AWG #12, (e) 30 Refrigerant Line Cu 1/4 (f) Grounded Object (g) Grounded HVAC Equipment. In this scenario, lightning current could enter in the same ways as found in Figure 4 with the addition of the flue on the roof and the compressor on the side of the house. These electrical entrances are similar to the outdoor light fixture in configuration A, except that they are closer to the grounding rod. The effects of a bonding wire are again tested by simulating with and without the bond wire present.

In these scenarios, the lightning strike could be direct or indirect. A direct strike could enter from above through the chimney, flue, compressor or outdoor light. An indirect strike could also enter through these locations as in the case of a nearby strike to a raised structure such as a tree, another house or a telephone pole that then jumps to one of these conductors. It is also possible that a streamer off of the main lightning channel could connect to one of these conductors. At the base of the house, lightning current could enter by

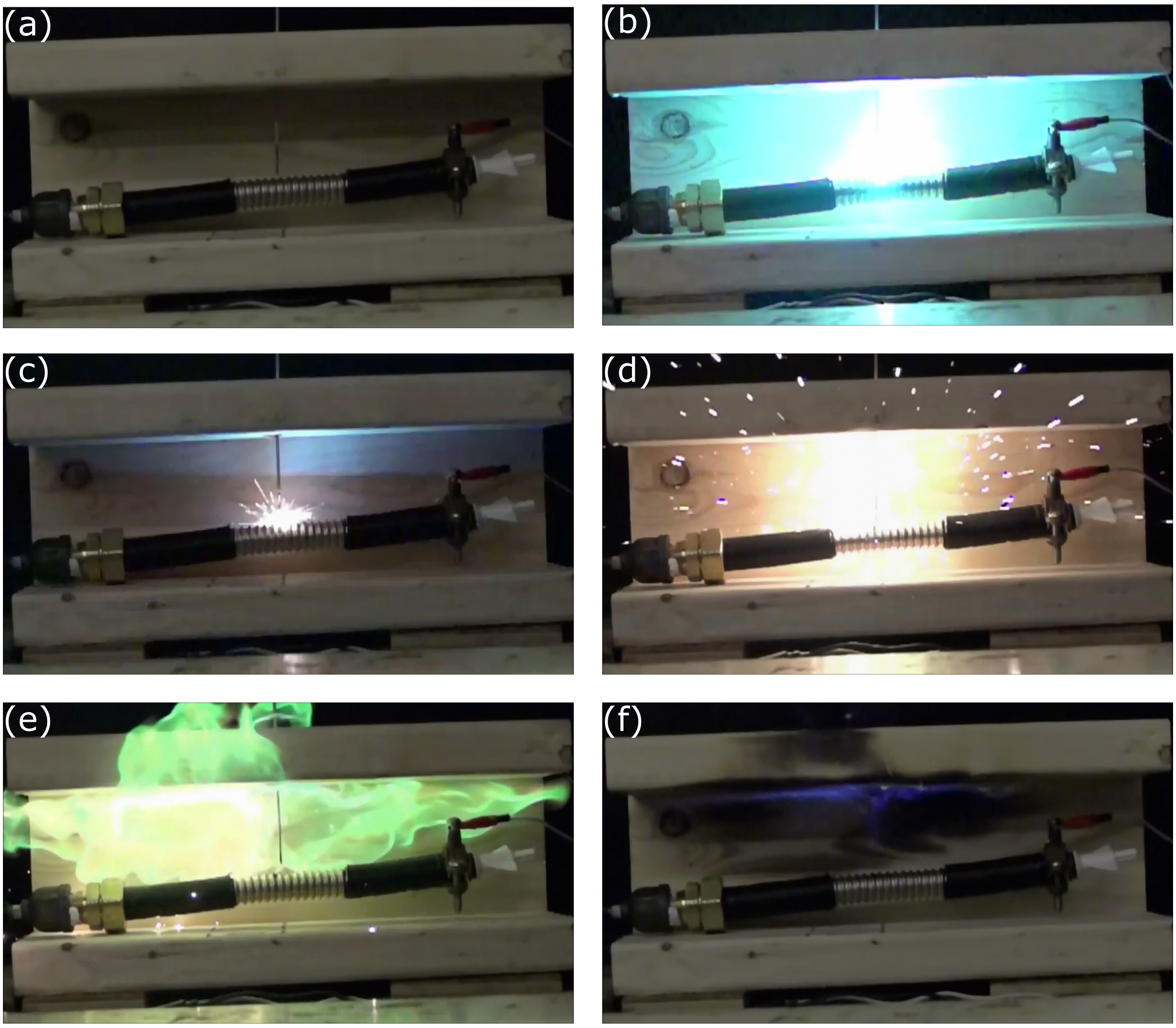

Fig. 3: Ignition of gas escaping from a hole in CSST caused by an electrical arc. Images are frames from a high speed video taken at 960 frames per second. The sequence shows (a) an electrode close the CSST immediately before arcing (b) flash produced by the arc before ignition (c) spatter flying away from the arc site (d) spatter flying further away from the arc site (e) ignition of the gas with hole visible (f) sustained burning with damage to wood.

striking the ground nearby and entering one of the buried conductors or striking farther away and traveling through the electrical or gas lines.

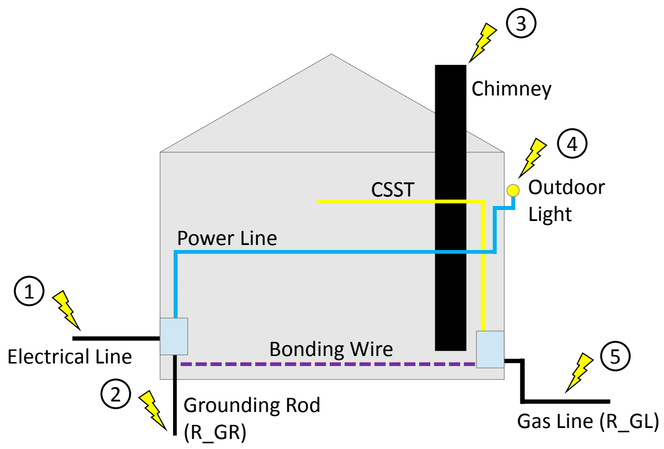

Fig. 4: Configuration A - diagram of a house with basic electrical and gas equipment. Lightning may enter the house by energizing the conductors at any of the five numbered locations.

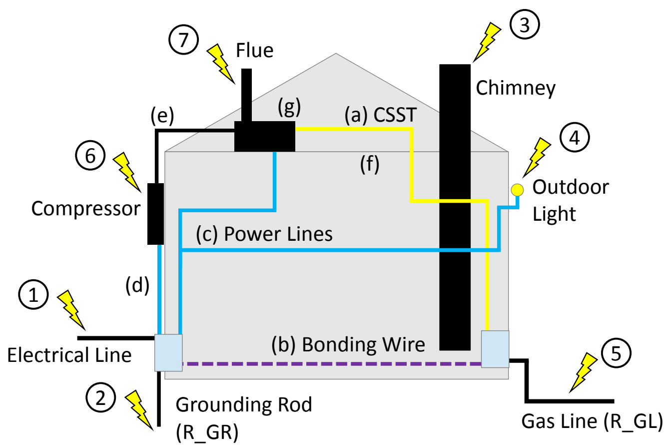

Fig. 5: Configuration B - diagram of a house with basic electrical, gas and HVAC equipment. Lightning may energize the conductors at any of the seven numbered locations.

4 Simulation Setup

We simulated the configurations in Figures 4 and 5 using Multisim (National Instruments) and LTSpice (Linear Technology Corporation) software.

A lumped element circuit model is used to model complicated electromagnetic effects. The circuits follow those in [8] and [9] for comparison. Lightning current is modeled as a current generator, with conductors and earth ground modeled as resistors and inductors. Capacitance of conductors was not modelled. The lumped element circuit model does not capture electromagnetic field effects such as mutual inductance. The model does not consider the detail of positive vs. negative lightning strikes, but could be expanded to include these variations. The circuit diagrams can be found in Figure 6 and 7.

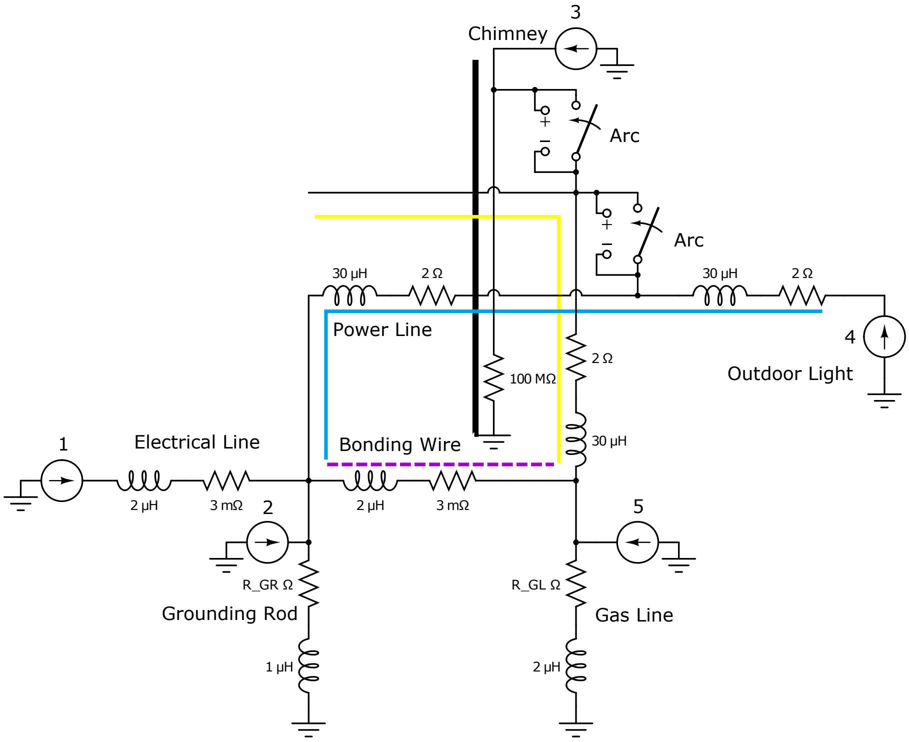

Fig. 6: Circuit diagram corresponding to configuration A. Conductors are modeled with resistors and inductors and lightning current is modelled as a current source. Though all sources are depicted together, only one source is used in each simulation. The values of R_GR and R_GL are varied in different simulations between 1 and 100 Ω. The arc is modeled with a voltage controlled switch. The ungrounded chimney is modeled to have a very large resistance to ground, 100 $M\Omega$. For simulations measuring current through the arc, the voltage controlled switches are activated at positive or negative 25 kV. Circuit element values are similar to those found in [8].

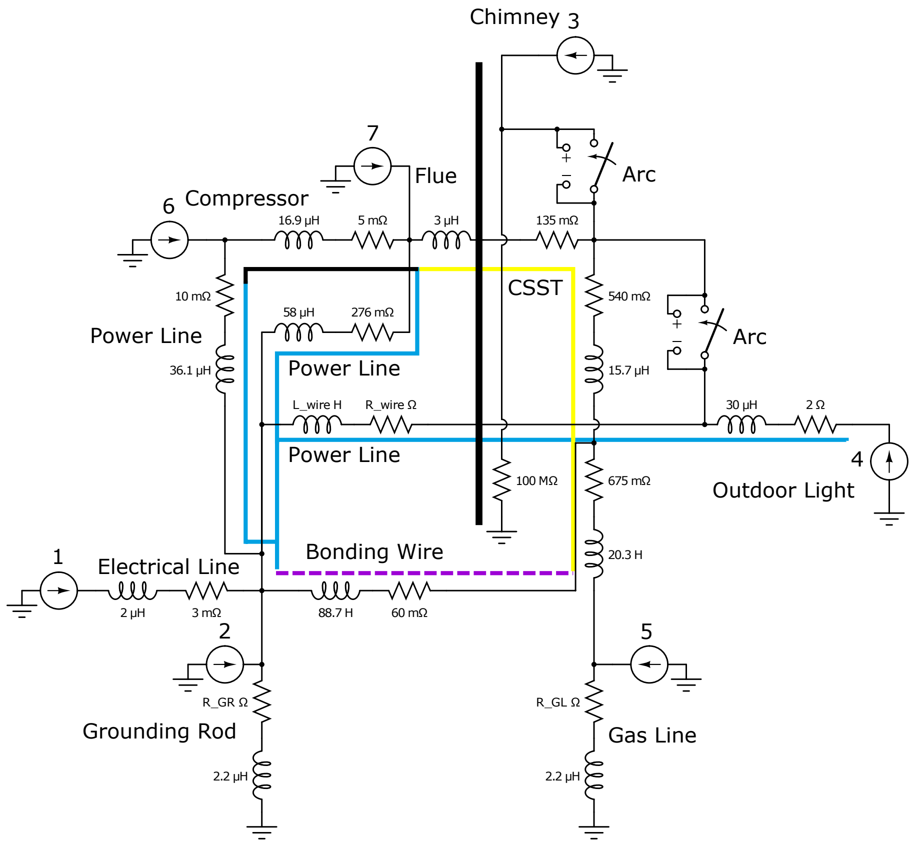

Fig. 7: Circuit diagram corresponding to configuration B. The circuit model is similar to configuration A, but modified according to [9], including the circuit element values.

4.1 Lightning Test Waveforms

International Electrotechnical Commission (IEC) standard 62305 "Protection Against Lightning" suggests parameters for lightning waveforms based on work as early as 1975 [11, 12, 13, 14]. An exponential waveform based on parameters in the standard and earlier work was chosen for lightning surge testing. The waveform is characterized by three values: (1) rise time (T_1), (2) fall time(T_2) and (3) maximum current(i_{max}).

The first parameter characterizes the exponential rise time, determined as the time from 0% to 100% of the maximum current from a line drawn through the 10% and 90% points of the rise curve. The second parameter characterizes the exponential decay, determined as the time from the 0% mark used for T_1 until the curve falls to 50% of its maximum current. Different parts of the lightning strike can be modelled with the same waveshape, but different parameters such as the following:

Table 3: Lightning waveform parameters corresponding to different types of lightning impulses.

Lightning impulse type	Waveform parameters
First positive impulse	10/350 μs
First negative impulse	1/200 μs
Subsequent negative impulses	0.25/100 μs

Annex E of IEC 62305 provides parameters specifically for surge overcurrents on low-voltage systems. The highest level for a direct strike is a 10/350 μs shape with a peak of 10 kA. The highest for an indirect strike is an 8/20 μs with a peak of 5 kA. These values have been used to test surge protection devices and some people have also adopted them for CSST testing, although the justification is unclear.

These standards are based on research done almost 30 years ago and specifically apply to surge protection. Assuming that lightning could strike nearby a structure and most of the current goes into a gas pipe which would be a much better conductor than the soil, the current parameters would be much closer to the recent research cited earlier [16]. The peak current cited was 50 times larger and the max di/dt was about 175 times larger than a 10 kA, 10x350 waveform. Thus the 10 kA, 10x350 and the 5 kA, 8x20 waveforms may grossly underestimate the energy of direct or indirect lightning strikes. We use the 10/350 waveform for comparison with other reports, but it should be understood that real lightning current, direct or indirect, is often much more energetic.

The rate of change of current and the inductance in the circuit also strongly affects the voltage. For an inductor, voltage is proportional to the rate of change of current, so a faster rise time results in more voltage. The 10x350 waveform does not approximate the possible rate of change of currents; the average rise rate of the 10x350 μs waveform is only 1 kA/μs with a maximum rise rate of approximately 2.3 kA/μs. In the literature cited previously the maximum rise rate was 400 kA/μs [16]. We used the same simulation from Figure 4, but varied the rate of change of current up to 400 kA/μs (0.25/100 waveform), with an earth ground resistance of 10 Ω for the gas line and 25 Ω for the electrical line with the lightning entering the gas line.

4.2 Conductor Resistances

Previous reports measured CSST resistance and inductance to be approximately 7.3 $m\Omega/m$ and 2.4 $\mu H/m$ for 0.5 inch tubing and 4.5 $m\Omega/m$ and 2.5 $\mu H/m$ for 1 inch tubing. Resistance and inductance may vary slightly depending on the diameter because the geometry will change slightly.

We assume electrical wiring in a house is copper wire. Different gauges of wire may be used depending on how much current an electrical line is anticipated to carry and different gauges will have different resistances. For other conductors in a house such as refrigerant lines or HVAC equipment we use the same values reported in [9].

4.3 Earth Ground Resistances

Resistance to earth ground measures how much resistance current will encounter going into the earth. It is often desirable to have low resistance earth ground so current can easily flow into the earth, not allowing charge to build up and create high voltages [26]. 5 Ω is a typical ground standard for telecom applications, but can be as low as 1 Ω or less. NFPA 70 recommends less than 25 Ω for one grounding rod (though that is not the requirement if there is more than one grounding rod) and the IEC 62305-3 recommends less than 10 Ω [26].

The range of earth ground resistances encountered in practice may be significantly larger than the 1-25 Ω given by the standards above. An earth ground resistance is proportional to the soil resistivity which can vary by orders of magnitude depending on the type of soil and water content [27]. It has also been shown that resistance of grounding systems changes over time due to natural effects such as corrosion [28, 29]. Furthermore, it is possible that connections loosen over time or there is accidental damage to a residential system resulting in increased resistances. It is possible that ground resistances could be 100 Ω or more in practice. Finally, the ground impedance is a function of the frequency, which can be very high when dealing with lightning. We model earth ground resistances between 1 and 100 Ω as a conservative estimate.

5 Results

5.1 Initiation

Simulations were conducted with and without the presence of a bonding wire connecting the CSST where it entered the structure to an earth ground to determine the effects of bonding in different scenarios. Table 4 shows different scenarios for configuration A defined by the values in the left five columns (where the lightning enters, the waveshape of the lightning current, the earth ground of the grounding rod and the gas line and the impedance of a wire in the house) and the two columns on the right are the maximum voltage without and with the bond wire. Only scenarios where the voltage between the CSST and another conductor is greater than 25kV are reported, indicating sufficient voltage to initiate an arc.

Table 4: Simulation results for configuration A. Maximum voltage with and without bond wire is above the 25 kV arc initiation threshold.

Lightning Entrance	Lightning Waveshape ($\mu s/\mu s$-kA)	R_{GR} (Ω)	R_{GL} (Ω)	R_{WIRE}/L_{WIRE} ($\Omega/\mu H$)	Vmax w/o Bond (kV)	Vmax w/Bond (kV)
1/2	0.25/100-40	1	100	2/30	420	168
	0.25/100-40	100	1	2/30	3977	413
	0.25/100-40	100	100	2/30	3977	266
4	10/350-10	1	1	2/30	75	74
	10/350-10	100	100	2/30	1015	74
	10/350-10	1	1	10/150	368	366
	10/350-10	100	100	10/150	1096	366
	0.25/100-40	1	1	2/30	13048	12795
	0.25/100-40	1	1	10/150	63558	63306
5	0.25/100-40	1	1	2/30	841	336
	0.25/100-40	1	100	2/30	3978	437

We simulated 64 different combinations of parameter values and found that for 40 of them a bonding wire would not prevent arcing. In each case the voltage drops when a bonding wire is introduced, but how much it drops depends strongly on where the lightning enters, what the earth ground resistances are and what the impedance of other conductors in the structure are. For example, when the lightning current enters at 1, 2 or 5 the bond wire provides a good current divider and the 10/350 waveform at 10kA is not sufficient to initiate an arc in this configuration. Strong lightning current like a direct strike would be sufficient in these cases resulting in voltages up to 437kV. Another example, when lightning enters at 1 or 2, the resistance of the gas line and the impedance of the wire in the structure do not affect the voltage if the ground rod resistance is small as seen on lines 1, 2, 5 and 6. On the other hand, when the ground rod resistance is larger as could be the case of a poor or damaged ground rod or poor soil, voltage increases and depends on the resistance of the gas line. R_{GR} is the ground rod resistance, R_{GL} is the gas line resistance, R_{WIRE} it he bonding wire resistance and L_{WIRE} is the bond wire inductance.

For the case of lightning entering through 4, the bonding wire is not very effective in any of the cases at lowering the voltage. The maximum voltage simulated with a bond wire present was 63MV. The scenario for lightning entering 3 would likely produce larger voltages, but we did not simulate that scenario because it is difficult to approximate the impedance of an ungrounded conductor to ground. In that case the charge would build up until an arc to a grounded object is found.

We ran the same simulations for configuration B and show results for scenarios that would still result in an arc in Table 5. For this configuration, there were scenarios with the 10/350 waveform resulting in an arc for everywhere the lightning enters. We did not simulate lightning entering 2 because they were so similar to the case entering 1 and did not simulate lightning entering 3 as described above. For lightning entering 4, 6 and 7 the bonding wire does little to reduce the voltage. It appears that when lightning enters at any location where there is not a grounding wire, it is not very effective at reducing voltage. It can also be seen that the results for lightning entering 1 and entering 5 are approximately reciprocal.

Table 5: Simulation results for configuration B. Maximum voltages with and without bond wire are above the 25 kV arc initiation voltage.

Lightning Entrance	Lightning Waveshape ($\mu s/\mu s$-kA)	R_{GR} (Ω)	R_{GL} (Ω)	R_{WIRE}/L_{WIRE} ($\Omega/\mu H$)	Vmax w/o Bond (kV)	Vmax w/Bond (kV)
1	10/350-10	100	1	0.376/58	51	35
	0.25/100-40	1	1	0.376/58	399	337
	0.25/100-40	100	1	0.376/58	1252	997
4	10/350-10	1	1	0.376/58	143	143
	10/350-10	1	1	1.88/290	709	708
	0.25/100-40	1	1	0.376/58	24788	24727
	0.25/100-40	1	1	1.88/290	122347	122285
5	10/350-10	1	100	0.376/58	51	35
	0.25/100-40	1	1	0.376/58	399	337
6	10/350-10	1	100	0.376/58	32	27
	0.25/100-40	1	1	0.376/58	4108	3889
7	10/350-10	1	1	0.376/58	36	34
	0.25/100-40	1	1	0.376/58	6218	5868

5.2 Melting

We ran simulations for configurations A and B using the same parameters as in the case of initiation. For melting we are primarily concerned with how much charge enters or exits the CSST through the arc. For configuration A with lightning entering at 1 as portrayed in [8], the current through the arc depends on the relative resistances of the ground rod and the gas line. When the lightning current enters the structure where there is a branch to a good ground, the current is diverted strongly away from the CSST. There are many more scenarios possible though. We start examining the case where lightning enters the structure at a location other than one that is well grounded. We then look at all of the simulation results to show where grounding does not prevent melting and cases where it makes the chances of melting greater.

Figure 8 shows the case of lightning entering the outdoor light in configuration A. The different values of R_{GR} and R_{GL} are shown with a maximum current ranging from less than 1 kA to almost 10 kA. The total charge ranges from less than 0.2 C to more than 4 C. When the bonding wire is placed, the current and therefore charge becomes independent of the ground values. This occurs because the impedance of the bond wire is so small, the ground rod and gas line are essentially connected electrically. For some combinations of resistances, the bond wire will result in a smaller charge and for others it will actually result in a larger charge.

To examine the effects on current when there is a bonding wire, we fix $R_{GR} = 10$ and $R_{GL} = 25$, but vary the impedance of the wire representing a conductor in the house that could arc with the CSST as seen in Figure 9. In the presence of the bond wire the relative earth ground resistances become irrelevant, but the impedance of other conductors will affect the current through the arc. So even if the bond wire connects the grounds, the impedance in the structure that has nothing to do with the CSST will affect the charge through the arc and determine if a hole will be melted in the CSST.

We now look at the simulations more comprehensively. In Table 6 we show selected cases for which the presence of the bonding wire does not prevent melting and in some cases actually results in greater charge through the arc for configuration A. It happens when lightning enters through 3 or 4. In the case where the current enters the gas line the bond wire provides a good current divider. In the case where the current

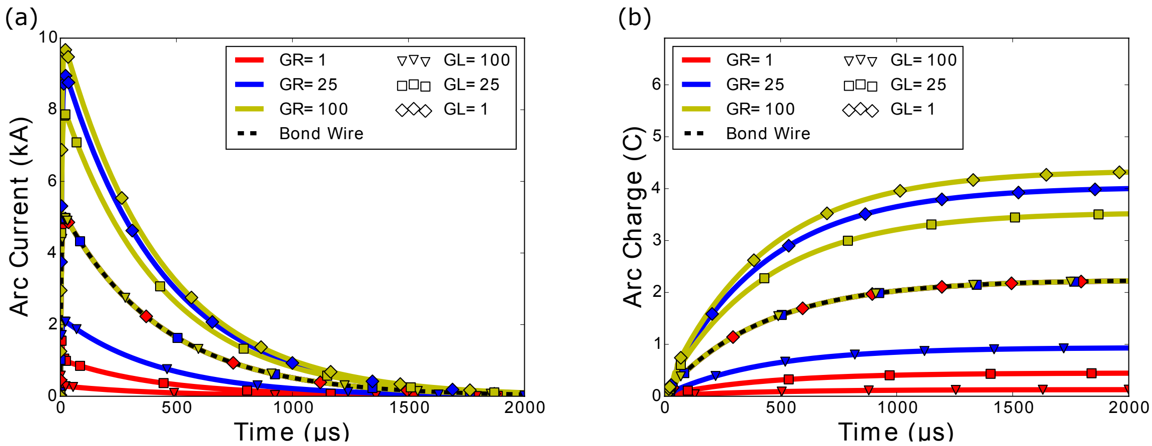

Fig. 8: Simulation results for configuration A showing arc current (a) and charge (b) where lightning enters in location 4 (an outdoor light fixture). R_W is fixed at 2 Ω and L_W is fixed at 30 μH. Ground resistance (GR) and Gas line resistance (GL) vary as shown. When a bond wire is present, the current and charge do not vary when GL and GR vary. This result shows that for some GL and GR values, bonding may actually increase the likelihood of CSST melting.

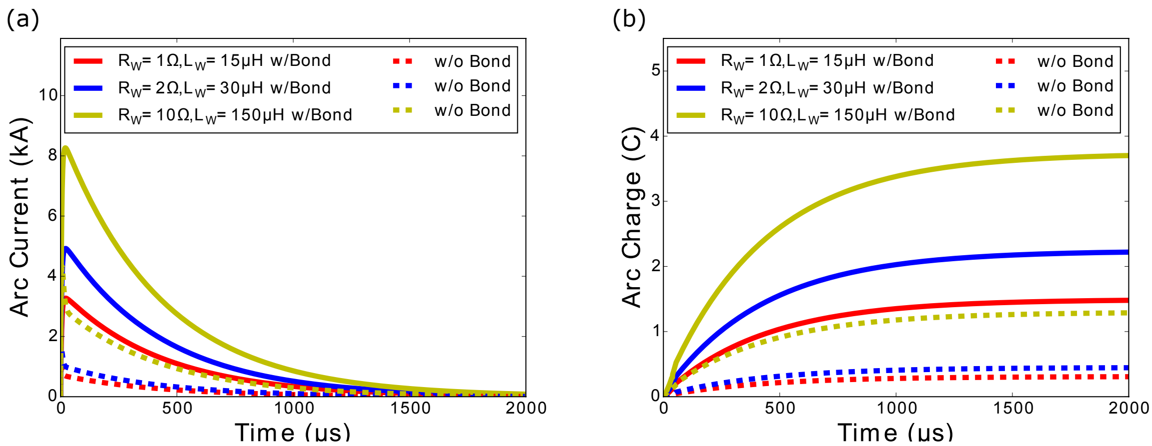

Fig. 9: Simulation results for configuration A showing arc current (a) and charge (b) where lightning enters in location 4 (an outdoor light fixture). Ground resistance (GR) is fixed at 1 Ω and Gas line resistance (GL) is fixed at 25 Ω. Structure wire parameters R_W and L_W vary as shown. In these cases adding the bond wire increases the likelihood of CSST melting, but depends on the impedance of conductors within the structure.

enters the electrical line, current through the CSST is only a concern if the electrical earth ground is large. In that case the bond wire again provides a good current divider. In Table 7 we show selected cases where the bonding wire again does not prevent melting and in some cases the bonding wire results in greater charge through the arc for configuration B. This scenario is different because there are more places for the lightning to enter and the configuration of conductors is more complicated. In both Table 6 and 7 there are cases where melting would not occur without a bond wire and would occur when a bond wire was inserted.

Table 6: Simulation results for selected parameters in configuration A showing effect on arc charge with and without bond wire. In some cases the bond wire is only marginally helpful, while others show it will increase the likelihood of CSST melting.

Lightning Entrance	Lightning Waveshape ($\mu s/\mu s$-kA)	R_{GR} (Ω)	R_{GL} (Ω)	R_{WIRE}/L_{WIRE} ($\Omega/\mu H$)	Arc Charge w/o Bond (C)	Arc Charge w/Bond (C)
3/4	10/350-10	1	1	2/30	2.22	2.22
	10/350-10	100	1	2/30	4.32	2.22
	10/350-10	1	100	2/30	0.13	2.22
	0.25/100-40	100	1	2/30	5.56	2.86
	10/350-10	1	100	10/150	0.43	3.7
	0.25/100-40	1	100	10/150	0.56	4.76

Table 7: Simulation results for selected parameters in configuration B showing effect on arc charge with and without bond wire. In some cases the bond wire is only marginally helpful, while others show it will increase the likelihood of CSST melting.

Lightning Entrance	Lightning Waveshape ($\mu s/\mu s$-kA)	R_{GR} (Ω)	R_{GL} (Ω)	R_{WIRE}/L_{WIRE} ($\Omega/\mu H$)	Arc Charge w/o Bond (C)	Arc Charge w/Bond (C)
1	0.25/100-40	100	1	0.376/58	5.59	2.89
	0.25/100-40	100	100	0.376/58	2.84	1.47
3/4	10/350-10	1	100	0.376/58	0.05	0.69
	0.25/100-40	1	100	0.376/58	0.06	1.02
	0.25/100-40	1	100	1.88/290	0.06	1.29
	10/350-10	100	1	0.376/58	4.35	1.42
5	0.25/100-40	1	100	0.376/58	5.59	2.89
	0.25/100-40	100	100	0.376/58	2.84	1.47
6	10/350-10	1	100	0.376/58	0.04	0.28
	10/350-10	100	1	0.376/58	4.34	1.39

6 Discussion

Simulating initiation, we found that peak voltage was strongly dependent on where the lightning entered the structure and the relative resistances of earth ground connections. We also found that maximum voltage strongly depends on the maximum change in current over time. Our simulations do not exhaustively cover all potential situations, but show that for reasonable values of resistance and rise time, it is possible to produce voltages in the 100 kV - 1 MV range. The voltages could be even higher when factoring in the electrostatic induction of a nearby lightning strike. These results suggest bonding the gas line to a strong earth ground does not prevent arc initiation in many scenarios. For grounding to be an effective method for preventing arcs in all scenarios, a bond wire would have to be in parallel with the CSST connected to any conductor in the house that could be energized by lightning current.

Simulating melting, we found that charge through an arc strongly depends on where the lightning enters the house, how conductors are grounded and the impedance of conductors in the structure. Our results show that when lightning does enter a house, adding a grounding wire in some situations actually increases the charge through an arc. This increases the probability of melting and perforation. Strongly grounding the CSST turns it into a lightning rod as a low-resistance path to ground. Our results also show that charge through an arc strongly depends on the impedances of conductors in the house and the relative earth impedances. Someone installing CSST and a bond wire would not likely have the ability to measure these impedances or make modifications sufficient to prevent perforation of the CSST in the foreseeable lightning events.

7 Conclusions

Though previous reports have demonstrated simulation results showing that earth grounding of CSST with a bond wire helps prevent arc initiation and melting of the CSST, those reports used specific scenarios with specific parameters and only considered lightning entering the gas or electrical lines. For a broader range of probable scenarios and parameters, we found several cases where grounding does not reduce voltage enough to prevent arc initiation nor reduce charge through the arc enough to prevent melting. In some cases we found that grounding increased the charge through the arc, increasing the probability of perforation. Our work suggests that grounding only helps prevent damage caused by lightning in certain situations, such as when current enters through the gas line. In contrast to previous reports [6, 7, 8, 9], the simulation work we have performed demonstrates that grounding cannot prevent lightning current from perforating CSST. Although the present work was based on modeling and simulations, these prior reports were also based on modeling and simulations but using a narrower range of scenarios for the location of lightning entering the structure. The results of these prior reports and this paper indicate that in some cases grounding will help prevent melting, in some cases it will not and in some cases it will increase the risk of melting. This has important consequences for the protection of homes in which CSST is installed.

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9 Appendix

Table 8: Expanded simulation results for configuration A (extension of Table 4). Maximum voltage with and without bond wire is above the 25 kV arc initiation threshold.

Lightning Entrance	Lightning Waveshape ($\mu s/\mu s$-kA)	R_{GR} (Ω)	R_{GL} (Ω)	R_{WIRE}/L_{WIRE} ($\Omega/\mu H$)	Vmax w/o Bond (kV)	Vmax w/Bond (kV)
1	0.25/100-40	1	1	2/30	420	168
	0.25/100-40	1	100	2/30	420	168
	0.25/100-40	100	1	2/30	3977	413
	0.25/100-40	100	100	2/30	3977	266
	0.25/100-40	1	1	10/150	420	168
	0.25/100-40	1	100	10/150	420	168
	0.25/100-40	100	1	10/150	3977	413
	0.25/100-40	100	100	10/150	3977	266
2	0.25/100-40	1	1	2/30	420	168
	0.25/100-40	1	100	2/30	420	168
	0.25/100-40	100	1	2/30	3977	413
	0.25/100-40	100	100	2/30	3977	266
	0.25/100-40	1	1	10/150	420	168
	0.25/100-40	1	100	10/150	420	168
	0.25/100-40	100	1	10/150	3977	413
	0.25/100-40	100	100	10/150	3977	266
4	10/350-10	1	1	2/30	75	74
	10/350-10	1	100	2/30	75	74
	10/350-10	100	1	2/30	1015	75
	10/350-10	100	100	2/30	1015	74
	10/350-10	1	1	10/150	368	366
	10/350-10	1	100	10/150	368	366
	10/350-10	100	1	10/150	1096	366
	10/350-10	100	100	10/150	1096	366
	0.25/100-40	1	1	2/30	13048	12795
	0.25/100-40	1	100	2/30	13048	12795
	0.25/100-40	100	1	2/30	13048	12796
	0.25/100-40	100	100	2/30	13048	12796
	0.25/100-40	1	1	10/150	63558	63306
	0.25/100-40	1	100	10/150	63558	63306
	0.25/100-40	100	1	10/150	63559	63306
	0.25/100-40	100	100	10/150	63559	63306
5	0.25/100-40	1	1	2/30	841	336
	0.25/100-40	1	100	2/30	3978	437
	0.25/100-40	100	1	2/30	841	336
	0.25/100-40	100	100	2/30	3978	336
	0.25/100-40	1	1	10/150	841	336
	0.25/100-40	1	100	10/150	3978	437
	0.25/100-40	100	1	10/150	841	336
	0.25/100-40	100	100	10/150	3978	336

Table 9: Expanded simulation results for configuration B (extension of Table 5). Maximum voltages with and without bond wire are above the 25 kV arc initiation voltage.

Lightning Entrance	Lightning Waveshape ($\mu s/\mu s$-kA)	R_{GR} (Ω)	R_{GL} (Ω)	R_{WIRE}/L_{WIRE} ($\Omega/\mu H$)	Vmax w/o Bond (kV)	Vmax w/Bond (kV)
1	10/350-10	100	1	0.376/58	51	35
	10/350-10	100	1	1.88/290	51	35
	0.25/100-40	1	1	0.376/58	399	337
	0.25/100-40	1	100	0.376/58	399	337
	0.25/100-40	100	1	0.376/58	1252	997
	0.25/100-40	100	100	0.376/58	1058	822
	0.25/100-40	1	1	1.88/290	399	337
	0.25/100-40	1	100	1.88/290	399	337
	0.25/100-40	100	1	1.88/290	1252	997
	0.25/100-40	100	100	1.88/290	1057	828
4	10/350-10	1	1	0.376/58	143	143
	10/350-10	1	100	0.376/58	143	143
	10/350-10	100	1	0.376/58	164	154
	10/350-10	100	100	0.376/58	153	148
	10/350-10	1	1	1.88/290	709	708
	10/350-10	1	100	1.88/290	709	709
	10/350-10	100	1	1.88/290	709	709
	10/350-10	100	100	1.88/290	709	709
	0.25/100-40	1	1	0.376/58	24788	24727
	0.25/100-40	1	100	0.376/58	24788	24727
	0.25/100-40	100	1	0.376/58	24789	24727
	0.25/100-40	100	100	0.376/58	24789	24727
	0.25/100-40	1	1	1.88/290	122347	122285
	0.25/100-40	1	100	1.88/290	122347	122285
	0.25/100-40	100	1	1.88/290	122347	122285
	0.25/100-40	100	100	1.88/290	122347	122285
5	10/350-10	1	100	0.376/58	51	35
	10/350-10	1	100	1.88/290	51	35
	0.25/100-40	1	1	0.376/58	399	337
	0.25/100-40	1	100	0.376/58	1252	998
	0.25/100-40	100	1	0.376/58	399	337
	0.25/100-40	100	100	0.376/58	1058	823
	0.25/100-40	1	1	1.88/290	399	337
	0.25/100-40	1	100	1.88/290	1252	998
	0.25/100-40	100	1	1.88/290	399	337
	0.25/100-40	100	100	1.88/290	1058	823
6	10/350-10	1	100	0.376/58	32	27
	10/350-10	1	100	1.88/290	32	27
	0.25/100-40	1	1	0.376/58	4108	3889
	0.25/100-40	1	100	0.376/58	4108	3889
	0.25/100-40	100	1	0.376/58	4108	3889
	0.25/100-40	100	100	0.376/58	4108	3889
	0.25/100-40	1	1	1.88/290	4108	3889
	0.25/100-40	1	100	1.88/290	4108	3889
	0.25/100-40	100	1	1.88/290	4108	3889
	0.25/100-40	100	100	1.88/290	4108	3889
7	10/350-10	1	1	0.376/58	36	34
	10/350-10	1	100	0.376/58	48	40
	10/350-10	100	1	0.376/58	36	34
	10/350-10	100	100	0.376/58	36	34
	10/350-10	1	1	1.88/290	36	34
	10/350-10	1	100	1.88/290	48	40
	10/350-10	100	1	1.88/290	36	34
	10/350-10	100	100	1.88/290	36	34
	0.25/100-40	1	1	0.376/58	6218	5868
	0.25/100-40	1	100	0.376/58	6218	5868
	0.25/100-40	100	1	0.376/58	6218	5868
	0.25/100-40	100	100	0.376/58	6218	5868
	0.25/100-40	1	1	1.88/290	6218	5868
	0.25/100-40	1	100	1.88/290	6218	5868
	0.25/100-40	100	1	1.88/290	6218	5868
	0.25/100-40	100	100	1.88/290	6218	5868

Table 10: Expanded simulation results for Configuration A. Each entry includes parameter values where adding a bonding wire results in greater charge through the arc, increasing the risk of melting and ignition.

Lightning Entrance	Lightning Waveshape ($\mu s/\mu s$-kA)	R_{GR} (Ω)	R_{GL} (Ω)	R_{WIRE}/L_{WIRE} ($\Omega/\mu H$)	Arc Charge w/o Bond (C)	Arc Charge w/Bond (C)
3	10/350-10	1	1	2/30	2.22	2.22
	10/350-10	1	100	2/30	0.13	2.22
	10/350-10	1	1	10/150	3.49	3.7
	10/350-10	1	100	10/150	0.43	3.7
	10/350-10	100	100	10/150	2.31	3.7
	0.25/100-40	1	1	2/30	2.86	2.86
	0.25/100-40	1	100	2/30	0.16	2.86
	0.25/100-40	1	1	10/150	4.49	4.77
	0.25/100-40	1	100	10/150	0.56	4.76
	0.25/100-40	100	100	10/150	2.97	4.77
4	10/350-10	1	100	2/30	0.13	2.22
	10/350-10	1	1	10/150	3.49	3.7
	10/350-10	1	100	10/150	0.43	3.7
	10/350-10	100	100	10/150	2.31	3.7
	0.25/100-40	1	100	2/30	0.16	2.86
	0.25/100-40	1	1	10/150	4.49	4.77
	0.25/100-40	1	100	10/150	0.56	4.76
	0.25/100-40	100	100	10/150	2.97	4.77

Table 11: Expanded simulation results for Configuration A. Each entry includes parameter values where a bonding wire reduces charge through the arc, but not enough to prevent melting.

Lightning Entrance	Lightning Waveshape ($\mu s/\mu s$-kA)	R_{GR} (Ω)	R_{GL} (Ω)	R_{WIRE}/L_{WIRE} ($\Omega/\mu H$)	Arc Charge w/o Bond (C)	Arc Charge w/Bond (C)
3	10/350-10	100	1	2/30	4.32	2.22
	10/350-10	100	100	2/30	2.22	2.22
	10/350-10	100	1	10/150	4.33	3.7
	0.25/100-40	100	1	2/30	5.56	2.86
	0.25/100-40	100	100	2/30	2.86	2.86
	0.25/100-40	100	1	10/150	5.57	4.77
4	10/350-10	1	1	2/30	2.22	2.22
	10/350-10	100	1	2/30	4.32	2.22
	10/350-10	100	100	2/30	2.22	2.22
	10/350-10	100	1	10/150	4.33	3.7
	0.25/100-40	1	1	2/30	2.86	2.86
	0.25/100-40	100	1	2/30	5.56	2.86
	0.25/100-40	100	100	2/30	2.86	2.86
	0.25/100-40	100	1	10/150	5.57	4.77

Table 12: Expanded simulation results for Configuration B. Each entry includes parameter values where adding a bonding wire results in greater charge through the arc, increasing the risk of melting and ignition.

Lightning Entrance	Lightning Waveshape ($\mu s/\mu s$-kA)	R_{GR} (Ω)	R_{GL} (Ω)	R_{WIRE}/L_{WIRE} ($\Omega/\mu H$)	Arc Charge w/o Bond (C)	Arc Charge w/Bond (C)
3	10/350-10	1	100	0.376/58	0.05	0.69
	10/350-10	1	100	1.88/290	0.05	0.86
	0.25/100-40	1	100	0.376/58	0.06	1.02
	0.25/100-40	1	1	1.88/290	1.95	1.96
	0.25/100-40	1	100	1.88/290	0.06	1.29
4	10/350-10	1	100	0.376/58	0.05	0.69
	10/350-10	1	100	1.88/290	0.05	0.86
	0.25/100-40	1	100	0.376/58	0.06	1.0
	0.25/100-40	1	1	1.88/290	1.95	1.96
	0.25/100-40	1	100	1.88/290	0.06	1.29
6	10/350-10	1	100	0.376/58	0.04	0.28
	10/350-10	1	100	1.88/290	0.04	0.32
	0.25/100-40	1	100	0.376/58	0.06	0.64
	0.25/100-40	1	100	1.88/290	0.06	0.73

Table 13: Expanded simulation results for Configuration B. Each entry includes parameter values where a bonding wire reduces charge through the arc, but not enough to prevent melting.

Lightning Entrance	Lightning Waveshape ($\mu s/\mu s$-kA)	R_{GR} (Ω)	R_{GL} (Ω)	R_{WIRE}/L_{WIRE} ($\Omega/\mu H$)	Arc Charge w/o Bond (C)	Arc Charge w/Bond (C)
1	0.25/100-40	100	1	0.376/58	5.59	2.89
	0.25/100-40	100	100	0.376/58	2.84	1.47
	0.25/100-40	100	1	1.88/290	5.59	2.78
	0.25/100-40	100	100	1.88/290	2.84	1.41
3	10/350-10	100	1	0.376/58	4.35	1.42
	10/350-10	100	1	1.88/290	4.35	1.5
	0.25/100-40	1	1	0.376/58	1.91	1.76
	0.25/100-40	100	1	0.376/58	5.6	3.55
	0.25/100-40	100	100	0.376/58	2.84	2.14
	0.25/100-40	100	1	1.88/290	5.6	3.6
	0.25/100-40	100	100	1.88/290	2.84	2.3
4	10/350-10	100	1	0.376/58	4.35	1.42
	10/350-10	100	1	1.88/290	4.35	1.5
	0.25/100-40	1	1	0.376/58	1.91	1.74
	0.25/100-40	100	1	0.376/58	5.6	3.54
	0.25/100-40	100	100	0.376/58	2.84	2.13
	0.25/100-40	100	1	1.88/290	5.6	3.6
	0.25/100-40	100	100	1.88/290	2.84	2.3
5	0.25/100-40	1	100	0.376/58	5.59	2.89
	0.25/100-40	100	100	0.376/58	2.84	1.47
	0.25/100-40	1	100	1.88/290	5.59	2.78
	0.25/100-40	100	100	1.88/290	2.84	1.41
6	10/350-10	100	1	0.376/58	4.34	1.39
	10/350-10	100	1	1.88/290	4.34	1.39
	0.25/100-40	1	1	0.376/58	1.71	1.6
	0.25/100-40	100	1	0.376/58	5.59	3.49
	0.25/100-40	100	100	0.376/58	2.84	2.07
	0.25/100-40	1	1	1.88/290	1.72	1.66
	0.25/100-40	100	1	1.88/290	5.59	3.47
	0.25/100-40	100	100	1.88/290	2.84	2.11