ELECTRICAL CHARACTERIZATION OF CORRUGATED STAINLESS STEEL TUBING COMPONENTS AND SYSTEMS

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ABSTRACT

The failure of Corrugated Stainless Steel Tubing (CSST) has been documented in many fires that have been associated with lightning energy being dissipated into structures. Testing has been carried out by both CSST manufacturers and by the NFPA to determine the susceptibility of CSST to puncture when exposed to lightning energy.

In 2009, the National Fuel Gas Code (NFPA 54) was altered so as to require so called 'direct bonding' of CSST systems to the electrical system for purposes of safely dissipating lightning energy. The code requirements, although intended for lightning, make no mention of NFPA 780 requirements, which have very specific requirements for conductors used in Lightning Protections System (LPS's).

To date, CSST has not been fully characterized in a full scale residential setting. While lengths of CSST have been characterized in terms of resistance and inductance per unit length (bulk characteristics), data does not exist that shows the electrical interaction of CSST with other structural components. As an example, CSST is required to use steel sleeves ("nailers") which minimize the risk of nail puncture. These steel sleeves have iron as their base material. Classical E/M training tells us that an inductor can be created by a current carrying conductor which passes through an iron sleeve. What effect (if any) this has on charge times is unknown. Is it possible that phenomenon such as SWR (Standing Wave Ratio) and discontinuities should be considered in the layout or design of a CSST system? Will adherence to the 'lightning' code (NFPA 780) in terms of bending radii and angles of inclusion have an effect on bonding and grounding of CSST? Does the installation of CSST in buildings with metal framing present a challenge?

The authors have tested individual lengths of CSST, as well as CSST as installed in the field. The testing has made use of both transient and steady state techniques. We use this data to show in what ways CSST can be considered a component part of a larger electrical circuit. We also take issue with current practices of testing CSST, to include the NFPA's research and the testing of 'improved' CSST products.

BACKGROUND

CSST was first introduced in the United States in about 1988. Since that time, there has been a realization that CSST can fail when exposed to energy from a lightning strike. One of the authors (MEG) presented a paper on the subject at the *Fire and Materials Conference* in 2005. [1]One of the factors that became clear early on was that the material was never properly tested. Documentation from the NFPA shows that lightning energy was never considered when the product was being approved for listing. [2]

The industry response has been somewhat lame, with attempts being made to blame someone else for the deficiencies that this product has. As an example, in 2006 the industry started pushing 'direct bonding,' even though that solution had never been properly tested or verified. Moreover, the NEC contains no definition of so called direct bonding. At one time, the industry believed that the solution was to run a bonding wire from the gas manifold (or other hard pipe) to the electrical grounding system.[3] That location has now been changed to the hard pipe after the gas meter and before any CSST.[4] The industry felt that *all* gas systems should be bonded; this ignores the reality of the NEC, which requires bonding of gas systems to prevent electrical shock injury. In that many water heaters and gas fireplaces have no electrical energization, they are not likely to become energized and thus require no bonding. Moreover, in an all gas house, such as a cabin with a fireplace and water heater, there is no electrical system.

The lack of knowledge with electrical components and / or electrical concepts continues on, even today. One proponent of CSST usage presented a Power Point presentation on CSST, and used the following slide, Photo 1.[5]

Photo 1, Showing 'Air Core' Inductors In Bonding Connection

This lone picture shows well the depravity of electrical knowledge in the CSST industry. The pigtails in the bonding jumpers are essentially air core inductors, and have no place in a lightning protection scheme. The same *Power Point* advises that installers should avoid contact between CSST and 'other metallic systems.' Nevertheless, Photo 2, taken from the installation manual of one manufacturer, demonstrates the usage of CSST in a structure with steel studs.[6] A later bulletin from the same manufacturer admonishes the user as follows:

> *Care should be taken when installing Gastite tubing runs to maintain as much separation as reasonably possible from other electrically conductive systems in the building.* [7]

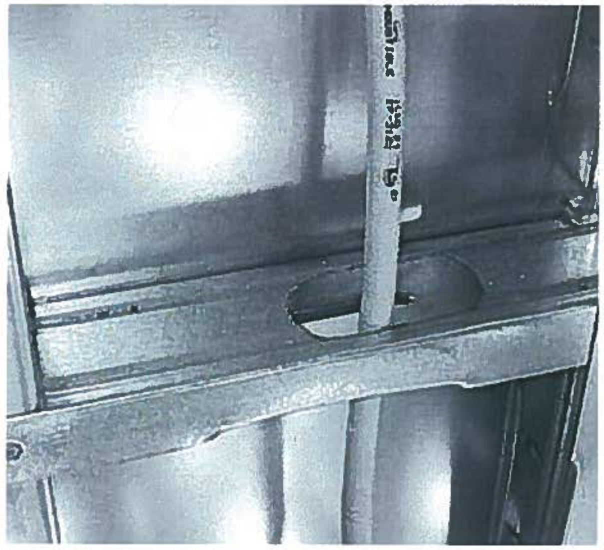

Photo 2 – CSST Within Steel Stud Space

In 1999, the NEC had an error in its wording in regards to bonding and grounding.[8] This wording caused confusion and mis interpretation of the NEC's intent in regards to 250-104b – *to prevent electrical shock.* A *Formal Interpretation* (FI) was issued by the NEC, stating that a gas appliance which uses electricity is considered to be bonded to the electrical grounding system when the *Equipment Grounding Conductor* (EGC) attached to such a grounded gas appliance is connected to the electrical system – IE, a grounded line cord or length of type NM with a ground wire will suffice. [9]

The industry approached the *National Electrical Code* committee, particularly *Code Making Panel* (5 CMP 5 – Grounding*)* and attempted to have the NEC conform to the perceived needs of the CSST industry. The industry was rebuffed.[10] The NEC is NOT the code that deals with lightning, and the panel members felt that the problem was the thin walled nature of CSST, and the solution would not be had by passing a knee jerk amendment to the NEC which had not been tested.

In the last several years, the industry and the NFPA had the *National Fuel Gas Code* (NFPA 54) amended to read as follows:

> *CSST gas piping systems shall be bonded to the electrical services grounding electrode when the gas service enters the building, the bonding jumper shall not be smaller than 6 AWG copper wire or equivalent.* [11]

The industry did work with the NFPA to produce a research document entitled *Validation of Installation Methods for CSST Gas Piping to Mitigate Indirect Lightning Related Damage*
[12] The documents outline electrical research into the interaction of CSST and lightning energy. However, as will be detailed here, the document is lacking in several respects.

RESEARCH

The authors undertook to characterize CSST, and feel that that this characterization is 'key' in understanding how lightning damage can be mitigated.

DIELECTRIC STRENGTH OF JACKETING

One of the authors (MEG) used to work at a firm that designed avionics. One of the design rules learned was that airplane surfaces should, if possible, avoid the use of nonconductive paint. This was to prevent the concentration of electrical charge in the event of an electrical discharge from lightning. In a plasma, it is believed that parallel 'arcs' to and from the same surfaces do not exist at the same point in time. The weakest point in such a painted surface (the area of least paint and / or of contaminants) will break down and funnel the energy into the one area.

With CSST, the manufacturer have essentially all used a PE (Poly Ethylene) jacketing to cover the metallic pipe. Testing of the dielectric with a Vitrek 944i shows that the dielectric strength of the jacketing is between ~ 15 and 20 kilovolts. The thickness of the dielectric varies (see photo 3), but in general it is in the range of about 30 mils. Research shows that PE has a dielectric strength of about 500 to 550 volts per mil.[13]

Photo 3

The end results are that the electrical energy associated with lightning is seen to be focused by the use of the jacketing. US Patent 8399767, assigned to a CSST manufacturer, contains the following language:

> *Metals are electrically conductive materials, making CSST a very good pathway for electrical currents. This leads to the potential for a flashover if the CSST is installed in close proximity to another conductor within a structure and either one becomes energized. A flashover like this is often the result of a lightning event but it is foreseeable that other events may also be capable a producing a sufficient voltage differential between conductors. It is possible that a flash like this can cause enough heat generation to melt a hole in the CSST, allowing fuel gas to escape. This scenario is worsened by the dielectric jacket that often surrounds CSST. This jacket only typically breaks down in a very small area, creating a pinhole as a result of the flashover. This phenomenon focuses the flash and concentrates the heating of the stainless steel inside. The result is a reduced capability of the CSST to resist puncture from flashover compared to un-jacketed pipe.* [14]

A patent assigned to another manufacturer (7044167) contains the following description:

> *Another drawback to existing tubing is that the tubing is often contained within a jacket. Typically, the jacket is made from an insulative material. In the event that the piping is introduced to an electrical charge (e.g., from direct or indirect lightning), charge accumulates on the jacket and can burn through the jacket to the tubing resulting in a breach of the tubing.*[15]

A review of the CSST standard, ANSI LC-1, shows no requirement that there even is a jacketing material on CSST. [16] The following language is used:

> *For tubing which includes a nonmetallic coating or covering, the coating shall comply with the international color designation of yellow.*

While the jacketing *is* present and *does* serve to focus the energy, it has no practical electrical insulating qualities. Tests by the authors using a Vitrek 944i on *field installed* CSST show that the dielectric strength in the field varies between about 1500 volts and 20,000 volts. The jacketing becomes snagged and / or contaminated during installation, resulting in bare spots or thinned and contaminated spots. Thus, there truly is no need for an electrically insulating jacket. The jacket cannot be reliably used as an insulator due to the aberrations brought on by installation practices. The jacketing also serves to concentrate the charge in one spot, making penetration of the tubing more likely. We further note that the above two excerpts from patents refer to the problem, and a method of how to improve CSST by spreading the charge over a greater area.

Testing carried out under the direction of one of the authors at Lightning Technologies demonstrated the phenomenon we herein describe. We saw increases in withstand charge by a factor of ~ 4:1 when unjacketed CSST is compared to yellow CSST.

And finally, we note that the jacketing does serve the purpose of 'smoothing' the outer mechanical appearance, which makes the CSST easier to install, should it have to be pulled over sharp edges, like gusset plates and the like. The PE takes out the roughness of the corrugations.

ROUTING OF BONDING CONDUCTORS

A further demonstration regarding the lack of electrical expertise in trying to rectify CSST problems is found by analyzing the D&I guides from the CSST manufacturers, the 2009 version of NFPA 54 (*Fuel Gas Code*) and the document NFPA 780, *Standard for Installation of Lightning Protection Systems.* These codes and documents deal with the harnessing of lightning energy by way of use of bonding. Bonding essentially tries to 'fix' all metal points together electrically so they are at the same potential. If nearby items are at the same potential, there is no 'incentive' for electrical currents to jump or 'arc' from one surface to another. Without arcing, there is no lightning damage. If (as an example) the chimney metal stack and nearby CSST are at the same voltage, the *equipotential* surfaces will prevent the arcing from the chimney stack to a nearby length of CSST (or vice versa).

The NEC, as noted earlier, is not a text for preventing lightning damage. It is essentially intended for frequencies of 50, 60 and possibly 400 hertz. (Europe, United States, and computer mainframe power, respectively) The NEC is NOT intended to deal with lightning frequencies (harmonic content) which are many decades greater than that of NEC power. The underlying electrical theory can be approached in several ways.

The first manner to approach a problem of lightning and bonding is to realize that what is *equipotential bonding* at 60 hertz is not necessarily an equipotential bonding scheme at lightning frequencies. As an example, Figure 1 shows two wires or conductors that can be assumed to bonding conductors.

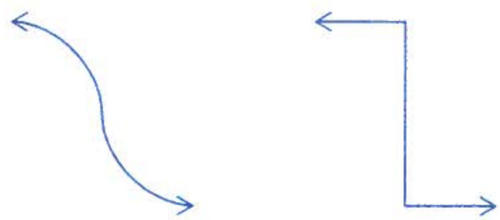

Figure 1 – 2 Different Geometric Configurations Of Bonding Conductors

While the lenths of wire may even be the same length and same diameter (gauge) and construction, they will function much differently at 60 Hz than at lighting frequencies. We can analyze this in several different ways. We consider the following techniques:

1.) Reflections

It is well known that an electrical wave can propagate down a wire. As it does so, it *may* encounter discontinuities. A *right angle bend* in a wire is such a discontinuity. At the point of such a discontinuity, a portion of the energy is reflected back towards the source. This is known as a *reflected wave*, and does create differences of voltage amoung points along the equipotential bonding wire. This reflection is the basis for the operation of test instruments known as TDRs, or Time Domain Reflectometers.

2.) Inductance

Inductance is the property in a wire whereby a change in current causes a voltage in itself and in nearby wires. Electrical engineers treat inductance by one of two ways, *steady state* and *transient*.

Steady State Analysis

The two wires in Figure 1 can be assumed, for purposes of discussion, to be carrying sine waves at 1 MHz. At the right angle bends, the surfaces of the same wire, but at right angles with each other, react with one another to create self inductance. For this reason, at HF (High Frequency), the bonding wire that has gentle transitions will have a smaller impedance than will the bonding wire with right angle turns. The impedance of an inductor with inductance ***L*** at frequency ***f*** is quantified as follows:

$$Z_{(\text{ohms reactive})} = 2\ \text{pi}\ f\ L.$$

At 60 hertz, the differences in the two bonding wires are almost zero. When carrying HF, the differences in impedance are significant. When carrying 10,000 or so amperes, significant changes in impedance result in large voltage drops, making arcing much more likely.

Transient Analysis

The transient analysis of the two bonding wires from Figure 1 uses a different scheme, one that is caculus based. The voltage drop **V** across an inductor of inductance L is based on the time derivate (*di/dt*), where changes in current are references to time (the current slew rate).

$$V_{(volts)} = L\ (di/dt)$$

Current can change in the range of 400,000 amperes per microsecond with lightning, making any small increase in inductance a major player in creating differences in potential between so called *equipotential* surfaces. [17]

Significance of Bonding Conductor Routing

The significance of bonding conductor routing is two fold. First off, if cxecuted improperly, fires can be caused. Photo 3, taken from a US government publication, shows a high speed frame of bonding wire being avulsed at a kink when subjected to carrying artificially induced lighting currents. [18]

Photo 3 – Bonding Wire Failing When Carrying Lightning Current

The second reason for the desirability of low impedance bonding is so that surfaces at different potentials initially can equalize quickly in potential, such that the surfaces are less likely to arc from one to another.

Is Bonding Conductor Routing 'New Science"?

The use of 'gentle' bends to handle lightning type currents is not new science or technology. In fact, the NFPA has been aware of the issues of lightning conductor routing for many years. The best example of this is found in NFPA 780. (See 4.9.5 of NFPA 780) This document specifically states that angles of less than 90 degrees are to be avoided on conductors, and also that bending radii on conductors shall exceed 8". [19] If the industry and the NFPA are serious about safely dissipating lightning energy, then there needs to be congruence. What is deemed adequate for routing of lightning energy with what the NFPA 54 standard requires should also be consistent with what the NFPA 780 panel members require. At the present time, there is no such agreement.

GROUNDING MEASUREMENTS

The authors have been part of numerous investigations where personnel have used clamp-on meters to try and determine ground efficacy. The 'typical' measurement is taken by a meter that operates at 2403 Hz and is non contact. [20] The power source for the meter is a 9 volt battery, and a calibration standard helps insure accuracy. Thereafter, claims have been made that a system did or not perform adequately (in terms of grounding) because of the measurements taken by the hand held meter. Once again, this is a gross misunderstanding of electrical principals, this time as they relate to grounding.

The first assumption is that a ground measurement taken after a fire will be the same as before the fire. Factors that change such measurements include the water used for suppression and the damage to the plumbing and electrical systems. The use of PEX piping will bring about little (if any) change of ground measurements due to a fire, while damage to copper piping or grounding conductors can severely impact grounding.

The second incorrect assumption being made is that 25 ohms represents a 'good' ground. Instead, 25 ohms is consistent with what the NEC requires. The IEEE 'colored' book series makes reference in both the Red and Green books to 5 ohms. [21, 22] Once again, there is a pervasive lack of knowledge on this aspect of grounding.

The third and fourth criticisms are somewhat related. It is folly to think that a battery powered instrument using a standard 9 volt cell can adequately test a grounding system that might be expected to carry 10,000 amperes or more. Similarly, research has shown that the impedance of an earth ground that is carrying lightning energy is in fact dependent on the level of insult. [23] Rather, the ground measurement which is of the most use is the value present when the system is carrying currents from a lightning discharge. The electrical energy being carried (dissipated) can alter the insulating layers of soil, making them conductive; energization from an inductive coil powered by a 9 volt battery cannot accurately simulate what occurs when lightning enters (and dynamically alters) the grounding path. In that the resistance value of soil is dynamic when overwhelmed by lightning, it would seem that repeatable (and relevant) measurements are a lofty and unattainable goal.

The final criticism is that a 2403 Hz sine wave does not have the spectral content of lightning type signals. As has been earlier stated, LF (Low Frequency) sine waves do not accurately model or predict HF response.

TESTING CAVEATS

As mentioned earlier, the NFPA commissioned a study on CSST. The second phase of the study was entitled *Validation of Installation Methods for CSST Gas Piping to Mitigate Indirect Lightning Related Damage*. The research includes the following statement:

> *Direct lightning strikes are outside of the scope of this project. Indirect strikes that induce currents in various residential structures are far more numerous than direct strikes, providing motivation to deal with this category of event.* [24]

It is very clear from the title and the wording of the report that little to no interest has been paid to the *direct* strike. Perhaps the wording would be more accurate if it stated:

> Direct strokes are outside the scope of this project. While direct strokes are less common than indirect strokes, they represent an energy form that CSST cannot reliably deal with in a safe manner.

The motivation to deal with the direct strike is that it is far more damaging, and a homeowner has no 'say' in what kind of lightning may strike his / her abode.

A second caveat that should be considered regarding testing is the development of test waveforms used by the CSST industry. Two waveforms, LC-1024 and LC-1027, are used to test the robustness of enhanced CSST products. LC-1024 is designed to simulate an indirect strike. [25] As noted earlier, indirect strikes are only part of the problem. The direct strike, while perhaps occurring less often, is capable of delivering a much greater charge of electrical energy.

An additional testing caveat relates to the use of CSST in steel structures. Photo 2, showing the routing of CSST through steel studs, is an example of what should have been tested for. Similarly, steel 'nailers' are meant to house and protect CSST from nail strikes. While steel does not have the magnetic properties of a soft ferrite, it still has the possibility to change response time of what is essentially an RL circuit. Similarly, should a separate bond be used to prevent flashover from the steel housing of a stud space to the CSST? Should nailer construction be changed such that brass (a non ferrous material) is required? These questions remain unanswered.

SUMMATION

While *some* electrical characterization of CSST has taken place, most of it has been after the installation of hundreds of millions of feet of the product. CSST does *not* have the robustness of black pipe, due to its susceptibility of damage from lightning. We gave demonstrated that what is deemed good electrical practice by the NFPA, through its 780 panel, has been completely ignored by the industry and by the NFPA 54 panel. The vulnerability of CSST to puncture has been shown to be enhanced by the focusing properties of the jacketing that has dielectric properties.

ABOUT THE AUTHORS

Mark Goodson received a BSEE from Texas A&M in 1979, and is licensed to practice engineering in numerous states. After engineering school, he attended UT Southwestern (Dallas) in a forensic medicine track. He was the first PE to serve on the State of Texas Electrical Board. From 1989 to 1991, he served as a Court Special Master. He is the PE selected to sit on the Texas State Fire Marshal Science Advisory Workgroup, SAW. He is a member of the Editorial Review Board for the *Fire & Arson Investigator*. Mr. Goodson is the principal in the firm Goodson Engineering of Denton, Texas. He holds 3 patents on fire safety, and has 4 more pending. He has published 35 peer reviewed technical articles, with 30 of them dealing with fire science. He has published in the *Fire & Arson Investigator*, *Journal of Forensic Sciences, American Journal of Forensic Pathology*, and the *Forensic Sciences Gazette*. Mr. Goodson serves as a consultant to many Medical Examiners' Offices in Texas.

Dr. Dave Icove is an internationally recognized expert on fire and arson investigation. Recruited by the FBI in 1983 to become one of their first criminal profilers at the Behavioral Science Unit in Quantico, Virginia, Dr. Icove developed the present-day motive classification system for arsonists. He has a PhD in Engineering, is the co-author of several textbooks including Forensic Fire Scene Reconstruction, Kirk's Fire Investigation, and Combating Arson-for-Profit. He has testified as an expert witness in federal and state courts, including three times before U.S. Congressional Committees regarding arson legislation. Retiring in 2005 as a Federal Law Enforcement Agent from the U.S. Tennessee Valley Authority Police, Dr. Icove is now a Research Professor in the College of Engineering at the University of Tennessee, Knoxville; and a Reserve Deputy in the Fire Investigations Unit of the Knox County Sheriff's Office. He is a licensed Professional Engineer in eleven states and was recently elected a Fellow in the Society of Fire Protection Engineers.

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