Does Corrugated Tubing + Lightning = Catastrophic Failure?

Robert A. Durham, *Senior Member, IEEE*, and Marcus O. Durham, *Life Fellow, IEEE*

***Abstract*—In conducting analysis of systems that have failed as a result of lightning and transients, the authors have observed repeated incidences associated with corrugated flexible tubing (CFT). Corrugated stainless-steel tubing is one of a group of flexible pipes used for low-pressure gas. This tubing is increasingly used not only in processes but also in laboratories, warehouses, and office facilities for distribution of heating gas. These products were designed with mechanical properties in mind. The design does not directly consider electrical characteristics; however, since these piping systems are constructed of conductive metals, they will have electrical properties. Despite the observed tendency of this piping to fail during lighting and transient events, there has been no coherent hypothesis for the phenomenon of CFT failure due to lightning. This paper will address the electromagnetic response of these tubing systems. Ten electrical properties are correlated to the impact of lightning and transients on materials such as corrugated tubing.**

***Index Terms*—Bonding, corrugated flexible tubing (CFT), corrugated stainless-steel tubing (CSST), Goubau line, grounding, lightning, transients.**

NOMENCLATURE

$\mathbf{q}$	Heat capacity (in BTU).
$\mathbf{C}$	Specific heat (in BTU per pound degree Fahrenheit).
$\mathbf{m}$	Mass (in pounds).
$\Delta\mathbf{T_m}$	Change in temperature (in degree Fahrenheit).
$\mathbf{H_f}$	Heat of fusion (in BTU per pound).
$\boldsymbol{\rho}$	Density (in pounds per cubic inch).
$\mathbf{L_{ser}}$	Series inductance (in microhenries).
$\mathbf{L_{par}}$	Parallel inductance (in millihenries).
$\mathbf{C_{ser}}$	Series capacitance (in millifarads).
$\mathbf{C_{par}}$	Parallel capacitance (in microfarads).
$\boldsymbol{\omega_d}$	Damped natural frequency (in radians)

I. INTRODUCTION

IN CONDUCTING analysis of systems that have failed as a result of lightning and transients, we have observed repeated incidences associated with corrugated flexible tubing (CFT) [1]. The authors have researched lightning and transient phenomena and protection in many different applications [2]–[8]. Lightning is a natural phenomenon that cannot be stopped. However, it can be controlled and the energy can be diverted [2], [7], [8].

Corrugated stainless-steel tubing (CSST) is one of a group of flexible pipes used for low-pressure gas. Another type of tubing that exhibits a similar response to lightning is a flexible copper pipe.

These materials were designed with mechanical properties in mind, but the design did not directly consider electrical characteristics. Since these piping systems are constructed of conductive metals, they will have electrical properties. The electrical properties of these piping systems determine the response of the tubing to electromagnetic energy such as lightning and other high-frequency phenomena.

Despite the widely recognized phenomena, there has been no coherent hypothesis for the phenomenon of CFT failure due to lightning. This paper will address the electromagnetic response of these tubing systems. A brief discussion of the characteristics of lightning is undertaken. Applicable codes and standards are addressed. Finally, ten electrical properties are correlated to the impact of lightning and transients on materials such as corrugated tubing. Practical implementations and configurations of piping systems to prevent damage from discharges will be addressed in future publications.

II. LIGHTNING TRANSIENTS

Before addressing the analysis of failures from lightning events, the characteristics of lightning and transients should be identified. There are three possible vehicles for lightning influence: 1) a direct strike; 2) an indirect strike or an induced potential; and 3) an earth charge.

For the first mechanism, a direct-strike lightning is simply the discharge of electromagnetic energy developed above the earth. It discharges through a conductive path to earth. The discharge path is often metal. However, stacks, trees, and posts in earth also make a good path. Concrete is also a possible path because of its low resistivity compared to most soils.

Fig. 1 shows the complete circuit of a lightning strike from the tower, through the cloud, and then back to earth in a fair-weather region. The charges on various structures, earth, and clouds are displayed as well. Note the electric field intensity under the cloud versus the fair-weather area.

Manuscript received June 23, 2010; accepted September 28, 2010. Date of publication May 18, 2012; date of current version July 13, 2012. Paper 2010-PCIC-256, presented at the 2010 IEEE Petroleum and Chemical Industry Technical Conference, San Antonio, TX, September 20–22, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Petroleum and Chemical Industry Committee of the iEEE Industry Applications Department.

R. A. Durham is with THEWAY Corporation, Tulsa, OK 74147 USA, and also with D^2 Tech Solutions, Madison, MS 39110 USA (e-mail: rdurham@ThewayCorp.com).

M. O. Durham is with THEWAY Corporation, Tulsa, OK 74153 USA, and also with The University of Tulsa, Tulsa, OK 74104 USA (e-mail: mod@ThewayCorp.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIA.2012.2200069

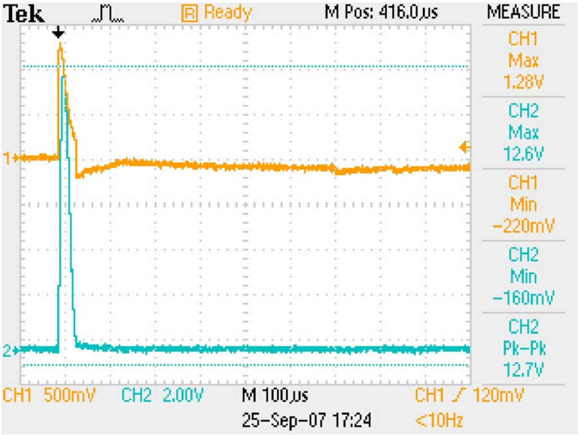

Fig. 1. Lightning discharge.

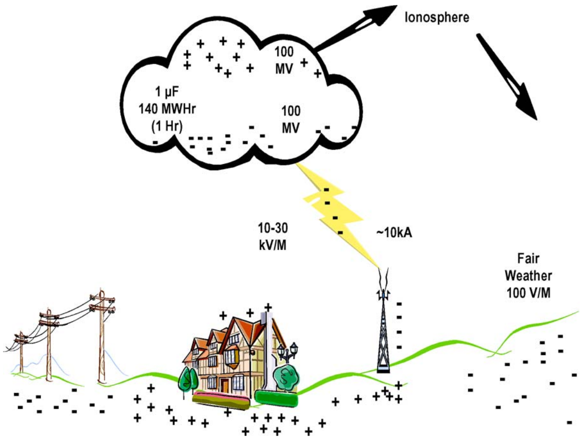

Fig. 2. Voltage and current transients.

The actual discharge is a direct strike. A direct strike carries the most energy and results in the most damage. This is what most people think of when they discuss a lightning strike.

The second mechanism, i.e., an indirect strike, will also result from a discharge. A potential is built up between the cloud and earth. Any conductive surface within this field will develop a proportional potential. When the cloud discharges, a charge remains on the metal and must be dissipated. This remaining energy will find all possible paths to earth.

The charge typically builds on a metal surface with a large area that rises above the earth. This may be a metal chimney, a flue pipe, an antenna, or a transmission line. The charge travels along the metal to a point of discharge. Energy can then discharge to a surface that has a lower impedance path to earth. Since the charge buildup, as well as the resulting potential difference, is quite large, it can easily "jump" across normal electrical insulation, as well as a substantial air gap.

For the third mechanism, i.e., earth charge, the earth will be energized by lightning in the area of impact. The charge creates a higher potential than both the surrounding earth and conductors in contact with the earth. The energy will dissipate to form a uniform field.

The result of this dissipation is current flow from the area of impact. All conductive paths in the area will develop current flow. Adjacent conductors will not develop a large potential difference. Remote conductors, however, can have a substantial difference in potential as a result of this earth charge.

III. STROKES

A lightning strike is not a single event. The strike begins with a downstroke toward the earth. An upward leader meets the stroke. A return stroke then completes the process. A detailed analysis is discussed in previous papers [2], [8].

As air is ionized from the initial strike, the impedance of the air is reduced. This may result in multiple strokes in a very short span of time. These may discharge to the same location or a nearby area. This would be recognized as multiple strokes.

A single strike will create a dispersed field near the area of discharge. The energy is not discharged at a single point; rather, it will be distributed to numerous spots. If the metal surface that carries the charge to earth is lightweight enough, the dispersed discharge will look like numerous pits on the metal surface.

St. Elmo's fire is visual plasma created by a corona discharge about a grounded object during a thunderstorm. The phenomenon clearly shows the dispersed effect of the electromagnetic field. We have observed that arrays in the field that distribute lightning energy create an effect of St. Elmo's.

Ball lightning is another dispersed electromagnetic field that is visible. Ball lightning is generally a spherical shape that develops and often travels along a conductor to a discharge point. It is a long-duration phenomenon and may last for seconds. The lead author has been fortunate to witness this rare phenomenon.

IV. FREQUENCY

Lightning has a radio-frequency range of about 100 kHz to an excess of 120 MHz. Furthermore, the transient wave-shape produces many harmonics.

Any comparison of transients requires a standardized test procedure. *ANSI C62.41* describes the industry-accepted waveform, applications, and test procedures [9]–[12]. A 1.2/50 wave-shape is used to evaluate open-circuit or voltage responses. A 1.2/50 wave-shape describes an impulse signal that rises from virtually zero to its crest in 1.2 μs and declines to one-half crest value in 50 μs. For short circuit or current responses, an 8/20 wave-shape is used.

The lightning-type waveform shown in Fig. 2 has the voltage on the top curve and the current on the bottom curve. These curves illustrate that lightning energy is a pulse with a very rapid rise and a slower decay time.

The standard waveform described in *C62.41* represents a nominal 1-MHz pulse. This frequency was appropriate for analysis when it was developed for power equipment. Unfortunately, it is not representative of faster lightning waveforms, which may be 100 times higher in frequency.

V. FAILURE PROCESS

Observation of numerous failures due to lightning has revealed a pattern that is consistent with electrical circuit analysis for high frequency. In the case of CFT, the lightning charge can

Fig. 3. Large surface with multiple discharge points.

Fig. 4. Charge is transferred at a heavy wall.

be derived via any of the three mechanisms. The energy transfer process is tabulated.

1) The entry energy is generally from a charge buildup on a large metal surface.
2) The charge is transferred to the metal pipe by a contact or a connection.
3) The charge exits from the metal pipe to a ground path such as other pipes, air conditioning lines, or electrical cables.
4) The entrance/exit charge creates arcing if it is through a heavy wall such as a connector.
5) The entrance/exit charge penetrates thin metal.
6) Bonding must be made between adjacent metals that can conduct lightning energy.
7) Grounding is ineffective unless performed closer than every 20 ft to an effective earthing point.

The photos in Figs. 3–6 illustrate the failure mechanisms.

VI. LITTLE HISTORY

An increase in lightning-related incidences has been observed in certain types of construction. Not so many years ago, metal water pipes were common. Black steel pipe was used for gas, and cast iron pipe was used for sewer.

When in contact with the ground, the metal lines are considered among the best of all grounding electrodes. In addition, the metal lines effectively bonded most of the metal in a structure. Any metal vent pipes or related protrusions above the structure were in effect bonded via contact with the metal lines. The heavy wall metal lines are no longer used in most construction.

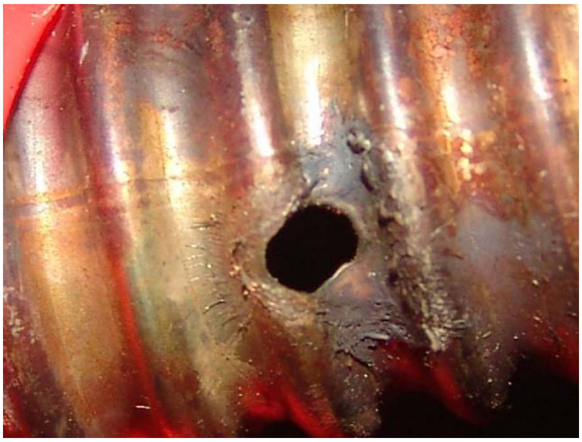

Fig. 5. Charge exit at a thin wall.

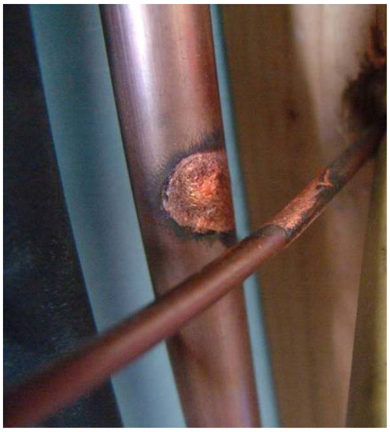

Fig. 6. Horizontal ground wire discharge to a vertical copper pipe.

Stacks were originally brick, stone, or masonry, not metallic, as most contemporary stacks are. Some structures would be somewhat conductive when wet, but in general, they were mostly insulators in good contact with earth.

The proliferation of metal stacks and flue pipes acts as an attraction and energy storage for lightning. These flues are large-area structures and easily become charged when a cloud passes over. Potential charge buildup exists even if the metal is not exposed to a direct strike. In order to control this buildup, metal vent flues must be bonded to a grounding electrode system.

The "Lightning Code" (*NFPA 780*) addresses the thickness of steel that is acceptable to withstand a lightning strike [13]. If that thickness is not used for vents and other metal exposed to lightning, then the metal must be effectively bonded and grounded.

Arcing and damage will exist only where there is not a good continuous low-impedance high-current-capacity path to ground.

VII. STANDARD PRACTICE

NFPA 70, National Electrical Code (NEC) is predominantly structured for 60-Hz alternating-current power that is well behaved [14]. NEC designs are inadequate and inappropriate for high-frequency energy such as lightning.

NFPA 780, Standard for the Installation of Lightning Protection Systems addresses lightning installations [13].

IEEE 142, Grounding for Industrial and Commercial Power Systems addresses grounding for general structures [15].

Other standards such as *API 2003, Protection Against Ignitions Arising out of Static, Lightning, and Stray Currents* consider specific conditions for petroleum environments [16].

Other sources of design practices are published papers and articles by authorities in the field.

The use of these standards and design practices has produced equipment and installations that safely operate in a concentrated hydrocarbon (oil and gas) environment in the presence of lightning. CFT is being used as a gas pipe. If it is expected to operate acceptably, it is imperative that it complies with and would be installed according to these well-recognized long-used industry standards and practices.

VIII. TEN INCONGRUITIES

The flexible tubing consists of three components, namely, the pipe, the end connectors, and the jacket around the pipe. The combination of these components defines the electrical characteristics of the tubing.

There are ten areas that relate to the electrical properties and resulting failures of corrugated piping in the presence of high-frequency energy as follows:

1) jacket thickness;
2) wall thickness;
3) tuned resonator;
4) high-frequency impedance;
5) wire size;
6) number of grounding connections;
7) bonding;
8) voltage levels;
9) damage at high levels;
10) electromagnetic waveguide.

Each of these areas will be investigated for its contribution to the failure mechanism.

A. Jacket Thickness

A typical jacket on CSST is polyvinyl chloride (PVC). The thickness of the PVC is nominally 20 mils. A PVC material is suitable for electrical insulation. The authors have chaired industry standards and published numerous papers based on their research and testing of insulation materials for high-energy hazardous environments [17]–[21].

Insulations are typically tested at rated voltage plus 1000 V. A 600-V rated cable constructed of similar PVC material has a 45-mil wall thickness [14]. As the insulating value of a material is dependent on its thickness, we can use this to estimate the insulating values of the PVC jacket. In addition, 20 mils of PVC have an effective rating of about 300 V. As insulation, a 300-V rating is not adequate for high-energy transients such as lightning.

TABLE I
MATERIAL PROPERTIES

Material	*q*
CSST	0.00765
Black	0.0949
Alum	0.0112
Copper	0.0271

Insulations such as the 20-mil jacket on CSST act like a dielectric, which creates a capacitor between the flexible tubing and any other conductive surface nearby. The dielectric properties allow a charge buildup on the metal tubing, which must be then discharged, creating a point of potential damage.

Point 1: A 20-mil PVC jacket has effectively no insulation characteristics when dealing with lightning level energy.

B. Wall Thickness

The susceptibility of metal to heat damage is directly related to its mass. Mass is dependent on material properties and volume. A pipe of the same length and diameter will have mass proportional to wall thickness. Thicker walls will have more mass and less propensity for heat damage.

It is recognized by *NFPA 780* that steel with a wall thickness of 3/16 in (0.1875 in) will not be damaged by lightning [13].

The black pipe used for gas has a nominal wall thickness of 0.109 in for 1/2-in-diameter schedule 40 construction. Other sizes and ratings have varying thickness. Although still below the safe thickness, the wall is substantial and will seldom be penetrated.

A copper tubing of 0.033 in that is well grounded is used for lightning rods without significant damage [13]. The extensive large-conductor grounding-and-bounding system protects the electrodes from damage.

The wall thickness of CSST is 0.008 to 0.010 in (8–10 mils). This is very thin and is approximately the thickness of an aluminum beverage can.

The actual energy that will create a hole is given by the heat transfer equation

$$q = Cm\Delta T_m + mH_f. \tag{1}$$

Heat capacity q (see Table I) is the energy required to raise the temperature of the material to the melting point, and then to actually melt the material. C is the specific heat, which is the energy to raise the temperature of the mass by one degree. H_f is the heat of fusion, which is the energy for a mass to change state. ΔT_m is the temperature change from the initial to the melting temperature. In addition, m is the mass being translated. Mass can be calculated by combining the volume of the material that changes state (melts) and the density of the material ρ.

The properties of various pipes and tubings are well-known chemical properties. The materials of interest have been collected by others when comparing heat to melt pipe [22]. All pipe and tubing in Table II is nominal 1/2-in diameter. Wall thickness is given in inches.

Compare the amount of energy required to create a 100-mil-diameter hole in each of the pipes.

TABLE II
HEAT

Material	C	ΔT_m	H_f	ρ	Wall
CSST	0.12	2528	122.527	0.286	0.008
Black	0.1	2678	122.7	0.284	0.109
Alum	0.215	1148	170	0.09751	0.035
Copper	0.092	1909	91.1	0.324	0.04

TABLE III
IMPEDANCE OF TUBING

Diameter	Length	Type	R Ohm	L ser μHy	L par mHy
1/2	7	CSS	0.264	1.2	1.9
1/2	7	CSS+connect	0.257	1.2	1.4
1/2	20	CSS	0.62	5.6	1.66
1/2	20	CSS+connect	0.52	5.6	1.55
1.25	6	CSS	0.206	0.4	2.27

Note the significantly lower level of energy required to penetrate CSST versus other piping types. As an example of this phenomenon, Figs. 5 and 6 show damage to components on the same pipe system that were exposed to the same energy. Clearly thin wall stainless steel (SS) is more likely to be damaged.

Point 2: The energy to damage the thin wall (0.008 in) of a flexible steel tubing is 12 times less than the energy required to damage a thicker (0.12 in) black steel pipe.

C. Tuned Resonator

Impedance is the opposition to electromagnetic energy. Impedance Z consists of three components. The resistance R component represents the conversion of electromagnetic energy to heat. The capacitance C component represents the electric charge. The inductance L component represents the magnetic capability.

All conductors have an inherent property of resistance. The shape of the conductor and how it is bent creates an inductance. Any long conductor has an inductance component regardless of size.

The electrical resistance and inductance of the corrugated tubing were measured to obtain the electrical circuit passive values for a relatively straight pipe shown in Table III.

The readings were obtained using a Philips PM6303 meter operating at 1 kHz. Because of the electrical characteristics of impedance, the capacitance and inductance effects will combine to only show a net effect. These are relative numbers. The dress and shape of leads makes a substantial difference in the readings. In particular, the capacitance component will vary.

Lines two and five of Table III show values with the manufacturer-supplied brass connectors in place on the CSST. These connectors are used to connect the CSST to other gas piping systems, such as the service entrance.

An observation of particular note is that the value of the resistance and the parallel inductance decreases when the connectors are added. The brass-to-SS connection (see Table IV) creates a cathodic cell with capacitive effects. The voltage across the cell appears as a negative resistance to the meter.

TABLE IV
BRASS TO SS

Type	R Ohm	C ser mFd	C par μFd
Connection	0.96	40	50

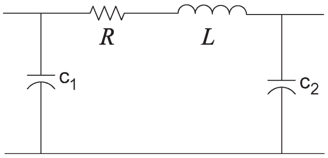

Fig. 7. CSST circuit model.

Of more significance to an electrical analysis, the capacitance at the connector joined with the resistance and inductance of the flexible tubing creates a tuned circuit with a natural frequency. The circuit model is shown in Fig. 7.

The natural frequency ω_d of this tuned circuit can be calculated from

$$\omega_d = \sqrt{\left(\frac{1}{\sqrt{LC}}\right)^2 - \left(\frac{R}{2\sqrt{L/C}}\right)^2}. \tag{2}$$

Resonance occurs when the natural frequency matches a lightning transient frequency component. Resonance is the point when peak energy is transferred. Greater energy transfer will increase heating effects in the resistance and will result in increased damage.

Point 3: Dissimilar metals on the tubing and connectors create a cathodic cell with capacitance and, consequently, a natural frequency.

D. High-Frequency Impedance

For high-frequency transients such as lightning, impedance is a critical electrical parameter. Impedance is highly sensitive to frequency f

$$Z = R + j2\pi fL. \tag{3}$$

The performance of any conductor at high frequency (in megahertz) is considerably different than the performance at 60 Hz or direct current (0 Hz). Considering frequency alone, the inductance effect for lightning is a million times greater than that at power-line frequencies.

The analysis used for power-line frequencies, therefore, cannot be applied to lightning frequencies. Unfortunately, most engineers allow their power frequency experience to interfere with investigation of lightning-related events.

The metal of the pipe system is an electrical conductor. The impedance of the pipe path increases with higher frequency from transient energy, including lightning. Consequently, there is an increased tendency for the energy to find an alternative path with lower impedance. When energy flows through the tubing, damage can occur where energy enters or exits the tubing (point of discharge).

The resistance of the corrugated pipe is roughly 30 $\text{m}\Omega/\text{ft}$, which is in the neighborhood of the resistance of AWG 22 wire. For a typical length of 50 ft, the total resistance is 1.5 Ω.

As a circuit element, the tubing is an effective inductor. The inductance correlates to that of a long straight wire. Typical inductance for this size conductor is 0.5 μH/ft [23].

For a lightning pulse of 1 MHz, the inductive reactance is 3 Ω/ft. For 10 MHz, the impedance increases to 30 Ω/ft. At 100 MHz, the opposition is an astounding 300 Ω/ft. Furthermore, the inductance and resultant impedance will substantially increase as the conductor pipe is bent

$$\begin{aligned} X_L &= 2\pi f L = 2\pi(100 \times 10^6)(0.5 \times 10^{-6}) \\ X_L &\approx 300\ \Omega/\text{ft}. \end{aligned} \tag{4}$$

At these values of impedance, energy on the pipe will attempt to discharge to surrounding materials. Our previous research for long inductive conductors has shown that, at lengths greater than 20 to 30 ft, the metal pathway is no longer an effective conductor [2], [8].

At higher frequencies of 100 MHz, a 10-ft length of a 1/2-in conductor will have an impedance value of 3000 Ω. Others have done tests specifically with CSST [24]. Their results show that, at conductor lengths greater than 10 ft, there will be a discharge from CSST. This result is consistent with the circuit model just discussed.

To summarize, the impedance of the flexible tubing has three competing effects. The capacitance creates a charge. The resistance creates a conductive path. However, the inductance creates so much impedance that the charge and resulting current attempt to leave the tubing for a lower impedance path. The metal makes the tubing a conductor, but the inductance increases impedance and causes the current to discharge from the pipe.

Point 4: The impedance due to inductance and frequency is so large that resistance is insignificant.

E. Wire Size

The grounding issues in *NEC* Article 250 are predominantly oriented to 60-Hz electrical power and for personnel safety. The grounding requirements do not conform to high frequency. Other standards such as *NFPA 780* must be considered for higher frequency protection.

NEC allows the grounding equipment conductor to be the grounding mechanism for the gas pipe. The wire size corresponds to the current rating of the circuit. In most circuits, that will be AWG 12. This equipment grounding conductor is installed for personnel safety.

Manufacturers have developed a recommendation of directly bonding a CSST connector to ground with AWG 6 wire. This size is next to the minimum wire in the *NEC* for a grounding electrode conductor [14]. Again, the size is based on the capacity of the supply circuit.

For handling lightning energy, *NFPA 780* is the recognized standard. According to this standard, the minimum allowable size for a copper main conductor cable is 57 400 cm (1/0 AWG) [13]. The size is huge in comparison with the previous two wire sizes used with pipe.

Point 5: NEC equipment bonding standards are not the appropriate reference for handling lightning conditions.

F. Number of Grounding Connections

As illustrated earlier in the impedance discussion, the total pathway length for controlling lightning must be very short and with the minimum number of bends.

To distribute energy, *NFPA 780* requires at least two paths from any electrode. Furthermore, the electrodes in a standard configuration can be a maximum of 20 ft apart.

These values correlate with our previous research and publications that were developed independent of *NFPA 780* [2], [3], [22].

Tests by others using CFT in particular have shown that, to prevent arcing, the maximum length a bond can be is 10 ft [24]. In essence, a grounding system must be connected within 10 ft of any point on the corrugated tubing.

Point 6: Multiple grounding conductors must be used.

G. Bonding

Bonding is a separate issue from grounding. Grounding for lightning is to carry the energy to earth where it can be dissipated. Bonding is a connection between adjacent metals to prevent a potential from developing between the metals. Bonding is an attempt to create an equal potential so that current will not flow, and potential differences do not exist.

Both the *NEC* and *NFPA 780* direct that metal parts shall be bonded under numerous conditions and constraints [13], [14]. Perhaps the most common and readily identified metal interconnection requirement in the *NEC* is metal within 8 ft vertically or 5 ft horizontally of ground or grounded metal objects and subject to contact by persons. The distances are primarily a touch potential issue rather than an arcing issue.

Considering our observations about lightning, electrical systems, and risk of damage, several points should be considered.

1) Bond large protruding metal surfaces to earth.
2) Bond the flexible tubing and pipe to earth.
3) Isolate any crossing metal surface for a distance greater than the arcing distance.
4) If it is necessary to cross, bond between the pipe and any metal surface within the arcing distance.

One bond is not adequate because of the electromagnetic energy differential between locations.

Point 7: Bonding is a system not a single point.

H. Voltage Levels

Lightning has tremendous energy. Lightning is a high-frequency high-potential high-current signal. The potential of a strike is about 300 kV to 1 000 000 V according to NASA reports. The voltage corresponds to very large electrical power transmission lines. The peak current is about 120 kA with a typical value of 40 kA. As noted earlier, the frequency can be in excess of 100 MHz.

Energy stored on a conductor will arc across free space. The dielectric strength of dry air is an electric field gradient of about 30 000 V/cm. Since lightning can create energy fields far in excess of that value, it is not unusual to find arcing over a considerable distance. Once the air is energized and an ionized path develops, the distance will be much greater.

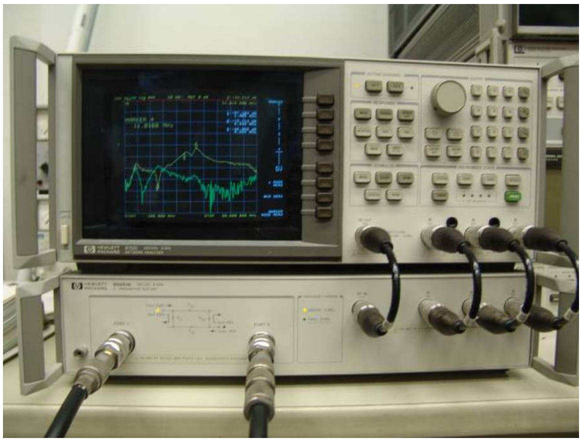

Fig. 8. Spectrum analyzer.

Evaluation of damage due to lightning effects must consider these very large voltages. For low-voltage equipment (< 1000 V) and sensitive electronic devices, standard tests are conducted up to 6000 V. These are simply breakdown of insulation and are not necessarily intended to study mechanical damage to the components due to high voltages.

For evaluation of mechanical damage such as heating and welding due to lightning energy, evaluation must be necessarily conducted at voltages that correlate to the temperature of the heat generated from the lightning event. Tests at 6000 V provide little information.

Point 8: Lightning voltage thermal correlations require up to hundreds of kilovolts.

I. Damage at High Levels

The extent of damage to components with electrical characteristics is dependent on the physical phenomenon of the installation. The major variables are the following:

1) energy level of the lightning discharge;
2) configuration of the tubing, including diameter, length, and bends;
3) ground electrode resistance;
4) bonding impedance to other metal.

A lightning-related discharge will create a carbon path. This path is conductive and will allow more current to flow. This, in turn, creates a larger path until failure occurs. A typical low-level damage to the flexible tubing is a small-diameter hole, as shown in Fig. 5. However, at elevated potential and current, damage has resulted in rupture and separation of the pipe.

Point 9: Lightning effects range from arc tracks to rupture.

J. Electromagnetic Waveguide

The response of the corrugated tubing to an electromagnetic field was evaluated. Tests were conducted using a spectrum analyzer, as shown in Fig. 8. A horn radiator was used to transmit the signal toward a CSST pipe. Another horn antenna was used to receive the signal from the pipe.

At higher frequencies, the pipe was a good electromagnetic signal conductor. The performance increased with frequency.

To verify that the CSST was the waveguide, the horns were reoriented and the pipe was moved. The signal always followed the pipe regardless of its orientation.

In a conventional waveguide, electromagnetic waves and energy are transmitted on the interior of the conductor. However, there is a class of waveguides that conveys electromagnetic waves on the exterior surface of the conductor.

In 1899, Sommerfeld demonstrated that a surface wave could be transmitted along a cylindrical conductor [25]. In the 1950s, Goubau showed that a single conductor will propagate a surface mode wave with low attenuation.

The tubing appears to have some characteristics of a Goubau waveguide transmission line. This is a single conductor that carries electromagnetic energy. The magnetic wave measured by the H field is circular about the conductor. The electric wave measured by the E field is perpendicular to the surface. The energy propagates along the length of the conductor.

Goubau demonstrated that the waveguide performance could be enhanced by two simple techniques that keep the wave along the conductor, i.e., thin layer of dielectric material and corrugation of the surface.

The Goubau transmission line depends on the physics of the conductor. The first requirement is a dielectric about the conductor. The dielectric keeps directing the electric field back toward the conductor. The PVC jacket on the CSST tubing is a dielectric. Second, corrugation on the surface of the line would enhance its electromagnetic properties.

Lightning creates a surface wave along the earth. The wave appears to readily traverse a corrugated tubing. The properties that make the tubing flexible and offer some mechanical protection (corrugation and PVC jacket) are the properties that contribute to the tubing being an electromagnetic transmission line.

The precise mechanism and model that supports the waveguide response has not been identified and requires further research; nevertheless, it has been adequately measured in the laboratory that a corrugated flexible pipe is an effective carrier of electromagnetic energy at frequencies above 10 MHz. The energy transfer is through the air without mechanical contact with an electrical source.

Point 10: The pipe will guide high-frequency electromagnetic energy such as lightning and transients.

IX. CONCLUSION

A lightning event imparts significant energy on conductors in the area of a discharge. These conductors include not only electrical conductors but also other metallic conductive systems such as gas pipe. On any piping system, lightning damage is more likely when the following conditions exist.

1) The transient energy is large.
2) Large metal surfaces protrude above other grounded surfaces.
3) Metal conductors have sharp changes in direction, including corrugation and bends.
4) Metal conductors have thin mass.
5) The conductor is poorly grounded.
6) Inadequate bonding is provided between metal.

7) The location is at the end of the line that carries the transient.

The electromagnetic characteristics of CSST make it particularly susceptible to lightning damage. Ten characteristics of CSST that influence damage from lightning or transient events have been identified as follows:

1) jacket thickness;
2) wall thickness;
3) tuned resonator;
4) high-frequency impedance;
5) wire size;
6) number of grounding connections;
7) bonding;
8) voltage levels;
9) damage at high levels;
10) electromagnetic waveguide.

REFERENCES

[1] *NFPA 921: Guide for Fire and Explosion Investigations*, Nat. Fire Protection Assoc., Quincy, MA, 2004.

[2] M. O. Durham and R. Durham, “Lightning, grounding, and protection for control systems,” *IEEE Trans. Ind. Appl.*, vol. 31, no. 1, pp. 45–54, Jan./Feb. 1995.

[3] M. O. Durham and R. Durham, “Grounding system design for isolated locations and plant systems,” in *Proc. Inst. Elect. Electron. Eng. Petroleum Chem. Ind. Committee*, Denver, CO, Sep. 1995, pp. 145–153.

[4] M. O. Durham and R. A. Durham, “Ground system design considerations for vessels,” *IEEE Ind. Appl. Mag.*, vol. 7, no. 6, pp. 41–49, Nov./Dec. 2001.

[5] M. O. Durham and R. A. Durham, “Data quality and grounding in mixed use facilities,” *IEEE Ind. Appl. Mag.*, vol. 12, no. 3, pp. 67–73, May/Jun. 2006.

[6] M. O. Durham, R. A. Durham, and K. D. Durham, “Transient voltage surge suppression design and correlation,” *IEEE Ind. Appl. Mag.*, vol. 8, no. 5, pp. 31–36, Sep./Oct. 2002.

[7] M. O. Durham and R. A. Durham, “Flat Earth Society Perception of Grounding,” in *Proc. Frontiers Power Conf.*, Stillwater, OK, Oct. 2006.

[8] M. O. Durham, R. A. Durham, R. Overton, and C. Ozment, “Lightning damage: An act of god or act of negligence,” in *Proc. 40th Annu. Frontiers Power Conf.*, Stillwater, OK, Oct. 2007.

[9] *IEEE Standard for Gapped Silicon–Carbide Surge Arresters for AC Power Circuits*, ANSI/IEEE Std. C62.1-1989, 1990.

[10] *IEEE Guide for the Application of Gapped Silicon–Carbide Surge Arresters for Alternating Current Systems*, ANSI/IEEE Std. C62.2-1987, 1989.

[11] *IEEE Guide for the Connection of Surge Arresters to Protect Insulated, Shielded Electric Power Cable Systems*, ANSI/IEEE Std. C62.22.1-1996, 1997.

[12] *IEEE Standard Test Specification for Gas-Tube Surge Protective Devices*, ANSI/IEEE Std. C62.31-1987.

[13] Nat. Fire Protection Assoc., Quincy, MA, *NFPA 780: Standard for the Installation of Lightning Protections Systems*, 2000.

[14] *NFPA 70: National Electrical Code*, Nat. Fire Protection Assoc., Quincy, MA, 2011.

[15] *Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book)*, IEEE Std. 142, 1991.

[16] *API 2003, Protection Against Ignitions Arising out of Static, Lightning, and Stray Currents*, Amer. Petroleum Inst., Washington, DC, 1991.

[17] M. O. Durham, R. A. Durham, and R. Hulett, “History and development of IEEE standards for downhole cable,” *IEEE Trans. Ind. Appl.*, vol. 43, no. 2, pp. 436–443, Mar./Apr. 2007.

[18] M. O. Durham, R. A. Durham, and D. Anderson, “What are standardized equations for acceptance of hi-pot tests and for voltage drop?” in *Proc. PCIC*, Indianapolis, IN, Sep. 1998, pp. 281–287.

[19] M. O. Durham, D. H. Neuroth, K. Ashenayi, and T. Wallace, “Field test technology relationships to cable quality,” *IEEE Trans. Ind. Appl.*, vol. 31, no. 6, pp. 1381–1389, Nov./Dec. 1995.

[20] G. Baker and M. O. Durham, “Correlations of submersible cable performance to Neher–McGrath ampacity calculations,” *IEEE Trans. Ind. Appl.*, vol. 28, no. 2, pp. 282–286, Mar. 1992.

[21] M. O. Durham and J. Vandevier, “Electrical submersible pump cable standards and specifications preview,” *IEEE Trans. Ind. Appl.*, vol. IA-20, no. 5, pp. 1367–1471, Sep./Oct. 1984.

[22] M. Goodson and M. Hergenrether, *Investigating the Causal Link between Lightning Strikes, CSST, and Fire*, Oct. 2005.

[23] *The ARRL Handbook*, Amer. Radio Relay League, Newington, CT, 2000.

[24] B. Kraft and R. Torbin, *Effectiveness of Direct Bonding of Gas Piping in Mitigating Damage from an Indirect Lightning Flash*, 2007. [Online]. Available: http://thecuttingedgellc.com/html/bonding.html

[25] R. E. Collin, *Field Theory of Guided Waves*, 2nd ed. New York: IEEE Press.

Robert A. Durham (S’90–M’92–SM’06) received the B.S. degree in electrical engineering and the M.E. degree in technology management from The University of Tulsa, Tulsa, OK, and the Ph.D. degree in engineering management from Kennedy Western University, Cheyenne, WY.

He is the Principal Engineer of D^2 Tech Solutions, Madison, MS, an engineering- and technology-related firm concentrating on mechanical and electrical systems and conversions. He is also the Chief Engineer of THEWAY Corporation, Tulsa, an engineering, management, and operations group that conducts training, develops computer systems, and provides design and failure analysis of facilities and electrical installations. He specializes in power systems, utility competition, controls, and technology integration. He also served as President of Pedocs Inc., a natural resources developer. He is a nationally recognized author and has published magazine articles on multiple occasions.

Dr. Durham is registered as a Professional Engineer in five states. His work experience is broad and encompasses all areas of the power industry. His technical emphasis has been on all aspects of power systems from electricity-generating stations to EHV transmission systems and to large-scale distribution systems and power applications for industrial locations. He has received several awards from technical and professional organizations such as the IEEE. His extensive client list includes the development of a broad spectrum of forensic, electrical, and facilities projects for many companies. He is also involved with the audit of market participants in competitive utility markets to ensure that these facilities are adhering to the rules of the market.

Marcus O. Durham (S’64–M’76–SM’82–F’93–LF’11) received the B.S. degree in electrical engineering from Louisiana Tech University, Ruston, LA, the M.E. degree in engineering systems from The University of Tulsa, Tulsa, OK, and the Ph.D. degree in electrical engineering from Oklahoma State University, Stillwater.

He is the Principal Engineer of THEWAY Corporation, Tulsa, a company that provides design and failure analysis of facilities and electrical installations. He is also a Professor at The University of Tulsa. He has published seven books and three e-books used in university-level classes.

Dr. Durham is a Registered Professional Engineer, a State-Licensed Electrical Contractor, a Federal Communications Commission-Licensed Radiotelephone Engineer, an Extraclass Amateur Radio Operator, and a Commercial Pilot. His professional recognition includes Fellow of the American College of Forensic Examiners (ACFE), Diplomate of the American Board of Forensic Engineering and Technology, Certified Homeland Security by the ACFE, Certified Fire and Explosion Investigator by the National Association of Fire Investigators, member of the Society of Petroleum Engineers, Task Group Member of the American Petroleum Institute, member of the National Fire Protection Association, and member of the International Association of Arson Investigators. He was the recipient of the IEEE Richard Harold Kaufmann Medal “for development of theory and practice in the application of power systems in hostile environments.” He was recognized with six IEEE awards for his standards development work. He has been awarded numerous times for the more than 130 technical papers he has authored. He is acclaimed in Who’s Who of American Teachers, National Registry of Who’s Who, Who’s Who of the *Petroleum and Chemical Industry of the IEEE*, *Who’s Who in Executives and Professionals*, *Who’s Who Registry of Business Leaders*, Congressional Businessman of the Year, and Presidential Committee Medal of Honor. Honorary recognition includes Phi Kappa Phi, Tau Beta Pi, and Eta Kappa Nu.