LIGHTNING, TRANSIENT & HIGH FREQUENCY IMPACT ON MATERIAL SUCH AS CORRUGATED TUBING

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Abstract – 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.

The nature and frequency of lightning strokes is considered. The failure process is investigated. Standards and articles provide adequate minimum design for installation.

Ten areas of electrical systems correlate to lightning impact. These are (1) jacket thickness, (2) wall thickness, (3) cathodic cell, (4) high frequency impedance, (5) wire size, (6) number of grounding connections, (7) bonding, (8) voltage levels, (9) damage at high levels, and (10) electromagnetic waveguide.

Actual photos illustrate lightning interaction on a charged metal surface, transfer of energy to a pipe system, exit damage on a pipe, and intense arcing on a grounding electrode conductor.

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 phenomenon and protection in many different applications [2,3,4,5,6,7,8]. Lightning is a natural phenomenon that cannot be stopped. However, it can be controlled and the energy diverted.

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 flexible copper pipe.

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

Previously, there has been no coherent hypothesis for the phenomenon of corrugated flexible tubing 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 material such as corrugated tubing.

LIGHTNING TRANSIENTS

Before addressing the failure analysis, the characteristics of lightning and transients should be identified. There are three possible vehicles for lightning influence. These are (1) a direct strike, (2) indirect strike or induced potential, and (3) 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, 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.

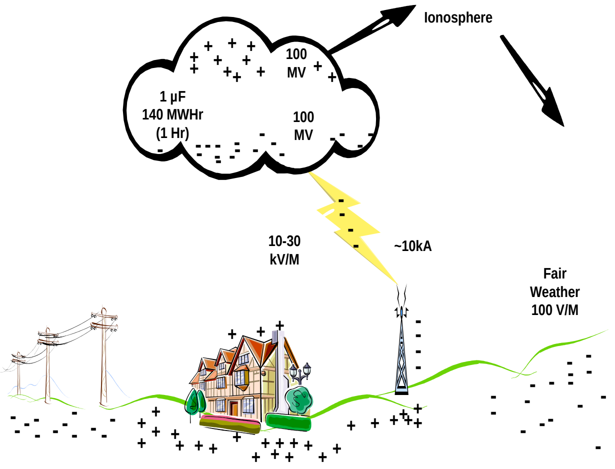

Figure 1: Lightning discharge

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

The second mechanism, 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, flue pipe, antenna, transmission line, or similar conductor. The charge travels along the metal to a point of discharge. The energy then can discharge to a surface that has a lower impedance path to earth. Since the charge build-up and 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, 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.

STROKES

A lightning strike is not a single event. The strike begins with a down stroke 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; 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 arrays which 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 which 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.

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 [9,10,11,12]. 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 Figure 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.

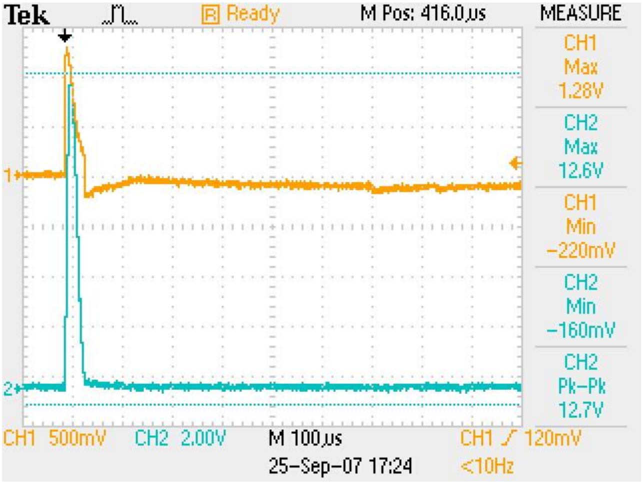

Figure 2: Voltage and current transients

The standard waveform described in *C62.41* represents a nominal 1 MHz pulse. That frequency was appropriate for analysis when it was developed for power equipment.

Unfortunately, it will not be representative of faster lightning waveforms which may be 100 times higher in frequency.

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 pipe, the lightning charge can be derived via any of the three mechanisms. The energy transfer process is tabulated.

1. The entry energy is generally from a charge build up on a large metal surface.
2. The charge is transferred to the metal pipe by contact or a connection.
3. The charge exits from the metal pipe to a ground path such as other pipes, air conditioning lines, or NM electrical cable.
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 metal that can conduct lightning energy.
7. Grounding is ineffective unless performed closer than every 20 feet to an effective earthing point.

The photos in figures 3 through 6 illustrate the failure mechanisms.

A LITTLE HISTORY

An increase in lightning related incidences has been observed in certain types of construction. Not so many years ago, metal water pipe was 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

Figure 3: Large surface with multiple discharge points

Figure 4: Charge is transferred at heavy wall

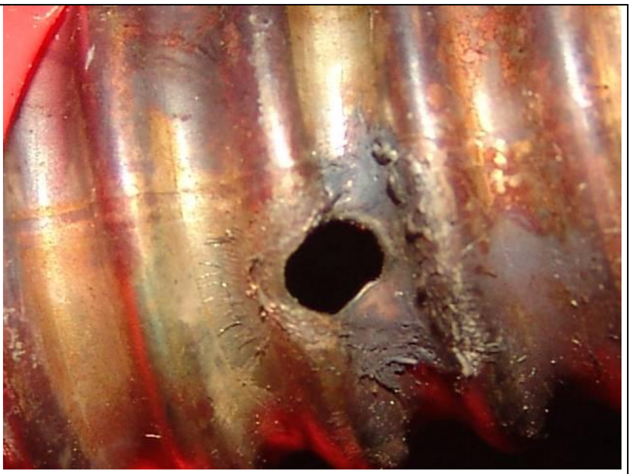

Figure 5: Charge exit at thin wall

Figure 6: Horizontal ground wire discharge to vertical copper pipe.

no longer used in most construction, resulting in loss of a bonding and grounding system.

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

The proliferation of metal fireplace stacks and flue pipes act 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.

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. As noted earlier, the authors have written numerous peer-reviewed award-winning papers on the topic of grounding and protection from lightning damage in the presence of oil and gas.

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. Corrugated flexible tubing is being used as a gas pipe. If it is expected to operate acceptably, it is imperative that it comply with and be installed according to these well recognized, long used industry standards and practices.

TEN INCONGRUITIES

Flexible tubing consists of three components: 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.

1. Jacket thickness
2. Wall thickness
3. Cathodic cell
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.

JACKET THICKNESS

A typical jacket on CSST is polyethylene. The thickness of the thermoplastic polymer is nominally 20 mils. The 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 [17,18,19,20,21].

Insulations are typically tested at rated voltage plus 1000 volts. A 600 volt rated cable constructed of similar polymer 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 thermoplastic jacket. 20 mils of polyethylene have an effective rating of about 300 volts. As insulation, a 300V rating is not adequate for high energy transients such as lightning.

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

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

WALL THICKNESS

The susceptibility of metal to heat damage is directly related to its mass. Mass is dependent on material properties and volume. Pipe of the same material, 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 inches (0.1875") will not be damaged by lightning [13].

Black pipe used for gas has a nominal wall thickness of 0.109 inches for ½-inch 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.

Copper tubing of 0.033 inches, which is well grounded, is used for lightning rods without significant damage [13]. The extensive, large conductor, grounding and bounding system protect the electrodes from damage.

The wall thickness of corrugated stainless steel tubing is 0.008 to 0.010 inches (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.

$$q = Cm\Delta T_m + mH_f$$

The heat capacity (q) is the energy required. 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. And m is the mass being translated.

The properties of various pipe and tubing 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 1 is nominal ½-inch diameter [23].

Table 1 – Material Properties

Material	*C* *BTU/lbm F*	*ΔT_m* *F*	*H_f* *BTU/lbm*	*Density* *lbm/in^3*	*Wall* *in*
CSST	0.12	2528	122.53	0.286	0.008
Black	0.10	2678	122.7	0.284	0.109
Alum	0.215	1148	170	0.0975	0.035
Copper	0.092	1909	91.1	0.324	0.04

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

Table 2 - Heat

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

Figures 5 and 6 are on the same pipe system and exposed to the same energy. Clearly thin wall is more likely to be damaged.

Point 2: The energy to damage the thin-wall (0.008") of flexible steel tubing is 12 times less than the energy required to damage thicker (.109") black steel pipe.

CATHODIC CELL

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 corrugated tubing was measured to obtain the electrical circuit passive values for relatively straight pipe shown in Table 3.

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.

Table 3 – 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+conn	0.257	1.2	1.4
1/2	20	CSS	0.62	5.6	1.66
1/2	20	CSS+conn	0.52	5.6	1.55
1.25	6	CSS	0.206	0.4	2.27

An observation of particular note is the value of the resistance and the parallel inductance decreases when the coupling is added. The brass to stainless steel connection creates a cathodic cell with capacitive effects. The voltage across the cell appears as a negative resistance to the meter.

Table 4 – Brass to SS

Type	*R Ohm*	*C ser mFd*	*C par µFd*
Coupling	0.96	40	50

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.

Resonance occurs when the natural frequency matches a lightning transient frequency component. Resonance is the point that 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 a capacitance and consequently a natural frequency.

HIGH FREQUENCY IMPEDANCE

For high frequency transients such as lightning, impedance is a critical electrical parameter. The impedance is highly sensitive to frequency (*f*).

$$Z = R + j2\pi fL$$

The performance of any conductor at high frequency (MHz) 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 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 enters and exits tubing, damage can occur at the point of discharge.

The resistance of the corrugated pipe is roughly 30 mΩ / foot, which in the neighborhood of the resistance of AWG 22 wire. For a typical length of 50 feet, the total resistance is 1.5 Ohms.

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 µHy per foot [24].

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

$$X_L = 2\pi fL = 2\pi(100 \text{ x}10^{6})(0.5 \text{ x}10^{-6}) \approx 300\ \Omega/\text{ft}$$

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 feet to 30 feet, the metal pathway is no longer an effective conductor [2,8].

At higher frequencies of 100 MHz, a 10 foot length of ½-inch conductor will have an impedance of 3000 Ohms. Others have done tests specifically with CSST [25]. Their results show that at conductor lengths greater than 10 feet, there will be a discharge from CSST. That 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 the resistance is insignificant.

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 equipment grounding conductor to be the grounding mechanism for appliance gas pipe. The wire size corresponds to the current rating of the circuit. This may be as small as AWG 14. This equipment grounding conductor is installed for personnel safety.

Manufacturers have developed a recommendation of direct 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 is 57,400 CM (1/0 AWG) [13]. That is huge in comparison to the previous two wire sizes used with pipe.

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

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 feet apart.

These values correlate with our previous research and publications which were developed independent of *NFPA 780*.

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

Point 6: Multiple grounding conductors must be used.

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 metal 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 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. The high impedance creates a large voltage difference in a short distance.

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

VOLTAGE LEVELS

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

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 Volts per centimeter. Since lightning can create energy fields much in excess of that value, it is not unusual to find arcing over a considerable distance. Once the air is ionized, the arcing distance will be much greater.

Evaluation of damage due to lightning effects must consider these very large voltages. For low voltage equipment (<1000 V) and sensitive electronics devices, standard tests are conducted up to 6,000 volts. 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 necessarily must be conducted at voltages that correlate to the temperature of the heat. Tests at 6,000 volts provide little information.

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

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

1. the energy level of the lightning discharge,
2. the configuration of the conductor including diameter, length, and bends, and
3. the ground impedance including electrode resistance and bonding.

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. Typical low level damage to flexible tubing is a small diameter hole as seen in Figure 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.

ELECTROMAGNETIC WAVEGUIDE

The response of corrugated tubing to an electromagnetic field was evaluated. Tests were conducted using a spectrum analyzer as shown in Figure 7. 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 it was the CSST that was the waveguide, the horns were reoriented and the pipe was moved. The signal always followed the pipe, regardless of its orientation.

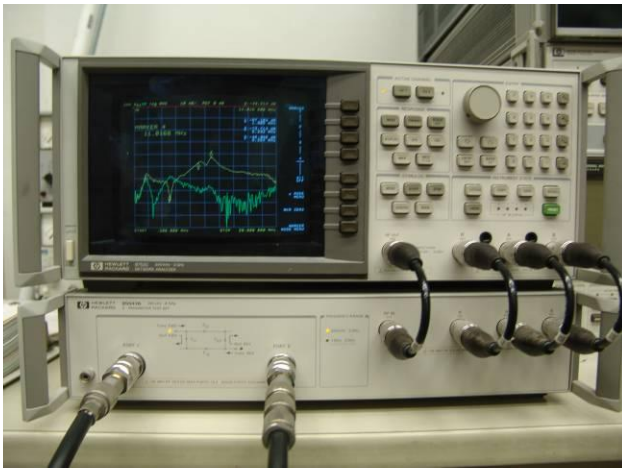

Figure 7: Spectrum Analyzer

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

In 1899, Sommerfield demonstrated that a surface wave could be transmitted along a cylindrical conductor [26]. In the 1950's, 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 the waveguide performance could be enhanced by two simple techniques that keep the wave along the conductor: thin layer of dielectric material and corrugation of the surface.

The Goubau transmission line depends on the physics of the conductor. The first consideration is a dielectric about the conductor. The dielectric keeps directing the electric field back toward the conductor. The PVC jacket on 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 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 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.

CONCLUSIONS

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 line that carries the transient.

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VITAE

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