FORENSIC ENGINEERING ANALYSIS OF

The Potential for Perforation of Corrugated Stainless Steel Tube (CSST) by Energized Branch Circuits in Fire Conditions



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ABSTRACT

The possibility of Corrugated Stainless Steel Tube (CSST) being perforated by lightningrelated arcing is a known phenomenon. Release of fugitive gas from the resulting hole(s) has obvious consequences for the potential causation of fires and explosions. The degree to which this risk can be reasonably mitigated by specific installation practices such as bonding of the CSST to ground is a matter that has been under study by others at the direction of a committee of the National Fuel Gas Code.

Another potential manner in which CSST could become perforated might be contact with an energized branch circuit conductor in fire conditions that compromise the integrity of both the CSST and wire insulation. CSST perforated in this manner would typically be a victim of an existing fire and not causative of the fire. This proposed scenario of CSST hole creation has been used to argue that CSST holes in specific fires were not directly caused by lightning-related activity and thus did not cause the fire.

When perforated CSST is found on a fire scene, fire investigators should try to determine the way in which the holes were created. This may not be such a simple task, as the subject fire and suppression efforts may have destroyed or moved the items involved in the fire. Reasonable efforts should be made to identify and retain any circuit conductors in the area of the perforated CSST and trace these conductors to their source. Additionally, any other nearby conductive items such as pipes, ducts, fireplace or chimneys should be examined for evidence of involvement in creation of the holes.

To assist the investigator in assessing the potential of victim CSST holes created by contact with energized branch circuits, a series of tests was conducted. These tests subjected energized non-metallic (NM) cable in close contact with grounded CSST to fire conditions. Multiple tests were run until either the overcurrent protection device (circuit breaker) opened, a hole was arced in the CSST, or a steady state condition of neither occurrence was noted. These tests placed the CSST and NM cables in various arrangements, consistent with those that might occur in actual construction.

Statistical analysis of CSST perforations in the testing of the various arrangements is provided. Additionally, metallurgical analysis including microscopy and SEM / EDS analysis was undertaken for any perforations in the CSST that occurred in the testing. Also provided are flame stability observations and gas pressure measurements for any flames resulting from CSST perforations. Consulting the testing data and analysis should assist the fire investigator in determining the cause of any holes in CSST that are found in a post-fire examination.

BACKGROUND

Corrugated Stainless Steel Tube (CSST) is a material used to plumb fuel gases inside structures. It is used as an alternative to traditional black steel pipe or copper tubing. CSST construction is governed by the ANSI LC-1 standard, Fuel Gas Piping Systems Using Corrugated Stainless Steel Tubing (CSST). Generally, the material is a 300 series stainless steel tube of about 0.20-.25mm (0.008-0.01 inch) wall thickness, corrugated circumferentially to allow flexibility, and covered with a protective plastic jacket. There are a number of manufacturers of CSST, with relatively little difference in electrical characteristics among products, at least with respect to CSST that lacks an electrically conductive outer jacket.¹

As has been documented in great detail by others, CSST has been known to perforate when subjected to electrical arcing discharge.² Generally, post-fire melted holes in CSST can be assumed to arise from electrical arcs, as common structural fires do not normally create temperatures sufficient to melt stainless steel.³ Fires allegedly caused by arc-perforated CSST have been the subject of numerous lawsuits, including a nationwide class action suit. One condition where arc perforation has been known to occur is when a structure, in which CSST is one of several electrically conductive elements, is subjected to lightning insult. This may be due to the energy of a direct lighting strike or induced EMF within conductive elements from a nearby strike. However, lightning is not the only potential source of electrical energy within a structure, indeed normal household electrical power is present in essentially every structure.

One way in which household electrical energy can compromise CSST is if the CSST becomes a current carrving conductor of a sufficiently large and long enough duration current to compromise the CSST jacket. The most common occurrence of this would be if CSST became a ground fault current path. Normal CSST jackets experience breakdown failure at between 33,000 and 60,500 volts when at normal temperatures.⁴ However, when CSST becomes a current carrying conductor, resistive heating of the stainless steel (a comparatively poor electrical conductor) heats the surrounding jacket, compromising its insulating ability and exposing the now energized stainless steel tube. Contact of this energized, uninsulated tube to some adjacent grounded metal objects can cause arcing perforation or perforation due to high current density heating at the point of contact. This failure mode for CSST has been seen in the field and recreated in the lab by the authors.

Another alleged way in which CSST can be perforated by electrical energy is when junctions of CSST and electrical conductors are subject to fire attack. Any holes formed in this manner would be considered "victim" holes, as the compromising fire must have started by means other than the event that created the perforation. In some cases, forensic experts have opined that holes found in CSST after a fire clearly correlated to a lighting event were actually victim holes. That is, the lightning event caused a fire that then attacked the CSST / conductor junction and caused a perforation in the CSST. It is this alleged failure mode of CSST that is the focus of this paper.

QUESTIONS TO BE ANSWERED

Given the above-related background, several questions are apparent. First, is it possible that fire attack to a junction of CSST and a household electrical conductor can cause CSST perforation? Perhaps fault current between the ungrounded (hot) and grounded (neutral) or grounding conductors in the cable would always trip a circuit breaker before arcing to the CSST occurs. Indeed, there are three layers of insulation / jacketing between the hot conductor and the CSST metal (hot conductor insulation, NM jacket, CSST jacket) versus one for arcing between the hot conductor.

Assuming that it is possible for arcing perforation to occur in this manner, how frequently would it occur under conditions where it could occur? That is, if the conditions are such that arcing can occur (CSST / conductor touching, circuit energized, direct fire attack to the joint), does arcing perforation occur in every instance or only rarely? Additionally, are there differences in the likelihood of its occurrence if the orientation of the CSST and conductor varies?

Assuming that such arcing can occur, additional questions arise. For example, is there any sort of pattern or signature to the CSST perforation or the involved conductor that could be used to identify this specific manner of perforation? This information might be useful in determining if a hole is a lightning arc caused hole versus a victim hole. Finally, are there any observations regarding the characteristics of burning fuel gas escaping from holes that are of potential interest? In prior investigations, these characteristics (flame stability, flame lift off) have sometimes been the subject of debate.

TEST ARRANGEMENT

The practical experimental replication of the exact conditions in a house fire can be somewhat difficult to achieve. For example, in the subject testing it would be impracticable to burn down a dozen or so homes, each outfitted with the required CSST and electrical circuit wiring. However, consideration can be made to creating a test apparatus that adequately creates the conditions required to test for answers to the posed questions.

Consider the conditions that would be required, or most likely to cause, victim arcing between CSST and branch circuit wiring. The CSST and conductors would have to be actually touching as household voltage levels would be insufficient to jump arcs over gaps between the cable and CSST.⁵ A carbonized char path in the form of burned insulation is necessary to form a conductive path and start the arc. Obviously, the circuit would have to be energized, so the potential for arcing is greater early in the fire. This is because the longer the fire has burned away from the CSST / conductor junction the greater the likelihood the fire has already tripped the involved circuit breaker or the power to the structure has been disconnected. The same logic indicates that direct fire exposure, as opposed to intense radiant exposure, is most likely to cause arcing between CSST and branch circuit wiring. The time required to reach fire conditions creating intense radiation away from the junction (e.g. post flash over / fully involved fire) allows time for circuits to be de-energized by other means than an arc at the CSST / conductor junction.

Considering the above factors, a test apparatus was created that subjected to direct fire attack five parallel energized NM cables in contact with a section of 2.5-3.0 kPa (10-12 inch water column)

LP gas-charged CSST. The fire was created by burning a wood crib located beneath the intersection of the cables and CSST. Each cable was supplied by a separate 20 amp circuit breaker. The fire was ignited, using charcoal lighter fluid as an accelerant, and the junction of the cable and CSST burned until each of the five circuit breakers tripped. The fire was then extinguished and the junction of the cable and CSST examined to determine if the CSST had been perforated. A photograph of the test apparatus is shown in Figure 1 and a schematic of the apparatus is shown in Figure 2. A photograph of the apparatus during a fire test in shown in Figure 3. As detailed in the subsequent sections of this paper, use of this testing apparatus did result in perforation of the CSST in some cases. Twelve tests were run, each with 5 NM cable conductors, either 12/3 or 14/2 each with a ground. In this manner, a total of 60 individual exposures of NM cable to CSST in fire conditions were accomplished. The first 6 tests (30 cables) were run with the NM on top of the CSST and the last 6 tests (30 cables) with the NM under the CSST. In the latter condition, a wood block was inserted under the NM (away from the CSST) to lift the NM and ensure good contact with the CSST. In all cases each circuit was checked with a digital ohmmeter prior to ignition to ensure good connections.

Any perforations of the CSST were subjected to visual examination and stereoscopic microscope examination. All perforation samples were prepared by removal from the main body of CSST by abrasive saw cut, taking care to not damage the tube interior by first inserting rolled paper toweling in the tube. The samples were manually cleaned of burned insulation debris and then cleaned with Alconox. Eight samples were chosen to examine by Scanning Electron Microscope (SEM) and subject to Energy Dispersive X-Ray Spectroscopy (EDS) analysis. During both the stereoscopic microscope and SEM analysis, attention was directed toward hole morphology and splatter patterns including the interior of the tube near any holes. EDS was used to determine if, and the degree to which, metal transfer occurred between the copper conductor and the CSST.

In addition to the above-related items, observations were made as to static and flowing gas pressures during the tests. Where perforations occurred, observations were made as to the stability of flame at the holes. The CSST was then turned such that the perforations were directed away from any debris and changes in stability noted.



FIGURE 1 Test Apparatus



FIGURE 2

Test Schematic



FIGURE 3 Test Number 5

RESULTS

As previously indicated, during the testing there were occurrences of perforations in the CSST due to arcing. Specifically, in the 30 cables burned with the NM on top of the CSST, 14 sites (47%) developed perforations in the CSST. In two of these instances, two holes were created by one NM cable, resulting in 16 actual holes from 14 NM cables. In the 30 cables burned with the NM under the CSST. 5 sites (17%) developed perforations in the CSST, all single perforations. Detailed results are given in Table 1. Given these results, it is apparent that, under certain conditions, holes can be created in CSST due to electrical arcing from energized conductors during fire attack.

Examination of the perforations indicate a typical morphology that have the following range of features. The holes ranged in size from a minimum size of 1 mm (<1/16 inch) to a maximum size of about 4mm (0.16 inch). These dimensions are as measured across the longest axis of the hole, as the holes are not perfectly circular. Hole locations were on the crest of the CSST corrugations in 14 of the 21 total holes formed. In only two occasions were the holes in the valley between crests, the remainder were in the sides of the corrugations. Two SEM images of typical holes are shown in Figures 4 and 5.

Stereoscopic microscope and SEM examination indicate all perforations exhibit substantial and obvious accumulated melt at the perimeter of the holes. This is as opposed to a sharp, well defined edge. Additionally, the holes were generally "funnel shaped" with the hole at the exterior of the CSST larger than the hole at the CSST inside diameter. No evidence of cracking was noted around any of the holes.

Test No.	NM Location	Number of Conductors	Number of Conductors Creating Holes
1	Over CSST	5	4
2	Over CSST	5	0
3	Over CSST	5	1*
4	Over CSST	5	2
5	Over CSST	5	4
6	Over CSST	5	3*
Subtotal		30	14
7	Under CSST	5	0
8	Under CSST	5	0
9	Under CSST	5	1
10	Under CSST	5	2
11	Under CSST	5	1
12	Under CSST	5	1
Subtotal		30	5

* Two holes created from one conductor

TABLE 1

Results



SEM Image of Hole 4 from Test 1. The Arrow Points to a Small Area Subjected to an EDS Analysis that is shown in Figure 6.



FIGURE 5 SEM Image of Hole 1 from Test 5.

Examination of the interior of the tubes show a morphology consistent with that mentioned above. Additionally, splatter was generally observed on the interior of the tube opposite from the hole's location. This splatter was small in size, but sometimes numerous in quantity.

Eight perforation samples were subjected to EDS analysis. In all cases submitted for EDS analysis, some copper was noted to have deposited on the perimeter of the perforations. For example, see Figures 4 and 6. Generally, this copper was not difficult to find. Additionally, some of the splatter found on the interior of the tubes opposite from the hole location were found to contain copper upon EDS analysis.



FIGURE 7 Arc Notch in a Conductor that Arced to CSST.

Examination of the conductors that arced to the CSST generally show a normal geometry of arc notch with a central raised portion surrounded by a recessed notch into the conductor.⁶ A typical example is shown in Figure 7. In no case did any conductor arc sever. Generally, the notch depth was between a minimum of just a slight surface indentation to a maximum of no more than 1/2 way through the conductor.

Generalized observations were made as to flame stability from the burning fuel gas escaping from the holes. Of course, when perforations occurred during the actual fire tests the escaping gas was ignited by the



FIGURE 6



wood crib fire. Once all five circuit breakers were tripped, the wood crib fire was extinguished by pouring water on the burning wood. When this occurred it was noted that the escaping LP gas continued to burn. In this condition, the gas is issuing from a hole with burned electrical conductors, and for tests with NM under the CSST, wood debris in front of the hole. When the conductors were moved away from the hole. or the CSST turned to direct the gas away from any object in front of the hole, the flames would lift to the point of "blow off" and selfextinguishment. However, conductors and / or wood debris in front of the hole consistently served to anchor the flame and allow continued combustion. The above observations were made using LP gas at 2.5-3.0 kPa (10-12 inch water column). It was noted that gas pressures increased in the CSST during the fire test due to expansion of the gas inside the tube. When perforation occurred, flowing gas pressures decreased by 0.5-2.0 kPa (2-8 inches of water column) depending on the number and size of holes.

An additional test was made to study flame stability using natural gas.

In this test, a section of CSST with a hole, was connected to a natural gas source at 1.7 kPa (7 inches of water column). Natural gas flames generally exhibited a lesser tendency to blow off and self-extinguish as compared to LP fueled flames. Natural gas flames at 1.7 kPa (7 inch water column) would stabilize with the flame front located about 50 mm (2 inches) from the hole. However, the flame stability was marginal, varied with hole size and location, and the flame could be extinguished with relative ease by blowing it out. Another observation was that if natural gas was suddenly supplied to the tube and ignited by a small pilot next to the hole, the flame would lift off and self-extinguish. However, if an object was located in front of the hole, for example a piece of NM cable, then the flames would not lift off and the flame would stabilize. Photographs of this testing are shown in Figures 8 and 9.



FIGURE 8 Natural Gas Flame Stable, but Lifted from the CSST Hole without an Object in Front of the Hole.



FIGURE 9 Flame Stabilized Closer to the CSST Hole by the Presence of Wiring in Front of the Hole.

ANALYSIS

In the subject testing, it was determined that perforations occurred in 47% of the cases where the NM cable was on top of the CSST. However, when the NM was on the bottom, perforations only occurred in 17% of the cases. Some consideration can be made as to why a difference might exist between the two conditions. One reason may involve the requirement that the NM cable and CSST maintain contact via a conductive path of char to allow creation of an arc. In the condition of the NM cable over the CSST, any lengthening (including thermal expansion) in the lighter conductors would likely cause the conductors to sag into closer contact with the CSST. In the opposite condition of the conductors under the CSST, sag would cause the conductor to move away from the CSST and result in a lesser tendency to arc. It might be claimed that a lesser degree of contact existed between the conductors and CSST when the conductors were on the bottom due to the design of the test, however great care was taken during the testing to insure

that the bottom NM conductors were definitely touching the CSST at the start of each test run.

In any case, it is clear that electrical conductors and CSST would have to be touching during a fire for arcing to occur between the two, due solely to normal household voltages. This requirement for physical contact would seem to be more easily maintained if the NM cable is resting on top of the CSST, given the greater stiffness of the CSST. The difference in the potential for perforation noticed in the testing would seem to support this proposition.

Examination of the perforations uniformly show substantial accumulated melted material around the perimeter of the hole. In no cases was a ragged, sharp edge hole noted. Additionally no cracking was noted to propagate from the holes into the base metal around the holes. This would indicate a level of energy exchange that was sufficient to melt the material, but insufficient to propel most melt away from the hole or create thermal gradients in the surrounding material

sufficient to induce cracking. This finding can be considered consistent with the generally small size of the notches and lack of arc severing in the corresponding conductor. As previously noted, copper transfer from the conductor to the melted material was uniformly found without great effort. This observation could be used to help identify the manner in which arcing may have occurred. For example, holes in CSST that lack evidence of copper in the surrounding ejecta, or have significantly different morphology, would seem unlikely to have been created by normal household electrical activity in the manner tested.

Observations regarding flame stability were made during all of the testing. Flames burning at a hole in CSST are referred to as diffusion flames. These rely on a supply of combustion air from the surrounding environment to achieve a combustible mixture, as only fuel gas and no air exists inside the CSST. Gas and combustion air mix by both diffusion and entrainment with mixing at the interface of the gas plume and surrounding air. At low gas outlet velocities (low gas pressures), this mixing and entrainment is less vigorous and a lazy yellow flame results. As gas pressures increase, gas outlet velocity increases and this entrainment and mixing increase resulting in better mixing, and a more sharply defined, blue, and leaner flame. Also as gas pressure increases, the flame front, the plane of burning nearest the hole, moves away from the hole. The location of this flame front is the point at which the outward mixture velocity in front of the hole matches a property of the gas air mixture called the flame speed. The flame speed is a somewhat variable property for differing fuel gasses, Reynolds Number, temperatures and mixtures.7 The flame front becomes stationary and stabilizes at the point at which the mixture velocity matches the flame speed. This is analogous to a fish swimming upstream at 5 mph in a 5 mph river, the fish appears stationary.8

As previously indicated, flames issuing from the LP-supplied CSST holes would generally blow off without some material located in front of the hole. This is explained by, in that specific circumstance, the velocity of gas air mixture in front of the hole exceeding the flame speed for LP gas in that specific condition. This can be confirmed by lowering the LP gas pressure, which does result in a stable flame front being established. As also indicated, natural gas flames were observed to be somewhat more stable, and would generally establish a stable flame front at the 7 inch water column pressure tested. In that case, the lower mixture velocity due to the lower natural gas supply pressure, in combination with the specific properties of the natural gas mixture in that condition, allow a stable flame front.

Significantly, in both the LP and natural gas-fueled conditions, a stable flame was maintained when material was present in front of the hole. This can be understood by considering the object's effect on the velocity of the gas air mixture. As the mixture contacts the object, certain portions of its flow velocity are arrested and even reflected back toward the hole. In these portions, the mixture velocity is reduced below the flame speed and a zone of stable combustion achieved. These observations may have significance in considering the potential for holes in CSST (created by any means) to start a fire. For example, observations that blow off prevents stable flame front creation in open laboratory conditions should not be summarily used to support a contention that a fire was not caused by fire anchored at that hole. Indeed, it is hard to imagine any scenario that a hole could occur in CSST that did not have some object in front of the hole. Holes created by arcs from both household electrical power and lighting both require two electrodes to occur, therefore it would seem that an object would normally be in relatively close proximity to the hole.

9

CONCLUSIONS

Returning to the questions that were raised earlier in this paper, the work has answered, or at least allowed some insight into, the questions. Clearly it is possible to create arced holes in CSST by exposure to energized conductors in fire conditions. Additionally, the locations of the CSST and conductors affect the potential for arcing, with the potential greater if the conductor is on top of the CSST. However, it is not the case that arcing to the CSST should be expected in every case that it could arise. The test apparatus and methodology ensured direct contact between the CSST and NM cables, and that flames were confined to a rather small area around the junction of the two. Even when these circumstances were controlled to try and promote the potential for arcing to the CSST, perforation occurred in a minority of cases. The likelihood of these promoting conditions arising in any specific fire and actually causing CSST perforation must be judged by the facts of that specific fire. However, the subject testing indicates that household electrical conductors would cause victim holes in CSST only in extraordinary circumstances.

Examination of the CSST perforations and involved conductors have allowed some potentially useful conclusions to be reached. Generally, both holes and conductors involved in the perforations exhibit substantial accumulated melt. That is, the holes are not sharp edged and do not exhibit cracking and the melt has not been blown fully away from the hole. Copper residue is apparent in the ejecta around the hole. Conductors exhibit normal arc notch morphology and are not severed. If a specific CSST hole and conductor in consideration on a fire scene lacked the above features, it would seem unlikely to have been caused by arcing due to normal household voltages. However, that is not to say that CSST holes and

conductors that have these features were likely caused by household voltage, only that the morphology of the hole and conductor does not rule out that possibility. This same pattern may well be created by other means, the consideration of which is beyond the scope of this paper.

Finally, the testing allowed ample opportunity to examine the stability of flames arising from gas escaping holes in CSST. Generally, flames from holes in LP-charged lines were less stable as compared to natural gas-charged lines. For both gasses, flames were stable and anchored to the area of the hole when objects such as wood or electrical conductors were present in front of the hole. This should be taken as a general observation as testing the limits of stability at various object distances, hole sizes, and gas types and pressures was not a specific goal of the testing. However, it is clear that flame stability and blow off characteristics for flames from CSST holes in lab settings lacking objects near the holes should not be used to contend the improbability of stable flames in real world circumstances where objects are near the holes.

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