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Introduction

When large current is conducted in highly resistive soil, sufficient heat can be produced to fuse the soil and create a fulgurite, a glassy, tubular object. The fulgurite has a slightly elliptical tubular shape, approximately .5 to 2 cm in diameter. Usually the inner walls are smooth and glassy, but the exterior surface is rough and rock-like. In nature, lightning can create fulgurites when cloud-to-ground flashes strike the earth, producing underground current channels.

Very little is known about the production of fulgurites, and the processes associated with lightning that are capable of forming them are of great interest. The cloud-to-ground flash begins with a stepped leader, a predischarge that propagates from cloud towards the ground when sufficient negative charge is accumulated at the base of the cloud. The average current that flows through this leader is of the order of 100A for tens of milliseconds. The stepped leader is immediately followed by a return stroke. The return stroke is an upward-moving discharge launched from the ground along the stepped leader channel. This return stroke typically propagates between the ground and cloud base in 70μs using the leader channel as its transmission medium. The peak current, about 30kA, is reached within a few microseconds and falls to one-half peak value in 20-60μs. If the lightning is a multiple stroke flash, a dart leader could traverse the channel and initiate another return stroke typically after many tens of milliseconds. The peak current of subsequent strokes is about 10-15kA. After some strokes a continuing current of about 100A can flow for longer times than that of the return stroke current (in the order of 100ms) [1]. Of these primary lightning processes, the return stroke is most likely responsible for the fulgurite production; this conjecture is based upon the data collected in 1993 by Kumazaki et al.[2] in an experiment to produce fulgurites at a high voltage laboratory, inside a container (inside dimensions of 132 X 1480mm) using high energy arcs from an impulse generator. Fulgurite production rates were recorded for several current magnitudes and discharge times. The highest production rate occurred with a discharge time of 20-50μs and within a current range of 5-15kA, typical subsequent return stroke values.

Kumazaki et al.[3] also successfully produced a fulgurite in the same container using rocket triggered lightning. This experiment consisted of a rocket trailing a wire connected to an electrode in one end of the container of raw materials (sand taken from the riverside of the Tempaku River, Japan), with another electrode on the other side of the container connected in series with the measuring equipment to ground. After two triggerings the container was opened and a fulgurite 3 cm long with an outer diameter of 1 cm was found.

The data contained within were obtained in an experiment by the University of Florida, Centre d'Etudes Nucleaires de Grenoble (CENG), and Power Technologies Inc. (PTI) testing the effects of lightning on unenergized power distribution systems performed from June to September 1993[4]. In this phase of the experiment, three 15kV cables were buried five meters apart at a depth of one meter in a cleared field at Camp Blanding, Florida to measure the responses, voltages and currents, of buried cables to lightning strikes directly to the earth. Lightning was artificially triggered using rockets trailing grounded wires. These rockets were launched at various positions along a launching track positioned over the cables. A sketch of the launching track is shown in Figure 1, and a photograph of the excavation/launching site and is shown in Figures 3 and 4. About 20 lightning flashes were triggered in the 1993 experiment. The leader/return stroke sequences in triggered lightning are believed to be similar to subsequent leader/return stroke sequences in natural lightning.

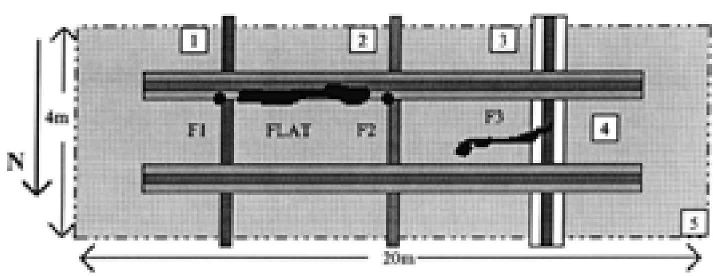


Figure 1: Launching track with location of buried cables.

1) directly buried l5kV cable 2) 15kV cable with exterior shield 3) l5kV cable in a 3 inch PVC pipe 4) launch Rails 5) area excavated. F1, F2, F3) Fulgurites FLAT) Flat fulgurite

Data recorded for each lightning flash included the current, horizontal magnetic field (at 50 and 110 meters), and vertical electric filed (at 30, 50 and 110 meters). An important product of this experiment was the creation of fulgurites attached to the power cables in the earth surrounding the launch site.

While other experiments have produced fulgurites in containers using triggered lightning and high voltage arcs, it is believed that this is the first success in the artificial production of fulgurites in the natural earth.

Data and Results

In May - June 1994, the site was excavated, and the fulgurites were found. The excavation process was a slow, methodical one. The entire launch site, approximately 4 X 20m, was first cleared of the grassy top layer (at the time of the lightnings, there was no vegetation, however, it had grown back during the year between triggering and excavation). Then layer-by-layer the soil was removed until each fulgurite was located. Once the fulgurites were located, archaeological recovery methods were used to remove them. Three complete vertical fulgurites were unearthed, along with numerous branches and fragments.

Since the temperature of the lightning channel is related to the amount of current conducted in the channel, the current measurements for the return strokes are very important. The average return stroke current produced in the triggered lightning was 14.8kA with a standard deviation of 7.8kA. A histogram of the maximum current magnitudes is shown in figure 2.

Several of the flashes recorded were multistroke flashes; some flashes had up to seven return strokes. Thus, there could be several current pulses following the same path and contributing to the formation of the fulgurite. Unfortunately it is not known which flashes produced the individual fulgurites. There are three distinct fulgurites connected to the buried cables, while the total number of triggered flashes is about 20.

The fulgurite labeled F1 is pictured in Figure 5. F1 is a nearly vertical tube beginning under the southern concrete rail and ending at the first buried cable. The exterior surface of the fulgurite was mostly granite gray with patches of a milky white color. There were numerous craters (openings) and bumps on the surface that looked as if branches were being formed but were not able to develop away from the main trunk. Through these

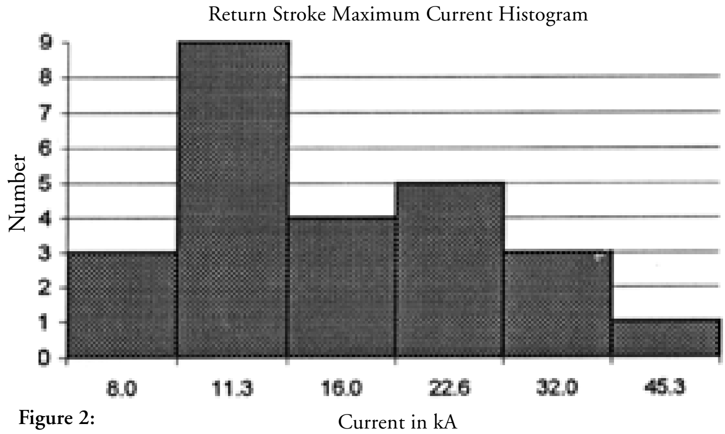


Figure 2:

craters the smooth, glassy interior surface is visible. The cable's insulator was penetrated by the lightning strike where the fulgurite connected to the cable. A close up photograph of the damage to the first cable is shown in Figure 6. During excavation F1 was broken into several pieces and had to be reconstructed. The fragility of these fulgurites could have been due to the shockwaves generated during the subsequent lightnings triggered in the relatively small area. The constant heating and cooling of the soil, from the numerous lightning, as well as natural weather changes over the year interim, could have also caused the thin walls of the fulgurites to expand and contract contributing to their condition. To strengthen the fulgurites and limit the amount of reconstruction necessary, a clear plastic hardening compound, Polyvinyl Butyral, was brushed on the fulgurites and surrounding soil.

The second fulgurite was excavated over the next buried cable. This cable was an exterior shielded cable, but also was damaged by the lightning flash. The fulgurite labeled here F2 is pictured in Figure 7, and is also nearly vertical with a length of approximately 1 meter and an average diameter of 1.5 centimeters at the top and about .4 centimeters at the cable. This fulgurite was the most complete fulgurite excavated, because it was unearthed in one piece with very little reconstruction necessary. F2 also started underneath the concrete rail and traveled

Figure 3: A photograph of the launch site during the excavation; the third fulgurite is barely visible by the shovel.

Figure 4: A close-up photograph of the excavation site and the launch rail.

down until making contact with the buried cable. A close up photograph of the damage done by this lightning is shown in Figure 8. Both fulgurites were connected to the underside of

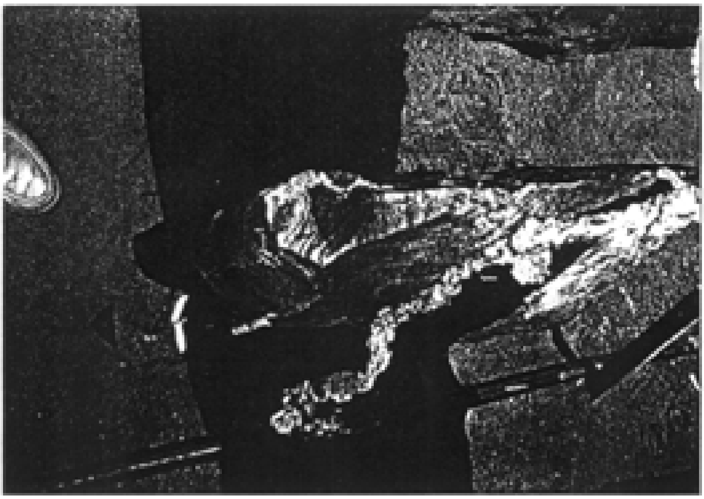


Figure 5: Fulgurite F1 after excavation and reconstruction. F1 is about 1 meter long and terminated at the first 15kV cable.

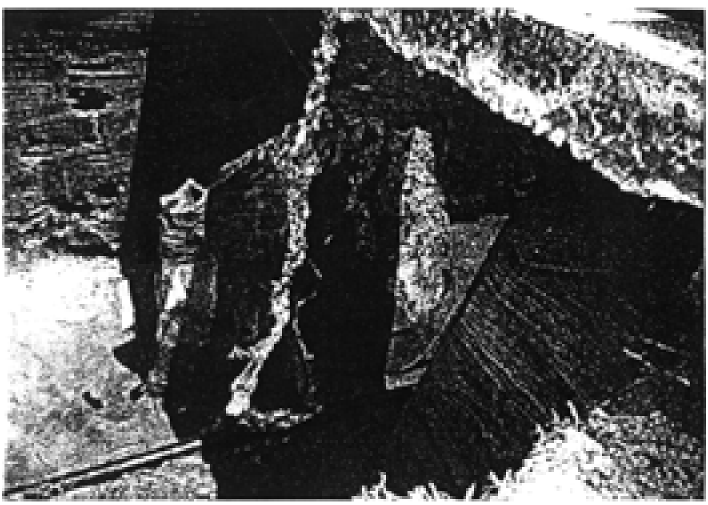


Figure 6: A close-up of the damage to the first 15kV cable from the strike(s) that created fulgurite F1.

the concrete rail and ended by penetrating the insulation of the buried cable. An interesting horizontal fulgurite was found between fulgurites F1 and F2 on the underside of the concrete

Figure 7: Fulgurite F2 started under the launching rail and terminated at the second buried cable.

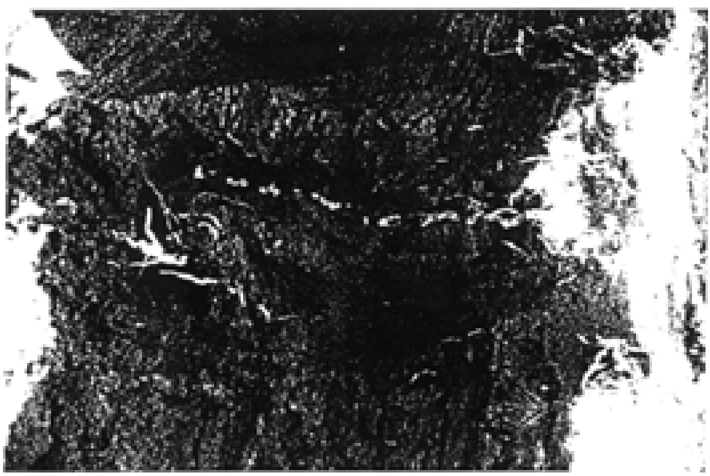


Figure 8: Fulgurite F2 during the excavation process. The fulgurite is encased in a protective jacket to minimize damage during excavation and transportation.

rail. This flat fulgurite was about 2mm thick, 3cm wide, and 5m long, and is pictured in Figure 9. The fulgurites might have connected to the railing because the conductivity of the reinforcement steel rods inside the cement or perhaps the moisture

Figure 9: The flat fulgurite found between the fulgurites F2 and F3 underneath the southern concrete slab.

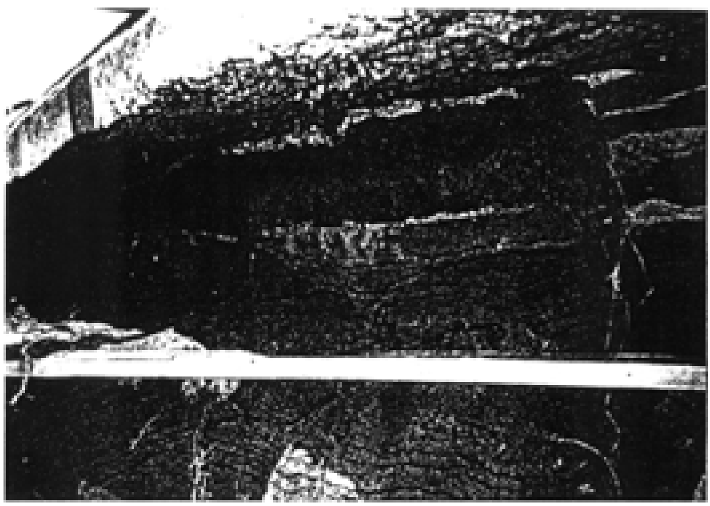


Figure 10: The third fulgurite was not completely vertical, but it did travel toward and connect with the third cable.

trapped in the railing made the rail a preferred path for the lightning to pass through. Because these fulgurites were quite long, they were difficult to unearth and transport. Figure 10 is

Figure 11: A close up of the damage done to the PVC pipe surrounding the third 15kV cable.

a picture of part of the excavation process for fulgurite F2. In this photograph the fulgurite has been encased in a jacket, or cast, with most of the soil still around it to prevent it from being disturbed during transport. The entire jacket is brought to a laboratory where the fulgurite can be removed in a more suitable environment using the proper equipment.

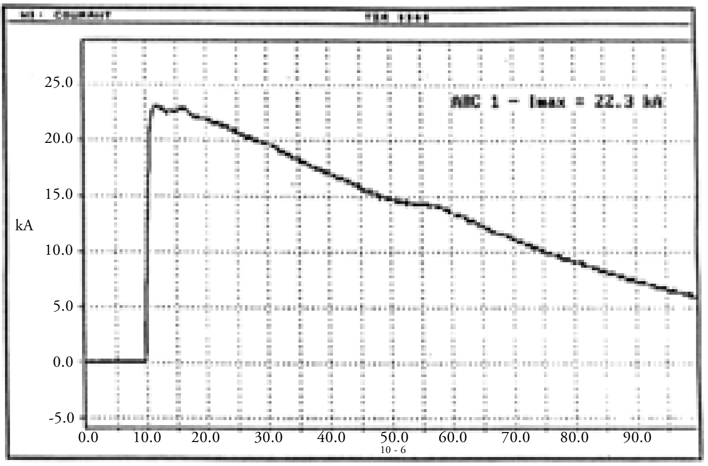
The third distinct fulgurite found was the longest one created in the experiment. While it only traveled from slightly below the top soil to the third cable, about a meter down, it did not travel directly down like the other two fulgurites. The path of this fulgurite, F3, was in steps, and is shown in Figure 11. Like the previous two vertical fulgurites, F3 also made contact with the buried cable, damaging the cable and 3 inch PVC pipe encasing the cable. The pipe was melted and distorted where contact occurred. A close up photograph of this damage is shown in Figure 12.

In the soil between F2 and F3, several centimeters deep, many relatively small fulgurite fragments were found. Some of these fragments were sphere shaped with a diameter of about 1-2mm, while others were tube like branches resembling limbs on a treebranch. Since these fragments were found near the surface, they could have been created by surface flashes, similar to the flash shown in Figure 13. Figure 13 was acquired, courtesy of Fisher and Schnetzer, from an experiment in Ft. McClellan-1993 but, several surface flashes were also observed during the UF/PTI experiment.

The ability of the earth to dissipate current discharges from lightning depends on the earthing resistance of the plasma chan-

Figure 12: An example of a surface arcing caused by lightning triggered at Ft. McClellan, Alabama by sandia National Laboratories of Alberquerue, New Mexico (courtesy of R. Fisher).

CEA-DRN-DTP-STI-LASP 1993. Rocket Triggered Lightning Experiment -EPRI/PTI -RTL. Test Facility



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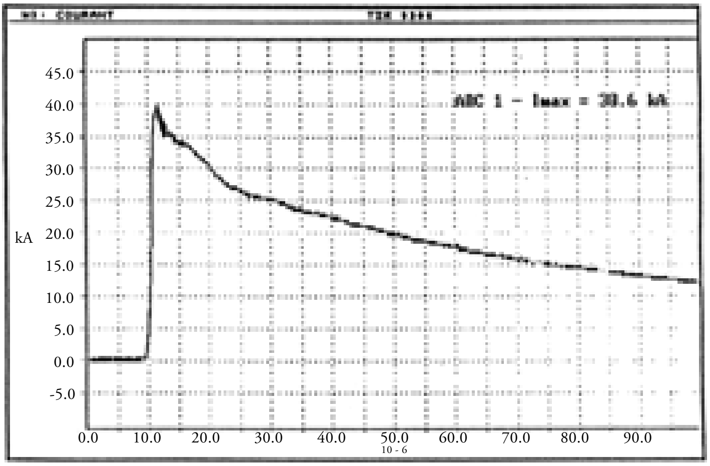

nel formed by the flash. The earthing resistance of the electrode (the lightning channel) is an ohmic resistance of the soil surrounding the electrode and can be approximately calculated for various electrode designs. The earthing resistance for the triggered lightning discharges can be roughly calculated using fulgurites F1 and F2 as preserved shapes of the plasma chan-

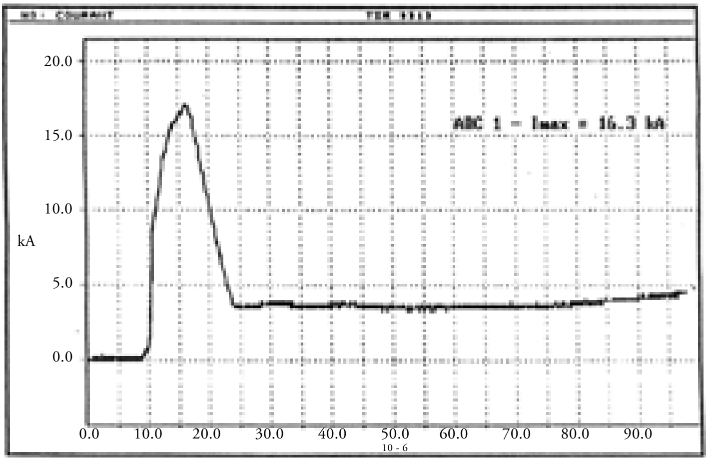

Figure 13: Examples of triggered-lightning return-stroke currents measured by CENG at Camp Blanding, Florida 1993.

nels during each respective flash. Since these fulgurites are basically vertical tubes, the earthing resistance can be calculated using a vertical rod model, with the lengths and diameters described by the fulgurites. The equation approximating the earthing resistance for a rod is : $R = \frac{P}{2\pi L}\left(\ln\frac{8L}{d} - 1\right)$ where p, resistivity, is the resistance in Ω for a 1m cube of homogeneous soil, and *L* and *d* are the length and diameter of the rod respectively [6]. The earthing resistance for the surface flashes can also be approximated using an electrode model consisting of a metal strip about 3cm in diameter of various lengths. The equation approximating the earthing resistance for a strip electrode is: $R = \frac{P}{\pi L}\ln\frac{2L}{1.36d}$ where *L* and *d* are estimated from visual measurements during the flashes and known surface channel parameters [6]. PTI measured the soil's resistivity to be about 4000 Ω-m around the sandy launch site, and this value can be used for both calculations. Table 1 shows the approximate earthing resistance for the vertical and surface plasma channels generated by the triggered lightnings.

Conclusions

In the present study fulgurites were created in the earth using triggered lightning. It was uncertain which lightning process fused the sand into the glasslike material, so many of the cloud-to-ground processes were inspected. From the characteristics of these processes (stepped leader, return stroke, dart-leader, and continuing currents) and data by Kumazaki et al [2], from creating fulgurites in the laboratory, the return stroke is most likely the process that creates fulgurites. This conjecture could be further tested with other experiments using triggered lightning and high energy arc generators. In triggered lightning experiments, the measuring equipment should be capable of re-

Electrode Model	Length	Diameter	Earthing Resistance
Rod	1m	3cm	2.9k
Rod	1m	2cm	3.2k
Strip	1m	3cm	5.0k
Strip	5m	3cm	1.4k
Strip	10m	3cm	788.7
Strip	20m	3cm	438.5

Table 1:

cording the entire lightning flash to determine if other processes, other than the return stroke, have a substantial influence on the fulgurite's creation. The experiments in high voltage laboratories could provide a controlled environment where current magnitudes and time intervals could be established for different types of soil. In these experiments, it would be better to use large containers of soil, relative to the small containers used in the high voltage lab experiments mentioned in the text; the creation of fulgurites in these large containers would probably better simulate natural creation in the earth. With these experiments maybe a better understanding of how nature creates the beautiful phenomena known as fulgurites.

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THE EVENT

PETRIFIED LIGHTNING FROM CENTRAL FLORIDA

A PROJECT BY ALLAN MCCOLLUM

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