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Attempts to Create Ball Lightning from Triggered Lightning

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14. ABSTRACT
During the 2008 ball lightning experiment, around 100 different material samples were exposed to both relatively continuous (initial stage and inter-stroke continuing current) and to impulsive (return stroke) triggered lightning current. All events with properties similar to those reported by eye-witness and laboratory accounts of ball lightning were produced by slowly varying, relatively low amplitude currents during the initial stage of the triggered-lightning process. No events with sustained luminosity duration greater than 100 ms were recorded as a result of impulsive return stroke currents. The luminous balls observed above the stainless steel plates most closely resembled the accounts of ball lightning described in the literature. We apparently duplicated the laboratory experiments of Stephen and Massey (2008) and Paiva et al. (2007) who produced small combusting metal spheres from arcs to metals and of Versteegh et al. (20008) who produced a flame-like phenomena via arcing in water containing calcium chloride.

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I. Introduction

The ball lightning research reported here was motivated by two classes of recent laboratory experiments and a new theory of the formation of ball lightning: (1) the laboratory experiments of Paiva et al. (2007) and Stephan and Massey (2008) in which arcs terminating on solid silicon and other metals produced apparent ball-lightning-like phenomena, (2) the laboratory experiments of Versteegh et al. (2008) and others referenced in that work in which luminous, flame-like structures were produced above dirty water through which electric arcs were passed, and (3) the new theory of Abrahamson and Dinnis (2000) in which ball lightning is modeled as being formed from silicon originally resident in sand and released by a lightning strike to subsequently re-oxidize.

Ball lightning (in French: boules de feu, éclair en boule, foudre globulaire; in German: Kugelblitz; in Russian: sharovaya molniya) is a phenomenon for which there exist numerous witness reports but little, if any, verifiable scientific documentation such as photographs or video records (Rakov and Uman, 2003). Despite the lack of acceptable documentation, the properties of ball lightning are relatively well known from statistical analyses of observers' reports spanning a period of three centuries. There are at least nine significant compilations of eyewitness observations of ball lightning, containing almost 5000 reports (Rakov and Uman, 2003). From a few percent to about 10 percent of individuals who live in regions with appreciable thunderstorm activity have apparently seen ball lightning. It follows that ball lightning may not be as rare as often portrayed.

There may be more than one type of ball lightning, and hence there may be multiple mechanisms by which ball lightning is generated. The most commonly reported observation is of an orange-to-grapefruit-size sphere (the range for the vast majority of reports is from the size of a golf ball to that of a basketball), which is usually red, orange, or yellow in color with luminosity about as bright as a 60 watt light bulb. Ball lightning is most often reported to have a duration of a few seconds, during which time it generally moves more or less horizontally (it does not rise as would hot air) and then decays either slowly and silently or abruptly and explosively. Detailed statistics on size, color, duration, and other properties are found in Rakov and Uman (2003). The luminosity of ball lightning is reported to be roughly constant until it extinguishes. It is most often seen spatially close to and just after a cloud-to-ground lightning flash. It appears to be able to pass through glass windows and metal window screens. There are a significant number of credible reports of ball lightning occurring within metal (aluminum) aircraft. Ball lightning is sometimes reported to have an odor and sometimes to leave burn marks. Human beings are seldom, if ever, injured or killed by ball lightning. Most reports of injury and death are from the 18^{th} and 19^{th} centuries and can probably be attributed to ordinary lightning or to meteors. Since ball lightning and meteors are both referred to in the literature from that time period as "fireballs", it is not surprising that some reports of the effects of fireballs that actually refer to meteors have been misinterpreted as being due to ball lightning. Ball lightning is occasionally reported to be generated indoors from high-power electrical equipment such as battery-bank switches.

There have been many theories devised to explain ball lightning (Rakov and Uman, 2003). None is completely satisfactory, a number violate accepted laws of physics, most do not simulate the observed characteristics of ball lightning, and some are clearly unrealistic (e.g., electron-position annihilation, miniature black holes, cosmic rays focused by cloud electric fields, quantum mechanical plasmas). Ball lightning models can generally be divided into two classes: those that are internally powered and those that are externally powered.

Ball lightning of the type observed in Nature has apparently not been produced in the laboratory, although many luminous phenomena created in the laboratory are claimed by their creators to be ball lightning or to have some relation to ball lightning. Recent laboratory work by Paiva et al. (2007) and Stephen and Massey (2008) involve electric arc discharges impinging on solid silicon and other metals, resulting in the production of small luminous metal spheres, perhaps not unlike the "sparks" observed in arc welding. The recent laboratory studies of Versteegh et al. (2008) and others, in which flames above salt water and water containing calcium chloride are produced when arcs are passed through the liquid are suggestive of ball lightning and are of interest in that lightning often strikes pools of dirty water or wet earth. In the ball lightning theory of Abrahamson and Dinnis (2000) silicon contained in sand ($Si0_2$) is robbed of its oxygen by a lightning strike to Earth containing material that combines with the oxygen, and thereafter the silicon is postulated to form "webs" which re-oxidize in the form of luminous balls.

The research described here involves artificially initiating (triggering) lightning from natural thunderstorms using the rocket-and-wire technique [e.g., Uman et al., 1997; Rakov, 1999; Rakov and Uman, 2003] and directing the triggered-lightning current to a variety of different materials in an attempt to create ball lightning. For this study, we triggered 8 lightning flashes to a total of about 100 samples of fluids, solids, and vegetation, as described in the next section. The experiments were performed during Summer 2008 at the International Center for Lightning Research and Testing located on the Camp Blanding Army National Guard Base in North-Central Florida, five miles East of Starke, Florida.

II. Background and Experimental Setup

The tower rocket launching facility is shown in Figure 1. Rockets trailing ground wires are launched from twelve aluminum launching tubes on the top of the 11 m tower. The current of a typical rocket-and-wire triggered lightning is comprised of two distinct sequential current intervals or phases. The first is the Initial Stage (IS). The Initial Stage is composed of an upward positive leader (UPL) current followed by an Initial Continuing Current (ICC). The ICC typically flows for some hundreds of milliseconds following the initiation of an upward positive leader from the tip of the ascending triggering wire (at an altitude of 100 to 300 m) and the subsequent connection of that leader with the cloud charge overhead (at perhaps 7 km). The Initial Stage current is typically relatively low in current amplitude, from less than a hundred amperes to several kilo-amperes. Following the UPL current and the ICC, during which the triggering wire is destroyed (typically about 10 ms after initiation of the UPL), the second phase of the triggered lightning occurs consisting of one or more dart-leader/return stroke sequences that typically traverse the remains of the channel left by the ICC. Return stroke (RS) currents for rocket-triggered lightning are impulsive (rise times of less than 1 us) and average 10-15 kilo-amperes in peak amplitude. Return strokes are sometimes followed by continuing currents of hundreds of amperes with a duration of tens to hundreds of milliseconds, not unlike the ICC.

During the 2008 rocket-triggered lightning/ball lightning study, two different physical configurations were used to route the lightning current to and/or through the various material samples. The initial setup of the ball lightning experiment was completed on May 16, 2008, and involved a single path to ground for both IS and RS currents. In the initial configuration a T&M Research R-7000-10 Current Viewing Resistor (shunt) was used to measure the current at the tower launcher. The shunt has an internal resistance of 0.001Ω and a bandwidth of 8 MHz. Current waveforms were transmitted to the Launch Control trailer via Opticomm fiber-optic links and digitized on a Lecroy oscilloscope sampled at 100 MHz. A description of the initial support structure for the material samples follows (see Figures 1, 2, 6): A 20 ft section of 4 inch-diameter PVC was outfitted with standoffs that supported sections of copper braided wire (Fig. 6). Spark gaps were positioned along the shield braid where material samples could be inserted for exposure to incident lightning current. The base of the PVC pole was attached to a hinge mechanism on a support pole at the northwest corner of the launch tower. The top of the PVC pole was connected to a wooden post at the Launch Control trailer via non-conducting polypropylene rope. Using a pulley system, researchers could raise and the lower the PVC pole (supporting the material samples) from the safety of the Launch Control trailer located 50 m to the north. A galvanized steel plate was mounted on the conducting path at each end of the PVC pole. In the elevated position, the galvanized plates on the PVC pole lined up with galvanized plates mounted on the support pole on the northwest corner of the launch tower. Small (1 cm) spark gaps were left between the galvanized plates on the PVC pole and the tower to prevent the plates from welding together during a triggered lightning event. Arcs at the top and bottom of the PVC pole due to these two spark gaps are clearly observed in the video records. The tower launcher was connected directly to the galvanized plate at the top of the northwest tower support pole via a length of braided wire. A short length of braided wire connected the bottom galvanized plate to a vertical copper rod. The lower end of the copper rod was positioned in the center of a 6 ft diameter swimming pool filled with salt water (5-10 g NaCl per gallon) (Figure 2). Braided wire was fastened to the circumference of the swimming pool and then grounded to the launch tower grounding system. An approximately 3 ft radial spark gap was created between the copper rod and the outer edge of the swimming pool.

The second physical configuration of the ball lightning experiment was completed on June 15, 2008 (see Figure 3). The goal of the second experimental setup was to separate the two current components, IS and RS, of the rocket-and-wire triggered lightning. This was accomplished by constructing an intercepting wire over the top of the tower launcher. Four 20 ft sections of 4 inch-diameter PVC supported a rectangle of ¾ inch-galvanized pipe. While the IS current flows through the tower launcher on a path to ground as in the initial measurement setup, after vaporization of the triggering wire, subsequent dart-leader/return stroke sequences attach to the intercepting wire above the tower launcher from which the RS current is diverted to a separate path. The RS current was carried via braided wire to a second incident current measurement box positioned on top of a second telephone pole installed approximately 7.5 m west of the northwest tower support pole (pole to the right in Figure 3). A wooden crossbar was connected to the new pole to the tower for structural rigidity. A T&M Research R-5600-8 Current Viewing Resistor (shunt) was used to measure the RS current. The shunt has an internal resistance of 0.00125 Ω and a 12 MHz bandwidth. Like the IS measurement, RS current waveforms were transmitted to the Launch Control trailer via Opticomm fiber-optic links and digitized on a Lecroy oscilloscope sampled at 100 MHz. An identical PVC pole, hinge mechanism, and pulley system was constructed and mounted on the new telephone pole for the

RS position of the ball lightning study. For most triggered lightning attempts during the 2008 season, similar material samples were mounted on both the IS and RS PVC poles in order to determine whether long duration/low amplitude or impulsive/high amplitude currents were more likely to produce ball lightning or ball-lightning-like effects.

A satellite photograph showing the physical layout of the International Center for Lightning Research and Testing is shown in Figure 4. Structures described below are annotated in red type. Photographic data from the 2008 ball lightning experiment were acquired by a Phantom v7.0 High-Speed camera, four Sony HDR-HC5 high-definition video cameras, and four Nikon N2000 35 mm SLR cameras. The Phantom camera was operated from the Launch Control trailer located approximately 50 m north of the launch tower. The Phantom camera acquired data at a frame rate of 500 frames/sec (2 ms resolution) and was triggered at the time of the rocket launch. A Sony HD camera and Nikon 35 mm SLR also recorded the same field of view from the launch control trailer. In addition, Sony HD cameras were also placed in the Test House, Office Trailer, and Instrumentation Station 2 (IS2). Additional 35mm SLR cameras were placed in the Test House and in the Office Trailer. Each 35 mm camera was configured to take a 6 second time-exposure triggered at the time of the rocket launch. Two stacked ND4 neutral-density filters were used on all 35 mm cameras to prevent over-exposure.

There were a total of eight successful triggered lightning events during the ball lightning experiment, four with both IS and RS currents and four with only IS currents. Table 1 provides general background information on all eight events including the launch time, peak current, number of strokes, and the quasi-static electric field at ground when the rocket was launched. Rocket triggered lightning events are designated by UF-08XX where the last two numerical digits correspond to the shot number of the calendar year. The first triggered lightning event of the year on June 10, 2008 was the only attempt made to create ball lightning with both the IS and RS currents routed through the material samples on the same path to ground. All events catalogued after June 10, 2008 use the intercepting wire described previously to divert the return stroke current to a string of material samples separate from that of the IS current.

Table 1. Triggered Lightning Events During the Ball Lightning Experiment

Shot	Date	Launch Time (UT)	Result	Peak RS Current (kA)	Number of Strokes	E-Field (kV/m)
UF 08-02	6/10/08	19:32	IS & RS	24	6	-5.5
UF 08-04	6/29/08	21:36:29	IS	-	-	-5.2
UF 08-08	6/30/08	18:41:24	IS & RS	18	5	-5.7
UF 08-11	7/12/08	17:52:49	IS & RS	17	3	-5.9
UF 08-12	7/23/08	18:40:21	IS	-	-	-5.8
UF 08-13	7/27/08	20:22:21	IS	-	-	-6.2
UF 08-17	9/11/08	20:36:56	IS	-	-	-5.3
UF 08-18	9/17/08	22:04:15	IS & RS	21	9	-6.3

A complete listing and detailed description of all material samples used during the ball lightning experiment are found in Appendix A. The listings are catalogued by date and shot number corresponding to entries in Table 1. For each shot, material samples are listed for both the IS and RS poles (when applicable) in order of descending physical height placement on the respective poles.

III. Results and Discussion

Of the eight successful triggered lightning events of the 2008 season, only two events, in our judgment, produced high-speed photographic data worthy of discussion in the context of ball lightning. All other material ignition, a total of about 100 material samples, produced luminous durations significantly less than 350 ms and/or had other characteristics inconsistent with ball lightning. Phantom high-speed video data were obtained for seven of the eight events (not for the triggered flash on 6/30/08). High-definition video records on 6/30/08 indicate that no luminous events that could fit the description of ball lightning occurred during the triggered flash. The presented results and discussion will detail the two rocket-and-wire triggered flashes, occurring on 6/10/08 and 9/17/08, that were of significance regarding natural ball lightning and previous laboratory attempts at its creation. Of all the flashes studied, the glowing ball/balls generated above the stainless steel plates on 9/17/08 most resembled natural ball lightning. We discuss now the following triggered events and observations of those events:

1) <u>6/10/08</u>
    - Flame in/above the swimming pool filled with salt water
    - Falling glowing silicon particles

2) <u>9/17/08</u>
    - Persistent glowing ball/balls above stainless steel plates
    - Persistent glow above a pine tree trunk resting in a swimming pool filled with salt water

6/10/08: UF 08-02

The first successful triggered lightning flash of the 2008 season was a unique event. Normally, the initiation of a sustained upward leader ensues several seconds after the rocket launch when the rocket has reached an altitude of the order of a hundred meters. In this event, there were a full seven seconds of elapsed time between the rocket launch and the initial stage of the triggered flash. As a result, no 35 mm still photographs were acquired. The triggering wire was very likely falling at the time of flash initiation. The IS current for UF 08-02 was also long in duration, between 700-800 ms with a charge transfer greater than 61.5 C. Arcs are seen on the material samples placed on the PVC pole approximately 90 ms prior to the full ignition of the triggering wire. The first visible arc in the salt water-filled swimming pool located on the ground occurs around 80 ms after the full ignition of the triggering wire. A “flame” appears above the water surface in the swimming pool at this point and persists for 432 ms. The flame generally expands upward and outward in size during this time and peaks in luminous intensity during sequences of ICC pulses, impulsive events superimposed on the initial continuing current having durations up to several milliseconds and current amplitudes up to the kilo-amperes range. Interestingly, the ICC continues for another 230 ms after the flame extinguishes. There is visible arcing in the pool during this time period, but no arcs appear above the water surface. Figure 5 shows a sequence of ten cropped frames extracted from the Phantom video at 48 ms intervals during the ICC process spanning the total 432 ms that luminous phenomena were evident above the water surface. The first frame corresponds to the initial arc seen in the swimming pool 80 ms after the full ignition of the triggering wire. The flame reached a maximum width of approximately one meter.

Following the ICC and after the first return stroke (peak current 21.2 kA), a new flame persisted above the water surface in the swimming pool for a total of 46 ms. There are 26 ms of continuing current following the return stroke before an M-component occurs 28 ms after the first stroke. The flame extinguished approximately 18 ms after the M-component. The second return stroke (peak current 8 kA) occurred 132 ms after the first stroke. There was no appreciable continuing current following the second stroke and the flame above the pool lasted only for 6 ms. The third return stroke (24 kA) occurred 162 ms after the first stroke, and was followed 10 ms later by the fourth return stroke (4.4 kA). Luminosity persisted above the swimming pool for 90 ms following the third stroke. The continuing current duration following the third stroke was approximately 47 ms. The fifth return stroke (16.3 kA) occurred 274 ms after the first stroke and was followed by the sixth return stroke (3.7 kA) 8 ms later. The flame in the pool lasted for 4 ms following the fifth stroke and only 2 ms following the sixth stroke. Neither the fifth or sixth stroke had any appreciable continuing current. In summary, from these observations, it appears that there is a strong correlation between the lifetime of the flame in the swimming pool and the presence of slowly varying, relatively long-duration current flow (due either to the IS process or to continuing current following a return stroke).

The second interesting ball-lightning related event occurring during UF 08-02 resulted from the explosion of two silicon wafers (detailed material description in Appendix A) mounted on the PVC pole. A photograph of the lightning-damaged silicon wafers is shown in Figure 6, which, as noted earlier, also shows the braided wire offset from the PVC pipe and the spark gaps in the braided wire. The first silicon particles appear to erupt from the wafers approximately 212 ms after the full ignition of the triggering wire. However, the primary silicon particle shower did not begin until around 520 ms after the triggering wire fully ignited. The full duration of the silicon particle shower is approximately 3.35 s. However, most individual particles appeared to strike the ground between 0.75-1.25 s after being emitted from the lightning-struck silicon wafers. A picture showing ten extracted frames at 280 ms intervals, a total of 2.52 s, from the silicon particle shower is shown in Fig. 7. The first frame corresponds to a time 520 ms after the full ignition of the triggering wire. Most particles demonstrated relatively constant luminosity as they fell, and they also appeared to fall with reasonably constant acceleration. A video was created showing the luminosity from the falling silicon particles integrated over the full particle shower. The final frame from the video is shown in Figure 8 from which it is clear that the falling particles retained a constant luminosity, a characteristic reported for ball lightning. Velocity profiles were measured for numerous falling silicon particles, indicating that they fall under the influence of gravity. Additionally, individual particles are seen to deflect when they strike the structures below them and bounce when they impact the ground. A typical velocity profile is shown in Figure 9 with a linear regression line. Attempts were made to measure the sizes of various falling silicon particles from the Phantom video records with a known size reference point at the same distance from the lens. However, most of the particles were at most two pixels in size. With such poor resolution and blooming effects, the only statement that can be made regarding particle size is that most were likely less than 2 cm in extent (one pixel is approximately equal to 2 cm).

9/17/08: UF 08-18

The rocket-and-wire triggered lightning on 9/17/08 was a nine-stroke flash with peak return stroke current of 21 kA. For this event, no material samples were placed on either the IS or RS PVC poles. The IS and RS currents were separated into different paths. Twelve gauge solid core copper wire was used to short-circuit the spark gaps on both poles. The IS current was routed from the PVC pole to a galvanized steel threaded rod electrode mounted vertically and about 4 inches above the top plane of two stacked 304 stainless steel plates, as shown in Fig. 10. The tip of the top electrode was filed to a sharp point. The top stainless plate was 0.5 inches in thickness and the bottom stainless plate was 1.5 inches in thickness. Both plates were square with a side length of 12 inches. The two stainless plates were connected together by a piece of braided wire and were in pressure contact. A second galvanized steel threaded metal rod electrode was filed to a sharp point and mounted under the bottom stainless plate with a spark gap of approximately 3 inches. The PVC pipe in the foreground of Figure 10 is at approximately the same height as the top of the wood stand, but the camera perspective makes the pipe look higher. The top rod electrode passes through about 9 inches of the wood support structure. The inset of Figure 10 shows an extracted Phantom video frame during the triggered flash on 9/17/08. From the view shown in Figure 10 and an orthogonal view, it is evident that the glowing region encompasses a portion of the top electrode, with that electrode being evident both above and below the luminous region after the luminous region separates from the stainless steel plates. The locations of the 304 stainless plates, foreground PVC pipe, and top electrode are marked in Figure 10 for height reference.

A piece of braided wire connected the bottom metal rod electrode to a freshly cut pine tree trunk resting in the swimming pool filled with saltwater. A large galvanized nail was used to connect the braided wire to the cambium through the top of the pine tree trunk. A second piece of braided wire was connected to the cambium on the bottom side of the pine tree trunk by another galvanized nail and then clamped to the grounded ring electrode on the circumference of the swimming pool. The nails were used in an attempt to force the incident current to pass through the pine tree trunk as opposed to arcing directly over the bark to the ring electrode.

The full duration of the persistent glow around/above the stainless steel plates was approximately 648 ms. The distinct ball-shaped luminous glow was seen separated from the stainless steel plates for approximately 266 ms. Interestingly, the only clear evidence of arcing damage to either stainless steel plate occurred on the bottom face of the bottom plate (Figure 11).

Figure 12 shows twenty extracted Phantom video frames from the stainless steel plate experiment. The frames shown were taken at 16 ms intervals from just prior to the full separation of the glowing ball from the stainless plates, 328 ms after the first arc is seen on the stainless plates, to the point in time where all the glowing sections were extinguished, 648 ms following the initial arc on the stainless plates. In the images shown, the top glowing region is above the stainless steel plates. Figure 12 also shows ten extracted Phantom video frames at 16 ms intervals of the persistent glow on/above the pine tree trunk (time progressing from left to right, distance scales in units of meters).

The full IS duration of UF 08-18 was approximately 300 ms with a charge transfer of 6.8 C. The initial arc above the stainless plates was seen around 45 ms prior to the complete ignition of the triggering wire. After the triggering wire exploded, a constant intense luminous glow was seen surrounding the stainless plates for 340 ms. This glow expanded to nearly a meter in diameter and is assumed to be the combination of multiple continuous arcs above and below the stainless plates. Around 342 ms after the explosion of the triggering wire, the luminous glow receded and broke into a distinct oblong ball-shape form suspended approximately 12 inches above the top stainless steel plate. The initial ball was, at maximum, 28 inches in width and 19 inches in height. Twenty-six milliseconds after the oblong glowing ball became clearly separated from the stainless plates, it split into two distinct round ball-shaped forms that shrunk gradually in size with each subsequent frame. The two glowing balls appeared to remain relatively stationary. They did not appear to rise. When the balls became clearly split, the left ball was 17 inches wide and 13 inches in height. The right ball was 13 inches wide and 13 inches in height. The first return stroke occurred approximately 394 ms after the explosion of the triggering wire. Ideally, the intercepting wire over the top of the tower launcher should divert the entire return stroke current to the return stroke path to ground. However, during UF 08-18, a portion of the incident current due to the first four return strokes passed down the IS path to ground; and after the first return stroke, the arcs from the stainless steel plates persisted for 10 ms (the frames showing return stroke luminosity are not presented in Figure 12). However, the return stroke did not contribute to <u>any</u> <u>change</u> in luminosity to the two distinct glowing balls suspended above the plates. The glowing balls appeared to remain entirely unaffected by the return stroke. Around 18 ms after the first return stroke, the left glowing ball began to lose shape and split into two distinct sections. The top left ball was 8 inches in width and 5.3 inches in height, the bottom left ball was 13 inches in width and 8 inches in height, and the right ball was 13 inches in width and height. The second return stroke occurred 6 ms later. The arcs from the electrodes to the stainless plates only persisted for 4 ms and again had no affect on the existing suspended illuminated balls. Around 2 ms after the second return stroke, the glowing form above the plates split into four distinct sections, each with size ranging from 4 inches to 13 inches in width and 13 inches in height. The luminosity of each section declined uniformly with each subsequent frame. About 16 ms after the second return stroke, five distinct balls were visible, ranging in size from 4 inches to 8 inches. The third return stroke occurred 18 ms after the persistent glow splits into five sections, but again, the arcs on the stainless plates due to the return stroke current had no affect on the suspended glowing form above. All five sections declined steadily in luminosity until the top left ball extinguished 48 ms after the third return stroke. Twelve milliseconds later, the bottom left ball vanished, leaving three illuminated regions. The fourth return stroke occurred 2 ms after the fourth ball disappeared. The surviving glowing sections remained unchanged by the fourth return stroke. About 40 ms after the fourth return stroke, the right-most glowing section extinguished, leaving two faintly illuminated regions. The fifth return stroke occurred 12 ms after the third glowing section disappeared. However, there was no detectable illumination on the stainless plates due to the stroke. From this point forward in time, all of the four subsequent return stroke currents appeared to follow the diverted (RS) path to ground from the intercepting wires. The bottom ball vanished around 10 ms after the fifth return stroke, and the remaining ball disappeared 30 ms later. Table 2 lists the peak currents and times for the first five return strokes relative to the full ignition of the triggering wire.

Table 2. Peak current and return stroke times relative to the full ignition of the triggering wire for UF 08-18

Stroke	Peak Current (kA)	Time (ms)
1	11.6	394
2	9.2	418
3	20.8	452
4	16.2	514
5	7.6	566

Although the bottom face of the bottom stainless steel plates is clearly marked by arcing (Figure 11), the top face of the top plate, which was wet with rain, showed no evident damage except for some small marks on the edges of the plate, although the glowing region appeared to have emanated from the top. While the composition of the resulting luminous ball is uncertain, the stainless steel plates, galvanized steel electrodes, water, and the surrounding wooden support frame may all have made some contribution to the observed luminous phenomenon.

As noted above, a freshly cut pine tree trunk was placed in a swimming pool filled with saltwater and connected directly to the IS path to ground. An identical experiment was constructed on the return stroke path to ground. During the IS process, the first glow on the top of the pine tree trunk is seen 4 ms after the initial glow on the stainless plates overhead and around 38 ms prior to the full explosion of the triggering wire. The illuminated region reached a maximum width of about 19 inches before completely separating from the top of the pine tree trunk 342 ms after the initial glow was recorded. The glowing region above the pine tree appeared to rise slightly and declined in luminosity with each subsequent frame. The smaller persistent glowing region directly on top of the pine tree extinguished around 42 ms after the separation. The first return stroke occurs 90 ms after the glowing region separated from the top of the pine tree trunk. Similar to the stainless steel plates, the arcs around the pine tree due to the return stroke current had no affect on the glowing region above the top of the tree trunk. The second return stroke occurred 24 ms later and also had no affect on the remaining glowing region. After the second return stroke, the glowing region above the pine tree declined in luminosity and became disorganized. It finally disappeared around 28 ms after the second return stroke. The full duration of the glow on/above the pine tree trunk was approximately 484 ms, while the clearly separated glowing region survived for approximately 142 ms. No persistent glowing regions were recorded on/above the pine tree trunk placed in the RS path to ground. While the composition of the glowing region above the pine tree is also uncertain, we expect that sap, water, electrode metal, and the wood itself may have all made contributions. The first frame in the image sequence shows the glowing region on the pine tree just prior to separation. The following nine images show the glowing region gradually rising above the pine tree as it declined in size and luminosity. Phenomena similar to that described for the pine tree trunk above were recorded on four separate occasions (UF 08-11, UF 08-12, UF 08-13, UF 08-17), all during the initial stage process of rocket-and-wire triggered lightning. In each case, the glowing regions extinguished within 350 ms.

IV. Comparison with Laboratory Ball Lightning Experiments

We have apparently duplicated, with uncontrolled triggered lightning currents, two classes of laboratory experiments purported in the literature to represent ball lightning or some aspects of ball lightning. The first class of experiments, the experiments of Stephan and Massey (2008), following the initial work of Paiva et al (2007), showed that electric arcs on silicon, aluminum, and copper could produce liquid metal spheres of 0.1 to 1.0 mm diameter that glow by surface combustion. These glowing balls may well represent one class of phenomena that has been described as ball lightning. We show a similar if not identical phenomena in Figures 7 and 8, although our optical system resolution is such that the balls appear to be centimeter size. Perhaps the human eye would also interpret them as much larger than their actual size. Figures 7 and 8 show a shower of glowing objects, whereas Stephan and Massey (2008) and Paiva et al. (2007) were able to produce single glowing spheres in the controlled laboratory environment. Perhaps we sometimes produced single spheres, but those would have been difficult to detect with our experimental setup.

The second class of experiments, those producing flame-like phenomena above dirty water in which arcing occurs, is exemplified by the work of Versteegh et al. (2008). We produced flame-like phenomena of similar shape and duration, as shown in Figure 5. It is not clear to us that this phenomena, while interesting, has any direct relation to natural ball lightning.

V. Summary

During the 2008 ball lightning experiment, around 100 different material samples were exposed to both relatively continuous (initial stage and inter-stroke continuing current) and to impulsive (return stroke) triggered lightning current. All events with properties similar to those reported by eye-witness and laboratory accounts of ball lightning were produced by slowly varying, relatively low amplitude currents during the initial stage of the triggered-lightning process. No events with sustained luminosity duration greater than 100 ms were recorded as a result of impulsive return stroke currents. The luminous balls observed above the stainless steel plates most closely resembled the accounts of ball lightning described in the literature. We apparently duplicated the laboratory experiments of Stephen and Massey (2008) and Paiva et al. (2007) who produced small combusting metal spheres from arcs to metals and of Versteegh et al. (20008) who produced a flame-like phenomena via arcing in water containing calcium chloride.

VI. References

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Appendix A

List of Samples

6/10/08: UF 08-02

Note: Material samples are listed according to their physical placement on the PVC pole. Samples are listed in order of decreasing height placement.

1. **Brass #1 -** 1/8 inch brass rod with diameter of 3.18 mm implying 7.94 mm^2 cross sectional area. The center necked down area is 2 mm X 2 mm with a 4 mm^2 cross sectional area. A pre-flash still image of this sample is located under file name: **pole1brass1_060608_0802.jpg**.

2. **Copper #2** - #10 copper wire with a diameter of 2.57 mm and cross sectional area of 5.2 mm^2. The center necked down area is 1.4 mm X 1.4 mm with cross sectional area of 1.96 mm^2. A pre-flash still image of this sample is located under file name: **pole1copper2_060608_0802.jpg**.

3. **Aluminum #1 –** aluminum wire with a diameter of 4.46 mm and cross sectional area of 15.6 mm^2. The necked down section has dimensions 3 mm X 3 mm (9 mm^2 cross sectional area) and is 4 mm long. A pre-flash still image of this sample is located under file name: **pole1aluminum1_060608_0802.jpg**.

4. **Copper #1** - #10 copper wire with a diameter of 2.57 mm and cross sectional area of 5.2 mm^2. The necked down section has dimensions 1.8 mm X 1.8 mm with a 3.24 mm^2 cross sectional area. A pre-flash still image of this sample is located under file name: **pole1copper1_060608_0802.jpg**.

5. **Aluminum #2 –** aluminum wire with a diameter of 3.4 mm (3.08 mm^2 area). The necked down section has dimensions 2 mm X 2 mm with a 4 mm^2 cross sectional area. A pre-flash still image of this sample is located under file name: **pole1aluminum2_060608_0802.jpg**.
6. **Aluminum Plate #1 –** Aluminum plate that is 0.060 inch thick with dimensions of 4.5 inches X 7 inches. Electrical connection is made on one side via #10 AWG stranded wire connected to 2 existing holes. Electrode on other side made from ¼ inch – 20 thread pointed steel rod with a gap of 3/16 inch. A pre-flash still image of this sample is located under file name: **pole1aluminumplate1_061008_0802.jpg**. A post-flash still image of this sample is located under file name: **061108_0802_Alplate#1.jpg**.

7. **Silicon #1 –** Silicon wafer that is 0.025 inch thick. The wafer has height of 3.75 inches and length 5.75 inches. Electrodes are 1/4 inch threaded steel rods on each side of the wafer located 2.2 inches from flat side and 1.2 inches above bottom. 4-inch PVC pipe ring added for support on the wafer. A pre-flash still image of this sample is located under file name: **pole1silicon1_061008_0802.jpg**. A post-flash still image of this sample is located under file name: **061108_0802_Si#1.jpg**.

8. **Silicon #2 –** One half of a full disk with ¼ inch threaded steel rod electrodes located on each side of the silicon surface with a gap of ¼ inch. 4-inch PVC pipe rings support both sides. A pre-flash still image of this sample is located under file name: **pole1silicon2_061008_0802.jpg**. A post-flash still image of this sample is located under file name: **061108_0802_Si#2.jpg**.

9. **Pool –** 45 gallons of water at 5g Sodium Chloride (salt) per gallon, totaling 225 g of Sodium Chloride. The ring electrode is around the edge of the pool 1 inch below water level. There are two grounding rods, one on each side of the pool. The lightning current electrode comes down into the pool an inch below the surface of the water in the center of the pool.

6/29/08: UF 08-04

Note: Material samples are listed according to their physical placement on each PVC pole. Samples are listed in order of decreasing height placement.

ICC Pole

1. **Silicon #3 –** Solid attachment to the dull side of silicon wafer with a 2 inch gap on the mirrored side. A pre-flash still image of this sample is located under filename: **Pole1Silicon3_061208.jpg.** A post-flash still image of this sample is located under filename: **062908_0804_Si3.jpg**.

2. **Copper Powder #1 –** Two grams of dry, spherical, -100 mesh, 99.5% metals basis of copper powder in PVC container. A pre-flash still image of this sample is located under filename: **Pole1Copperpowder1_062308.jpg**. A post-flash still image of this sample is located under filename: **062908_0804_Cupowder1.jpg**.

3. **Aluminum Plate #2 –** ¼ inch thick piece of aluminum cut from a 2 inch aluminum angle. There is a one inch gap to a steel bolt electrode.

4. **Copper #2 -** #10 AWG copper wire with a diameter of 2.57 mm. The necked down portion of the copper wire has dimensions 1.4 mm x 1.4 mm for a cross-sectional area of 1.96 mm^2.

5. **Copper #3 -** #14 AWG copper wire with a necked down portion in the middle of the sample. The copper wire has a diameter of 0.064 inch, while the necked down portion has a diameter of 0.032 inch and respective cross-sectional area of 0.00161 inch^2 of 1.04 mm^2.

6. **Copper #4 –** 0.043 inch or 1.11 mm diameter copper wire with a necked down portion of diameter 0.55 mm. It has a cross-sectional area of 0.48 mm^2.

7. **Brass #2 –** 0.061 inch diameter or #14 AWG brass wire (1.58 mm diameter) with a necked down portion of diameter 0.79 mm. It has a necked down cross-sectional area of 0.98 mm^2.

8. **Silicon Powder #1 –** One gram of dry, Crystalline, -325 mesh, 99.5% metals basis silicon powder in a PVC container. A pre-flash still image of this sample is located under filename: **Pole1Siliconpowder1_062308.jpg**. A post-flash still image of this sample is located under filename: **062908_0804_Sipowder1.jpg**.

9. **Unknown MSE Sample #1 –** unknown sample in tube from Materials Science Engineering Department.

10. **Pool –** Water filled pool with a ratio of 10g NaCl per gallon of H2O. A post-flash still image of the pool and its electrode is located under filename: **063008_0808_Pool1electrode.jpg**.

Return Stroke Pole

1. **Silicon #4 –** A solid attachment is made to the dull side of silicon wafer with a 2 inch gap on the mirrored side.

2. **Aluminum Powder #1 –** One gram of dry, spherical, APS 10.0 – 14.0 micron, 98% metals basis aluminum powder in PVC container.

3. **Aluminum Plate #3 –** Aluminum plate with dimensions 4.5 inches by 7 inches. Electrical connection on one side via #10 AWG stranded wire connected to 2 existing holes. Electrode on opposite side made from ¼ -20 thread pointed steel rod with a 2 inch gap.

4. **KNO3 and Silicon Powder #1 –** One gram each of KNO3 and silicon powder for a total of 2 grams inside a PVC container.

5. **Sulfur and Silicon Powder #1 –** One gram each of sulfur and silicon powder for a total of 2 grams inside of a PVC container.

6. **Bat Guano #1 –** roughly two grams of bat guano in a PVC container.

7. **Aluminum Wet Powder #1 –** One gram of aluminum powder with the same specifications as dry aluminum powder in a PVC container. Two milliliters of H2O is added to the sample to provide moisture.

8. **Copper Wet Powder #1 –** Two grams of copper powder with the same specifications as copper powder #1. 2 milliliters of H20 is added to the sample to provide moisture.

9. **Pool –** Water filled pool with a ratio of 10g NaCl per gallon of H2O. A post-flash still image of the pool and its electrode is located under filename: **063008_0808_Pool2electrode.jpg**.

06/30/08: UF 08-08

Note: Material samples are listed according to their physical placement on each PVC pole. Samples are listed in order of decreasing height placement.

ICC Pole

1. **Silicon #3 –** Solid attachment to the dull side of silicon wafer with a 2 inch gap on the mirrored side. A pre-flash still image of this sample is located under filename: **Pole1Silicon3_061208.jpg.** A post-flash still image of this sample is located under filename: **063008_0808_Si3.jpg**.

2. **Copper Powder #1 –** Two grams of dry, spherical, -100 mesh, 99.5% metals basis of copper powder in PVC container. A pre-flash still image of this sample is located under filename: **Pole1Copperpowder1_062308.jpg**. A post-flash still image of this sample is located under filename: **063008_0808_Cupowder1.jpg**.

3. **Aluminum Plate #2 –** ¼ inch thick piece of aluminum cut from a 2 inch aluminum angle. There is a one inch gap to a steel bolt electrode. A pre-flash still image of this sample is located under filename: **Pole1Aluminumplate2_061208.jpg.** A post-flash still image of this sample is located under filename: **063008_0808_Alplate2.jpg**.

4. **Copper #2** - #10 AWG copper wire with a diameter of 2.57 mm. The necked down portion of the copper wire has dimensions 1.4 mm x 1.4 mm for a cross-sectional area of 1.96 mm^2. A pre-flash still image of this sample is located under filename: **Pole1Copper2_061208.jpg**. A post-flash still image of this sample is located under filename: **063008_0808_Cu2.jpg**.

5. **Copper #3** - #14 AWG copper wire with a necked down portion in the middle of the sample. The copper wire has a diameter of 0.064 inch, while the necked down portion has a diameter of 0.032 inch and respective cross-sectional area of 0.00161 inch^2 of 1.04 mm^2. A pre-flash still image of this sample is located under filename: **Pole1Copper3_061208.jpg**. A post-flash still image of this sample is located under filename: **063008_0808_Cu3.jpg**.

6. **Copper #4 –** 0.043 inch or 1.11 mm diameter copper wire with a necked down portion of diameter 0.55 mm. It has a cross-sectional area of 0.48 mm^2. A pre-flash still image of this sample is located under filename: **Pole1Copper4_061208.jpg**. A post-flash still image of this sample is located under filename: **0063008_0808_Cu4.jpg**.

7. **Brass #2 –** 0.061 inch diameter or #14 AWG brass wire (1.58 mm diameter) with a necked down portion of diameter 0.79 mm. It has a necked down cross-sectional area of

0.98 mm^2. A pre-flash still image of this sample is located under filename: **Pole1Brass2_061208.jpg**. A post-flash still image of this sample is located under filename: **063008_0808_Brass2.jpg**.

8. **Silicon Powder #1 –** One gram of dry, Crystalline, -325 mesh, 99.5% metals basis silicon powder in a PVC container. A pre-flash still image of this sample is located under filename: **Pole1Siliconpowder1_062308.jpg**. A post-flash still image of this sample is located under filename: **063008_0808_Sipowder1.jpg**.

9. **Unknown MSE Sample #1 –** unknown sample in tube from Materials Science Engineering Department.

10. **Pool –** Water filled pool with a ratio of 10g NaCl per gallon of H_2O. A post-flash still image of the pool and its electrode is located under filename: **063008_0808_Pool1electrode.jpg**.

Return Stroke Pole

1. **Silicon #4 –** A solid attachment is made to the dull side of silicon wafer with a 2 inch gap on the mirrored side. A pre-flash still image of this sample is located under filename: **Pole1Silicon4_061208.jpg.** A post-flash still image of this sample is located under filename: **063008_0808_Si4.jpg**.

2. **Aluminum Powder #1 –** One gram of dry, spherical, APS 10.0 – 14.0 micron, 98% metals basis aluminum powder in PVC container. A pre-flash still image of this sample is located under filename: **Pole3Aluminumpowder1_062308.jpg**. A post-flash still image of this sample is located under filename: **063008_0808_Alpowder1.jpg**.
3. **Aluminum Plate #3 –** Aluminum plate with dimensions 4.5 inches by 7 inches. Electrical connection on one side via #10 AWG stranded wire connected to 2 existing holes. Electrode on opposite side made from ¼ -20 thread pointed steel rod with a 2 inch gap. A pre-flash still image of this sample is located under filename: **Pole3Aluminumplate3_062308.jpg**. A post-flash still image of this sample is located under filename: **063008_0808_Alplate3.jpg**.

4. **KNO3 and Silicon Powder #1 –** One gram each of KNO_3 and silicon powder for a total of 2 grams inside a PVC container. A pre-flash still image of this sample is located under filename: **Pole3KNO3Siliconpowder1_062408.jpg**. A post-flash still image of this sample is located under filename: **063008_0808_KNO3Sipowder1.jpg**.

5. **Sulfur and Silicon Powder #1 –** One gram each of sulfur and silicon powder for a total of 2 grams inside of a PVC container. A pre-flash still image of this sample is located under filename: **Pole3Sulfursiliconpowder1_062408.jpg**. A post-flash still image of this sample is located under filename: **063008_0808_SulfurSipowder1.jpg**.

6. **Bat Guano #1 –** roughly two grams of bat guano in a PVC container. A pre-flash still image of this sample is located under filename: **Pole3Batguano1_062408.jpg**. A post-flash still image of this sample is located under filename: **063008_0808_Batguano1.jpg**.

7. **Aluminum Wet Powder #1 –** One gram of aluminum powder with the same specifications as dry aluminum powder in a PVC container. Two milliliters of H2O is added to the sample to provide moisture. A post-flash still image of this sample is located under filename: **063008_0808_WetAl1.jpg**.

8. **Copper Wet Powder #1 –** Two grams of copper powder with the same specifications as copper powder #1. 2 milliliters of H20 is added to the sample to provide moisture. A post-flash still image of this sample is located under the filename: **063008_0808_Wetcopper1.jpg**.

9. **Pool –** Water filled pool with a ratio of 10g NaCl per gallon of H2O. A post-flash still image of the pool and its electrode is located under filename: **063008_0808_Pool2electrode.jpg**.

07/12/08: UF 08-11

Note: Material samples are listed according to their physical placement on each PVC pole. Samples are listed in order of decreasing height placement.

ICC Pole

1. **2.5g Powder Carbon -** 2.5g powder Carbon in a PVC container. A post-flash still image of this sample is located under filename: **071208_0811_pole1powdercarbon.jpg**.

2. **Bat Guano and SiO2 -** Bat guano mixed with Si02 in a PVC container. A post-flash still image of this sample is located under filename: **071208_0811_pole1batguano_Si02.jpg**.

3. **Copper #2** - #10 AWG copper wire with a diameter of 2.57 mm. The necked down portion of the copper wire has dimensions 1.4 mm x 1.4 mm for a cross-sectional area of 1.96 mm^2. A post-flash still image of this sample is located under filename: **071208_0811_pole1copper2.jpg**.

4. **Copper #3** - #14 AWG copper wire with a necked down portion in the middle of the sample. The copper wire has a diameter of 0.064 inch, while the necked down portion has a diameter of 0.032 inch and respective cross-sectional area of 0.00161 inch^2 of 1.04 mm^2. A post-flash still image of this sample is located under filename: **071208_0811_pole1copper3.jpg**.

5. **Copper #4 –** 0.043 inch or 1.11 mm diameter copper wire with a necked down portion of diameter 0.55 mm. It has a cross-sectional area of 0.48 mm^2. A post-flash still image of this sample is located under filename: **071208_0811_pole1copper4.jpg**.

6. **Brass #2 –** 0.061 inch diameter or #14 AWG brass wire (1.58 mm diameter) with a necked down portion of diameter 0.79 mm. It has a necked down cross-sectional area of 0.98 mm^2. A post-flash still image of this sample is located under filename: **071208_0811_pole1brass2.jpg**.

7. **Pool #1** - Pool filled with 10g NaCl per gallon of water. The electrode is made from connecting the shield braid into the center section of a tree roughly a foot in length. A post-flash still image of this sample is located under filename: **071208_0811_treeinpool1.jpg**.

Return Stroke Pole

1. **2.5g Powder Carbon -** 2.5g powder Carbon in a PVC container. A post-flash still image of this sample is located under filename: **071208_0811_pole3powdercarbon.jpg**.

2. **Bat Guano and SiO2 -** Bat guano mixed with Si02 in a PVC container. A post-flash still image of this sample is located under filename: **071208_0811_pole3batguano_Si02.jpg**.

3. **Pool #2** - Pool filled with 10g NaCl per gallon of water. The electrode is made from connecting the shield braid into the center section of a tree roughly 0.5 foot in length. A post-flash still image of this sample is located under filename: **071208_0811_treeinpool2.jpg**.

07/23/08: UF 08-12

Note: Material samples are listed according to their physical placement on each PVC pole. Samples are listed in order of decreasing height placement.

ICC Pole

1. **Stainless Steel Plates -** located on launch tower level 3.

2. **3.5 g wet powdered Carbon -** suspended PVC container

3. **Sn+Ag2S+Ag+H2O -** suspended PVC container

4. **Bat Guano + Powdered Carbon -** suspended PVC container

5. **Copper #2 (#10 AWG) -** notch of 0.025”

6. **Copper #3 (#14 AWG) -** notch of 0.015”

7. **Copper #4 (#18 AWG) -** notch of 0.017”

8. **Brass #2 (#14 AWG) -** notch 0.017”

9. **Brass #3 (#14 AWG) -** notch 0.022”

10. **Copper #5 (#28 AWG)**

11. **Copper #6 (#22 AWG)**

12. **Pool #1** - Pool filled with 10g NaCl per gallon of water. The electrode is made from connecting the shield braid into the center section of a tree roughly a foot in length.

Return Stroke Pole

1. **3.5 grams wet powdered Carbon -** suspended PVC container

2. **Sn+Ag2S+Ag+H2O -** suspended PVC container

3. **Bat guano + powdered Carbon -** suspended PVC container

4. **Pool #2** - Pool filled with 10g NaCl per gallon of water. The electrode is made from connecting the shield braid into the center section of a tree roughly a foot in length.

07/27/08: UF 08-13

Note: Material samples are listed according to their physical placement on each PVC pole. Samples are listed in order of decreasing height placement.

ICC Pole

1. **Stainless Steel Plates -** located on launch tower level 3.

2. **3.5 g wet powdered Carbon -** suspended PVC container

3. **Sn+Ag2S+Ag+H2O -** suspended PVC container

4. **Bat Guano + Powdered Carbon -** suspended PVC container

5. **Copper #2 (#10 AWG) -** notch of 0.025”

6. **Copper #3 (#14 AWG)** - notch of 0.015”

7. **Copper #4 (#18 AWG) -** notch of 0.017”

8. **Brass #2 (#14 AWG) –** notch of 0.017”

9. **Brass #3 (#14 AWG) –** notch of 0.022”

10. **Copper #5 (#28 AWG)**

11. **Copper #6 (#22 AWG)**

12. **Pool #1** - Pool filled with 10g NaCl per gallon of water. The electrode is made from connecting the shield braid into the center section of a tree roughly a foot in length.

Return Stroke Pole

1. **3.5 grams wet powdered Carbon –** suspended PVC container

2. **Sn+Ag2S+Ag+H2O –** suspended PVC container

3. **Bat guano + powdered Carbon –** suspended PVC container

4. **Pool #2** - Pool filled with 10g NaCl per gallon of water. The electrode is made from connecting the shield braid into the center section of a tree roughly a foot in length.

09/11/08: UF 08-17

Note: Material samples are listed according to their physical placement on each PVC pole. Samples are listed in order of decreasing height placement.

ICC Pole

1. **3.5 g wet powdered Carbon -** suspended PVC container

2. **Sn+Ag2S+Ag+H2O -** suspended PVC container

3. **Bat Guano + Powdered Carbon -** suspended PVC container

4. **Copper #2 (#10 AWG) -** notch of 0.025”

5. **Copper #3 (#14 AWG) -** notch of 0.015”

6. **Copper #4 (#18 AWG) -** notch of 0.017”

7. **Brass #2 (#14 AWG) -** notch 0.017”

8. **Brass #3 (#14 AWG) -** a notch 0.022”

9. **Copper #5 (#28 AWG)**

10. **Copper #6 (#22 AWG)**

11. **Stainless steel plates**

12. **Pool #1** - Pool filled with 10g NaCl per gallon of water. The electrode is made from connecting the shield braid into the center section of a tree roughly a foot in length.

Return Stroke Pole

1. **3.5 grams wet powdered Carbon –** suspended PVC container

2. **Sn+Ag2S+Ag+H2O –** suspended PVC container

3. **Bat guano + powdered Carbon –** suspended PVC container

4. **Deuterium Water**

5. **Pool #2** - Pool filled with 10g NaCl per gallon of water. The electrode is made from connecting the shield braid into the center section of a tree roughly a foot in length.

09/17/08: UF 08-18

Note: Material samples are listed according to their physical placement on each PVC pole. Samples are listed in order of decreasing height placement.

ICC Pole

1. **Stainless Steel Plates**

2. **Pool #1** - Pool filled with 10g NaCl per gallon of water. The electrode is made from connecting the shield braid into the center section of a tree roughly a foot in length.

Return Stroke Pole

1. **Pool #2** - Pool filled with 10g NaCl per gallon of water. The electrode is made from connecting the shield braid into the center section of a tree roughly a foot in length.

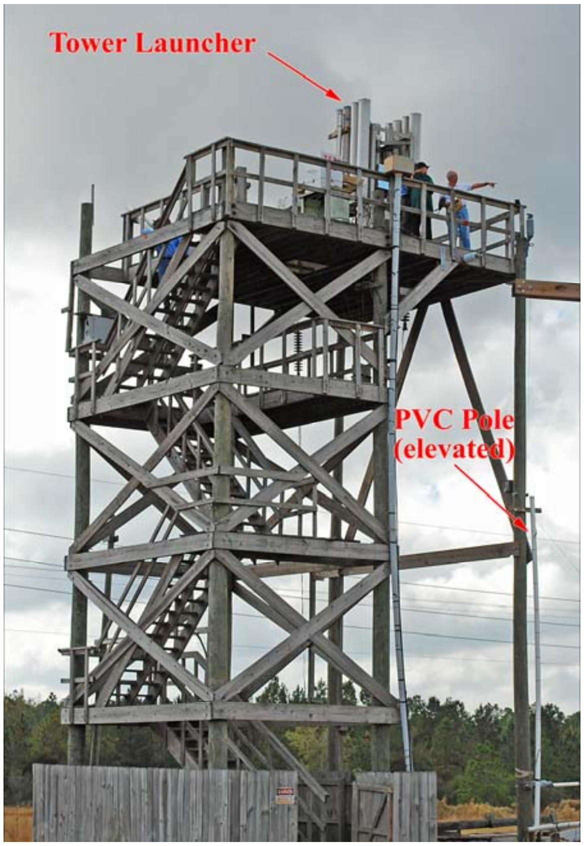

Figure 1. Full View of Launch Tower and Initial Ball Lightning Setup

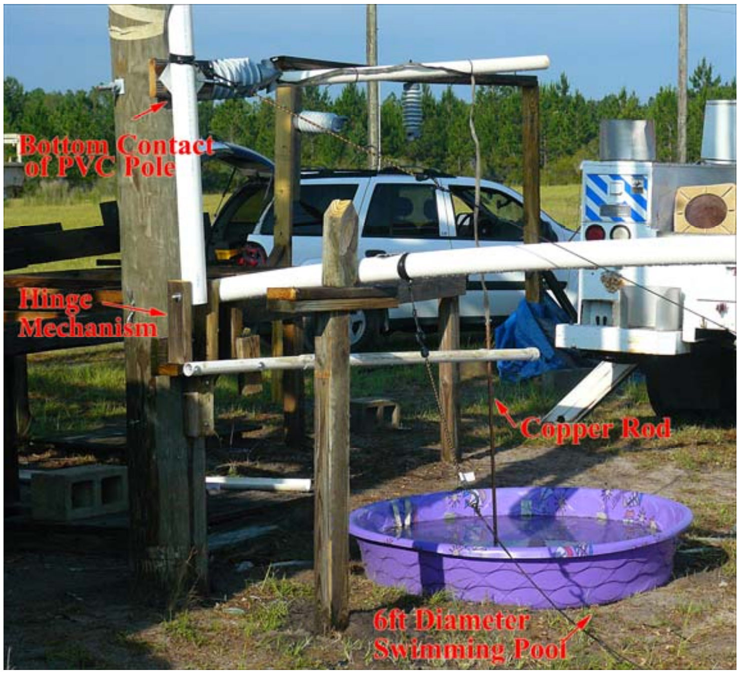

Figure 2. Base of PVC Pole, Copper Rod, and Grounded Swimming Pool

Figure 3. Final Ball Lightning Setup

Figure 4. Satellite View of the ICLRT Showing Structure Locations

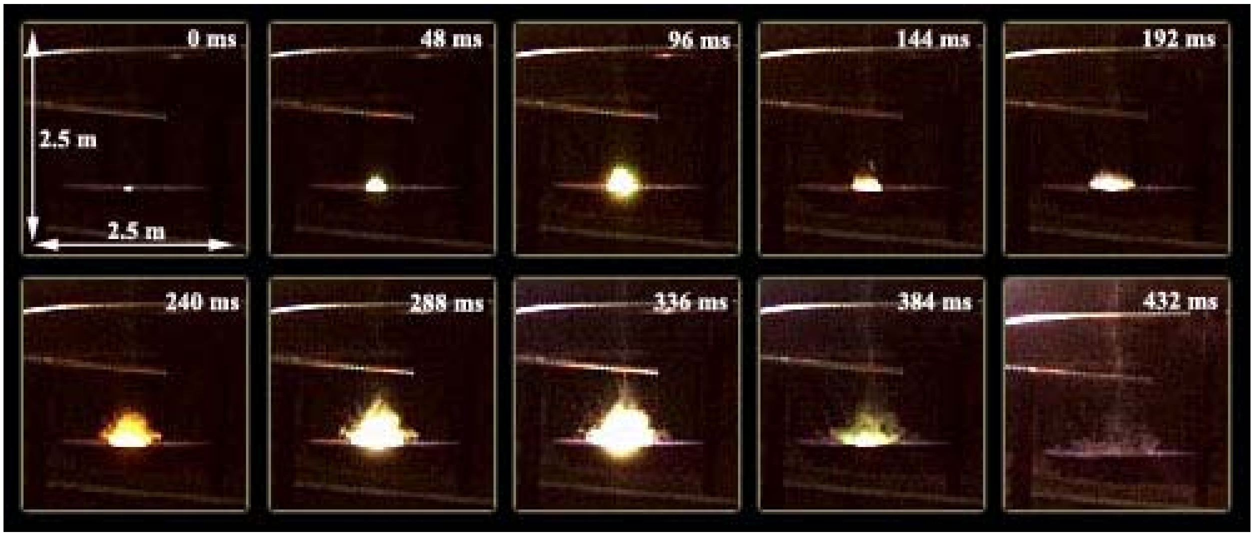

Figure 5. Extracted Frames of the Swimming Pool Flame During the ICC Process of UF 08-02 Starting 80ms after the Full Ignition of the Triggering Wire

Figure 6. Lightning-damaged Silicon Wafers

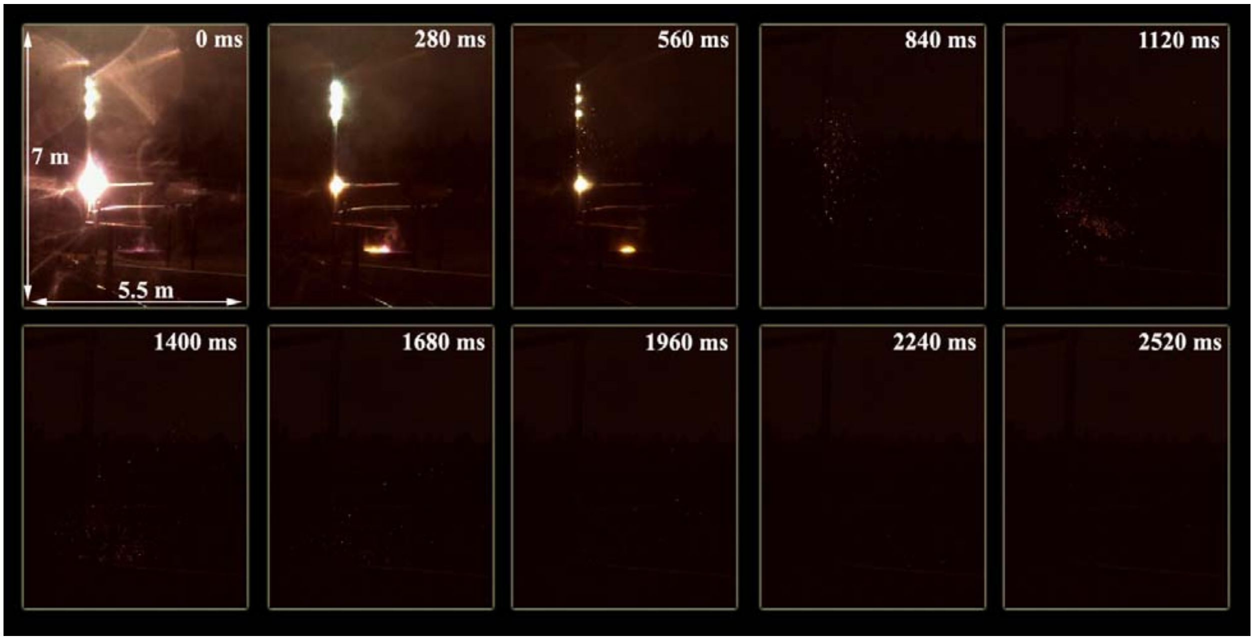

Figure 7. Extracted Phantom video frames showing the silicon particle shower from UF 08-02

Figure 8. Extracted Video Frame Showing Integrated Luminosity from the Silicon Particle Shower

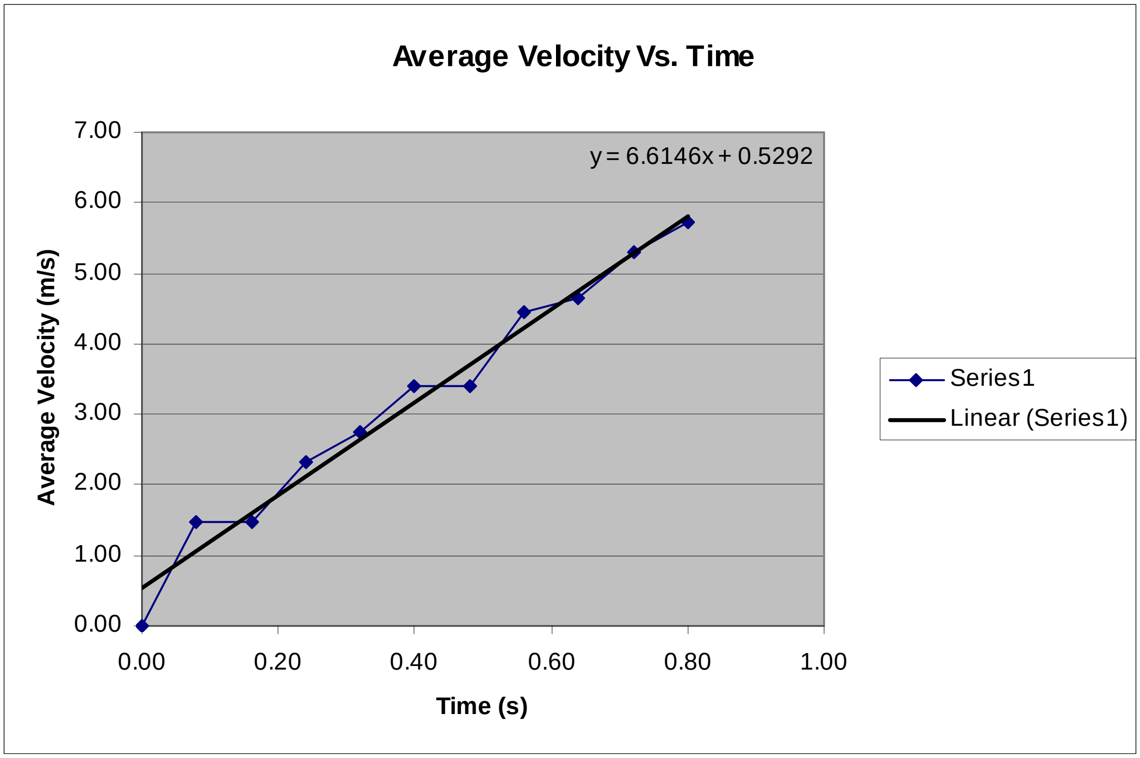

Figure 9. Velocity Profile of Falling Silicon Particle

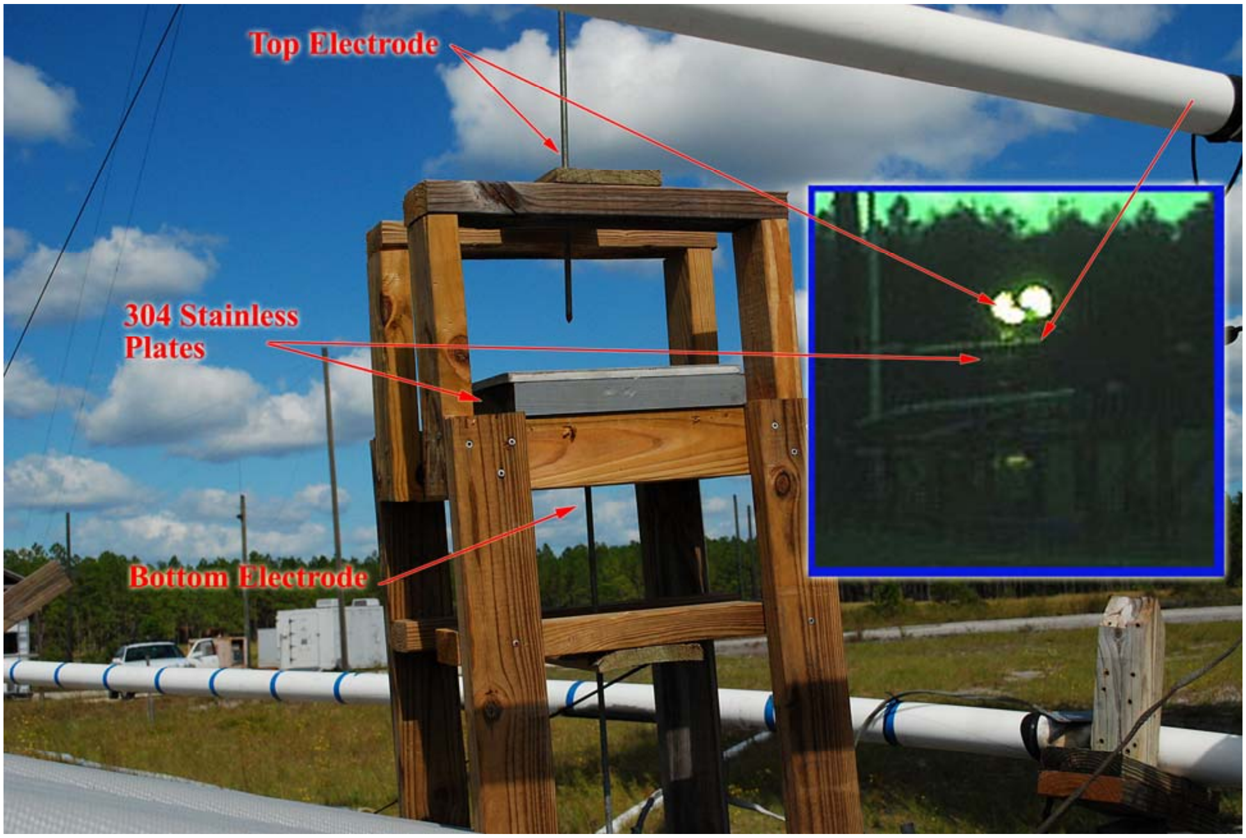

Figure 10. Stainless Steel Plate Experiment Placed on the IS Path to Ground

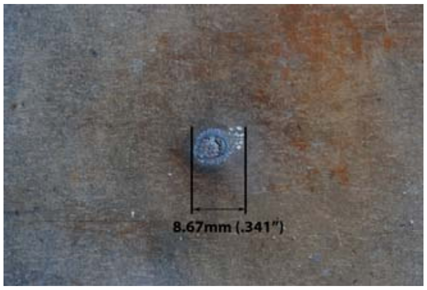

Figure 11. Arc Mark on the Bottom of the Lower Stainless Steel Plate

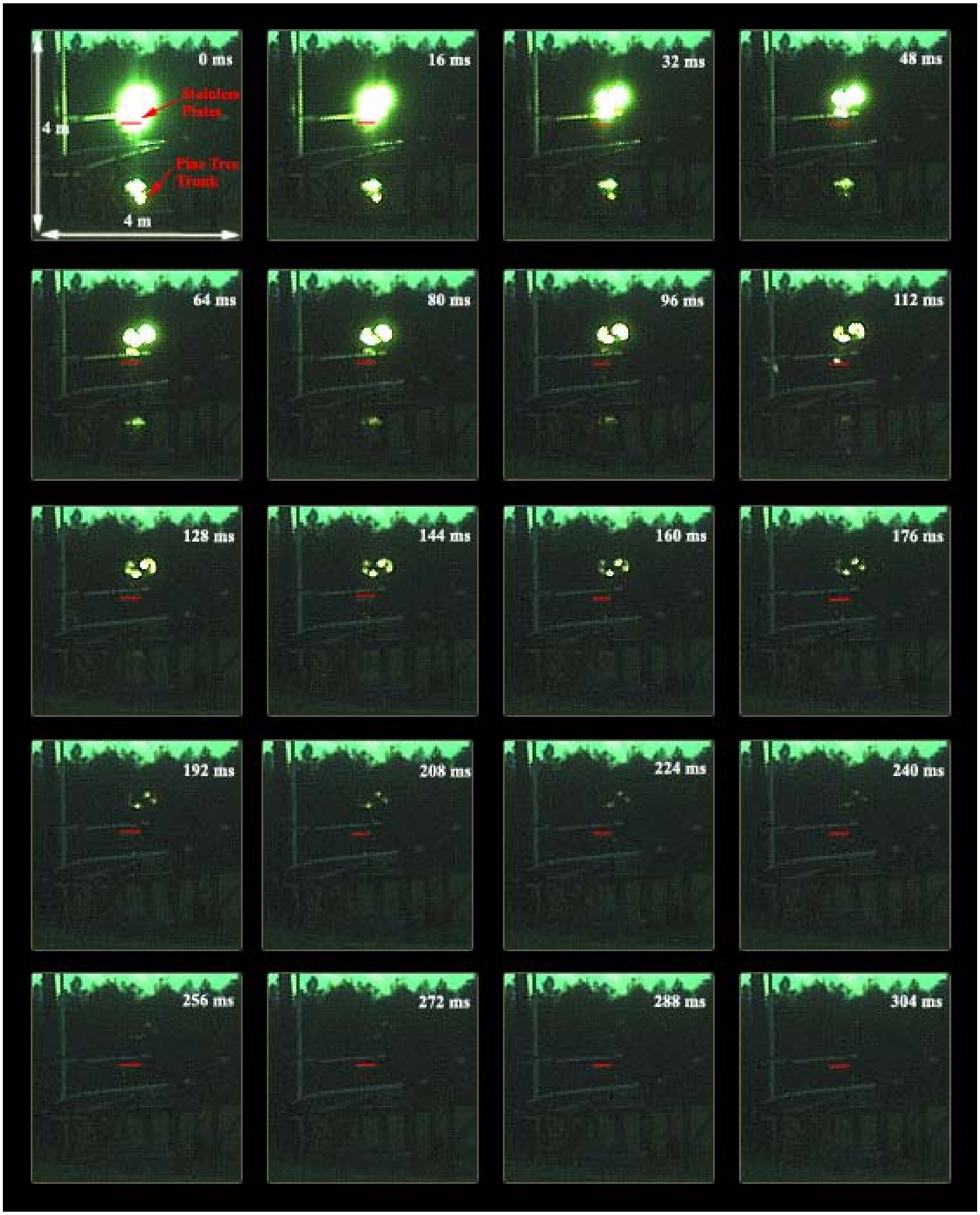

Figure 12. Extracted Phantom video frames showing persistent illuminated regions on/above both the stainless steel plates (top glow) and the pine tree trunk (bottom glow) during UF 08-18. The red horizontal line marks the location of the top stainless steel plate.

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