Abstract— We present results of the structural lightning protective system (LPS) tests conducted in 2004 and 2005 at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. Lightning was triggered using the rocket-and-wire technique, and its current was directly injected into the LPS. The test configurations in 2004 and 2005 differed in the lightning current injection point, number of down conductors, grounding system at the test house, and the use of surge protective devices. The primary objective was to examine the division of the injected lightning current between the grounding system of the test house and remote ground accessible via the neutral of the power supply cable. In 2004, the mean value of the peak current entering the electrical circuit neutral in search of its way to remote ground was about 22% of the injected lightning current peak, while in 2005 it was about 59%. For comparison, over 80% of the injected peak current was observed to enter the electrical circuit neutral in similar 1997 tests at the ICLRT in which a different test house was used (Rakov et al., 2002 [1]).

Index Terms— Lightning protective system, grounding, triggered lightning.

I. INTRODUCTION

In 1997, the University of Florida (UF), using triggered lightning (e.g., Rakov, 1999 [2]) and a small test residential structure at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida, examined two hypothetical scenarios suggested by the International Electrotechnical Commission (IEC) for the lightning current distribution in the electrical circuit of a residential building equipped with a lightning protective system when this system receives a direct strike.

In these two IEC scenarios, either 25 or 50% of the total lightning current is assumed to enter the building’s electrical circuit neutral and to flow to the distribution transformer’s ground and to other remote grounds in the system. It is important to note that the IEC current distributions assume that the current waveshapes in all parts of the circuit are the same, while in the experiment the current waveshapes in the two ground rods (one ground rod for the lightning protective system and one for the power supply system) of the test house differed markedly from the current waveshapes in other parts of the test system. The grounding system of the test house was subjected to triggered-lightning discharges for three different configurations, with the house’s electrical circuit (a utility meter followed by simulated resistive loads) being connected to the secondary of a pad-mount transformer, about 50 m distant. The primary of the transformer was connected to a 650-m underground cable, which was open-circuited at the other end. The cable neutral was grounded at the transformer and at the open-circuited end. The test system was unenergized. Results of the 1997 experiment are presented by Rakov et al. [2002]. The two ground rods at the test house appeared to filter out the higher frequency components of the lightning current, allowing the lower frequency components to enter the house’s electrical circuit neutral. In other words, the ground rods exhibited a capacitive rather than the often expected and usually modeled resistive behavior. This effect was observed for dc resistances of the ground
rods (in typical Florida sandy soil) ranging from more than a thousand ohms to some tens of ohms. The peak value of the current entering the test house’s electrical circuit neutral was found to be over 80% of the injected lightning current peak, in contrast with the 25 or 50% assumed in two IEC-suggested scenarios.

A new test residential structure (see Fig. 1), typical of Florida housing, has been recently constructed at the ICLRT. This structure (test house) was used in triggered-lightning testing of structural lightning protection in 2004 and 2005. In both years, the test house was equipped with a lightning protection system (LPS) in accordance with the National Fire Protection Association standard (NFPA 780 [3]).

![Fig. 1. The test house at the ICLRT whose LPS was subjected to direct lightning strikes in 2004 and 2005. Approximate dimension of the house are 10 x 7 x 6.5 m³. Photo from 2005.](image)

## II. EXPERIMENTAL SETUP

### 2004 Experiment

In 2004, the LPS, schematically shown in Fig. 2, was installed on the test house by a Lightning Safety Alliance (LSA) team. The lightning current was injected to one (south) of the three interconnected air terminals that were connected via two down conductors (downleads) to ground rods at opposite corners of the house (see Fig. 2). There were two LPS ground rods at each SW and NE corners, separated by about 6.1 m and connected by a buried horizontal conductor. There was an additional power supply system ground rod in the middle of the north side of the house. This ground rod was connected by a buried horizontal conductor approximately 3.4 m long to one of the NE corner LPS ground rods (see Fig. 2). Electrical diagram is shown in Fig. 3. The interior electrical wiring of the house was disconnected and replaced by a simulated load composed of two resistors (4 and 6 ohms) at the inside distribution box. MOV surge protective devices (SPDs) were installed between the two phase conductors and the grounded neutral. A watt-hour meter was installed between the house electrical circuit and the underground power feeder (600-V cable). There was no power to the house, and the other end of the 600-V cable was terminated at Instrumentation Station 1 (IS1), 50 m away, in 50-ohm resistors. The cable’s neutral was also grounded at IS1 using a single vertical ground rod with a length of 12 m. The grounding resistance of the ground rod at IS1 was 69 Ω. Vertical ground rods at the test house had a length of 2.7 m, with dc grounding resistances for each grounding location being given in Fig. 3. The dc grounding resistance of the entire system unburied was 130 Ω and for the entire system buried 113 Ω. Grounding resistances were measured using the fall-off-potential method.

![Fig. 2. Diagram of the lightning protective system of the test house in 2004. All conductors below the plane labeled “Ground Level” are buried (in direct contact with earth). See also Figure 3.](image)

Currents were measured at six points, labeled A, B, C, D, G, and K (see Figs. 2 and 3). Points A and B were on downleads at two opposite corners of the house. Point C was the power supply system ground, and point G was the ground at IS1. Point D is on the ground conductor from the power entry box (service entrance panel) down to the power supply system ground rod. A Pearson 110A current transformer was used to measure the current at point K, and 1-mΩ shunts were used at points A, B, C, D, and G.

The lightning current was directed, via a 32-m long metallic conductor, from the tower launcher to one (south) of the three test house air terminals (see Fig. 2).

![Fig. 3. Electrical diagram of test system configuration for 2004. Currents A, B, C, D, and K were measured at the test house, and current G was measured at IS1, 50 m away.](image)

### 2005 Experiment

The LPS for the 2005 experiment, installed on the test house on May 23, 2005, was a modification to the LPS installed in 2004. The 2005 setup consisted of two interconnected air terminals, four down conductors, and five ground rods (four for the LPS and one for the power supply system) interconnected by a buried loop conductor referred to as a ring grounding electrode or counterpoise...
(see Fig. 4). Electrical diagram is shown in Fig. 5. LPS vertical ground rods each had a length of 2.7 m, with dc grounding resistances being given in Fig. 5. The power supply system ground rod had a length of 3 m and measured grounding resistance of 524 Ω. The dc grounding resistance of the entire test house grounding system buried was 121 Ω. The dc grounding resistance of the ground rod at IS1 was 69 Ω. As in 2004, the test system was unenergized.

Currents were measured at six points, labeled A, A1, B, B1, D, and G (see Figs. 4 and 5). One-mΩ shunts were used to measure current at all the points.

The lightning current was directed from the tower launcher, via an instrumentation box located at the position of the middle air terminal in 2004 (removed in 2005) on the roof of the test house (see Fig. 1), to the horizontal conductor connecting the two LPS air terminals.

Nicolet Isobe 3000 fiber-optic links were used to transmit signals from the sensors (1-mΩ shunt or current transformer) to the digital storage oscilloscopes (DSOs) in the Launch Control trailer in both 2004 and 2005. Two types of DSOs, a Yokogawa DL716 (2 s record length) and LeCroy Waverunner LT344L (5 ms record length) were used. The Yokogawa and LeCroy data were sampled at 2 and 20 MHz, respectively. The Yokogawa triggered once per flash, while the LeCroy could trigger up to ten times per flash.

III. DATA

2004 Experiment

In 2004, a total of 2 lightning flashes were triggered for the test house experiment on June 23, 2004. One flash contained 9 and the other 2 leader/return stroke sequences. Both flashes were triggered using the tower launcher and effectively transported negative charge to ground. The initial stage current (Rakov 1999 [2]) was directed to ground at the tower base, so that it did not enter the LPS of the test house. Return-stroke peak currents ranged from 3.6 to 17.8 kA.

Injected lightning current and currents in ground rods A, B, and C, and currents at points D and K for stroke 3 of a nine-stroke flash 0401 are shown in Fig. 6 (injected, A and B in (a) and C, D and K in (b)).

2005 Experiment

In 2005, from July 15, 2005 to August 7, 2005, 8 flashes were triggered for the test house experiment, including 6 flashes containing 8 return strokes, and 2 flashes containing the initial stage (IS) current only. Both the IS and return-stroke currents were injected in the LPS. Return-stroke peak currents ranged from 6.8 kA to 34 kA. Examples of data from the 2005 experiment for one stroke (0521-1) are shown in Figs. 7 to 11.
Return-stroke peak currents and current half-peak widths (HPW) at different measurement points for nine strokes of flash 0401 are shown in Figs. 12 and 13, respectively. Currents in ground rods at the test house exhibited considerably smaller half-peak width than either injected current or the current at point D (see Fig. 13). This is consistent with the 1997 experiment (Rakov et al., 2002 [1]). Thus, higher-frequency current components tend to flow to ground locally, while lower-frequency components travel to remote ground at IS1, 50 m away. Note that some lower-frequency components apparently entered the ground via the buried horizontal conductor connecting ground rods B and C. Bejleri et al. (2004) [4] reported, from a different experiment, that vertical ground rods connected to a counterpoise (buried horizontal loop conductor) tended to dissipate primarily higher-frequency components, while lower-frequency components were primarily dissipated by the counterpoise. Additional reasons for the observed differences in current waveshapes in different parts of the circuit (see Fig. 3) are discussed below.

Current at point A (SW grounding location at the test house, which is nearest to the current injection point) is typically the largest, even larger than the injected current. This could be due to electromagnetic coupling to the measuring and circuit and, additionally, could be due to electromagnetic coupling to the large vertical loop (some tens of square meters) formed by the conductors of the lightning protective system of the test house (see Fig. 2). Indeed, current waveforms at point A are considerably more narrow than incident current waveforms (see Fig. 6) and often appear as the time derivative of the incident current.

Peak values of the injected current and the current

IV. ANALYSIS AND DISCUSSION

2004 Experiment
entering the electrical circuit neutral in its search for remote ground (current D) for 2004 are characterized in Table I.

### Table I

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Injected Current, kA</th>
<th>Current D, kA</th>
<th>Current D relative to Injected Current, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>3.6</td>
<td>0.8</td>
<td>16</td>
</tr>
<tr>
<td>Maximum</td>
<td>17.8</td>
<td>3.4</td>
<td>28</td>
</tr>
<tr>
<td>Arithmetic Mean</td>
<td>9.4</td>
<td>2.1</td>
<td>22</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>4.1</td>
<td>0.9</td>
<td>3.6</td>
</tr>
<tr>
<td>Geometric Mean</td>
<td>4.7</td>
<td>1.9</td>
<td>22</td>
</tr>
<tr>
<td>Sample Size</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

Peak value of current D in percent of the injected peak current varied from 16 to 28%, with a mean value of 22%, which is significantly lower than the over 80% in the 1997 experiment. The difference is apparently due to much better grounding in 2004.

Currents measured at point G (ground rod at IS1) were corrupted, due to arcing from the instrumentation box to a grounded (buried, bare-neutral) power cable that was part of another experiment. However, current at point D (assumed to be equal to the current entering the neutral of the 600-V cable) can be viewed as a proxy for current at point G, provided that there was no insulation breakdown along the cable. For one stroke (0401-7), arcing at IS1 did not occur during the initial 6 µs or so, and, as a result, current at point G was not corrupted during this time interval and could be compared to the corresponding current at point D (see Fig. 14). As seen in Fig. 14, currents at points D and G are very similar during the initial 6 µs or so, suggesting that no insulation breakdown occurred along the 600-V cable. It is worth noting that stroke 0401-7 was the smallest one (injected peak current of 3.6 kA; see Table I). Other strokes had peak currents up to 17.8 kA (see Fig. 12 for peak current), and larger strokes could well cause breakdown of cable’s insulation, as was observed in the 1997 (Rakov et al., 2002 [1]) and 2005 experiments (discussed below).

### 2005 Experiment

Results of the 2005 experiment are illustrated in Figs. 7 through 11 and Figs. 15 through 17, which show current waveforms and their parameters for stroke 1 of flash 0521. This was a single-stroke flash as seen in the overall current record shown in Fig. 7. Current waveforms measured in all four downleads, A, A1, B, and B1, are presented in Fig. 8. Note that the distribution of the injected current among the four downleads is more uniform than in 2004 (between two downleads, A and B, see Figs. 2 and 3), in part due to the difference in current injection point. As expected, the sum of four downlead current waveforms matches well the injected current waveform (see Fig. 9). The sum of four downlead currents minus the current at point D represents the current going to the grounding system of the test house, the latter being compared to the injected current in Fig. 10. Note that the current to the grounding system of the test house, (Sum – D) in Fig. 10, is normalized to the injected current in order to compare only the waveforms. It is clear from Fig. 10 that the lower-frequency components associated with the tail of the injected current do not go to the grounding system of the test house and have to find their way to the remote ground (at IS1), accessible via the neutral of the power supply cable. Currents at points D (to the house’s electrical circuit neutral) and G (to the remote ground) are compared in Fig. 11. The difference between these two currents is likely to be due to the breakdown of and leakage through the insulation of the buried 600-V power supply cable.

![Fig. 14. Injected return stroke current and currents at points D and G (see fig. 3) for stroke 0401-3, displayed on a 10 µs time scale. Note that currents D and G are similar during the first 6 µs, prior to arcing at IS1.](image)

![Fig. 15. Return-stroke peak current at different measurement points for stroke 0521-1. Inj. = Injected current. Sum = sum of four downlead currents (A, A1, B, B1). D and G are currents at measurement points indicated in Fig. 5.](image)

![Fig. 16. 30-90% current risetime at different measurement points for stroke 0521-1. Refer to Fig. 15 for the horizontal axis legend.](image)
Peak values of the injected current and the current entering the electrical circuit neutral (current D) for 2005 are characterized in Table II. Peak values of current D in percent of the injected peak current varied from 51 to 72% with a mean value of 59%. Thus, in 2005, more than a factor of two larger current was forced to find its way to the remote ground than in 2004. This is a somewhat unexpected result, since the grounding system of the test house in 2005 was presumably better than in 2004: five vertical ground rods interconnected by a buried loop conductor (counterpoise) of a total length of about 37 m vs. two groups (two or three) of vertical ground rods, each group interconnected by a buried horizontal conductor (or conductors) of a total length of about 15.6 m.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Injected Current, kA</th>
<th>Current D, kA</th>
<th>Current D relative to Injected Current, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>6.8</td>
<td>4.4</td>
<td>51</td>
</tr>
<tr>
<td>Maximum</td>
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<td>8.5</td>
<td>72</td>
</tr>
<tr>
<td>Arithmetic Mean</td>
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<td>6.6</td>
<td>59</td>
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<tr>
<td>Standard Deviation</td>
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<td>1.8</td>
<td>83</td>
</tr>
<tr>
<td>Geometric Mean</td>
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<td>6.1</td>
<td>58</td>
</tr>
<tr>
<td>Sample Size</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

In 2005, SPDs and simulated loads were disconnected from the electrical circuit. As a result, the watt-hour meter (protected only by built-in spark gaps) showed signs of electrical arcing and burning, with evidence of metal being melted both inside and outside the meter. The absence of load apparently did not influence significantly the overall current distribution, since most of the current tends to flow along the neutral toward the remote ground (compare currents K and D in Fig. 6).

There were signs of arcing between a phase conductor and the neutral conductor of the 600-V triplexed cable inside the watt-hour meter box, specifically to the metal conductor plugs (on the rear of the meter). There was also damage to the insulation of the 600-V cable. The two phase conductors of the cable had 10 and 8 holes melted through their insulation, and the neutral conductor insulation had 3 holes. The holes measured from 3 to 4 mm in diameter. There were other signs of damage on the 600-V cable insulation, including pitting, surface melting, and circular demarcations, all indicative of electrical arcing. Some of the damage to the 600-V cable might have been caused by the 2004 strikes (the cable was not excavated after 2004 testing). For comparison, in 1997, the 600-V cable had about 40 holes in the insulation of its neutral conductor. This cable was replaced with a new one before 2004 testing.

V. SUMMARY

We have presented results of the structural lightning protective system (LPS) tests conducted in 2004 and 2005 at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. Lightning was triggered using the rocket-and-wire technique (e.g., Rakov 1999 [2]) and its current was directly injected into the LPS. The test configurations in 2004 and 2005 differed in the lightning current injection point, number of down conductors (downleads), grounding system at the test house, and the use of surge protective devices (SPDs).

The primary objective was to examine the division of the injected lightning current between the grounding system of the test house and remote ground accessible via the neutral of the power supply cable. In 2004 (two pairs of interconnected LPS ground rods plus a bonded power supply system rod), the mean value of the peak current entering the electrical circuit neutral was about 22% of the injected lightning current peak, while in 2005 (four LPS ground rods plus power supply system rod), the mean value of the peak current entering the electrical circuit neutral was about 22% of the injected lightning current peak, as shown in Fig. 17. The horizontal axis legend points for stroke 0521-1. Refer to Fig. 15 for the horizontal axis legend.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES


