Incab

OPGW Lightning Theory and Practice

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President

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- Certificates of Completion will be issued to all participants via the RCEP.net online system.
- As such, it does not include content that may be deemed or construed to be an approval or endorsement by the RCEP.

ENGINEERING RCEP
REGISTERED CONTINUING EDUCATION PROGRAM

PURPOSE STATEMENT / COURSE DESCRIPTION
Registered continuing education program

OPGW Engineering 401 – Lightning:
Theory and Practice will teach attendees about:

- The nature of a lightning strike, including frequency and intensity
- Resources for a transmission line engineer to draw upon when designing for lightning.
- The four (4) Lightning Class levels and how to choose one
- Coping with lightning damage and the steps to repair it

LEARNING OBJECTIVES

After this class, you will be able to:

1. State that **lightning** is the **second leading cause of OPGW failure** in the field
2. State the **four (4) components** of a lightning strike waveform and which one damages cable
3. Understand what **Keraunic Level** defines
4. Explain the **four (4) Lightning Class levels**
5. Assess the **level of lightning protection** your system might need
6. Understand the industry standards for testing lightning protection capability of a cable design
7. Explain your options for **repair** or **replacement** if lightning damages your OPGW

Incab University "School of Excellence in Fiber Optics"
Agenda

- Introduction
- Course Description
- Learning Objectives
- Presentation
- Q&A (Technical questions only)
- Let's start!

Recall that OPGW...

Protects Against Lightning & Provides Telecommunication Capability

- Optical Ground Wire or «OPGW»
  - Per IEEE 1138-2021 (USA and some countries)
  - Per IEC 60794-4-10 (Many other countries)

- Primary function of OPGW is to be a shield wire for a transmission line:
  - **To protect the phase conductors from lightning**
  - To provide a path for fault current

- Secondary function: housing optical fiber for data and communications

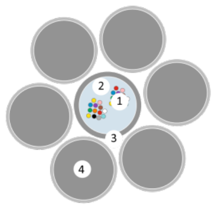
- In use since the late 1980's

OPGW – Quick Review of 3 Design Types

(Including a *rough* qualitative assessment of the lightning performance of each…more about this later)

1. Center Tube Type – has two variants

A. Plain Stainless-Steel Tube (SSLT)

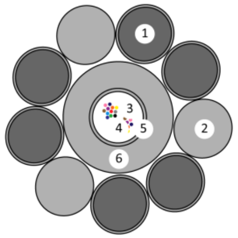


OPGW C Good

CONSTRUCTION:

1. Optical fiber Corning SMF-28 Ultra
2. Water-blocking gel
3. Stainless Steel Loose Tube (SSLT)
4. Aluminum-Clad Steel Wire (ACS)

B. SSLT with aluminum-cladding or in aluminum pipe

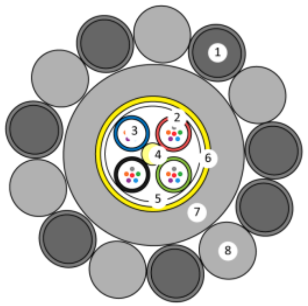


OPGW C Good

CONSTRUCTION:

1. Aluminum-Clad Steel Wire 20SA
2. Aluminum alloy wire
3. Water-blocking gel
4. Optical fiber Corning SMF-28 Ultra
5. Stainless Steel Loose Tube (SSLT)
6. Aluminum jacket

2. Aluminum Pipe Type (stranded plastic tubes)

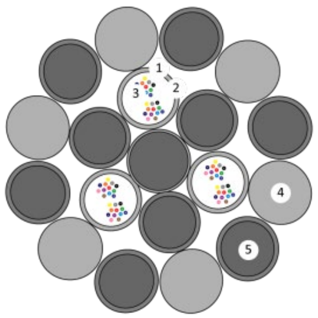


OPGW AP Better

CONSTRUCTION:

1. Aluminum-Clad Steel Wire 20SA
2. Gel filled loose tube
3. Optical fiber Corning SMF-28 Ultra
4. Central strength member FRP
5. Water-swellable tape
6. Thermal barrier
7. Aluminum pipe
8. Aluminum alloy wire

3. Stranded Stainless-Steel Tube (SSLT) Type



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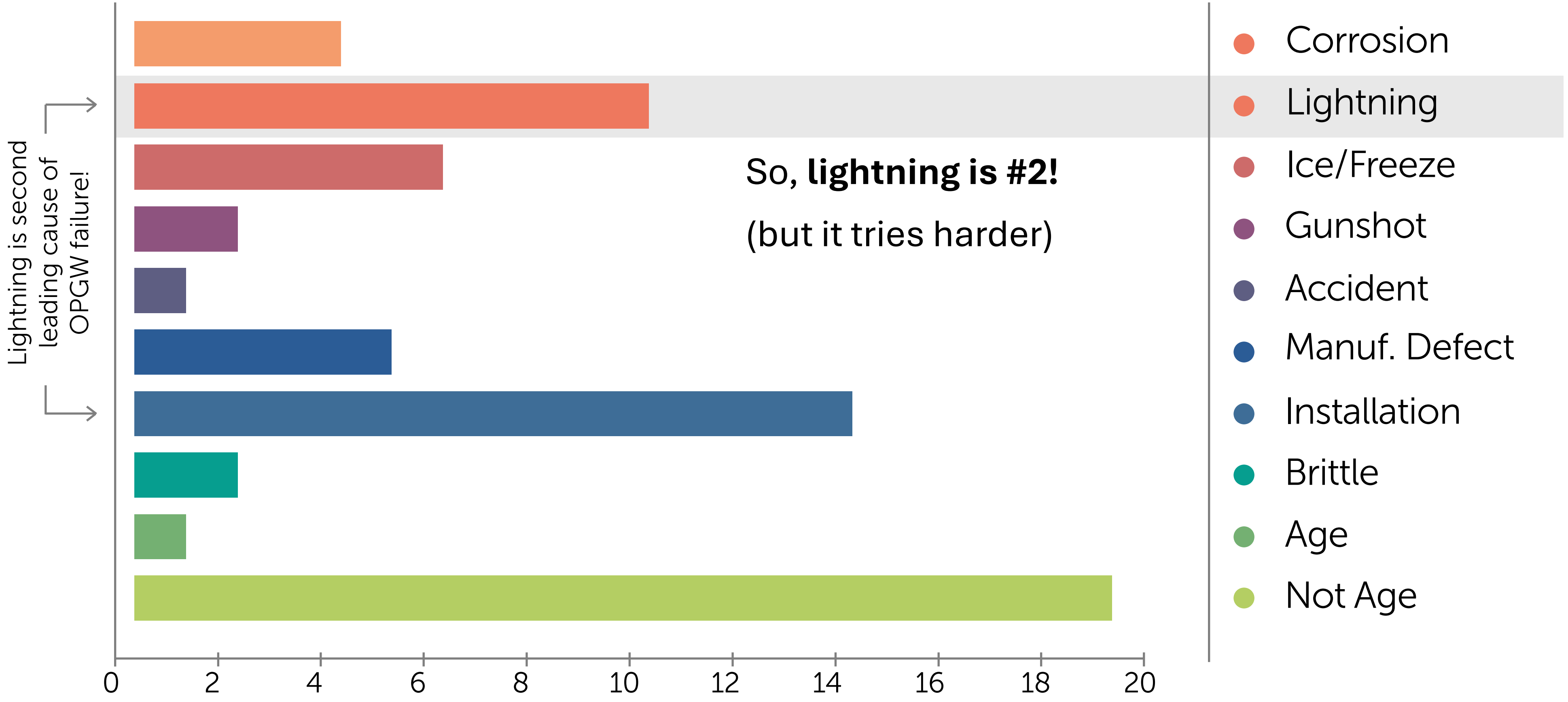
5. Aluminum-Clad Steel Wire 20SA

Why is Lightning Performance of Concern?

Consider: Data on OPGW Failure by Type



Source: 2017 UTC Telecom & Technology presentation by Mike Unser of Salt River Project (SRP) and Dan Newman of Burns & McDonnell

Theoretical Background

What Comprises a Lightning Strike?

- We see a single flash, but a lightning strike actually has **four (4) components**

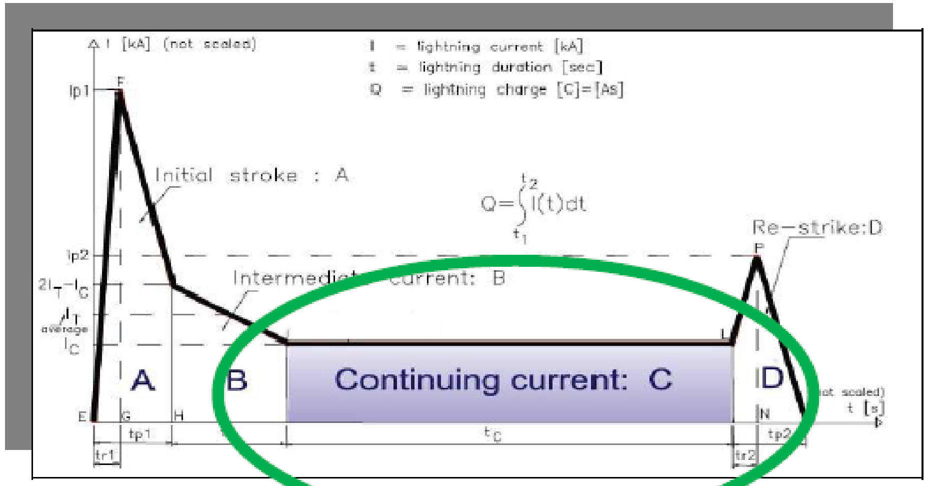
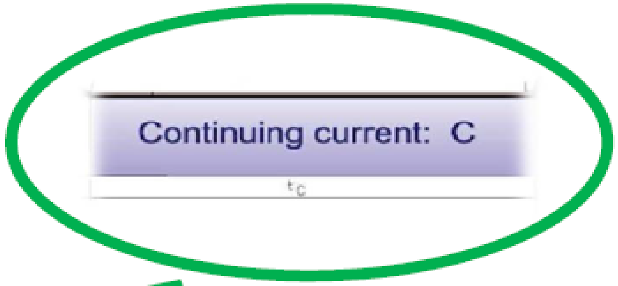


Fig. 1 Conventional waveform of current in a lightning discharge[1]

The 4 Components:

A. Initial stroke
B. Intermediate current
C. **Continuing current**
D. Re-strike



We will soon see that this continuing current component is the most damaging

Aside: Is this just a coincidence?

- A lightning strike has four (4) components

- There are "Four Horsemen of the Apocalypse"

I'll leave you to ponder this for yourself…

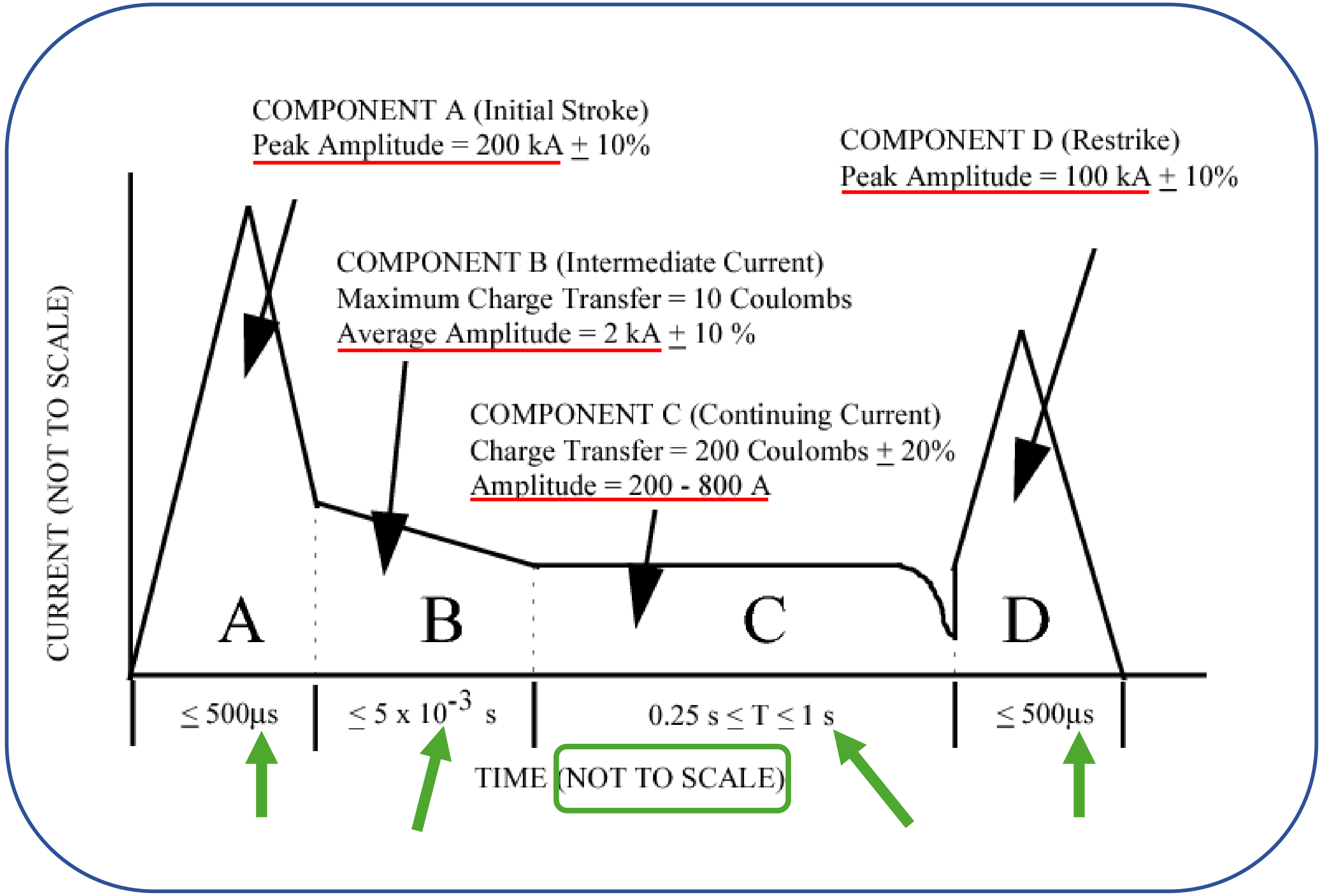
Back to our topic!

Theoretical Background

So, what's really doing the damage? (and why)

Examine the waveform, and…

1. Observe the amplitudes (intensity)
2. Notice the durations:
   - A = microseconds = 10^{-6}
   - B = milliseconds = 10^{-3}
   - C = seconds = 10^{0}
   - D = microseconds = 10^{-6}



Theoretical Background

The Energy in each Component

- Now, integrate across the wave form (simplifying the continuing current):
  - A ≈ 50 Amp·seconds (A·s) = 50 Coulumbs (C)
  - B ≈ 10 C
  - C ≈ **300 C**
  - D ≈ 24 C

🡐 This is why Continuing Current does the damage!
Its energy content is nearly an order of magnitude greater than the others!

- Remember this "Coulombs thing" for later...

Note: 1 A·s = 1 C and is commonly called the "**Charge Transfer**"

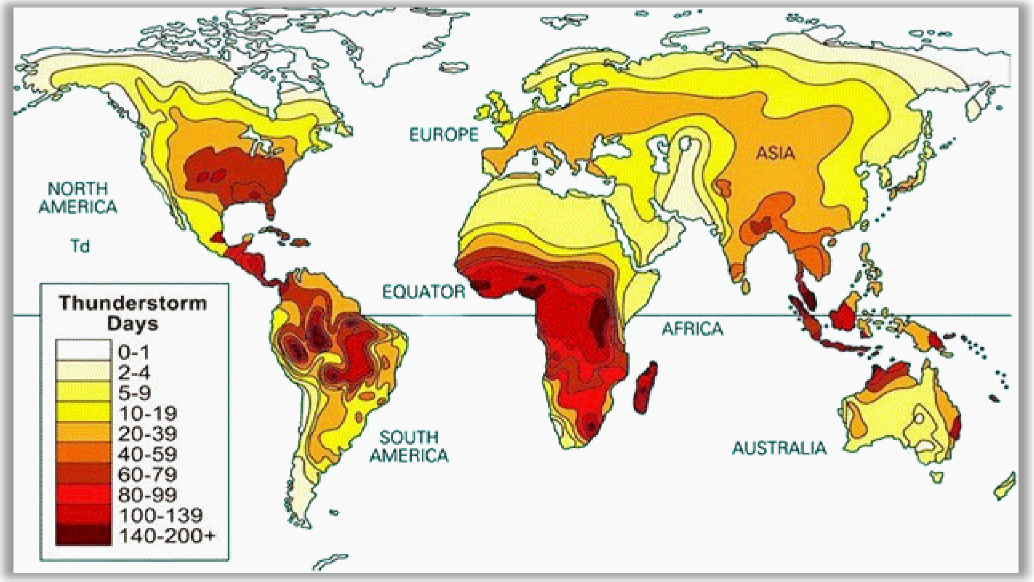
Just a Little More Background

Isokeraunic Levels

- "Keraunic Level" (sometimes "ceraunic") average number of days per year with lightning detected
  - Originally by sound of thunder
  - Then by electronic detection of radiowave disruptions
  - Now by satellite using near-infrared detection
  - Adding "iso" just means "same level within an area"

- Sources include:
  - Vaisala (www.vaisala.com) – Data for a fee
  - US NOAA/National Weather Service refer to Vaisala

    (Interesting. Must be big money in lightning data?)
  - Others on the internet



World Isokeraunic Level Map

Source: electrical-engineering-portal.com

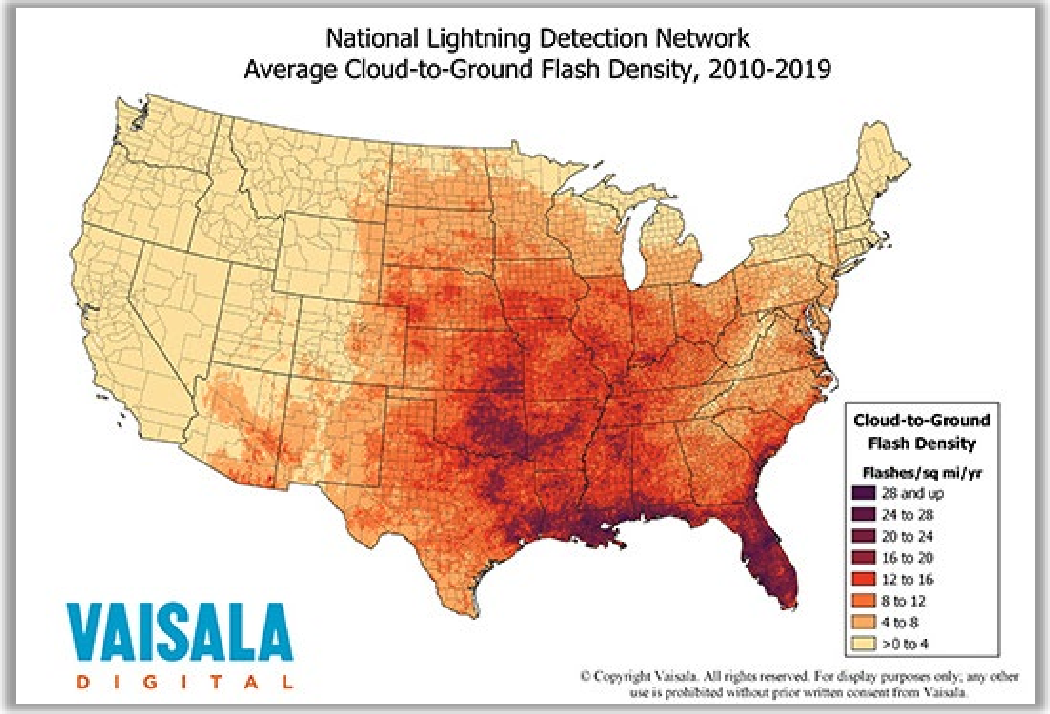
Just a Little More Background, cont'd

Isokeraunic Level Maps

- An **isokeraunic level** map will show you the number of flashes that occur in your area each year
- Isokeraunic levels <u>correlate</u> with the likelihood of lightning damage
    - Not 100% predictive
    - Provide zero information about intensity or duration
      - You don't know the energy of the strikes

➔ So, use these maps "gently"

(guidelines later)



USA Isokeraunic Level Map

Source: www.vaisala.com/en/products/national-lightning-detection-network-nldn

Application

Putting Theory Into Practice

- The key question of this webinar:

  How should a transmission line engineer incorporate lightning performance into their line design?

- I will (humbly) propose a framework…

Application

A Framework for Line Design for Lightning

Here is a Four (4) Step Framework

1. Use the resources available to you wisely
2. Decide what you will do
3. Observe field performance
4. Iterate as appropriate

(Notice the 4 again!)

Application Framework

Step 1: Consider the resources available

- What resources are available to you as a transmission line engineer?

  1. Your utility's experience
  2. Data/conclusions from studies
  3. The standards for OPGW (Laboratory testing)
  4. Cable manufacturers

  Let's look at each…

(Another set of 4!)

Resource #1 - Experience

Insight from Direct Experience – Conventional Groundwires

- What <u>conventional</u> (non-optical) groundwires has your utility used?
  - Examples: 3/8-inch HS/EHS, 7#8 ACS, etc.
- What has been the track record of those cables?
  - Any incidents of lightning damage?
  - If yes, how bad?
    - Broken wires that could be repaired versus complete failure
  - If yes, how frequent?
    - "Often" versus "Once in a blue moon"

Resource #1 - Experience

Insight from Direct Experience – OPGW

- What OPGW cables has your utility used, if any?

- What has been the track record of those cables?
  - Any incidents of lightning damage?
  - If yes, how bad?
    - Broken wires that could be repaired versus complete failure
  - If yes, how frequent?
    - “Often” versus “Once in a blue moon”

Resource #1 - Experience

Draw Upon That Direct Experience

- Formulate and apply “Lessons Learned” from either or both conventional groundwire and OPGW
    - If you have experienced “significant” damage, then face the truth
      ➔ Change something! (Ideas on what later)
- Has your utility collected data on the frequency or intensity of lightning in your service area?
    - If so, take advantage of any such available data!

Resource #2 - Studies

Insights from Studies

- Ideally, we could find published studies that document the severity of lightning by geographical area

- Unfortunately, comprehensive studies with “actionable data/conclusions” do not exist. What is available is quite limited:

    - Some published data suggests that negative polarity strikes occur more frequently in the field and can be more damaging

    - Other data suggests no significant difference in damage from positive versus negative polarity strikes

- So, not much help here at present, but we can be hopeful for the future

Resource #3 - Standards

Insights from the Standards

- What insights can you glean from the standards?
- Recall, the two standards commonly used are:
  - IEEE 1138-2021
  - IEC 60794-4-10

Resource #3 - Standards

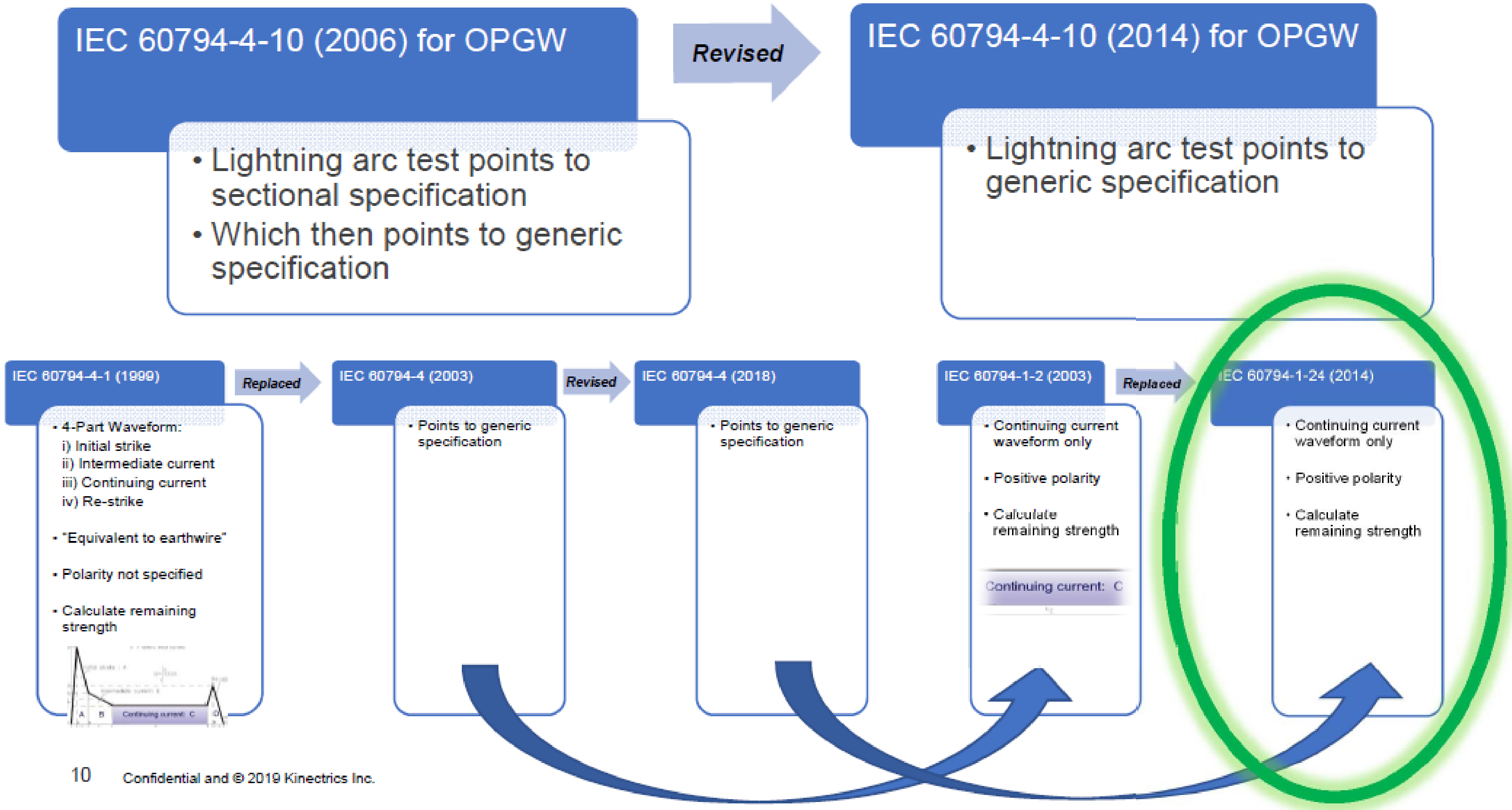
Evolution of the Standards

- 1990's = Still early days of OPGW
    - No standard for lightning until IEC in 1999
        - 1994 version of 1138 had no lightning test
    - Some manufacturers/utilities doing "Lightning Tests" in the form of "Impulse Tests"
        - Roughly equivalent to waveform Component A
        - Few, if any, cables fail because:
            - Component A does little to no damage because its energy is low
            - Very subjective and very easy pass/fail criteria

But, there was recognition that something standardized and better was needed

Resource #3 - Standards

Evolution of IEC 60794-4-10:2014



Let's look at the key provisions of the required lightning testing...

Source: Kinectrics

Resource #3 - Standards

Key Provisions of IEC 60794-4-10:2014 Lightning Testing

- Five (5) simulated strikes ("hits") with <u>positive</u> polarity
- Continuous current component only (waveform component C)
- Pass/Fail based on <u>calculating</u> the cable's remaining strength excluding broken wires.
    - Must be $\geq$ 75% RBS
    - Accurate?
        - What about burnt/damaged wires or possibly annealing?

          Hold that thought!

Resource #3 - Standards

Evolution of IEEE 1138-2021

IEEE 1138-1994

- No lightning arc test

Revised →

IEEE 1138-2009

- Continuing current waveform
- Negative polarity
- Tension Test to measure remaining strength
- Acceptance tied to Rated Tensile Strength (RTS)
- All 5 hits must meet minimum remaining strength requirements

Revised →

IEEE 1138-2021

- Similar test method as 2009
- Tension Test
- Modified acceptance criteria
- Acceptance tied to Maximum Rated Design Tension (MRDT)
- Statistical approach: 4/5 hits must meet minimum remaining strength requirements

Let's again look at the key provisions of the required lightning testing…

Source: Kinectrics

Resource #3 - Standards

Key Provisions of IEEE 1138-2021 Lightning Testing

- Five (5) hits with <u>negative</u> polarity
- Continuous current component only (waveform component C)
- Pass/Fail based on <u>testing</u> the cable's remaining strength
  - 2009 – Must be $\geq$ 75% RBS
    - Reasoning: NESC 250B loading allows 60% RBS + 15% as "margin for error"
    - Unintended consequence: Smaller center tube type designs tend to fail
  - 2021 – Must be $\geq$ MRDT = Maximum Rated Design Tension
    - Reasoning: Cable should not exceed MRDT during operation
    - Smaller center tube type designs MRDT typically 40 – 60% RBS
      - So, should pass, but…

Resource #3

Lightning Class Levels

Both IEC and IEEE have Four (4) “Lightning Class Levels”

Class Level = Standardized “severity levels” based on charge transfer (C)

Standardized levels allow you to:

- **Compare/Contrast Test Results** – You can use test results for a relative comparison between two or more cable designs:
  - Different designs – Design A compared to Design B
  - Different design types – Center tube vs. aluminum pipe vs stranded SSLT
  - Different manufacturers – Likely a function of design differences, although perhaps optical performance differences could show up
- **Verify** – You can use test results to verify that your cable design can withstand your specified Class Level

Resource #3

Standards

- What are the Lightning Class Levels? Which should I use?

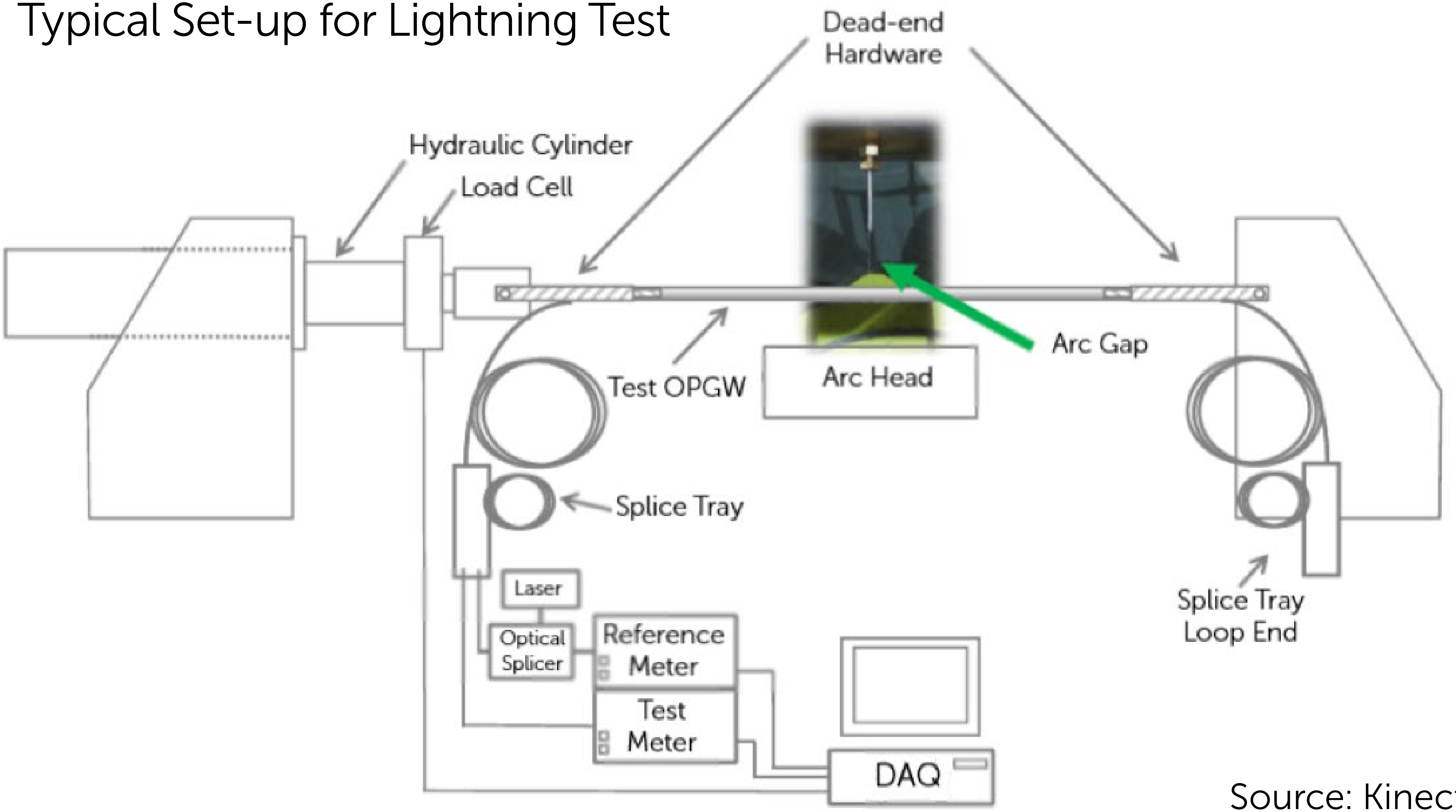
Parameter	Class 0	Class 1	Class 2	Class 3
Current (Amperes)	100	200	300	400
Duration (Seconds)	0.5	0.5	0.5	0.5
Charge Transfer (Coulombs)	50	100	150	200

← Most severe!

→ Which class should you use? Hold that thought for later, please!

Lab Testing

Typical Set-up for Lightning Test



Source: Kinectrics

Lab Testing

What Happens After the Simulated Strike?

- After simulated strikes, the remaining strength of the cable is either:
    - IEC Standard – Calculated based on the remaining, <u>unbroken</u> wires
    - IEEE Standard – Measured by tension testing

Lightning arc damage in center of tension test

Cable typically breaks at location of simulated lightning strike, where wires burnt and/or broken

Source: Kinectrics

Lab Testing

Applying “Acceptance Criteria” (Pass/Fail)

- IEC Standard.
  - Calculate remaining strength based upon remaining, unbroken wires
  - Ignore “burnt” (= damaged) wires
  - Consequently, these do *not* factor into the calculated remaining strength (!)
- IEEE Standard.
  - Measure remaining strength by tension testing
  - Consequently, burnt/damaged wires do reduce the actual remaining strength

Lab Testing

Example of Applied Acceptance Criteria

- Center tube type design with single outer layer of 8 x ACS wires
- Test strike **broke 0** wires, but **burned/damaged 3** wires
- Notice the difference between the Calculated and Measured acceptance criteria:

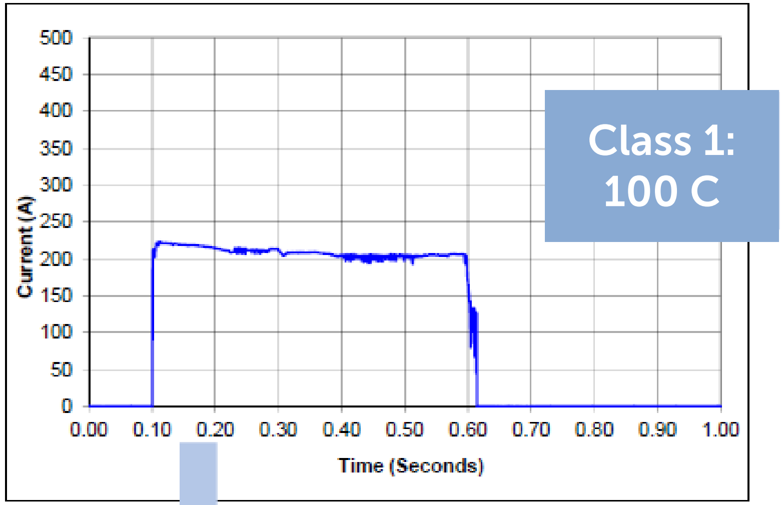
Calculated	Measured
No broken wires	No broken wires
8 Unbroken ACS wires	3 Burnt wires
Calculated = 100% RTS	Measured = 70% RTS
>75% RTS	<75% RTS
PASS	FAIL

(per 1138-2009)

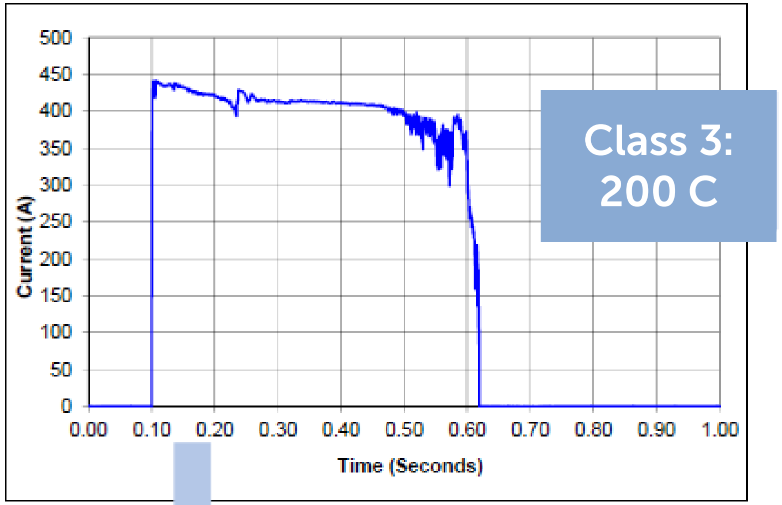
Source: Kinectrics

Lab Testing

Example of Effect of Lightning Class



Measured Remaining Strength = 79% RTS



Measured Remaining Strength = 54% RTS

Source: Kinectrics

Lab Testing
Acceptance Criteria Postscript

- Isn’t it intuitively obvious to a casual observer that the Measured criterion is better?

  ➔ Consider: Possible trade-offs:
    - Added cost and time to a test that is already expensive (≈ $25 k)
    - Some labs can do electrical tests, but not mechanical ones

- What about “improving” the Calculated criterion by treating burnt/damaged wires as if they are broken?

  ➔ A “third” answer only muddies the water more
    - In the example we considered: 63% RBS remaining (neglecting tube)
    - OK. Now what? Fails 1138-2009, but might pass 1138-2021

Applied Insights from the Standards

Bottom Line – What the standards, in particular lab testing, can do for you

- I again (humbly) propose a four (4) step framework:

1. Select a lightning class level

2. Perform a lightning test

3. Assess the results
   - Both immediate and long-term

4. Iterate as appropriate

(Yes, the 4 returns!)

Applied Insights from the Standards

Mike's 4-Step Framework (patent pending*)

1. Select a Lightning Class Level for your OPGW
   - There is no specific way to do this (unfortunately), so…
     - Unless, that is, you have intensity and duration data(!)
   - Use scientific sorcery, SWAG, or guesstimate to pick a class
   - Isokeraunic data can help to "put it in the ballpark":

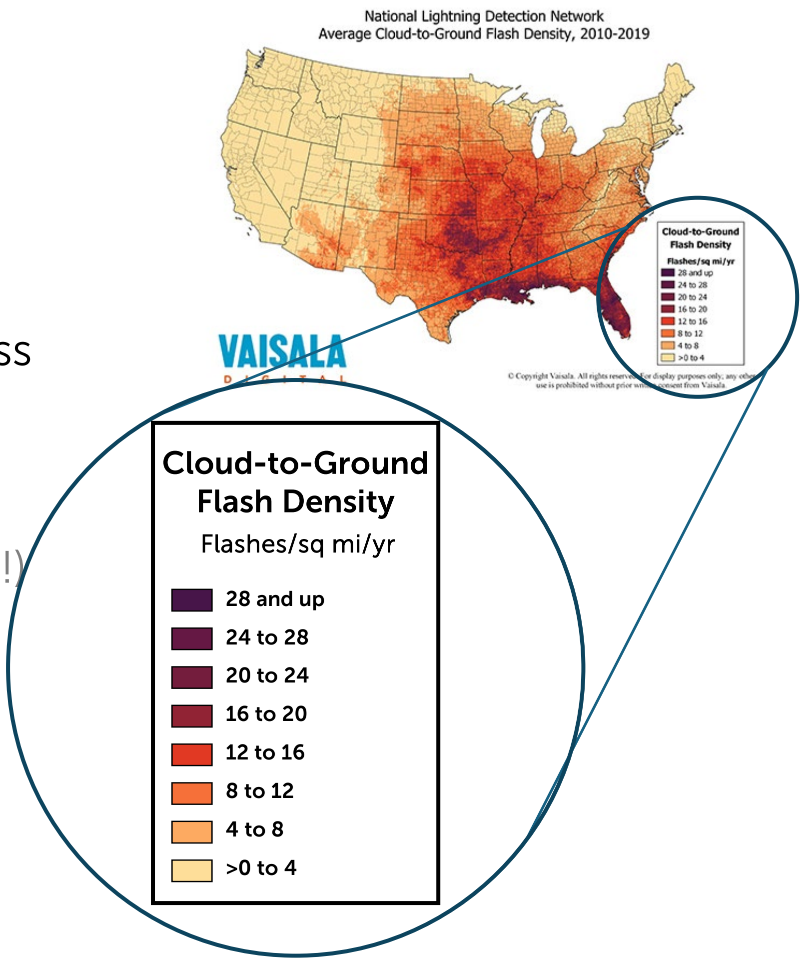
   Example: (Note! This is totally arbitrary! It just maps nicely!)

   Class 0 (50 C) – 0 to 8 flashes/mile^2/year

   Class 1 (100 C) – 8 to 16

   Class 2 (150 C) – 16 to 24

   Class 3 (200 C) – 24 and up



(* - just kidding!)

Applied Insights from the Standards

Framework, continued

2. Do the testing!

3. Assess the results

    - Did the cable pass?

    - Even if yes, consider: Is the remaining strength adequate?
        - What if a cable's MRDT is < 60% RBS?
        - How does this compare to your loading criteria?
          (Note: NESC 250B allows up to 60% RBS)
        - Does your utility consider "Extreme Ice" or "Concurrent Wind and Ice" loading conditions? (NESC 250C and D allow 80% RBS)

Applied Insights from the Standards

Assessment Should Be an On-Going Process

A. Is field data or experience available to give context to the results?
   - If so, compare the severity of lab testing damage to actual field damage
     - My observation is that lab damage seems to be more severe than actual damage reports from the field
   - If not, perhaps start collecting it?

B. Monitor field performance, adjust your specifications (or expectations?) accordingly, and iterate if necessary
   - Keep in mind that improving lightning performance will likely come with tradeoffs relative to other design considerations (diameter, weight, cost, etc.)

Resource #4 – Manufacturers

Draw Upon the Experience of OPGW Manufacturers

- All have had strikes on their cables (real or lab) & all have had damage to their cables
    - What have they learned?
    - Filter and compare
    - Challenge when it seems appropriate
- I can only speak to my and Incab's experience
    - Could you really trust others anyway?

Resource #4

One OPGW Manufacturer's Experience

- Here is a summary of our experience (≈ 30 years in total!):
  - General Guideline #1 -
    - A "risk management" approach says that if you design *well* for fault current, then you will also get good lightning performance (Free bonus!)

  Note: Fault current is discussed in detail in a separate presentation/webinar

  - General Guideline #2 –
    - There are no other guidelines, because there's no agreement in our industry on precisely how to design for lightning

  ➔ However, we can offer **five (5) observations** we think are helpful…

Resource #4 – Our Observations

Observation #1 — Size Matters

A. A larger wire is less likely to be burned through than a smaller one
   - In response, some utilities have adopted minimum wire sizes
   - Often see ≥ 2.9 - 3.0 mm, but the value is picked arbitrarily
     - There's no data or scientific basis for the size chosen
   - Drawing upon field experience makes a sense (Ex: #8 ACS wire (3.26 mm))
     - Example: ≥ #8 ACS wire = 3.26 mm
     - Not saying I agree with this approach (I do not), but I respect it

B. Overall cable diameter (OD) seems to be a factor as well
   - Spreads the strike energy out over a larger area?
   - We observed in testing that Cable AP with a larger OD, but smaller outer wires, had fewer broken wires than Cable CA with a smaller OD, but larger outer wires

Resource #4 – Our Observations

Observation #1 – Size Matters

Caution!

Before adopting a minimum wire size, consider the tradeoffs, too!

Increasing either wire size or cable OD also increases:
Cost
Weight of the cable
Structural loading

And, it may decrease:
Maximum reel length
(Could mean more pulls/set-ups and splice points)

Resource #4 – Our Observations

Observation #2 — Material Matters

- All else being equal, ACS wire performs better than AY wire
  - (but, galvanized would be better still)
- Consequently, some utilities require all-ACS outer layer
  ➔ But, again, consider the trade offs in cable weight and cost
- However: Remember those testing results from a previous slide?
- There was another wrinkle in them…
  - Cable AP had a larger OD and smaller outer wires, and it had a mixed ACS/AY wire outer layer
  - Cable CA had a smaller OD and larger outer wires that were all ACS!
  - Nevertheless, Cable AP had fewer broken wires than Cable CA(!)

Resource #4 – Our Observations

Observation #3 — Wire Count Matters, too

- X amount of energy (remember those Coulombs?) will burn Y number of wires
  - Y/12 wires < Y/8 wires
    - So, a cable with 12 wires will have a greater residual strength than a cable with only 8 wires (all else being equal)

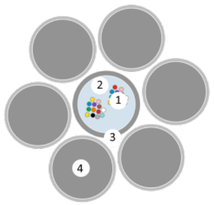
- The testing results mentioned before are consistent with this observation

Resource #4 – Our Observations

Observation #4 — Design Type is a Factor… Rough guidelines:

1. Center Tube Type – has two variants

A. Plain Stainless-Steel Tube (SSLT)



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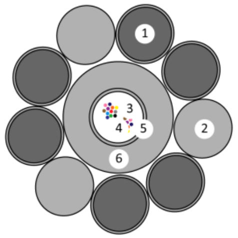

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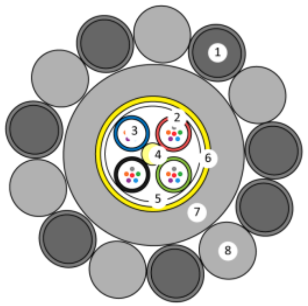

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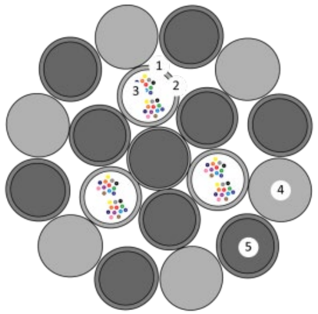

OPGW S

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➔ But, again, consider the trade offs in cable size, weight, and more!

Resource #4 – Our Observations

Observation #5 — Low footing resistance correlates with low incidents of lightning damage

- Strikes more likely to hit on or near a structure (75% per the EPRI "Red Book")
  - On the structure means the cable not hit
  - Near the structure means hits might be on the supporting accessories:
    - Dead-ends and suspensions have greater mass
      - Acts to dissipate the energy across more metal
    - Armor rods tend to have larger diameters than the cable wires
      - Size effect plus more metal to dissipate the energy
  - Assumes the supporting accessories are grounded

➔ Creates conditions that push the odds in your favor

Reality Factor

Life in the Real World

- You can do an excellent job in specifying your cable with respect to its lightning performance:

    - **But, the Reality Factor says you will still have cable damage eventually**

- What to do?

Coping with Lightning Damage
The Repair Option

- "Repair rods" may be an option if the optics are still working just fine

Guideline (not a hard rule!):

50% remaining strength

➔ Must confirm with accessory supplier!

- Cable manufacturer can help you estimate remaining strength
- Some cable manufacturers may require higher remaining strength or have other application limitations

Advantages:

- Won't require replacing cable
- Can be quick, if rods on hand

Disadvantages:

- "Estimated" strength implies possible error
- Hassle factor of installing
- Sourcing/stocking rods

Coping with Lightning Damage
The Replace Option

- You may want to–or be forced to–replace a section of cable

  Big Consideration: Time

  Remember historic* OPGW lead time is 10 – 12 weeks ARO!

- **Workaround 1**
  - Use ADSS or dielectric cable as a temporary repair

Advantages:

- Can be done with the line still energized
- Can be done quickly

Disadvantages:

- Extra work
- Vulnerability
- Sourcing/stocking the cable and accessories

(* - currently longer!)

Coping with Lightning Damage

The Replace Option

- **Workaround 2**
  - Keep an emergency length of cable (ideally on a steel reel) plus accessories (ideally in a sealed crate) on hand

Advantages:

- Can be done quickly
- Permanent
- No scrambling to obtain cable and accessories (assuming you remember where your kit is)

Disadvantages:

- Cost of sourcing and maintaining the kit
  - (beware of "borrowing")
- Figuring out the quantities (How much is enough?)

Tip: OK to reuse tangents, but dead-ends must be new

Coping with Lightning Damage
The Replace Option

- **How much to replace?**
  - **Just the affected span** = Adds two splice points but requires less cable and accessories
  - **Span to closest splice point** = Adds one splice point but requires more cable and accessories
  - **Entire segment** = Doesn’t add a splice point but requires much more cable and accessories (Seems like overkill)

In case you were wondering: Typical added splice loss at 1550 nm will be 0.01 dB, and the maximum will be $\leq$ 0.05 dB

Just One More Thing...

Short-Term Communications Effects

- Lightning **can** have adverse **short-term effects** on communications
  - **10-Gbps systems** = No problem
  - **100-Gbps systems** = Have had problems starting here
    - Use “coherent transmission” techniques—in particular, dense wavelength division multiplexing (DWDM)—to boost data rates
    - Strike effects on the order of micro- to milliseconds cause bit errors
    - Causes:
      i. Sudden mechanical and thermal shock?
      ii. Electromagnetic field (EMF) coupling? Likely. Recall that light is a form of EM energy
    - Solutions:
      i. Built-in electronic error correcting systems help
      ii. Wire selection and adjusting laylength may help (being researched)

Lightning – Theory and Practice

Recap

- **Assess** your utility's lightning performance experience to date
- **Use** all the resources available to you: experience, studies, standards, suppliers
- **Decide** if your utility's OPGW specifications should include a Lightning Class Level or other specific design requirements
- **Test** to confirm that your OPGW meets your requirements and adjust accordingly to what the testing shows
- **Monitor** your OPGW's field performance
- **Prepare** for the eventuality of lightning damage

Thank you

Questions?

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