Lightning Test for OPT-GW cables

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1. **Test set up** :

- The tests shall be performed on the **mid-point** of a sample of OPT-GW not less than **10 m** long. The minimum length of the fiber under test shall be **100 m**.
- Fiber attenuation shall be measured using a light source and a power meter (or an OTDR= optical time domain reflectometer) connected to either end of the test fiber.
- A typical arrangement presented in [1] which can be used for the lightning test is shown in **Fig. 1**. The iron rod shall be used as the electrode which shall be positioned above the OPT-GW. The electrode and the OPT-GW shall be connected by a fuse wire. The iron rod tip should have a diameter of about (1....2) mm, the fuse wire diameter should be in a range of 50-100 mm, and the gap distance between the iron rod and the OPT-GW cable should be (25....40) mm. As an example , Lightning Technologies Inc., Pittsfield, Massachusetts, is using a gap of 25 mm and the Institute of Plasma Physics, Warsaw, Poland is using a gap of 40 mm. After each hit, the destroyed fuse wire will be replaced with a new one.

1- Turnbuckle
2- Insulator
3- Dead-end clamp
4- Plate
5- Iron rod (electrode)
6- Fuse wire
7- Tensiometer (Dynamometer)
8- Supporting frame

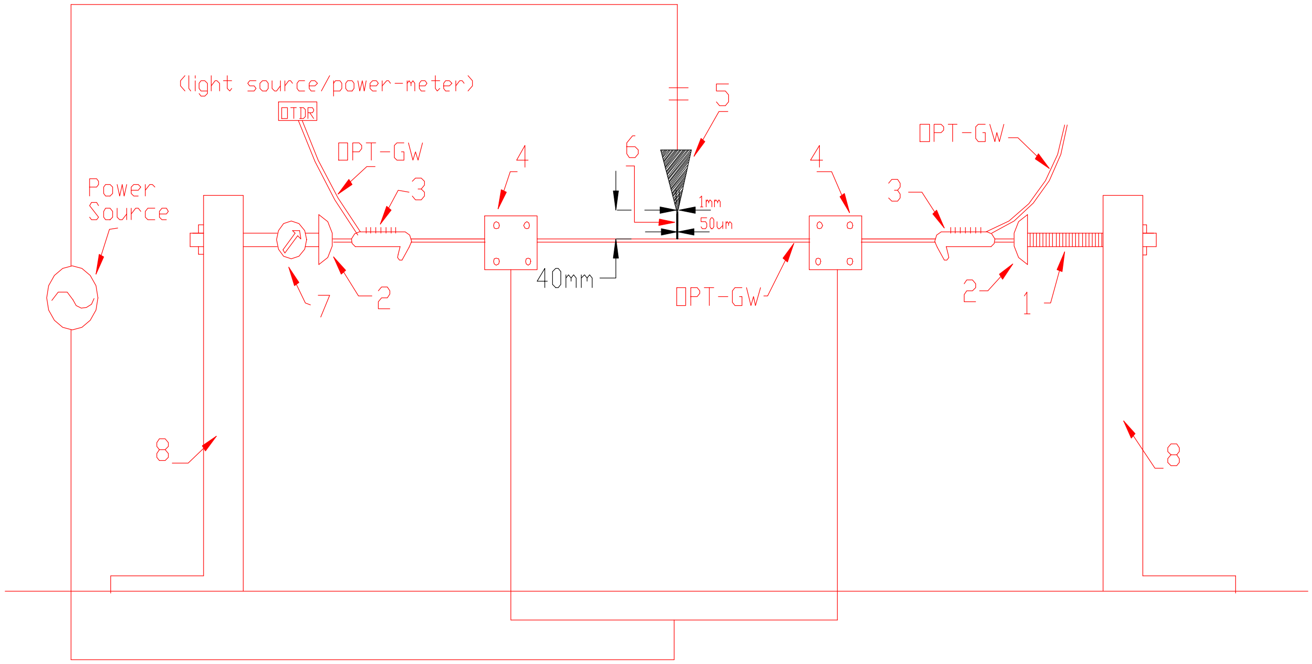


Fig. 1 - Typical Lightning Test Arrangement

2. Test Conditions :

The sample shall be subjected to a simulated lightning strike (see **Fig.2**) having **4 components**:

1. Initial stroke: **A**
2. Intermediate current: **B**
3. Continuing current: **C**
4. Re-strike: **D**

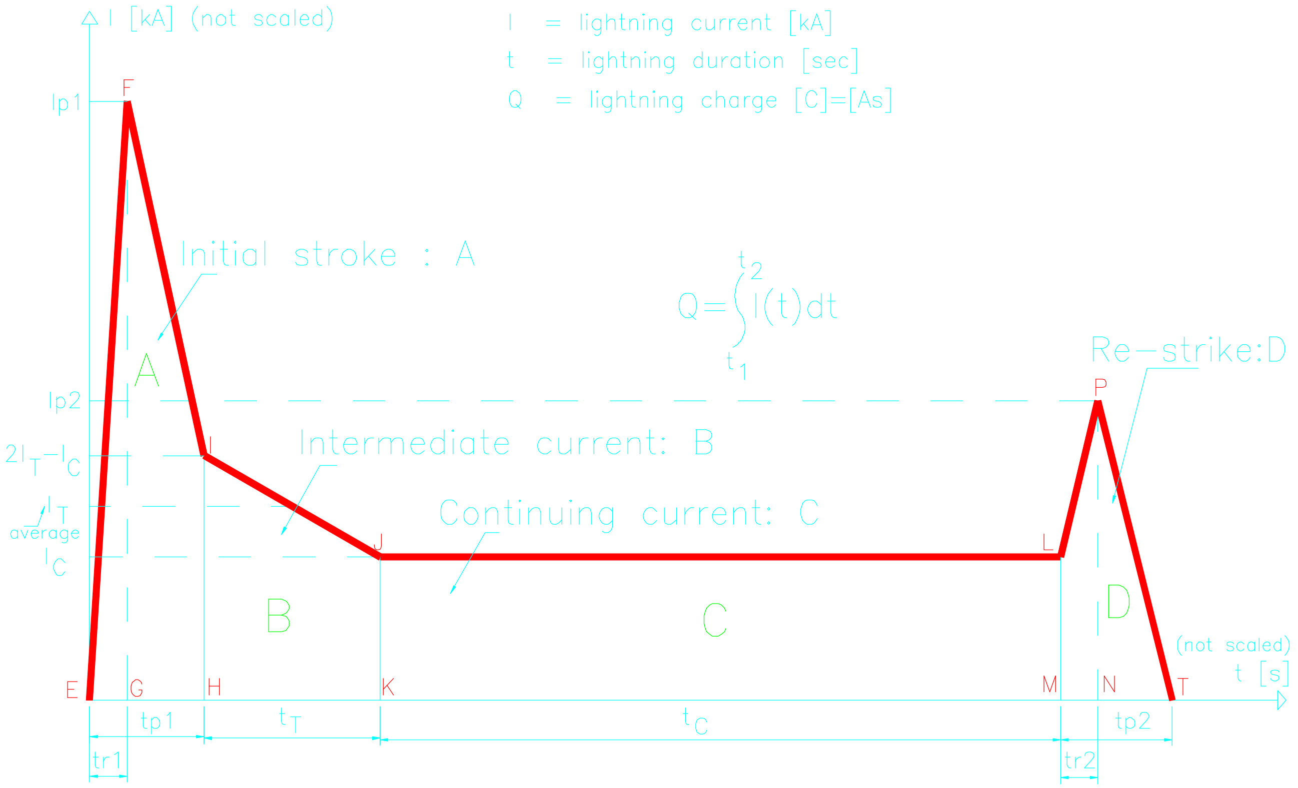


Fig. 2 - Lightning Current Form in Test

Total Transfer Charge: Q_T :

Generally, the charge is defined by : $Q_T = \int_{t1}^{t2} I_{(t)} \bullet dt =$ area under function $I_{(t)}$; in this particular case:

$\boxed{Q_T = Q_A + Q_B + Q_C + Q_D}$, where:

formula (1):

$$Q_A = triangle\,area \quad EFG + trapezium \quad area \quad FIHG = \frac{I_{p1} \bullet t_{r1}}{2} + \frac{(I_{p1} + 2 \bullet I_T - I_C) \bullet (t_{p1} - t_{r1})}{2}$$

formula (2):

$$Q_B = trapezium \quad area \quad IJKH = \frac{(2 \bullet I_T - I_C + I_C) \bullet t_T}{2} = I_T \bullet t_T$$

formula (3):

$$Q_C = rec\tan gle \quad area \quad JLMK = I_C \bullet t_C$$

formula (4):

$$Q_D = trapezium\, area \quad LPNM + triangle \quad area \quad PTN = \frac{(I_C + I_{p2}) \bullet t_{r2}}{2} + \frac{I_{p2} \bullet (t_{p2} - t_{r2})}{2}$$

Component (see Fig .2):	**Parameter:**	**Value:**
1. Initial stroke: **A**	Peak current: I_{p1}	**100 kA** see note (1)
	Charge : Q_A	**10 C** see note (2)
	Rise time: t_{r1}	**20** ms see note (3)
	Pulse length: t_{p1}	**200** ms
2. Intermediate current: **B**	Average current: I_T	**1 kA** see note (4)
	Charge: Q_B	**5 C**
	time: t_T	**5 ms**
3. Continuing current: **C**	Current: I_C	**See note (5)**
	Charge : Q_C	**See note (5)**
	time: t_C	**[0.25....0.5] sec**
4. Re-strike: **D**	Peak current: I_{p2}	**50 kA**
	Charge : Q_D	**2.5 C** see note (6)
	Rise time: t_{r2}	**10** ms see note (7)
	Pulse length: t_{p2}	**100** ms

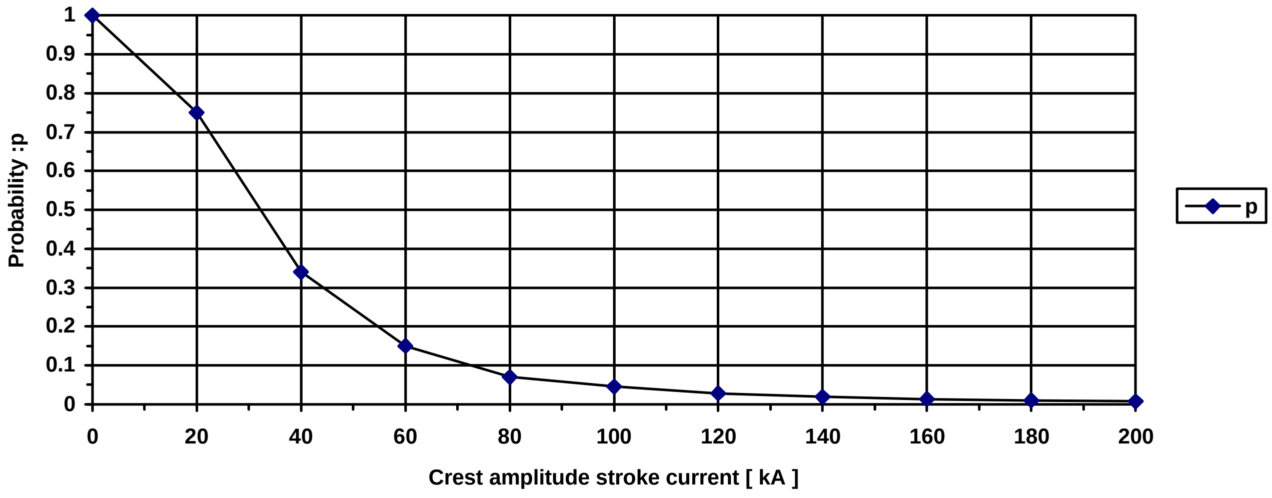
Notes:

(1) AFL chose **" worse case "** : 100 kA , even if the probability of occurrence of such a value , according to [2], from field combined data, is: $p = 0.045 = 4.5\%$ .Reference [1] requires 200 kA, but this value has a very small probability of occurrence: $p = 0.007 = 0.7\%$ Generally ,the usual lightning stroke peak values are in the range 20-40 kA , with a probability of occurrence, according to [2] : $p = (0.3...0.8) = (30\%.....80\%)$ (**see Fig.3**). The lightning stroke amplitude probability of distribution: $P_{(I)}$ is given by formula [9] :

$$\boxed{P_{(I)} = \frac{1}{1 + \left(\frac{I}{31}\right)^{2.6}}}$$, where : $I = (2.......200) \quad kA$

(2) this charge value remains approximate **constant** for a range of continuing current component $I_C = (50...500)$ **A.** Please see formula **(1).** AFL recommends a continuing current component in a range smaller than that: $I_C = (50...200)$ **A**, because this is the usual range presented in literature [11].

Fig.3



(3) The main problem is the **rise time**. AFL inquired many labs about their lightning test facilities and parameters. AFL chose a lightning impulse wave : 20/200 ms , the **rise time**: 20 ms being a value that could be obtained in many lightning labs (i.e. Lightning Technologies Inc, Massachusetts). For smaller values of rise time: 1-10 ms only some military laboratories would be able to reach 100 kA in such a small time rise . For such a steep slope you need big generators that the civil labs wont be able to perform.

(4) Intermediate current of about 1 kA , with 1 ms duration were observed at the Empire State Building [12]. AFL chose 5 ms duration to cover the worst cases.

(5) The values of I_C and t_C (resulting Q_C) will be **agreed** between the **purchaser** and **manufacturer**. Generally, the "worst duration scenario" would mean $t_C = 0.5$ sec. Generally, AFL recommends that the value of I_C to be in the range: **(50 ..... 200) A**, resulting for the "worst duration scenario" a range of charges: $Q_C = (12.5\ldots.100)$ **C .** This charge range covers even the worst cases presented in the technical literature [11] where: I_C =(100....300) A, duration: $t_C = 0.25$ sec, charge : $Q_C = (25\ldots.75)$ C. For even a bigger range of current I_C=(50...500) A and with the other data previously presented, resulted the values of charges : Q_A ,see formula (1), and Q_D, see formula(4). After a thorough analyze of the technical literature regarding lightning tests [3], [4], [5], [6], [7], [8], [9], [10], and based also on the AFL experience in OPT-GW lightning tests, AFL is proposing a method **" Algorithm to establish the lightning stroke continuing component values"** following presented in this paper.

(6) This charge value remains approximate **constant** for a range of continuing current component $I_C = (50..500)$ **A.** Please see formula **(4).** AFL recommends a continuing current component in a smaller range: $I_C = (50..200)$ **A** , to be in agreement with the technical literature [11].

(7) It was observed that if the rise time of the re-strike is very small (a **very steep slope**), less than 1 ms , it might have a great impact upon the **electro-magnetic** field around the OPT-GW and some additional small mechanical forces, the so called" pinch-effect forces" would apply on the

OPT-GW. But this effect can be observed at a re-strike wave form: $0.1ms/10ms$ which is extremely, if not impossible to reproduce in the existing laboratories. So if someone would like to experiment this possible effect , and the test doesn't become **extremely expensive** (you need special huge generators), it could be used for the re-strike a wave form $1\,ms\ /\ 50\,ms$ (only a military lab would perform it) .

Algorithm to establish the lightning stroke continuing component values:

Step 1 : **Number of strokes per 100 miles per year that hit the line :** N_L :

Input Data (Provided by the purchaser) :

1. **Isokeraunic Level** : I [thunderstorm-days/year] **see note (7)**
2. **Spacing between groundwires**: b [ft] **see note (8)**
3. **Tower Height** : h_t [ft]
4. **Groundwires Height**: h_{GW} [ft] **see note (9)**
5. **Lightning constant**: k [-] **see note (10)**

Notes:

(7) In the Overhead Transmission Line Location.

(8) Between the OPT-GW and the conventional groundwire.
If only the OPT-GW is installed (**no conventional groundwire**) : b **=0 .**

(9) h_{GW} = value at **mid-span** for the groundwires **final sag @ maximum ambient temperature** (i.e. 40^{o} C = 105^{o} F).

(10) k =**0.25** (for most cases) ; k =0.5 (for rare cases : very strong lightning strokes).

Output Data :

Using the formula from [2] (**See Fig. 5**) we obtain N_L , the number of lightning strokes/100miles/year, that hit the line:

$$\boxed{N_L = \frac{k \bullet I \bullet 100}{5280} \bullet \left\{ 4 \bullet \left[h_t - \frac{2}{3} \bullet \left(h_t - h_{GW} \right) \right] + b \right\}} \qquad \textbf{formula (5)}$$

where: h_t [ft]
h_{GW} [ft]
$h_t - h_{GW} = sag_{GW}$ [ft] @ max. ambient temperature (i.e. 40^{o} C)
b [ft]
$k = 0.25$ [-]

As a matter of fact, this formula results from the “ strike incidents equations” method.

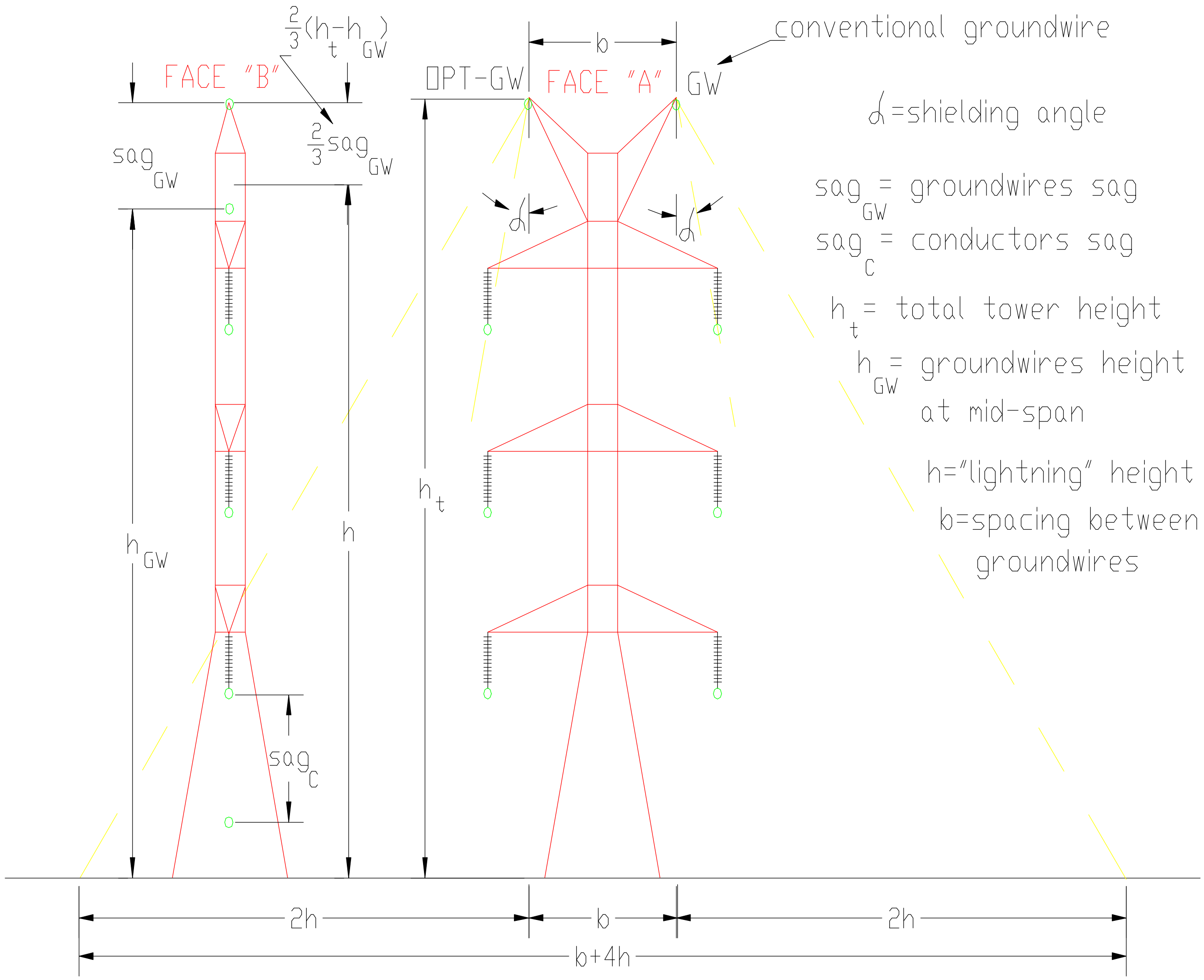


Fig. 5 - Width of the right of way shielded from lightning strokes

Step 2: Number of strokes/100 miles/year: N_{OPT-GW} that might strike the OPT-GW:

According to [2] , from composed field data selected for a long period of time , during many years, it resulted the following conclusions:

Structure type	Span [ft]	[m]	Nominal Line Voltage [kV]	N_{OPT-GW}	N_{tower}
Tall steel towers	1000-1500	300-450	230 - 500	$0.6 \bullet N_L$	$0.4 \bullet N_L$
Small steel towers	400 -1000	120-300	33 - 110	$0.4 \bullet N_L$	$0.6 \bullet N_L$
Wood poles	300 - 1200	90-365	33 - 230	$0.75 \bullet N_L$	$0.25 \bullet N_L$

For steel towers the rule would be: **" the shorter the span, the higher the probability that the lightning strikes go on tower, instead of the OPT-GW ".**
The number of strokes to the structure: N_{tower} depends, according to [9], directly on the ground stroke density: N_g for the area of the transmission line. The calculation of the total number of strokes to hit the line : N_L can be done in many ways, according to [9] :one method would be to use the "EGM= Electrogeometric" Model (or as is also known as " the strike distance" theory) . Briefly, in this model the lightning stroke is assumed to vertically approach earth, and will strike the first object that comes within the striking distance (shieldwire, phase conductor, tower or ground). The strike distance S is expressed as [9]:

$$\boxed{S = A \bullet I^n} \quad [\mathrm{m}] \text{ , where :}$$

I is the peak stroke current [kA]
A is a constant (often A=8 or 10 is used)
n =0.65.
Another method is the so called " Strike Incident Equations" [2] , as an example it is used formula:

$$\boxed{N_S = \frac{N_g}{10} \bullet \left(28 \bullet h_t^{0.6} + b\right)} \text{, where :}$$

$N_S = N_{tower} =$ the flash rate on the structure (tower) $\left[strokes/100km \bullet year\right]$
$h_t =$ tower height [m]; $b =$ spacing between groundwires [m]
N_g $\left[strokes/km^2 \bullet year\right]$ =ground stroke density, given by formula [9] : $\boxed{N_g = 0.04 \bullet I^{1.25}}$, where:
$I\left[thunderstorms - days/year\right]$ =isokeraunic level;

From this method also derived **formula (5)** which is the most common used, therefore AFL choose it as the most adequate for the purpose of this paper.

Step 3: The continuing current parameters:

From the number of strokes that hit the OPT-GW: N_{OPT-GW} , statistics shows that only **1%** to maximum **3%** represents expected " incidents" ,damages to the OPT-GW cable. A good design is considered to be when the number of " incidents", expected damages to the OPT-GW cable is **equal** or **less** than **1 incident /100 miles/year**. Taking in consideration this assumption and the fact that AFL chose the **"worst duration scenario":** $t_C =$ **0.5 sec.** and one of the **worse peak amplitude** : I_{p1} =100 kA , which has a very small probability of occurrence : $p = 0.045$, (the usual values being I_{p1} = 20-40 kA , with a probability $p \approx 0.3...0.8$), AFL decided to consider that the percent should be 1%:

$$\boxed{D_{OPT-GW} = 1\% \bullet N_{OPT-GW}}$$

where: $D_{OPT-GW} =$ **expected damages, " incidents" on OPT-GW /100 miles/year**

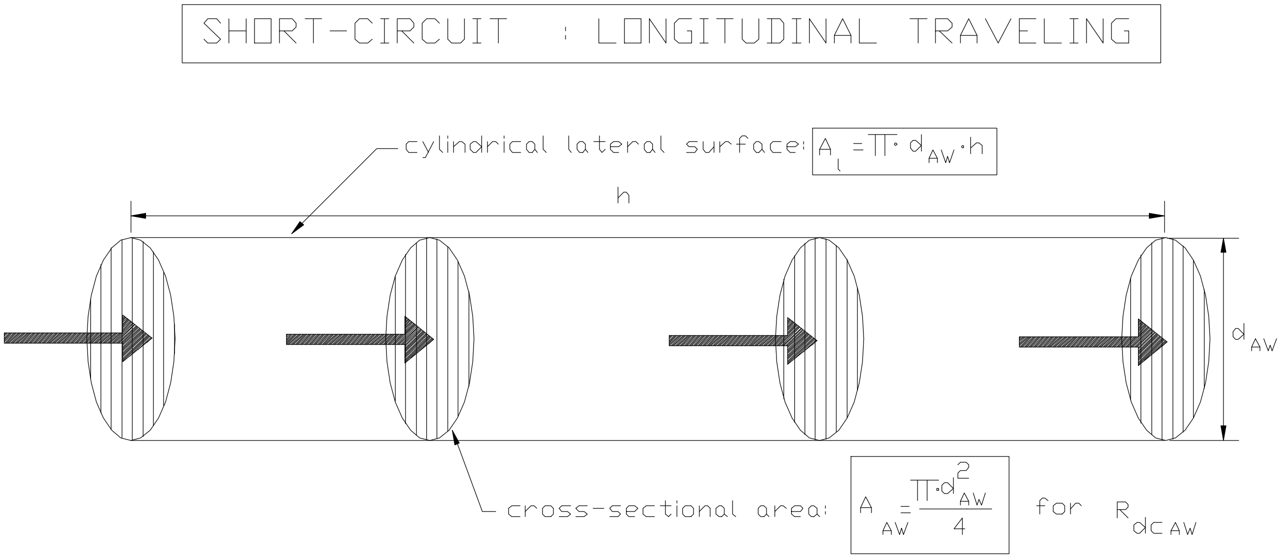
$N_{OPT-GW} =$ **number of strokes on OPT-GW /100 miles/year**

Step3.1. Lightning stroke continuing component charge transfer: Q_C :

3.1.1. AW Strand:

Assumptions:

- the short-circuit will **longitudinally** travel the AW wire.



- the lightning stroke will **transversally** hit the AW wire in a spot and then will travel through a cone surface inside the wire. The cone top angle: $a = 90^0$ (this is the incidence " hit spot" angle). The cross-sectional area that is traversed by the lightning current (and that will be used in the d.c. resistance calculations) will be:

$\boxed{A_{AWl.s.} = p \bullet h^2}$ where:

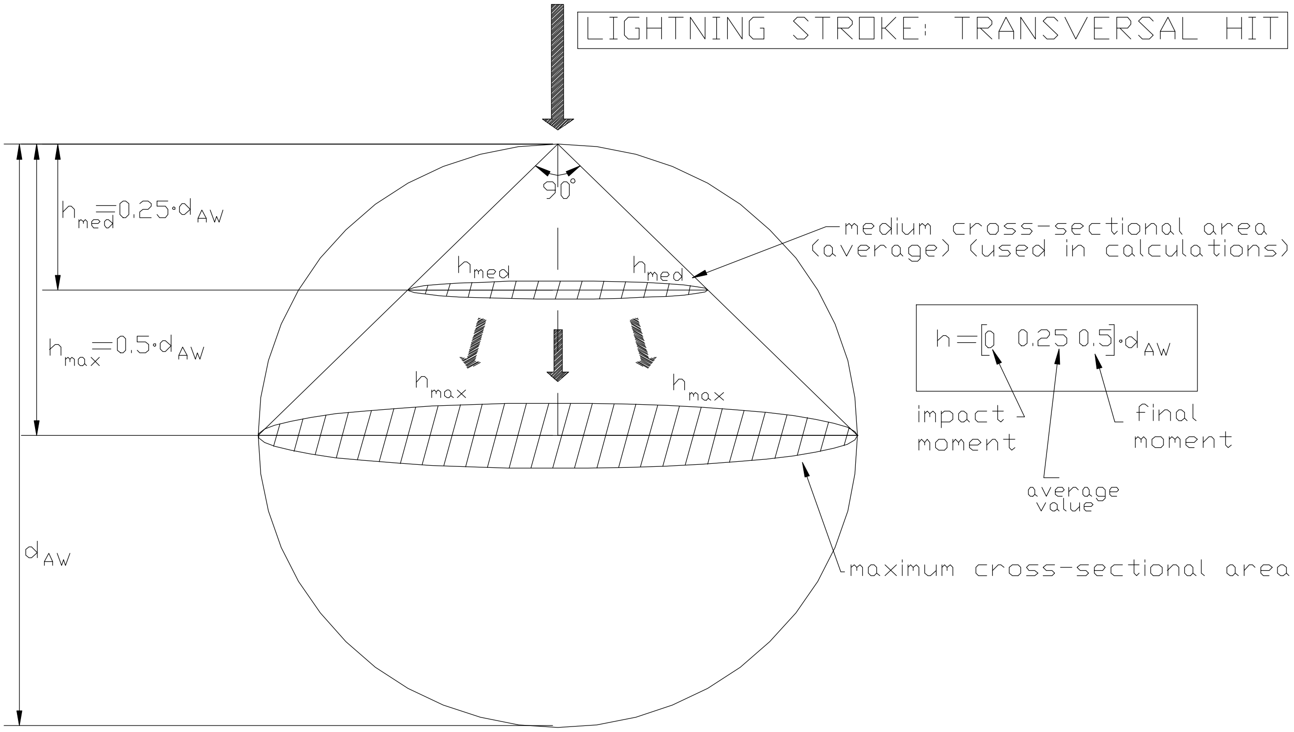
$A_{AWl.s.} =$ cross-sectional area for lightning stroke

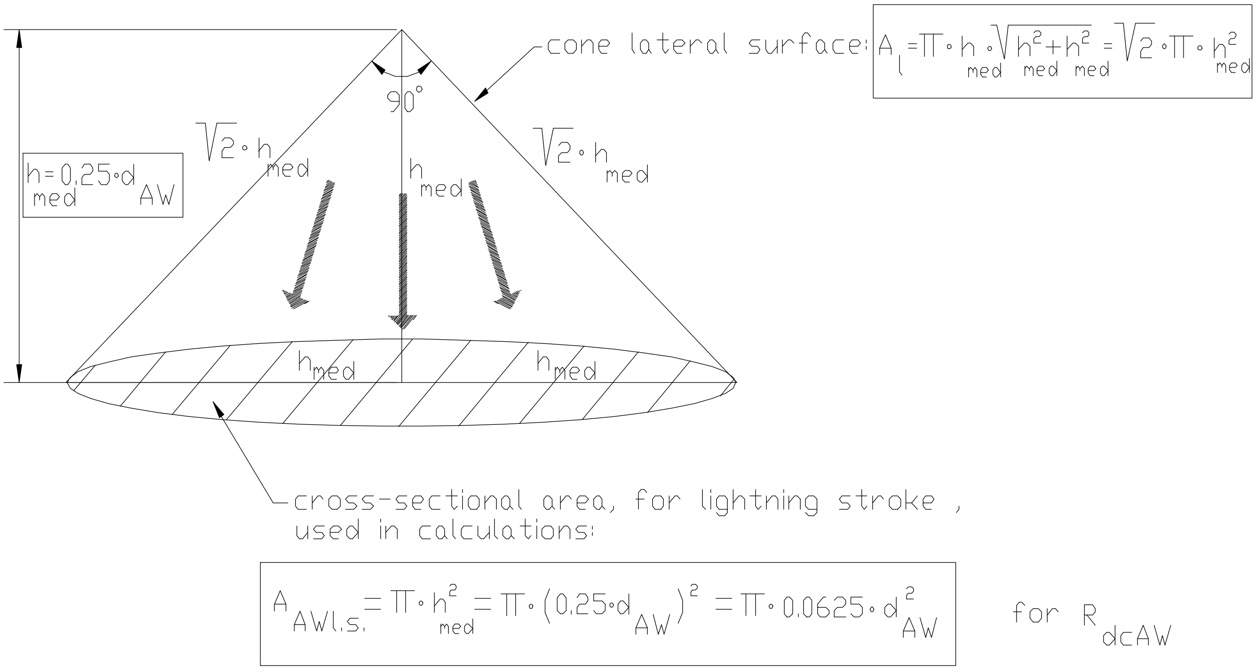
$$h = [0 \ldots\ldots\ldots\ldots 0.25 \ldots\ldots\ldots\ldots 0.5] \bullet d_{AW}$$

↓	↓	↓
impact moment	**average value**	**final moment**

We decided to use in the lightning stroke calculations **the medium (average) height of the cross-sectional area** :

$$\boxed{h_{med} = 0.25 \bullet d_{AW}} \quad \Rightarrow \quad \boxed{A_{AWl.s.} = p \bullet h_{med}^2 = p \bullet \left(0.25 \bullet d_{AW}\right)^2 = p \bullet 0.0625 \bullet d_{AW}^2}$$





a) D.C. Linear Resistance of AW at 20^{o} C: R_{dcAW}^{20C} :

$$R_{dcAW}^{20C} = \frac{P_{AW}}{A_{AWl.s.}} \bullet K1 \bullet K2 = \frac{P_{AW}}{p \bullet 0.0625 \bullet d_{AW}^{2}} \bullet K1 \bullet K2 = \frac{K1 \bullet K2 \bullet P_{AW}}{p \bullet 0.0625} \bullet \frac{1}{d_{AW}^{2}} \qquad [\Omega / km]$$

$P_{AW} = 0.0848 \quad \Omega \bullet mm^2 \ / \ m$ **(20.3 %) (AW resistivity)**

$P_{AW} = 0.0638 \quad \Omega \bullet mm^2 \ / \ m$ **(27 %) (AW resistivity)**

$K1 = 1000 \quad m / km$

$K2 = 1.02$

$\Rightarrow R_{dcAW}^{20C} = \frac{440.52}{d_{AW}^2} \quad [\Omega / km]$ **(20.3 %)** $\Rightarrow R_{dcAW}^{20C} = \frac{4405.2 \bullet 10^{-6}}{d_{AW}^2} \quad [\Omega / cm]$ **(20.3 %)**

$\Rightarrow R_{dcAW}^{20C} = \frac{331.43}{d_{AW}^2} \quad [\Omega / km]$ **(27 %)** $\Rightarrow R_{dcAW}^{20C} = \frac{3314.3 \bullet 10^{-6}}{d_{AW}^2} \quad [\Omega / cm]$ **(27 %)**

where: $d_{AW} \quad [mm]$

b) <u>AW temperature coefficient of resistance at 20^o C:</u> $a_{AW} = 0.0036 \quad [1/^0C]$
(both 20.3% & 27%), independent of d_{AW} !

c) <u>AW resistivity at maximum allowable temperature</u>: r_{AW}^{180C} **:**

$r_{AW}^{180C} = R_{dcAW}^{20C} \bullet A_{AWl.s.} \bullet \left[1 + a_{AW} \bullet (t - t_a)\right] \quad [\Omega \bullet cm]$

$A_{AWl.s.} = p \bullet 0.0625 \bullet d_{AW}^2 \quad [mm^2] \Rightarrow A_{AWl.s.} = 0.001963495 \bullet d_{AW}^2 \quad [cm^2]$**, where:** $d_{AW} \quad [mm]$

$a_{AW} = 0.0036 \quad [1/^0C]$

$t = 180 \quad [^0C]$ =final AW temperature

$t_a = 20 \quad [^0C]$ standard resistance temperature

$\Rightarrow r_{AW}^{180C} = 13.6317 \bullet 10^{-6} \quad [\Omega \bullet cm]$ (20.3%)

$\Rightarrow r_{AW}^{180C} = 10.256 \bullet 10^{-6} \quad [\Omega \bullet cm]$ (27 %)

Conclusion: r_{AW}^{180C} **independent of** d_{AW} **! As it was expected the resistivity should not be a function of the wire diameter !**

d) <u>AW specific heat</u> : $S_{AW} = 0.502 \quad [J / g \bullet {}^{0}C]$ (20.3%)

$S_{AW} = 0.533 \quad [J / g \bullet {}^{0}C]$ (27 %)

S_{AW} **is independent of** d_{AW} **!**

e) <u>AW density</u>: $G_{AW} = 6.59 \quad [g / cm^{3}]$ (20.3%)

$G_{AW} = 5.91 \quad [g / cm^{3}]$ (27 %)

G_{AW} **is independent of** d_{AW} **!**

For the lightning stroke test it could be used the same fault current formula (*) that is used for the short-circuit test but with the following assumptions:

- **short-circuit current is longitudinally traveling through the whole surface of the cable, affecting the AW strands, the AlAlloy strands, and the AL pipe as a whole system. It's a total surface, extended, fault current. That's why in the fault current formula (*), applied for the short-circuit, all the parameters:**
    - G **density**
    - S **specific heat**
    - a **temperature coefficient of resistance**
    - r **resistivity**

have values referring to the total cable: OPT-GW, and not to one of the cable components (AW strands, AL strands, Al pipe) !

- **lightning stroke current is hitting transversally the cable in a spot , so it's a local fault current affecting the local AW or AL wire that is hit (and , as field statistics shows, the next 2 adjacent wires in a smaller proportion. In lab test, sometimes more than 3-5 adjacent wires are affected, but in a very small proportion). That's why in the fault current formula (*) ,applied for lightning stroke, all the parameters:**

    - G **density**
    - S **specific heat**
    - a **temperature coefficient of resistance**
    - r **resistivity**

have values referring to only 1 wire (the one hit by lightning !). This could be an AW (20.3 % or 27%) strand or an AlAlloy 6201 strand.

$$\boxed{I_C = \frac{Q_C}{t_C} = \sqrt{\frac{G_{AW} \bullet S_{AW} \bullet \ln\left[a_{AW} \bullet \left(T_F - T_A\right) + 1\right]}{r_{AW}^{180C} \bullet a_{AW} \bullet t_C}} \bullet A_{AWl.s.} \bullet 10^{-2} \qquad [A]}$$

formula (*)

where: $\boxed{A_{AWl.s.} = p \bullet 0.0625 \bullet d_{AW}^{2}}$ is the cross-sectional area for lightning stroke , so it results:

$$\boxed{\Rightarrow Q_C = \sqrt{\frac{G_{AW} \bullet S_{AW} \bullet \ln\left[a_{AW} \bullet \left(T_F - T_A\right) + 1\right] \bullet t_C}{r_{AW}^{180C} \bullet a_{AW}}} \bullet p \bullet 0.0625 \bullet 10^{-2} \bullet d_{AW}^{2} \qquad [C]}$$

where: $d_{AW} \quad [mm]$

$T_F = 180^0 C$ = final AW temperature
$T_A = 40^0 C$ = initial AW temperature = maximum ambient temperature

$$\Rightarrow Q_C = 10.3 \bullet \sqrt{t_C} \bullet d_{AW}^2 \quad [C] \quad \textbf{(20.3 \%)}$$

where: $t_C = [0.25.....0.5]$ [sec]
d_{AW} $[mm]$

“ good duration scenario”: $t_C = 0.25$ $\sec \Rightarrow Q_C = 5.15 \bullet d_{AW}^2$ **(20.3 %)**
“ worst duration scenario”: $t_C = 0.50$ $\sec \Rightarrow Q_C = 7.3 \bullet d_{AW}^2$ **(20.3 %)**

both “duration scenarios” for the “worst incidents scenario” : D=1 damage/100 miles/year.

$$\Rightarrow Q_C = 11.6 \bullet \sqrt{t_C} \bullet d_{AW}^2 \quad [C] \quad \textbf{(27\%)}$$

where: $t_C = [0.25.....0.5]$ [sec]
d_{AW} $[mm]$

“ good duration scenario”: $t_C = 0.25$ $\sec \Rightarrow Q_C = 5.8 \bullet d_{AW}^2$ **(27 %)**
“ worst duration scenario”: $t_C = 0.50$ $\sec \Rightarrow Q_C = 8.2 \bullet d_{AW}^2$ **(27 %)**

both “duration scenarios” for the “worst incidents scenario” : D=1 damage/100 miles/year.

3.1.2. AlAlloy 6201 Strand:

Following the same analyze and assumptions that we did for the AW wire, it will result:

a) D.C. Linear Resistance of AlAlloy 6201 at 20^o C: R_{dcAL}^{20C} :

$$R_{dcAL}^{20C} = \frac{P_{AL}}{A_{ALl.s.}} \bullet K1 \bullet K2 = \frac{P_{AL}}{p \bullet 0.0625 \bullet d_{AL}^2} \bullet K1 \bullet K2 = \frac{K1 \bullet K2 \bullet P_{AL}}{p \bullet 0.0625} \bullet \frac{1}{d_{AL}^2} \quad [\Omega / km]$$

$P_{AL} = 0.032841$ $\Omega \bullet mm^2 / m$ **(AlAlloy 6201 resistivity)**

$K1 = 1000$ m / km

$K2 = 1.02$

$$\Rightarrow R_{dcAL}^{20C} = \frac{170.603}{d_{Al}^2} \quad [\Omega / km] \qquad \Rightarrow R_{dcAL}^{20C} = \frac{1706.03 \bullet 10^{-6}}{d_{AL}^2} \quad [\Omega / cm]$$

where: d_{AW} $[mm]$

b) <u>AlAlloy temperature coefficient of resistance at 20^{o} C:</u> $a_{AL} = 0.00347 \quad \left[1/{}^{0}C\right]$
independent of d_{AW} !

c) <u>AlAlloy resistivity at maximum allowable temperature</u>: r_{AL}^{180C} **:**

$$r_{AL}^{180C} = R_{dcAL}^{20C} \bullet A_{ALl.s.} \bullet \left[1 + a_{AL} \bullet (t - t_a)\right] \quad [\Omega \bullet cm]$$

$A_{ALl.s.} = p \bullet 0.0625 \bullet d_{AL}^{2} \quad \left[mm^2\right] \Rightarrow A_{ALl.s.} = 0.001963495 \bullet d_{AL}^{2} \quad \left[cm^2\right]$**, where:** $d_{AL} \quad [mm]$

$a_{AL} = 0.00347 \quad \left[1/{}^{0}C\right]$

$t = 180 \quad \left[{}^{0}C\right]$ =final AL temperature

$t_a = 20 \quad \left[{}^{0}C\right]$ standard resistance temperature

$\Rightarrow r_{AL}^{180C} = 5.209 \bullet 10^{-6} \quad [\Omega \bullet cm]$

Conclusion: r_{AL}^{180C} **independent of** d_{AL} **! As it was expected the resistivity should not be a function of the wire diameter !**

d) <u>AlAlloy 6201 specific heat</u> : $S_{AL} = 0.888 \quad \left[J / g \bullet {}^{0}C\right]$ S_{AL} **is independent of** d_{AL} **!**

e) <u>AlAlloy 6201 density</u>: $G_{AL} = 2.68 \quad \left[g / cm^3\right]$ G_{AL} **is independent of** d_{AL} **!**

$$\boxed{I_C = \frac{Q_C}{t_C} = \sqrt{\frac{G_{AL} \bullet S_{AL} \bullet \ln\left[a_{AL} \bullet (T_F - T_A) + 1\right]}{r_{AL}^{180C} \bullet a_{AL} \bullet t_C}} \bullet A_{ALl.s.} \bullet 10^{-2} \quad [A]} \qquad \textbf{formula (*)}$$

where: $\boxed{A_{ALl.s.} = p \bullet 0.0625 \bullet d_{AL}^{2}}$ is the cross-sectional area for lightning stroke , so it results:

$$\boxed{\Rightarrow Q_C = \sqrt{\frac{G_{AL} \bullet S_{AL} \bullet \ln\left[a_{AL} \bullet (T_F - T_A) + 1\right] \bullet t_C}{r_{AL}^{180C} \bullet a_{AL}}} \bullet p \bullet 0.0625 \bullet 10^{-2} \bullet d_{AL}^{2} \quad [C]}$$

where: $d_{AL} \quad [mm]$

$T_F = 180^{0}C$ = final AL wire temperature
$T_A = 40^{0}C$ = initial AL wire temperature = maximum ambient temperature

$$\Rightarrow Q_C = 14.18 \bullet \sqrt{t_C} \bullet d_{AL}^2 \qquad [C]$$

where: $t_C = [0.25.....0.5] \quad [\text{sec}]$
$d_{AW} \quad [mm]$

The AlAlloy 6201 wire has a higher conductivity factor than AW wire , so the heat dissipation is faster and greater, but it's tensile strength it's smaller than that of the AW wire. According to ASTM B398, Table 2 , we have:

- for AlAlloy 6201 wire:

diameter =(1.55...... 3.37) mm , results tensile strength factor: 48000 lbs/sq.in.
diameter ≥ 3.37 mm, results tensile strength factor: 46000 lbs/sq.in.
specific heat factor : 0.888 J/gC

- for AW 20.3% wire:

diameter =(1.96..... 3.28) mm, results tensile strength factor: 195000 lbs/sq.in.
diameter =(3.28.......3.48) mm, results tensile strength factor: 190000 lbs/sq.in.
diameter =(3.48..... 3.67) mm, results tensile strength factor: 185000 lbs/sq.in.
specific heat factor: 0.502 J/gC

Taking into account these data AFL decided to consider:

•an average reduction tensile strength factor of : $\frac{48000}{195000} \cong 0.25$

•an average increasing heat factor of : $\frac{0.888}{0.502} \cong 1.77 \cong 1.8$

$$\text{general factor} \quad = \underset{\text{Heat}}{\underset{\uparrow}{1.8}} \bullet \underset{\text{Tensile Strength}}{\underset{\downarrow}{0.25}} = 0.45$$

So, the maximum allowable charge in the test not to broke the AlAlloy wire should be corrected by this factor:

$$Q_C = 14.18 \bullet 0.45 \bullet \sqrt{t_C} \bullet d_{AL}^2$$

where: $t_C = [0.25.....0.5] \quad [\text{sec}]$
$d_{AW} \quad [mm]$

" good duration scenario": $t_C = 0.25 \quad \text{sec} \Rightarrow Q_C = 3.2 \bullet d_{AL}^2$
" worst duration scenario": $t_C = 0.50 \quad \text{sec} \Rightarrow Q_C = 4.52 \bullet d_{AL}^2$

both "duration scenarios" for the "worst incidents scenario" : D=1 damage/100 miles/year.

For lower number of incidents /100 miles/year it could be used formula:

$$Q_{D_X} = D_X \bullet Q_{D_1}, \text{ where: } D_X = 0.1........1 \quad [incidents/100miles/year]$$
$$D_1 = 1 \quad [incidents/100miles/year]$$

According to [10], the **non-steady state heat balance equation** is:

$$\boxed{q_c + q_r + m \bullet C_p \bullet \frac{dT_C}{dt} = q_s + I^2 \bullet R_{(T_C)}}$$ **[W / ft]**

↓ ↓ ↓ ↓ ↓

convection losses **radiation losses** **heat capacity** **sun gain** **Joule losses**

where:

$q_c =$ convected heat losses [W / ft]
$q_r =$ radiated heat losses [W / ft]
$m \bullet C_p =$ conductor heat capacity [Ws / ft ^{o}C]
$q_s =$ heat gain from sun [W / ft]
$I^2 \bullet R_{(T_C)} =$ Joule losses [W / ft]

There are two weather possibilities when lightning stroke occurs, hitting the OPT-GW :

- cloudy, going to start raining
- cloudy, already raining

But, even if at the lightning stroke occurrence the OPT-GW is not under direct sun, before that cloudy weather , it could have been a sunny weather, very hot, and the OPT-GW could have gained, in time, some heat from sun.

In the formula (*) we premeditatedly neglected the term $q_s = a \bullet Q_s \bullet \sin q \bullet A'$ (heat gain from sun), because we would otherwise be obliged to add some new input data , relatively difficult to know , especially for the customer who should be able to provide them to us, like:

$a =$ solar absorptivity
$Q_s =$ solar radiated heat flux
$q =$ sun's rays angle of incidence [degrees] , which is a function of:

- $H_c =$ sun altitude
- $H_e =$ conductor elevation above sea
- $Z_c =$ sun azimuth
- $Z_e =$ conductor azimuth

This term: q_s , as can obviously be noticed from the non-steady state heat balance equation, is decreasing the current : I_C , and thus the transfer charge : Q_C :

$$I_C = \frac{Q_C}{t_C} = \sqrt{\frac{q_c + q_r + m \bullet C_p \bullet \frac{\Delta T_C}{\Delta t_C} - q_s}{R_{(T_C)}}} \quad \text{neglecting } q_s \Rightarrow \quad I_C = \frac{Q_C}{t_C} = \sqrt{\frac{q_c + q_r + m \bullet C_p \bullet \frac{\Delta T_C}{\Delta t_C}}{R_{(T_C)}}}$$

$$\Rightarrow \quad I_C = \frac{Q_C}{t_C} = \sqrt{\frac{(q_c + q_r) \bullet \Delta t_C + m \bullet C_p \bullet \Delta T_C}{R_{(T_C)} \bullet \Delta t_C}}$$, and from this form results formula (*) .

Because we want to avoid new input data, difficult to know, we neglect the term q_s, which is reducing $I_C \quad (Q_C)$. But, to be closer to the real $I_C \quad (Q_C)$ values, we decided to apply a reduction factor due solar heat gain :

$$k_s = \sqrt{1 - \frac{q_s}{q_c + q_r + m \bullet C_p \bullet \frac{dT_C}{dt}}}$$

According to [10] , for ACSR wires the ratio : $\frac{q_s}{q_c + q_r + m \bullet C_p \bullet \frac{dT_C}{dt}} \cong 0.1$

In the OPT-GW lightning test, which has a local impact, mainly on the AW or AlAlloy strands , the ratio probably has the same value like the ratio for the ACSR wires, therefore it could be used the reduction factor: $k_s = \sqrt{1-0.1} = \sqrt{0.9} = 0.95$. If someone would like to be more accurate in calculations, that means to take in consideration the sun gain, he can apply this reduction factor. But due to the fact that the test take place in an indoor lab, AFL decided not to apply this "sun gain" reduction factor.
Therefore, it will result the following tables (the values were rounded to the first upper integer number for the "worst incident scenario": D=1):

<u>Step 3.2</u>. <u>Tables, Diagrams and example of calculation</u>:

Qc [C] = continuing component charge limit for broken ("burned through") wires " worst duration scenario: $t_C = 0.5$ [sec] D_X = expected OPT-GW incidents/100 miles/year			
D_X	**AW (20.3 %)**	**AW (27 %)**	**AlAlloy 6201**
0.1	$0.8 \bullet d_{AW}^2$	$0.9 \bullet d_{AW}^2$	$0.5 \bullet d_{AL}^2$
0.2	$1.6 \bullet d_{AW}^2$	$1.8 \bullet d_{AW}^2$	$1 \bullet d_{AL}^2$
0.3	$2.4 \bullet d_{AW}^2$	$2.7 \bullet d_{AW}^2$	$1.5 \bullet d_{AL}^2$
0.4	$3.2 \bullet d_{AW}^2$	$3.6 \bullet d_{AW}^2$	$2 \bullet d_{AL}^2$
0.5	$4 \bullet d_{AW}^2$	$4.5 \bullet d_{AW}^2$	$2.5 \bullet d_{AL}^2$
0.6	$4.8 \bullet d_{AW}^2$	$5.4 \bullet d_{AW}^2$	$3 \bullet d_{AL}^2$
0.7	$5.6 \bullet d_{AW}^2$	$6.3 \bullet d_{AW}^2$	$3.5 \bullet d_{AL}^2$
0.8	$6.4 \bullet d_{AW}^2$	$7.2 \bullet d_{AW}^2$	$4 \bullet d_{AL}^2$
0.9	$7.2 \bullet d_{AW}^2$	$8.1 \bullet d_{AW}^2$	$4.5 \bullet d_{AL}^2$
1	$8 \bullet d_{AW}^2$	$9 \bullet d_{AW}^2$	$5 \bullet d_{AL}^2$

Qc	**[C] = continuing component charge limit for " burned through" wires: AW 20.3 %**													
D_X	d_{AW} **[mm] (20.3%) ; " worst duration scenario": $t_C = 0.5$ [sec] D_X = expected OPT-GW incidents/100 miles/year**													
	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3	3.1	3.2	3.3
0.1	3.2	3.5	4	4.2	4.6	5	5.4	5.8	6.2	6.7	7.2	7.6	8.1	8.7

0.2	6	7	7.6	8	9	10	11	11.6	12	13	14	15	16	17
0.3	9	10	11	12	13	15	16	17	18	20	21	22	24	26
0.4	12	14	15	16	18	20	21	23	24	26	28	30	32	34
0.5	16	17	19	21	23	25	27	29	31	33	36	38	40	43
0.6	19	21	22	25	27	30	32	34	37	40	43	45	48	52
0.7	22	24	26	29	32	35	37	40	43	46	50	53	56	60
0.8	25	28	30	33	36	40	43	46	49	53	57	60	64	69
0.9	28	31	34	37	41	45	48	52	55	60	64	68	72	78
1	32	35	38	42	46	50	54	58	62	67	72	76	81	87

Qc	**[C] = continuing component charge limit for “ burned through” wires: AW 20.3 %**													
D_X	d_{AW} **[mm] (20.3%) ; “ worst duration scenario”:** $t_C = 0.5$ **[sec]** D_X **= expected OPT-GW incidents/100 miles/year**													
	3.4	3.5	3.6	3.7	3.8	3.9	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7
0.1	9.2	9.8	10.3	11	11.5	12	13	13.4	14	14.7	15	16	17	17.6
0.2	18	19	20	21	23	24	25	26	28	29	30	32	33	35
0.3	27	29	30	32	34	36	38	40	42	44	46	48	50	52
0.4	36	39	41	43	46	48	51	53	56	58	61	64	67	70
0.5	46	49	51	54	57	60	64	67	70	73	77	81	84	88
0.6	55	58	61	65	69	72	76	80	84	88	92	97	101	105
0.7	64	68	72	76	80	84	89	93	98	102	107	113	118	123
0.8	73	78	82	87	92	96	102	107	112	117	123	129	135	140
0.9	82	88	92	98	103	108	115	120	126	132	138	145	152	158
1	92	98	103	109	115	121	128	134	141	147	154	161	169	176

Qc	**[C] = continuing component charge limit for “ burned through” wires: AW 20.3 %**													
D_X	d_{AW} **[mm] (20.3%) ; “ worst duration scenario”:** $t_C = 0.5$ **[sec]** D_X **= expected OPT-GW incidents/100 miles/year**													
	4.8	4.9	5											
0.1	18	19	20											
0.2	36	38	40											
0.3	55	57	60											
0.4	73	76	80											
0.5	92	96	100											
0.6	110	115	120											
0.7	128	134	140											
0.8	147	153	160											
0.9	165	172	180											
1	184	192	200											

Qc	**[C] = continuing component charge limit for “ burned through” wires: AW 27 %**													
D_X	d_{AW} **[mm] (27 %) ; “ worst duration scenario”:** $t_C = 0.5$ **[sec]** D_X **= expected OPT-GW incidents/100 miles/year**													
	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3	3.1	3.2	3.3

0.1	3.6	4	4.3	4.7	5	5.6	6	6.5	7	7.5	8	8.6	9	10
0.2	7	8	8.6	9	10	11	12	13	14	15	16	17	18	19
0.3	10	11	12	14	15	16	18	19	21	22	24	25	27	29
0.4	14	15	17	18	20	22	24	26	28	30	32	34	36	39
0.5	18	19	21	23	25	28	30	32	35	37	40	43	46	49
0.6	21	23	25	28	30	33	36	39	42	45	48	51	55	58
0.7	25	27	30	32	35	39	42	45	49	52	56	60	64	68
0.8	28	31	34	37	40	44	48	52	56	60	64	68	73	78
0.9	32	35	38	42	45	50	54	58	63	67	72	77	82	88
1	36	39	43	47	51	56	60	65	70	75	81	86	92	98

Qc	**[C] = continuing component charge limit for “ burned through” wires: AW 27 %**													
D_X	d_{AW} **[mm] (27 %) ; “ worst duration scenario”:** $t_C = 0.5$ **[sec]** D_X = **expected OPT-GW incidents/100 miles/year**													
	3.4	3.5	3.6	3.7	3.8	3.9	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7
0.1	10.4	11	11.6	12	13	14	14.4	15	16	16.6	17	18	19	20
0.2	20	22	23	24	25	27	28	30	31	33	34	36	38	40
0.3	31	33	34	36	38	40	43	45	47	49	52	54	57	59
0.4	41	44	46	49	51	54	57	60	63	66	69	72	76	79
0.5	52	55	58	61	64	68	72	75	79	83	87	91	95	99
0.6	62	66	69	73	77	81	86	90	94	99	104	109	114	119
0.7	72	77	81	86	90	95	100	105	110	116	121	127	133	138
0.8	83	88	92	98	103	108	115	120	126	132	139	145	152	158
0.9	93	99	104	110	116	122	129	135	142	149	156	163	171	178
1	104	110	116	123	129	136	144	151	158	166	174	182	190	198

Qc	**[C] = continuing component charge limit for “ burned through” wires: AW 27 %**													
D_X	d_{AW} **[mm] (27%) ; “ worst duration scenario”:** $t_C = 0.5$ **[sec]** D_X = **expected OPT-GW incidents/100 miles/year**													
	4.8	4.9	5											
0.1	20.7	21	22											
0.2	41	43	45											
0.3	62	64	67											
0.4	82	86	90											
0.5	103	108	112											
0.6	124	129	135											
0.7	144	151	157											
0.8	165	172	180											
0.9	186	194	202											
1	207	216	225											

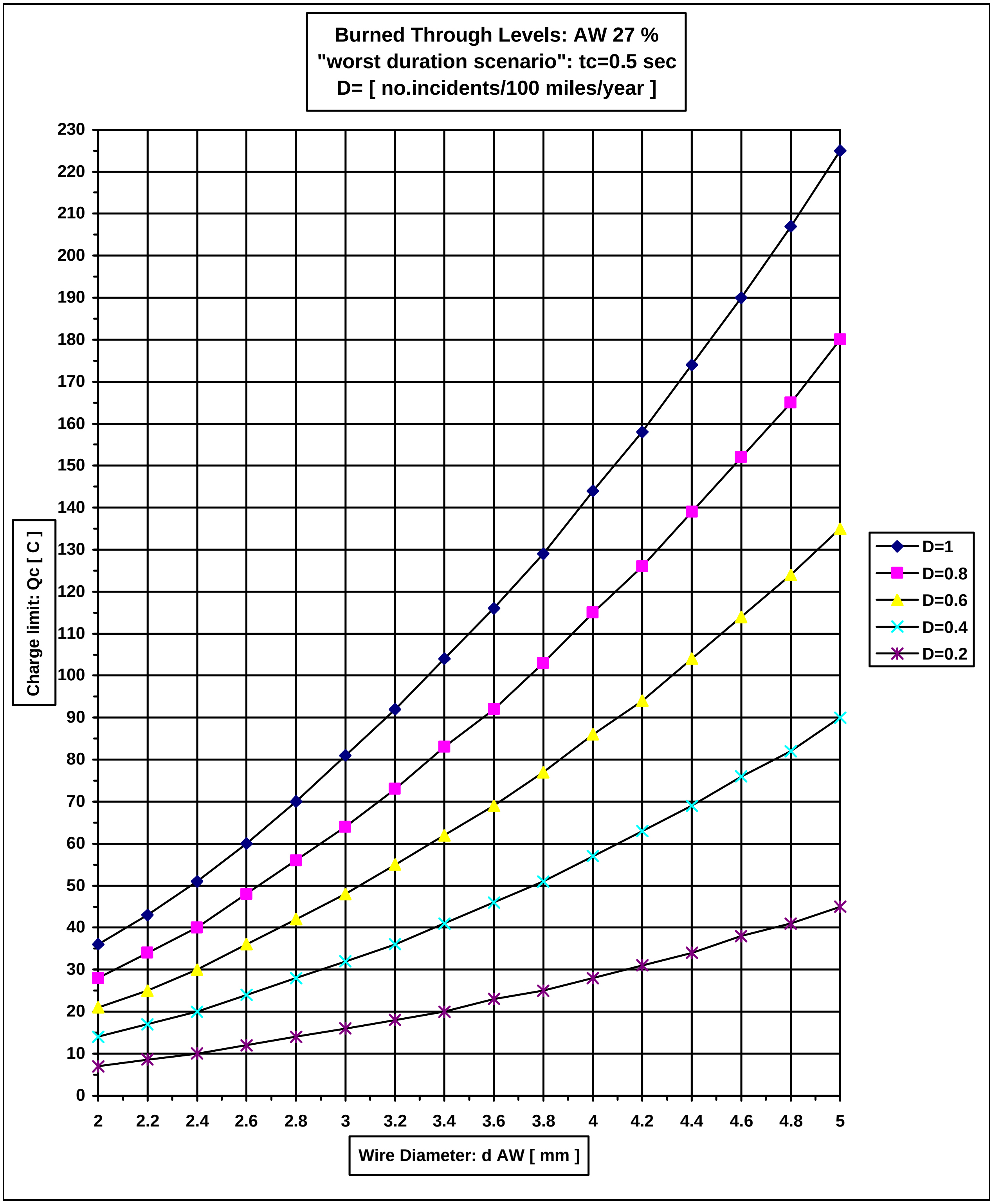
Qc	**[C] = continuing component charge limit for “ burned through” wires: AlAlloy 6201**													
D_X	d_{AL} **[mm] ; “ worst duration scenario”:** $t_C = 0.5$ **[sec]** D_X = **expected OPT-GW incidents/100 miles/year**													
	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3	3.1	3.2	3.3

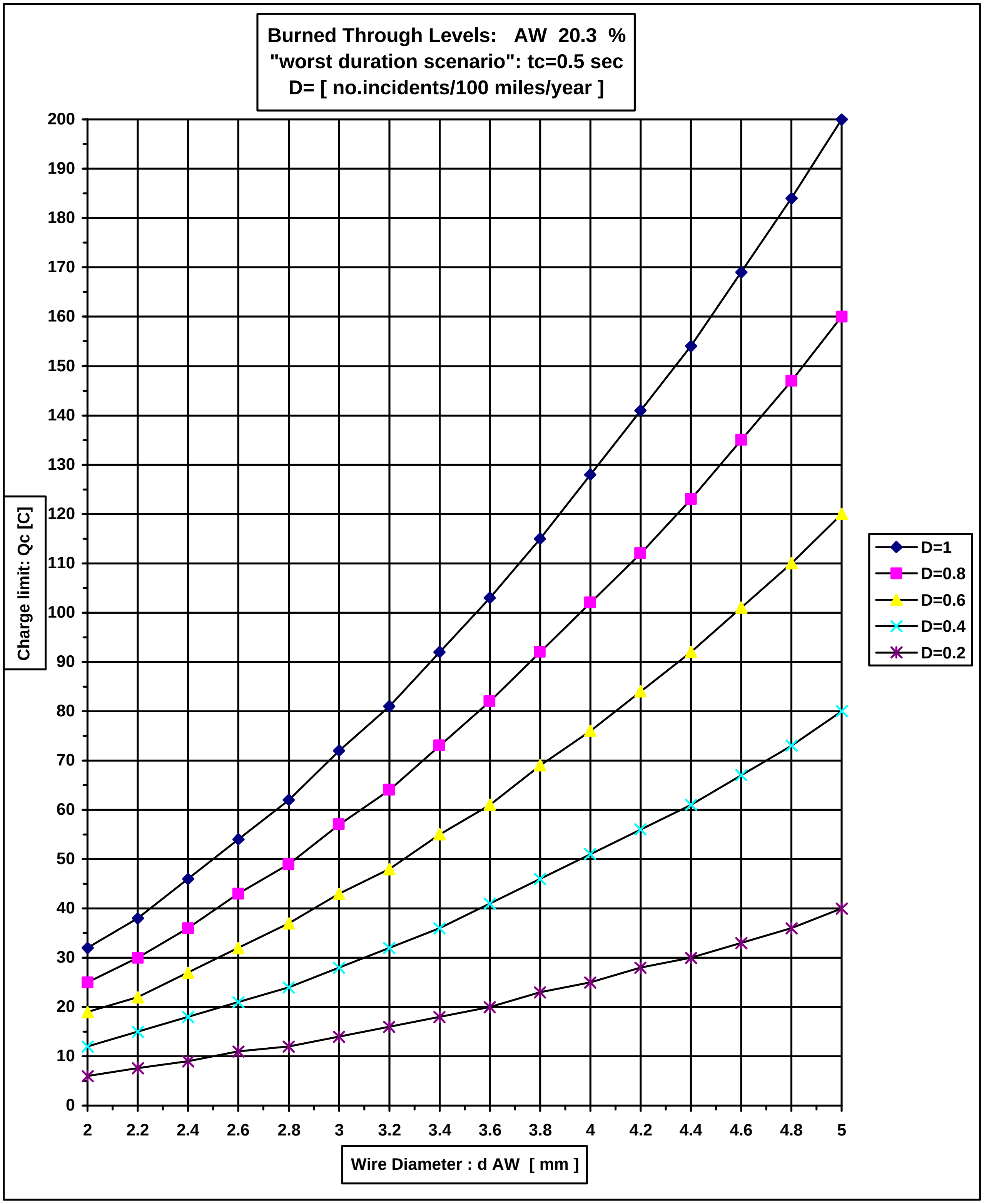
0.1	2	2.2	2.4	2.6	2.8	3.1	3.3	3.6	3.9	4.2	4.5	4.8	5.1	5.4
0.2	4	4.4	4.8	5.2	5.6	6.2	6.6	7	7.8	8	9	9.6	10	11
0.3	6	6.6	7	7.8	8.4	9.3	10	11	12	12.6	13	14	15	16
0.4	8	9	9.6	10.4	11	12	13	14	15	16	18	19	20	21
0.5	10	11	12	13	14	15	16	18	19	21	22	24	25	27
0.6	12	13	14	15	16	18	19	21	23	25	27	28	30	32
0.7	14	15	16	18	19	21	23	25	27	29	31	33	35	37
0.8	16	17	19	20	22	24	26	28	31	33	36	38	40	43
0.9	18	19	21	23	25	27	29	32	35	37	40	43	45	48
1	20	22	24	26	28	31	33	36	39	42	45	48	51	54

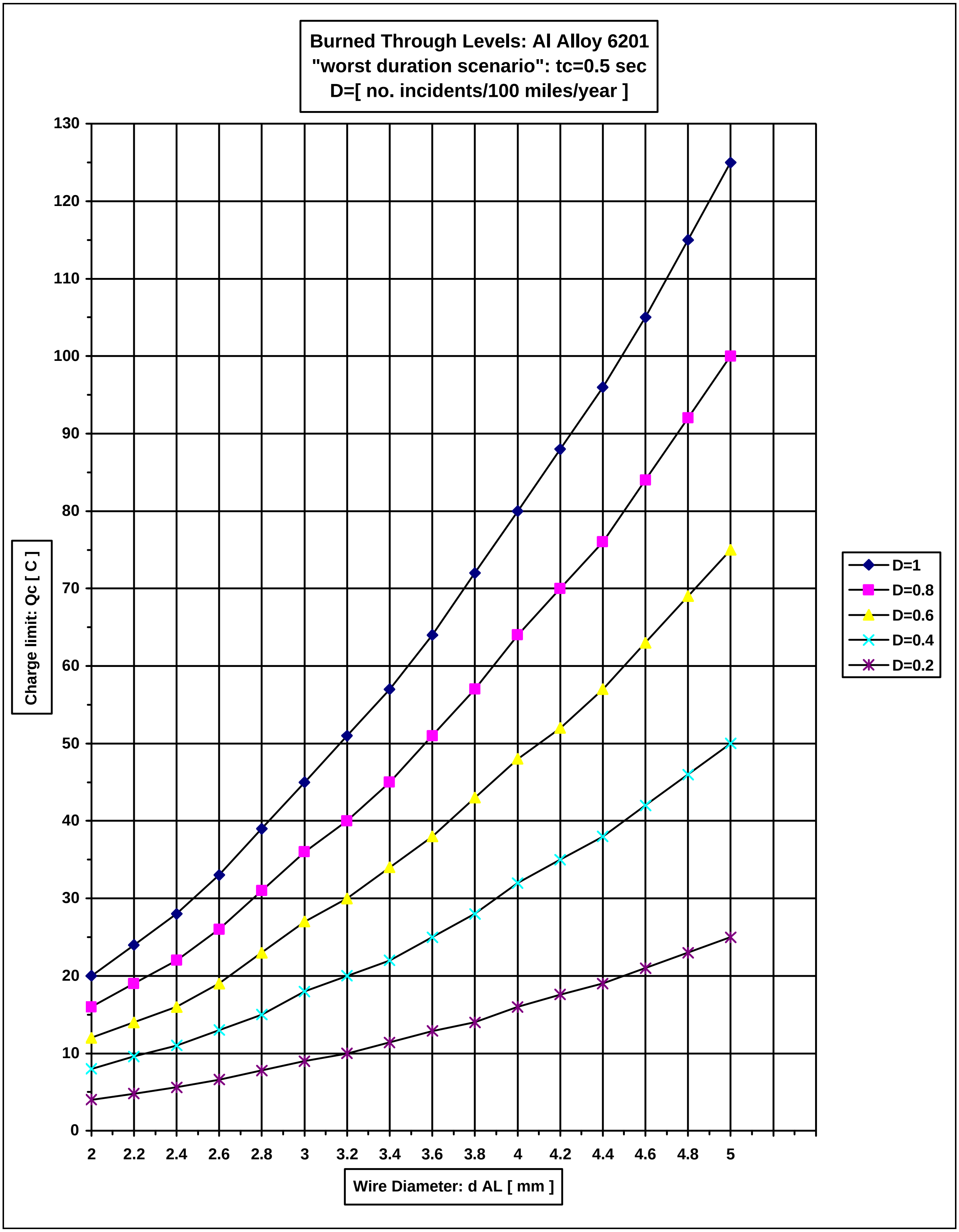
Qc	**[C] = continuing component charge limit for “ burned through” wires: AlAlloy 6201**													
D_X	d_{AL} **[mm] ; “ worst duration scenario”:** $t_C = 0.5$ **[sec]** $D_X =$ **expected OPT-GW incidents/100 miles/year**													
	3.4	3.5	3.6	3.7	3.8	3.9	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7
0.1	5.7	6.1	6.4	6.8	7.2	7.6	8	8.4	8.8	9.2	9.6	10.1	10.5	11
0.2	11.4	12	12.9	13	14	15	16	17	17.6	18	19	20	21	22
0.3	17	18	19	20	21	22	24	25	26	27	28	30	31	33
0.4	22	24	25	27	28	30	32	33	35	36	38	40	42	44
0.5	28	30	32	34	36	38	40	42	44	46	48	50	52	55
0.6	34	36	38	40	43	45	48	50	52	55	57	60	63	66
0.7	39	42	44	47	50	53	56	58	61	64	67	70	73	77
0.8	45	48	51	54	57	60	64	67	70	73	76	80	84	88
0.9	51	54	57	61	64	68	72	75	79	82	86	90	94	99
1	57	61	64	68	72	76	80	84	88	92	96	101	105	110

Qc	**[C] = continuing component charge limit for “ burned through” wires: AlAlloy 6201**													
D_X	d_{AL} **[mm] ; “ worst duration scenario”:** $t_C = 0.5$ **[sec]** $D_X =$ **expected OPT-GW incidents/100 miles/year**													
	4.8	4.9	5											
0.1	11.5	12	12.5											
0.2	23	24	25											
0.3	34	36	37											
0.4	46	48	50											
0.5	57	60	62											
0.6	69	72	75											
0.7	80	84	87											
0.8	92	96	100											
0.9	103	108	112											
1	115	120	125											

Thus resulting the following useful design “lightning” test **diagrams** :


Burned Through Levels: AW 27 %
"worst duration scenario": tc=0.5 sec
D= [no.incidents/100 miles/year]
Charge limit: Qc [C]
Wire Diameter: d AW [mm]
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
4.2
4.4
4.6
4.8
5
D=1
D=0.8
D=0.6
D=0.4
D=0.2


Burned Through Levels: AW 20.3 %
"worst duration scenario": tc=0.5 sec
D= [no.incidents/100 miles/year]
Charge limit: Qc [C]
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
4.2
4.4
4.6
4.8
5
Wire Diameter : d AW [mm]
D=1
D=0.8
D=0.6
D=0.4
D=0.2


Burned Through Levels: Al Alloy 6201
"worst duration scenario": tc=0.5 sec
D=[no. incidents/100 miles/year]
Charge limit: Qc [C]
130
120
110
100
90
80
70
60
50
40
30
20
10
0
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
4.2
4.4
4.6
4.8
5
Wire Diameter: d AL [mm]
D=1
D=0.8
D=0.6
D=0.4
D=0.2

example of calculation : **345 kV horizontal single circuit line, latticed steel towers (see Fig. 6):**

basic span : s = **1100 [ft] = 335 [m]**
$h_t =$ **90.5 [ft] = 27.58 [m]**
$h_{GW} =$ **60.5 [ft] = 18.44 [m] (** $sag_{GW} = 30' = 9.14m$ @ $40^o C \cong 105^0 F$)
$b =$ **7 0 [ft] = 21.3 [m]**

It was installed an AFL- OPT-GW 30/38mm^2/496 ($d_{AW} = 3.1$ mm $d_{AL} = 3.1$ mm **)**

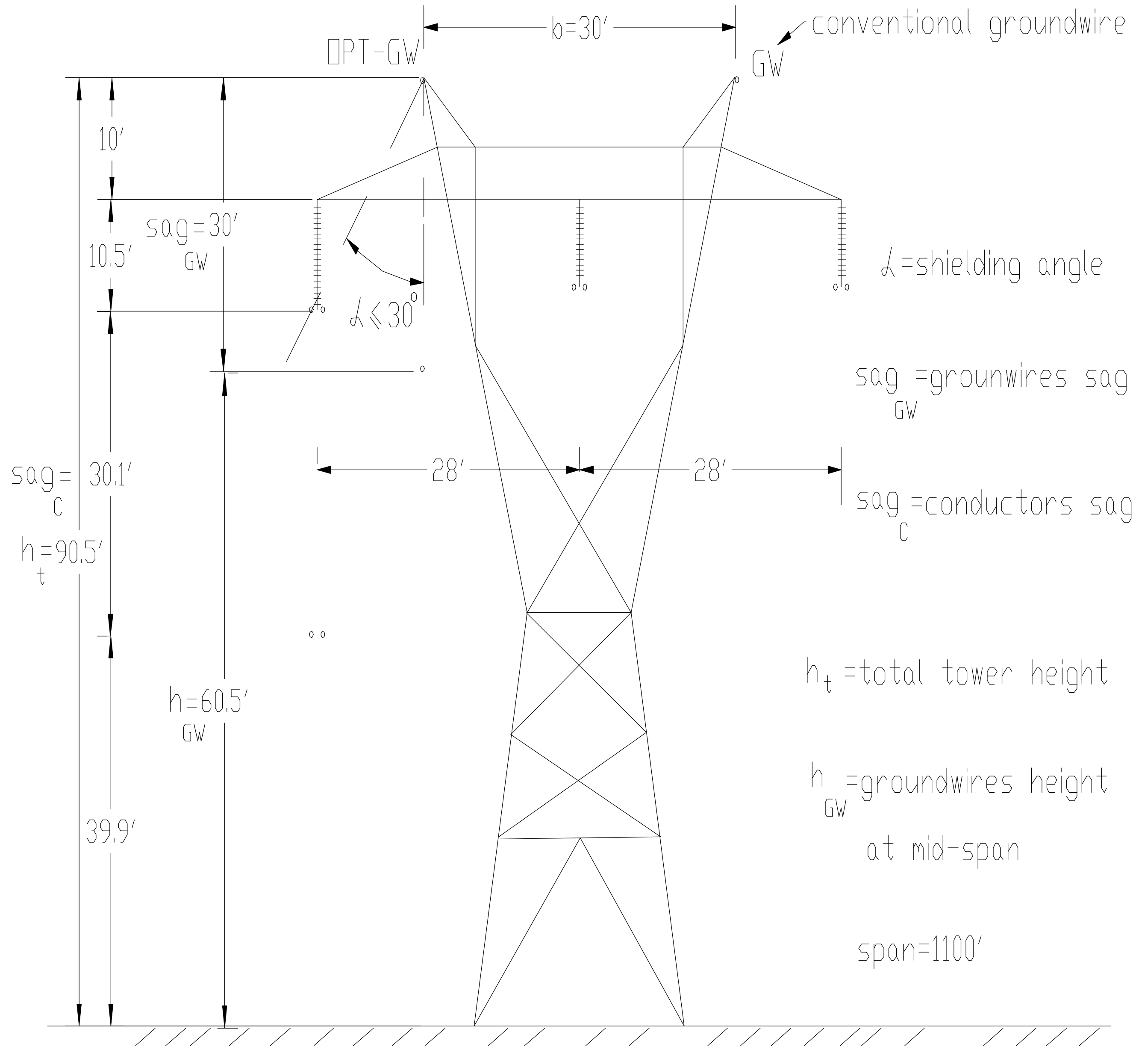


Fig.6 - Example of calculation for a 345 kV horizontal single circuit tower

Following the 3 steps previously presented in the algorithm results:

"Scenario"	I **[thunderstorm-days/year]**	N_L **[line strokes/ 100 miles / year]**	$N_{OPT-GW} = 0.6 \bullet N_L$ **[OPT-GW strokes/ 100 miles/ year]**	D_{OPT-GW} **[OPT-GW incidents/ 100miles/ year]**
Good	**30** (Nevada)	**44**	**26**	**0.3**
Worse	**100** (Florida)	**148**	**89**	**0.9**

Using the tables from pages 17, 18 and 19 , for the "worst duration scenario": $\boxed{t_C = 0.5\sec}$ **the maximum allowable values for a 3.1 mm wire diameter in order not to be broken, " burned through", would be:**

"Scenario"	D_{OPT-GW} **[incidents/ 100 miles/year]**	$Q_C(AW20.3\%)$ **[C]**	$Q_C(AW27\%)$ **[C]**	$Q_C(AlAlloy)$ **[C]**
Good	**0.3** (Nevada)	**22**	**25**	**14**
Worse	**0.9** (Florida)	**68**	**77**	**43**

"Scenario"	D_{OPT-GW} **[incidents/ 100 miles/year]**	$I_C(AW20.3\%)$ **[A]**	$I_C(AW27\%)$ **[A]**	$I_C(AlAlloy)$ **[A]**
Good	**0.3** (Nevada)	**44**	**50**	**28**
Worse	**0.9** (Florida)	**136**	**154**	**86**

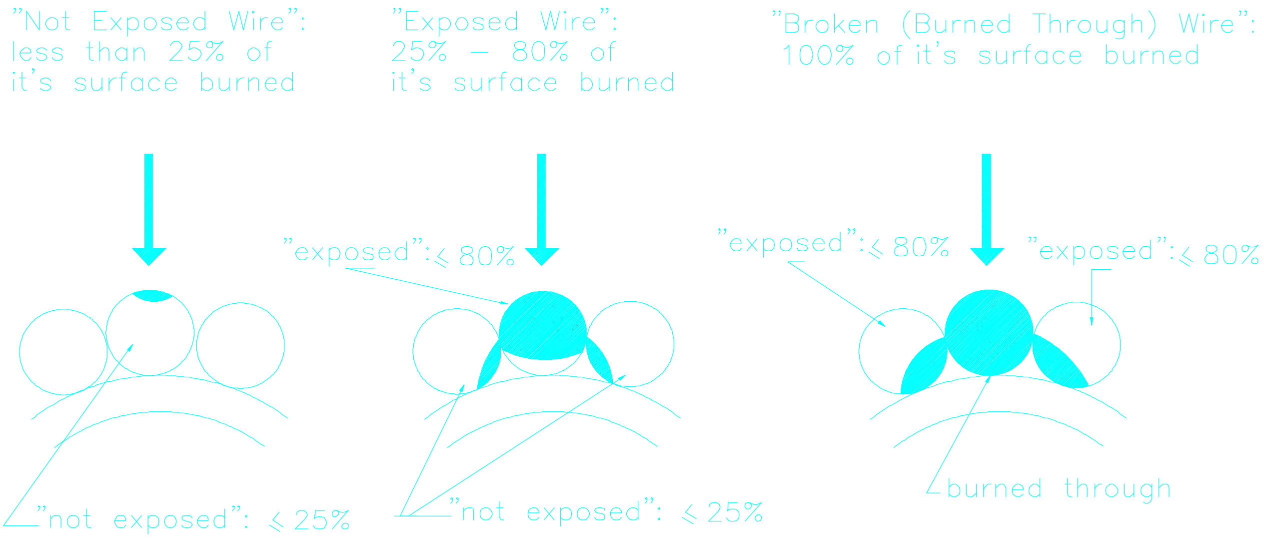
3. Test Procedure:

- The **initial** temperature of the OPT-GW shall be set at **40^o C** before the current pulse application. Between each application , the OPT-GW **must** be **cooled** down to this temperature.
  Note: from the initial temperature of the cable point of view is better to take the" worst scenario" that means to expect to be equal with the maximum ambient temperature when lightning strokes might occur.
- The lightning simulation tests : **5 hits** , are carried out on the same OPT-GW sample, **but not** necessary at the **same place** on the OPT-GW. In real field lightning strike conditions, the contact spot, as a rule, moves along the wire during discharge. It lowers the damaging effect of lightning.
- The minimum length of the OPT-GW sample should be **10** m , with the performing spot on the **mid-point** of this length.
- The minimum fiber length under test should be **100** m.
- All the **4 components**: **A, B, C, D** of the test will have **negative polarity**, with **no oscillation form.**
- The **rise time** of component : **A** : $t_{r1} = 20ms$ and of component **D**: $t_{r2} = 10ms$.
- The **pulse length** of component : **A** : $t_{p1} = 200ms$ and of component D: $t_{p2} = 100ms$.
- The peak current amplitude will be different :
  - for component **A** : $I_{p1} = 100kA$
  - for component **D** : $I_{p2} = 50kA$.

- The **applied tensile load** on the sample OPT-GW shall be **15%-25% R.B.S.** (Rated Breaking Strength) , a value **closer** to the real field conditions at EDS (Every Day Stress).
- **Fiber attenuation** shall be measured using a power meter connected to either end of the test fiber.
- The iron rod tip diameter =[1....2] mm ; the fuse wire diameter =[50....100] *mm* ; the gap distance between the iron rod and the OPT-GW cable should be [25.....40] mm.
- After each hit, the destroyed fuse wire will be replaced with a new one.

4. Test Pass/ Fail Expectations:

- AFL will calculate **the remnant strength** of the cable based on the number of **broken ("burned through")** strands. **Attached** will be calculation of the **reduced strength** of the cable versus **number** and **type** (AW 20.3%, AW 27% or AlAlloy) of **broken wires**.
- The cable is expected to have at least 75% of it's rated breaking strength after each test (hit).
- The **Test Failure** will be considered **only** if the **remnant strength** of the **cable** is less than **75% R.B.S, and not the fact that 1 or more wires are broken !**
- **Armor rods** will be used to **repair** the cable if there are 1 to 4 broken wires.
- **Only** the **broken** (**" burned through"**) wires will be taken into consideration for **reducing** the OPT-GW cable rated breaking strength (R.B.S.), and not the " exposed" wires (see Fig. 7):
    - " Not exposed wire" = less than 25% of it's surface burned
    - " Exposed wire" = 25%-80% of it's surface burned.
    - "Broken wire" =" Burned through wire" = 100% of it's surface burned.



- **Aluminum pipe** may be burned, but **not burned through** .
- Measured **temporary** change in **attenuation**: $\Delta a \le 0.5 \quad dB/km$ @ 1550 nm.

Optical Measurements Proposals (for the temporary change in attenuation) :

- $0.1ms$ sampling cycle duration (considering the shortest event $\approx 1ms$ and 10 samples for it), synchronized to trigger @ -0.2 sec. offset .

- minimum sample rate = $10 Megasamples / \sec$, synchronized to trigger.
- ideal sample rate = $100 Megasamples / \sec$, synchronized to trigger.
- Total test duration = $200ms + 5ms + 0.5s + 100ms = 0.5053s$

  ↓ ↓ ↓ ↓

  components: A B C D

- Total sampling duration = Total test duration + $0.4s = 0.9053s$
- Data package ≈ 600 $kbyte$
- recommend: ≤ 0.002 dB uncertainty @ $100 Megasamples / \sec$ sample rate.
- recommend: 0.01 dB resolution @ $100 Megasamples / \sec$ sample rate.
- suggest: ≥ 50 dB dynamic range.

- due to the fact that maybe only one fiber might be affected , we suggest to connect :
  - ■ all fibers for fiber counts : 1x8, 1x12, 3x8, 3x12, 4x8 and 4x12
  - ■ 4 fibers/unit for fiber counts: 7x8+1x12 and 8x12

Note 1: The lab would need two anchors with a capacity of 3 tons each, located at appropriate spread to accommodate sample, hardware and tensiometer.

Note 2: Discharge lead must be moveable along cable axis or , better, anchors and apparatus must be moveable to enable using a "fresh" spot for each hit. Recommended distance between the spots where the iron rod (the discharge) will hit the cable : 80 cm.

Note 3: For the Electrical System :

- ■ must know timing uncertainty.
- ■ must use $0.1ms$ resolution minimum.
- ■ must know under or over shoot values.

- Measured **long term** change in **attenuation**: $\Delta a = 0.$ dB/km @ 1550 nm.

5. Laboratory Tests:

AFL tested two OPT-GW cables for a foreign customer: the Polish Power Grid Company (PPGC) / World Bank Contract. These two types of OPT-GW cables, purchased by the Polish customer for a 220 kV d.c. had the following main characteristics:

1) OPT-GW 30/38 mm^2 /496:

Al Alloy strands no./ diameter [mm]	4 / 3.10
Al Clad Steel strands (AW 20.3 %) no./ diameter [mm]	5 / 3.10
O.D. OPT-GW [mm]	12.6
Breaking Load (including strength of the AL pipe) [kgf]	5865
Actual Fiber Count	12

2) OPT-GW 14/37 mm^2/443:

Al Alloy strands no./ diameter [mm]	3 / 2.42
Al Clad Steel strands (AW 20.3 %) no./ diameter [mm]	8 / 2.42
O.D. OPT-GW [mm]	11.24
Breaking Load (including strength of the AL pipe) [kgf]	5251
Actual Fiber Count	12

The test set up was identical to the one presented in this paper, with the following parameters:

- **iron rod tip diameter = 1 mm ; fuse wire diameter = 50** mm
- **gap distance between iron rod and the OPT-GW cable = 40 mm**
- **test tensile load = 20 % R.B.S.**
- **the iron rod (electrode) and it’s adjacent apparatus was mounted on a moveable bench, to enable using a “ new fresh” spot for each new hit, after each hit the table was moving, distance between each hit being about 80 cm.**
- **It was performed only components A ,B, C. Anyway, component D (the re-stroke) would had been added a very small charge, about 2.5 C, so it wouldn’t influence too much the total charge transfer and our calculations regarding the cable thermal capacity. This component D would have been important for indirect effects like: electric and magnetic field strength, but there were no measurements regarding these indirect phenomena.**

For the OPT-GW cable 30/38 mm^2 **/496 the parameters values (for the last 2 hits , with the biggest charge transfer) were:**

Hit No.	**Component**	**Parameters**	**Total Charge Q_T [C]**	**Conclusions after the tests**
1	**A** R=2.727 $m\Omega$ V=284 V	rise time: $t_{r1} = 12ms$ pulse length: $t_{p1} = 320ms$ Amplitude: $I_{p1} = 104kA$ Charge: $Q_A = 9C$	$Q_T = Q_A + Q_B + Q_C =$ $= 9 + 4.2 + 82.5 = 95.7C$	Only about 40% of the diameter of the hit strands were melted. No "burned through" wires noticed. Al Pipe not affected. Measured temporary change in attenuation $\Delta a \leq 0.4dB/km$ $@1550nm$. Measured long term change in attenuation: $\Delta a \leq 0dB/km$ $@1550nm$
	B C=1.2 mF V=3.5 kV	time: $t_T = 5.6ms$ Average Current: $I_T = 750A$ Charge: $Q_B = 4.2C$		
	C C=33 mF V=2.5 kV	time: $t_C = 0.6s$ Current: $I_C = 137.5A$ Charge: $Q_C = 82.5C$		
2	**A** R=2.727 $m\Omega$ V=284 V	rise time: $t_{r1} = 16ms$ pulse length: $t_{p1} = 310ms$ Amplitude: $I_{p1} = 103kA$ Charge: $Q_A = 8.8C$	$Q_T = Q_A + Q_B + Q_C =$ $= 8.8 + 4.2 + 94 = 107C$	Only about 50% of the diameter of the hit strands were melted. No "burned through" wires noticed. Al Pipe not affected. Measured temporary change in attenuation $\Delta a \leq 0.4dB/km$ $@1550nm$ Measured long term change in attenuation: $\Delta a \leq 0dB/km$ $@1550nm$
	B C=1.2 mF V=3.5 kV	time: $t_T = 5.5ms$ Average Current: $I_T = 764A$ Charge: $Q_B = 4.2C$		
	C C=33 mF V=2.86 kV	time: $t_C = 0.56s$ Current: $I_C = 168A$ Charge: $Q_C = 94C$		

So the test that **was performed in Poland proved** that an AW 20.3% wire with a diameter =3.1 mm **withstands a total charge** of $Q_T = 95.7 \quad C$ without being "burned through" (broken).This value is very close to the value AFL established using the algorithm previously presented. The **algorithm** gives a **total allowable charge** for this 3.1 mm wire diameter of AW 20.3 %:

$$\boxed{Q_T = Q_A + Q_B + Q_C + Q_D = 10 + 5 + 76 + 2.5 = 93.5 \quad C}$$

Note: $Q_C = 76 \quad C$ **you can find in the table from page 17 (the continuing component, the most important one).**

6. Conclusions:

- The lightning current impulses ,**without constant constituent**, causes formation of rather large (up to 100 mm^2) erosion spot on wire surface. As a rule , erosion spreads over 3 adjacent wires and assumes the form of surface melting.
- Form of erosion considerably changes under lightning current impulses **with constant constituent** In this step, according to the tests that have been done [3], discharge sticks to one of strands of the outer layer. Erosion takes the form of a crater. **Craters can be found both inside the contact spot and outside it.** Distance between craters can be up to 5 cm. Numbers of craters, their depth of melting and area vary in a random manner. Sometimes a continuous erosion path can be observed, resulted obviously from uninterrupted movement of a contact spot along one of the outer strands. Movement of a contact spot under current constant constituent could be caused by several factors: magnetic forces, aerodynamic streams (which arise from shock-wave split [3]) ,thin layer of oil that covers the wire, etc.
- The **AFL test** will simulate the **heaviest incidence** happening in nature, when lightning discharge **sticks** to a **single point** on the wire surface. In real conditions such occurrences are extremely rare. The lightning spot trends to move along the wire , lowering the discharge effect.
- So, for this OPT-GW ($d_{AL} = d_{AW20.3\%} = 3.10 \quad mm$) resulted :

Maximum allowable total charge transfer not to have " burned through " wires	
THEORETICAL - AFL ALGORITHM	**LAB TEST in Poland** (Institute of Plasma Physics and Laser Microfusion)
93.5 C	**95.7 C**

Therefore this **AFL Algorithm** could be **used in future projects**, for other customers (each one with different OPT-GW design, different Overhead Transmission Line design, different AW / AL strands diameter, different isokeraunic levels, spans, type and geometry of towers, etc.) **to establish** the total **charge value** for which the OPT-GW will be tested.

7. References:

[1] "Draft IEC 1396 : Electrical mechanical and physical requirements and test method of optical ground wires"- July 1996

[2] "EHV Transmission Line Reference Book"- EPRI, 1983, Chapter 8

[3] " Effects of artificial lightning on overhead ground wires" - Martin A. Uman, Lightning Location and Protection, Inc., Gainesville, Florida, April, 1980

[4] "IEEE Design Guide for improving the Lightning Performance of Transmission Lines"- IEEE P1243, October 1992

[5] "Technical Report on Certification Tests of OPT-GW 24 SM 125 mm^2/662 "H" manufactured by Alcoa Fujikura Ltd- USA"- ORGRES, Ministry of Fuel and Power of Russian Federation, Moscow 1993

[6] "Travel Time of Transmission Towers" - Chisholm, W.A. , IEEE, Vol. PAS-104, No. 10, October 1985

[7] " Dielectric Phenomena in High-Voltage Engineering" - F. W. Peek, Jr., 1955

[8] " CEMIG- Mexico Test Reports on 27/42 mm2/ 555 Alloy/AW OPT-GW manufactured by Alcoa Fujikura Ltd." - August 1995

[9] " Analysis of Lightning & Environmental performance of Overhead DC Transmission Lines" - Gary C. Thomann, Power technologies, Inc., September 1994

[10] " IEEE Standard for Calculating the Current -Temperature Relationship of Bare Overhead Conductors"- IEEE Std. 738 - 1993

[11] K. Berger :"Messungen und Resultate der Blitzforsching der Jahre 1955-1963, auf dem Monte San Salvatore", Bull. Schewiz. Electrotech. Ver. , Volume 56: 2-22 , 1965

[12] J.H. Hagenguth and J.G.Anderson : " Lightning to the Empire State Building" , AIEE Transactions , Volume 71, Part 3, pp.641-649, 1952