

Arc tracking energy balance for copper and aluminum aeronautic cables

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Abstract. Arc tracking tests have been carried out between two voluntarily damaged aeronautic cables. Copper or aluminum conductors have been exposed to short circuits under alternating current. Various data have been recorded (arc voltage and current, radiated power and ablated mass), enabling to determine a power balance, in which every contribution is estimated. The total power is mainly transferred to the cables (between 50 and 65%, depending on the current and the cable type), and causes the melting and partial vaporization of the metallic core and insulating material, or is conducted or radiated. The other part is deposited into the arc column, being either radiated, convected or conducted.

1. Introduction

Fault arcs occurring in aeronautic electrical circuits may lead to significant electrical harnesses damages and should be eliminated or at least controlled to limit their consequences. In particular, short circuits occurring between two adjacent cables may lead to a particular phenomenon called “arc tracking” [1,2] corresponding to the propagation of the arc along the cables due to the cable metallic core ablation and to the surrounding dielectric material degradation. In traditional aircrafts, one solution consists in using copper cables with appropriate insulating material mainly composed of polytetrafluoroethylene (PTFE), a fluorocarbon polymer. New airplane concept introduces two strong constraints: lowering of weight and increase of the electrical power. The consequences of these constraints are the partial or total replacement of copper with aluminum in the cables, the increase of alternating current (AC), the strong increase of direct current (DC) parts and DC buses in the electrical circuit, and the replacement of metal by composite materials in the structure. These changes require the problem of electric arcs and arc tracking to be carefully considered again.

The present study aims to quantify the power transfers from the tracking arc to the environment in AC circuit at atmospheric pressure. It should be noted that there are very few academic works dedicated to the study of arc tracking. This lack of published data concerning the arc tracking phenomenon is associated to the difficulty to characterize the arc due its very unstable behavior. In the present work, arc tracking tests are carried out between two aeronautic cables (each one connected to a phase of the AC circuit) following a specific procedure, and the main objective is to evaluate the various terms of power, based on several experimental measurements (current, voltage, radiated flux and mass loss) and on some theoretical analysis. The total power is calculated, as well as the power transferred to the cables (by means of the electrode voltage fall). The part causing the melting and vaporization of the cables is estimated, considering a total melting and a partial vaporization of the ablated matter, and then the power lost by conduction and radiation of the cables is inferred. Another part of the initial input power is transferred to the arc column. The radiated power of the plasma is then estimated, considering that the Vacuum Ultra Violet is absorbed in the very first microns of air, and the power lost by convection and conduction in the plasma is inferred.



2. Experimental setup

2.1. Material

The setup presented in Figure 1 was developed to create a fault arc between two cables for an adjustable period of time (from 10 ms to 10 s). The AC power supply, manufactured by Puissance Plus, has been specially developed for this study. It can be used in single-phase or two-phase (with 120 degrees phase shift) configuration and current is adjustable up to 350 A rms. The phase-to-neutral voltage can also be set, the maximum value being 230 V rms (400 V phase-to-phase). Then the frequency can be chosen between 380 and 800 Hz with a 2 Hz resolution.

The characteristics of the tested cables are given in Table 1. The first one is mainly made of aluminum (Cable 1) while the second one is mainly made of copper (Cable 2). Due to copper higher conductivity a smaller diameter for the later has been chosen (10 instead of 8 in the American Wire Gauge system) in order to get the same nominal current.

Type	AWG	Main material	Nominal current	Insulating layer thickness (mm)	Diameter of the metallic core	Mass proportion of metal
Cable 1	8	Aluminum	35 A	0.25	3.26 mm	81 %
Cable 2	10	Copper	35 A	0.25	2.59 mm	91 %
Cable 3	10		35 A	0.62	2.59 mm	75 %

Table 1. Characteristics of the various tested cable types.

For both cables the insulating material (polyimide layer wrapped with a sheath of PTFE) has a thickness of 0.25 mm. In order to study the effect of this parameter a third cable, similar to Cable 2 but with a 0.62 mm insulating layer thickness has been tested. All tests were performed with the association of two similar cable samples.

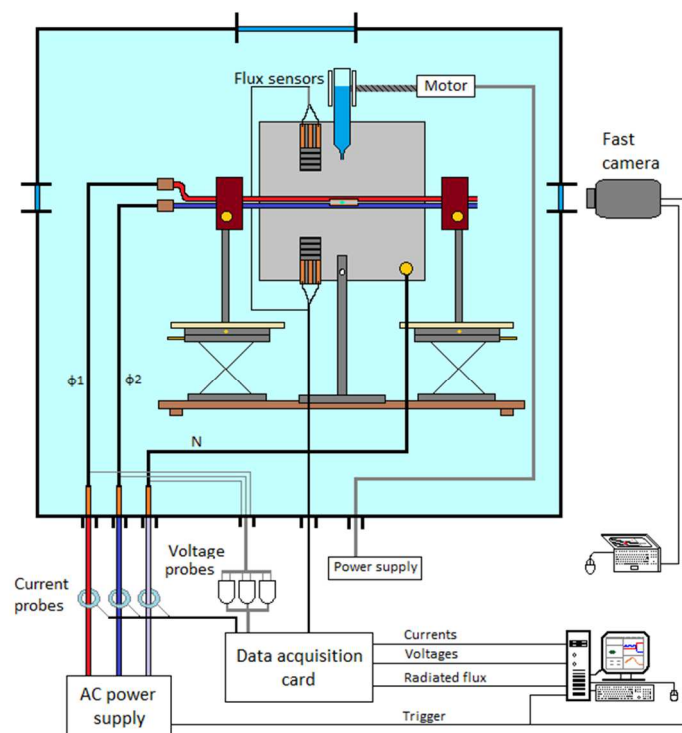


Figure 1. Experimental setup.

A specific procedure has been developed to cause arc ignition. For each experiment, the insulating sheath wrapping the metal core is partially stripped (one half of the cable circumference, for a length of 1 to 2 cm) on each cables. Then the two cables are bond together so that the two stripped areas are close to contact. Particular attention must be paid to this: if the contact between the two bare metal parts is too good there is just a short circuit, but no arc and if the spacing is too large ignition is not possible. The optimal distance is close to 1 mm. In the case of Cable 3 the sum of the thickness of the two insulating layers is about 1.2 mm and the distance is adjusted through deformation of the metal core (which is not solid, but constituted of small wires bundles). The insulating adhesive tape that bonds the cables is placed close to the striped area to avoid separation of the cables during the arc lifetime, due to electromagnetic force. The very erratic behavior of the arc can indeed lead to early arc extinction that is unwanted for our study and a tight cable holding is a good way to avoid this.

Each cable is connected to one phase. The ignition is facilitated with droplets of salted water (0.7% of NaCl) falling from a vial held above the stripped zone of the cables (this system works with a motor). The tests are carried out in a cylindrical chamber, at atmospheric pressure.

Tests in AC with a 230 V open-circuit phase-to-neutral voltage have been done for the three cable types (see Table 1) and for three current values: 175 A, 245 A, and 350 A. The frequency is 800 Hz. An aluminum plate (10cm × 10cm, 1.2 mm thick), representing the fuselage, is placed near the cables and connected to the neutral.

2.2. Measurements

Several kinds of measurements are done simultaneously: electrical measurements, radiation heat flux measurements and high speed imaging. The starting signal from the computer is used as a synchronization trigger for the power supply, the acquisition system (a National Instrument PXI 6221 board and an SCB 68 interface box) and the fast camera.

Electrical data are recorded for every test. The voltage between the two cables (connected to two different phases) is measured using DP-25 differential probes manufactured by Pintek. The voltage between each phase and the neutral (connected to the aluminum plate) is also measured with two additional similar probes. The current is measured in each phase and in the neutral using LF 505-S probes manufactured by LEM. Two heat flux sensors are placed around the cable samples along two perpendicular directions. They are positioned at a radial distance of 9.5 cm in a plane perpendicular to the cables axis, at the position where insulating sheath is removed. These sensors, manufactured by Captec, consist in thin strips of thermocouples (about 0.1 mm thick) arranged in a 1 square centimeter array. They deliver a voltage proportional to the heat input and are calibrated by the manufacturer so that the output voltage is proportional to the incoming radiated power. Each sensor is provided with its calibration data with a $10^{-3}\mu\text{V}$ accuracy (e.g. 1 W.m^{-2} corresponds to $0.485\mu\text{V}$). All radiation from Vacuum Ultra Violet (VUV) limit ($0.2\mu\text{m}$) up to far infrared ($12\mu\text{m}$) are integrated. The temporal response of these sensors is about 80 ms and while it is not possible to observe fast fluctuations the duration of the tests (500 to 1000 ms) is sufficient to reach a stable value corresponding to the average radiated power. Measurements with an arcing time lower than 100 ms are not taken into account and the plateau is generally reached in a few hundreds of milliseconds. The sensors have to be frequently replaced: they are damaged by strong arc radiation and impacts of molten metal from the cables and their performances drop after only a few experiments. High speed imaging is performed with a Phantom V9 camera positioned outside the chamber, perpendicularly to the direction of the arc propagation. The recording speed is 1000 frame/s. Finally, the cables are weighed (with an accuracy of 0.1 mg) before and after each test, in order to determine the mass loss.

Due to the high instability of the arc, extinction often happened before the end of the selected time. Thus, many similar experiments have to be performed to get usable results.

3. Power balance

The considered power balance is presented below in Figure 2.

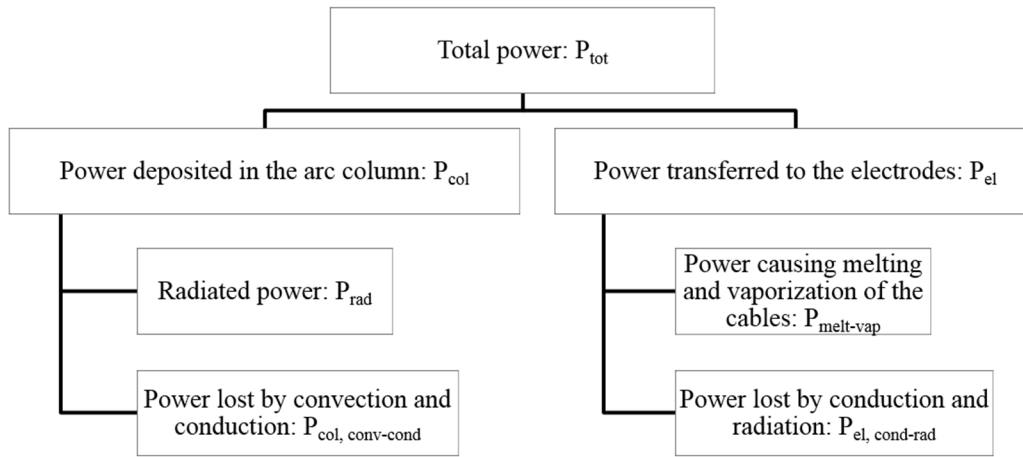


Figure 2. Power balance.

3.1. Total power

The electrical data recording allows calculating the total average power, as expressed in equation (1):

$$P_{tot} = \frac{1}{t_{arc}} \int u(t)i(t)dt \quad (1)$$

where t_{arc} is the arc duration. The voltage u (between the two phases) can be expressed as in equation (2):

$$u = U_{el} + u_c \quad (2),$$

where U_{el} is the electrode voltage fall (detailed below), and u_c is the arc column voltage. U_{el} is assumed to be not dependent on the current.

Part of this power P_{tot} is transferred to the cables constituting the electrodes, while the remaining part is deposited in the arc column.

3.2. Electrodes

The arc column voltage can be expressed as follows in equation (3):

$$u_c = E_c l \quad (3),$$

where E_c is the average electric field within the plasma column, and l is the length of the arc column. The combination of (2) and (3) yields to the following equation (4):

$$u = U_{el} + E_c l \quad (4)$$

We assume that E_c does depend neither on the current or the shape of the arc. Thus, the total voltage u is supposed to be a linear function of l . The extrapolation to a length equal to zero is used to get an estimation of the electrode voltage fall U_{el} . It yields to 18 V for copper cables, and 19 V for aluminum cables in the case of DC current as shown in figure 3. The accuracy of these values is rather low but they correspond quite well to values found in literature [2,3]. Similar measurements were performed in AC for the three tested currents, but the

method is less accurate due to the more unstable behavior of the arc, the orientation of the plasma plume changing every half period. Values between 15 and 25 V were obtained and considering the error margins it has been decided to use the values obtained in DC current, since no more accurate data were found in literature concerning voltage fall in AC current.

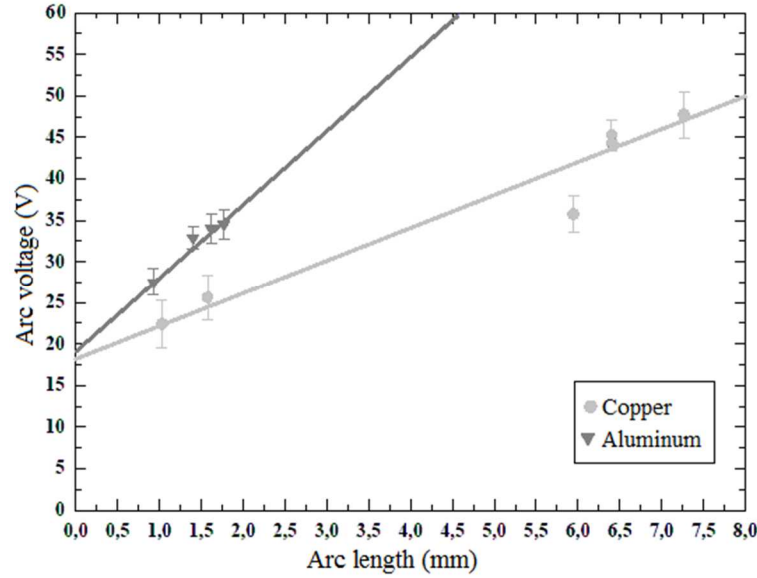


Figure 3. Determination of electrode voltage fall for copper and aluminum cables (DC current: 100 A). The solid lines correspond to liner fit of data.

We can then calculate the total average power P_{el} transferred to the electrodes, by multiplying the electrode voltage fall by the root mean square value of the current I_{RMS} (equation (5):

$$P_{el} = U_{el} \cdot I_{RMS} \quad (5)$$

Part of this power causes metal melting and vaporization, and can be expressed as in equation (6):

$$E_{metal} = E_{melt} + E_{vap} \quad (6),$$

where E_{melt} is the energy required for the melting of the metal, and E_{vap} is the energy required for its vaporization. It is clear that all the ablated metal is melted but only a small part is vaporized. These two energies can be expressed as in the following equations (7) and (8):

$$E_{melt} = m \cdot L_{melt} + \int_{T_{sol}}^{T_{melt}} m \cdot C_{sol}(T) \cdot dT \quad (7)$$

$$E_{vap} = m \cdot L_{vap} + \int_{T_{melt}}^{T_{vap}} m \cdot C_{liq}(T) \cdot dT = m \cdot L_{vap} + m \cdot C_{liq}(T_{vap} - T_{melt}) \quad (8),$$

where T_{sol} , T_{melt} , and T_{vap} are the solid initial, melting and vaporizing temperatures, respectively; L_{melt} and L_{vap} are the latent heats of melting and vaporization respectively, C_{sol} and C_{liq} are the heat capacities at solid and liquid state, respectively, and m is the ablated metal mass (about 1 g for a 500 ms test at 244 A). C_{sol} varies with temperature, but C_{liq} remains constant [4]. Table 2 summarizes the thermodynamic data used to calculate the energy required for melting and vaporizing copper and aluminum. For better clarity, the energy per mass unit (in $J \cdot g^{-1}$) to heat the solid material from ambient temperature (300 K) to melting temperature is given instead of solid heat capacity (in $J \cdot g^{-1} \cdot K^{-1}$). Only a small part of the ejected metal is vaporized, but the exact proportion is

unknown. Considering an analogy with plasma processes involving transient electric arcs and partial vaporization of electrodes (such as low voltage circuit breaker or lightning impact [5]), we assume that the amount of molten matter actually vaporized is 1%.

The insulating material ablation should also be taken into account. Since it is mostly composed of PTFE, we choose the value of 2.6 kJ/g for the heating, melting and evaporation of the ablated cable mass corresponding to the insulating material [6].

	Copper	Aluminum
Melting point (K)	1358	933
Boiling point (K)	2843	2791
Melting latent heat (J/g)	205	400
Boiling latent heat (J/g)	4725	10875
Energy for heating solid (J/g)	467	667
Liquid heat capacity (J.g ⁻¹ .K ⁻¹)	0.517	1.177
Energy required for melting (kJ/g)	0.7	1.1
Total energy required for melting and vaporization (kJ/g)	6.2	14.1

Table 2. Thermodynamic data of copper and aluminum.

For those thermodynamic calculations, the mass proportion of metal and insulating material are taken into account. The power $P_{el,cond-rad}$, which is transferred to the cables but not involved in melting and vaporization, is lost by conduction and radiation. It is calculated as follows in equation (9):

$$P_{el,cond-rad} = P_{el} - P_{melt-vap} \quad (9),$$

where $P_{melt-vap}$ is the power causing melting and partial vaporization of the cables.

3.3. Arc column

The total power P_{col} deposited in the arc column is calculated by subtracting the power transferred to the cables from the total power. Part of this power is radiated. The power flux measured by the flux sensors yields to the total radiated power assuming that the arc is punctual and by integrating the power density (assuming that it derives only from the arc column) over the surface of the sphere of radius equal to the average distance from the arc to the sensor (here 9.5 cm). The assumption of a punctual source is rather good considering the size of the plasma (around 1-3 mm). The obtained signal is converted according to the sensors calibration so that we get directly the radiated power as a function of time. The average radiated power P_{rad} can then be expressed as follows in equation (10):

$$P_{rad} = 4\pi d^2 P_{meas} \quad (10)$$

where d is the distance between the arc and the sensors, and P_{meas} is the average value given by the flux sensors. It can be either the average value of the two sensors if the responses are close to one another, or only the one which gives the highest values (one of the two sensors could be partially hidden by a cable), over the period where the value of measured radiated power reaches a plateau.

Since the experiments have been performed in air at atmospheric pressure, all the radiation with a wavelength lower than 200 nm (called Vacuum Ultra Violet or VUV radiation) is absorbed in the ambient air within a few microns, mainly because of photodissociation and photoionization of oxygen molecules. Due to these phenomena, the radiation measured by our sensors (located a few cm from the arc) does not include the VUV part of the radiation directly emitted by the arc. Since this part is far from being negligible (it could be equal or even greatly higher than non-VUV radiation) it is mandatory to get information on this contribution. Total

removal of oxygen is difficult to achieve (even by filling the chamber with nitrogen, the gas will still contain some oxygen as impurities). Moreover, even for the non-VUV part the uncertainties associated to radiation flux measurement (see figure 6) are quite high. Then the calculation of the Net Emission Coefficient (NEC) [7,8] appears to be a good complementary approach to determine the total radiated power that allows getting VUV contribution and comparing non-VUV contribution to measurements. The NEC is computed as the divergence of the total radiation flux at the center of an isothermal sphere of radius R_p (power per volume unit and per solid angle unit). Radiation power is integrated over a large range of photon energy corresponding to the wavelength range from 30 nm to 5 μm . Two examples (99% air + 1% Cu or 1% Al) are presented in Figure 4, showing the variation of the total NEC and the partial NEC (i.e. for $\lambda > 200$ nm, which does not include the VUV part) for a plasma radius $R_p = 2\text{mm}$ as a function of temperature. In our case one can assume that the mean temperature in the core of the plasma is close to 15 000 K, by comparison to thermal plasmas in similar conditions such as encountered in low voltage circuit breakers [9]. The results show that for both materials the total NEC is similar ($\sim 3.0^9 \text{ W.m}^{-3}.\text{sr}^{-1}$ at 15000 K), as seen in figure 4. However the contribution of the non-VUV part is not the same: while it is 30 % for copper it is only 15 % in the case of aluminum. However this strong predominance of VUV radiation has little impact on our energy balance: even if the VUV radiation is not directly measured by the flux sensors, it is indirectly taken into account in the other power terms. Indeed, the power absorbed by oxygen molecules (VUV radiation) is either emitted again in the visible light or in the infrared radiation range (so it is detected by the flux sensors), or lost by convection and conduction (heating of the gas and of the plasma, which is also considered in our balance). All our determination of radiated energy (by mean of heat flux sensors or by calculation) have to be considered carefully since they present quite large uncertainties (due to the simplifying assumptions considered for calculation and to sensor noise level for measurements, see figure 6).

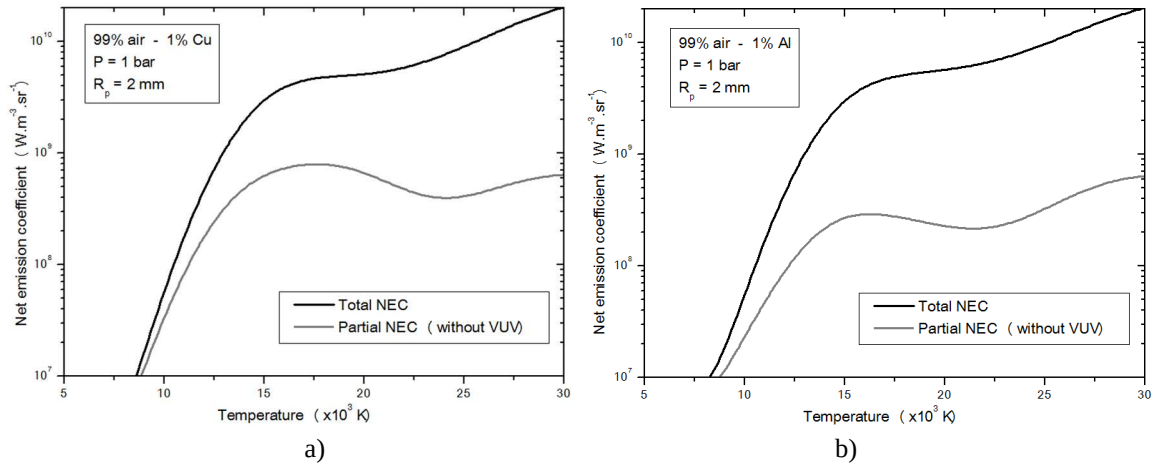


Figure 4. Comparison between the NEC and the partial NEC (without VUV) for mixtures of 99% air and a) 1% Cu, b) 1% Al (mass proportions), and for a 2mm R_p (plasma radius).

Another part of the power transferred to the arc column is lost by convection and conduction. This power, $P_{col,conv-cond}$ dissipated in the arc column is inferred by subtraction as follows in equation (11):

$$P_{col,conv-cond} = P_{col} - P_{rad} \quad (11)$$

4. Results and discussion

Table 3 presents a synthesis of the power balance for the considered cables and currents. The results for each case correspond to an average of several tests (at least 10) realized in these conditions. The uncertainties given for erosion rate (in g/s), erosion speed (in g/cm, calculated from the erosion rate by considering the linear mass) and the associated power $P_{melt-vap}$ arise from statistical dispersion of the results on mass loss measurement. The uncertainties concerning total power P_{tot} and the power at the electrodes P_{el} (10 to 15%) result from the

uncertainties associated to voltage fall measurement. The uncertainties for $P_{el,cond-rad}$, P_{col} and $P_{col,conv-cond}$ do not appear in Table 3, since these values are not experimental data but the results of subtraction on the other terms. Concerning the radiated power P_{rad} , the value of 1300 W has been used for all cases. This choice is based on power flux measurement and calculation (see below). Both methods lead to quite high uncertainty but the combination of the two allows estimating it to about 20% and since the difference between copper and aluminum is low it was not relevant to consider it. Most of the total power (P_{tot}) is transferred to the electrodes (part corresponding to P_{el}) but this proportion decreases with current, from 65% at 174 A to 53% at 350 A in the case of cable 1. It is larger for copper than for aluminum (65% and 56% for cable 1 and 2, respectively) at 244 A but there is almost no difference at higher current. Since they are based on the electrical measurements, which present good accuracy and time resolution, the total average power and the power transferred to the electrodes seem to be the most reliable calculated results. The erosion speed increases with current and is greater for copper than for aluminum. However the use of a thicker insulating layers (cable 3) notably reduces it.

Cable	I rms (A)	Erosion rate (g/s)	Erosion speed (cm/s)	P_{tot} (W)	P_{el} (W)	$P_{melt-vap}$ (W)	$P_{el,cond-rad}$ (W)	P_{col} (W)	P_{rad} (W)	$P_{col,conv-cond}$ (W)
Cable 1	174	0,9±0.3	2.31± 0.8	5099±750	3306±330	1318±439	1988	1793	1300	493
Cable 1		1,5±0.2	3.85± 0.5	7630±900	4636±460	2196±293	2440	2994	1300	1694
Cable 2	244	2,1±0.5	4.20± 1	6738±1000	4392±440	1881±447	2511	2346	1300	1046
Cable 3		2,1±0.2	3.39± 0.3	7898±400	4392±440	2510±239	1882	3506	1300	2206
Cable 1		2,3±0.3	5.90± 0.8	12502±1100	6650±670	3367±439	3283	5852	1300	4552
Cable 2	350	3,2±0.3	6.40± 0.6	11501±1000	6300±630	2866±269	3434	5201	1300	3901
Cable 3		3,3±0.3	5.32± 0.5	12246±1100	6300±630	3944±356	2356	5946	1300	4646

Table 3. Power balance

The electrical measurements give information not only on voltage and intensity, but also on the occurrence of discharge and on the potential transfer of the arc to the aluminum plate. In Figure 5, a typical case is presented. In a first step (from 0.25 up to 0.4 s) the arc occurs between the cables, so there is no current in the neutral, and the voltage between each phase and the neutral is equal to the open circuit phase-to-neutral voltage (i.e. around 325 V peak value). In a second step (from 0.4 up to 0.55 s), the arc transfers to the aluminum plate, so the current in the neutral suddenly grows to a non-zero value, and the voltage between each phase and the neutral drops during the transfer time. Then the transfer stops (from 0.55 up to 0.75 s) and the arc occurs again only between the cables. The total duration of the test is 0.5 second.

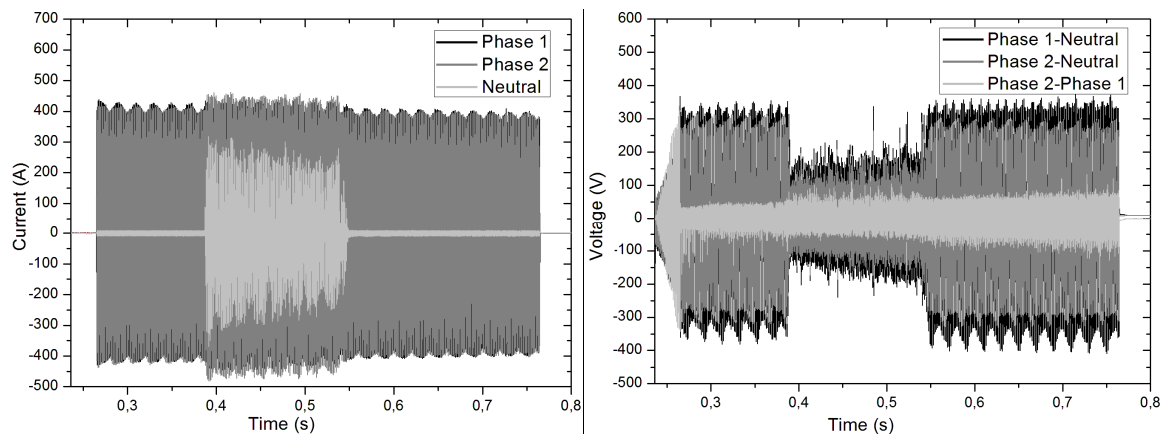


Figure 5. Electrical data from a test on an aluminum cable with a 350A current input. The power transfer of the arc to the aluminum plate can be noticed between around 0.4 and 0.55 s.

About half of the power transferred to the cables corresponds to the power needed to cause their melting and partial vaporization. This proportion increases with current (from 40% at 174 A to 51 % at 350 A in the case of aluminum) and seems to be higher for aluminum than for copper (47% and 43%, respectively, at 244 A). This result is obtained assuming that the same proportion of metal (1%) is vaporized for both cable. However the larger fume production in the case of copper cables might be related to higher metal vaporization rate, which means that the proportion is underestimated in the case of copper. In the case of a large insulating layer (cable 3) the part corresponding to cable ablation becomes dominant, especially at high current. We observe very often that molten metal droplets remain on the cables and solidify. These droplets are not taken into account in the ablated mass measurement, so the power causing the melting of the corresponding amount of metal is missing in the balance.

The data given by the flux sensors do not exhibit a real influence of the current and the type of cable on the radiated power. As an example the radiated flux for cable 1 at 174 A and for cable 2 at 244 A are given in figure 6. In both cases the flux is measured at about 10500 W/m², which corresponds to a power of 1200 W. The horizontal light grey line represents the considered value, corresponding to the average between sensors 1 and 2 at the plateau indicating stable configuration.

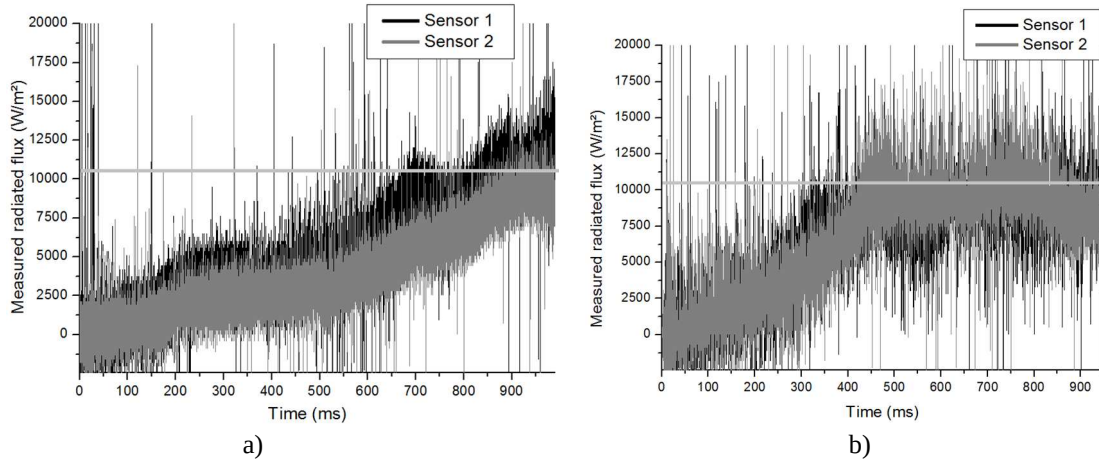


Figure 6. Measured radiated flux: a) cable 1 (aluminum) at 174 A; b) cable 2 (copper) at 244 A.

These results were compared to the estimation provided by the NEC. Considering that the plasma radius R_p is equal to 2 mm, the height of the arc $h = 3$ mm, that the mean temperature of the plasma core is approximately 15000 K, and that the plasma consists in 99% air and 1% Cu or 1% Al (thus the NEC ε_N is around $3.10^9 \text{ W.m}^{-3}\text{sr}^{-1}$), we obtain:

$$P_{rad,calc} = 4 \cdot \pi^2 \cdot R_p^2 \cdot h \cdot \varepsilon_N \approx 1400 \text{ W} \quad (12)$$

Then even if the signal from heat flux sensors is rather noisy and erratic both results are compatible and the average value of 1300 W used in Table 3 seems to be a reasonable approximation. The proportion of the power deposited in the arc column corresponding to radiated power decreases with current and is larger for copper than for aluminum. The use of thicker insulating sheath strongly decreases the ratio at 244 A. At high current the differences between the three cables reduce and the ratio does not exceed 25%, while at 174 A it is greater than 70% for aluminum. For the tests involving cables 1 samples, we can observe a white sheath at the surface of the projected metal droplets, which could be alumina Al_2O_3 . As the reaction of oxidation of aluminum is highly exothermic, this phenomenon could modify the power balance, but it is difficult to estimate this additional input of energy.

5. Conclusion and perspectives

Short-circuit tests of arc tracking have been performed between two aeronautic cable samples, in copper or aluminum under alternating current and at atmospheric conditions. A power balance has been realized, which shows that about half of the total power is transferred to the cables, causing their degradation (melting and partial vaporization of the metallic core and degradation of the insulating material). This proportion is greater for aluminum than for copper but in the latter case it might be underestimated, since stronger vaporization seems to occur in the case of copper cables. Besides, since the erosion speed is lower, for the same input energy the length of damaged cable will be smaller in the case of aluminum. One can also note that the use of a thicker insulating layer helps reducing the damages, since for similar energy transferred to the electrodes for cable 2 and cable 3 the erosion speed is lower for cable 3. In addition, the fact that a larger part of energy is associated to cable degradation (greater quantity of insulating material) means that there is less energy available to cause other damages, such as on the surrounding structure. This power deposited in the electrodes can be divided into two parts, the main one corresponding to the melting and vaporization of the cables and the other being lost in material (heat conduction losses in the cables and thermal radiation). Another part of total input power is deposited in the arc column, where it is either radiated, or lost by convection or conduction. The power emitted in the VUV range is not received by the flux sensors, as it is immediately absorbed, but it is taken into account in the balance, because it is either reemitted (at greater wavelength: near IR mainly) or involved in plasma heating. A next step will consist in performing the same tests under reduced pressure (0.1 bar), to represent an aeronautic configuration in a better way (cruise altitude) and investigate the behavior of the arc in such conditions. Moreover, the current energy balance does not take into account the effect of any chemical reaction. In particular the oxidation of aluminum is a very exothermic reaction leading to possibly non negligible additional energy input. Further work will be dedicated to the study of formation of alumina and the influence of the oxidizing nature of the plasma forming gas (tests in pure nitrogen).

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