# Lightning Discharge Heating of Aircraft Skins

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**A comprehensive study has been conducted, for the first time, to determine the maximum temperature expected at the back surface of a metal skin when lightning strikes to an airfoil. The ignition temperature of jet fuel vapor (~1320° C) can be exceeded at the interior surface with thicknesses of titanium which might be structurally proper. The minimum thickness of titanium sheet which may be safely used as a skin which is the wall of a fuel tank was tentatively established. That, with aluminum, safety from this lightning hazard is obtained with sheets of 0.080-in. thickness has been established by practical experience, but the margin of safety has been unknown. It now has been evaluated approximately. The study required consideration of the maximum time a lightning terminal spot will remain at one location, the maximum anticipated current which will flow throughout the period of discharge terminal fixation, the energy transfer from the arc discharge to the metal and the ohmic heating in the metal, and finally of the transient heat flow problem with the combined heat sources. In obtaining practical results, approximate analysis was combined with simplified laboratory tests.**

## I. Problem

THE temperature to which titanium (Ti) skin metal may rise at the terminal of a lightning discharge to an aircraft is of serious concern when a single sheet constitutes the outer wall of a fuel tank. Of particular interest is the maximum anticipated temperature of the back surface. Jet fuel vapors may ignite if exposed to a hot-spot temperature of about 1320°C for even a small number of milliseconds.[1] Titanium has a higher melting point of 1700°C. The heating can be particularly severe with Ti because of its low thermal and electrical conductivities.

This potential for explosion has not been considered a problem when an aluminum (Al) skin was used, because the thermal and electrical conductivities of Al are high and also the structural requirements dictated a thick skin (compared to a Ti skin), i.e., 2.0 mm (0.080 in.), or greater. While there appears to be no evidence that a lightning strike has caused the explosion of a fuel tank with a 2.0 mm Al wall,[2] no analysis existed to show the margin of safety. In supersonic airplane design it has become necessary to know the minimum thickness of Ti sheet which will assure safety.

## II. Fundamentals

The area on the metal receiving the discharge current will be referred to as the arc cathode or anode spot. Considering a simple Ti sheet of specified thickness, the temperature prediction study involved obtaining answers to four major questions. First, will the spot (anode or cathode) successively relocate during the total lightning flash? Second, if the spots do change locations, what will be the maximum time either spot will remain fixed at any one location? Third, for the most severe condition, what flow of current shall be assumed during the period the spot remained fixed? Finally, with these questions answered, what time will be required to reach a specified maximum temperature at the back surface of the sheet? An answer to each of these questions has been obtained.

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In heavy-current short-arc research, it has been well established that there is a very strong tendency for a spot of either polarity to remain in a fixed location, even in a strong air blast, when the spot surface metal is boiling.[3]

However, the results of the first wind-tunnel tests[4] made for the writer's company with relatively long arc discharges offer strong promise that a terminal spot will never remain fixed on an airfoil surface in flight, except at a trailing edge. In these limited initial tests, neither terminal remained in one location on either Ti or Al for longer than 5 msec. This time will be spoken of as a sticking time.

Attention was concentrated primarily on the heating under the anode spot. The reason for this was, in part, that on a high melting temperature material such as Ti the surface of an anode spot will be at a higher temperature than that of a cathode spot.[5] Further, the anode spot will have the greater tendency to stay fixed when the surface is boiling.[6] Also, the anode heating is the easier to analyze since the anode spot current density and, as a consequence, its surface temperature are roughly constant over a wide range of current magnitudes.[6,7] Even with large amplitude lightning strokes, it is judged very unlikely that the current density might possibly be much larger during an initial period of time long enough to be of any consequence in this heating problem.

A pessimistic evaluation further considers that, with constant current density, when the discharge current decreases the essentially circular anode spot not only becomes smaller, but decreases concentrically with respect to its original center. Therefore, some small central area will be heated throughout the period the spot remains fixed. It is primarily the heating of the Ti metal under this small central area that will determine the maximum hot-spot temperature on the back surface.

The conservative assumption must be made that in addition to the repeated large short-duration stroke currents, there will be a continuous flow of current between strokes. The current flowing at the end of the sticking time will define the size of the central area which will be heated continuously as long as the spot stays fixed. The magnitude of the current at the end of the sticking period and the time current has been flowing are the cardinal matters. The maximum stroke current is apparently of minor importance since, with the relatively extremely short duration larger currents (to the first-order approximation) simply a larger spot area is covered—with the larger radii areas covered for only a rela-

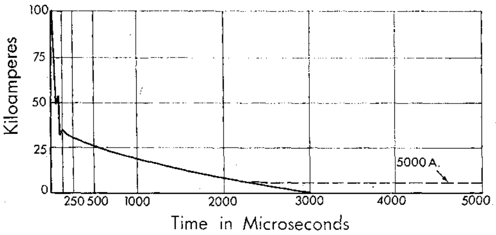


**Fig. 1 Representative lightning stroke derived from recorded data (Ref. 8).**

tively brief time (refer to the current vs time characteristic of Fig. 1). The low thermal conductivity of Ti prevents the central area from having its temperature affected much by the heating in the surrounding area of the spot.

An analysis of the heating must include both the diffusion of heat from the high-temperature spot surface and the ohmic (joule) heating due to the current flowing in the metal. In principle, the simultaneous heating due to these sources can be calculated. However, even the transfer of heat from the arc to the surface is in need of further study. The three-dimensional problem of heat generation and flow within the finite thickness sheet is in itself very complicated. Though the problem is being attacked by others, as yet no complete mathematical analysis exists. To give guidance to our thinking and planning of tests, and to a limited degree, to analyze the experimental data, some simple approximate calculations have been carried out by the writer.

## III. Characteristics of Lightning Flashes

By a lightning flash is meant the total discharge. The discharge usually consists of a number of short-time high-current strokes. Most often in the time intervals between strokes, there is a very much smaller continuing current of a few hundred to some thousands of amperes.

The current vs time characteristics of lightning strikes to ground are sufficiently well known that probabilities as to the shape, magnitude, and duration can be stated.[8] Progress is being made in measuring the characteristics of lightning strikes to aircraft,[9] but the amount of data obtained must still be considered as very limited. The writer assumes strikes to ground and cloud-to-cloud discharges equally severe. Aircraft may encounter either.

There are very few separate strokes with time intervals between strokes of less than 10 msec, or greater than 150 msec. The most frequent interval is 40 msec. The most frequent total duration of a discharge to ground is 0.25 sec, durations exceeding 1.0 sec being unusual. The typical current-time curve shape for a first stroke has been suggested[8] as reproduced in Fig. 1; but here all current magnitudes are shown as five times the typical value in order to represent a very severe stroke.

The magnitude of the continuing current is very variable. An actual record exists[10] of a discharge with an extremely large long-time flow of current, showing a maximum current through a 5-msec period of about 1200 amp; in another strike through a 2-msec period a 10,000-amp current has been recorded.[11] As a most pessimistic maximum value for design purposes, the writer assumes the current flowing at the end of the initial 5-msec period to be 5000 amp. A 5000-amp continuing current has been added as a dashed line to the stroke representation of Fig. 1.

## IV. Anode Surface Conditions

A well-documented analysis of the anode phenomena in arcs of high current and short duration has been made by Cobine and Burger.[7] They deduce that, to a first-order approximation, all the input power to the anode spot can be carried off by evaporation at some equilibrium temperature. For most metals, the anode spot surface rises to considerably above the boiling temperature. (The amount of heat flowing into the metal is small compared to the evaporation loss.)

Since the anode current density averaged over the spot area is found to be close to constant[6,7] for a wide range of currents, the surface temperature tends to be constant. This is an extremely important simplifying circumstance when the heat flow from the anode spot into the metal is to be considered.

Arc anode surface temperatures for Al and Ti are reproduced from Cobine and Burger in Table 1. Although the uncertainty in input power density was determined as about one order of magnitude, the uncertainty in temperature is only about ±300°K with Al and ±600°K with Ti.

## V. Motion of the Discharge Terminal

In this aircraft problem, a prime question is whether, or not, in air flows at aircraft speeds the terminal spots of a lightning discharge will somehow change their locations as the current decreases with time to the order of a few thousand amperes, the expected maximum value of the continuing current after about 5 msec.

Ordinary movement, i.e., the simple shifting of the location, of a spot is to be differentiated from a spot transfer, which will be considered in the next section.

As stated earlier, there exists a very strong tendency of the cathode and, in particular, of the anode spot to remain fixed when the surface is boiling. Ti has been found to be among the most difficult materials on which to cause the arc terminal to move.[6]

At present, there is general agreement among the experts in arc research that with heavy currents an air blast has essentially no effect and that, indeed, a strong transverse magnetic field must be employed to cause either arc terminal to move while appreciable current still flows. With a high-speed gas flow there is only a relatively low flow velocity very close to the surface. Since, at atmospheric pressure, the cathode (and anode) phenomena occur in the space extremely close to the surface ($<10^{-4}$ cm), the effect of the air blast in causing arc motion should be negligible. The situation is little different with airplane flight conditions at high altitudes.

## VI. Transfer of the Discharge Terminal

Investigators have sought correlation between the spacings of the markings on aircraft produced by lightning and the combination of the aircraft velocity and the time between strokes of a lightning flash; but correlation was not found because, as recent evidence now tells us, none should necessarily exist.

The discharge terminals should not, in the ordinary sense, move. But in the wind-tunnel tests, they did change location, leaving markings much like those produced in an actual strike to an aircraft—where the discharge terminal appears to have been swept across a surface.

By spot transfer is meant, as illustrated in Fig. 2, the stretching out of an arc originally struck at location A with the leading edge of the column coming close enough to the

**Table 1 Arc anode temperatures**

| Material | Boiling point, °K | Anode spot temperatures, °K Minima | Maxima | From experimental data |
|---|---|---|---|---|
| Ag | 2485 | 2390 | 2980 | 2880 |
| Al | 2600 | 2640 | 3320 | 3270 |
| Ti | 3550 | 3850 | 5040 | 5050 |
| W | 5950 | 6700 | (8300) | 7470 |

electrode to establish a new cathode or anode spot at some location B. When a new spot does establish, because the current is directed from the original spot, the resistance of the column between the old and new spots rapidly increases until that section of the discharge ceases to exist.

Cathode spot transfer does not occur under all conditions where it appears to have the opportunity. Consider the arcing horn of Fig. 3. Due to the initial action of heating of the air by the arc, the arc will bow upwards to take the dotted position. In general, the original terminal spots will not move. At the apparent new terminal points P of the bowed section, there can appear to be only a little burning, but this often is just a deposition of hot metal. We are confronted with the important question of under what conditions will the discharge terminals actually transfer.

A number of facts concerning the fixation, or sticking, and the transfer of anode and cathode spots have been established in the work of Winsor and Lee.[6] They forced arcs to move with high average velocities, through the utilization of high-intensity crossed magnetic fields. They saw clear exhibition of the formation of new spots and the extinction of the old ones, both at the anode and the cathode. They could not conclude whether the column had to actually make contact with the electrode or whether the voltage gradient simply reached the necessary value to cause breakdown. The anode and cathode spots jumped ahead randomly, apparently independent of each other, so that either spot could lead or lag the other, although both lagged the column. Again, these features were noted in the wind-tunnel tests. A new cathode spot was found much more difficult to establish than a new anode spot, causing the cathode spot to generally exhibit the longer sticking times.

The formation of a cathode spot on metal in contact with plasma is expected to occur with processes similar to the transition from a glow discharge to a cold arc. The formation of an anode spot on metal in contact with plasma appears to have not yet been discussed in any detail.

Forcing the column into close proximity of the electrodes is essential for arc transfer. But, also, experiments have shown that a high-current density facilitates the striking of an arc to a new cathode.[12] For example, in some circuit breakers the arc is moved by a magnetic field into a gradually narrowing slot in metal plates; when the current density is forced to a high enough value the arc transfers at once to the plates.

The likelihood of a spot transfer being induced increases not only with current but with gas pressure. The current density of the normal glow discharge increases as the square of the gas pressure; the energy input per unit area of the cathode or anode spot increases rapidly with pressure. The likelihood of spot transfer therefore appears to also increase rapidly with pressure. Conversely, then, the likelihood of transition is expected to be smaller at high flight altitudes.

Experiments have shown that the glow-arc transition time, hence the discharge terminal transfer time, will be somewhat dependent on the cleanliness of the metal surface.[6] The transition is more difficult to produce on clean than on oxided metals. In practice serious consideration of the effect of the metal surface condition or treatment on both anode and cathode spot transfer times appears merited.

The details of the interaction of the airflow with the section of the arc column between an old and a new spot, i.e., between locations A and B in Fig. 2, may be extremely important. First, the nature of the airflow in the immediate region seemingly should have a direct effect on whether the arc column is forced close enough to the metal surface to allow a new attachment. Secondly, the degree of local air turbulence can have a very large effect on increasing the resistance of the section of arc between the original spot and the potential new spot position; the mixing of cool air into the arc column plasma has a strong deionizing effect. If the resistance of the column between the two spot positions is increased the probability of the arc transferring must increase.

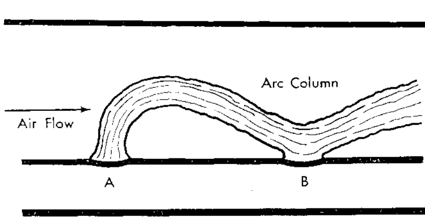

Fig. 2 Transfer of arc terminal in cross air blast.

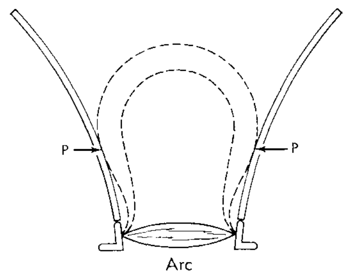

Fig. 3 Arc column distortion without spot transfer.

## VII. Wind-Tunnel Arc Terminal Spot Transfer Tests

Of first importance is the matter of how long the anode or cathode spot will remain at one location. Recent tests designed primarily by others† in our organization and executed elsewhere‡ showed that, with 25-cm long discharges having current magnitudes of 50–1600 amp in airflows of 155–230 mph, both the anode and cathode spots did transfer their location, on Ti, Al, or anodized Al, in times not longer than 5 msec. The maximum sticking time on Ti may have been as short as 3 msec. About 40 tests were made with variations in surface conditions as well as in current and airflow. Photographic records were obtained with 2500 frames/sec. Their limited data apparently constitute the only photographic recording of high-current arc spot transfers in high-speed aerodynamic flow.

## VIII. Approach for Solving the Heating Problem

The specific question to be answered was that of with what thickness of simple Ti sheet would the most severe lightning flash cause the maximum back surface temperature to just attain the critical value for initiating a jet fuel vapor explosion, taken tentatively as 1320°C. A reasonable answer to the problem can be obtained by steady-current tests in conjunction with approximate analysis.

The bases for the conditions of test have been stated in Sec. II. The duration of the current flow should equal the maximum expected sticking time between either anode or cathode spot transfers. The test current should have a magnitude equal to that of the most severe anticipated continuing current after a time of flow equal to the maximum expected sticking time. Pessimistic values of sticking time and maximum desired test current were taken as 5 msec and 5000 amp.

## IX. Laboratory Steady-Current Titanium Hot-Spot Tests

### A. Apparatus and Procedure

As a practical procedure, tests were made to find the length of the period of current flow necessary to just attain the critical temperature with different selected values of

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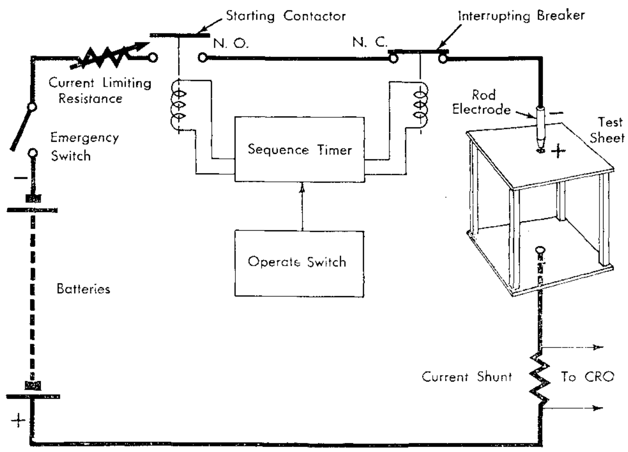


**Fig. 4 Circuit arrangement for steady-current tests.**

current, for sheets of different thicknesses. From the data, plotted as a family of curves, the minimum permissible sheet thickness became evident.

For testing with steady-current discharges, apparatus was set up with the circuit arrangement shown in Fig. 4. Normally, the test sheet was the anode. The cathode rod electrode had a blunted conical point. The electrode gap was normally 0.5 cm. Comparative tests with a 0.2-cm gap to 0.10-cm thick Ti revealed little difference in heating times. The discharge was started by shorting the gap with 0.02-cm-diam tungsten wire, emerging from a drilled hole on the axis of the electrode tip and continuing on the axis. With a carbon cathode, the anode spot formed and remained on the axis. The open-circuit battery voltage was about 120 v.

The maximum temperature attained at the back side of the test sheet under the center of the anode spot was determined by the use of Tempilaq temperature-indicating coatings. With a very thin coating, this material provided the temperature indication with a temperature persistence time of only 7 msec. The results were appropriate for comparison with the ignition temperature $\theta_c$ because the same method of measurement was used by others[1] in finding $\theta_c$ in explosion ignition tests with hot spot areas of similar size. For *a* typical hydrocarbon mixture, they found the time $t$ in msec required to reach $\theta_c$ (from room temperature) to be approximately

$$\log_{10} t = 1 + 5.4 \times 10^{-3}(1450 - \theta_c) \qquad (1)$$

over a range of $10 \leq t \leq 10^4$. Extrapolation to $t = 5$ msec gave $\theta_c = 1440°C$. The value $\theta_c = 1320°C$, used as a fix throughout our study for $t \leq 5$ msec, was selected to be a conservative value.

### B. Experimental Results

The maximum discharge current obtainable with our laboratory apparatus was 2900 amp; the minimum discharge time was 2.5 msec. For Ti test sheets of selected thicknesses $d$, the times $t_c$ to reach a back-surface critical temperature $\theta_c$ of 1320°C, as a function of discharge current $I$, are plotted in Fig. 5 as solid squares.

The empirical equation fitting quite closely all the experimental results of Fig. 5 has simply the form of a heat diffusion equation

$$I = 4.8 \times 10^2(d^2/t_c)(\text{cgs}) \qquad (2)$$

where $I$ is in amperes. The solid curves through the experimental points for Ti were all plotted from this single expression.

## X. Analysis of Heating at an Anode Spot

### A. General Considerations

The study of temperature calculations was limited to the determination of hot-spot temperatures at the back of single Ti sheets, with the heating due to the lightning discharge simulated by a steady current flow.

The methods of analyses have been documented in detail.[13] In this paper only brief comments are given regarding the procedures. Certain results which were obtained are presented in conjunction with the discussion of the experimental data.

The relative magnitudes of the contributions of the diffusion and ohmic heating processes vary with the discharge duration. With very short times, only a small amount of heat can diffuse into the metal because of the time limitation. Of real interest is the point that, even with extremely high currents, in the very short time a main lightning stroke exists even the sum of the diffusion heating and the ohmic heating will be small.

Well supported by experiment, the assumptions which follow greatly lessen the problem of analysis for Ti. 1) The anode spot current density (the average over the spot area) will be essentially constant over a wide range of current and can be taken as 50,000 amp/cm². (Essentially the lower of the limits found by Winsor and Lee[6] is taken because the Ti sheet to be used in aircraft is an alloy with about 6% Al; on Al the current density has the lower limit of 17,000–36,000 amp/cm².) 2) The anode spot surface temperature will be close to constant and can be taken as 4500°K or 4200°C. 3) The location of the discharge terminal i.e., the anode spot, will be stationary during the time period considered. 4) As the anode current changes, the circular anode spot will increase and decrease about a fixed center.

The electrical resistivity and the thermal properties have been taken as fixed in order to make the calculations tractable. The values used were arrived at from consideration of data[14] in the vicinity of 1500°C. These values were electrical resistivity $\rho = 1.8 \times 10^{-4}$ ohm-cm, thermal con-

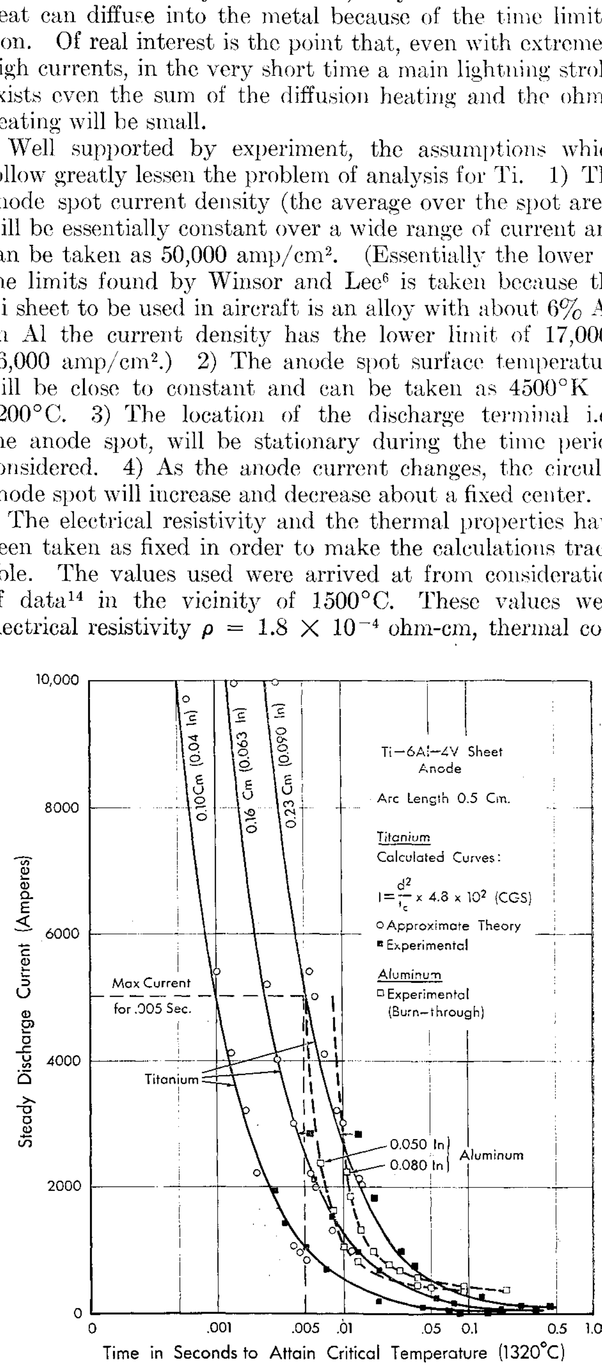


**Fig. 5 Time required to attain critical back-surface temperature with Ti. Solid curves are extrapolations for Ti by the empirical equation. Also shown is the experimentally determined time required to just cause a hole to be burned through an Al sheet.**

ductivity $k = 0.04$ cal/cm/°C, specific heat $c = 0.16$ cal °C/g, and density $\delta = 4.4$ g/cm$^3$, giving $\alpha = k/c\delta = 0.057$.

An initial question is whether or not the time required for the Ti anode surface to be raised to the temperature of 4500°K is appreciable compared to the time during which the heat input occurs. With an energy input rate of $3.0 \times 10^5$ joules/sec,[7] calculations[15] showed that the boiling point of 3550°K will be reached in 0.1 msec and 95% of the equilibrium temperature of 4500°K will be reached in about 0.6 msec. Therefore, the assumption of a 4500°K surface will be acceptable for approximate calculations for the shortest times of interest in this study.

The heat input from the anode spot surface by diffusion, the ohmic heat generation, and the temperature rise in the metal were determined by approximate analyses. (More precise future evaluations may very well differ greatly in detail.) These results, in conjunction with the test data, were helpful in creating an approximate picture of the physical situation and in obtaining estimates of the times to reach the critical back-side temperature—particularly for discharges of shorter times and larger currents than could be attained with our test apparatus. The combined approach permitted a reasonable appraisal of the heating to be expected with a lightning flash.

### B. Approximate Analysis with Negligible Ohmic Heating

With small continuing currents of less than a few hundred amperes and associated long times of 10–100 msec, the heating is primarily by diffusion from the anode spot surface. The ohmic heating can be neglected. Such a case could exist if, for instance, the discharge located at a trailing wing edge where the spot could remain fixed.

Since the longest times of interest in this paper are only of the order of 5 msec, the case of only diffusion heating from the anode spot will not be discussed. Readers interested in this case may find our approximate analytical treatment[13] of it to be of interest.

### C. Approximate Analysis with Diffusion and Ohmic Heating

Occasionally a continuing current of thousands of amperes is flowing at a time as long as 5 msec after the main surge of a stroke. Especially during the first few msec, ohmic heating may also be important.

A simple approximate calculation procedure considering both sources of heating yielded results numerically in good agreement with experiment for the short-time range of $0.5 < t < 5$ msec for Ti. This procedure has also been reported.[13]

Our simple, admittedly very crude, calculation procedures were arrived at after considerable study to gain insights as to relative magnitudes in physical processes. The total of the calculations were made with the same set of formulas with but a single empirical constant evaluated by matching calculated with the experimental values. One reason that useful results can be obtained by simple calculations in this very complex problem is that, because of the low thermal conductivity of Ti, during the short time there is a heat input the heat remains rather close to where it was generated. Therefore, for instance, in considering the heat flowing from the spot surface the problem may be treated, in part, as one with a sheet of infinite thickness. A second reason is that certain major errors can be largely compensating.

The time $t_c$ to attain $\theta_c$ with a particular assumed value of steady current $I$ was calculated for a range of currents and selected sheet thicknesses. In Fig. 5, circular points have been added to show the values of calculated $t_c$ for selected $I$ up to 10,000 amp.

## XI. Conclusions from Application of Results of Analyses and Laboratory Tests with Ti to Actual Lightning Flash Data

Referring to Fig. 5, it is reasonable to place moderate reliance on the extrapolation of the curves [plotted from the empirical Eq. (1)] to 5000 amp, in view of the good correlation between these curves, the short-time analysis points (circles), and the laboratory steady-current data (solid squares). The writer anticipates that higher current test points probably will show the current to rise even more rapidly at the shorter times than indicated by the curves.

Main lightning stroke surges, which may have a peak value in excess of 100,000 amp, by measurement have been found to last for not more than a few tenths of a msec; the very high surges generally have even shorter duration times. Because of these stroke characteristics and because the $I$ vs $t_c$ curves rise so rapidly, the main surge is not expected to be the determining current in this heating problem.

The lightning current which flows for as long as the tentative maximum sticking time of 5 msec is exceedingly unlikely to be as great as 5000 amp. The curves indicate that with this sticking time and current a 0.23-cm (0.090-in.) thick Ti sheet offers marginal safety. If the anode spot on a 0.23-cm sheet should remain fixed for less than 5.0 msec before transferring, it would be extremely improbable that $\theta_c$ would be attained—regardless of the lightning stroke current magnitudes at shorter times. This is true because at the shorter times the increase in current required to produce $\theta_c$, as time is decreased, is greater than the expected increase in actual lightning current. With our present data, the writer believes 0.23 cm is very reasonable minimum thickness to use as a fix in practice.

If the maximum sticking time with 5000 amp should be established to be only 3 msec, about the same degree of safety would be obtained with a 0.18-cm sheet. Assuming our analysis and test data are approximately correct, any less pessimistic assumptions as to the sticking time and the current flow during the sticking period would constitute a compromise on safety. The certainty of the answer is expected to be improved by others by the completion of a quite exact mathematical analysis of the heating in the metal under a stationary anode discharge terminal, by anticipated refined wind-tunnel arc spot-transfer tests, and perhaps through added knowledge of the cloud-to-cloud lightning flash current magnitudes.

## XII. Margin of Safety with an Aluminum Skin

It was stated earlier that there appears to be no evidence that a lightning strike has caused an explosion of a fuel tank with an Al wall 2.0 mm (0.080 in.) thick, but that the margin of safety was unknown. Since Al melts at <1320°C an explosion could occur immediately after a hole melted through the wall at a time $t_M$. In steady-current tests, $t_M$ vs $I$ data were obtained for Al sheets with thicknesses of 0.050 and 0.080 in. In Fig. 5, curves have been drawn through these test points, which are plotted as open squares. The test procedure was the same as with Ti, except that Al data were obtained with photoelectric detection of the burn-through time.

The reason for freedom from explosions with Al skins emerges. The curve of the current required for producing burn-through of 0.080-in. sheet rises almost vertically for spot sticking times of less than about 10 msec. If the maximum sticking time proves to be 5 msec, it is seen that even with 0.050 sheet burn through is very improbable. The margin of safety with 0.080 Al sheet accordingly appears quite large.

By a comparison of the experimental results, if the maximum sticking times are 5 msec, it can be concluded that for safety from a fuel vapor explosion a 0.050-in. Al sheet appears to be about equivalent to a 0.090-in. Ti sheet with a 5000-amp current, or to 0.075 in. with 3000 amp. If it can be quite definitely established that the spot fixation time on Al is never greater than 5 msec, the important conclusion can be reached that a 0.080-in. thick single-layer Al fuel tank skin is overly safe against lightning strikes.

## XIII. Recommendations for Further Experimental Work

To establish a more nearly final answer for Ti, it is recommended that the maximum time a discharge terminal (either anode or cathode) will remain at a fixed spot before transferring be investigated further. Tests are needed with each of the separate conditions of 1) the range of discharge currents to include larger values and 2) the air densities and degrees of turbulence at the airfoil surface to be approximately those which will exist at an altitude of 40,000 ft during travel at whatever planned flying speed will cause the lowest air density at the skin surface. The same extremes in the airflow conditions in the locale of the arc spot and immediate arc column as can exist in actual flight should be simulated. Surface condition, treatment, and irregularities should be parameters.

It is further recommended that the experimental work be extended to provide data for checking our results and those of forthcoming sophisticated analyses. Specifically, tests should be included in which a steady discharge of 5000 amp of 5-msec duration is caused to terminate 1) on 0.060- and 0.090-in. thick Ti sheets to determine if the critical temperature is attained at the back surface and 2) on 0.050- and 0.080-in. Al sheets to determine if burn through is attained with either.

Finally, to best establish confidence, or to dispute the findings of this study, a 0.060- and a 0.090-in. Ti sheet should be subjected (as both anode and cathode) to the highest surge current available (perhaps 200,000 amp) followed by a continuing current of about 5000 amp for a 5-msec total time duration—for a full-stroke check for possible attainment of the critical temperature.

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