The Effects of Atmospheric Conditions on Aircraft Radio Equipment

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ABSTRACT. The ranges of temperature, pressure and humidity likely to be experienced by aircraft radio equipment are given. Test chambers to reproduce these conditions in the laboratory are described. The general effects of changes of temperature, pressure, and humidity are then discussed, with particular reference to the problems of flash-over at high altitude across the surfaces of insulating materials together with flash-over between air-insulated conductors at high frequencies and high altitudes.

1—GENERAL

One of the most striking of the special conditions encountered by aircraft radio equipment is the extraordinarily rapid variations of temperature, pressure, and humidity to which it is subjected. The fuselage of an aircraft in a tropical climate at rest on the ground and exposed to the sun is likely to rise to a temperature of nearly 60°C, the pressure being approximately 30 in. of mercury and the humidity 95 per cent. In less than half an hour for civil aircraft, the conditions may have changed to a temperature below 0°C (for unheated parts of the aircraft), and to a pressure of 15 in. of mercury, while the humidity may be saturation, or may have dropped below 50 per cent, depending on the weather conditions. For military aircraft of the fighter type the changes are even more striking, as the ceiling is higher and the rate of climb much greater. Less than fifteen minutes could cause a drop in temperature of nearly 100°C and a reduction in pressure to less than 8 in. of mercury. Figure 1 shows the normal variation of temperature with altitude for Northern and Southern Australia (Lawrence, 1943), as well as the 'standard' variation specified by the International Commission for Air Navigation in 1920, together with sub-arctic winter conditions and tropical summer conditions. Figure 2 shows the variation of pressure with altitude for the two extreme conditions of tropical summer and arctic winter. Such rapid variations of temperature, pressure, and humidity produce at least four major effects on the radio equipment, namely :—

(i) Mechanical stresses due to expansion and contraction.

(ii) Changes in the electrical constants of the circuits due to effects such as temperature coefficient of resistance, temperature coefficient of dielectric constant, and changes in inductance and capacitance due to temperature coefficient of expansion causing changes in dimensions of inductors and capacitors.

(iii) Changes in insulation resistance and 'creepage' or surface corona due to the presence or absence of condensed moisture on the surface of insulating material together with reduction of atmospheric pressure.

(iv) Reduction of the voltage required to produce flash-over or corona between air-insulated conductors as the pressure falls.

Dealing with the above effects in more detail, the expansions and contractions caused by the extreme range of temperatures encountered is very liable to cause moving parts to 'seize.' Control switches, variable capacitors, variometers, relays and rotating machines in particular are liable to this trouble. Special attention must also be given to parts that

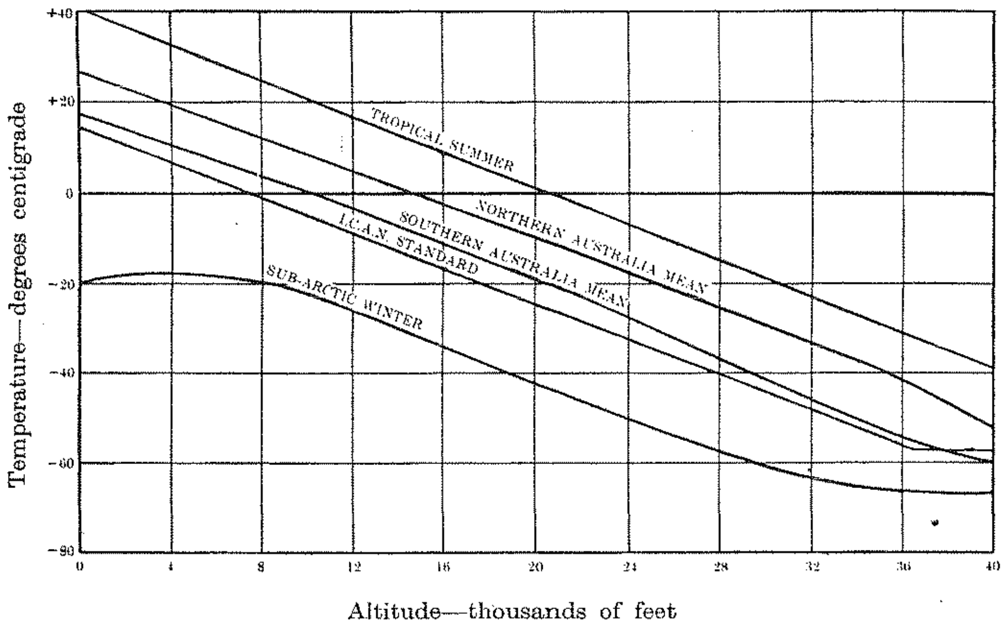

FIGURE 1—Variation of temperature with altitude.

are lubricated as the lubricant itself may freeze. In addition, mechanical fracture of insulating material caused by differential expansion or contraction, coupled with a tendency for some materials to crystallise at low temperatures means that the mechanical design of all components requires careful investigation from this angle. As regards changes in the electrical constants of the circuits caused by expansion of the materials, similar precautions regarding choice of materials and mechanical design of the components can largely offset this effect. In the same way, proper choice of components can do much to mitigate the changes experienced due to temperature-coefficient of resistance and dielectric constant, particularly in the latter case, by the use of negative temperature-coefficient capacitors to provide compensation (Bushby, 1943). It is also possible to do much by proper circuit design so that performance of the equipment is not critically dependent on absolute values of a large number of components.

Certain types of protective devices are not suitable for aircraft equipment due to the extreme temperature range, for example, low melting point fuses and also time-delay relays operated by the curvature of a compound strip heated by a resistance element. In both cases the ratings are liable to be considerably altered by the extreme changes of temperature and pressure. One condition that may be met is the case of equipment installed in a heated cabin so that only the pressure falls, the ambient temperature being practically unaltered. This will result in a greater reduction of rating of resistors and other components if they rely on air

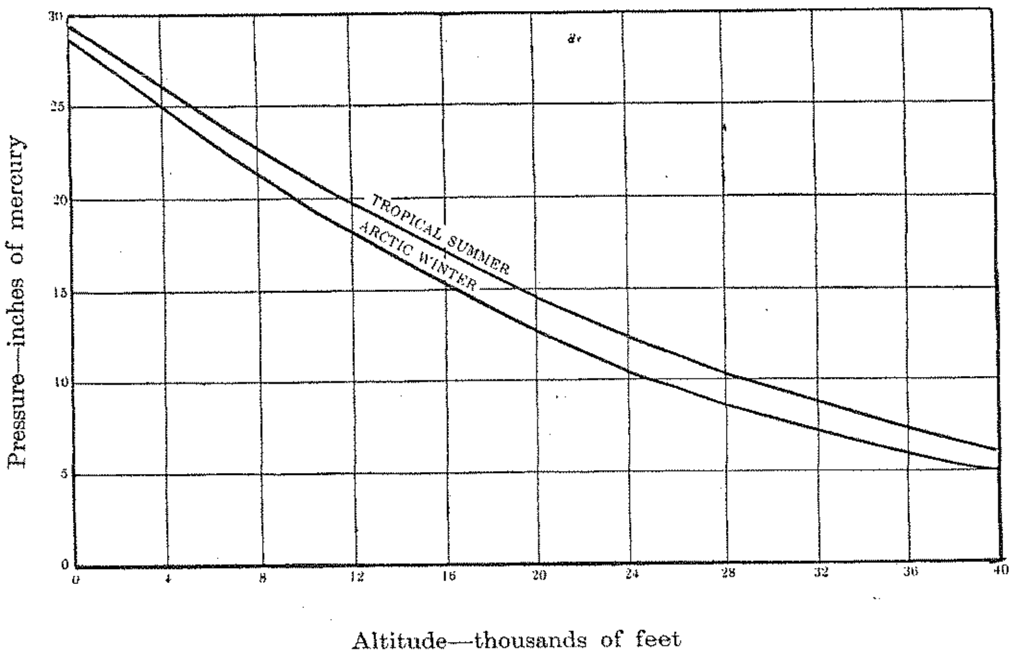

Figure 2—Variation of atmospheric pressure with altitude.

correction for cooling, since only the density of the cooling air will be reduced. Clark (1942) mentions that it is desirable to double, approximately, the ratings of resistors for altitudes of 30,000 feet even although the ambient temperature has fallen. He also states that batteries may be expected to function satisfactorily up to about 28,000 feet, but above this trouble may be expected.

2—TEST CHAMBERS FOR SIMULATING FLIGHT CONDITIONS

In order to simulate flight conditions in the laboratory it is necessary to provide suitable test chambers in which pressure, temperature, and humidity may be controlled over the range of conditions encountered. An analysis of the influence of extreme climatic conditions on radio equipment and components, together with methods of testing, has recently been given by Coursey (1944). The worst conditions likely to be experienced by the radio equipment in the aircraft seem to be the case of high ambient temperature and high relative humidity at normal atmospheric pressure, corresponding with a grounded aircraft in the tropics, and low atmospheric pressure and low temperature, corresponding to the aircraft in flight at high altitude. These two extremes are the usual ones cited in both civil aviation and military specifications, and some degree of uniformity is now to be found in the specifications in existence, although there are many differences in details. Some of the more important of the relevant publications include

(a) Information Circular 5/1940 issued by the Department of Civil Aviation, Australia (1940).
(b) Aircraft Radio Equipment Airworthiness, Manual 16, issued by Civil Aeronautics Administration, Department of Commerce, Washington, D.C. (1941).
(c) Wireless Telegraphy Board Specification No. K110, H.M. Stationery Office, London (1939).
(d) Interim Specification 101 issued by Standards Association of Australia (1944).
(e) Allied Services Radio and Signal Equipment Specification No. CL 1001B, issued by Inspection Division, Department of the Army, Australia (1944).

A generally accepted 'tropical' test for aircraft equipment is to submit the apparatus to an atmosphere of clear vapour maintained at 95 per cent relative humidity and + 50°C for a period of 48 hours, the equipment being operated intermittently during this time. Immediately upon removal from this atmosphere, the equipment is operated according to its ratings and after 4 hours, the receiving equipment shall have substantially recovered the sensitivity it possessed prior to the test, and the transmitter shall have regained its normal power output. No signs of corrosion or other deterioration is permitted. Another test is also well recognized and is known as the 'temperature' test. In this case the equipment, while not operating, is subjected to an ambient temperature of about + 55°C for sufficient time for all parts to reach this temperature, and is then operated at 20 per cent over-voltage for 12 volts and 24 volts d-c equipment and 10 per cent over-voltage for 115 volts a-c equipment, for one hour. It is then operated at 10 per cent below normal voltage to determine any deleterious effects of the above test. It is next subjected to an ambient temperature of $-40°C$ under the same conditions as for the high-temperature portion of the test, and is operated at $\pm$ 10 per cent of normal voltage and must show no defects. The remaining test is the low-pressure test, in which the equipment must operate at air pressures corresponding to 31 in. of mercury down to 8 in. of mercury. In some specifications the low-temperature and low-pressure conditions are combined into a single test; this combined condition is the more usual in practice and is likely to be more severe than the two single tests.

A number of special test chambers have been described in the literature, one example being that installed by the General Electric Co. (America) in 1937. This is briefly discussed in 'Communications,' (1937), and it is stated that facilities are provided for combined temperature, pressure and humidity control over large ranges of values. The testing of radio components for tropical conditions is discussed by Coursey (1942) and he describes suitable chambers and the relative merits of steam injection compared with evaporation from an open pan of water in the chamber. Our own experience agrees with Coursey in that the steam injection method is much more severe, and is also very difficult to control. Much more consistent and repeatable results have been obtained with the evaporation method than with steam injection. The use of steam bled from the normal factory heating service was not satisfactory due to impurities present in the vapour, mostly iron from the pipes, but even with steam from distilled water, fed through glass and rubber pipes, it is difficult to obtain as consistent results as with the evaporation method, probably due to much poorer control of the true conditions inside the chamber, supersaturation being the chief difficulty. Some test chambers are described by MacDonald (1943), but details of the methods of humidity control are not given; here again the tendency seems to be to combine the variation of all three variables, pressure, temperature, and humidity, in the one chamber. A more recent example of this is the very elaborate Vose Memorial Altitude Test Chamber installed by the Sperry Gyroscope Company ('Aero Digest,' 1944).

*The low-pressure low-temperature chamber used in the development and production testing of aircraft equipment designed by the writer consists of a well-lagged cylindrical vessel with domed ends, one of which is used as the door; an external view is shown in figure 3. A motor-driven pump is used to evacuate the chamber and a simple Bourdon pressure gauge (not visible in figure 3) indicates the pressure inside. Refrigeration

*The performance specification and procurement of the low-temperature chamber was the responsibility of Mr. A. J. Campbell, B.Sc., B.E., the chamber being supplied by Carrier Air Conditioning Ltd.

is obtained by the expansion of carbon dioxide through an expansion valve, the cooling pipes being coiled round the inside of the chamber as shown in figure 4. Both expansion and exhaust valve openings are controllable, and two pressure gauges indicate inlet and exhaust pressure. In the photograph of figure 3 can be seen two liquid thermometers inserted in the inlet and exhaust pipes. The operation of this chamber is somewhat difficult due to the tendency of the expansion valve to freeze up, the settings of the valves being fairly critical to prevent this. Since the photograph of figure 3 was taken, resistance thermometers have been inserted much closer to the valves, and additional ones are also used to measure the temperature of various parts of the chamber itself. Another difficulty experienced in the operation of the carbon dioxide refrigeration system is the deposition of liquid impurities from the CO_2 cylinders in the cooling pipes. The pipes require fairly frequent blowing out with steam to prevent choking up. Temperatures down to $-60°C$ at a chamber pressure of 7 in. of mercury are obtainable, the time taken to attain this degree of refrigeration in the chamber itself being half to one hour, depending on conditions. Generally, however, it takes a further 3—5 hours for the equipment under test to get down to $-40°C$ as the cooling is almost entirely dependent on radiation, and in most equipments the surface area is comparatively small, whereas the mass of metal inside the equipment case is frequently considerable. Usually, about 5 cylinders of CO_2 are required for one run. It seems that this system of refrigeration is not suitable for temperatures appreciably below $-40°C$, and for quicker refrigeration it would have been desirable to go to a mechanical system involving a compressor for the refrigerant and a circulating pump for circulation of a liquid coolant through the pipes in the chamber; the increase in capital cost would, however, have been appreciable.

Figure 4 shows a set-up for testing equipment, and includes a fan for circulating the air in the chamber, and remotely-controlled motors for performing various switching and tuning operations on the equipment during a run. Ample cable outlets are provided for electrical supplies to the equipment in the chamber and for illumination; inspection ports are also provided. One effect that is observed at the conclusion of a low-temperature low-pressure test is the very extensive deposition of frost on the equipment when outside air is admitted to the chamber. This provides a set of conditions somewhat similar to that experienced in an aircraft in diving from high altitudes, the rate of admission of the air determining the equivalent diving speed. Although this condition of rapidly changing pressure and temperature does not seem to appear in military specifications, it is interesting to observe the effect on the equipment. The installation shown in figure 4 inside the chamber, on one occasion at the end of a test, on the admission of air, became very heavily 'iced-up.' Most of the controls

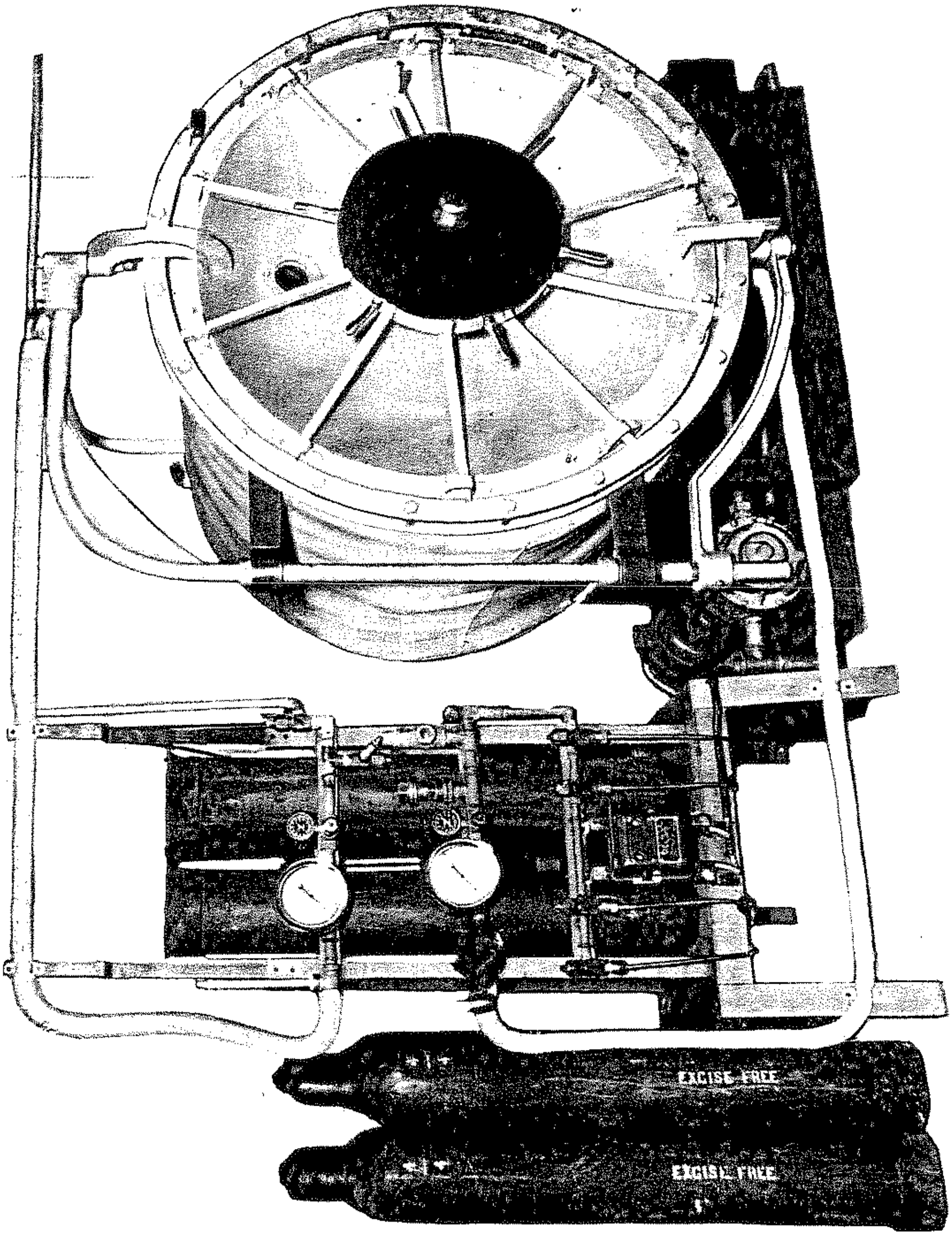

FIGURE 3—External view of low-temperature low-pressure test chamber.

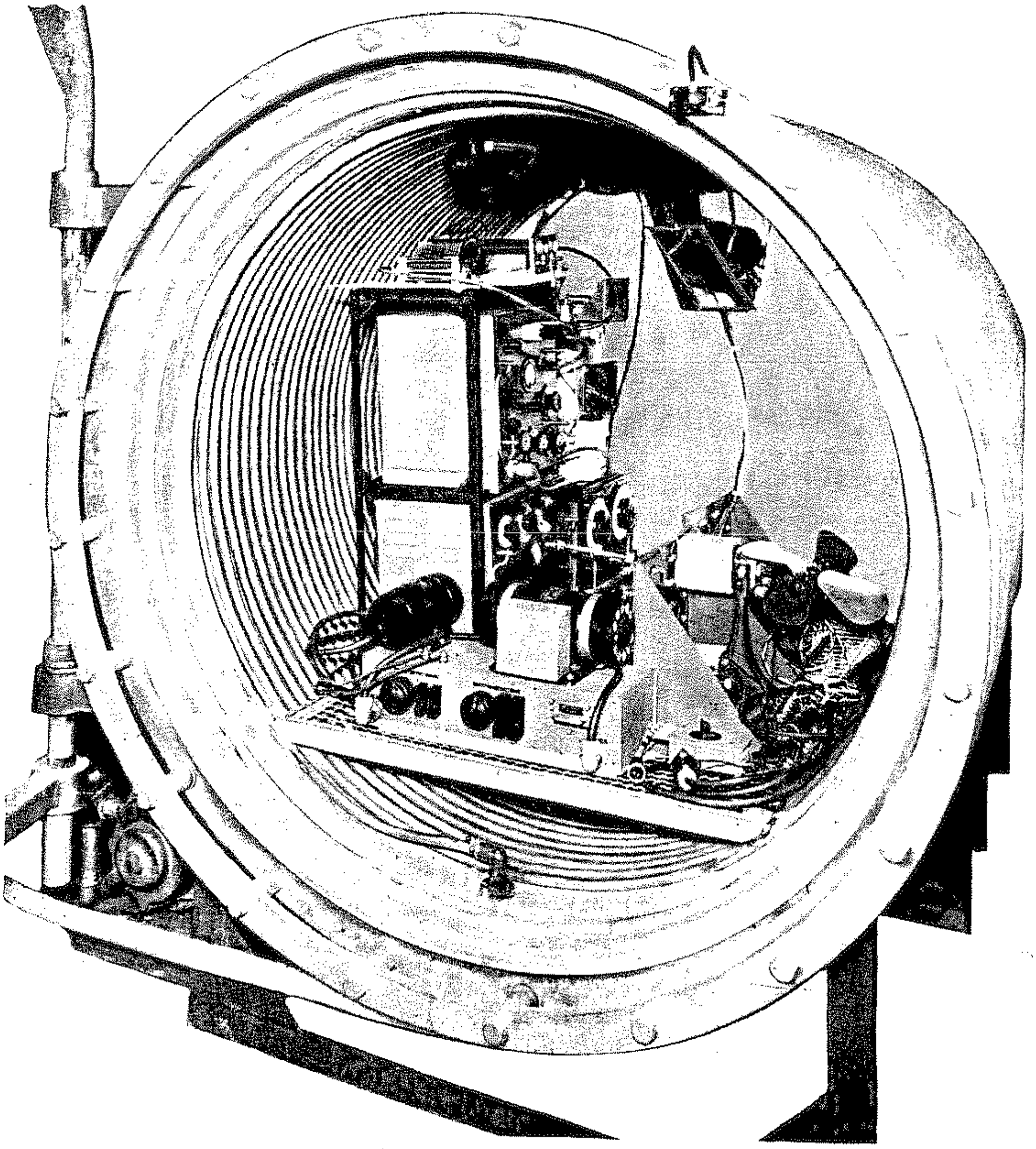

FIGURE 4—Internal view of low-temperature low-pressure test chamber.

were so covered in ice that they could not be moved, and the meters were frozen over so that they could not be read, but the transmitter and receiver continued to operate satisfactorily even under these extreme conditions. It is most unlikely that the inside cabin of an aircraft would ever approach such severe conditions although, as is well known, the exposed surfaces of aircraft do, in fact, frequently become heavily iced over.

3—Surface Creepage and Surface Flash-over.

Referring now to surface ' creepage ' and flash-over, it is clear that the rapid changes of temperature and pressure experienced in aircraft is liable to cause the condensation of moisture on insulating surfaces, and this,

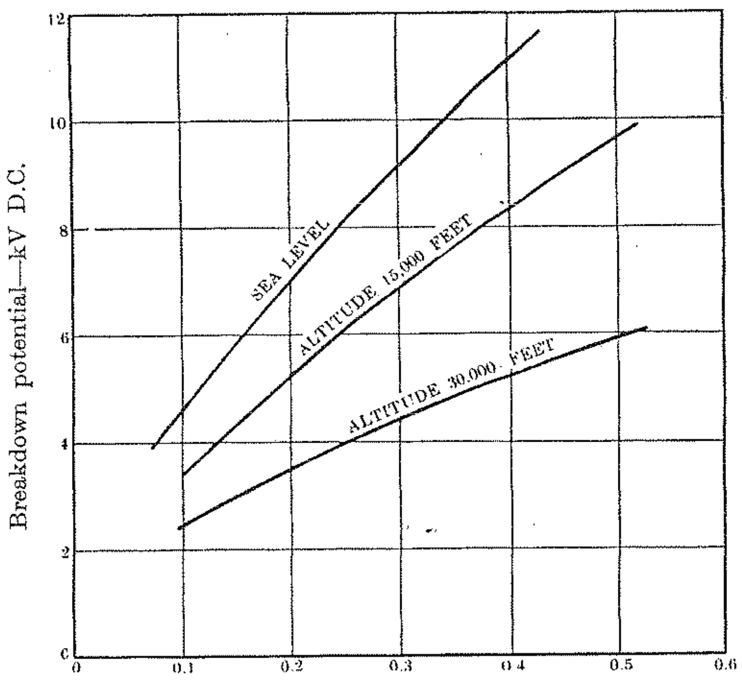

Figure 5—Break-down voltage across a dry surface (after Berberich, Moses, Stiles and Veinott).

coupled with a diminution of atmospheric pressure, will accentuate ' creepage ' troubles across the surface of the insulation. The subject of surface breakdown of solid dielectrics is discussed at some length by Whitehead (1932), but, as he points out, there are many discrepancies in the published works. The effect of altitude on the surface flash-over of insulating materials has been investigated by Moses (1939) and more recently in greater detail by Berberich, Moses, Stiles and Veinott (1944). Some measurements of the corona-starting voltages, as distinct from flash-over, between metal studs in insulating surfaces for various altitudes have been made by Wilson (1944). The results given by Berberich, Moses, Stiles and Veinott of surface flash-over voltage in dry air against altitude for various electrode spacings with d.c. applied are shown in figure 5. The electrodes consisted of $\frac{1}{2}$ in. brass squares $\frac{1}{16}$ in. thick mounted flat on the insulating material with sharp

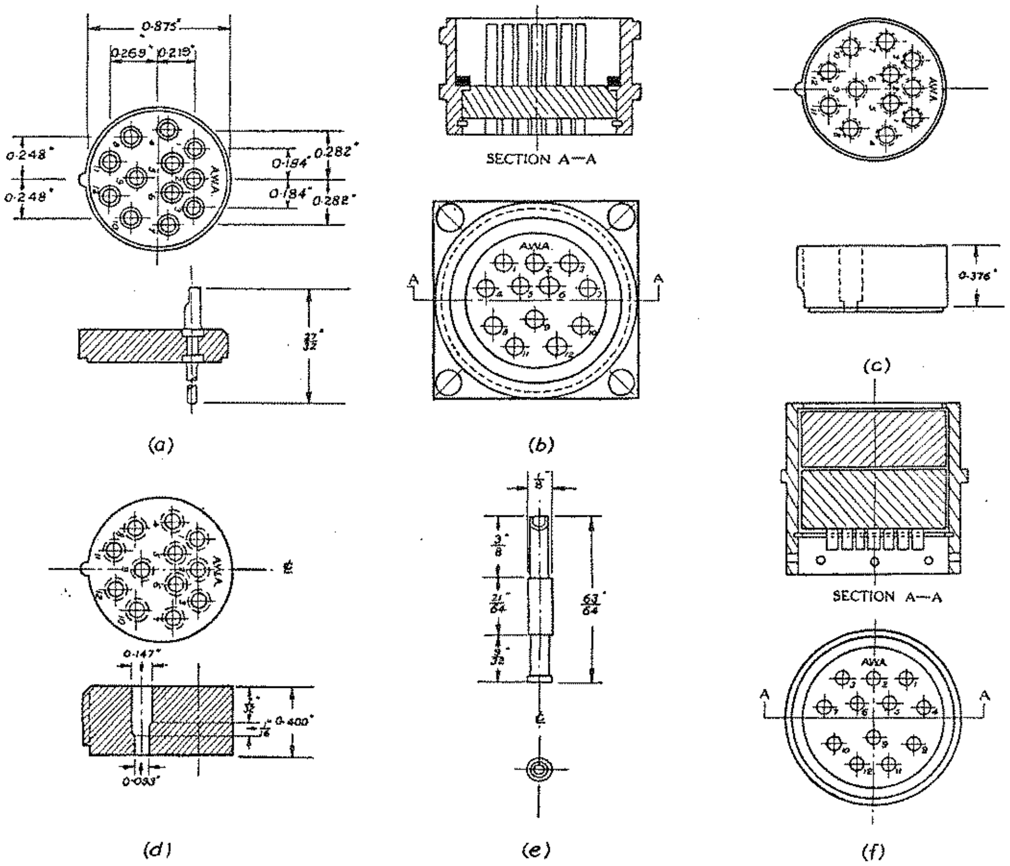

FIGURE 6—Diagrams of 8-pin and 12-pin cable connectors for which d-c flash-over tests are given in Table 1.

corners opposite, the insulating material being paper-base phenolic-bonded Micarta with a surface finish of two coats of iron-oxide-filled alkyd resin paint. The reduction in flash-over voltage from sea-level to 30,000 ft. is seen to vary from about $\frac{2}{3}$ths for the larger spacings to one half for smaller distances. The effect of moisture on the surface was also investigated, and the conclusion was reached that a further decrease of the order of 50 per cent. took place due to this. It seems, therefore, that the total reduction in flash-over voltage from sea-level in unsaturated air conditions to 30,000 ft. saturated air would entail a total reduction of $\frac{1}{6}$ to $\frac{1}{4}$ flash-over voltage, depending on the spacing.

Some results of flash-over tests on d.c. are given in table 1 for 8-pin and 12-pin cable connectors specially designed for aircraft equipment, the connectors being shown in figure 6.

Voltage applied between	8-Pin Plug and Socket		12-Pin Plug and Socket	
	Sea-level Unsaturated Air Volts	35,000 ft. Saturated Air Volts	Sea-level Unsaturated Air Volts	35,000 ft. Saturated Air Volts
Pins 1 and 2	>4500	1500	3500	1550
1 and 4	4300	1450	3900	1400
1 and 5			3500	1700
2 and 5			2700	1700
2 and 6			3700	1450
2 and 3	4100	1200	3100	1600
3 and 6			3000	1700
3 and 7	2800	1550	2900	1550
4 and 5			2700	1400
4 and 8	>4400	1550	4000	1250
5 and 6			3000	1750
5 and 9			3700	1450
6 and 7			2700	1500
6 and 9			3300	1450
7 and 10	>4400	1600	3800	1450
8 and 11			4300	>1200
9 and 11			3300	1550
9 and 12			2900	1800
10 and 12			4100	1150
9 and 8	>4800	1800	3700	1800
9 and 10	3700	1800	3500	1950
Pin 1 and shell		1400	3800	1550
2 and shell		1950	2700	1900
3 and shell		1450	2700	1550
4 and shell		1550	2700	1300
7 and shell		1200	2500	1250
8 and shell		1750	3500	1450
10 and shell			3500	1450
11 and shell			3300	1550
12 and shell			3700	1300

TABLE 1—D-c flash-over voltages of 8-pin and 12-pin cable-connectors for unsaturated air at sea-level and saturated air at 35,000 ft.

Figure 6 (a) shows the details of the bakelite moulded male portion of the 12-pin connector, and 6 (b) shows how this is inserted in a metal shell; details of locking rings and cable clamps are omitted. Figures 6 (c) and 6 (d) show the moulded bakelite fillers for the female portion of the connector. These two bakelite mouldings serve to insulate and retain the 12 female metal contacts shown in figure 6 (e) in a metal shell as shown in figure 6 (f) The 8-pin connector referred to in table 1 is made similarly to the 12-pin but omitting pins 5, 6, 11 and 12, thus providing increased spacing around pin 9. The ratings of the connectors shown in figure 6 are as follows. For the 12-pin connector the operating voltage between any two pins or between any pin and the shell shall not exceed 400 volts d.c. The current carried per contact shall not exceed 3 amperes d.c. at the maximum operating voltage or 6 amperes d.c. at voltages not exceeding 32 volts d.c. For the 8-pin connector the ratings are the same except for contact No. 9, for which the rating is 750 volts d.c. between it and any other pin or the shell.

The voltage ratings given above represent a reasonable factor of safety on the results of table 1 and in fact no case has yet been reported to the writer of failure of these connectors due to voltage flash-over when operated in accordance with these ratings. The flash-over voltages in table 1 are given for two conditions, one being at ordinary atmospheric pressure, humidity well below saturation and the other at a pressure of 7in. of mercury corresponding to an approximate altitude of 35,000 ft., and 100 per cent., humidity, but at room temperature. The tests were performed with the

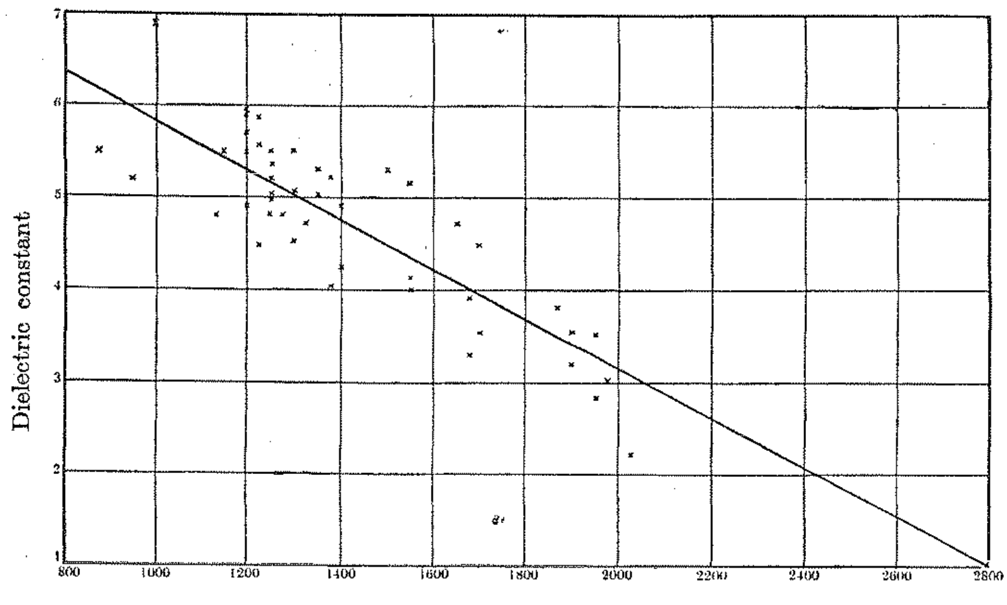

Figure 7—Dielectric constant against corona voltage between needle points 1 cm. apart resting lightly on the surface of the material. Test frequency 300 kc.

plug and socket screwed together and leads attached to the appropriate points, then inserted in a bell-jar over a pan of water. Pressure was reduced until the water boiled and finally adjusted to 7in. of mercury. This resulted in a film of moisture being deposited over the contents of the bell-jar. The d-c voltage was applied at low potential and slowly increased until flash-over occurred.

It is clear that tests such as those shown in table 1 do not lead to any accurate law governing flash-over under various conditions as there are too many imponderables involved, including manufacturing variations from unit to unit and the condition of the surface. However, they do serve to establish a working rule that is sufficiently accurate for design purposes, and also to set a rating on the component allowing a normal engineering factor of safety. For example, a reduction to one-quarter of rating of voltage flash-over at sea-level, for operation up to 35,000 ft. would be a reasonable working rule for electrode spacing of the order $\frac{1}{16}$ in. to $\frac{1}{8}$ in., of similar configuration to those shown in figure 6. This agrees roughly with the reduction given by Berberich, Moses, Stiles and Veinott for saturated air at this altitude.

The dielectric constant of the material on the surface flash-over between electrodes has been shown (Whitehead, loc. cit.) to have a considerable effect on the flash-over voltage as this will affect the electric field distribution, and table 2 gives the results of some tests involving this variable. The measurements were made by observing the voltage at which visible corona first appeared between two needle points (gramophone needles) resting lightly on the surface of the insulating material and spaced 1 cm. apart. The tests were carried out at a frequency of 300 kc in unsaturated air at atmospheric pressure, and were made primarily for the purpose of quality control of purchased insulating material. It seems likely that the tests do not give much indication of quality but are a somewhat indirect and inaccurate method of measuring dielectric constant.

It will be noted in table 2 that the dielectric constant was measured at 1 Mc and the corona voltage at 300 kc, but this discrepancy is not likely to alter the general conclusion, since the change of dielectric constant with frequency in this range is usually quite small. The results of table 2 and the points plotted in figure 7 are the average of at least three observations on each sample. As would be expected, the corona voltage is not strictly proportional to dielectric constant, since other variables are also involved, in particular, the state of the surface under test (polished, unpolished, etc.), but there is sufficient evidence to show that the use of high dielectric constant materials is undesirable unless the surface path can be kept long. In aircraft equipment this is frequently a matter of some difficulty owing to the space and weight requirements.

4—Flash-over Between Air-Insulated Conductors at High Frequency and High Altitude.

The reduction of voltage required to produce corona and/or spark-over between air-insulated conductors as the air pressure falls sets a practical limit upon the altitude for which non-pressurised radio equipment can be designed to give satisfactory operation. A very extensive literature exists covering the conduction of electricity through gases, arising from the work done by Sir J. J. Thomson and followed up by numerous investigators

Material	Corona Volts R.M.S. Freq. 300 kc	Dielectric Constant Freq. 1 Mc
Loaded Ebonite		
D.P. Loaded (sheet)	1950 volts	3.5
D.P. Loaded (rod)	1900 ,,	3.54
WT22 (light)	1870 ,,	3.8
WT22 (rod—light)	1680 ,,	3.9
Stabec	1650 ,,	4.7
Ebonite.		
Jeffries (Castle brand)	1500 ,,	5.3
Dunlop (shiny)	1950 ,,	2.82
Dunlop (matt)	1975 ,,	3.0
Ebonite 70	1700 ,,	4.46
Ebonite 613	1850 ,,	3.19
Advanx	1680 ,,	3.27
Canvas Bakelite.		
F10810	1200 ,,	5.93
F294	1200 ,,	5.89
Moulded Products	1400 ,,	4.9
1st Grade Bakelite.		
E5578	1550 ,,	4.12
E5089/1	1650 ,,	3.51
XXXP/SR	1550 ,,	4.0
2nd Grade Bakelite.		
Menzies	1250 ,,	5.2
P296/316	1250 ,,	5.2
XX (brown)	1350 ,,	5.02
XXX	1375 ,,	4.04
XP (choc.)	1300 ,,	4.51
P5342/1	1350 ,,	5.3
XP14	1300 ,,	5.05
XP MS	1200 ,,	5.7

Material	Corona Volts R.M.S. Freq. 300 kc	Dielectric Constant Freq. 1 Mc
3rd Grade Bakelite		
PQ	1150 volts	5.5
Bakelite A	1225 ,,	5.57
Formatex	1000 ,,	6.9
P5297	1250 ,,	5.08
P992	1225 ,,	5.88
P793	1200 ,,	5.27
P5342/547	1275 ,,	4.8
E10785	1250 ,,	5.35
Tufnol (Ship)	1250 ,,	5.0
Tufnol (Kite)	1200 ,,	5.5
Tufnol (Brown Swan)	1250 ,,	5.5
Tufnol (Black Swan)	875 ,,	5.5
Penthane	1200 ,,	4.9
K.J.K.	1375 ,,	5.23
Moulded Bakelite.		
Ellitane M	1325 ,,	4.7
Ellitane 2M	1225 ,,	4.47
X4933/6	1300 ,,	5.5
XMB262	1400 ,,	4.24
X20/5	1250 ,,	4.8
Ebonoid Rod	1550 ,,	5.15
Steatite.		
Ducon	1130 ,,	4.8
Ferro Enamels	950 ,,	5.2
Miscellaneous.		
Victron	2025 ,,	2.2
Air	2800 ,,	1.0

TABLE 2—Dielectric constant and corona voltage at 300 kc between needle points 1 cm. apart resting lightly on the surface of the material.

including particularly J. S. Townsend (1910). The theory of spark-over under the conditions of a uniform electric field appears to be reasonably well understood and a great number of experimental results have proved that Paschen's Law, 'sparking potential = function of product of pressure times spark-length,' holds over wide limits of $p \times l$. Whitehead (1927) gives a large number of references to experimental results to show that Paschen's Law for air holds over the range 0.1 to 20,000 for the product $p \times l$ where p is the pressure in mms., and l the spark-length in cms. He also says (page 41): "However, no general formula has been devised to represent the whole curve, but for a limited range a straight line can be found to represent the results with sufficient accuracy." Whitehead gives a number of diagrams summarising the experimental results over a wide range of $p \times l$, and from these the curves of figures 8 and 9 have been

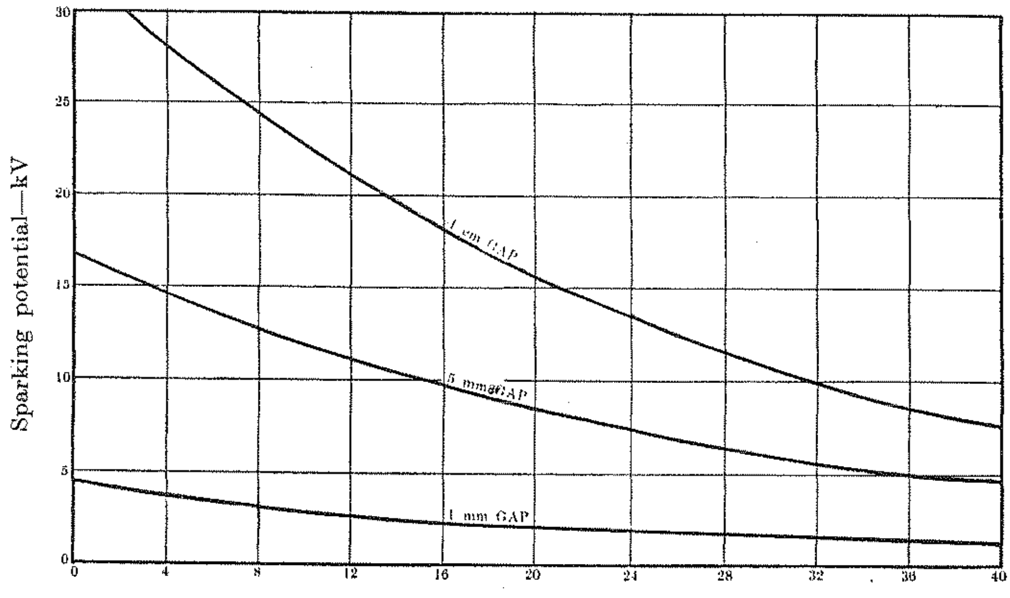

FIGURE 8—D-c spark-over voltage against altitude for parallel plate gaps in air (after Whitehead).

produced. Figure 8 shows the sparking volts for d.c. against altitude between parallel electrodes for spacings of 1 mm., 5 mm., and 1 cm., and figure 9 shows the gap in inches against altitude for 1500, 2500, 5500 and 10,000 volts. Although the curves of figures 8 and 9 are useful as a design basis, the more usual problem is not that of d-c spark-over but rather of r.f., particularly in transmitters. A wealth of information has been published on 50 to 60-cycle corona and spark-over voltages for uniform fields, also for the cases of parallel wires, concentric cylinders, needle-gaps and sphere-gaps; this field is very well covered by Peek (1929). The values of sphere-gap break-down for d.c. and power frequencies at normal pressure and temperature are covered in great detail by ' British Standard Rules for the Measurement of Voltage with Sphere-Gaps ' (1939). The case of radio-frequency corona and spark-over, particularly at pressures down to about one-sixth of atmospheric, has not been so well examined. The theoretical study of this subject is very much complicated by the rapid reversals of polarity of the electrodes and, in fact, Loeb (1939) dismisses this subject (page 550) as follows : " Spark Breakdown with Alternating Current —The discussion of this involved subject can add little to a book on fundamental processes. It is clear that alternating potentials complicate the picture by reversing electrodes, where these are dissimilar, and by launching field-distorting space charges of positive and negative ions, which, owing to differences in mobilities of electrons and ions and diffusion, will accumulate in complicated ways. The diversity of electrode shapes and the changes

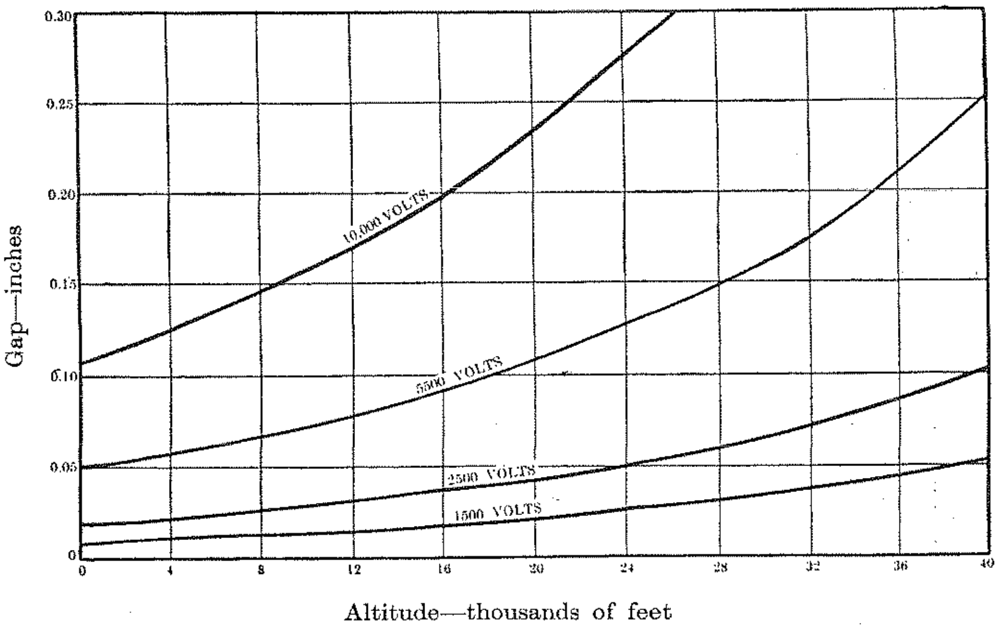

FIGURE 9—Length of spark-gap against altitude for various break-down voltages ; parallel plate gaps with d.c. applied (after Whitehead).

produced by changes of frequency make lengthy discussion in a text of this scope hardly worthwhile."

Sphere-Gaps at High Frequency and High Altitudes—The effect of high frequency on the spark-length at atmospheric pressure has been investigated by a number of workers, but the published results are not altogether consistent. Clark and Ryan (1914) have investigated the sphere-gaps discharge at frequencies of 123, 255 and 612 kc for 7 in. spheres at spacings from 0.25 in. to 1.1 in. using a Poulsen arc generator, and have shown a lowering of the voltage of about 4.5 kV, that is about 12 per cent. Leontiewa (1922) gives some results of spark-over voltage with frequency in the range 7 Mc to 150 Mc for 5 mm. spheres using damped waves of unstated decrement; he shows that the higher the frequency the greater the voltage required to break down a given gap. Similarly Reukema (1928) using sine waves, has made some measurements for frequencies up to 425 kc for spheres of diameter 6.25 cm. with spacings in the range 0.2 in. to 1.0 in., and found that the break-down voltage was unaltered up to 20 kc and was then reduced by about 13 per cent. of the 60 cycle value for all frequencies between 60 kc and 425 kc. His theory suggests that the sparking voltage should be unaltered up to about 6 Mc, when a further decrease might be expected. More recently Seward (1939) has measured the spark-over voltage for sphere-gaps (both 5 mm. and 14 mm. spheres) in the frequency range 100—900 kc. Seward states that the reduction in voltage break-down for sphere-gaps should be approximately proportional to the frequency and should be independent of the electrode curvature until a stable brush discharge occurs, when new conditions will then apply. The experimental results given in the above frequency range agree with this proportionality. Seward states that the reduction in voltage should increase progressively until the frequency is such that the electrons are no longer able to travel from one electrode to the other before voltage reversal occurs. His results for sphere-gaps are shown in table 3; he makes no mention of irradiating any of the gaps with ultra-violet light.

TABLE 3

Freq. kc.	5 mm. dia. spheres.		14 mm. dia. spheres.	
	Electrode Spacing mm.	Per Cent Reduction on 50 cycle results.	Electrode Spacing mm.	Per Cent Reduction on 50 cycle results.
109	5	1.5		
	10	1.2		
	15	1.6		
	20	1.4		
	25	1.37		
	30	2.0		
600	5	6.8	14	6.8
	10	6.4	28	6.8
	15	6.5	42	6.8
	20	7.6		
	25	9.2		
	30	10.9		
900	5	11.1		
	10	10.4		

Some additional measurements have been made by Alford and Pickles (1940) at the single frequency of 13 Mc for both sphere and needle gaps as well as other forms of electrodes. These experimenters used only the one size of sphere, namely 2 in. in diameter ; they have compared these results with the break-down voltage at 60 cycles per second of $2\frac{5}{8}$ in. diameter spheres; Peek (loc. cit.) shows that the effect of changing the sphere diameter by this small amount at these spacings will not alter the result by more than ± 5 per cent. Readings were taken for gaps in the range 0.05 in. to 0.3 in., and appear to show that at 13 Mc the break-down voltage for 2 in. spheres at these spacings is practically the same as for 60 cycles per second. Ekstrand (1940) gives results for spheres of 2.0 cm. and 5.08 cm. diameters for gaps of 0 — 0.8 in., and shows that for the smaller spheres there is no difference in break-down voltage for the two frequencies 700 kc and 1,800 kc, results for both frequencies being about 20 per cent. below that for 60 cycles per second break-down. For the larger diameter spheres measurements were made only at 700 kc and here the break-down voltage was found to be about 17 per cent. below that for 60 cycles per second. Even allowing for

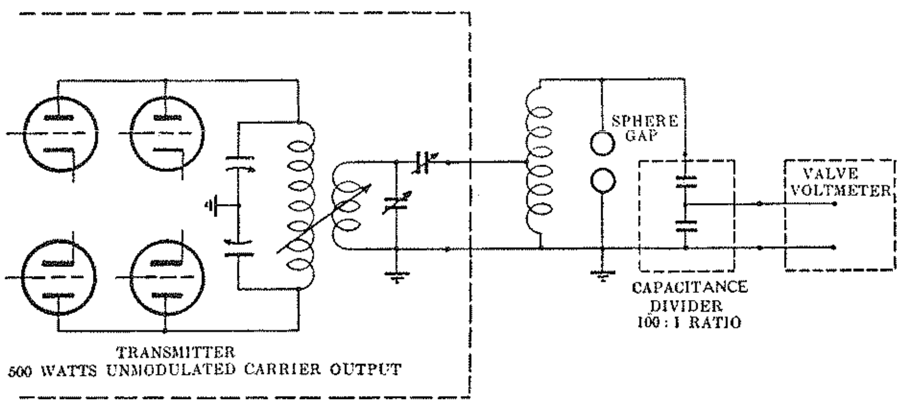

FIGURE 10—Circuit used for measurement of flash-over voltage of 2.0 cm. diameter sphere-gaps at radio frequencies.

the difference in diameter of the spheres used compared with those used by Seward, as given in table 3 above, there appears to be a considerable discrepancy. Both experimenters have used similar methods, one sphere being earthed in each case, and similar voltage generating equipment is described, so that there should be little difference in harmonic content of the test voltages. Slightly different methods of measuring the applied voltages were employed, however, as Seward used an electrostatic voltmeter in conjunction with a capacitance potential-divider whereas Ekstrand measured the r-f current through a known capacitance connected across the line. In the light of the above brief summary of the more relevant literature relating to spark-over of sphere-gaps in air at atmospheric pressure at radio frequencies, it seems that no definite conclusions could be drawn for the range of frequencies commonly used in aircraft in which fairly high r-f voltages are generated. Even for the simple case of sphere-gaps for frequencies that occur in aircraft, namely up to 10,000 volts peak in the frequency range 100—20,000 kc at normal atmospheric pressure, the published information appears to be inadequate.

In view of the uncertainty of the behaviour of even simple electrodes such as spheres at high frequency and high altitude, some measurements have been made on 2.0 cm. diameter spheres at 2.50 Mc and 19.13 Mc at spacings in the range 0.050 in. to 0.500 in. The circuit arrangement used

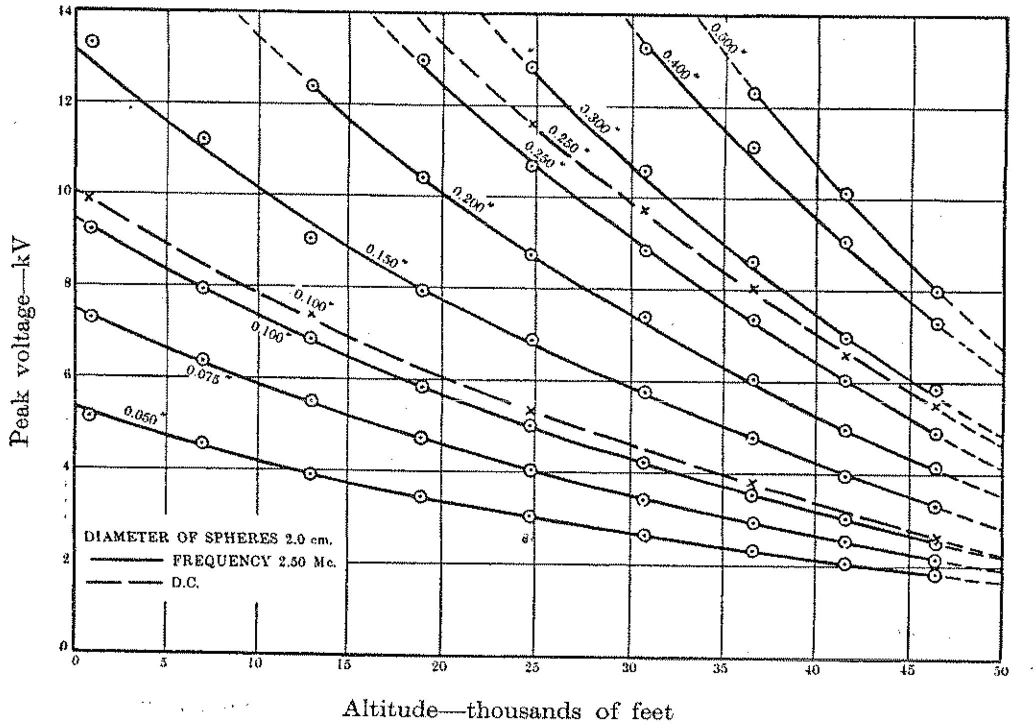

Figure 11—Spark-over voltages of a sphere-gap at a frequency of 2.50 Mc and at d.c.

in making the measurements is shown in figure 10. The tuned circuit external to the transmitter was resonated at 19.13 Mc by using only the capacitance of the sphere-gap and voltage-divider. The spheres were enclosed in a bell-jar and pressure was read by means of a standard simple altimeter. The modulation on the carrier was measured and found not to exceed 3 per cent. In all cases spark-over occurred before any visible corona; no ultra-violet irradiation of the gap was used, but the points are seen to lie fairly closely on the plotted curves. Figure 11 shows the results of measurements at a frequency of 2.50 Mc and figure 12 for a frequency of 19.13 Mc. Each point on the curves is the arithmetic mean of six observations of break-down voltage. Included in these two diagrams are curves taken on the same sphere-gap for break-down on d.c. at the two spacings of 0.100 in. and 0.250 in., the negative side being earthed. Voltage measurement in this case was made using an electrostatic voltmeter. Some check measurements were also made at a frequency of 6.23 Mc, and these gave an even smaller departure from the d-c values than the curves of either figures 11 or 12. All measurements shown in figures 11 and 12 were made at room temperature, and the air density corresponding to the pressure and temperature has been converted to the altitude equivalent to this density for the I.C.A.N. standard atmosphere (Air Ministry, 1939).

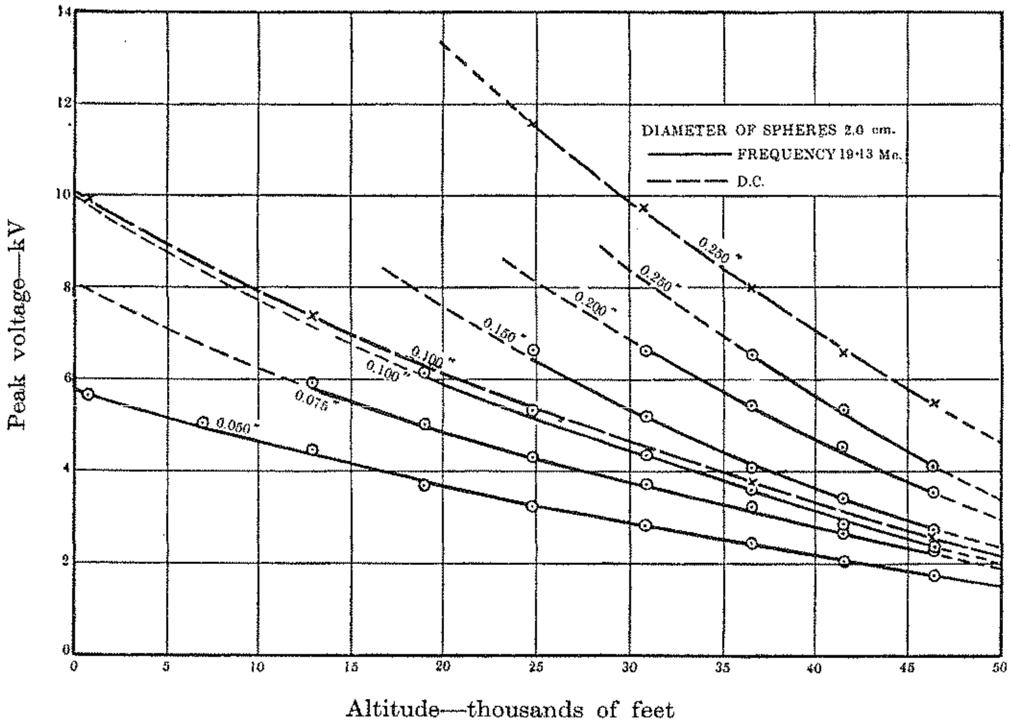

FIGURE 12—Spark-over voltages of a sphere-gap for various spacings at a frequency of 19.13 Mc and at d.c.

The decrease in spark-over voltage at frequencies from 2.5 Mc to 19 Mc for sphere-gaps of 2 cms. diameter for distances of the order 0.25 in. is seen not to exceed 25 per cent. of the d-c value for altitudes up to 50,000 ft., the biggest discrepancy being at the larger spacing at the highest frequency. This is substantially in agreement with Alford's and Pickles' results at 13 Mc, where the spark-gap was small compared with the sphere diameter. The discrepancies at frequencies up to 19 Mc are of the same order as those reported by Ekstrand at frequencies of 700 kc and 1,800 kc. Hence, for sphere-gaps in which the spacing is small compared with the diameter, it may be assumed that the effect of frequency on the spark-over voltage up to 20 Mc need not greatly concern the designer of radio equipment.

Capacitor	1		2		3		4		5		6	
Plate Thickness Airgap Spacing Condition of Edges	0.022 0.015 Sharp		0.024 0.020 Sharp		0.0225 0.0245 Sharp		0.022 0.040 Sharp		0.024 0.060 Sharp		0.027 0.066 Buffed	
'Test Voltage' Frequency	Pressure 30″	7″	Pressure 30″	7″	Pressure 30″	7″	Pressure 30″	7″	Pressure 30″	7″	Pressure 30″	7″
50–60 cycles					2720							
375 kc									2600	1240		
500	1500	870					2700	1300				
700					2470							
1500					2460							
4000			1600	840								
5000												1200
10000	1050	650	1400	610					1900	900		
13000												
20000				520								
Origin	A.W.A.		A.W.A.		Ekstrand		A.W.A.		A.W.A.		A.W.A.	

TABLE 4—Measurement of spark-over of various air-dielectric condensers.

Spark-Over Voltage of Variable Capacitors at High Frequencies and High Altitude—In the papers by Ekstrand and by Alford and Pickles some additional measurements are recorded of the r-f voltage ratings of a number of variable capacitors, and in the course of the production development of aircraft equipment designed by the writer, a number of such tests were also made on various capacitors. The results are given in table 4 as well as the relevant measurements by Ekstrand and Alford and Pickles. From a study of table 4, it will seem that the best that can be deduced are the somewhat rough empirical rules for capacitors design. The reduction in rating on flash-over of the value for 50 cycles per second up to 20,000 kc should be at least one-half at normal atmospheric pressure, and for equipment for use in aircraft up to 35,000 ft. altitude, this half value should be still further reduced by about one-half to one-third, that is, the total reduction of rating of the value for normal atmospheric pressure at 50 cycles per second should be about one-quarter to one-sixth for operation at 20 Mc and an altitude of 35,000 ft. This may represent over-design but, failing actual tests on

7		8		9		10		11		12		13		14
0.040 0.066 Buffed		0.025 0.080 Rounded		0.040 0.192 Rounded		0.062 0.192 Rough		0.064 0.719 Rounded		0.064 0.719 Rough		0.128 0.218 Rounded		0.062 0.040
Pressure		Pressure		Pressure		Pressure		Pressure		Pressure		Pressure		Pressure
30″	7″	30″	7″	30″	7″	30″	7″	30″	7″	30″	7″	30″	7″	30″
3100		4200		8400		6000—6800		24000		15000—17000		14000		9300—10900
		3780		7590				14280				13500		
				6820				11700						
	1360													
						2800—4300				5200—8200		13700		4200—6600
A.W.A.		Ekstrand		Ekstrand		Alford & Pickles		Ekstrand		Alford & Pickles		Ekstrand		Alford & Pickles

TABLE 4—Measurement of spark-over of various air-dielectric condensers.

the component, is a reasonable working rule in view of the present lack of knowledge.

Spark-Over Voltage of a Wire to a Conducting Plane—Some results have also been obtained for the case of a wire close to a conducting plane. This is of importance in transmitter design as high-voltage leads frequently have to be spaced off from the conducting sides of the containing box. The results are shown in figure 13 for spacings of $\frac{1}{4}$ in. to $1\frac{1}{2}$ in. in air at a pressure of 7 in. mercury at a frequency of 10 Mc. The wire sizes vary from 18 gauge to $\frac{3}{16}$ in. diameter rod. It will be seen that the points lie fairly well on the curves, with one or two exceptions, and the effect of increasing diameter on the break-down voltage is well illustrated. Some additional readings were taken on the effect of frequency at 5, 10 and 20 Mc for a $\frac{1}{4}$ in. spacing at 7 in. mercury pressure, and these results are shown in table 5.

Here again there are some minor inconsistencies in the results, but broadly a reduction factor of 0.8 of the break-down voltage at 5 Mc would be a reasonable working rule for operation at 20 Mc. There is some evidence that the effect is slightly more pronounced the smaller the diameter of the

TABLE 5.

Wire Size.	Frequency Mc	Spark-over Voltage.
18 gauge	5	3200
	10	3100
	20	2700
16 gauge	5	3300
	10	3350
	20	2750
14 gauge	5	3450
	10	3450
	20	3000
12 gauge	5	3700
	10	3800
	20	3200

wire, but this is by no means conclusively shown. In all the observations given in figure 13 and table 5, spark-over occurred before there were any visible signs of corona.

Although the information summarised above is helpful in the initial design stages of aircraft equipment in which high r-f voltages are produced, it is clear that precise design data is not yet available for r-f spark-over and corona voltages in air at various pressures and with various electrode configurations. The designer is therefore forced to make tests on models of the

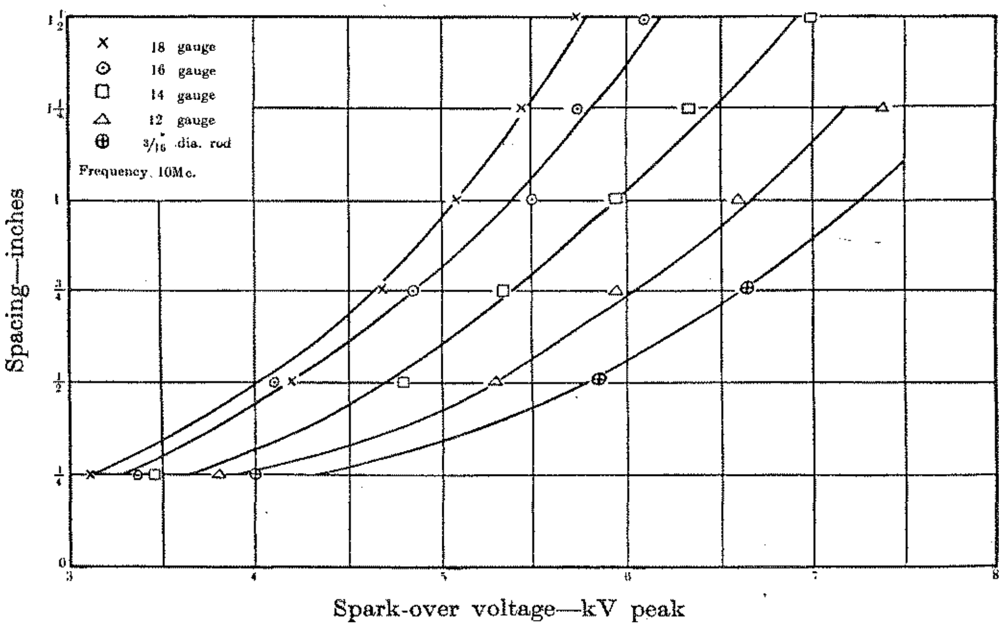

Figure 13—Spark-over voltages between a wire and a conducting plane for various distances in air at a pressure of 7 in. mercury and a frequency of 10 Mc.

equipment at frequencies and air pressures corresponding to the worst conditions likely to be encountered, and then allow a reasonable engineering factor of safety to cover the lack of precise knowledge of the subject.

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