Operation of Transmitters at Altitude, by R. Heppinstall

1 INTRODUCTION

A proportion of terrestrial UHF TV transmitters are situated at high altitude. There are quite a number located above 2286 m (7500 ft), and indeed one is located at 4267 m (14,000 ft) above sea level. At such altitudes, the air density is significantly lower than that at sea level and the voltage at which external breakdown between electrodes can occur is correspondingly reduced. This note addresses some of the issues involved.

2 AIR COOLING

Specifications for air cooling generally state the flow of air required (in, for example, litres per minute) to produce effective air cooling at sea level. However, air cooling depends upon the mass of air flowing. Consequently at altitude, where the air density is reduced, the volume flow must be increased in the ratio of air density at sea level to air density at altitude in order to maintain the mass flow.

Values of the air density at various altitudes are given in column 2 of Table 1[1]. Column 3 shows air density values normalised to the value at sea level. They can be represented with a good degree of accuracy, for altitudes up to 5 km, by the equation:

$$p_d = 1 - 0.09H + 0.002H^2$$

where H is the altitude in kilometres.

Altitude (km)	Air Density (kg/m^3)	Normalised Air Density	Multiplying Factor
0.0	1.225	1.000	1.000
0.5	1.167	0.953	1.050
1.0	1.112	0.908	1.102
1.5	1.058	0.864	1.158
2.0	1.007	0.822	1.216
2.5	0.957	0.781	1.280
3.0	0.909	0.742	1.348
4.0	0.819	0.669	1.496
5.0	0.736	0.601	1.664

Table 1 Air density at various altitudes

The final column of Table 1 gives the reciprocal of the normalised values. This is the factor by which the volume air flow at sea level has to be multiplied to obtain the same mass flow at altitude. The normalised values and the multiplying factors are plotted in Figures 1 and 2.

3 VOLTAGE BREAKDOWN

The breakdown voltage across a smooth gap is that voltage at which a self-sustaining discharge takes place. For a particular gas it varies with both the gas density (usually plotted as pressure, p, assuming uniform density distribution) and with the electrode spacing, d. It is a function, though not a linear one, of the product pd.

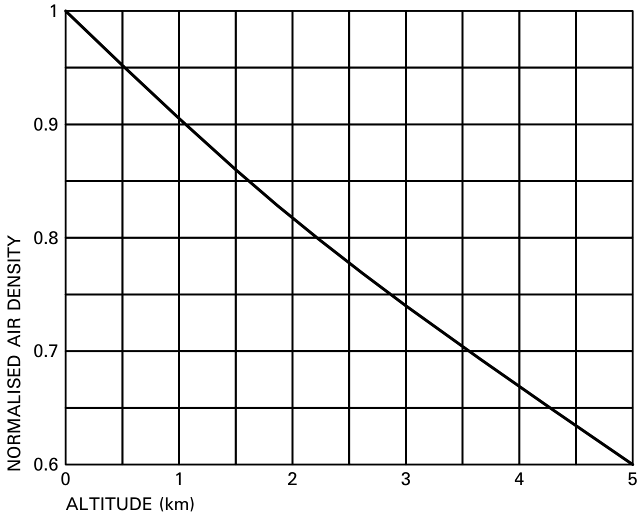

Fig. 1 Air Density versus Altitude

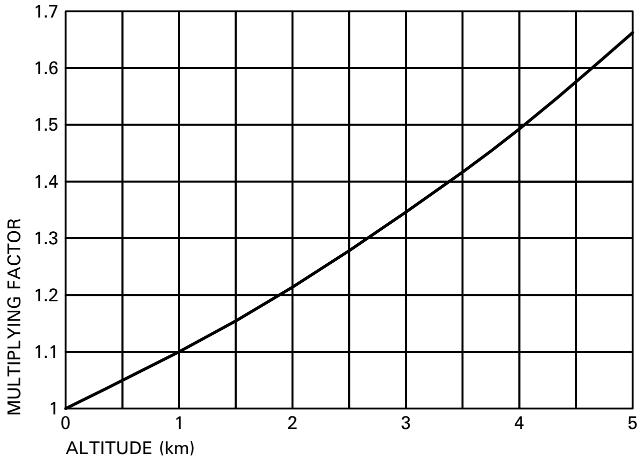

Fig. 2 Multiplying Factor versus Altitude

The breakdown depends upon the ionising opportunities open to an electron in the gap. These are a function of:

(a) The energy of the electron in relation to its mean free path; that is, the distance it will move on average before colliding with a gas molecule.

(b) The number of molecules in the path.

(c) The nature of the gas.

The shape of the curve of breakdown voltage against the product pd, the Paschen Curve[2], can be deduced on general grounds. For a gap of a particular size, containing gas at a relatively high pressure, the mean free path of the electron is relatively small and the voltage required for breakdown increases as the pressure increases – the energy of the electron has to reach ionising energy before a collision with a gas molecule. However, at low values of pressure, the mean free path of the electron may be so high that there is little chance of an ionising collision before the electron has crossed the gap. In these circumstances, the breakdown voltage

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H d	0.0	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0
1	30.9	29.6	28.4	27.2	26.0	24.8	23.7	21.7	19.7
2	58.0	55.5	53.1	50.7	48.5	46.3	44.2	40.2	36.5
3	84.5	80.8	77.2	73.8	70.4	67.2	64.1	58.2	52.8
4	110.7	105.8	101.1	96.5	92.1	87.8	83.7	76.0	68.8
5	136.6	130.5	124.7	119.0	113.5	108.2	103.1	93.6	84.6
6	162.4	155.1	148.2	141.4	134.8	128.5	122.4	111.0	100.4
7	188.1	179.6	171.5	163.6	156.1	148.7	141.6	128.4	116.0
8	213.7	204.1	194.8	185.8	177.2	168.8	160.7	145.7	131.6
9	239.2	228.4	218.1	207.9	198.3	188.8	179.8	162.9	147.2
10	264.6	252.7	241.2	230.0	219.3	208.8	198.8	180.1	162.7

Table 2 Calculated breakdown voltages (kV) as a function of altitude H (km) and gap length d (cm)

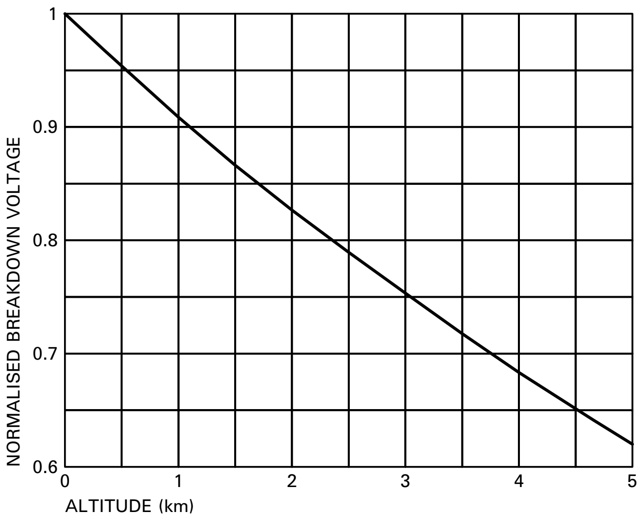

Fig. 3 Breakdown Voltage versus Altitude

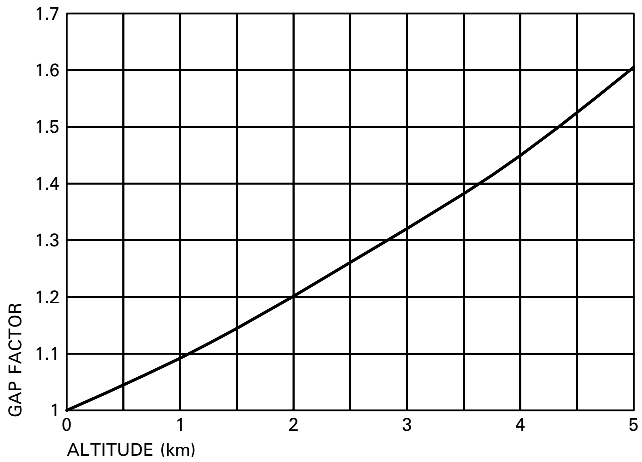

Fig. 4 Gap Factor versus Altitude

decreases as the pressure increases, provided that it is sufficient to produce ionisation when a collision does occur. Obviously, there is a value of the product pd for which the breakdown voltage is a minimum. This depends on the nature of the gas in the gap. For air the relevant values at the point of minimum voltage are:

$$\text{Product pd} = 7.46 \times 10^{-3} \text{ bar mm}$$

$$\text{Voltage} = 327 \text{ V}$$

The values of the product pd of interest to the operation of UHF TV terrestrial transmitters at high altitude are appreciably higher than 7.46×10^{-3} bar mm. In this region, and for gap lengths in the range 0.01 to 20 cm, the uniform breakdown voltage of air at a humidity of 11 g/m^3 is given by the equation[3]:

$$Vs = 24.4 p_d d + 6.53 (p_d d)^{1/2}$$

where Vs = Breakdown voltage in kV;
d = Gap length in cm;
p_d = Air density relative to its value at a pressure of 1013 mbar and a temperature of 20 °C.

Table 2 shows values of breakdown voltages calculated for various gaps by substituting the values of normalised air densities given in the Table 1 into the above equation. Table 3 overleaf shows uniform field breakdown voltages normalised, for each value of d, to the value at sea level (when H is zero). These normalised values are, to a sufficiently good degree of accuracy, independent of gap length. The average of these values is plotted as a function of altitude, see Figure 3.

Figure 4 is a plot of F, the reciprocal of the average values as a function of altitude. This is the factor by which the size of any smooth gap has to be increased in order to maintain the same margin against voltage breakdown at altitude as that which existed at sea level.

4 TESTING DEVICES FOR USE AT ALTITUDE

As discussed above, the voltage at which devices such as IOTs can be operated at altitude is less than that at which they can be operated at sea level, because the voltage at which breakdown occurs in air is lower. This does not affect the 'internal' electrical characteristics of the device, but will affect voltage breakdown across, for example, external flanges. In a situation where proving tests can only be done at sea level, careful consideration has to be given to the nature of those tests. A two-stage process should be adopted:

A) Test the tube at the required operating voltage – this will prove that the 'internal' electrical characteristics of the tube are satisfactory.

d \ H	0	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0
1	1.0	0.958	0.919	0.880	0.841	0.803	0.767	0.702	0.638
2	1.0	0.957	0.916	0.874	0.836	0.798	0.762	0.693	0.629
3	1.0	0.956	0.913	0.873	0.833	0.795	0.759	0.689	0.625
4	1.0	0.956	0.913	0.872	0.832	0.793	0.756	0.687	0.621
5	1.0	0.955	0.913	0.871	0.831	0.792	0.755	0.685	0.619
6	1.0	0.955	0.913	0.871	0.830	0.791	0.754	0.683	0.618
7	1.0	0.955	0.912	0.870	0.830	0.791	0.753	0.683	0.617
8	1.0	0.955	0.912	0.869	0.829	0.790	0.752	0.682	0.616
9	1.0	0.955	0.912	0.869	0.829	0.789	0.752	0.681	0.615
10	1.0	0.955	0.911	0.869	0.829	0.789	0.751	0.681	0.615
Average	1.0	0.956	0.913	0.872	0.832	0.793	0.756	0.687	0.621
F	1.0	1.046	1.095	1.147	1.202	1.261	1.323	1.456	1.610

Table 3 Normalised breakdown voltages as a function of altitude H (km) and gap length d (cm)

B) Carry out an 'ionisation' test on the tube at an elevated voltage. Insulators can sustain a high voltage without breakdown before subsequently failing at that voltage. Pre-breakdown ionisation currents can exist and these can be measured by commercially available equipment which can detect a minute quantity of charge transfer; this is known as an ionisation tester. Ionisation tests should be done at a voltage equal to the required operating voltage multiplied by the factor F, as given in Table 3, corresponding to the altitude at which the tube is to be operated. However, it would be wise to increase this voltage by 10%, for example, to provide some 'headroom'.

For example, for an IOT intended to operate at a beam voltage of 35 kV at an altitude of 3 km, performance tests should be carried out at 35 kV and ionisation tests at 50 kV (35 x 1.323 plus 10%). For non-vacuum components, such as IOT cavities or transmitter circuit components, ionisation tests would also be required at about 50 kV.

5 COMPONENT PERFORMANCE

The RF output of high power UHF TV amplifiers is normally 50 Ω rigid coaxial line. There are different standard sizes for this, each size having a different power rating, dependent on the frequency of operation. Two power ratings are generally quoted – a peak power rating dependent on the voltage breakdown characteristics of the feeder, and an average power rating dependent on the temperature to which the inner conductor is allowed to rise. Both these ratings should be reduced for altitude. The relevant reduction factors[4] are given in Table 4. Note that the reduction for the peak power rating is more than that for the average power rating.

Altitude above sea level (km)	Average power derating factor	Peak power derating factor
0	1.00	1.00
1.524	0.92	0.83
2.438	0.87	0.73
3.200	0.84	0.66
4.572	0.78	0.55

Table 4 Altitude derating factors for 50 Ω transmission line

6 COMMENTS

The above discussion has been based on uniform field breakdown voltages. In particular, the voltages quoted in Table 2 would have to be reduced for non-uniform fields, such as those occurring between electrodes of pointed shapes. Nevertheless, the normalised breakdown voltage information presented in Table 3 and Figure 3 should provide a reasonable guide to the change in voltage at which breakdown should occur as a function of altitude. It should be noted that the analysis given assumes that standard air conditions apply (air temperature 20 °C, humidity 11 g/m^3) Variations from these values, whether at sea level or altitude, will affect breakdown voltages.

REFERENCES

1. "American Institute of Physics Handbook", Third Edition, published by McGraw-Hill, table 3d-2, p3.70.
2. "The Arc Discharge: Its Application To Power Control", by H. de B. Knight, published by Chapman and Hall Ltd., 1960, see pages 10 – 11 and 138 – 140.
3. "Electrical Breakdown of Gases", by J. M. Meek and J. D. Craggs, published by John Wiley & Sons Ltd., page 539.
4. "Broadcast Engineering", July 1998, Special Report: Transmission Technology, by Bob Leonard.