(Paper No. 77).

SOME PROBLEMS OF HIGH VOLTAGE TRANSMISSION IN THE LOWER HIMALAYAS.

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Introduction.

1. The most economical design of a high voltage transmission line is usually a question of balancing the conflicting requirements of insulation, voltage regulation, efficiency and mechanical stability. These requirements conflict most where high voltage lines are used for comparatively small loads in mountainous districts, subject to tropical temperatures, *e. g.* the lower Himalayas.

2. As regards insulation, there are two types to be considered: those at the supports, usually formed of porcelain, and that of the air in between: the insulation of the supports is more intimately bound up with that of mechanical stability as will be seen later, and is best dealt with under that head.

3. The insulation of the air, however, in the case of lines operating at pressures exceeding 44,000 volts, is a matter of predominating importance at high altitudes; especially when subjected simultaneously to high temperatures.

4. The strength of the air as an insulator depends upon two factors :—

(*a*) The voltage gradient to which it is submitted, which in turn varies with the spacing and diameter of the conductor;

(*b*) The density of the air, which in turn depends upon the combined effect of altitude and temperature.

5. Again as regards regulation and efficiency the type and size of cable depend upon two chief factors :—

(*a*) The K. V. A. miles to be handled, *i. e.* the combination of voltage, power and distance, and

(*b*) The combined effect of the resistance, diameter and spacing of the cables themselves.

6. It will thus be seen that having selected the transmission voltage for any given power and distance, the minimum size of cable permissible depends upon its own diameter, spacing and the altitude and temperature of the locality; for example, although for purposes of regulation a cable of No. 1 S. W. G. size would suffice when operating at a voltage of 66,000 volts, it would be impossible to use a cable of such a small size at an

altitude of 6,000 feet and a larger cable would have to be employed. This would, however, p rmit of a reduced voltage, which again, in turn, would permit of a smaller diameter cable from the point of view of corona.

7. The problem is, however, further complicated by the question of mechanical stability. It is desirable for reasons of economy to adopt as long spans as possible consistent with mechanical stability, since long span construction reduces the number of towers and insulating supports, each of which forms a point of weakness in operation.

8. Spans up to 5,000 feet have recently been constructed on high voltage lines in the U. S. A. while the Chaba-Chair line, on the Simla scheme, includes several spans exceeding 3,000 feet, which were believed to be some of the longest in existence at the time they were constructed.

9. Long spans have to be designed to withstand two sources of damage :—

(*a*) The breaking of the conductors, due to over stressing (usually due to accumulations of snow and sleet combined with wind) ; and

(*b*) Contacts due to swinging.

The first requires conductors of great tensile strength and small diameter, while the second requires conductors of considerable weight and stability, and small diameter : both these requirements, besides conflicting mutually are opposed to those of conductivity, freedom from corona loss.

10. It will thus be seen that the selection of the best type and size of conductor is a matter of considerable complexity requiring a careful investigation of the following :—

(*a*) The density of the air due to the combined effect of altitude and maximum air temperature.

(*b*) The K. V. A. miles to be transmitted, the permissible voltage fluctuation, and the efficiency loss, including that required for condensers.

(*c*) The meteorological conditions, as regards combinations of wind pressure, minimum temperature and snow or sleet loading.

(*d*) The longest span and greatest permissible dip in the line and the combined effect of elasticity and expansion on the latter.

(*e*) And finally the comparative cost of various combinations of lines of different voltage, size of cable and synchronous condensers of varying size with their sub-stations and switchgear.

11. It is proposed to deal with these in three separate parts as follows :—

(i) Corona at varying altitude and temperature ;

(ii) Regulation and efficiency with special reference to constant voltage transmission.

(iii) Mechanical stability of long span construction.

PART I.

Corona at varying altitude and temperature.

12. The phenomena of corona have been well investigated by Mr. F. W. Peek of the General Electric Company of America; the results of his investigations will be found in "Dielectric Phenomena in High Voltage Engineering" published by the McGraw Hill Book Company in 1915.

13. Ordinary air at atmospheric pressure when subjected to a voltage gradient exceeding certain limits, ranging round 50 to 100 KV per centimetre, tends to break down. The phenomena can be observed round the surface of any conductor when charged to a high pressure, as soon as the potential gradient of the air in molecular contact with the surface of the conductor exceeds the above limits. At first a crackling sound is heard, and as the pressure is raised a distinct bluish glow can be observed. The air has ceased to be an insulator and has now become a conductor.

14. The loss of power from a transmission line when operated at a pressure sufficient only to cause even a slight glow discharge, may amount to several kilowatts per mile : it is, therefore, the usual practice to limit the voltage to a pressure not exceeding the "Disruptive Critical Voltage" (hereafter referred to as e_o).

15. Peek's formulae for the disruptive critical voltage and the disruptive gradient on transmission lines, which have now been generally adopted, are discussed in Chapters 3 to 6 and 9 of the above treatise and are :—

(*i*) Disruptive critical voltage $= e_o = 123\ m_o\ \delta\ r \log \frac{s}{r}$ in Kilovolts to Neutral.

(*ii*) Disruptive gradient $= g_o = \frac{e_o}{r \log\ e \frac{s}{r}}$

Where :—

δ = Air density factor = 1 at 29·9″ Barometer and 77° Fahr.

and $\therefore = \frac{17{\cdot}9b}{459 + t} = \delta$

Where :—b = barometric pressure in inches.
t = temperature in degrees Fahrenheit.
r = radius of conductor, inches.
s = distance between conductor centres in inches
m_o = Irregularity Factor :—
= 1 for polished wires.
= 0·98—0·93 for roughened or weathered wires
= 0·87—0·83 for seven strand cables.

[e. in K. V. between lines for 3 phase $\Delta^{a\,r}$ =spacing $\therefore$ $=123\sqrt{3}$ m. δ r log $\frac{s}{r}$. For flat spacing the value of e_o for the centre cable is 4% less : while adopting m_o=·87, we get :—

e_o in kilovolts for 3 phase flat spacing equals :—

$$KV = (123 \times \sqrt{3} \times \frac{96}{100} \times \cdot 87)\,\delta \times r \log \frac{s}{r}.$$

$$= \text{say } J \times r \log \frac{s}{r}.$$

Where $J = 178\,\delta$

and $\delta = \frac{17 \cdot 9b}{459+t}$

That is $r \log \frac{s}{r} = \frac{K.\,V.}{J}$]

16. For variation of air pressure b with altitude, under fine weather conditions (*i. e.*, sea level barometer 29·9 and 77° Fah. at all altitudes), see Chart No. 1.

17. During bad weather the barometer may drop, aggravating the effect of altitude ; this, however, will seldom if ever occur at the same time as the maximum temperature and this will usually exceed in effect that of the lowered barometer due to bad weather.

18. In the special case of the Himalayas, the air temperature t, is one of the most important factors to be decided.

19. Chart No. 1 also shows the maximum temperature at varying altitudes as supplied by the Meteorological Department. This represents the maximum temperature of the air at a few feet above the ground ; we are, however, concerned with the temperature of the air in actual molecular contact with the surface of the cable. Now this *must* be higher than that of the surrounding air, since it has to receive and convey away the heat generated in the cable by the passage of current as well as that absorbed by direct radiation from the sun.

20. The total heat received by the cable

$$H_r = H_s + H_g$$

Where :—H_s =that received from the sun

H_g =that generated from the $C.^2R.$ losses at such loads as will occur during the hottest time of the day.

This heat is then dissipated by :—

(*i*) Radiation into surrounding space ; and

(*ii*) Conduction to the surrounding air.

21. *Heat received* H_s. Adopting a figure of 150 watts/cm² as the heat received from the sun and a radiation constant of ·25 for an aluminium surfaced cable (which is approximately equivalent to mercury or cast iron) we get the following results for cables for three different sizes recently investigated :—

Item No.	Al. Steel cable size Cir. Mils.	Diameter an exposed area/ cm. run.	Watts per cm. length.	
Col.	1	2	3	4
1	250,000	1·63	·0611	
2	300,000	1·78	·0667	
3	350,000	1·92	·073	

22. *Heat generated* H_g. In the case under consideration the total current under mid-day conditions amounted to 383½ amperes and assuming standard resistances for the cables under consideration, based on an assumed cable temperature of 130° Fah., we get the following total energy generated per centimetre length :—

Item No.	Size cable C. M.	Ohms 1,000 ft.	C^2R foot run.	Watts Cm. run.	Total $H_r = H_s + H_g$ Watts Cm. length.
Col.	1	2	3	4	5
1	250,000	·07	10·32	·339	·4001
2	300,000	·588	8·66	·284	·3508
3	350,000	·0504	7·43	·244	·317

23. This energy has then to be both radiated and conducted into the surrounding air with a temperature in the cable of T_c ° Cent. (absolute) and in the air of say 115° Fah., *i. e.*, 46, 1/9° Cent., or 316° Cent. (Abs).

24. *The heat radiated* (E_r) from a body of temperature $T^\circ c$ Abs. to the surrounding space at a temperature 319° Abs., is by Stefan's Law :—

$$E_r = K\left(T_c^4 - T_a^4\right)A \times r.$$

Where :—$K = 5{\cdot}35 \times 10^{-12}$ Watt Secs. per cm^2
$T_a = 319°$ cent. *i. e.*, the air temperature.

A=Exposed Area=$\pi \times$ diameter of cable=π d and r=Radiation constant=·25.

$$\therefore E_r = \frac{4{\cdot}205\ T_c^4}{10^{12}} - \frac{4{\cdot}375\ d}{100}$$

Similarly *the heat conducted* (E_c) to the surrounding air is :—

$$E_c = \frac{A\left(T_c - T_a\right)}{R_c}$$

Where R_c = Resistance to heat flow of combined cable and air, contact, in Watt Secs. Cm^2 Cent.° Units.

25. This is an unknown quantity, but can be approximated by using Peclet's formula—

$$R_c = \frac{1}{A+ABD}$$

Where :—
D=Difference in Temp.° Fah. (Abs.)
and A & B are constants in B. T. U./Hour sq. ft. Fah.° Units and are :—
For dull metallic surface A=1·53
B=·0037
and R_c is the *Total* contact resistance for *two* Air-Metal surfaces, one each side of the plate.

$$\therefore R_c = \frac{1}{2A+2ABD} = \frac{1}{3{\cdot}16+{\cdot}0117\ D}$$

$$\therefore R_c \text{ in Watt Sec. } Cm^2 \text{ Cent.° Units} = \frac{1}{K\,(3{\cdot}16+{\cdot}0117\ D)}$$

where K=Unit conversion Factor=·579.

$$\therefore E_c = \pi\, d\left(T_c - 319\right) \times {\cdot}579\left\{3{\cdot}16+{\cdot}0117\left(T_c - 319\right)\right\}$$

From which E_c can be obtained (like E_r) in terms of T_c.

Total heat dissipated $\therefore = E_r + E_c = H_r$ (already computed).

26. This results in an equation of the form :—

$$aT_c^4 + bT_c^2 + dT_c = H_r$$

which can be solved graphically with the following results :—

Item No	Size of cable C.M.	$H_r \times 1000$	T_c	$T_c - T_a$ Cent.°	Temp. rise Fah.°
Col.	1	2	3	4	5
1	250,000	400·1	352	33¼°	60°
2	300,000	350 8	344½	25½°	45¾°
3	350,000	317·0	339¾	20¾°	37,1/3°

27. The temperature rise of the actual conductors above that of the surrounding atmosphere, therefore, varies from 20° to 35° cent. which is the sort of figure that might be expected in practice: up to date no research appears to have been done on the temperature rise of cables under tropical sun conditions: it is to be hoped that something of this sort will be done in the near future: the effect of the increased temperature on the ohmic resistance of the cables is very appreciable and has to be taken into consideration in all regulation problems.

28. We are, however, concerned, not with the temperature of the cable but with the temperature of the air in molecular contact with it (referred to in future as the "contact air)." At first sight it would seem that the temperature of the air in such close proximity *must* be very nearly equal to that of the cable: a number of corona curves have been worked out for temperature rise varying from 10° to 70° Fah. resulting in an enormous increase in the size of the cables necessary.

29. These are shown in curve D to E Chart No. 3 for interest's sake: they are of no practical value, however, since it stands to reason that if the heat is to be conducted from the cable to the surrounding atmosphere, the air, even in immediate contact, *must* be at a much lower temperature, otherwise no heat flow would take place. The "contact air" is therefore at some lower temperature intermediate between that of the cable and the atmosphere.

30. Assuming an absolutely windless day, the air heated up in the vicinity is carried away at once by convection currents, the velocity of which cannot be easily computed: for practical purposes, however, we are justified in assuming a wind velocity of a few miles per hour.

31. Assuming a breeze of 5 m. p. h., the actual quantity of air displaced by meeting the cable amounts to—$223{\cdot}5 \times d$ cub. cms. per second,

where d is the diameter of the cable. Assuming that the whole of this displaced air comes into contact with the cable (an assumption which is scarcely justified but is sufficiently accurate to start with, for our present purposes) the whole of the heat transmitted from the cable has to be received by this quantity of air: the result is an ordinary problem in heat transference with the following assumptions:—

(*i*) Specific heat of air = ·24 Calories per gram per degree cent.
(*ii*) Air density calculated for fair weather sea-level at—say 117° Fah. = 001103 grams/cc.
(*iii*) 1 Calorie = 4 195 Watt Seconds.

The resulting temperature rise of the contact air for a 250,000 C. M. Al. Steeel Cable works out to just under 1° Cent., *i. e.*, 1·78° Fahr.

32. If the air current were to drop 1 mile per hour the actual weight of air to be heated would be 5 times, or approximately 9° Fahr. We are, therefore, safe in assuming a maximum temperature difference between the "contact air" and the surrounding temperature of about 10° Fahr. This has been added to the temperatures quoted by the Meteorological Department as shown in Chart No. 1.

33. From the data now available it is possible to calculate S & J; see Table A.

34. Now $\text{rlog}\ \frac{s}{r} = K.V./J.$, so that $\text{rlog}\ \frac{s}{r}$ at any particular altitude, rises directly as the line pressure; it is therefore, a simple matter to calculate J for a number of different altitudes and from these the value of $\text{rlog}\ \frac{s}{r}$ for different line pressures: the corresponding cable diameters can then be ascertained, using Chart No. 2, provided the spacing is known.

35. The spacing to be adopted varies with the line pressure and for the purposes of this investigation can be assumed to vary in accordance with Chart No. 2. This curve is really only applicable to ordinary flat country conditions *i. e.*, "plains-construction": for mountain construction, however, it is often necessary to adopt much greater spacing for the lower pressures, since the spacing is then governed not so much by questions of corona and line drop, as by mechanical considerations such as contacts, etc., on long spans. As, however, there are generally sure to be short lengths of flat country at the higher altitudes where the cheaper "plains construction" can be adopted, it is usually safer to adopt the smaller spacing shown on the curve.

36. The resulting relations between cable diameter and altitude for line voltage varying from 44 to 132 k V are shewn on Table B and Chart No. 3.

37. The three curves marked B, C and D to E illustrate the effects of corona in increasing the cost of a line under these conditions due to altitude alone (B) also to altitude combined with a constant high temperature (C) and finally to the temperature rise of the air in immediate molecular contact with the cable. (D to E).

38. As an example of the use of the Chart, supposing it is desired to transmit 12,000 kW from Una (the junction of a proposed line from Mandi to Lahore and Ambala) to Kalka, a distance of 57½ miles :—

First, on the assumptions that this line will eventually have to operate at 132 kV so as to supply Delhi ; and

Secondly, on the assumption that the line will never be required to supply beyond Ambala and can, therefore, probably be designed for 66 kV only.

39. In the first case it will be seen that assuming the adoption of standard sized cables for those parts of the route above 4,000 feet a 350,000 C. M. cable will have to be used, while for everything above 1,100 feet a 300,000 C. M. cable.

40. Now investigations show that in order to supply 12,000 kW at Kalka at constant voltage (since the voltage drop from Ambala to Kalka and Simla will in any case approximate 10 per cent. necessitating a constant voltage supply at Kalka) it would only be necessary to instal a comparatively small amount of synchronous machinery at Kalka.

41. If, however, this line is to be operated at 66,000 volts, although from the point of view of corona a very much smaller cable could be employed, it will be found that in order to supply the same 12,000 kW at Kalka at constant voltage no less than 8,500 K. V. A. of synchronous machinery will be required even with cables as large as the above so that little if any economy will result by adopting the lower pressure.

42. There will, however, be some intermediate pressure between 66 and 132 kilovolts, which will require less synchronous machinery and at the same time will not necessitate such large cables for corona purposes. The decision as to the most economic voltage is hence a matter of considerable complexity and can only be arrived at by investigating several different pressures and plotting the results.

43. Again, supposing it is desired to transmit 4000 kW from Kalka to Simla with a pressure drop of only 10 per cent. investigations show that a pressure of 33,000 volts will require a cable of about No. O S. W G, size whereas the minimum size of cable permissible at the Simla end at 5,000 feet and over with 66,000 volts is about the same. Further enquiries have shown that the most economic pressure to adopt is one about 50,000 volts. In this case, however, the cables are so small that mechanical considerations precluded its use on all spans exceeding 2,000 feet and it is therefore necessary to recompute the whole problem using copper-clad steel in place of aluminium, resulting in the adoption of a line using No. 3 S. W. G. at 44,000 volts as the most economical all round.

44. The final selection of the best *route* for a mountain line, therefore turns upon this question of corona voltage : *e. g.*, it may often be worth while increasing the length of the line to avoid a change of cable size, from previously adopted standards.

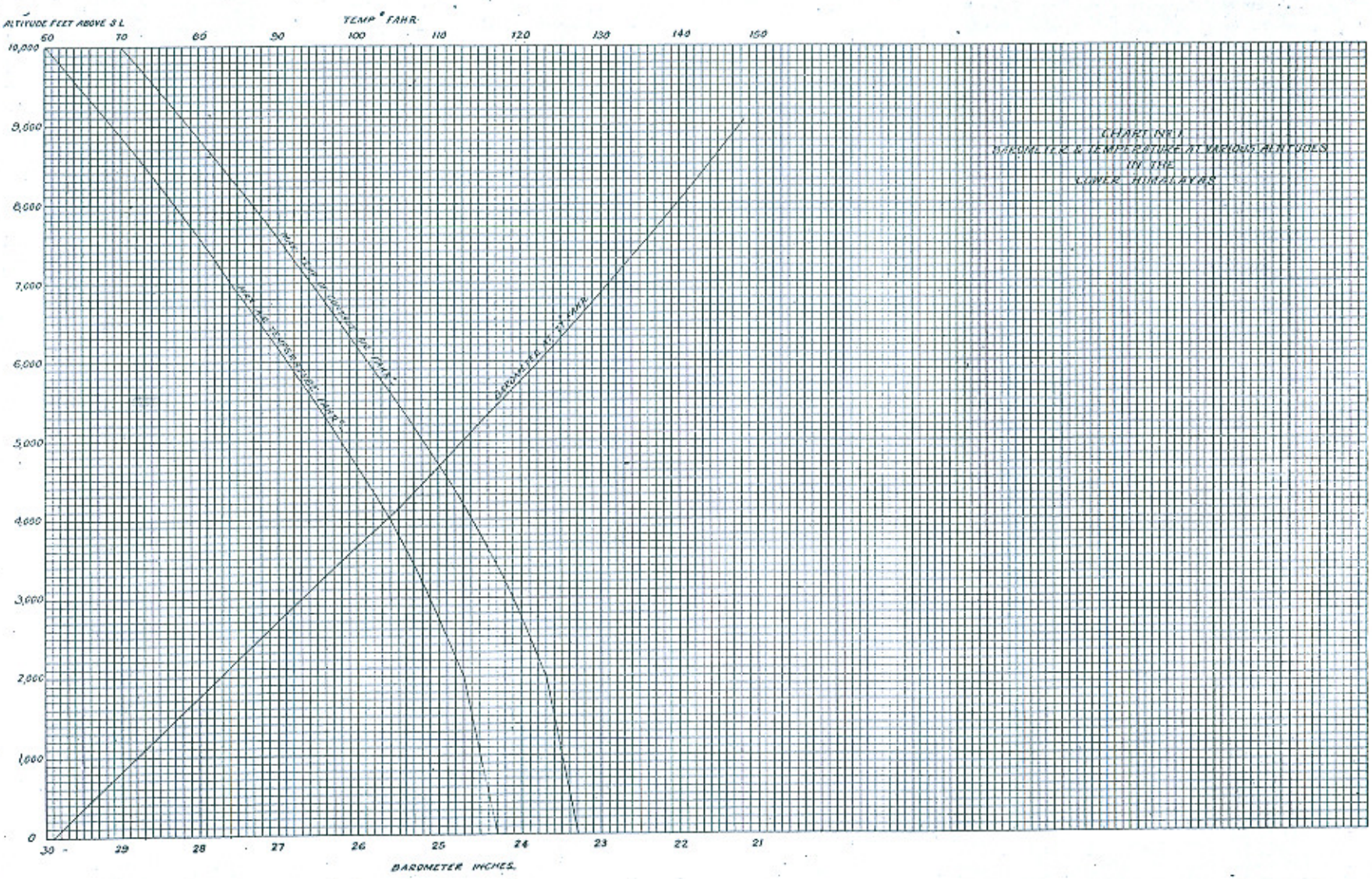
45. Thanks are due to Lt. A. Guthrie, R. E., for computing Chart No. 2 and to Lt. H. A., Kenyon, M. C., R. E., for computing the Tables and Chart No. 3 and for checking the heat calculations and proofs.

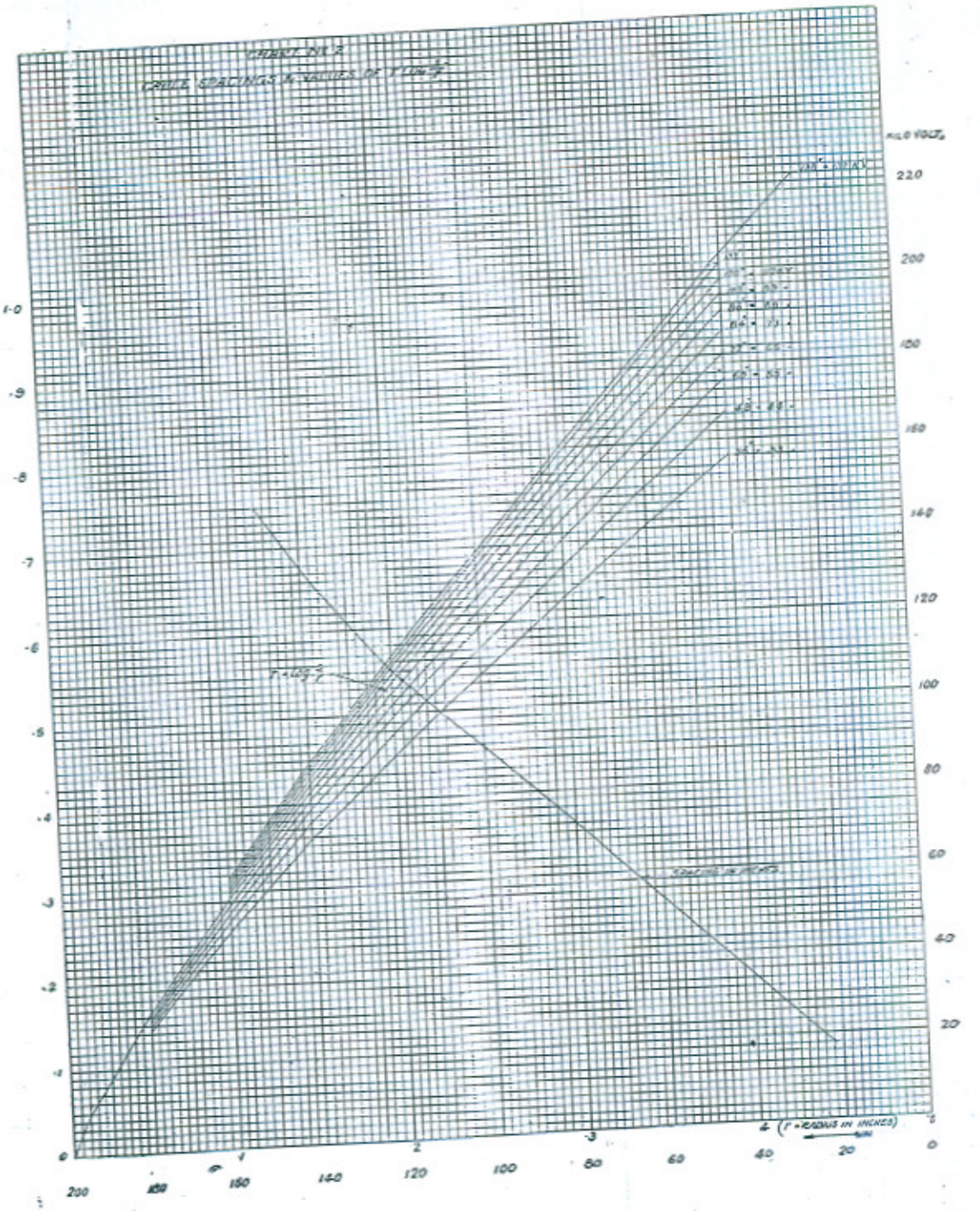
TABLE A.

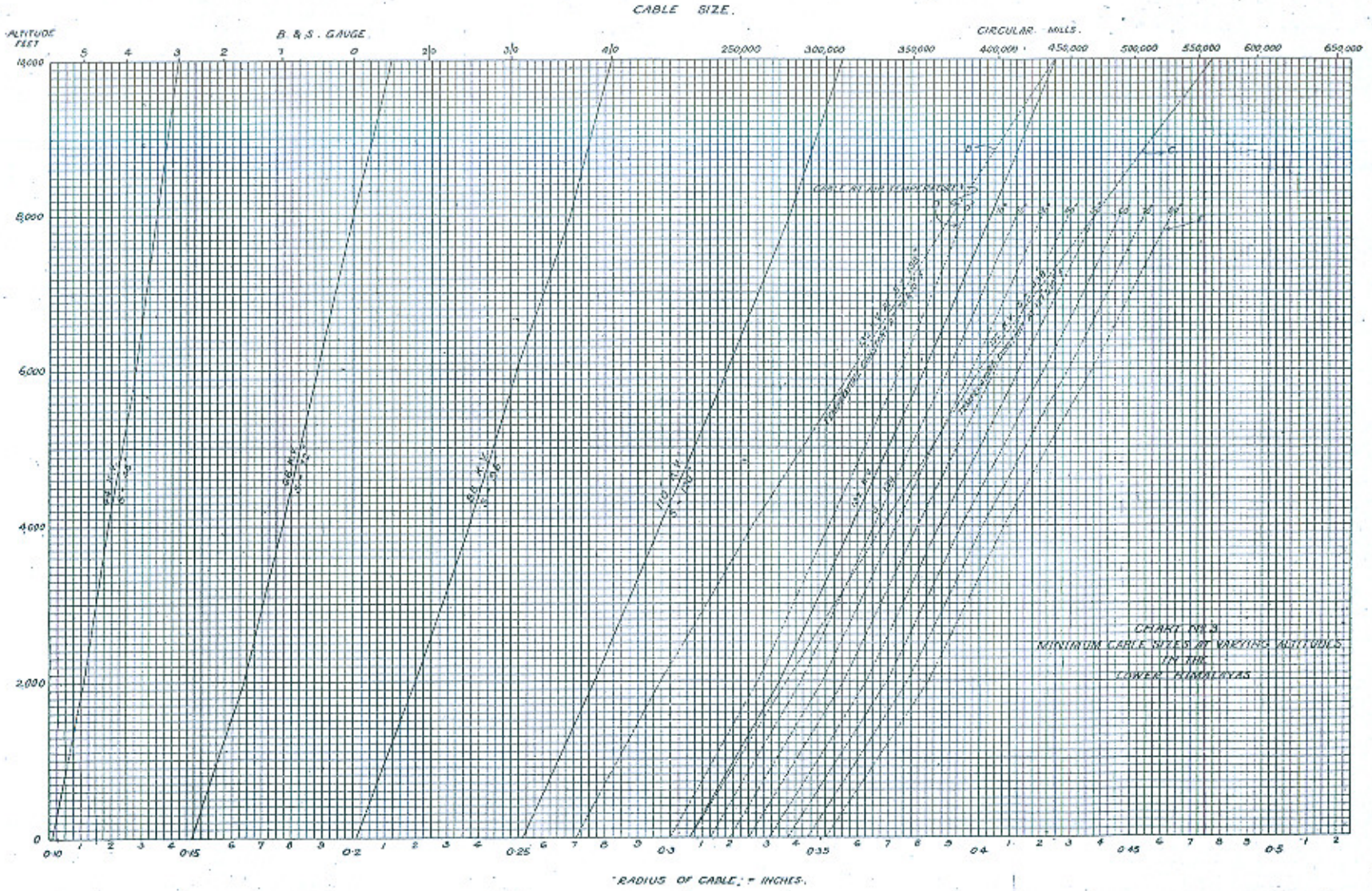
Item No.	Altitude feet.	B inches.	17·9 b.	t F°	459+t	(3/5) δ	J =178 δ	Remarks.
Col.	1	2	3	4	5	6	7	8
1	Sea-level	30	537	127	586	·915	162·9	
2	2,000	27·73	495	123	582	·851	151·5	
3	4,000	25·65	459	114	573	·801	142·6	
4	6,000	23·77	425	101	560	·759	135·1	
5	8,000	22·04	394	87	546	·722	128·3	
6	10,000	20·42	366	70	529	·692	123·0	

TABLE B.

Item No.	Altitude feet.	J	KV=44 s=48″.		KV=66 s=72″.		KV=88 s=96″.		KV=110 s=120″.		KV=132 s=138″.		KV=220 s=	
			$r \log \frac{s}{r} = KV/J$	r	$r \log \frac{s}{r}$	r	$r \log \frac{s}{r}$	r	$r \log \frac{s}{r}$	r	$r \log \frac{s}{r}$	r	$r \log \frac{s}{r}$	r
Col.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Sea-level	162·9	·2702	·101	·405	·147	·540	·201	·676	·254	·812	·306	1·351	
2	2,000	151·5	·2907	·111	·436	·164	·581	·220	·727	·277	·873	·335	1·452	
3	4,000	142·6	·3081	·119	·462	·177	·616	·237	·772	·297	·926	·358	1·541	
4	6,000	135·1	·3268	·128	·488	·188	·651	·252	·816	·318	·978	·382	1·629	
5	8,000	128·3	·3431	·135	·514	·200	·687	·269	·858	·338	1·029	·404	1·715	
6	10,000	126·0	·3578	·142	·537	·212	·716	·282	·895	·355	1·073	·425	1·788	


ALTITUDE FEET ABOVE S L
TEMP° FAHR.
50
70
80
90
100
110
120
130
140
150
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
30
29
28
27
26
25
24
23
22
21
BAROMETER INCHES.
CHART Nº 1.
BAROMETER & TEMPERATURE AT VARIOUS ALTITUDES
IN THE
KUMAON HIMALAYAS.


CHART NO. 2
CABLE SPACINGS & VALUES OF "f" (log f)
KILO VOLTS
220
200
180
160
140
120
100
80
60
40
20
0
1·0
·9
·8
·7
·6
·5
·4
·3
·2
·1
0
200
180
150
140
120
100
80
60
40
20
0
f (r = RADIUS IN INCHES)


CABLE SIZE.
ALTITUDE FEET
B. & S. GAUGE.
CIRCULAR MILLS.
18,000
8,000
6,000
4,000
2,000
0
5
4
3
2
1
0
2/0
3/0
4/0
250,000
300,000
350,000
400,000
450,000
500,000
550,000
600,000
650,000
COST PER MILE PER ANNUM
CHART NO 3.
MINIMUM CABLE SIZES AT VARYING ALTITUDES IN THE CENTRAL HIMALAYAS
0·10
0·15
0·2
0·25
0·3
0·35
0·4
0·45
0·5
"RADIUS OF CABLE" = INCHES.

DISCUSSION.

COLONEL BATTYE in presenting his paper drew attention to a misprint in paragraph 26 and explained that, owing to the short time available it had not been possible to carry out any actual experiments on the temperatures of cables under load in the sun during the hot weather. He then pointed out that even if this information had been available, it would only have been valuable for estimating the resistance of conductors for regulation purposes. It would by no means have cleared up the various assumptions that had to be made regarding the difference in the temperature of the actual cable itself and that of the area immediately surrounding and in molecular contact with the surface of the cable, which latter was the question of most immediate concern affecting corona limits. Under the circumstances it had been necessary to make certain assumptions, both as regards wind velocity and the manner in which heat was transmitted from the cable to the surrounding air. For the latter certain empirical formulæ ad had to be adopted, the basis of which had not been fully investigated prior to the completion of the paper.

The paper was an attempt to arrive at reasonable working data for estimating the cost of high voltage transmission lines in the lower Himalayas where the combined effect of altitude and temperature had to be provided for.

MR. PRESTON remarked that Colonel Battye's paper was very welcome as it indicated to other Engineers that the design and construction of overhead lines did not merely consist of putting up a few poles and slinging some wires on them. The problems to be solved in the correct design of overhead lines were as great as those in other Engineering Works both Civil and Mechanical and in the case of Hydro-electric Schemes involving long distance transmission the distribution and transmission system was often the most important and expensive part of the schemes. Not having had experience of long distance transmission in the hills he was unable to criticize Colonel Battye's paper in detail but thought that it presented a favourable opportunity of pointing out that Colonel Battye appeared to have changed his view since the Mandi site was discovered. Only 12 months ago in reply to a paper on the Electrical Equipment of the Railway Workshops Colonel Battye had stated that one of the great features of the Rupar Scheme was that no storage would be necessary at certain times of the year. However good the hydraulic features of the Mandi Scheme were, the site was undoubtedly less favourable than that at Rupar which was almost the centre of the load and was within comparatively easy reach of all towns between Lahore and Delhi whereas Mandi was nearly 300 miles from the latter place.

Further the fact that the transmission system for Mandi would cover ground, which, at certain times of the year, was very inaccessible and lacked communications did not augur well for Railway electrification. He considered that as regards site, Rupar was much the better scheme

and that if it could be developed at a reasonable cost it should be treated as an Imperial Project instead of a Provincial one and that its object should be to provide a source of energy for Railway electrification as well as for industrial purposes for the Punjab and Delhi Provinces. The situation of the proposed Mandi Scheme did not lend itself to this and he was of the opinion that unless the Railway would electrify, no scheme of this magnitude would be justified in the Punjab for industrial purposes only.

MR. MILNE pointed out that in paragraph 7 Colonel Battye advocated long span construction in the hills. In paragraph 8 he stated that spans of 5,000 feet had been used in the U. S. A. and that several spans of 3,000 feet and upwards were in use on the line from Chaba to Chair on the Simla system. He enquired as regards the former whether the spans referred to were not isolated spans of special, very expensive and elaborate construction which were rendered necessary on account of the configuration of the country which rendered it impossible to have intermediate towers or whether the author was referring to any particular system or systems which consistently adopted very long span construction on the score of economy and reliability.

With reference to the long spans on the Chaba-Chair transmission line, these were always a nightmare to Mr. Milne when he was responsible for the operation of the system. It was a foregone conclusion that this particular line would be out of service within half an hour of a snowstorm of even moderate intensity. The unfortunate experience of the practical operation of this particular line led to the abandoning of long span construction, wherever there was any likelihood of getting snow, when the reconstruction of the other two transmission lines on the system became necessary as the wooden poles with which they were originally constructed began to give out. Speaking from memory he believed the Chaba-Chair line was originally designed with a factor of safety of 2 under the worst conditions of temperature and wind but no allowance was made for snow. Actually, when constructing the line, the temperature at which the wires were strung was assumed to be some 20 or 30 deg. F. above the actual air temperature which of course increased the factor of safety, while when trouble was experienced on this line, the tension of all the long spans was reduced by putting in an extra strain insulator in series with the existing ones at each end of the span. In spite of these modifications trouble continued on the line whenever any snow fell.

Mr. Milne considered that there were so many unknown factors occurring in practice that in order to have a reasonably reliable line with long span construction in places where one met snow, it was necessary to introduce a large factor of safety in the calculations. If this were done for the worst conditions of snow and wind, it would, he considered, be found that with ordinary construction, the dip of the wires at times of maximum temperature would be so great that it would not be a practical

proposition to adopt spans of any abnormal length. If special construction in the way of steel bearer wires or automatic tension adjusters were adopted, the construction became expensive and of doubtful advantage from the economic point of view.

Another point of importance in long span construction in mountainous country was the fact that long spans obviously carry across deep valleys where the conditions of wind pressure, as recorded by the Meteorological Department did not apply. Abnormal and uneven pressures were obtained at various points along the spans which set up uneven and unestimateable tensions on both the wires and the structures.

As regards the liability of contacts, this was a matter of very little concern as contacts on a properly constructed line were of very rare occurrence in practice. They were hardly if ever known on spans of short or average length though theoretical calculations might show that such contacts were possible. Some experiments, extending over three months, which were carried out in Germany (it was believed) with two spans of 700 feet and three copper cables in each of ·23 square inch cross section, spaced at $23\frac{1}{2}$ and $31\frac{1}{2}$ inches respectively, shewed that with the smaller spacing the line swung into contact whenever a strong wind occurred. With the larger spacing, contact occurred only once and then with a hurricane blowing. When the wires were separated to $39\frac{1}{2}$ inches no contacts occurred.

As regards the effect of air temperature on the disruptive critical voltage, it appeared that with the varying conditions of temperature throughout the year, the question of deciding on the temperature that was to be adopted as a basis for calculation, evolved itself into a problem similar to Kelvin's Law for the most economical size of conductor in which it was necessary to adopt *average* conditions in combination with *average* loads to be dealt with. If the worst conditions were adopted any saving effected during times of operation under such conditions was likely to be more than counterbalanced by loss in capital charges during other periods of operation. Colonel Battye rightly said that the matter was one of extreme complexity and as there were so many speculative factors involved, both as regards the ultimate demand for energy on any particular line and the rate of growth of such demand, it appeared that the most satisfactory method to adopt was to use the minimum size of conductor possible to meet what was known to be the assured demand for a period of two or three years and during this period keep a close record of actual losses, both financial and electrical, under various atmospheric conditions and later on to alter the conductors in accordance with requirements from experience gained in the interim. This would at any rate ensure that there was no unnecessary over capitalization on the transmission in the first few years of development, which was a matter of very great importance.

MR. H. W. NICHOLSON in comparing the Bhakra and Mandi schemes considered that in going in for the latter the Author had now

found himself faced with serious transmission difficulties. He suggested that it was now time that one scheme was definitely decided on and seen through to the end.

COLONEL BATTYE, in reply to Mr. Preston's charge of inconsistency, pointed out that in the discussion referred to he had been dealing with some of the advantages of water power projects of the river flow type, of which the Sutlej River was an example, pointing out that these could be run at high load factor and could, therefore, be made the source of considerable bye-product power, for electrolytic and similar purposes, since they did not depend either upon seasonal or diurnal storage. The decision to drop the Sutlej River Project for the time being in favour of the Mandi scheme had been made on entirely different grounds, which, under the present circumstances, were of greater importance to the province than the provision of bye-product power. As Mr. Preston had criticised the adoption of the Mandi scheme in place of the Sutlej, it might be as well to use the present opportunity for explaining what had happened, although it was outside the real scope of the paper.

Colonel Battye then explained that in his report on the Sutlej River Project, he had definitely advised Government not to adopt the scheme, until certain difficulties connected with the scheme both technically and financially had been more fully investigated. After having investigated these matters he had advised Government to try and find some better site, for the first large scheme to be developed, and with this object in view had arranged with the Engineer in charge of the Hydro-Electric Survey to investigate the basins of the Ravi and the Beas before tackling other rivers. As a result of these investigations the Mandi scheme had been discovered. After going into the comparative advantages of the two projects it had been decided that, in spite of its longer transmission distances, the many other advantages connected with the Mandi scheme, which could be ranked amongst the 12 best sites in the world, far outweighed any advantages of position possessed by the Sutlej River scheme, at any rate, as a preliminary development. Under the circumstances it would be merely wasting public funds to develop the Sutlej in preference to the Mandi scheme. The chief objection to the Sutlej scheme was its long pipe-line and relatively low head, rendering speed regulation on rising loads difficult and necessitating complicated and expensive additions to the plant. The only alternative to this was an underground Power Station and for this the geological features were not suitable.

In reply to Mr. Milne he pointed out that he had concentrated most of his criticisms on a point touched on in the pre-amble which was really outside the scope of the paper. The whole question of long span construction would be fully dealt with later in part III of the paper. He pointed out, however, that there were in existence many lines contain-

ing long span construction of both the types referred to. Of these the first was usually used for crossing creeks, rivers or arms of the sea, while the Knoxville line was a recent example of the second.

As Mr. Milne had mentioned the matter he thought it would be as well to explain what had happened in the case of the Chaba-Chair line, which had apparently given him so much trouble.

In designing the transmission system for the Simla scheme, the experience gained by the Telegraph Department had been referred to as regards allowances for wind and ice. That Department which had had many year's experience of long span construction in the Himalayas had recorded the fact that no provision need be made for ice, as this had never been experienced. On the strength of this it had been decided to work to the usual factor of safety of 2 without ice. During the first year of operation, after the lines had been strung, ropes of snow up to 8" diameter had been experienced, under certain peculiar meteorological conditions, when the temperature was just about 32° Fah. and the snow was therefore, slightly sticky and there was no wind. The result was that most spans were immediately let out. Some of the long spans crossing valleys with dips of 500 feet, although made of silicon bronze conductors, could only have their factors of safety increased to $2\frac{1}{2}$ without snow by increasing the dip to the maximum amount permissible. Under the circumstances some of the long spans in the area above 5,000 feet altitude had given trouble. Recent enquiries from the Engineer in charge showed that most of the trouble experienced was not with the long spans, using silicon bronze, but with the more medium spans from 1,200 to 1,500 feet using No. 5 S.W.G. copper and especially where these passed through forests. Enquiry had also shown that the long spans below the snow line had never given a moment's trouble since they were first erected.

In all the more recent post-war estimates it has been decided to allow for snow ropes of 6" diameter combined with 1 lb. per square foot of wind pressure from 5,000 to 6,000 feet altitude and for $\frac{1}{2}$ inch of ice, combined with 11 lbs. per square foot of wind above 6,000 feet. If these conditions were combined with the use of aluminium steel or copper clad steel cables, on all spans exceeding 1, 500 feet no trouble need be anticipated.

All the spans of 2,500 feet and over on the Chaba-Chair line, of which there were a considerable number, used No. 3 silicon bronze conductors and had been so spaced as to render contacts physically impossible assuming maximum wind and complete out of phase swinging. When dealing with spans of this nature, with dips of several hundred feet, experience shewed that it was essential to take the effect of contracts into consideration (especially vertical contacts when snow might be experienced), although this was a matter of minor importance on short

span construction. Increasing the length of these long spans by a few inches due to the addition of an extra disc as tried by Mr. Milne would of course have no appreciable effect in reducing the tension on spans of this type in which the dip was often nearly a 5th of the span.

As regards Mr. Milne's final comment, Colonel Battye pointed out that the whole purpose of the paper was to ascertain the "minimum size" of conductor that could be adopted in conjunction with the most suitable voltage. It was, therefore, the problem of ascertaining this "minimum size" which necessitated an enquiry into the combined effect of altitude and temperature on corona limits. Although it was possible to raise the operating voltage after a few years operation, it was practically impossible to re-wire trunk transmission lines of the type under consideration. Such alterations might be feasible in the case of branch lines, but were out of the question on trunk lines in mountainous country. This being the case it was necessary to design the conductor to be capable of operating at the highest voltage eventually contemplated and that for which the towers and their spacings were designed.

Mr. Nicholson's remark regarding "serious transmission difficulties" was scarcely justified. The difficulties of transmission were not greater than those associated with any ordinary engineering undertaking and the corona limits worked out in the paper could safely be adopted without at the same time involving any serious extravagance.

In conclusion Colonel Battye pointed out that he had discussed the paper to some extent with one or two officers of the Meteorological Department who criticised the assumptions made in paras. 28 and 29, pointing out that "the air in molecular contact with the cable would be practically at the temperature of the cable itself, although the gradient might be very high in the first millionth of a millimetre and that therefore, the only satisfactory way of dealing with the matter was to experiment on sound lines, with a view to ascertaining the air temperature at the wire surface in sunshine." As regards the first it was probable that the actual air in molecular contact with the surface of the cable became ionised and therefore, became a conductor, thereby increasing the effective diameter of the conductor and in consequence reducing the potential gradient at its surface. This in effect was the mechanism of the visual corona discharge. The effect of ionising was to automatically increase the diameter of the cable until a point of stability was reached. The air whose temperature had therefore, to be ascertained was probably an appreciable molecular distance from the cables and probably several degrees cooler. It was true that this was a point which could only be cleared up satisfactorily by research and it was intended to refer the matter to the research department at Schenectedy with a view to having experiments made to ascertain the exact corona limits of cables at varying temperatures both of the cables and the surrounding air.

The nearest approach to an experiment of this nature so far recorded would be found on pages 68 and 69 of Mr. Peak's "Dielectric Phenomena." The purpose of the experiment was to ascertain the corona limits with varying currents in the conductor. Incidentally however, this resulted in varying temperatures both of the conductor and also of the surrounding air, both of which were recorded. If therefore, the objections noted above were valid the corona limits should correspond closely with that of the temperature of the cable rather than of the air. He had not yet had time to analyse the actual results recorded but it appeared on inspection that the result was the reverse and tended to confirm the general conclusions of the paper.