We now assume that under these conditions the predetector signal-to-noise ratio is 5 db and that the receiver noise factor is 10 db, which implies that the IF bandwidth will be 1 mc. Let us now consider a 12-channel frequency-division multiplex system, with a baseband of 12–60 kc. Using straightforward frequency modulation such a system could be accommodated in the 1-mc band with a peak frequency deviation of about ±400 kc. Thus an fm advantage of 20 log 400/60, *i.e.*, 16 db can be expected, giving a signal-to-noise ratio of 21 db in the baseband. Holbrook and Dixon give the peak power of a 12-channel signal as 17.5 dbm at a point of zero relative level, but we will use a figure of 16 dbm. Hence, considering a 3-kc channel, the unweighted noise level will be $21-16+10 \log 1{,}000/6=27$ db below a milliwatt at a point of zero relative level. This corresponds to a noise meter reading of 46 dba at −9-db relative level. The over-all median path loss is 23 db less than the 99 per cent value, so that the yearly median noise level in a telephone channel would be 23 dba at −9-db relative level. This last figure may be pessimistic since under median signal conditions the full antenna gain may be realized, resulting in a 5-db improvement.

At first sight these performance figures seem quite practical, but it must be remembered that they apply to a link of only 240 miles, and that for 1 per cent of the hours of a year, *i.e.*, 88 hours, the performance will be worse than 46 dba. It may be very much worse in fact, because under the 99 per cent conditions the pre-detector signal-to-noise ratio is must about at the threshold value and any further deterioration will result in a disproportionate increase in channel noise level. Diversity reception should reduce fading range below 99 per cent signal level; there is little doubt complete outage will sometimes occur. Remember also that no allowance for intermodulation distortion has been made.

Admittedly, the performance calculation just carried out is based on insufficient data and a certain amount of estimate, but it is thought that the discrepancy between these performance figures and those expected of a link in a main toll route is too great to permit the use of this type of transmission at present, except under most difficult circumstances, where physical or financial obstacles preclude the use of more conventional means of transmission. There is, however, a strong probability that future improvements in technique will modify this rather pessimistic view, and we are therefore continuing the tests. It is hoped to add diversity reception to determine what advantages can be gained, and, in order to save time and labor, an automatic signal-strength analyzer will be incorporated in the equipment.

ACKNOWLEDGMENT

Several parties have collaborated in these tests. The equipment design was suggested by Standard Telecommunication Laboratories of London, England; the detailed design and manufacture were carried out by Fabbrica Apparecchiature Per Comunicazioni Elettriche, of Milan, Italy. The sites were provided by the Italian and Spanish Administrations, who were also responsible for power supplies and other facilities. Installation was carried out by F.A.C.E., with the assistance of Società Italiana Reti Telefoniche Interurbane, of Milan, and Standard Electrica, of Madrid, Spain. The Transmitter site is staffed by Standard Electrica, of Madrid, while the receiver site is staffed by S.I.R.T.I., who are also analyzing the records obtained. The coordination of the tests is the responsibility of Standard Telecommunication Laboratories Ltd., to whom we are indebted for much of the information in this paper.

Data on the Temperature Dependence of X-Band Fluorescent Lamp Noise Sources*

W. W. MUMFORD† AND R. L. SCHAFERSMAN†

Summary—**This paper is concerned primarily with the performance of fluorescent lamps as microwave noise sources at 9,000 mc. In particular, it deals with the temperature dependence of the excess noise ratio of an 8-watt lamp running at a lamp current of 150 ma in a 10° *E*-plane holder. It was found that 1) the bulb temperature is much higher than that with a lamp current of 75 ma encountered in the 90° *H*-plane circuit investigated previously at 4,000 mc, hence the temperature coefficient of excess noise versus waveguide temperature obtained in the 4,000 mc circuit does not apply, 2) anomalous and unreproducible inversions in the temperature coefficient at these higher bulb temperatures have been observed, 3) these anomalies can be avoided by operating the bulb at lower temperatures, 40°C to 50°C, where the lamps appear to be just as uniform and stable and probably just as noisy as they are at 4,000 mc.**

During the last five years, fluorescent lamps have been used more and more as microwave noise sources for measuring the noise figures of microwave receivers. When these lamps are operated at or near their normal bulb temperature, 40°C, their available microwave noise power is stable with respect

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* This paper is reprinted from TRANS. IRE, Vol. I-4, pp. 40–46; October, 1955.

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to time and quite uniform from lamp to lamp. It appears to be practically independent of lamp current, bulb size, and frequency. These remarkable characteristics have led many workers in the microwave field to adopt the commercially available fluorescent lamp as a standard noise source. For this use the excess noise ratio was quoted by Mumford to be 15.84 db when his waveguide temperature was 32°C. The observed excess noise[1] decreased at higher waveguide temperatures at the rate of −0.055 db per degree centigrade. It was realized that this variation was probably due to the accompanying change of mercury vapor pressure in the discharge tube, and that a more universally applicable temperature coefficient could be obtained if the bulb temperature instead of waveguide temperature were used. Consequently, Chinnock obtained some more data and found that, in *that particular circuit*, the waveguide temperature was 8° less than the bulb temperature measured at point A in Fig. 1, about one inch outside the active waveguide. In our present circuits, however, it is more practical, and probably more reasonable, to measure the bulb temperature inside the active waveguide. In order to tie our results in with Chinnock's data more closely, we have now measured the bulb temperature at point B of Fig. 1 and found it to be 13° hotter than the waveguide temperature. This, then, leads us to expect that the excess noise from a fluorescent lamp is 15.84 db at a bulb temperature (measured inside the waveguide) of 45°C and falls off at the rate of −0.055 db per degree centigrade above 45°C.

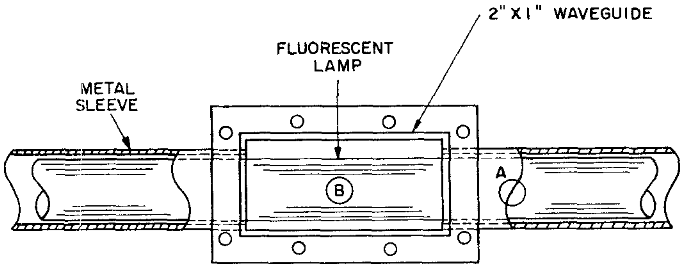

Fig. 1—90° H-Plane circuit used at 4,000 mc by Chinnock and Mumford in earlier work. The bulb temperature at A was 8°C hotter than the waveguide. The bulb temperature at B was 13°C hotter than the waveguide.

This relationship is plotted in Fig. 2, as curve C, together with the limiting values, the solid portion of curves A and D, observed by Chinnock on a sample of ten T-5 lamps running at 75 ma current. The work of Mumford and Chinnock was done at 4,000 mc.

At 9,000 mc, Harwick Johnson of RCA measured the bulb temperature coefficient of a T-5 fluorescent lamp running at 200 ma and obtained the relative data which, when plotted to coincide with curve C at 45°C, appears as curve B of Fig. 2. Also in this figure, plotted as circles, are the data on electron temperature by Adelaide Easley taken on a 40-watt T-12 fluorescent lamp running at 400 ma current. The agreement of these data is good, both in absolute value and in slope.

To apply these data to other circuits where the bulb temperature is greater, (in particular to the 10°E-plane circuits used at 9,000 mc where the lamp current must be increased to 150 or 250 ma to obtain a good impedance match) linear extensions have been drawn as dashed lines in Fig. 2. These extensions can be used to predict the performance of a fluorescent lamp as a function of waveguide temperature if the relationship between waveguide temperature and bulb temperature is known. Four curves of this relationship are presented in Fig. 3. Curves A and B are for the 4,000 mc circuit of Fig. 1 measured at points A and B respectively, with a lamp current of 75 ma. Curves C and D are for two 10°E-plane circuits in $1\frac{1}{4} \times \frac{5}{8}$ inch waveguide used at 9,000 mc,

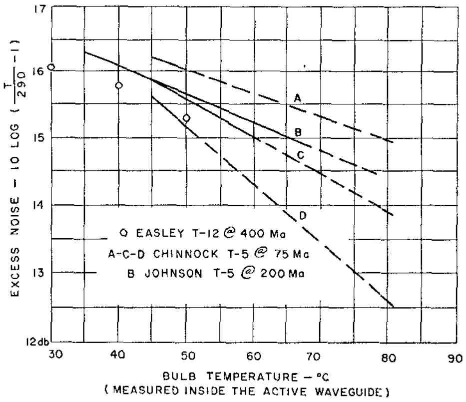

Fig. 2—Excess noise versus bulb temperature measured in the active region of the waveguide. A. Upper limit of Chinnocks' observations. B. Harwick Johnson's observations on a T-5 bulb at 9,000 mc with a lamp current of 200 ma. C. Chinnock and Mumford's observations on T-5 bulbs at 4,000 mc with a lamp current of 75 ma. D. Lower limit of Chinnock's observations. The points plotted are based on Easley's data on electron temperature measured on a T-12 lamp with a lamp current of 400 ma.

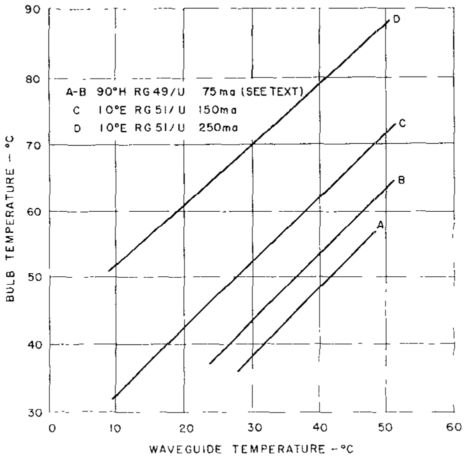

Fig. 3—Bulb temperature versus waveguide temperature for T-5 Fluorescent Lamps in various circuits.

A–B	90°H	RG49/u at 75 ma
C	10°E	RG51/u at 150 ma
D	10°E	RG51/u at 250 ma

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[1] The excess noise ratio is defined as $kTB\text{-}k290B/k290B$, where T is the noise temperature of the noise source.

with lamp currents of 150 and 250 ma, respectively. Curve D was obtained using the commercially available Kay Electric Microwave Mega-Node in RG51/U waveguide. Curve C applies to a similar circuit, mounted in a water bath, which was used in taking the data which will be presented here. From the curves of Fig. 3, we see that for a waveguide temperature of 40° the corresponding bulb temperature could be either 53°, 61.5°or 78.5°C, depending on the circuit and the current which is used. If one were to assume that the curve B applied to cases C and D, as some people have done, one could be off in bulb temperature by as much as 25°C, which might mean an error of over one db in the assumed excess noise.

Using the data of Fig. 3 and the extrapolations of Fig. 2 we can predict how we might expect the excess noise to vary with waveguide temperature for the two 9,000 mc circuits for 150 ma and 250 ma lamp current. This is shown in Figs. 4 and 5, respectively, where the predicted upper and lower limits and the curve based upon −0.055 db/°C are given. Also plotted in these figures are the data reported by J. H. Bollman of the Bell Telephone Laboratories in an unpublished memorandum. His average value, 14.6 db at a waveguide temperature of 32°, was based upon measurements made at 175, 200, and 250 ma. Hence it should appear low, as it does, on our 150-ma curves of Fig. 4 and high, as it does, on our 250-ma curves of Fig. 5. Actually his slope in Fig. 5 agrees fairly well with the predicted slope based on −.055 db per degree bulb temperature.[2] However, in Fig. 4 the agreement is poor. Bollman's data indicated a temperature coefficient of only −0.018 db per degree of waveguide temperature.

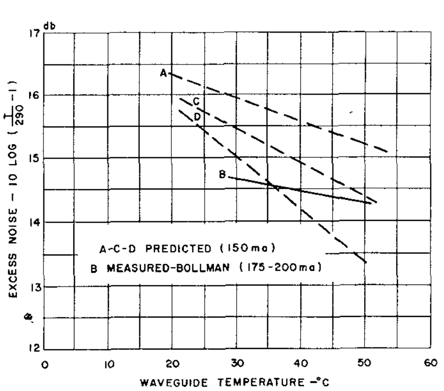

Fig. 4—Excess noise versus waveguide temperature for T-5 Fluorescent Lamps.

This discrepancy in temperature coefficient is but one of the things which disturbs us. The other is the large spread of the predicted values of excess noise at the usual operating waveguide temperatures of 40° to 50°C in the 10° E-plane X-band circuits. Also because there was a doubt that the linear extrapolations to the higher bulb temperatures were justified, an experiment was designed to explore the high bulb temperature region further. The measurements were directed toward the goal of a better comprehension of the limitations of these 9,000-mc fluorescent lamp noise sources.

For these measurements five new T-5, 8w fluorescent lamps were purchased locally and two lamps on hand were used. These lamps were numbered 1 through 7, with 1 and 2 being the lamps on hand. Lamp number five had an open filament and was discarded.

The excess noise was measured by noting the increase in output noise when a microwave circuit containing the lamp was applied to the input of a receiver whose noise figure was known. The excess noise was calculated from:

$$\frac{T}{290} - 1 = F(Y - 1).$$

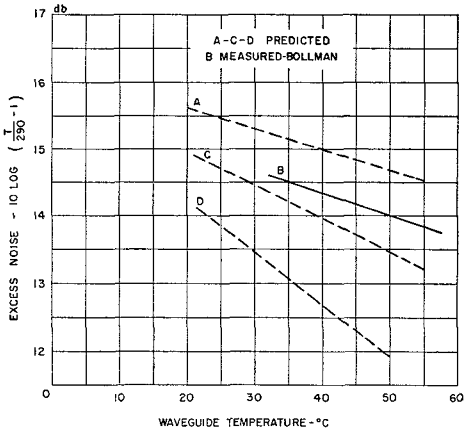

Fig. 5—Excess noise versus waveguide temperature for T-5 Fluorescent Lamps:
A–C–D Predicted for 250 ma
B Measured by Bollman at 250 ma.

Where $(T/290)-1$ is the excess noise ratio of the lamp under test, F is the noise figure of the receiver, and Y is the output noise power ratio with the receiver input terminated in the lamp and then terminated in a cold termination (290°K).

In order to have control over the rate of rise of waveguide temperature, the fluorescent lamp fixture was mounted in a water bath and the temperature of the water was taken and recorded as the waveguide temperature. The bulb temperature was measured with a calibrated thermistor in contact with the bulb inside the waveguide. The thermistor and its mounting were located on the side of the bulb, which was away from

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[2] If we had used Harwick Johnson's slope, Fig. 2, curve B, of −0.042 db per degree of bulb temperature, the agreement in slope would have been quite a bit better.

the microwave receiver and oriented to minimize disturbance of the electromagnetic field in the waveguide.

The procedure for taking a typical run was to start with cold water in the water bath, turn on the fluorescent lamp, and adjust its current to 150 ma. After a warm-up period in which equilibrium temperatures were established between the water bath and the bulb temperature, the measurements were begun. The output noise ratio Y was observed and the temperature of the water bath and the lamp bulb were recorded. Heat was applied gradually to the water bath from an external source and as the temperature rose slowly, readings of the Y factors were recorded along with the temperatures of the fluorescent bulb and its water bath. A complete run on one lamp was usually completed in two or three hours. The noise figure of the receiver was measured with an argon lamp (Philco L-1306, using 15.28 db for its excess noise) either before, during or after each run. From December 21, 1953, to January 6, 1954, thirteen runs (#I to XIII) were completed and the receiver was calibrated eleven times. The observed noise figure for these eleven calibrations ranged from 11.33 to 11.56 db. In order to see whether the receiver noise figure was changing during a run, the noise figure was measured for each point on the next four runs (XIV to XVII). The average standard deviation of the noise figure for these four runs (115 measurements) was only 0.022 db!

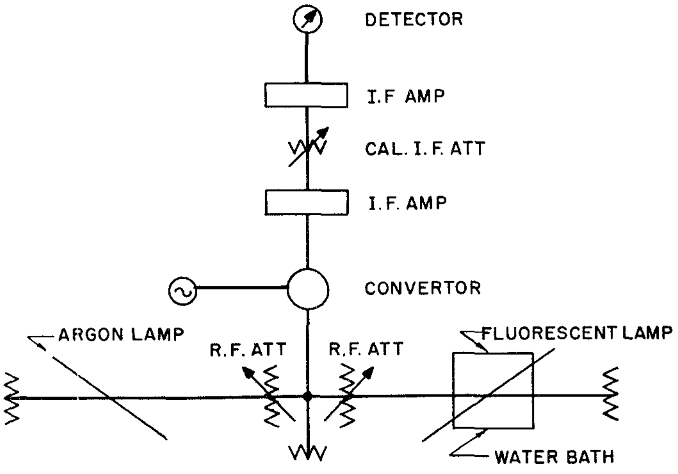

Fig. 6—Arrangement of measuring equipment.

The arrangement of the equipment for the last four runs was as shown in Fig. 6. Here we have two lamp holders connected to the input of the receiver through individual attenuators and a hybrid junction. The fluorescent lamps were inserted in one of the holders and the argon lamp standard was kept lighted in the other holder. By introducing attenuation in one branch, then the other, and then in both branches, the Y factors of both noise sources could be measured quickly. The data for a run on lamp #2 are plotted in Fig. 7. For comparison purposes the curves A, C and D of Fig. 2, which show the values predicted from previous data are superimposed. It is seen that these data on lamp #2 agree quite well with the predicted average value. Similar data on all six lamps are plotted in Fig. 8, which includes several runs on each of the lamps, and which gives an over-all picture of what was encountered. It is seen from this plot that the predicted values are lower than the observed values except in the region from 44° to 50° where the agreement is good.

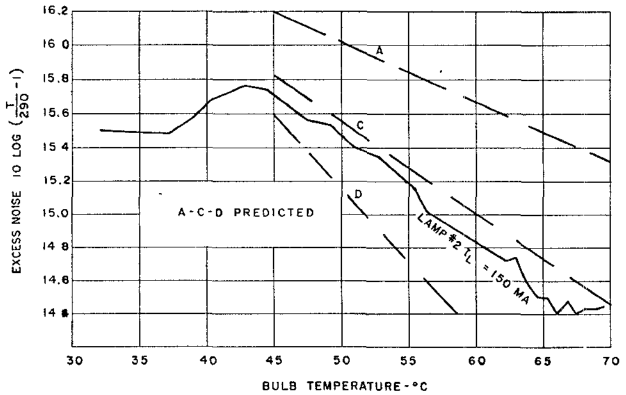

Fig. 7—Excess noise at 9,000 mc versus bulb temperature for one T-5 lamp running at 150 ma.

In looking at the data of Fig. 8, it can be seen that there are three general patterns or combinations of these three patterns. Runs which represent these patterns are plotted in Fig. 9, which gives the data on lamps #1 (run III), #4 (run XI), and #7 (run XV) as curves E, G, and F, respectively.

Table I summarizes the measurements with respect to type of curve obtained on all the runs. It gives the number of the run, the number of the lamp, the date, the

TABLE I

Summary of Excess Noise Data Versus Bulb Temperature on Six Fluorescent Lamps. Refer to Fig. 8 for the Key to the Pattern

Run	Lamp	Date	Pattern	Remarks
I	1	12/21/53	*E*	Preliminary run on an old lamp
II	1	12/22/53	*E*	Old lamp
III	1	12/23/53	*E*	Old lamp
VI	1	12/28/53	*E-F-G*	Old lamp
V	2	12/29/53	*E*	Old lamp
XVII	2	1/ 8/54	*E*	Old lamp
VI	3	12/30/53	*F*	New lamp
VII	3	12/31/53	*E*	Age 4½ hours
VIII	3	12/31/53	*E*	Polarity changed—Age 6 hours
XI	4	1/ 5/54	*G*	Age 16.5 hours
XIII	4	1/ 6/54	*G-E-F*	Age 20 hours
XIV	4	1/ 7/54	*F*	Age 22 hours
	4	3/16/54	*F*	Lamp touching waveguide—Age 25 hours
	4	3/17/54	*F*	Lamp not touching—Age 28 hours
IX	6	1/ 4/54	*E*	New lamp
X	6	1/ 4/54	*G*	Age 8 hours
XVI	6	1/ 8/54	*F*	Age 11 hours
XII	7	1/ 5/54	*F*	New lamp
XV	7	1/ 7/54	*F*	Age 2½ hours

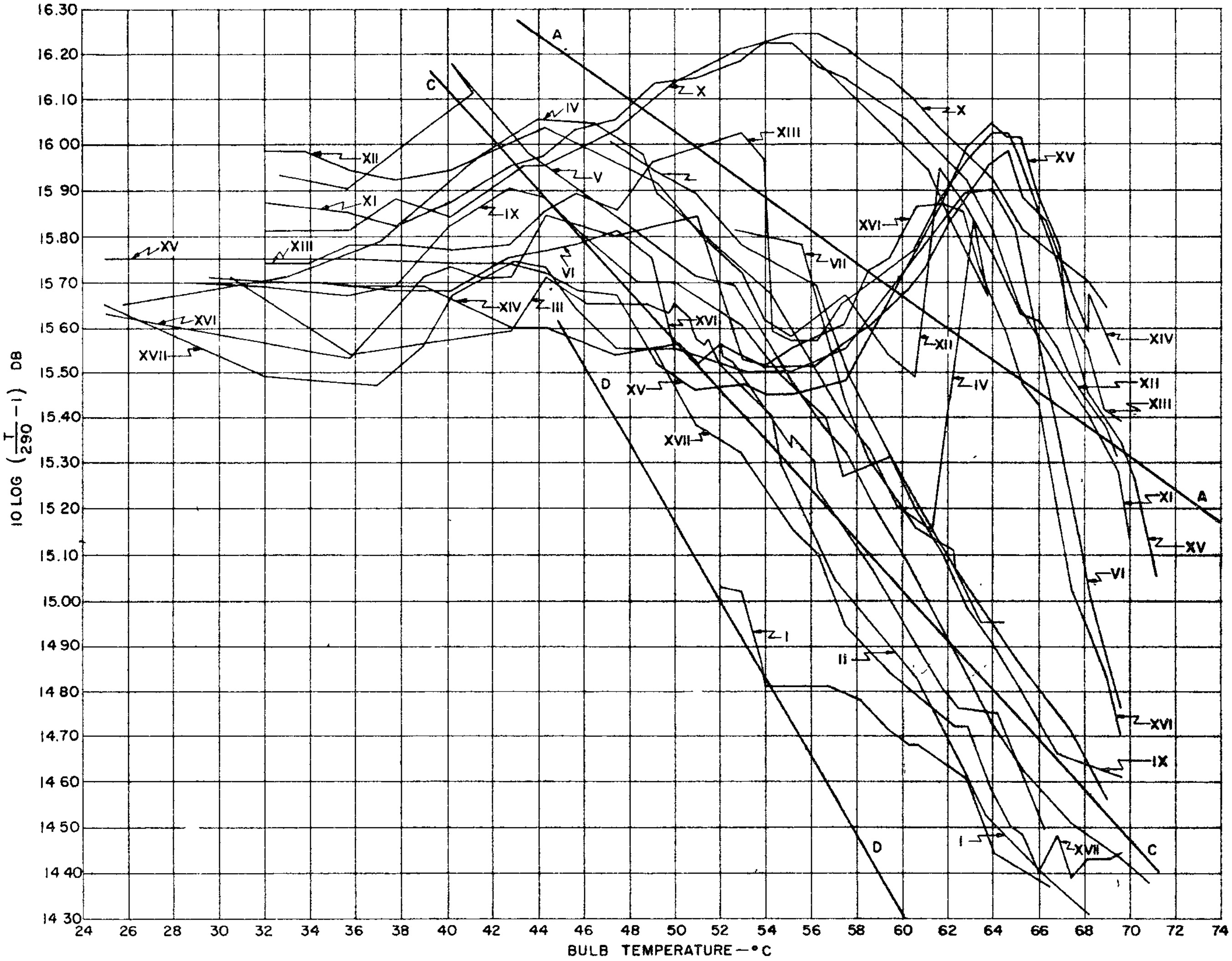

Fig. 8—Seventeen runs on excess noise at 9,000 mc versus bulb temperature for lamp current of 150 ma.

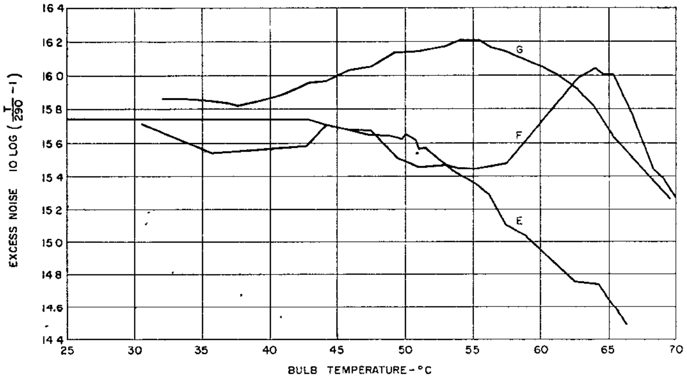

Fig. 9—Excess noise versus bulb temperature for T-5 fluorescent lamps at 150 milliamperes, showing three different parterns, *E*, *F* and *G*.

type of pattern and some remarks. Included in this table are two extra runs (not shown on Fig. 8), on lamp #4 which will be discussed later. The table shows that there are eight of the *E* patterns, seven of the *F* patterns, two of the *G* patterns and two runs in which combinations of all three patterns were evident. The two runs on lamp #2 were both of the *E* pattern, and the two runs on lamp #7 were both of the *F* pattern. On the other four lamps, some runs were of one pattern and other runs were of other patterns or combinations of other patterns. The insidious fact is evident, that a lamp may produce one of these patterns on one run and another on another run! Apparently we cannot depend upon a lamp to reproduce its curve from one day to the next at this lamp current, and we do not know why. Various excuses for this type of vagary have been offered, none of which, to date, has been substantiated.

It was suggested that interference from nearby radars caused the anomalies, but interference would have also shown up on the measurement of noise figure with the argon lamp on the last four runs.

It was suggested that differences in the mounting of the lamp in the circuit, *i.e.*, whether the lamp was touching the metal tubing of the circuit, thereby causing cooling of the bulb at that point, might cause the anomalous *F* type of curve. To check this point, two runs were

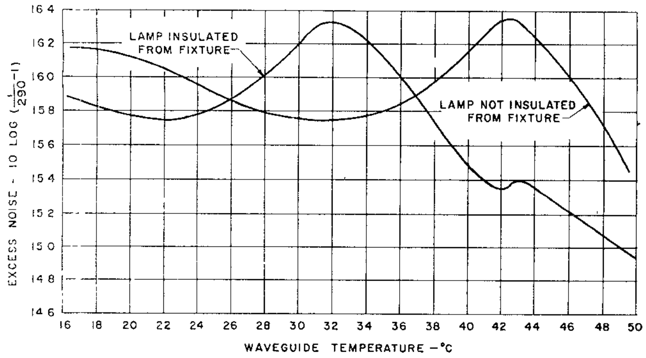

Fig. 10—Excess noise versus waveguide temperature for bulb touching and not touching the waveguide.

made on lamp #4 which had exhibited the anomaly, one run with the bulb located off center so that the bulb touched the brass tubing, and one run in which the bulb was insulated thermally from the circuit. These runs are plotted in Fig. 10. It is seen that there is a shift of the curve, but the anomaly existed under both conditions and in this case, at least, the reversal in slope was not due to this cause.

It was suggested that the reversal occurred only in new lamps, as, for example, shown by lamp #3. The data on lamp #6, however, does not support this hypothesis.

One suggestion which has not yet been followed up is that the anomaly is associated with oscillations of the discharge in the lamp. These oscillations which are bothersome at bulb temperatures *below* normal may appear again at temperatures *above* normal (by normal is meant 40–45°C, where these lamps are designed to work best as fluorescent lamps, and at which temperature they seem to work quite well as standard microwave noise sources).

The above data enables us to estimate better the reliability of fluorescent lamps as microwave noise sources at higher bulb temperatures. For this purpose Fig. 11 is presented, in which the limits of our present observations are given. At 45°C (bulb temperature), the average value of excess noise was 15.85 db and the spread was less than ± 0.25 db. This is in excellent agreement with values quoted by others at this and other frequencies. The normal bulb temperature of 8-watt fluorescent lamps running at 150 ma in a 10°*E*-plane circuit (such as the Kay Electric circuit) at room temperatures is 60°C and above, as indicated in Fig. 10. The average value of excess noise at 68°C bulb temperature was 15.06 db, with a spread of $+0.65$ db and -0.74 db. In addition to this rather large spread, these meager data indicate that there may be a good probability that the actual value for a single lamp may be close to either 0.5 db above the average or 0.5 db below the average, but one doesn't know which! Furthermore, the probability of its being nearer the average is very poor.

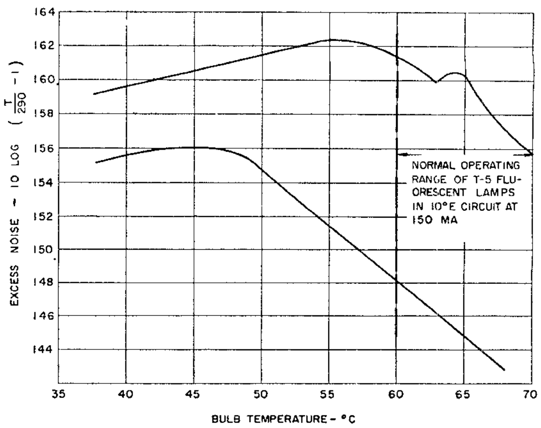

Fig. 11—Limits of present data on excess noise versus bulb temperature.

This evidence is based upon such a small sample that it can hardly be considered as conclusive. However, it does appear that unless measures are taken to maintain a bulb temperature between 40°C and 50°C, one should not expect the performance of the fluorescent lamp noise source to be adequate for precise measurements.

In view of this fact, it is suggested that argon lamps, such as the Philco L-1306 and Bendix TD-10 be used. The excess noise, 10 log $[(T/290)-1]$, for these lamps, is believed to be 15.28 db. Circuits and power supplies for the Bendix lamps are available from Kay Electric Company, Pine Brook, N. J. and from Waveline, Inc., Caldwell, N. J.

ACKNOWLEDGMENT

The careful work of Mr. C. E. Becraft, who made the observations and calculated and plotted some of the results, is gratefully acknowledged.

Mr. P. L. Hammann of the Bell Telephone Laboratories, Whippany, N. J., suggested that the X-band fluorescent lamp noise source be investigated and this suggestion came as a direct result of the observations of Mr. J. H. Bollman and Mr. L. L. Miller, of the Bell Telephone Laboratories at Murray Hill, N. J., who first observed these anomalies.

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