Long-Term Frequency Stability for a Reflex Klystron without the Use of External Cavities

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The reflex klystron is widely used as a tunable low-power oscillator in frequency-modulated microwave radio relay systems, both as the transmitter and as the local oscillator in the receiver. Automatic frequency control is generally used to limit frequency error due to drift of the transmitter klystron when the environmental temperature changes. In the TL Radio System developed at Bell Telephone Laboratories, the transmitting klystron frequency is stabilized by minimizing the effects of environmental temperature changes with completely passive methods. The 457A klystron frequency stability is better than 50 parts per million over an ambient temperature range of 100°C when used at mid-band. In the TL Radio System, the design objective for frequency stability of 500 parts per million is attained at extreme conditions of ambient temperature, atmospheric pressure, and voltage regulation; therefore the need for automatic frequency control has been eliminated.

The operating temperature of the 457A klystron in the TL Radio System is controlled by a liquid-vapor heat exchanger, which is described. The design of the klystron mechanical tuner includes compensation to minimize the thermal coefficient of frequency. The compensation feature is described, and typical results of the program to stabilize the klystron frequency are presented.

I. INTRODUCTION

The reflex klystron is widely used as a tunable low-power oscillator in frequency-modulated microwave radio relay systems, both as the transmitter and as the receiver local oscillator. Automatic frequency control is generally applied to the transmitting klystron to maintain the output frequency within acceptable limits. The frequency control is necessary because the klystron frequency is dependent on the operating voltages and the ambient temperature. The use of a high-Q stabilizing cavity in the output is not generally feasible since modulation is applied to the repeller of the transmitter klystron to obtain frequency modulation of the output. With well regulated power supplies, most of the frequency error is due to changes in the ambient temperature. This means that automatic frequency control mainly corrects for frequency errors due to ambient temperature changes.

Automatic frequency control requires a discriminator, coupled to the output of the system, which will develop an error signal when the frequency drifts away from the desired value. The discriminator usually consists of a high-Q stable reference cavity with associated networks to develop the proper error signal. For electronic automatic frequency control, the error signal is usually used to change the repeller voltage of the transmitting klystron in the direction and magnitude necessary to correct the frequency error. Changing the level of the repeller voltage affects the operating characteristics of the klystron, particularly the modulation linearity. Much less effect on modulation linearity is obtained when mechanical tuning of the klystron is used to correct for frequency errors due to changes in ambient temperature. In an electromechanical automatic frequency control, the discriminator error signal is used to actuate the tuning mechanism of the transmitting klystron to correct the frequency error. This method imposes requirements on the klystron tuning mechanism and the equipment needed for transforming the electric error signal to mechanical motion.

The TL Radio System uses the 457A klystron in conjunction with a liquid-vapor heat exchanger to eliminate completely the need for automatic frequency control of the transmitter. Stability of the output frequency over a wide range of ambient temperatures is obtained by completely passive methods. Two 457A klystrons, one as the transmitter and one as the receiver local oscillator, are used in each TL Radio unit. Essentially constant operating temperature for both klystrons is maintained by the constant boiling point of the liquid in the liquid-vapor heat exchanger. The effect of the residual temperature changes has been minimized by designing a temperature-compensating feature into the klystrons. Elimination of automatic frequency control results in lower system costs and maintenance. Further savings are realized since a blower to cool the klystrons is not required, and electronic automatic frequency control in the receiver is simplified because the receiver klystron frequency is also stabilized.

II. OBJECTIVES

The TL Radio System operates in the 10,700 to 11,700 megacycles common carrier frequency band. The design objective for frequency stability is a tolerance of ±0.05 per cent under all operating conditions for an ambient temperature range from −40° to +140°F. This objective was interpreted as an allowable error of ±5 megacycles. The allowable error was allocated to various parts of the TL Radio System; an error of ±2 megacycles was allotted for the 457A klystron and ±3 megacycles for variation in electrode voltages. In the klystron design this was considered to be an objective of less than ±1 megacycle error for thermal drift and less than ±1 megacycle error for mechanical variations due to shock or vibration. The objectives for the klystron were met, well within the maximum allowable error, by the following methods:

1. The mechanical tuner of the 457A klystron was designed to withstand the anticipated shock and vibration levels in the TL Radio System with a frequency error of less than 0.2 megacycle.

2. The klystron design was made compatible with the TL Radio liquid-vapor heat exchanger, which is an essentially constant temperature heat sink for the tube. The klystrons and heat exchanger are enclosed in a thermally insulated chamber to minimize the effects of changes in ambient temperature. The insulated chamber and liquid-vapor heat exchanger maintain the operating temperature of the klystron within 3°F for an ambient temperature range of −40° to +140°F at constant atmospheric pressure.

3. The mechanical tuner of the 457A klystron was designed to provide compensation for the thermal effects on frequency. The 457A specifications include a requirement that the thermal coefficient of frequency shall not exceed ±0.15 megacycle per degree Fahrenheit (klystron body temperature) when measured at the mid-band frequency of 11,200 megacycles. An adjustment of the compensation is provided so that the distribution during production may be maintained within these limits with an average value for the coefficient near zero. The specified thermal coefficient limits are equivalent to a frequency stability better than 50 parts per million over an ambient temperature range of 100°C for the operating conditions of the TL Radio System. The maximum thermal coefficient may be as high as 0.24 megacycle per degree Fahrenheit at an operating frequency of 10,700 megacycles. With extreme temperature conditions and maximum coefficient applied simultaneously, the frequency error due to thermal effects does not exceed 0.72 megacycle.

4. The klystron frequency stability is evaluated for the ambient tem-

perature range of $-40°$ to $+140°F$ at constant atmospheric pressure. Variations in atmospheric pressure will change the liquid boiling point and the klystron operating temperature. The extreme variation in atmospheric pressure for the worst areas of the country is not expected to exceed 0.75 pound per square inch or 40 mm Hg. This range of pressure will change the liquid boiling point slightly less than 3°F.

The effect of atmospheric pressure fluctuations is not included in evaluation of the klystron frequency stability for the following reasons:

1. Short-term variations in atmospheric pressure are generally small and are not correlated with changes in ambient temperature. The pressure effects may add to or subtract from the ambient temperature effects on the klystron. The combined effect will result in small random fluctuations.

2. Both ambient temperature and atmospheric pressure affect the klystron operating temperature in the same direction. That is, a decrease in ambient temperature or atmospheric pressure will lower the klystron operating temperature. Over extended periods of time, very low temperatures are frequently associated with high pressure conditions. The high pressure will oppose the effect of low temperature.

3. The entire ambient temperature range is used to evaluate the klystron frequency stability. This is equivalent to using the frequency at one temperature extreme as the reference. It is unlikely that any particular TL Radio location will be subjected to these extreme conditions. The additional margin obtained by adding the effect of adverse pressure conditions is not considered to be necessary.

III. LIQUID-VAPOR HEAT EXCHANGER

The liquid-vapor heat exchanger was selected as the simplest and most economical method for obtaining thermostatic control of the klystron frequency. The attributes of this method are:

1. No auxiliary power is required.

2. By attaching the liquid chamber directly to the heat source (the klystron body), an essentially constant temperature of the source can be maintained independent of ambient temperature.

3. The equipment is compact and the quantity of liquid required is small.

4. A wide range of klystron power input can be handled with negligible variation in operation temperature.

5. This method is completely passive.

The equipment used for making feasibility studies on the klystron is shown in Fig. 1. The klystron is bolted to the liquid chamber, or evapora-

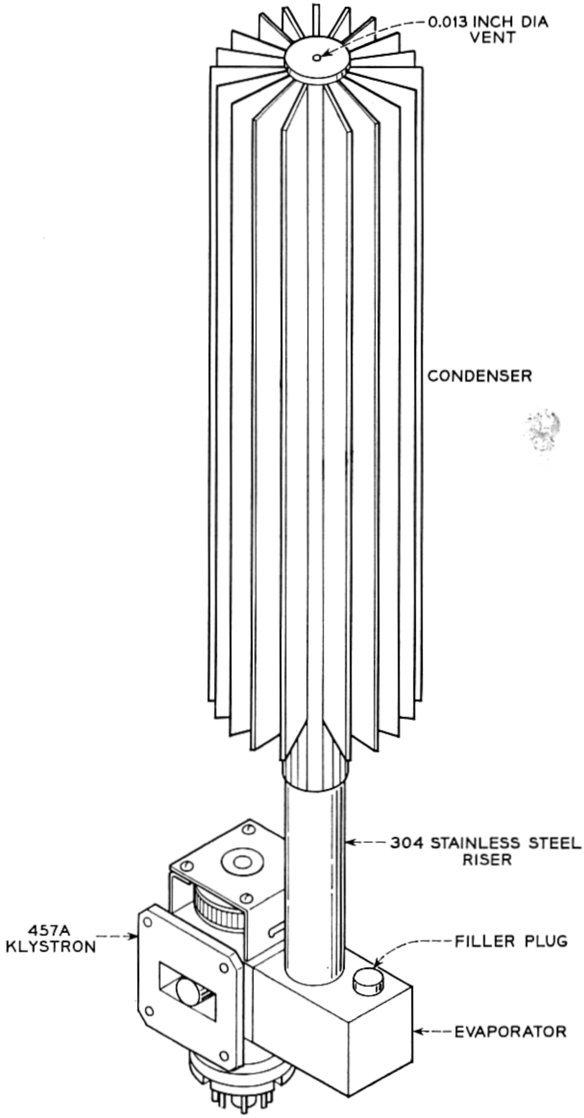

Fig. 1 — Experimental liquid-vapor system.

tor, and local boiling occurs at the evaporator wall attached to the klystron, which is the heat source. The contact surface is maintained at an essentially constant temperature slightly in excess of the liquid boiling point. In this common type of boiling, the heat energy is transmitted by conduction and convection to the liquid in contact with the heat source surface and then by convection from the liquid to the bubbles that form on the surface. The bubbles grow in size as more liquid is vaporized until they break away from the surface due to their own buoyancy and rise in the liquid. As a bubble rises, more energy is transferred to the bubble by vaporization and the size of the bubble increases until finally it bursts at the liquid-vapor interface. In the vapor region, condensation takes place on the condenser walls and the condensate flows down the walls to the liquid region. The energy released in condensation of the vapor is conducted through the condenser walls and finally dissipated to the environment by free convection and radiation.

Preliminary calculations, which were later substantiated by experimental data, indicated that an open system at atmospheric pressure was required to obtain a satisfactory temperature regulation for the klystron. A 0.013-inch diameter vent at the top maintains atmospheric pressure in the condenser and also limits the rate of liquid loss by evaporation to a satisfactory low level. Initial data were collected with 20 cubic centimeters of water in the evaporator. The low ambient temperatures anticipated for the TL Radio System involve a risk of equipment damage from freezing if water is used. A fluorocarbon liquid, FC-75, developed by the Minnesota Mining and Manufacturing Company, was also evaluated since this liquid does not freeze at temperatures as low as −80°F. The FC-75 liquid has a boiling point approximately the same as water, and both liquids were found to be equally satisfactory for controlling the klystron temperature. A slight advantage in the liquid loss due to evaporation was found with the use of the FC-75 liquid.

The feasibility study was made for an ambient temperature range of +35°F to +140°F. Typical results of this study indicated that the klystron body temperature varied by 20°F with a frequency change of 4.8 megacycles. Liquid loss measurements were also made for a 2000-hour (approximately 3 months) operating period. Typical results showed a total liquid loss of 3 cc. for FC-75 liquid and 5.5 cc. for water in the 2000-hour test period. In each case the test was started with 20 cc. of liquid in the evaporator, and temperature regulation of the klystron was not affected by the change in liquid volume. This study indicated that a considerable reduction in the effect of ambient temperature changes was possible with the liquid-vapor heat exchanger. The data collected during the study also indicated that the condenser could be much smaller and that reduction of the heat losses from the exposed surfaces of the klystron and evaporator would improve the temperature regulation of the klystron. Addition of thermal insulation around the unit yielded test results which substantiated these early conclusions.

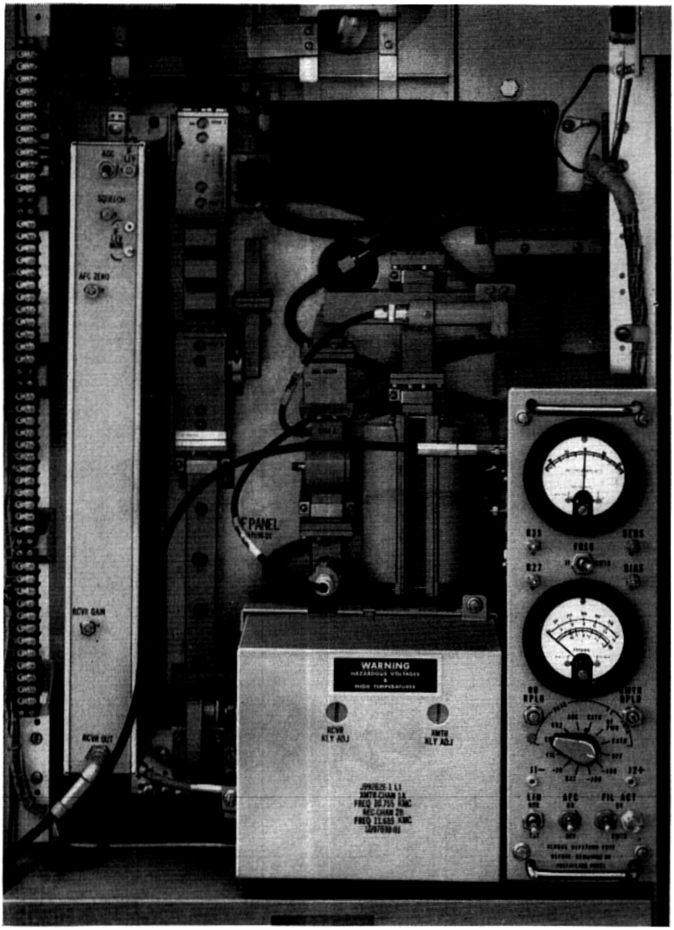

Fig. 2 — TL Radio System transmitter.

The experimental equipment shown in Fig. 1 was modified by molding an enclosure around the tube and evaporator of a very low density plastic (Eccofoam FP) having a wall thickness of approximately one inch. The insulation effectively isolated the klystron and evaporator from the ambient environment. Typical results of tests with the insulated unit indicated that the klystron body temperature varied 3°F for an ambient temperature range of $-40°$ to $+140°$F.

The experience gained during the feasibility studies led to considerable simplification of the final heat exchanger used in the TL Radio System. The appearance of the unit during operation is shown in Fig. 2. The

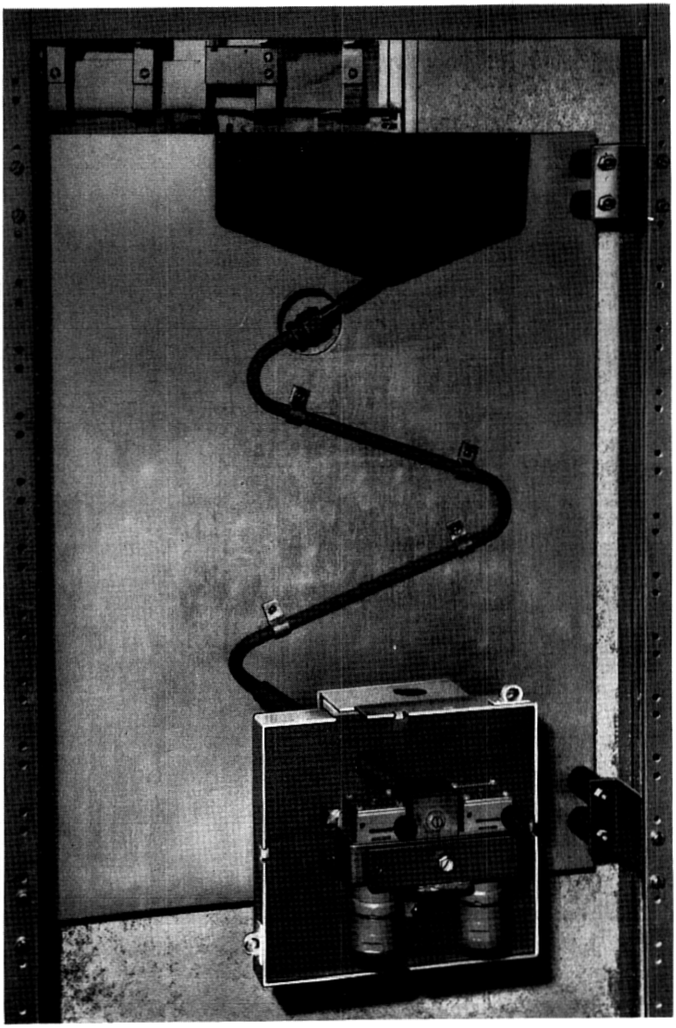

Fig. 3 — Cutaway view showing heat exchanger and condenser.

heavily insulated cover for the klystrons and the evaporator may be seen in the foreground. A cutaway view to show details is given in Fig. 3. Both the receiver and transmitter klystrons are cooled by a single evaporator. The condenser consists of a length of copper tubing clamped to an aluminum plate on which the receiver and transmitter components are mounted. The copper tubing is connected to the evaporator by stainless steel tubing to reduce conduction losses from the evaporator. The end of the condenser tubing is closed off by a rubber expansion chamber that is soft enough to permit expansion without any significant increase in pressure. The chamber, which may be seen at the top of Fig. 3, effectively limits loss of FC-75 liquid due to evaporation. Test results on this complete unit have shown that the temperature of the two klystrons is held to within 3°F for an ambient temperature range of −40°F to +140°F. These results, coupled with the thermal coefficient limits for the klystrons, mean that the thermal frequency drift of the transmitting klystron will not exceed 0.72 megacycle in the TL Radio System.

IV. 457A KLYSTRON THERMAL COEFFICIENT

The thermal coefficient of frequency for the 457A klystron is defined to be the change in frequency as a function of body temperature. The

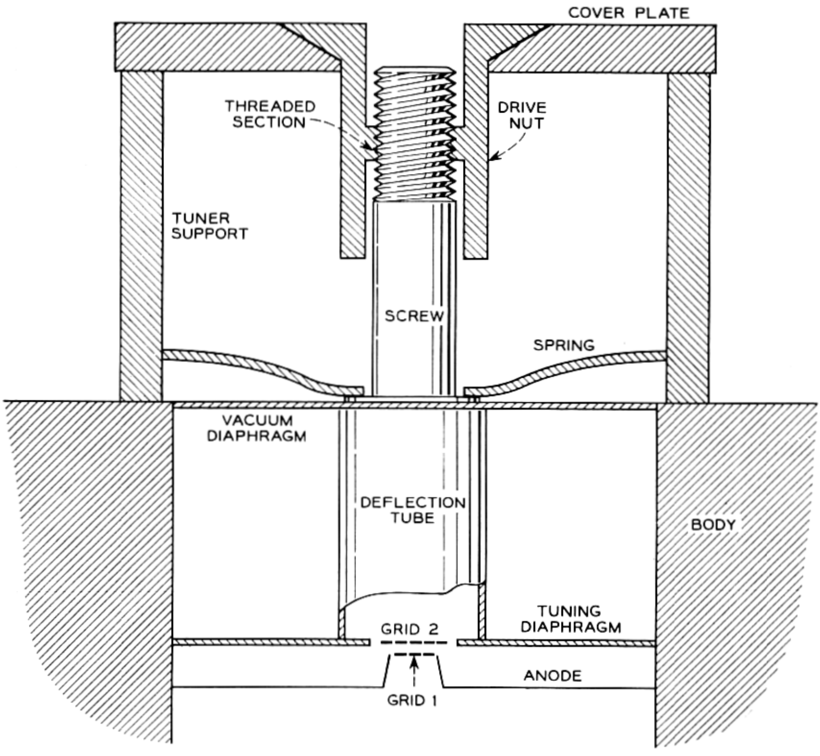

Fig. 4 — 457A tuner schematic.

limits for this coefficient are specified as ±0.15 megacycle per degree Fahrenheit when measured at the mid-band frequency of 11,200 megacycles. The klystron design includes a method for adjusting the coefficient so that the average value for continuous production of tubes can be maintained near zero. The tuning mechanism is shown in schematic form in Fig. 4. The frequency of oscillation depends on the spacing between the two grids. An increase in spacing increases the frequency; approximately six microinches change in spacing results in a one megacycle change in frequency. The first grid is part of the anode assembly, which is a rigid member brazed to the tube body. The second grid is mounted on the flexible tuning diaphragm, which in turn is connected to the vacuum diaphragm and tuning screw by the deflection tube. The drive nut seats on the cover plate, which is rigidly supported from the body by the tuner supports. The threaded section of the drive nut engages the tuning screw threads, and rotation of the drive nut moves the screw to change the grid spacing. A wormgear and tuning shaft, not shown in Fig. 4, are coupled to the drive nut to provide a means for manual tuning to any frequency from 10,700 to 11,700 megacycles. The tuner spring loads the screw to maintain intimate contacts between the threads and between the drive nut and cover plate. When the tube has been mechanically tuned to a desired operating point, the frequency is affected by thermal expansions of the various parts due to temperature changes. The frequency depends on the dimensions of the piece parts and their relationship to each other. The thermal properties of seven piece parts largely determine the thermal coefficient. These parts are: the anode, body, tuner supports, cover plate, drive nut, screw, and the deflection tube. Rigid control of the thermal properties of each part would be an expensive and complicated process. The degree of control required may be estimated from the thermal coefficient requirements in terms of grid spacing. The thermal coefficient is dictated by the TL Radio System requirements to within ±0.15 megacycle per degree Fahrenheit. To meet this requirement, the grid spacing change with temperature must be less than one microinch per degree Fahrenheit. A prohibitive accuracy of individual piece parts would be necessary to meet such requirements, and other factors, such as assembly variations, would further complicate the effect contributed by each part. Compensation for the gross effect of all thermal changes has been incorporated in the tube design, and adjustment of the compensation is included as a simple dimensional change on one piece part — the drive nut.

The basic principle of compensation is that at least two parts have opposite thermal effects. Adjustment of the compensation is readily made by changing the thermal expansion of one of these parts. The application of this principle to the 457A klystron may be explained with reference to Fig. 4. Expansion of the tuner supports increases the grid spacing with a resulting increase in frequency, while expansion of the drive nut and screw decreases the grid spacing and frequency. Expansions of all other parts may simply be considered to modify the relative effects of the supports, drive nut, and screw. The net change in grid spacing due to expansions of all parts determines the thermal coefficient of frequency for the klystron. The adjustable expansion characteristic is obtained by changing the effective lengths of the drive nut and screw, which are made from materials with widely different expansion coefficients.

The thermal coefficient of the klystron is defined as the frequency change in megacycles per degree Fahrenheit when the tube body temperature is changed within the range of 235°F to 255°F. The temperature range was selected to exceed the actual operating temperature changes in the TL Radio System but is small enough to assume that all thermal expansion coefficients of the parts are constants. The klystron thermal coefficient may be considered to be the result of two compensating expansions. Let $-E$ represent the expansion of the drive nut and screw combination expressed in terms of megacycles per degree Fahrenheit, with the negative sign indicating that frequency is decreased by an increase in temperature. Also let A equal the sum of all other expansions expressed in terms of megacycles per degree Fahrenheit, with the positive sign indicating that frequency is increased by an increase in temperature. The thermal coefficient (C) for the klystron may be simply expressed as

$$C = A - E \text{ megacycles per degree Fahrenheit.}$$

For the ideal coefficient of zero, A must equal E, and perfect compensation is realized. When the compensation is upset by unavoidable causes, for example by a new supply of raw material in some piece part, an adjustment in E can be made to again equalize the effects of A and E. This adjustment has been confined to the term E, since this is related to the drive nut. The materials used for the drive nut and screw were chosen to have widely different expansion coefficients. The bronze drive nut has a coefficient which is more than three times the coefficient for the iron-nickel alloy screw. The expansion of each part depends on its coefficient and effective length. By referring to Fig. 4, it is readily seen that the effective lengths of the drive nut and screw are determined by the mating of the threads on these two parts. Changing the position of the threaded portion of the drive nut changes the effective lengths of both parts. A considerable change in the klystron thermal coefficient can be attained by this method; the present piece parts can be modified to change the klystron thermal coefficient by as much as ±0.2 megacycle per degree Fahrenheit. Numerical values have been derived relating the dimensional change to the thermal coefficient change for application of thermal coefficient correction as required. The dimensional change in the drive nut is obtained by a simple machine set-up.

By application of reasonable tolerances on piece parts, adjustment of the thermal coefficient for individual klystrons is not necessary for production purposes. This is important since individual adjustment would require two thermal coefficient measurements, one before and one after adjustment. This would be a time-consuming and expensive procedure. A large assortment of drive nuts would also be required for selective use. For the first year of the 457A klystron production, the thermal coefficient for all tubes will be measured to obtain data on the distribution for the coefficient. Individual limits of ±0.15 megacycle per degree Fahrenheit will be applied to satisfy the TL Radio System requirements. On subse-

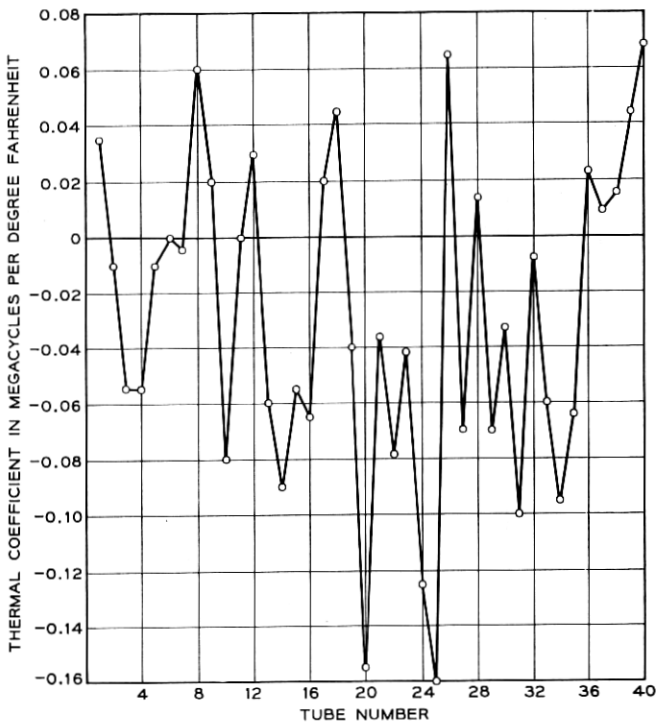

Fig. 5 — 457A thermal coefficients — 40 production tubes.

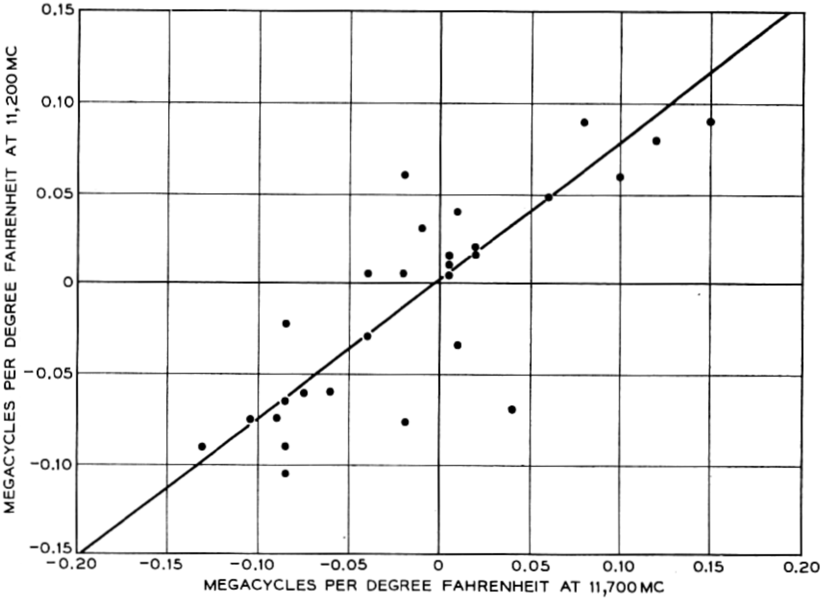

Fig. 6 — 457A klystron thermal coefficients.

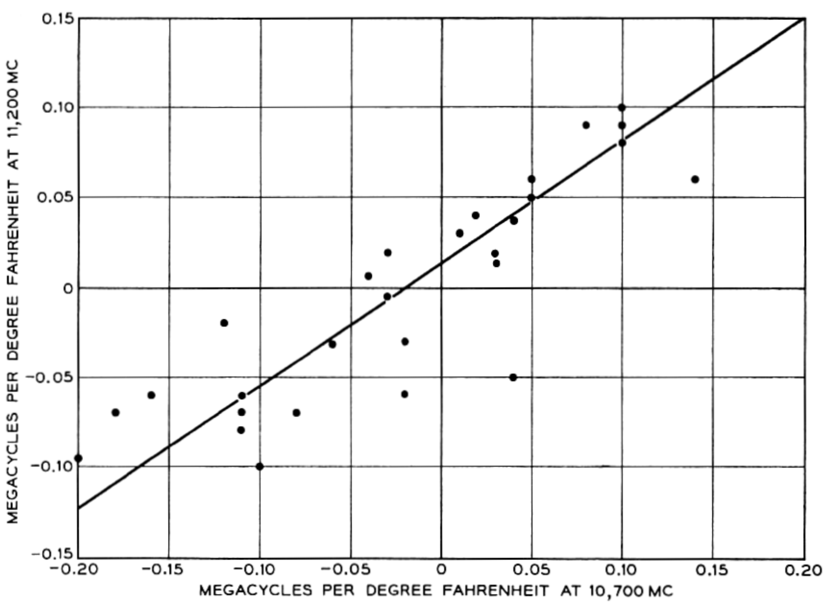

Fig. 7 — 457A klystron thermal coefficients.

quent production, the coefficient will be measured by a sampling plan to be determined by the experience of the first year of production. A dimensional change in the drive nut will be applied when necessary to maintain the average coefficient near zero.

The results of coefficient measurements for the initial 40 klystrons made under production conditions are shown on Fig. 5. These data show a distribution for the coefficient having an average of -0.029 mc per °F with a 3-sigma value of 0.165 mc per °F. This distribution represents early production experience with considerable variations in the supply of piece parts. For stable production with a continuity of supply, a tighter distribution is anticipated. Two individual points outside the 0.15 limit are shown in the distribution. In both cases a manufacturing deviation accounted for the dispersion. The data shown on Fig. 5 are for the thermal coefficient measured at the mid-band frequency of 11,200 megacycles. Correlation data for the coefficient at the extremes of the TL Radio frequency band are shown on Figs. 6 and 7. These data were collected on 28 tubes and indicate that limits of ± 0.15 mc per °F at mid-band correspond to limits of ± 0.20 mc per °F at 11,700 mc and $+0.20$ to -0.24 mc per °F at 10,700 mc. The extreme limits from these data will result in a frequency drift of 0.72 mc for the 457A klystron in the TL Radio System when subjected to an ambient temperature range of $-40°$ to $+140°$ Fahrenheit. For these extreme conditions, the 457A frequency error due to thermal effects is within the one-megacycle objective for the TL Radio System.

V. CONCLUSIONS

The frequency stability of the 457A klystron is within the TL Radio System objectives, and the need for automatic frequency control of the transmitter has been eliminated by passive methods. Elimination of the need for automatic frequency control reduces system costs and maintenance.

VI. ACKNOWLEDGEMENTS

As in any corporate development, many members of Bell Laboratories made important contributions to the designs of the 457A klystron and the heat exchanger. Particular mention should be made of the work of D. M. Sutter on heat transfer calculations, C. E. Apgar on the klystron mechanical design, and E. J. Neupauer on frequency drift measurements. The TL Radio System heat exchanger was developed at the Merrimack Valley Laboratories.