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(2) Development of
**A Very Low Noise
Traveling-Wave Tube.**

(1) Scientific Report No. 2,

~~Covering the Period~~

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ABSTRACT

The tube developed during this program met all of the objective specifications except that for a 2-db maximum tube noise figure. Theoretical and empirical data, however, indicate that this limit will be extremely difficult to achieve and that for a practical device the noise-figure limit based on the current state-of-the-art is about 2.5 db. Noise figures as low as 2.6 db were measured on tubes fabricated during this program.

The studies on low-noise techniques indicated that two basic mechanisms, operating either separately or in combination, were responsible for the low noise figures obtained in the objective tube. First, beam-cooling effects, based on crossed electric and magnetic fields, decreased tube noise by reducing the axial velocity fluctuations or by converting these fluctuations into a form that would not interact with the signal on the helix. Second, tube noise was reduced by the action of a dense space charge, which tends to dampen or filter space-charge waves in a slowly moving stream of electrons.

The major design effort during the program consisted of modifying the basic design of the electron gun structure of the RCA 6861 in order to incorporate newly developed noise-reduction mechanisms in the electron gun design.

A VERY LOW NOISE TRAVELING-WAVE TUBE

Scientific Report No. 2
Covering the Period March 15 to November 1, 1960

I. INTRODUCTION

The objectives of this program are to develop a very low noise traveling-wave tube and to demonstrate its operation at S-band frequencies. Traveling-wave tubes, because of their high gain, excellent stability, and broadband characteristics, are capable of exceptional performance as microwave amplifiers. Recently developed techniques for reducing the noise in these devices have greatly enhanced their already outstanding performance.

This report continues the discussion of noise-reduction techniques that was begun in Scientific Report No. 1. In addition, the success achieved upon incorporating various noise-reduction mechanisms in the objective tube is also reported herein.

II. TUBE PERFORMANCE VERSUS OBJECTIVE SPECIFICATIONS

The tube developed under this program was expected to meet certain objective specifications. Table I compares the actual tube performance with the objectives.

The tabulated data show that, with the exception of the tube noise figure, all of the objectives of the program were met and that sufficient guardbands exist on the specification limits to insure satisfactory tube performance. An

TABLE I
TUBE PERFORMANCE VS OBJECTIVE SPECIFICATIONS

<u>Characteristic</u>	<u>Objective Limits</u>	<u>Actual Performance</u>
Bandwidth	2.7 to 3.5 kmc	2.7 to 3.5 kmc
Tube noise figure	2 db (maximum)	2.6 to 4.0 db
Small-signal gain	25 db (minimum)	30 db (nominal)
Saturated power output	1 mw (minimum)	2 mw (nominal)
Focusing	solenoid	improved solenoid (jump-field focusing employed)
VSWR		
Input	2 to 1	1.3 to 1 (maximum)
Output	2 to 1	1.5 to 1 (maximum)

extrapolation of the empirical data, compiled during the studies of low-noise techniques, indicated that the theoretical lower limit of the noise figure in these particular tubes is possibly in the order of 1.5 db. However, variations in fabrication, processing, and tube operating parameters can be expected to raise this theoretical limit to a practical limit of approximately 2.5 db for this particular design. The succeeding paragraphs of this report describe those theoretical and empirical data that support this conclusion.

III. LOW-NOISE STUDIES

In Scientific Report No. 1, the general problem of reducing noise in traveling-wave-tube amplifiers was considered. The four noise-sensitive sections of the tube —

the cathode region, the beam-launching region, the impedance-transformation region, and the rf interaction region — were analyzed to determine where noise-reduction mechanisms should be applied and what types of mechanisms should be employed in order to achieve the lowest possible tube noise figure. On the basis of these analyses, the major effort of the program was expended in the design of a cathode which would best meet the low-noise requirements of the tube and in the development of optimum beam-launching techniques to insure a minimum of noise in the low-velocity drift region of the electron stream. In a secondary effort, steps were taken to reduce tube noise by selecting the optimum impedance-transformation method and by reducing rf circuit losses. This general approach to the noise problem in traveling-wave tubes has proved quite fruitful, in that, the noise figure of the objective tube is considerably lower than that of currently available traveling-wave tubes.

In the following paragraphs, some of the noise-reduction techniques discussed in Scientific Report No. 1 are clarified, and some additional noise-reduction possibilities are disclosed.

A. Noise-Reduction Mechanisms

The ultimate noise figure of a tube is a strong function of the cathode temperature and the physical nature of the cathode. The reduction in the tube noise figure below the value that corresponds to a given cathode temperature can be accomplished by either of two general methods, or by a combination of these methods. First, the noise in the electron beam can be decreased by

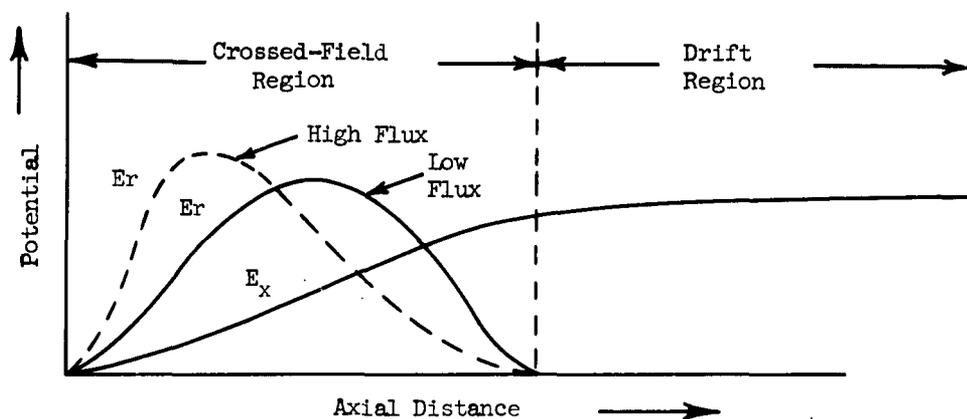
reducing the axial kinetic-voltage and current fluctuations or by converting these axial fluctuations into a form which will not interact with the signal wave on the tube helix. Second, the axial space-charge waves can be filtered or dampened to some degree by applying techniques which take advantage of the plasmic nature of a very slowly drifting beam of electrons.

B. Reduction of the Basic Noise in the Electron Beam

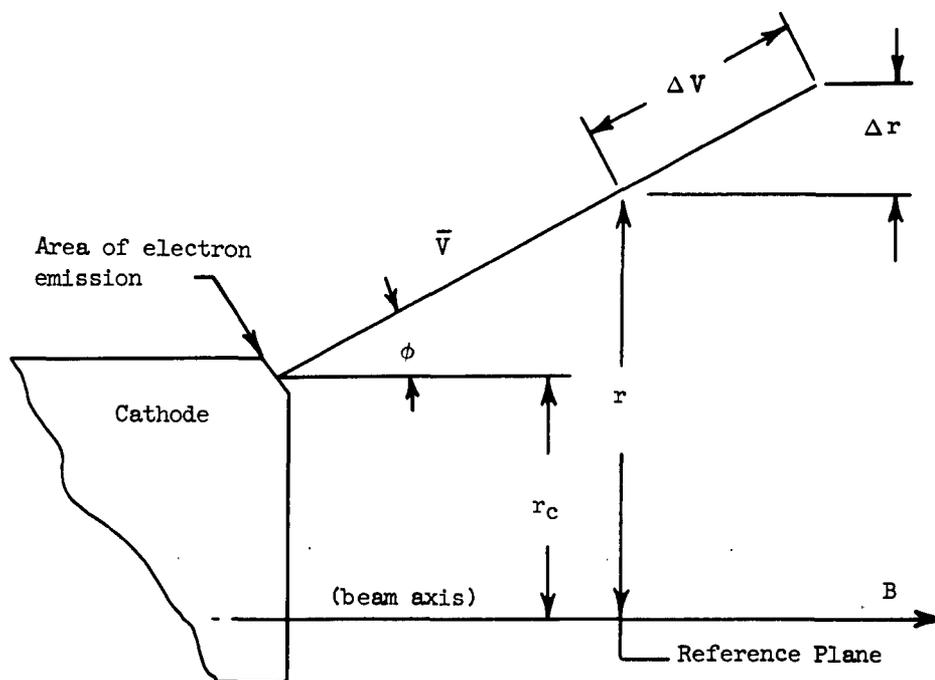
In Scientific Report No. 1, it was concluded that the basic noise in the electron beam could be reduced considerably by cooling the electron stream — that is, by decreasing kinetic-voltage fluctuation until the beam noise is below the level that normally corresponds to the cathode operating temperature. It was postulated that both electrostatic fields and crossed electric and magnetic fields could be used to achieve this cooling effect. A further analysis of the experimental test data indicated that of the two, the crossed field is the more effective cooling mechanism.

1. Effect of Crossed Electric and Magnetic Fields on Beam Noise. —

The very low noise tubes developed under this program have very specific beam-launching requirements. The beams must be launched into a two-dimensional electric field, which is strong near the cathode but decays into a relatively low-potential and lengthy drift region before the beam impedance is finally transformed to the impedance required in the rf interaction region. These conditions are illustrated in the approximate potential profiles of Figs. 5 and 14 in Scientific Report No. 1. These figures are re-presented here for convenience. (See Figs. 1 and 2.)



(a) Two-dimensional electrical fields possible at cathode-anode region.



(b) Launching Conditions

Fig. 1 — Noise reduction using cross-field effects to narrow the axial velocity spread of a beam of electrons.

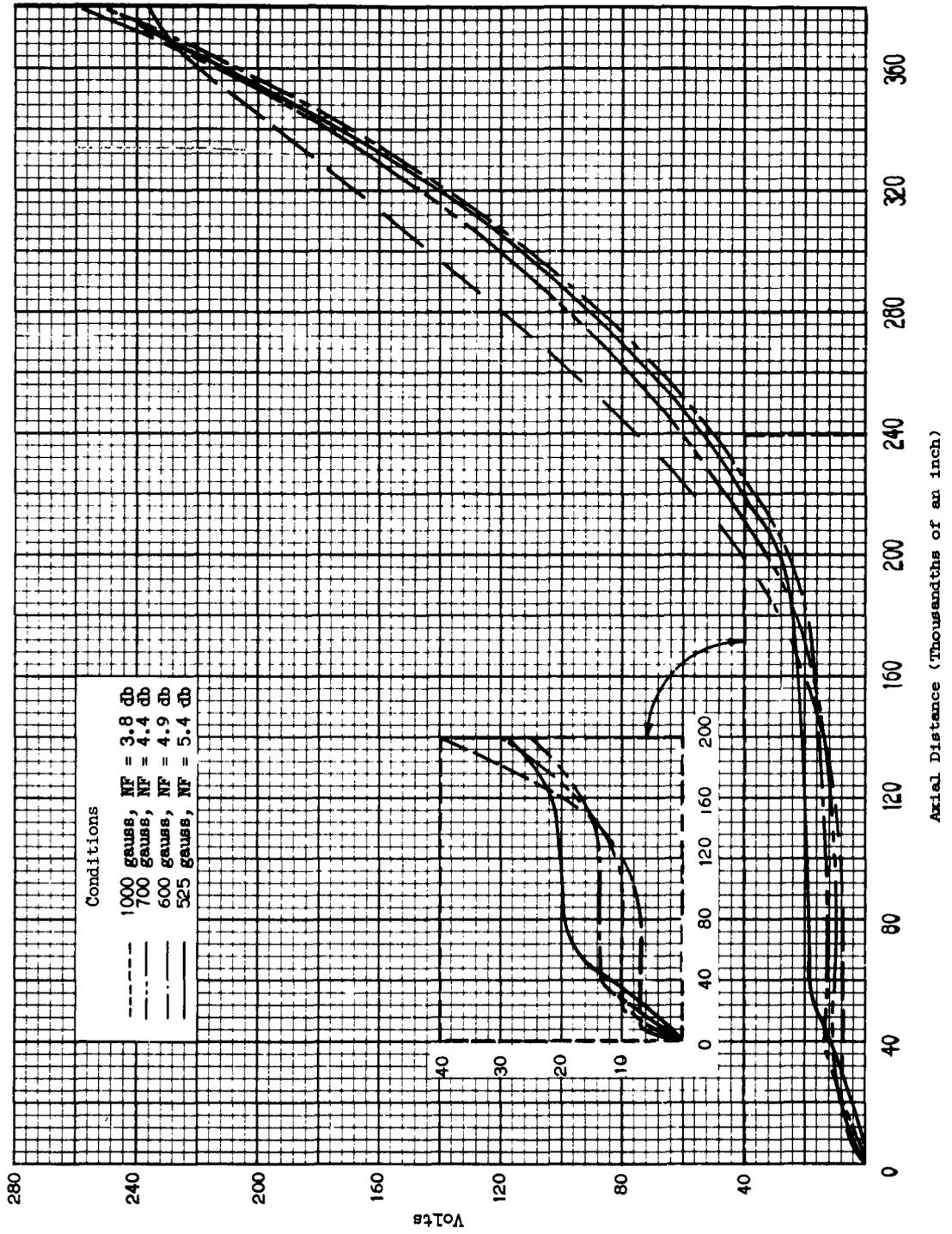


Fig. 2 -- Beam edge potential profile of a single RCA Type 6861 tube (Ser. No. 179).

An analysis of the data compiled in the evaluation of crossed-field noise-reduction mechanisms revealed the following:

1. For a fixed launching condition, as determined by the electron gun geometry and the potentials near the cathode, the tube noise figure is a strong function of the magnetic field, and it is periodic with this field.
2. The greatest noise reduction is usually obtained when the cyclotron frequencies, determined by the magnetic field, fall within the operating frequency band.
3. If the radial field component, E_r , is proportional to the beam forming voltage (voltage on grid No. 1), then the ratio of the radial field component to the magnetic field, E_r/B , is constant at the periodic points that show the greatest noise reduction.

The factors listed above are of great physical significance when crossed-field effects are being used to reduce the noise in the electron beam. The periodic variation of the noise figure, as a function of the magnetic field, is related to the focusing action of a trochoidal electron beam, launched under the crossed-field conditions. An analysis of the complex trochoidal motions shows that for some ratio of E_r/B , referred to as the field-neutralizing ratio, the trochoidal motion of the electron beam is a combination of a circular motion, at a frequency equal to the cyclotron frequency, and a precessional angular motion, $\dot{\theta}$. The angular precession is at a constant velocity, which is proportional to the field-neutralizing ratio. The velocity of the circular motion is proportional to the radius and is, therefore, a function of the magnetic field only.

The precessional angular velocity, $\dot{\theta}$, is an average drift velocity, in the θ direction, which is determined by the ratio E_r/B only and is therefore

independent of any components of thermal velocity. As shown in Fig. 1, the radial components of thermal velocities can interact and exchange energy with the radial component of the electric field. This concept was discussed in Section II, paragraph III-A of Scientific Report No. 1. The electric and magnetic fields are therefore adjusted to extract the maximum amount of energy from the radially displaced electrons. In essence, this requires that the electron move through one cycle of the cycloidal motion in proper phase with the radial component of the electric field in the cathode-anode region.

To extract the optimum amount of energy from velocity fluctuations that occur in the operating frequency range, the magnetic field should be adjusted so that the cyclotron frequencies are also in this range. This means that the electrostatic beam-launching conditions must be adjusted to maintain the ratio E_r/B at the correct field-neutralizing value.

Since the precessional velocity, $\dot{\theta}$, and the frequency of rotation, ω_C , do not change with the instantaneous velocity of the electron, the focusing of such a trochoidally launched electron stream is extremely constant, even when energy exchanges occur. This focusing causes a compression of the electron beam at the focal plane, which can be enhanced to some extent by a limited amount of shaping of the potential field gradient and magnetic field in the beam-launching region. These compression effects permit the development of the high space-charge current densities that are needed for space-charge filtering or dampening of the noise in the electron beam.

2. Effect of Space-Charge Dampening on Beam Noise. — Some reduction in noise current fluctuations has been achieved from the cushioning effect of a dense space charge located at the potential minimum. Although this noise cushioning effect is present in the tube being developed under this program, it will not be considered further here. This subject has been treated very adequately in the literature; moreover, the more recent noise-reduction theory emphasizes the plasma behaviors of a very dense stream of electrons.

Consider an electron stream that has been cooled by a reduction in the axial velocity spread of the electrons in the crossed-field region of the beam. If this electron stream is allowed to drift an appreciable distance at some relatively low velocity, an additional reduction in beam noise is usually observed. This drift region is shown in the potential-field plots of Fig. 1. The added noise reduction is attributed to the dampening effects on space charge waves of a slowly drifting electron stream, acting in conjunction with the smoothing effects of the magnetic field.

Figure 2 shows the beam edge potential profile as a function of the magnetic field. The shift of the drift region toward the cathode and the related decrease in the drift velocity, as a function of the magnetic field shown in the figure, are the results of changing the beam-launching conditions to compensate for higher magnetic fields. The launching conditions must be changed to maintain the proper field-neutralizing ratio.

After the electron stream passes through the drift region, the beam impedance must be transformed to the impedance required in the helix region. The manner in which this is accomplished must be one that causes a minimum amount of degradation in the tube noise figure. In general, the modified exponential type of impedance transformation is preferred, but a lens type of transformation may be more effective under certain conditions.

3. Effect of Space-Charge Filtering on Beam Noise. — The noise filtering action of a very dense space charge was considered to some extent in Scientific Report No. 1. In brief, a very slowly drifting cloud of electrons can act as a high-pass filter, in which the cutoff frequency is approximately equal to the plasma frequency. Thus, noise frequencies below the cutoff frequency cannot be propagated and will rapidly decay. Therefore, if the theory of space-charge filtering of noise is valid, then noise excitations below the cutoff frequency should be considerably reduced in the rf interaction region of the tube. This condition is illustrated by Fig. 3.

The figure shows that noise excitations below 3.8 kmc should be severely attenuated when the space-charge current density is in the order of 0.3 ampere per square centimeter. A simple calculation, on the tubes developed during this program, indicates that the space-charge current density in the beam-compressed region — that is, in the focal plane and drift region — is of this order of magnitude. Therefore, if such noise-shielding effects are present, the noise output of the tubes should rise sharply above 3.5 kmc. Such noise increases have

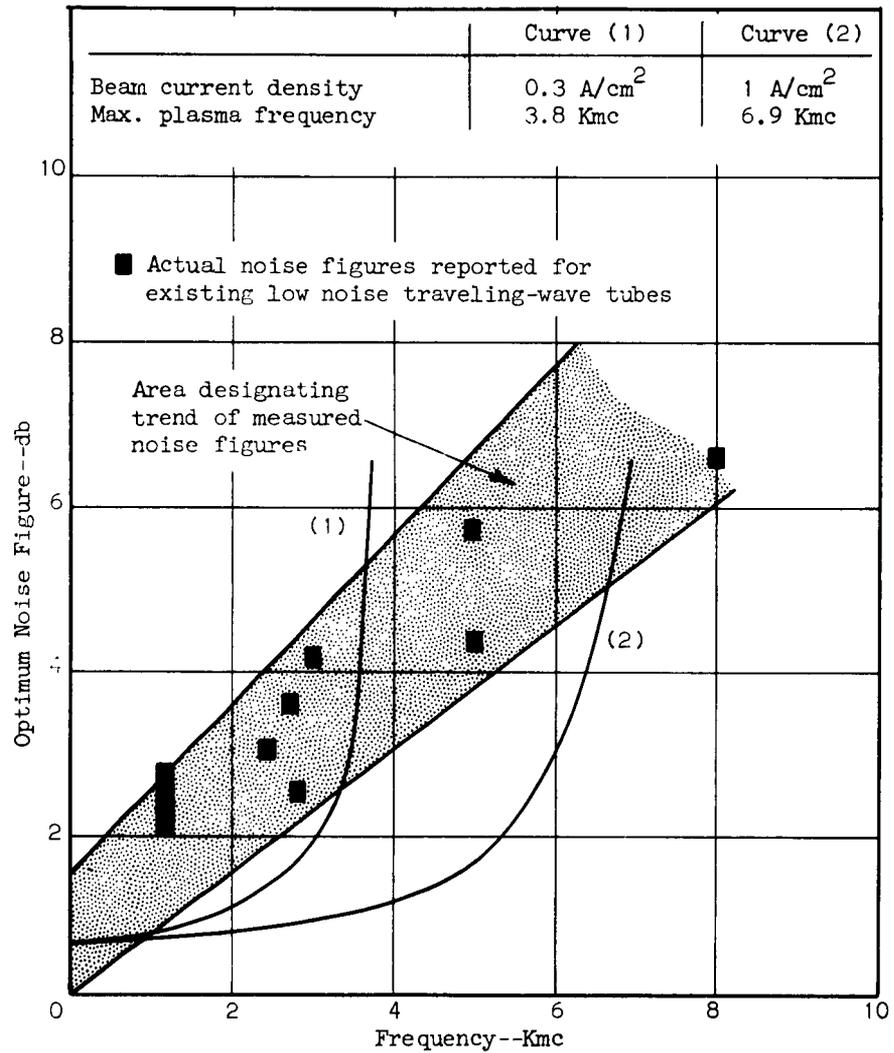


Fig. 3 — Theoretical optimum noise figure vs. frequency for various current densities.

been observed consistently during this program and are strong evidence to support the theory of noise filtering by a dense space charge. However, it must be remembered that an increase in shot noise in this frequency region has also been postulated,¹ and this factor complicates the analysis of the filter effect.

IV. TUBE DEVELOPMENT PROGRAM

The major effort during this program was expended in modifying the electron gun of the traveling-wave tube bottle design to improve the noise performance in these types of tubes. Early evaluations of an electron gun design based on that of the basic RCA 6861 traveling-wave tube indicated that this design was fundamentally capable of achieving tube noise figures in the order of 3 to 4 db.

In general, the improved electron gun design required:

1. A more extensive application of crossed-field noise-reduction techniques.
2. The development of a better low-noise cathode design, and the use of highly controlled cathode processing techniques.
3. The use of an impedance transformation process which would aid in decreasing the tube noise.
4. The utilization of space-charge cushioning effects to aid in reducing the tube noise.

The application of the techniques listed above has resulted in considerable reduction in tube noise. As discussed in paragraph III-A of this report, a significant amount of noise reduction was achieved from the cooling effects of the crossed

1. P. K. Tien and J. Moshman, "Monte Carlo Calculation of Noise Near the Potential Minimum of a High-Frequency Diode," J. Appl. Phys. , 27, 1067 (1956).

magnetic and electric fields, and from the dampening and filtering action of a dense space charge. Tube noise was also greatly reduced as a direct result of the cathode improvement program. The techniques developed for the fabrication and processing of suitable low-noise cathodes are described in the final report.

Some additional noise reduction was observed in experimental tubes that employed the lens type of impedance transformation. The requirements of this type of transformation, however, proved to be too critical in tubes that used the jump-field type of focusing solenoid. This incompatibility between the lens transformation and the jump-field solenoid was attributed to crossed-field effects, which caused the tube noise figure to become highly sensitive to frequency variations when the lens type of transformation was employed. Since the final tubes developed for this program will operate in a jump-field solenoid, the lens transformation was not incorporated in the final tube design. Empirical data indicate that if the magnetic-field configuration of the focusing solenoid were modified, the lens transformation could possibly be used to further reduce the tube noise figure.

Attempts were also made, during this program, to improve the noise-cushioning effects of the space charge by using an Einzel lens to create a second depressed-potential region in the tube, but these were unsuccessful. Experimental data showed that this depressed-potential lens system was unstable and that it tended to form an electron mirror under the conditions that were necessary to increase space-charge cushioning effects.

V. CONCLUSIONS

The theoretical and empirical studies conducted during this program provide substantial evidence that tube noise figures in the order of 2 to 3 db can be achieved in traveling-wave tubes that use an electron gun structure similar to that employed in the RCA type 6861 tube. However, in order to achieve this very low noise performance, the beam-launching conditions have to be electrostatically adjusted to obtain the greatest degree of compatibility with the magnetic-field configuration that is required to provide optimum cooling of the electron beam in the crossed-field region of the electron gun. Also, the optimum length of the low-velocity drift region must be selected, and impedance transformation techniques that maintain or improve the noise performance must be employed.

Theoretical and empirical data indicate that, in tubes of the type developed during this program, the theoretical lower limit of the noise figure is in the order of 1.5 db. However, since it is impossible to completely control such factors as cathode fabrication and processing, gas evolution, and losses in the rf circuit, the practical limit for this design is about 2.5 db. Any further basic improvements would require completely new approaches to the problem of noise reduction in beam devices. While some other theoretical approaches were considered earlier in this program, the approaches actually followed were selected mainly because of their greater probability of being reduced to practice.