Vol. 6 No. 3 May/June 1979

Advances in CRT Technology Part 2

WATKINS-JOHNSON COMPANY

Tech-notes

This issue of *Tech-notes* concludes a two-part discussion of CRT technology, which began with the March/April 1979 issue.

Limits on Electron-Gun Performance

An optical analogy of an electron gun is shown in Figure 1, (Reference 1). The function of the electron gun and its focusing system is to provide a dense, sharp, electron-beam image on the phosphor screen. This function is similar to that of an optical system that produces an intense image of a bright source. The source serves as the object for a lens which focuses its image into a small spot. In the optical system, the image brightness is dependent upon source intensity and distribution. In this simple comparison, the spot size produced by the electron gun is also dependent upon source intensity (cathode-current density) and distribution. The electrons are charged, however, and have an energy distribution, while the photons are uncharged (neutral). The practical limits (Reference 1) on electron gun performance are magnification, cathode loading and lens aberration. The fundamental limits on electron gun performance include thermal and space-charge effects.

The effect of magnification on spot size is shown in Figure 2, (Reference 1). As mentioned previously, there is an analogy between electron-optics and light-optics. For light-optics, when the object and image lie in media with different indices of refraction, the lateral magnification of an object, y, is given by,

$$M\text{ (optical)} = \frac{y'}{y} = \frac{S'n}{Sn'},$$

S represents the object distance, S′ the image distance and n is the index of refraction of the media. It is also true for a CRT that the image and object lie in regions with different indices of

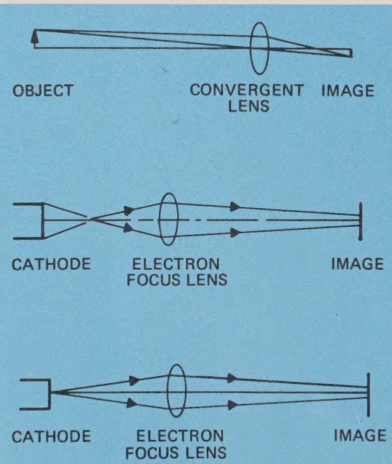


Figure 1. Optical analogy of electron gun.

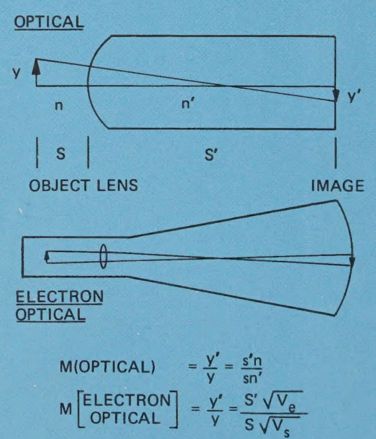


Figure 2. Effect of magnification on spot size.

refraction, since the potential is analogous to the index of refraction. For electron-optics, the lateral magnification, M, is given by,

$$M \text{ (electron-optical)} = \frac{y'}{y} = \frac{S'}{S}\left(\frac{V_e}{V_S}\right)^{1/2}$$

Where:

V_e = potential in region of cathode

V_S = screen potential

The resolution of most CRT's is limited by magnification because the image distance is much greater than the object distance and the screen potential is high enough to overcome space-charge effects.

The effect of lens aberration on minimum spot size is shown in Figure 3, (Reference 2). Spherical lens aberration is the inability of the entire lens to focus an image at the same point. The larger the radial fraction of the lens used, the worse the error, as illustrated in Figure 3. Almost every tube used today is limited by lens aberration.

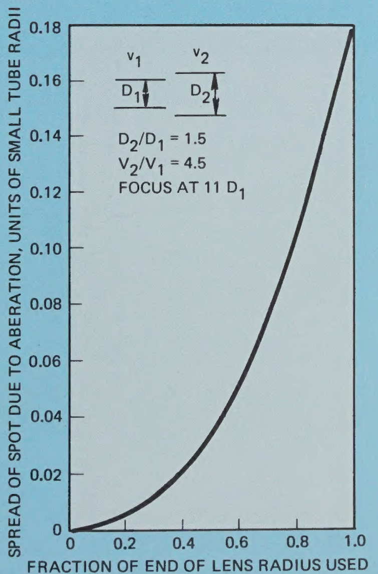


Figure 3. Effect of lens aberrations on minimum spot size.

The Langmuir Limit

The Langmuir limit (see Figure 4), Reference 3, is a thermal limitation. Langmuir's equation indicates the maximum current density which can be achieved in the image as limited by the velocity distribution of the electron beam. Langmuir made the following assumptions: the electrons leave the cathode with a Maxwellian velocity distribution, the focusing system obeys the Abbe sine law, the focusing system is free from aberrations, and space-charge is neglected. Note that in most tubes, M is between 0.5 and 1 and, therefore, the velocity distribution does not limit their performance.

Space-Charge Limitations

In the crossover gun, space-charge effects are encountered in both the crossover and drift regions. In the laminar-flow gun there is no crossover, and space-charge effects are primarily of concern in the drift region. Space-charge effects in the drift region tend to nullify the effect of the focusing lens, as shown in Figure 5, (Reference 4). Calculations based on the curves in Figure 6, (Reference 4), indicate that at the high voltages used today,

$$J = \frac{J_o}{M^2}\left[1 - (1-Z)\exp-\left(\frac{Ee}{kT}\right)\left(\frac{Z}{(1-Z)}\right)\right]$$

WHERE,

Z = $M^2 \mathrm{SIN}^2\beta$

M = THE LINEAR MAGNIFICATION

E = POTENTIAL AT IMAGE PLANE

β = HALF ANGLE OF CONE OF CONVERGENCE TO FOCUSED SPOT

J = CURRENT DENSITY AT FOCUSED SPOT (IMAGE)

J_o = CURRENT DENSITY AT OBJECT (CATHODE)

LIMITING VALUES OF J:

FOR M COMPARABLE TO OR GREATER THAN UNITY:

$$J = \frac{J_o}{M^2}.$$

FOR M SMALL COMPARED TO UNITY:

$$J = J_o\left(\frac{Ee}{kT} + 1\right)\sin^2\beta.$$

Figure 4. The Langmuir limit on peak current density.

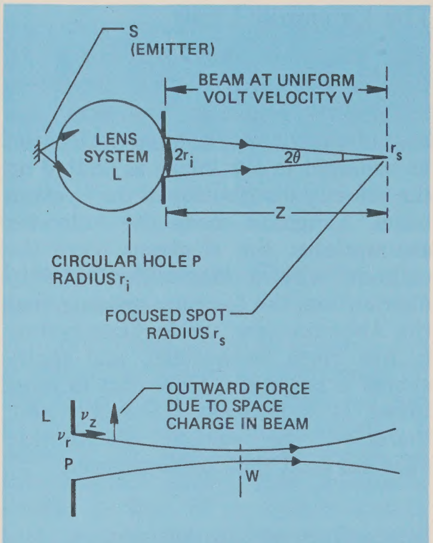


Figure 5. Space-charge in the drift region.

r_i/r_m	r_s/r_m	r_s/r_i	$(Z/r_i)\ (1/V^{3/2})^{1/2}$
54.60	1.030	0.0189	0.00350
44.81	1.038	0.0232	0.00363
36.97	1.048	0.0283	0.00378
30.65	1.059	0.0345	0.00393
25.53	1.072	0.0420	0.00410
21.38	1.068	0.0509	0.00429
17.99	1.106	0.0615	0.00449
15.22	1.128	0.0741	0.00470
12.34	1.153	0.0891	0.00494
11.05	1.182	0.1070	0.00520
9.488	1.216	0.1282	0.00549
8.187	1.256	0.1534	0.00580
7.039	1.302	0.1833	0.00615
6.187	1.354	0.2189	0.00653
5.419	1.415	0.2612	0.00696
4.771	1.486	0.3115	0.00743
4.221	1.568	0.3715	0.00796
3.753	1.664	0.4433	0.00856
3.353	1.775	0.5294	0.00923
3.012	1.906	0.6329	0.00999
2.718	2.060	0.7577	0.01086
2.562	2.165	0.8450	0.01143
2.3491	2.3491	1.0000	0.01242
2.165	2.562	1.183	0.01353
2.060	2.718	1.320	0.01433
1.906	3.012	1.580	0.01578
1.775	3.353	1.889	0.01743
1.664	3.753	2.256	0.01930
1.568	4.221	2.691	0.02143
1.486	4.771	3.210	0.02386
1.415	5.419	3.829	0.02664
1.354	6.187	4.569	0.02984
1.302	7.039	5.455	0.03354
1.256	8.187	6.518	0.03782
1.216	9.488	7.799	0.04280
1.182	11.05	9.345	0.04862
1.153	12.94	11.22	0.05544
1.128	15.22	13.49	0.0635
1.106	17.99	16.26	0.0730
1.088	21.38	19.65	0.0842
1.072	25.53	23.82	0.0977
1.059	30.65	28.94	0.1138
1.048	36.97	35.29	0.1332
1.038	44.81	43.16	0.1567
1.030	54.60	52.99	0.1852

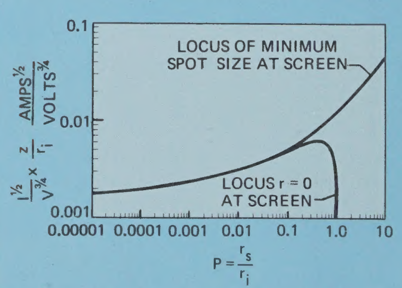


Figure 6. Space-charge limitations on minimum spot size.

space-charge in the drift region generally does not limit resolution.

Cathode Life

Langmuir's equation shows that the current density in the image is directly proportional to the emission current density from the cathode. Thus, resolution is directly proportional to emission current density, within limits. High resolution CRT's require high cathode loading. Oxide-cathode current densities (see Figure 7), Reference 5, have been measured and the maximum values found to range from .1 A/cm^2 at 700°K to 100 A/cm^2 at 1200°K. Practical values of oxide-cathode current densities for CRT's are limited by two factors:

At temperatures below 1000°K the cathodes are "poisoned" (degraded) in several hundred hours. At temperatures above 1150°K, the cathode material may sublime in several hundred hours. Thus, CRT cathodes are operated between approximately 1000°K and 1130°K.

The maximum average emission current density which can be drawn from an oxide cathode is limited by the potential life of the cathode (see Figure 8). The higher the current density, the faster the poisoning of the cathode. In practice, 0.3 A/cm^2 is considered the optimum maximum average loading; it

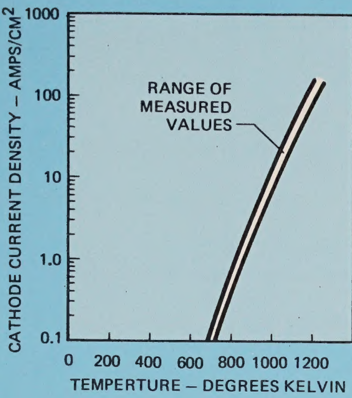


Figure 7. Saturated current densities from the oxide cathode.

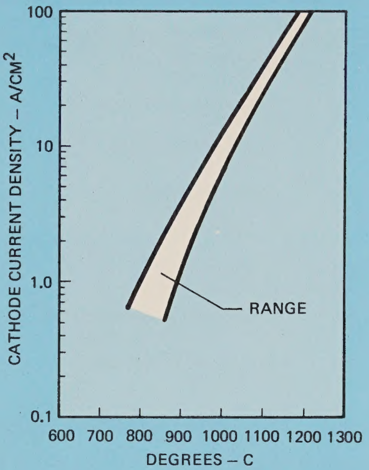


Figure 9. Dispenser cathode current densities.

provides CRT's with about a 10,000-hour life.

Emission current densities from dispenser cathodes have been measured and found to be similar to the values obtained with the oxide cathode (see Figure 9), Reference 6. The optimum operating temperature for the dispenser cathode is about 100°C higher than for the oxide cathode; at that temperature, it is possible to draw 1 A/cm^2 without degrading the cathode.

The life of the dispenser cathode (see Reference 6) is limited by the evaporation of the barium compound from the pores of the tungsten. Depending upon the particular dispenser cathode, lifetimes substantially in excess of 50,000 hours appear practical.

LOADING	LIFE HOURS	CATHODE CURRENT
1 A/CM^2	<1,000	1000 μA
0.3 A/CM^2	<10,000	500 μA
0.06 A/CM^2	<50,000	125 μA

ASSUMES A 0.02-INCH DIAMETER CATHODE

Figure 8. Oxide cathode life versus cathode loading.

CRT Phosphors and Their Limitations on CRT Life

A list of frequently-used phosphors appears in Figure 10, (Reference 7, 8). The phosphors, which differ in composition, color and persistence, are designated by various P numbers.

The older phosphors are designated by P-1 through P-39, while the newer, rare-earth phosphors are P-43, P-44 and P-45. In general, the rare-earth phosphors such as P-43 and P-44 exhibit discrete spectral peaks rather than broad bands of emission. These rare-earth phosphors may exhibit less brightness than conventional phosphors at low values of current density. As the current density is increased, however, the brightness of the rare-earth phosphors surpasses that of the others, which tend to saturate at lower current densities than the rare-earth phosphors.

The brightness of a phosphor decreases with use. Figure 11 indicates the relationship observed between the brightness of the phosphor and the time it has been exposed to a constant bombarding current density. The phosphor efficiency is found to decrease

JEDEC NO.	PHOSPHOR COMPOSITION	COLOR	PERSISTENCE (TO 10%)	COMMENTS AND APPLICATIONS
P1	ZINC ORTHOSILICATE ($Zn_2\,S_i\,O_4$: Mn)	YELLOW–GREEN	MEDIUM (24.5 ms)	EFFICIENT AT HIGH CURRENT DENSITIES PROJECTION TUBES
P2	ZINC CADMIUM SULFIDE (Zn Cd S: Cu)	YELLOW–GREEN	MED. SHORT (35 TO 70 μSEC)	SCOPE TUBES
P4	BLEND OF Zn S: Ag AND Zn Cd S: Ag	WHITE	22 μSEC AND 60 μSEC	TV MONOCHROME PICTURE TUBES
P7	CASCADED SCREEN (Zn S: Ag) CASCADED ON TO (Zn Cd S: Cu)	PURPLISH–BLUE, YELLOW–GREEN	MED. SHORT (25 TO 75 μSEC) LONG (400 ms)	LONG PERSISTENCE DISPLAYS SUCH AS RADAR
P11	ZINC SULFIDE (Zn S: Ag)	BLUE	MED. SHORT (25 TO 75 μSEC)	PHOTO RECORDING
P16	CALCIUM MAGNESIUM SILICATE (2 CaO HgO 2 SiO_2: Ce: Li)	ULTRA–VIOLET	VERY SHORT (0.12 μSEC)	FLYING SPOT SCANNERS
P20	ZINC CADMIUM SULFIDE (Zm Cd S: Ag)	YELLOW–GREEN	MEDIUM (APPROX 60 μSEC)	HIGH EFFICIENCY, SHORT PERSISTENCE
P22R	YTTRIUM ORTHOVANADATE (YVO_4: Eu)	RED	MEDIUM (1 ms)	COLOR TV
P22B	ZINC SULFIDE (Zn S: Ag)	BLUE	MED. SHORT (22 μSEC)	COLOR TV
P22b	ZINC CADMIUM SULFIDE (Zn Cd S: Ag)	GREEN	MED. SHORT (60 μSEC)	COLOR TV
P31	ZINC SULFIDE (Zn S: Cu)	GREEN	MED. SHORT (38 μSEC)	HIGH EFFICIENCY, MEDIUM PERSISTENCE
P39	ZINC SILICATE (Zm Si O_4: Mn, As)	GREEN	LONG (0.1 TO 1 SEC)	LOW REP RATE SYSTEMS
P43	GADOLINIUM OXYSULFIDE ($Gd_2\,O_2$ S: Tb)	GREEN	MEDIUM (1 ms)	HIGH BRIGHTNESS DISPLAYS
P44	LANTHANUM OXYSULFIDE ($La_2\,O_2$ S: Tb)	GREEN	MEDIUM (1 ms)	HIGH BRIGHTNESS DISPLAYS
P45	YTTRIUM OXYSULFIDE ($Yt_2\,O_2$ S: Tb)	WHITE	MEDIUM (2 ms)	HIGH BRIGHTNESS DISPLAYS

Figure 10. Cathode-ray tube phosphors.

with the number of coulombs deposited.

The relationship between, I, the aged intensity of the phosphors, I_o, the initial phosphor intensity, and N, the number of electrons deposited per cm^2, is given by Pfahnl's Law.

$$I = \frac{I_o}{(1 + CN)}$$

C is the burn parameter characteristic (rate of degradation) of each phosphor. Its reciprocal is the number of electrons per square centimeter needed to reduce the phosphor intensity to one-half its initial value. Note that the smaller the value of C, the larger the number of electrons required to reduce the efficiency of the phosphor.

Figure 12 indicates the phosphor aging curves for several phosphors. From these curves, it can be seen that P-1 has the greatest resistance to phosphor aging. Figure 13 is a table of the luminous efficiency and aging constants of several phosphors. Note that the efficiencies are given for lower values of the current density. It should not be concluded that at high current-density levels the values of luminous efficiency are directly related to their values at the lower current densities, since saturation of light output with increasing current density varies from phosphor-to-phosphor.

The table shown in Figure 14 represents an indication of the effect of the tube size on phosphor life. Three

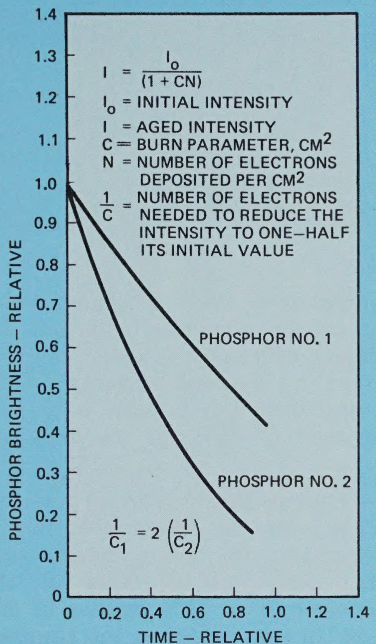


Figure 11. Generalized phosphor aging characteristics.

widely-used tube sizes have been selected. The 21″ size is typical of many computer terminal displays.

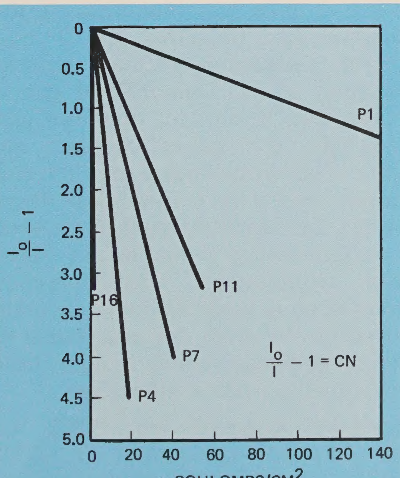


Figure 12. Phosphor aging curves.

PHOSPHOR	EFFICIENCY (LUMENS/WATT)	LIFE TO 50% OF INITIAL BRIGHTNESS (C/CM^2)
P1	30	>100
P4	30(COLOR DEP)	25
P7	20	25
P20	40–70	25
P22(G)	40–65	25
P31	35–45	25
P39	20	>25
P40	20	25
P43	40	>50
P44	35	>50
P45	20	>50

Figure 13. Aging characteristics of selected phosphors.

The 5″ x 5″ square size is characteristic of some of the airborne high-brightness, multipurpose displays. The 9″ diagonal represents the intermediate display size. The area of each tube size is given in square inches and square centimeters.

The operating time to 50% intensity, assuming a screen current of 200 microamps, has been calculated for both P-1 and P-4 phosphor. The brightness area factor indicates the ratio of the various display sizes and, therefore, the ratio of the various display brightnesses, given a constant screen current.

Note that the P-1 phosphor is capable of 18,000 hours operation before the brightness is reduced by a factor of two for the 21″ display. For the 5″ x 5″ display, the time drops to about 1500 hours. It should be noted, however, that the smaller display operates at 12 times the brightness of the larger display. Similar numbers are presented for the P-4 phosphor.

CRT Performance Using Advanced Technology

Figure 15 shows a photograph of an 8-inch rectangular, 70° CRT with a laminar-flow gun, which is a direct physical and electrical replacement for a crossover-gun CRT. Figure 16 presents a comparison of the performance of the two tubes at equal screen currents.

TUBE SIZE	USEFUL SCREEN SIZE (IN)	AREA		TIME TO 50% INTENSITY @ 200 μA CURRENT (HOURS)		BRIGHTNESS AREA FACTOR
		IN^2	CM^2	P1	P4	
21" DIAGONAL	12 x 16	192	1239	18,000	4500	1
9" DIAGONAL	5.4 x 7.2	39	252	3,656	914	4.9
5" x 5" SQUARE	4 x 4	16	103	1496	374	12.02

Figure 14. Effect of tube size on phosphor life.

The crossover-gun CRT used in the example is an 8-inch diagonal, high-resolution, 70° deflection, electrostatic-focus, magnetic deflection device. The Laminar-flow CRT uses different electrode shapes, but the electrode diameters, focus electrode, and overall gun lengths are identical.

To achieve the same current efficiency in both guns at 30-microampere (μA) screen current, the final aperture of the Laminar-flow tube has been changed from .075 inches to .050 inches. The data comparison listed in Figure 16 is typical of the improved performance obtainable with the Laminar-flow gun.

For the same grid-2 potential (300V), the Laminar-flow gun indicates a 30% higher resolution at less than one half the grid-1 cut-off voltage. Changing the Laminar-flow grid-2 potential to 916 volts produces a cut-off voltage of 70 volts, the same as that of the crossover gun. The resolution of the Laminar-flow CRT is almost twice that of the crossover CRT, but the current efficiency (screen current divided by cathode current) of the Laminar-flow gun is now only 35% compared to 46% for the crossover gun.

Figure 15. Photograph of 8-inch rectangular 70° Laminar-flow gun CRT.

At a Laminar-flow gun grid-2 potential of 300 volts, the current efficiency is comparable for both tubes, even though the exit aperture of the Laminar-flow is 30% smaller in diameter. In this condition, the Laminar-flow gun produces twice the current density in the exit aperture as that of the crossover gun. The grid drive is only 15 volts using the Laminar-flow gun, compared to 26 volts using the crossover gun.

When 916 volts are applied to the G-2 of the laminar-flow gun, the grid drive of the Laminar-flow gun at 24 volts is still 2 volts less than that of the crossover gun. Note that the "0" bias current (maximum cathode current available) of the Laminar-flow gun is greater than that of the crossover gun when the G-1 cut-off voltages are equal. This higher value of "0" bias current results in a lower grid drive for the Laminar-flow guns and allows a corresponding reduction in video drive requirements when cathode modulation is used. Although the data presented are only for one value of screen current, similar results have been obtained over a wide range.

Figure 17 presents some CRT life test data on an 8-inch, 70° CRT similar to the one discussed above. The tube employed an Einzel lens laminar-flow gun with dispenser

CRT TYPE	EXIT APERTURE DIAMETER	SPOT WIDTH		POTENTIAL			CURRENT		
		AT 50%	AT 5%	GRID–2	GRID–1 CUT–OFF	GRID–1 DRIVE FOR 30 μA SCREEN CURRENT	CATHODE	SCREEN	"0" BIAS
	(INCHES)	(INCHES)	(INCHES)	(VOLTS)	(VOLTS)	(VOLTS)	(μA)	(μA)	(mA)
COG	0.070	0.0057	0.0114	300	–70	26	68	30	1.7
LFG	0.050	0.0040	0.0076	300	–30	15	65	30	0.65
		0.0030	0.0062	916	–70	24	85	30	2.6+

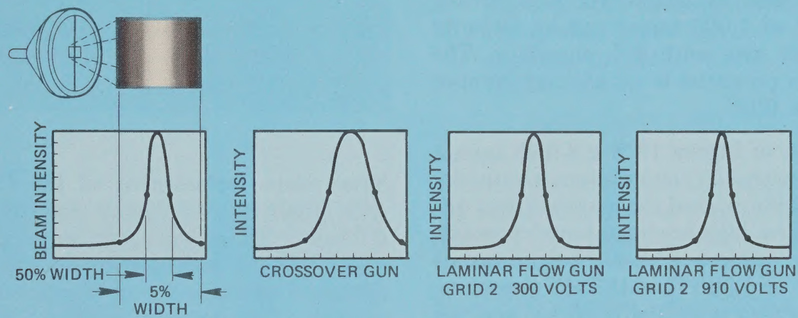


Figure 16. Crossover gun versus Laminar-flow gun performance data.

cathode. An examination of Figure 17 reveals that the "0" bias current increased slightly during the first thousand hours of operation, but was stable after that time. The P-43 efficiency was constant for about 1700 hours, after which time it started to decrease. At the value of cathode loading used, an oxide cathode would probably have ceased to emit

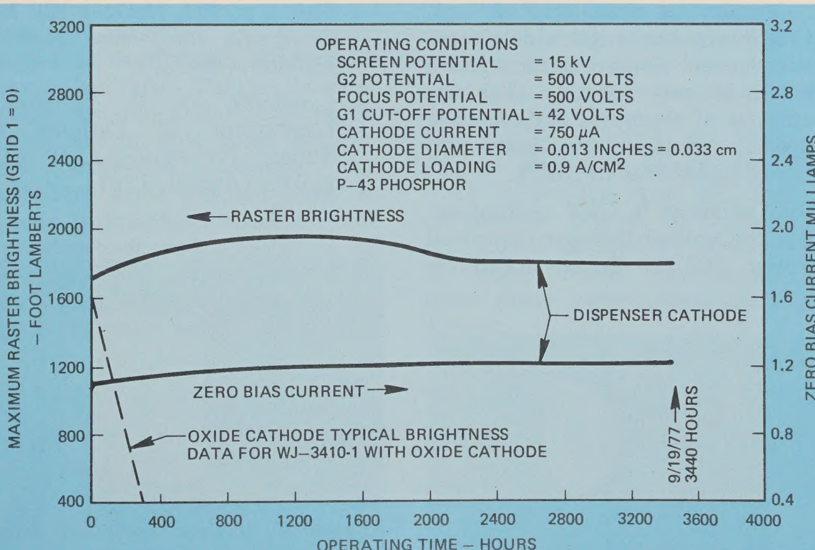


Figure 17. Laminar-flow gun with dispenser cathode CRT life test data.

in about 1000 hours. This tube was ultimately run 10,000 hours without any cathode degradation.

A 3-inch CRT with laminar-flow gun and dispenser cathode is shown in Figure 18. This tube is employed as a projection CRT in HUD's (head-up displays). It can achieve a peak line brightness of 20,000 fL, at a writing speed of 5,000 in/sec and on 60 hertz refresh rate with P-1 phosphor. The screen potential is 18 kV and the spot size is .008″.

Shown in Figure 19 is a 4-inch square CRT with LFG and dispenser cathode. This tube is used for a multisensor display in a high-brightness environment. It can achieve a raster brightness of 4,000 to 6,000 fL with P-43 phosphor. The screen potential is 20 kV and the spot size is .005″ to .006″.

A 5-inch, square CRT with LFG and dispenser cathode is shown in Figure 20. It can achieve a raster brightness of 3,000 to 5,000 fL with P-43 phosphor. The screen potential is 20 kV and the spot size is .007″ to .008″.

Conclusion

Although CRT's have their origins in the antiquity of the electronic age, they still are the most widely-used, high-resolution display devices. In a sense, it is only recently that the capabilities of electronic systems have started to approach the basic performance capabilities of CRT's.

Recent advances in CRT technology, such as the laminar-flow gun, improved phosphor, and the dispenser cathode have made replacement of the CRT with other display devices even more difficult. These advances have produced CRT's with higher resolution, increased brightness and substantially increased life, thereby making CRT's better than ever and reducing life-cycle cost.

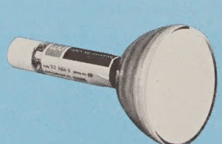


Figure 18. Photograph of 3-inch, round, high-brightness, Laminar-flow gun CRT.

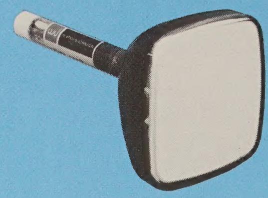


Figure 19. Photograph of 4-inch, square, 70°, high-brightness, Laminar-flow gun CRT.

References

1. Sears, F. W. *Principles of Physics III — Optics*, pp. 68-70, Addison-Wesley Press, Inc., Cambridge 42, Massachusetts, (1948).
2. Spangenberg, K. R. *Vacuum Tubes*, p. 392, McGraw-Hill Book Company, Inc., New York and London, (1948).
3. Langmuir, D. B. "Theoretical Limitations of Cathode Ray Tubes," *Proceedings I. R. E.*, 25, p. 977, (August, 1937).

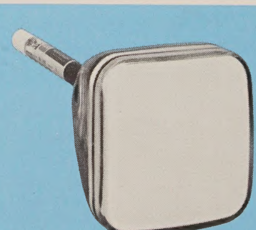


Figure 20. Photograph of 5-inch, square, 55°, high-brightness, Laminar-flow gun CRT.

4. Moss, Hillary. "On the Limit Theory of Circular Electron Beams," *Proceedings of the Fourth Symposium on Electron Beam Technology*, March, (1962). Sponsored by Alloyd Electronics Corp., 35 Cambridge Parkway, Cambridge 42, Massachusetts.

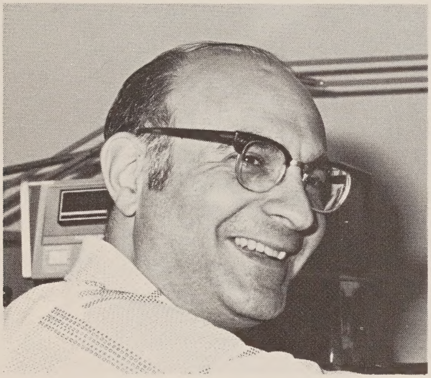
5. Wagener, P. S. *The Oxide Coated Cathode*, Vol. I and II, Chapman and Hall Ltd., London, (1951).

6. Zalm, P. and A. J. A. van Stratum, "Osmium Dispenser Cathodes," *Philips Technical Review*, 27, No. 3/4, pp. 69-75, (1966).

7. RCA Phosphor Publication TPM-1508B.

8. Larach, S. and A. E. Hardy. "Some Aspects of Cathodoluminescent Phosphors and Screens," *Proceedings of SID*, 16, No. 1, pp. 20-29, (1975).

Author:



Norman H. Lehrer

Norman H. Lehrer is presently employed as Staff Scientist, Stewart Division, by the Watkins-Johnson Company. He joined Watkins-Johnson Company almost nine years ago and shortly thereafter founded the Cathode-Ray Tube product line. He has been primarily responsible for the development and application of the laminar-flow gun to cathode-ray tubes. Prior to joining Watkins-Johnson Company he was president of Electro-Vision Industries, Inc. and manager of the Image Sensing and Display Department of the Hughes Research Laboratories.

While at Hughes, Mr. Lehrer was awarded the L. A. Hyland Patent Award in 1968 for recognition as one of the 12 initial outstanding inventors at the Hughes Aircraft Company. This award was based on his invention, promotion and development of the multimode storage tube, which is widely used in the western world's military aircraft. The Society for Information Display awarded him in 1974 its most prestigious award, the Frances Rice Darne Memorial Award, for "pioneering advancement of the display storage tube and continuing contributions to display technology."

Mr. Lehrer received his Master of Science Degree in Physics from New York University, and his Bachelor of Science Degree in Physics from the College of the City of New York. He holds several patents and has given many presentations on display devices.

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Printed in U.S.A.