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History and development of the color picture tube

E. W. Herold

This paper covers the early history of the shadow-mask color picture tube and its development up to approximately 1973. The shadow-mask tube by then was almost 25 years old and had established itself as the only successful color display for home television. Other color tube types that have been under laboratory investigation, but have not achieved commercialization, will not be described; for a more complete discussion that includes these types, the reader is referred to the Academic Press book, *Color Television Picture Tubes*, by Morrell, Law, Ramberg, and Herold.[1]

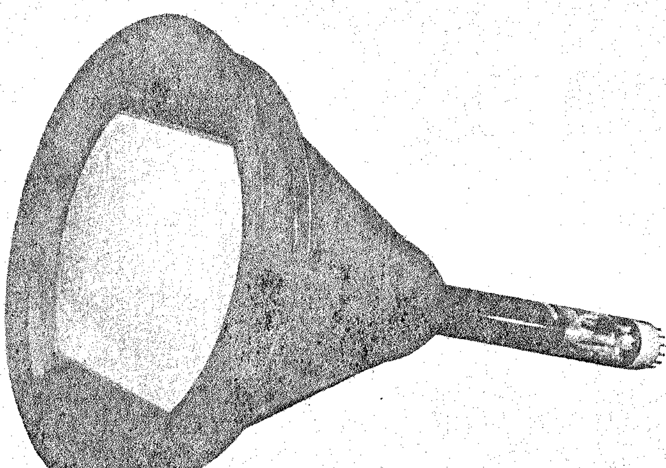

Fig. 1 — Picture of one of the first shadow-mask tubes.

SHADOW-MASK development started in September 1949. For anyone who was not involved, it is difficult to appreciate the inadequacy of color displays at that time. Black-and-white television was well established, with excellent pictures via the cathode-ray tube. For color, there were only three ways to display a picture. The first was the rotating color disc in front of a black-and-white picture tube. The method was severely limited in picture size and required scanning standards that were not compatible with black-and-white transmissions. A second method used three Schmidt-optics projection systems with images superimposed on the screen; this was too expensive for a consumer product. Finally, there was the most awkward of all — a combination of three orthogonal cathode-ray tubes viewed in superposition through large dichroic mirrors. This arrangement produced a direct-view picture of about 12-inch diagonal in a cabinet occupying the volume of two upright pianos!

In spite of these inadequate systems, work on color television in early 1949 went on at a feverish pace, with many predictions that some day soon a simple and low-cost color display would become available. To many experts in the electron-device field, these predictions seemed irrational, with no basis in reality. Yet, six months after starting work, some of these same skeptics (the writer included) were able to take to Washington four color receivers with a half-dozen spare tubes and put on a demonstration in which the performance achieved startled the entire industry. Color pictures were displayed on the shadow-mask color tube, using a compatible-color system essentially the same as the one now used throughout the world.

The mobilization of corporate resources

It all started at RCA Laboratories one day that September, 1949, when Dr. Elmer Engstrom, who then headed the Laboratories, asked the writer to organize and coordinate a company-wide program to develop a color tube. We were promised unlimited funds, top priority, and freedom to use all the technical expertise that RCA had available. There was only one catch: Feasibility was to be demonstrated in three months and a final result in six months. It seemed impossible because, although we had some ideas, none were technologically practicable. But research teams were set up to explore five different approaches that have been described elsewhere.[2] One available idea had been described some years before in an invention by a German named Flechsig.[3] He proposed the shadow effect of a grill of wires, with three electron beams, one for each color. It seemed clear to many that Flechsig had never tried to make such a tube, or he would have been embarrassed to put his name on the idea. What appeared to be equally impractical

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Dr. Edward W. Herold, was Director, Technology, Research and Engineering at the time of his retirement in November 1972. Dr Herold joined RCA in 1930 in Harrison, N.J., where he engaged in tube research. In 1942 he transferred to the newly established RCA Laboratories where he served as Director of the Radio Tube Laboratory and, later, the Electronics Research Laboratory. In 1957, he was placed in charge of the RCA group working on Princeton University's C Stellarator project for research on controlled thermonuclear fusion. In 1959 he was appointed Vice President, Research, for Varian Associates, returning to RCA in 1965, where he was a member of the Corporate Engineering Staff for the past seven years. Dr. Herold received the B.S. in Physics in 1930 from the University of Virginia and the M.S. in Physics in 1942, from the Polytechnic Institute of Brooklyn. That institution honored him with a Doctor of Science degree in 1961 for his "distinguished accomplishments in the fields of electron tubes and solid state devices." A Fellow and former Director of the IEEE, Dr. Herold is a member of the American Physical Society, the American Association for the Advancement of Science, the Society of Motion Picture and Television Engineers, Phi Beta Kappa and Sigma Xi.

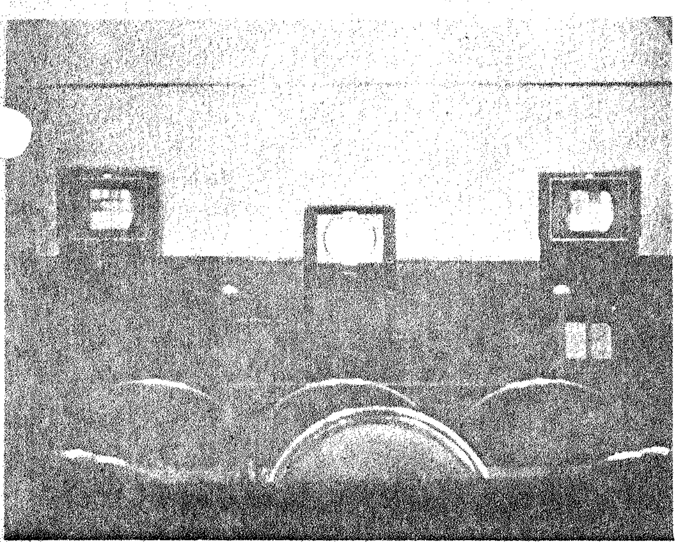

Fig. 2 — Picture of color receivers at the first demonstration, March 1950.

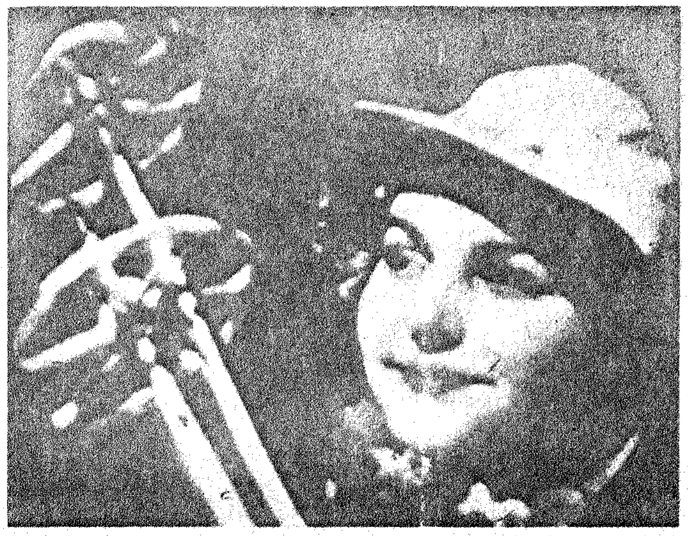

Fig. 3 — Picture taken of "ski girl" slide at time of first demonstration (original in color).

was modification suggested by Dr. A.N. Goldsmith[4]: thousands of tiny holes in a mask instead of wires, with three electron guns spaced 120° apart and separate deflection systems corrected for "keystoning". In our own laboratory, Mr. A. C. Schroeder[5] had proposed putting the three guns so close together that they would pass through the same deflection yoke. Even this seemed out of reach because no one saw how to line up several hundred-thousand tiny holes with an equal number of phosphor-dot triplets.

Nevertheless, in our crash program, Dr. Harold B. Law selected the Schroeder idea for exploitation. Law was skilled as well as tenacious, and he then made the key invention, called the "lighthouse"[6]. With this device, Law used light to simulate the shadowing of electrons. The light permitted use of photographic and lithographic processes to locate the phosphor dots in the desired positions back of the mask. The lighthouse is still the basis of today's manufacture of color tubes, and it still goes by the same name. The method worked so well that, in less than the prescribed three months, Law had a few square inches of color picture that proved feasibility, and he had built a first tube with a 7-in. diagonal screen. In three more months, a few hundred other people, working seven days a week, had helped produce a dozen or so tubes with a 12-in. diagonal picture of remarkable quality[7,8,9]. A picture of one of these first tubes is shown in Fig. 1. It used a 16-in. metal bulb and had a flat color screen and shadow mask mounted inside.

A one-gun variation of the shadow-mask tube [10] was devised by Dr. Russell R. Law (unrelated to Harold Law), who was part of the RCA group that worked so hard to make the shadow-mask tube a reality. However, the three-gun tube had so many advantages that the one-gun version is no longer of interest. In March 1950, two receivers of each type were taken to Washington to demonstrate to the F.C.C.[11]

In Fig. 2 there are three receivers: A black-and-white one in the center, the three-gun shadow mask at the right, and the one-gun shadow-mask receiver at the left. The picture was taken in March 1950 at the time of the demonstration. The picture quality of the three-gun tube is shown by Fig. 3 taken at the same time. Compared with today's tubes, the pictures were smaller, had only 7-fl highlight brightness and required an almost fully darkened room for satisfactory viewing. However, the industry reaction was overwhelming. A typical comment from the April 1, 1950 *TV Digest* is quoted as follows:

> "Tri-color tube has what it takes: RCA shot the works with its tri-color tube demonstration this week, got full reaction it was looking for....not only from....FCC...and newsmen, but from some 50 patent licensees...." "So impressed was just about everybody by remarkable performance, that it looks...as if RCA deliberately restrained its pre-demonstration enthusiasm to gain full impact."

This early experience deserves attention both because it was so dramatic, and because there's a lesson for all of us. This project was an example of how an apparently unattainable result can be achieved by use of unlimited effort. In fact, of course, there's no such thing as unlimited effort; yet, when a group of competent people are told that the sky's the limit — forget money, forget red tape, forget lines of authority — their enthusiasm has no bounds and even the unattainable becomes possible. If the shadow-mask idea had not worked out, at least two other ideas could have been brought to fruition. Unfortunately, there are far too few corporate or government executives who have the foresight and the nerve to authorize this kind of project. They usually insist on budgets, cost controls, cost/effectiveness analysis and, in the end, they may spend much more than would the "crash" program while often failing to achieve the desired result.

The 1950 tube was, of course, only a start. Most of the RCA group had what proved to be an erroneous idea. We believed there was one way only to achieve low enough cost to make the color tube practical, and that was to make every shadow mask exactly alike, and every phosphor screen identical with every other. We thought that they could then be mass-produced and any mask would work with any phosphor screen. Although the RCA group was making progress toward that goal, the accuracy required in construction of the screen and mask made this approach very difficult to carry out.

Another approach to mass production, which abandoned the interchangeability feature, was the result of the ingenuity of Mr. Norman Fyler[12], in late 1953, at CBS Hytron. Instead of the screen being placed on an internal flat glass plate as in the RCA approach, Fyler and his associates built a shadow-mask tube with a curved mask and direct photo-deposition of phosphors on the curved inside face of the tube. A crucial aspect of the system was that the mask was destined for use with that screen only. Exact duplication of parts was not necessary and the picture was larger and more appealing on the face of the tube than on the internal flat-screen plate in use by the RCA group. Fyler's design is now the standard way of making color tubes. It is interesting that, although Harold Law made his first screen by a settling process, he had also invented the direct photo-deposition of phosphors[13] and mentions it in his original paper.[6]

RCA technological advances

Although not the first with the curved mask, the RCA group had its own set of successes in the early 1950-1954 period. Several of their developments must be mentioned because they have remained in use ever since; without them there is some question whether the shadow-mask principle would have reached its present predominance. The first has to do with the convergence or coincidence of the three beams. Obviously, unless the red, green, and blue pictures coincide, *i.e.*, converge over the entire screen, a poor picture would result. The solution involved pointing the three guns to the center of the screen and providing both static and dynamic adjustments, via static and alternating magnetic fields. The important invention here was the incorporation in the three electron guns of internal pole pieces that permitted each beam to be independently adjusted.[14] The earliest shadow-mask tubes were easier to converge because they used only a 45° deflection, but this made the tubes awkwardly long. By devising the internal-pole-piece gun, it became possible to go to 70° deflection and ultimately to 90° and more.

A second RCA development that remains in use to this day relates to the curved mask principle employing photographic deposition of the three color phosphors; such deposition requires three separate exposures. The shadow-mask must be mounted and removed again for each exposure, without any shift in alignment when it is remounted. This is an exacting requirement, but a solution was found by mounting tapered metal studs at the sides of the faceplate cap.[15] The studs are engaged by circumferential springs on the light-weight frame that holds the curved shadow mask.

These two important technological advances were incorporated in the first large-scale production type introduced by RCA in 1954.[14] The tube had 70° deflection, with a 21-in.-diameter round metal bulb and the phosphors were photo-deposited on the curved glass faceplate. This type was used in most of the early color sets that established the NTSC color system as a commercial success. A few years later, 1958, the metal envelope was replaced by a glass one,[16] made possible by the development of a new frit-glass seal by Corning Glass: This frit fuses at a low temperature to make the seal. Upon further heating it converts to a crystalline material which provides a ceramic-like bond that cannot again be parted. As with some of the other early developments, the frit seal remains to the present day.

Other important developments that are only touched upon here were the slurry process that mixes the phosphors with the photoresist and the correction lens that is used in the lighthouse to preserve the match of phosphor dots with electron beam landing positions, particularly under large-angle beam deflection conditions. But beyond even these items, the period of 1954 to 1968 led to almost unbelievable advances in manufacturing technology; costs were reduced, quality and performance were greatly increased, and picture size, deflection angle, and brightness became comparable to those of black-and-white tubes. There were hundreds of other detailed improvements in guns, compensation for thermal expansion of the mask, phosphor deposition and mask making. Major advances were made in color phosphors, notably by use of rare-earth elements in the red phosphor. The shape of the picture tube face was made rectangular, and the tubes became much shorter by increasing the deflection angle to 90°. From a slow start, when few programs were broadcast in color, receiver sales and color broadcasts progressively increased, and many manufacturers entered the field of color tube manufacture. By 1967, about 15-million color tubes had already been produced and the shadow-mask tube was finally established as a commercial as well as a technical success.

In the most recent period, from 1968 to 1973, design changes continued but there were four dramatic developments that deserve more detailed scrutiny. These four are the Trinitron, the black-matrix phosphor screen, 110° deflection, and the self-converging Precision In-Line system. These are taken up in turn.

The Trinitron

About 1968, as a result of work at the Sony Corporation in Japan, a different design of shadow-mask tube was introduced under the name Trinitron.[17,18] As with many other color tube developments, the Trinitron was also the result of a team effort, in this case by S. Miyaoka, A. Ohkoshi and S. Yoshida. In Fig. 4, at the left, is shown the traditional round-hole shadow-mask arrangement. It uses three essentially separate electron guns in a delta configuration pointed at the center of the screen. Shown schematically at the right in Fig. 4 is the Trinitron gun which uses a single large-diameter lens with three in-line electron beams from the one gun. The shadow mask now consists of vertical strips, and the phosphors are deposited in vertical lines.

The Trinitron has three advantages over the traditional design. The large lens diameter reduces aberrations, so that the electron spot is more easily kept small. Secondly, the vertical apertures in the mask have no horizontal cross ties or structure, so that the vertical resolution is totally unaffected. A third advantage is that convergence of three in-line beams is simpler than with the delta-gun arrangement. Convergence of in-line beams is discussed in more detail later. Pictures produced by the Trinitron are reputed to be excellent.

Along with the advantages, there are some shortcomings. Because the mask has continuous vertical apertures, it cannot be spherically curved and be self-supporting, as with the round-hole mask. Thus, it is curved cylindrically and stretched on a relatively heavy frame. Trinitron designs are often longer than traditional ones of the same screen diagonal and deflection angle. In summary, the good technical performance is accompanied by a higher cost of manufacture and a less flexible receiver configuration.

The matrix screen

It has long been recognized that the "whiteness" of phosphor materials is a disadvantage in that it diffuses back any ambient light and reduces contrast. Transparent phosphors were tried in an attempt to reduce the back-scattered light but were far too inefficient. For a long time, the only low-cost solution was the use of a light-absorbing glass faceplate—

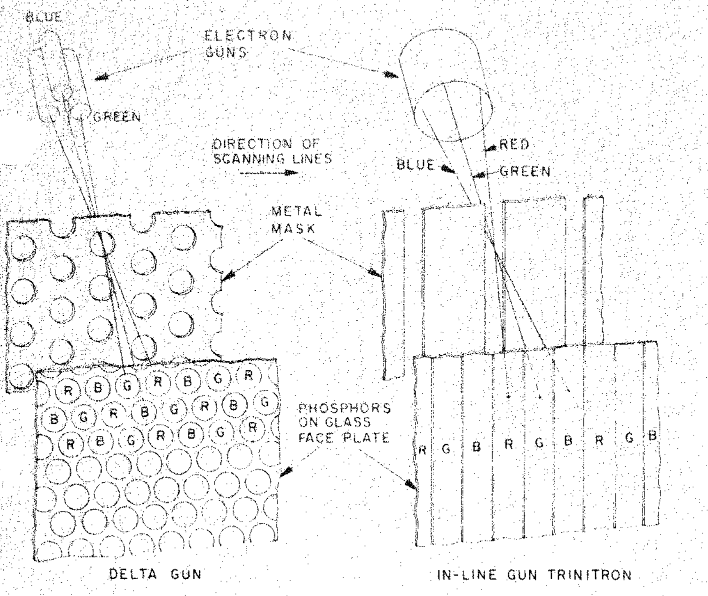

Fig. 4 — Trinitron system, compared with conventional delta-gun system.

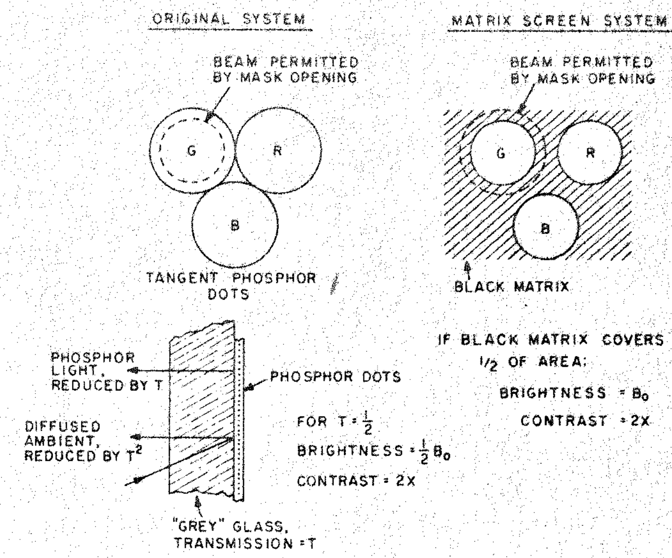

Fig. 5 — Grey-glass action and comparison with matrix screen.

the so-called "grey" glass. Grey glass works because the ambient light passes through the grey glass twice, but the phosphor-emitted light goes through only once. In Fig. 5 it is shown that, if the faceplate has a transmission T of the order of 0.5, the phosphor light output is cut in half; the diffused ambient goes down to T^2, *i.e.*, to one-quarter. Thus, by losing half the brightness, the contrast is doubled. Up to 1969, this was the only method in use to enhance contrast in color tubes.

Fig. 5 also shows one of the hundreds of thousands of phosphor-element triplets as they are located on the faceplate. In practical tubes, the mask openings must be made smaller than the phosphor dots so that slight inaccuracy of position will not change the color. The tolerance required can be as much as 25% of the diameter, so that the useful part of the phosphor covers only about 50% of the screen area. Color-tube workers had long recognized that it would be desirable to use black on any portion of the screen not needed for phosphor. This was first applied on a different type of color tube, called the line-screen index tube, developed by Philco but never put into production. About 1969, both RCA and Zenith announced shadow-mask tubes that used a black matrix on the faceplate, with round openings that permitted the phosphor dots to be seen. Only the Zenith version, published in 1969 by J. P. Fiore and S. H. Kaplan[19] is described, because it gives the largest improvement and is now available from most manufacturers, including RCA.

The matrix used by Fiore and Kaplan had round openings defining only the central useful area of the phosphor dots. This means that the maximum possible area of black is provided. However, to provide tolerance for possible beam position inaccuracy, it is now necessary to make the beam areas *larger* than the matrix openings, and this is done by opening up the mask holes to be larger than the holes in the traditional non-matrix mask. In the first RCA matrix tube, the beam spots, and therefore the mask holes, are smaller than the phosphor dots as defined by the matrix; and the system is said to have "positive" tolerance. With the Fiore-Kaplan matrix, the mask holes are larger than the useful size of the phosphor dots and the system is said to have "negative" tolerance. Tubes with this system are often loosely called "negative matrix" types.

The manufacturing procedure for the negative-tolerance matrix screen is considerably more complex than for the traditional non-matrix type, or for the positive tolerance type, but the result is most gratifying. Because the screen now has about 50% of its area covered by black, the back-scattered ambient light is cut in half just as with 50% grey glass, *but there is now no reduction in brightness.* In other words, the picture is twice as bright as the grey-glass tube for the same contrast.

The numbers used are illustrative only. In practice, there are many tradeoffs between the permissible tolerances, the matrix open area, and the glass faceplate transmission, which result in tradeoffs between brightness and contrast. Usually the tube designer uses both grey glass and matrix methods to achieve what he believes to be a best compromise. The matrix screen made a major advance in picture-tube performance and is now in extensive use in the United States. In Europe, matrix screens have not yet taken over. One reason may be that, with their 50-Hz standards, high brightness makes flicker more noticeable.

Large-angle deflection

One of the disadvantages of the standard cathode-ray tube when designed into a display console has always been its front-to-back length. It has been desirable to increase the deflection angle as much as possible to reduce this length. However, a large angle makes convergence of the three beams more difficult and requires high deflection power unless the neck diameter is reduced in inverse proportion, which produces a new set of problems. Fortunately, there is also a performance advantage in a wider deflection angle in that the beam has a shorter throw and the spot remains small for a higher current, so that the picture can be made brighter. Conversely, the picture can be sharper for the same brightness when the deflection angle is increased. The advance from the original 45° angle tube to 70° and then to 90° has been mentioned. In no way should achievement of these angle increases be considered easy; they were all difficult. But the goal remained even higher, and it was first achieved in 1970 by an RCA tube of 18-inch diagonal and 110° deflection[20]. The same year, a 25-inch tube with 110° deflection was announced by Philips[21]

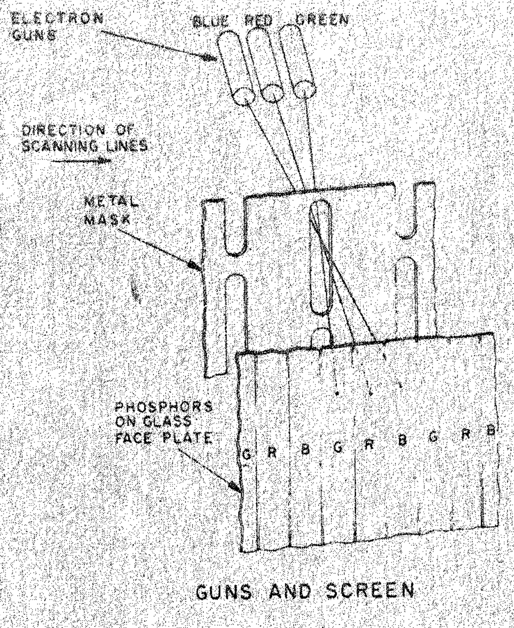

Fig. 6 — Precision in-line system.

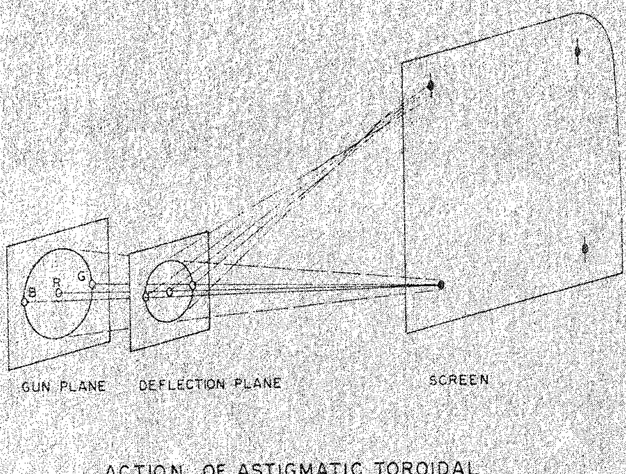

Fig. 7 — Astigmatic yoke action.

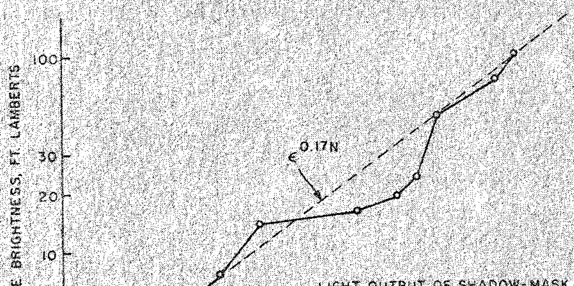

Fig. 8 — Plot of brightness increase from 1950 to 1973.

and one year later in a different form, by RCA[22]. The Sony engineers went just a little further, to a 114° Trinitron[23]. In all these cases, the deflection problem was aided by new yoke designs and by new solid state devices for horizontal deflection. The reduced cabinet depth permitted by these large-angle systems is considered highly desirable and, fortunately, the picture is improved as well.

The Precision In-Line system

The most recent advance in color tubes covered in this paper is known as the Precision In-Line system, announced in 1972 by RCA.[24] This system is also a radical departure from the traditional shadow-mask design. As with the Trinitron, the beams are in a horizontal line, as shown in Fig. 6, and the phosphors are in the form of vertical stripes. The mask, however, in distinction to that of the Trinitron, uses slits with horizontal supporting ties or webs. These webs are sufficient to provide overall rigidity to the mask so that it can be self-supporting and can be curved spherically. Thus, the manufacturing technology retains the low cost of the round-hole mask. In addition, the system solved one of the major problems of shadow-mask tubes, namely the convergence of the three beams over the entire screen.

With the traditional delta gun and round-hole mask, it is necessary to add special dynamic convergence hardware and appropriate adjustable ac signals in order to converge the three beams. The adjustments are made by the receiver manufacturer for each individual tube and sometimes must be touched up in the home. Replacement of the picture tube requires complete readjustment. In the typical traditional system, there are [illegible] such adjustments needed to obtain red, green, and blue pictures that are properly superimposed all over the screen. It [illegible] remarkable that a skilled technician, using a video dot pattern and a cross-hatch pattern, can get good convergence in a matter of minutes. Even so, convergence has always been an annoying difference between the simple black-and-white picture tube and the three-gun shadow-mask tube.

Use of an in-line gun, as has already been mentioned, simplifies convergence somewhat, but the ultimate in simplification came about by designing a special deflection yoke to complement the in-line gun and the line-screen system. When the yoke is aligned with the gun in the

Precision-In-Line system, no dynamic convergence adjustment is needed and none is provided. The yoke is aligned on the tube neck and can be permanently fixed in the tube factory. The combined tube and yoke can then be plugged into a receiver with almost the same simplicity as with a black-and-white tube. The principle employed is shown in Fig. 7. The yoke is purposely made astigmatic. An astigmatic system, as we know, produces an image that is distorted from that of the object. In this instance, a circular object is distorted into a vertical line. If the three beams lie on a horizontal diameter of the object circle, they then converge to the center of the vertical line. The only trick is to assure accuracy in the yoke field pattern so that the astigmatism occurs uniformly over the entire screen. Precision yoke fields were obtained by a ferrite core with slotted end pieces and toroidal windings in which every turn is exactly positioned in its correct slot. With this construction, the yokes are all essentially identical. In the tube factory, the yoke is positioned and then permanently attached to the tube neck. Center-screen static convergence is built into the gun and is touched up with small external magnets, also in the tube factory. Thereafter, the tube is ready for shipment and has eliminated the 12 dynamic convergence adjustments required by the traditional shadow-mask tube.

The Precision In-Line system can be thought of as an example of integration, not as complex as an integrated circuit, but sharing the advantage of a factory-designed system that greatly simplifies color receiver production and maintenance. In this system, we see a portent of the future, in which color tubes are no more difficult to use and install than is the ordinary single-beam cathode-ray tube.

Conclusion

The progress that has been made in the 24 years since 1950 is remarkable. Cost and picture quality have been tremendously improved. A large range of picture sizes, from 25-in. diagonal on down, were made available, and the length of tubes has been greatly reduced. Each year, approximately 20 million tubes are being manufactured, worldwide, representing a $2-billion part of the consumer electronics industry.

Perhaps the simplest factor for showing the improvement in picture performance is the screen brightness. In Fig. 8, the average brightness in a picture is plotted against the calendar year. The first tubes of 1950 had about 2 fl, average, and 7 fl in the highlights. By 1973, 100 fl average was obtainable, with several times as much in highlights. The dotted line on the exponential plot shows that the brightness has been increasing at a rate of 17% per year. It is small wonder that other color-tube concepts have failed to compete in the commercial market, even though they are technically feasible and much laboratory work has been done on them.

In Table I the milestones in the history of the shadow-mask tube are listed. What appeared as an impossibility in 1949 has evolved as one of the most remarkable and successful developments ever made in the history of the electron tube. It is also interesting that two of the major developments in recent years, the integrated circuit and the shadow-mask tube, have both come about through applications of photolithography. Those of us in the field of science and engineering tend to credit ourselves with the brains, the ingenuity, and the foresight to propose and carry out our new developments. In the case of the shadow-mask tube, much credit must go to the executives and financial entrepreneurs who were willing to take the risk in supporting the tremendous investment in manufacturing technology that was required. Without such an investment, color television as we know it today would not have been possible. The two men to whom the greatest credit in this respect must be given are David Sarnoff and Elmer Engstrom, the two RCA executives who steadily and consistently pushed ahead on the shadow-mask tube at a time when it looked as though it would never become profitable.

In this brief space, it is impossible to adequately acknowledge the many other technical and management contributors to this development. As the history of the past two decades is being studied, perhaps others will record their experiences so that the whole story will become known.

Table I — List of milestones in the development of the shadow-mask tube.

1950	First tube demonstrated
1953	Curved mask with phosphor on faceplate
1954	21-inch, 70° deflection tube
1954-1963	Period of manufacturing advances
1964	90° Deflection, rectangular tube
1965	Rare-earth phosphors
1968	Trinitron (3-beam gun, striped phosphor)
1969	Black matrix
1970	110° deflection
1972	Precision in-line system

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