History of Sound Motion Pictures

by Edward W Kellogg

Third Installment

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Our thanks to Tom Fine for finding and scanning the Kellogg paper, which we present here as a "searchable image".

John G. (Jay) McKnight, Chair
AES Historical Committee
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FINAL INSTALLMENT

History of Sound Motion Pictures

By EDWARD W. KELLOGG

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Developments Which Extended the Frequency Range

Better Light-Modulating System for Variable Area. Mention was made in the section on loudspeakers of a demonstration by Dimmick and Belar[179] of sound with extended frequency range. Aside from the improved loudspeakers and the ribbon microphone (whose response was practically uniform from 60 to 10,000 cycles) there were a number of advances that contributed to the result. The new galvanometer and optical system made so much more light available that it was feasible to reduce the width of the recording beam to $\frac{1}{4}$ mil, thus improving resolution. No small factor in giving clean high frequencies is avoidance of flutter, particularly rapid flutter such as 96 cycles. In the demonstrations, both recording and reproduction were on magnetic-drive machines.* (The rotary stabilizer was not yet available.)

Ground-noise reduction was by galvanometer bias with a single narrow line of transparent film when the modulation was zero, and it is my recollection that a measurement indicated a ratio better than 50 db between signal at full modulation and the ground noise when biased for zero modulation.

Nonslip Printer and Improved Sprocket-Type Printers. With the sprocket-type contact printers in almost universal use, a certain amount of slipping of the negative with respect to the print film is almost inevitable. The curvature at the sprocket compensates for a certain negative shrinkage at which the ratio of radii of the shrunk negative and unshrunk print stock is just equal to the ratio of their lengths. The sprocket diameter is designed to make this compensation correct for an average negative shrinkage, but it will be only approximate for negatives whose shrinkage differs from this assumed average. By mechanically stretching whichever film is shorter, two films can be moved together through an appreciable distance in perfect nonslipping contact. A printing system in which this was done was developed by the Technicolor engineers for their color transfer, but it was not used for sound prints. An extended investigation of the losses and irregularities in high-frequency response which result from slippage and imperfect contact during printing is reported by J. Crabtree in the October 1933 and February 1934 *Journals*.[232]

In 1934 C. N. Batsel described a nonslip contact printer[233] employing a principle proposed and demonstrated earlier by A. V. Bedford for a different application.[70,234] Bending a film stretches one face and compresses the other, and it is only necessary that the contacting surfaces of the two films be made equal. In the nonslip printer, the negative is rolled through the machine at fixed curvature, and the print stock (held against the negative at the printing point, where it is propelled solely by friction) is made automatically to assume the curvature at which identical numbers

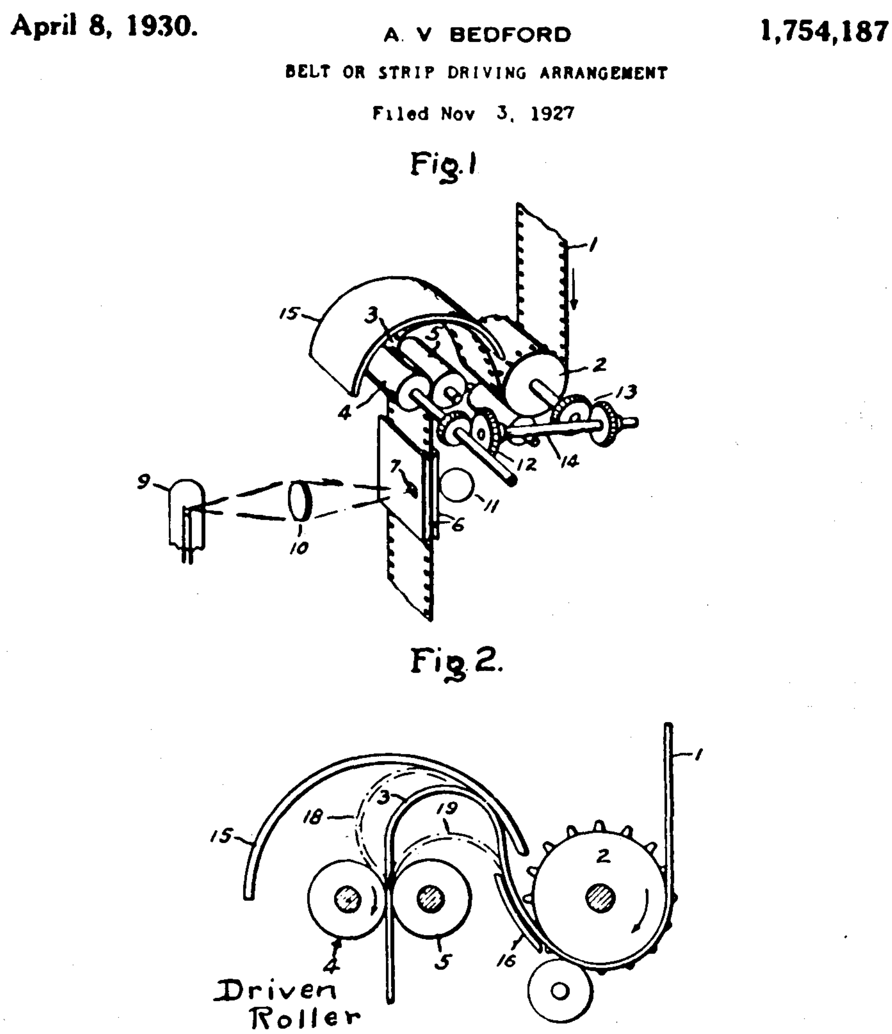

Fig. 17. Control of film speed by flexure (A. V. Bedford). Principle later used in nonslip printer.

* The special film-phonograph used in the demonstrations was a prototype of those used in the Disney *Fantasia* reproduction (see Fig. 7, p. 136, *Jour. SMPE*, Aug. 1941). The film was pulled by the magnetically driven drum over a curved supporting plate where the tracks were scanned, and was steadied at the other end of the plate by another drum with flywheel. This was an anticipation of the double flywheel system now used with magnetic tape and film.

of sprocket holes are fed through in a given time.

The nonslip printer was not built for sale by RCA, but free license and drawings were offered, and numerous laboratories built and used them, notably Consolidated Film Industries in Hollywood and Ace Film Laboratory in Brooklyn.[235]

A printer based on the identical principle was developed independently by R. V. Wood.[236]

Although nonslip printers were not made in large numbers, and did not to any great extent displace the conventional sprocket type of contact printer, they served to demonstrate how much improvement was possible through better printing, and in this way stimulated makers and users of sprocket printers to improve their machines and maintain them in the best possible condition. In a number of laboratories it appeared that better prints resulted if the teeth were removed from the side of the sprocket next to the soundtrack, leaving only a smooth supporting rim. The theory behind this is not clear unless it is that such disturbances of contact as are due to film sticking on the teeth are thus kept further from the soundtrack.

There were two reasons which limited the use of the nonslip printer. Since there is a very narrow region of close contact, the printing beam had to be narrow. Under such conditions any speed irregularities cause variation in print exposure, which sometimes becomes audible in density prints. While there is no valid excuse for such speed variations, this trouble contributed to the conclusion that the nonslip printer was unsatisfactory for density printing. Film laboratory operators were naturally averse to maintaining one type of printer for area and another for density. A more fundamental fault of the nonslip printer in making density prints is due to the fact that negative and positive perforations are not maintained in register. The more active developer circulation close to sprocket holes tends to darken these areas, resulting in a slight 96-cycle hum. The effects on the negative and print are compensatory provided the printing is done with the holes in registration, but cumulative if out of register. With a purely friction drive at the printing point the relative positions of positive and negative perforations are unpredictable and may drift slowly between one condition and the other. This results in a hum that comes and goes and is therefore more conspicuous than if steady. Area tracks are far less sensitive to such development variations.

Optical printers with independent filtering of negative and positive film motion would be subject to the same uncertainty with respect to relative perforation positions, but this problem comes up only with 35mm-to-35mm printing, for which optical printers are rarely used.

In spite of such improvements as have been made in developer turbulation in the processing machines, the sprocket type of printer does not appear to have any strong competitor for density prints. In such a situation the efforts of several Eastman engineers[112,113] to improve sprocket action are well justified. The shrinkage-compensating sprocket described above under "Mechanical Systems" should result in great improvements. The new film-base materials with their reduced shrinkage should also make for better results with printers of the sprocket type.[391]

Optical Printers. Cost and quick production have been dominating considerations in much 16mm production, and contact printing on the sprocket has prevailed, the printers being simpler than other types and available in large numbers to meet the heavy wartime demands. However, registration of negative and positive perforations is not a factor in the quality of 16mm prints of either density or area tracks. There is thus no obstacle on this score either to nonslip printers or to optical printers with independently filtered film motion, and both types have been used, the nonslip for printing from 16mm negatives, and the optical principally for printing on 16mm film from 35mm negatives,[237–239] but also with a 1 : 1 optical system for printing from 16mm negatives (Precision Film Laboratories, New York).[240]

The Eastman Co. has designed several models of optical reduction printers in which the 35mm and 16mm films are on sprockets on opposite ends of a single shaft and a U-shaped optical system is employed.[241] This system minimizes chances of slow "wows," but depends for good results on the degree of excellence attainable with sprocket action. The shrinkage-compensating, radial-tooth sprocket described in the section on "Mechanical Systems"[113] was developed with printer applications particularly in view.

Ultraviolet Light for Recording and Printing

For truly distortionless recording the ideal light spot would be of infinitesimal width. In practice, as various improvements made light of greater intensity available, the nominal width of the recording spot was reduced (to 0.00025 in.), but a limit is set by diffraction. With light of shorter wavelength lenses of the same dimensions can form a more nearly perfect image. This is one of the considerations that led to a study by Dimmick of the possibilities of recording with ultraviolet light. Even more important than the improved image definition was the fact that ultraviolet light is more rapidly absorbed in the emulsion than is visible light. The increased absorption must be compensated for by increased intensity, but the net effect is that the exposure is confined more nearly to the surface where the silver halide grains are more completely used, and the result is less graininess. Most important of all is that the light scattered by the emulsion does not spread as far sidewise, and thus enlarge the image, as does visible light.[242,243]

Dimmick reported the results of tests with ultraviolet in August 1936.[244] He had found it possible to obtain adequate exposure with the regular incandescent lamps and Corning No. 584 filters.

Conversion for ultraviolet recording involved provision for the filter, redesign of the objective lens, and substitution of glasses with less ultraviolet absorption for other lenses in the system. Many of the variable-area recording systems were converted. Single-film newsreel systems (with the sound recorded on panchromatic negatives) were especially benefited by use of ultraviolet.[245,246]

The results obtainable by the application of ultraviolet exposure to variable-density films were studied and reported by Frayne and Pagliarulo in June 1949.[247] They found major improvement in definition and reduced distortion, but only about 1 db reduction in ground noise. Further experiences with ultraviolet are reported by Daily and Chambers.[248]

Many printers were modified to print sound with ultraviolet. High-intensity mercury arc lamps were widely used for the printers.

Ultraviolet exposure gives lower gamma for the same development than does white light. Advantage has been taken of this in certain cases of density recording to reduce the gamma of the sound print without departing from optimum development for the picture.

Coated Lenses. Each time any optical or light-source improvement made an increase in image intensity possible, the benefit could be realized in terms of finer resolution and better high-frequency response.

When the results were published of some tests in which the reflection from glass surfaces had been materially reduced by applying quarter-wavelength coatings of certain low-index minerals,[249] Dimmick procured equipment, mastered the techniques of applying such coatings by evaporation in vacuum, and compared the merits of various materials and methods of hardening the deposited layer. Having found a satisfactory procedure, he treated all the glass-air surfaces in the RCA recording optical system. Although the loss at each glass-air surface is only about 5%, there are sixteen such surfaces (excluding the lamp bulb), and by reducing each to a magnitude of between 1 and 2%, a gain of more than 50% was possible in the brightness of the image on the film. Not only is the image thus brightened, but the stray light due to "lens flare" is reduced to a small fraction of its previous magnitude. A review of the subject, containing further references, has been published by W. P. Strickland.[250]

The first RCA coated-lens optical system to be field-tested was a "variable-intensity" system taken to Hollywood by Dimmick early in 1938 and used experimentally during some months at the Fox studios, C. N. Batsel being the RCA liaison engineer.[251] I believe that I am right in saying that the demonstrations of this system were partly responsible for arousing interest in the benefits to be had by such treatment of glass surfaces.

Within a short time the lenses in a number of the RCA recording systems were given low-reflection coatings, and the practice of coating lenses in both area and density recording systems spread rapidly.[252]

Dichroic Reflectors. As a by-product of the work on low-reflection coatings, Dimmick studied multilayer coatings of alternate high- and low-index materials.[253] With these he was able to produce plates having very high reflectivity in one part of the visible spectrum and very high transmission in another (65% reflection at 7500 A and better than 95% transmission between 4000 A and 5000 A).

The first motion-picture application of his "dichroic reflector" was for reflecting the red light of the recording light beam to a caesium phototube for monitoring, while losing practically none of the blue and violet light that produces the exposure.[254]

During the war there was heavy demand for dichroic reflectors, designed to various specifications, for the armed forces, and also great demand for low-reflection treatment of many optical devices. Selective reflectors of this type have also played an important part in color-television developments.[255]

Heat-Transmitting Reflectors. Another outcome of the development work on dichroic reflectors is a design in which the transition from high to low reflectivity occurs just beyond the end of the visible spectrum, so that as a mirror it would compete well in efficiency and whiteness with the best silver or aluminum mirrors, while the invisible heat rays are better than 75% transmitted.[255,256] No comparably effective means of separating the useful visible from the infrared radiation has been hitherto available, and we may look forward to extremely valuable applications.[257,258]

Measures for Reduction and Control of Distortion

There is hardly space here to mention the many refinements, including principles of good design, by which distortion has been kept low in microphones, amplifiers, recording devices, optical systems and reproducing systems. We shall confine ourselves to discussing the sources of distortion associated with photographic soundtracks. These may be listed as:

(1) background noise caused by graininess (especially in density tracks) or by scratches or dirt in the track area (most serious in area tracks);

(2) noise (hum) and amplitude modulation resulting from sprocket hole proximity;

(3) fluttter or "wows;"

(4) high-frequency loss;

(5) irregular high-frequency loss, and modulation of recorded sound, due to printer defects;

(6) waveform distortion due to misalignment of the aperture (slit) either in recording or reproducing, and to uneven reproducing-slit illumination;

(7) waveform distortion and production of spurious tones due to nonlinear input-output relations (more frequent in density recording than in area);

(8) waveform distortion and production of spurious sounds due to finite width of the recording slit and image spread in the film emulsion (a problem in the area system); and

(9) distortion due to overloading.

Measures for improving sound records with respect to background noise are discussed in part under "Ground-Noise Reduction," but also include extreme care as to cleanliness (especially in processing), to hardening and lubricating (waxing) the film,[259] to maintenance of projector condition, and to the several expedients by which the maximum reproduced volume can be increased.

Fine-grain film has made perhaps the greatest single contribution to improvement in ground-noise ratio, especially for density recordings, but its benefits have been in so many directions that only the present topic heading (Reduction and Control of Distortion) seems broad enough to include it.*

Various developments which improved high-frequency response have already been mentioned, and to these should of course be added the use of fine-grain film. The topic "Improved Printers" has also been included in the section on better high-frequency response. Reduction of flutter is dealt with in the section on "Mechanical Systems." Analytical studies of the distortion that results from misalignment (or azimuth errors) of recording or reproducing slits in the case of area recordings, have been published by Cook[260] and by Foster.[261] In the case of density tracks the effect of misalignment is practically equivalent to widening the scanning slit, the results of which in terms of high-frequency loss are given in a paper by Stryker.[262] Both Cook and Foster have published analyses of the distortion in area recording due to slit width.[263,264]

Calculations of the distortion resulting from certain cases of uneven slit illumination and with several types of area track have been published by Cartwright and Batsel.[265] A test film has been made available for checking light uniformity.[266] It has a number of very narrow recordings of a tone in a series of positions across the track, and their relative outputs when played indicate light intensity at the corresponding positions in the scanning beam.

Sprocket Holes and Irregular Development. The proximity of sprocket holes to the soundtrack causes various difficulties. Mechanically the variations in stiffness of the film cause it to bend in a form resembling a polygon instead of a true circle.[232,267] This causes 96-cycle flutter, less perfect contact in printers, and 96-cycle modulation of high-frequency tones if optical systems have small depth of focus and are not exactly focused for the average emulsion plane. More serious from the sound standpoint is the effect of the holes on development.[268,269]

In film development there is always a tendency to nonuniform developer activity due to local exhaustion. For example, over and near a large dense area the developer is slightly weaker in its action than over the middle of a lightly exposed area, and this in turn is weaker than the average of the bath. If the partly exhausted developer as it diffuses out of the emulsion is not immediately carried away from the film by currents in the liquid, it may creep along the film surface and weaken the development in such areas. If there is little fluid movement except that caused by the travel of the film, the direction of travel is often evident from the appearance of pictures.[270,271] Circulation of the liquid is somewhat freer near the holes and edges of a film than elsewhere, and therefore the development and average density greater. This was discussed in connection with printers.

The irregular development troubles are reduced by very active stirring or turbulation of the developer while the film is passing through.[272] Improvements on this score are reported by Leshing, Ingman and Pier.[273]

Uniformity of development is further improved if the emulsion has such characteristics that its "gamma infinity" is only slightly higher than the desired gamma. Film manufacturers have been

* It has been said that the entire evolution of sound reproduction can be divided into two parts: (1) the learning how to make a noise and (2) the reduction of distortion.

successful in producing fine-grain emulsions which come much closer to this desideratum than earlier types.

Waveform Distortions. The sensitometric studies and analyses about which we have already spoken are a part of the large body of literature bearing on the subject of distortion of the nonlinear type in density soundtracks. There have also been a number of experimental studies reported in this *Journal* giving distortion measurements with both density and area tracks. Two of the earliest of these were by Sandvik and Hall (October 1932)[274] and by Sandvik, Hall and Streiffert, October 1933.[275]

One of the most effective measures for reducing such distortions (second in importance only to avoiding overload) is by the use of push-pull soundtracks, and this applies about equally to density and area systems, although the causes of their distortions (Nos. 7 and 8 in the list) are quite different.

Two systems of testing for distortion (one for area and one for density systems) have assumed great importance since their introduction for ascertaining optimum ranges of exposure of negatives and positives. These are known as the "cross-modulation"[176] and the "intermodulation"[277] tests, and will be briefly described.

Overload. Overload in any element of the entire sound system other than in the soundtrack (either in the original recording or in the re-recording) means that the system has not been properly designed. It is easy to say that the way to avoid distortion due to overloads is not to overload, but that is asking too much. The price in terms of reduced average level is from a practical standpoint excessive. The levels set in recording are a compromise between too low an average level (with ground noise therefore more conspicuous) and too many and too bad-sounding overloads.*

In sections to follow, a number of expedients are mentioned for compassing a wider range between background noise and maximum reproduced level. These devices may be used either to make the background quieter or the loudest noises louder, and if properly applied can accomplish the latter with reduced instances of soundtrack overload.

Cross-Modulation Test to Determine Best Processing for Variable Area. While the variable-area system is not critical to gamma product it is subject to distortion, particularly at high frequency, due to the spread of the exposure outside the area of the actual image, caused by the scattering of light in the emulsion. This image spread increases with exposure. The distortion is largely in the form of a change in average transmission when a high-frequency wave is present. It is often referred to as "zero shift." It was particularly troublesome in some of the earlier 16mm recordings. It is possible however, by selecting the proper printing exposure, to make the image spread in the print neutralize that in the negative.[276]

In January 1938, J. O. Baker and D. H. Robinson described tests and equipment which became the standard method for ascertaining the correct relative negative and print densities.[176] For 35mm tests a 9000-cycle tone is 100% modulated at 400 cycles, but there must be no 400-cycle component in current supplied to the galvanometer. For a given negative exposure and development, a series of prints having different black area densities are made. They are then reproduced and the magnitude of the 400-cycle output measured and plotted (in db below the 9000-cycle level, or other reference) as a function of print density. The curve goes through a sharp minimum at optimum print density. With a negative of greater (black area) density the optimum print density is found to be higher. One of the most frequent problems is to select a recording exposure which will give maximum (or at least satisfactory) cancellation of cross modulation, when printed for a certain desired print density (say 1.4 to 1.6).*

Experience shows that if the 400-cycle cross-modulation is 30 db or more below full modulation, the sound is satisfactory. In similar manner if the print exposure and development are specified, the optimum negative density can be determined. For 16mm processing control, a 4000-cycle tone is modulated at 400 cycles. In push-pull recording the cross-modulation in the two parts of the track largely cancel each other and tolerances are extremely broad.

At the 1954 spring convention Singer and McKie[278] reported good results with an electrical compensating circuit, so that cross-modulation can be practically neutralized when making direct positives. This involves determining what function of frequency, exposure and (possibly) amplitude comes nearest to expressing the magnitude of the cross-modulation products.

Intermodulation Test for Variable-Density Control.[277] In the June 1939 *Journal* Frayne and Scoville describe a test for control of variable-density processing. In the earlier years of recording, the conditions for linear relation between negative exposure and print transmission were figured out by conventional sensitometric methods, with correction for the ratio of projection (or semispecular) density to diffuse density. But this is tedious, and a testing system which duplicated soundtrack recording and reproducing conditions was found preferable. In 1935 F. G. Albin[279] described a dynamic check on processing which consisted in making several recordings of a tone, all at the same fairly low amplitude, with a series of increasing mean valve-ribbon spacings. Comparison of the relative outputs from the print showed whether the slope of the curve of print transmission vs. negative exposure was constant or not. This was something of a forerunner of the intermodulation test. In the latter a tone of 1000 cycles or higher is superimposed on a low-frequency tone of, say, 60 cycles. Normally the level of the high-frequency tone is 12 db below that of the low tone, and the combined amplitude just short of overload. The print is run through a reproducing system, and the reproduced high-frequency tone separated out and measured for fluctuations in amplitude. Nonlinearity (distortion) becomes evident as fluctuations of the high-frequency tone, in general at rates equal to the frequency of the low tone or multiples of that frequency.

Fine-Grain Films.[280–282] While the many components of sound recording and reproducing systems were being improved, the great film companies were busy. In the period 1930–1940, the Eastman Co. offered at least seven new emulsions,[283] each of which offered some advantages for soundtrack application as compared with the currently used picture positive (Eastman No. 1301). In 1932 Eastman brought out No. 1359, intended for variable-density recording It was however similar to No. 1301 in contrast. In 1936 No. 1357 was brought out for variable-area recording, slightly faster than No. 1301 without sacrifice with respect to grain and resolution. With ultraviolet exposure it proved popular for variable-density recording. For release prints, however, the positive No. 1301 continued the almost universal choice except as similar films of other manufacture were used.

What was primarily wanted was finer grain, for this would mean cleaner, sharper images for variable-area tracks, less background noise in variable-density tracks, and better resolution and high-frequency response in all tracks. But fine grain in general means lower speed, or more exposure required, and too great sacrifice in this direction would make new films unacceptable. Another difficulty was that with many of the earlier fine-grain emulsions the image had a

*Most movie fans have probably forgotten what a gun sounds like.

*This test is made simpler than it might appear by the fact that when a high-contrast negative is used, the print black-area density is scarcely affected by differences in the black-area density of the negative, hence the printer light setting can generally be kept the same for the entire series of negatives.

brownish tone, which was objectionable in the picture, and so ruled these emulsions out for the release prints. Measures were found for correcting this fault in Eastman fine-grain positive No. 1302. The problem of exposure was less serious in the case of fine-grain films for release and for duplicating than for recording stock, although some changes in printers were required. Special films were introduced about 1937 for duplicating purposes.[284]

One of the chief problems in variable-area recording was due to image spread (beyond the exposed area), but it was found possible to make image spread in the print compensate for that in the negative. The criticism of one of the trial emulsions intended for variable-area negatives (No. 1360) was that it was *too* good in this respect for the currently used print stock.

Re-recording is the universal practice. Graininess and other imperfections in the original negative are transferred to the print, passed on to the second negative by the re-recording operation, and in the final printing are added to the graininess of the release print. The use of direct positives offered promise of eliminating at least one step which was contributing its share of noise. In 1937 Eastman introduced its No. 1360, and Du Pont its No. 216, both fine-grain films designed for making variable-area direct positives.

Changing to a new release stock represented a greater hurdle than the use of special films for negatives and for the re-recording print, so the general thought was to evolve the best possible films for these applications, and take what improvement could be gained in this way. As the story turned out, use of the fine-grain films did not become general until they were used also for the final release prints.

Film graininess contributes to background noise in much greater measure in the density system than in the area system, but the requirements seem to have been harder to meet. Many tests were run and studies made during the years 1938–1940, and a special committee representing those particularly interested in variable-density recording reported in the January 1940 *Journal*,[289] in which tentative specifications were given to guide in the development of the needed fine-grain films.

Du Pont No. 222 was one of the first fine-grain films to gain considerable acceptance, especially at the M-G-M and Paramount studios, where it was used for original negatives, re-recording prints, re-recorded negatives and for a limited number of release prints. High-pressure mercury lamps were substituted where needed to give the required printing exposure. Experience at the Paramount studios is reported by C. R. Daily in the same issue.[286] Figures published in these reports indicate that while a re-recording print might be 8 to 12 db better in signal-to-noise ratio than one made on the previous types of film, only 4-to-6 db net gain was to be expected in the release print if this were on the usual stock. This indicates why the real gains from use of fine-grain film were not achieved until they were used for the release prints as well as in the earlier stages. (See also references 287–290.)

Some difficulty was encountered in processing the negatives to a suitably low gamma, but it was accomplished by use of special developers. (Uniformity of development is almost impossible if the time is cut so short that the gamma is far below the "gamma-infinity" for the given emulsion and developer.) In order to permit somewhat higher values of gammas in the fine-grain negatives the practice was adopted in some laboratories of holding down that of the fine-grain release prints by printing the sound with ultraviolet light, which gives lower gamma for a given development than does white light.

In 1938 the Eastman Co. brought out a high-resolution film (No. 1360) for variable-area recording and in 1939 a recording film (No. 1366) for variable density. In 1941 the No. 1302 fine-grain positive which has been widely used for release prints, became available. In 1945 the Eastman Co. brought out a high-contrast fine-grain film (No. 1372) for variable-area recording and a low-contrast fine-grain film (No. 1373) for variable-density recording, which could be processed in regular picture-negative developers instead of requiring special low-energy developers. The same year Du Pont brought out a new fine-grain recording negative (No. 236) for variable density, whose contrast could be more easily controlled than previous types because of low gamma infinity.

The fine-grain recording films are all much slower than the previous recording films, (No. 1302, for example, requiring about four times the exposure of No. 1301), and recording optical systems, although improved by coated lenses, could not with tungsten lamps provide sufficient exposures for the combination of fine-grain and ultraviolet light, but use of the fine-grain films with white-light exposure went so far in affording the benefits of high resolution and low noise that the combination seemed hardly needed. On the other hand, printing fine-grain positives with ultraviolet light from high-intensity mercury arcs has been widely employed.

It is of interest that the Callier coefficient (ratio of specular to diffuse density) is less with fine-grain than with coarser-grain films, and the result is that a higher control gamma (in which the measurements are of diffuse density) is needed to give the optimum picture on the screen—for example 2.5 for No. 1302 as compared with 2.1 for No. 1301.[290]

Variable-Density vs. Variable-Area.[291,292] The rivalry between advocates of variable-density and variable-area recording is nearly as old as commercial talking pictures and has unquestionably promoted progress in both systems. The fact that the industry did not standardize on one or the other track does not seem to have been any handicap, for all theaters could play either type of track.

During the earlier years of commercial sound, the advantage seemed to be on the side of area for music but density for speech intelligibility. With both at their best there was little to choose in clarity of speech reproduction, but the density system seemed able to take more abuse without too serious loss of articulation. Before control of zero-shift was well in hand (see cross-modulation test[276]) this type of distortion seemed to do more damage to the quality of the high-frequency reproduction than the nonlinearity to which the density system is more subject. With improved techniques and equipment this difference disappeared.

Another factor which for a time was prejudicial to the area system was that, as compared with density recordings, low-level passages seemed to be excessively weak when the controls were set for satisfactory normal and high-level passages. One theory was that, due to some fault in equipment or system, there was "volume expansion," or actual exaggeration of level difference. To those most familiar with area recording such a theory appeared untenable. Measurements did not bear it out. Monaural or single-channel listening itself makes level differences seem greater than direct binaural listening. Could it not be that the density recordings by their nonlinearity produced a compression effect? I recall that one of the most confident exponents of this explanation was M. C. Batsel. One of the fundamental differences in the systems is that an area track overloads very abruptly, whereas in a density track the upper and lower limits of light transmission are approached more gradually. With such a characteristic, considerable overload (i.e. beyond the range of true linearity) can be tolerated without too objectionable effect, and it was thought that considerable advantage had been taken of what might be called permissible overloading in the density recordings as compared with those made on the area system.

A nearly equivalent effect in an area recording can be obtained by rounding the corners of the V-shaped opening in the aperture plate (whose image is the light spot on the slit as shown in Fig. 13). Transition curves are introduced at the outer (full-slit illumination) ends, while the vertex is drawn out to a finer point. Such curved apertures were tried and largely overcame the cause of criticism.

However, the use of electronic compressors (long employed in broadcasting studios) appeared preferable to sacrificing the range of low-distortion light modulation. Compressors were introduced in the recording channels with very satisfactory results. The first such compressors were tried at RKO and Warner studios and compression became the standard. If the original recording is on a wide-range (or low-background-noise) system, most of the compression is introduced in the re-recording to the release-print negative, but I am told that even with magnetic recording some compression is used (or at least available) in the initial recording.

Any simple and general statement of the relative signal-to-noise ratios of the two systems is impossible, since each has its own cause and type of ground noise: grain hiss in density, and ticks and pops due to dirt or scratches in the area system. Area starts with an initial advantage of about 6 db greater output, and if the film remains in good condition its signal-to-noise ratio is better. The variable-area system was chosen by the Bell Laboratories engineers for their stereophonic demonstrations.

As various improvements became available to the industry they worked to the benefit now chiefly of one system and now of the other. Fine-grain films helped both, but helped density more.

The higher output from variable-area tracks led to the proposal by Levinson[293] that intercutting of the two types of track be used as means for increasing reproduced volume range.

The RCA light-modulation system has been modified to record variable-density, by use of an out-of-focus image or "penumbra" on the slit in place of the usual sharply focused triangular spot.[183,294] This system modulated the light reaching the film by changing its *intensity*, whereas the light valve produced a spot on the film of constant intensity but varying height, and therefor varied the *time* of exposure.

The light valve also was modified to make variable-area records by turning it 90° so that the ribbons were vertical (parallel with the direction of film motion) and the motions of their edges imaged at 10 : 1 magnification on the film. This was the system employed for the stereophonic demonstrations.[208,295,296] Variable-area optical systems using light valves were shortly thereafter offered as optional equipment to licensees.

By using valves having one, two or three ribbons as needed, the light-valve system has been made to produce many of the various types of area track that are produced by the RCA galvanometer optical system by changing apertures.[183,184,297]

The strict adherence to one system (area or density) on the part of the major picture companies has in considerable measure broken down, and several are employing both systems, depending on the type of operation required.[298] For example M-G-M, while continuing to use double-width push-pull density for initial recordings,* releases on variable area. One of the reasons for changing to area for release prints is that projectionists often neglected to change their gain settings when switching back and forth between area and density tracks, with a result to the disadvantage of the film with lower output (note also interest in Perspecta Sound.)

Mention is made, in the discussion of control tones, of a system in which the control tone is of subaudible frequency and superimposed on the recorded sound. Modulation of the sound by the control tone is much more easily avoided in area recording.

Compressors.[299] In the previous section comparing the area and density systems, the first urgent need of electronic compressors was described, but their use has proved so advantageous as to have become quite general, both in recording and re-recording channels.[300] Electronic compressors had long been in use in radio broadcasting.[304,304a] In their application to sound recording, if there is no provision for re-expansion, they do not actually increase the reproduced volume range although they may seem to. A common characteristic compresses 20 db into 10 db at a uniform rate. This would rob any passage of expression only to a slight degree. As the overload point is approached it is common to make the compression more drastic, for example 20 into 3 db. This is sometimes called a limiter type of compressor. If (for example by means of control tone) provision is made for re-expansion, the compression may be such as to keep the loud passages, whatever their original magnitude, at nearly full track amplitude. (See section on "Stereophonic.")

Since initial consonants usually carry little power compared with vowels, the compressor may wait to act for the vowel, with resulting relative exaggeration of consonants (especially sibilants). This has been corrected by a high-frequency pre-emphasis in the modulation which controls the compressor.[301–303]

Anticipation in compressor systems is desirable (see section on "Ground-Noise Reduction"). Fast action of compressors is essential and avoidance of "thump" is one of the problems.[305,306]

Experiences in recording with compressors are reported by Aalberg and Stewart of RKO[300]. Experience with compressors at the Warner Bros. Studios is reported by B. F. Miller.[301]

Squeeze Track.[307] In view of the limited range of loudness which a soundtrack permits, and the very great range encountered in our ordinary experience, many expedients were tried for the purpose of increasing the range obtainable from the film. One of these was the "squeeze track" described by Wesley C. Miller of M-G-M.[307] If a variable-density track is reduced in width, both the noise and the modulation are reduced. The ground-noise reduction system described by Silent and Frayne in May 1932[188] may not have been as yet available, but the two devices are not equivalent and can be complementary. There is a practical limit set by film characteristics as to how far the ground-noise reduction, by reducing mean negative exposure, could be carried, and this was at about 10 db of reduction, but the noise can be still further reduced by narrowing the track. The controls in recording or in re-recording are used to avoid too low levels on the track, but some of the range can be restored by narrowing the track in the release print. There were several ways in which this could be done; one, for example, was by preparing a masking film and running the print through the printer a second time with the track width determined by the mask.

"Reversed Bias" System.[308] An expedient for obtaining greater output for bursts of high level sound was described by Hansen and Faulkner[308] of Twentieth Century-Fox. In effect the light-valve bias operates in the usual way for normal and low levels, but for passages of extra high level the mean ribbon spacing is increased to as much as twice normal while still being fully modulated. There is some resulting distortion, but substantial increase in print output. The loss of some relatively high-frequency output is probably not objectionable.

Wide Track and Push-Pull. By doubling the width of the track the noise would be expected to increase 3 db but the usefully modulated light would increase 6 db. While the improvement is not large, it is worth while, and has been widely employed for original recordings and for special purposes, when the sound print does not have to carry a picture.

Push-pull systems have also been developed for both density[309] and area[183] systems and for wide tracks[310,311] and standard-width tracks. Standard-width push-pull systems have been considered for general theater reproduction, but their actual use has been limited to places where the required special reproducing systems did not involve large investment. The push-pull system does not give any improvement in signal-to-noise ratio except for the few film

* Probably later adopted magnetic recording.

blemishes or other disturbances which affect the light through both sides alike. The principal advantage of the push-pull system is that it reduces distortion, and in the density system it may thereby somewhat increase the permissible ratio of light modulation. As applied to area recording it almost eliminates zero-shift distortion. With both systems, push-pull operation permits the use of faster-acting ground-noise reduction, since the "thump" caused by rapid change in transmitted light is largely cancelled. Milestones in the progress toward better sound are usually fixed in our minds by major demonstrations. Such a demonstration was given at the 1935 spring convention. Using wide-track push-pull density recordings, improved two-way (divided-frequency-range) loudspeakers and amplifiers with abundant reserve power, the engineers of the M-G-M Sound Department, under the direction of Douglas Shearer, gave impressive demonstrations.

Push-pull wide-track is regarded as the last word in photographic recording and has for years been used in many studios for original recording.

If the original recording is wide-track push-pull, the positive (which is edited and then used as the master for re-recording to the release-print negative) would be a print of the original. If the original is magnetic, the favored practice has been to re-record to a wide-track push-pull direct positive for the edited film. In eliminating the step of printing, the direct positive minimizes quality losses.

Control Tone.[312] The most effective way to reproduce the great range of sound volume encountered in natural sounds is to resort to compression for the recording and to expand in reproduction. It has always been the practice for the recordist to use his controls to maintain the recorded levels between the limits set by overload and a satisfactory margin above noise. Were a record made of each change in recording gain, and the projectionist given a cue sheet by which he could at the right times make the inverse changes in reproducing gain, the natural levels could be restored. Such a method of operation was at one time contemplated. However, manual controls in recording are too slow, and manual restoration of level too unreliable. Automatic control of gain on the other hand has been used very effectively. If space can be found on the film for an extra soundtrack, a continuous tone can be recorded with either its amplitude or its frequency automatically correlated with the gain of the recording amplifiers, so that it provides a complete record of the recording gain throughout the recording.

For example, a voltage derived from the modulation to be recorded (and thus a function of its initial level) can operate on the recording amplifier to change its gain as in any automatic compressor, and the same voltage can operate simultaneously on the control tone to make the appropriate change in either its amplitude or frequency. In reproduction the output of the control-tone track is then used to provide a voltage which is directly related to that which altered the recording gain, and can therefore be used to produce inverse, or compensating, changes in the reproducing gain.

The use of an extra soundtrack or recording to be used in the manner just described was, I believe, first proposed by C. F. Sacia of the Bell Laboratories, and described in U.S. Pat. No. 1,623,756. One of the first in the RCA group to become interested in control tones was Charles M. Burrill who experimented with tones superimposed on the modulation, but of either too high or too low frequency to be reproduced by the audio system, especially a subaudible tone such as 20 cycles. For film recording he proposed scanning the sprocket-hole area, and varying the magnitude of the resulting 96-cycle tone by blackening more or less of the film between perforations. Thus, if these areas are left clear, the 96-cycle tone is comparatively feeble, while the maximum is produced if they are black.

The sprocket-hole control track was developed for application by H. I. Reiskind and adopted by Warner Brothers for their "Vitasound" system, which will be described in the section on multiple-speaker systems.[326]

Control tones of the subaudible type have in recent years found use for producing spread-sound and stereophonic effects which are particularly appropriate for accompanying large-screen pictures. (See Perspecta Sound, under "Multiple-Speaker Systems" below.) The chief advantage of this method of recording the control tones is that it requires no changes in the recorders and scanning systems, the changes being confined to the electrical circuits. It meets the important practical requirement that reproduction must be acceptable on standard equipment (with no provision for control-tone use). Variable-area recording is better suited than variable-density for use with subaudible control tones, since with suitable processing more accurate linear relationship between input and output can be maintained throughout the range of modulation, thus avoiding modulation of the audio by the control tones. The maximum level which can be recorded must be reduced 2 or 3 db, to make room for the control tones, so that the sum of the two will not exceed the permissible maximum. Tones of 30, 35 and 40 cycles have been used for the controls.

A control-tone system used by adherents of the variable-density system was described by Frayne and Herrnfeld.[313] Between the normal soundtrack and picture areas, space was found for a soundtrack 0.005 in. wide. The authors give their reasons for believing that frequency modulation of the control tone would be more reliable than amplitude modulation. With a frequency range of one octave and using a bandpass filter, they found that in spite of the narrowness of the track it provided a 38-db signal-to-noise ratio. The system was designed to afford changes of gain for the sound up to 30 db, thus expanding the dynamic range by that amount. The soundtrack was of the standard-density type.

In certain systems in which three or more independently recorded soundtracks are used, the sound and picture are on separate films. This gives plenty of room for the control track, but the practice has been to allot only one track to the control and to superimpose the tones, separating them in reproduction by bandpass filters.

Class B Push-Pull. Of the possible systems of photographic recording, the Class B area track undoubtedly carries furthest the principle of low print transmission when the modulation is low. Such a system was described by Dimmick and Belar in 1934,[314] and favorable experience in its use was reported in 1939 by Bloomberg and Lootens of Republic Pictures,[315] where it had been adopted for original recordings and been used in the making of fourteen pictures at the time of the report. They have continued to the present time using the Class B push-pull system for all original recordings. They also reported the methods used for test and adjustment. In the Class B system one side of the track carries only the positive parts of the waves and the other only the negative. When there is no modulation there is no clear film, and no ground-noise-reduction system is needed; therefore the transient or initial clipping which ground-noise-reduction systems can produce are avoided. Two triangles of light (see Fig. 13) are formed at the plane of the slit (one for each half of the track) and their vertices just touch the slit with no current in the galvanometer. Exposure takes place only as one or the other triangle illuminates more or less of the slit. A feature not described in the papers just mentioned is shown in a September 1937 paper by Dimmick.[183] In the mask which is imaged at the plane of the slit to form the triangular light spots, a narrow slit extends from the vertex of each triangular opening, so that light is never completely cut off at this point. There is thus formed a continuous line at the middle of each half track, not wide enough to let an appreciable amount of light through the film, for it is so narrow that it is largely fogged in, but it prevents a slight wave-shape distortion which might otherwise be produced by image spread, just as the tip of the triangle crosses the slit.

Direct Positives. Recording direct positives, instead of recording negatives and then making prints from which to make re-recordings, would seem to offer important advantages in simplifying operations and reducing time loss. There would also be an advantage in reduced ground noise since one less film is used and thus one less source of graininess. The high-frequency losses due to the printer would also be avoided. In the section on "Ground-Noise Reduction," it was stated that a ground-noise reduction system applicable to variable-area direct positives had been developed with the feature of anticipation, so that initial clipping need never occur. It was further possible under these conditions to work with closer margins, and so reduce the width of clear film. This system and results of tests with it are described by Dimmick and Blaney in 1939,[199] with a further report by Blaney in 1944.[316]

The chief obstacle to making variable-area direct positives had been that an entirely satisfactory way of avoiding distortion due to image spread had not been found. In the negative-positive process image spread in the negative could be compensated by that in the print, but the direct-positive system left no place for that solution. There is, to be sure, a certain density for any film at which there is no image spread, and below which the blackened area is slightly less than the exposed area. With the recording films available for a number of years, the density which gave no spread, or zero shift, was so low that light passing through the darkened areas would result in considerable noise. In some of the later fine-grain recording films, however, the balance occurred at densities which were satisfactorily high, thus making direct positives feasible under conditions in which they had not been before. However, the direct-positive system described by Dimmick and Blaney was not limited to the use of special films. They used a push-pull system which goes so far toward neutralizing the effects of image spread that excellent results were obtained with the standard fine-grain recording stock for variable-area.[316,317]

In variable-density recording the same anticipation feature is not applicable, but the other advantages of direct positives for original recordings apply. The problem of recording a positive lies in the requirement that the film transmission shall not be a reciprocal of the exposure (hyperbola) which a non-reversing film tends to produce, but must have an inverse relationship expressible by a downward-sloping straight line, covering a large range of transmission. A method of correcting *in the reproduction* for the nonlinear transmission characteristic of a variable-density negative was described by Albersheim in 1937,[318] but this would limit the usefulness of the direct positives. Electrical compensation in the recording was described by O. L. Dupy of M-G-M in 1952.[319] An approximation to the desired relation is possible by recording on the toe of the H&D curve, but high-level output is not possible from such direct positives without serious distortion.

A radically different solution of the problem was described by Keith and Pagliarulo in 1949.[320] Superimposed on the audio current supplied to the valve was a 24-kc bias current of twice the magnitude required to modulate fully the light-valve opening at normal unmodulated spacing. The ribbons are in different planes so that they can overlap without clashing. The authors reported 8-db higher output from the direct-positive than from a standard-density print, and 6-db higher signal-to-noise ratio than a standard print without ground-noise reduction. Direct positives, generally push-pull, have come into wide use for editing and re-recording service.[321,322]

Electrical Printing. Successful recording of direct positives opens the way to "electrical printing," or putting soundtracks on release prints by a re-recording operation instead of by contact printing. This is discussed by Frayne.[323] While such a method would necessarily be more expensive, the elimination of the flutter and irregularities resulting from the action of most contact printers is a strong argument in its favor. Frayne finds possibilities of greatly improved sound by this method, particularly for 16mm color prints of the reversible type such as Kodachrome or Ansco-color.

Engineers have long been attracted by the possibility of improved resolution and reduced distortion in 16mm positives by direct recording,[324] but until the more recent developments, direct positives (except on reversal films) were not a success.

Limits of Volume Range. While ideal sound reproduction would seem to call for duplication of original sound levels it is questionable whether illusion or seeming naturalness is improved by going as far as this in the direction of loudness. In the applications of control-tone systems, where very high levels are attainable, the extremes have been scaled down by 10 db or more. With respect to the desirability of carrying reproduction to extreme low levels, W. A. Mueller[325] has shown that there is a definite practical limit set by general theater noise.*

Multiple-Speaker Systems

It has often been observed that musical reproduction gives greater satisfaction if it comes from several sources. The Music Hall at Radio City in New York has been equipped to make this possible, and thus has afforded numerous opportunities to verify the advantages of multiple sources. With reference to the effort to obtain "dynamic range," Garity and Hawkins[333] state that: "Three channels sound louder than one channel of three times the power-handling capacity. In addition, three channels allow more loudness to be used before the sound becomes offensive, because the multiple source, and multiple standing-wave pattern, prevents sharp peaks of loudness of long duration."

That dialog should be reproduced on a speaker as near as possible to where the actors are seen is never questioned, but music and many sound effects such as thunder, battle noise and the clamor of crowds are far more impressive and natural if coming from sources all around the listener. The effects obtainable are discussed by H. I. Reiskind[326] who also describes the equipment used in the sprocket-hole control-track system.

Vitasound. This system, used by Warner Brothers, is described by Levinson and Goldsmith.[327] It is the simplest of the systems employing spread-sound sources and control tone. It uses three similar loudspeakers, the usual screen-centered dialog speaker and two side speakers outside the screen area. The design of the system is based on the theory that the volume range which the film (with the usual ground-noise reduction) affords is adequate for dialog and such other sounds as come from the center speaker only, and that higher sound levels will be wanted only for music and sound effects for which the spread-sound source will also be wanted. The control-tone output is therefore used, first to switch in the side speakers, with no change in total sound power. Further increase in control-tone output raises the gain on all three speakers, up to a total of 10-db increase.

Stereophonic Sound. Mention has been made in the section on loudspeakers of the transmission of music and other sounds "in auditory perspective" from Philadelphia to Washington in 1933. Three microphones were spaced across the stage and their outputs separately transmitted to three similarly located loudspeakers at the auditorium where the sound was reproduced. The various

* Background noise makes the useful sound seem fainter than sound at the same level in a quiet place. This holds even though the background noise is not loud enough to interfere nor even to make the listener conscious of its presence.

orchestral sounds seemed to come from the appropriate places, and a moving source such as a man walking across the stage and talking seemed at the receiving end to move about. In 1941 and earlier,[328,329] similar demonstrations were given, with the difference that this time the sound was recorded and reproduced. As in the previous case, every effort was made by the engineers of the Bell Telephone Laboratories and Electrical Research Products Inc. to minimize all forms of distortion and to reproduce the sound in the full dynamic range of the original.

Since it appeared that for the immediate purposes of the project the films could be maintained in good condition with respect to abrasions and dirt, and that under such conditions the advantage in terms of signal-to-noise ratio is with the variable-area system, the recordings were of the variable-area type, made with an adaptation of light-valve optics. The recorder and reproducing machine carried the film through the translation points on smooth (toothless) drums, on whose shafts were damped flywheels of the liquid-filled type described by Wente and Müller.[81,104]

On the basis that the film track was capable of giving a signal 50 db above noise, while the orchestral music to be reproduced had a range of 80 db, compressors were used in recording, and expandors in the reproducing system designed to compensate exactly* for the compression in recording. The compressors made no change of gain until the signal neared full track level and above this made the gain the inverse of the sound level, thus keeping the recorded level just below track overload. The level of the amplified microphone output controlled the magnitude of an oscillator tone, which tone was simultaneously recorded in a fourth track and applied to the recording-circuit compressor. In reproduction the same tone controlled the expandor gain. Because the levels at the three microphones did not necessarily rise and fall together, the compressors in the three channels were independently controlled by their own modulation levels. This necessitated use of three control tones, but these were recorded superimposed in one track and separated in reproduction by filters.

In order to give the compressor time to operate when a sudden increase of sound level occurred, an "anticipation" system was employed, using two microphones. The compressor operation was determined by the output of the microphone closer to the source, while the second microphone furnished the sound to be recorded.

As further insurance against audible background noise, the system of "pre-emphasis and post-equalization" of high-frequency components of the sound was employed. The usual ground-noise-reduction system by light-valve bias was not used, being made less necessary by the compressor-expandor (or "Compandor") system.

The October 1941 issue of the *Journal* carries discussions by Fletcher,[329] Steinberg,[330] Snow and Soffel,[331] Wente and Müller,[104] and by Wente, Biddulph, Elmer and Anderson,[332] of various aspects and elements of the stereophonic system.

Despite the unquestionable success of the stereophonic system in reproducing the subjective effects of sounds coming from the sources located as seen on the screen, and the impressiveness of the musical and sound effects which it was capable of handling, the motion-picture industry made no immediate move to adopt or apply it. A factor which undoubtedly militated against interest in utilizing the stereophonic system was that only for the patrons near the front of a theater did the screen subtend a large enough angle to make the difference between stereophonic and single-channel reproduction impressive. It appears to be another case of a development ahead of its time. With the recent advent (commercially) of the wide-film systems CinemaScope and Cinerama, stereophonic sound, supplemented by "spread sound," plays an essential role in providing the desired overall effects.

Fantasound: Fantasia. Walt Disney and his engineers had a somewhat different idea of what might be accomplished by means of multiple-track recordings with control tones. It might be appropriate to say that they proposed to make their spread-sound effects an art rather than a science. Duplication of an original distribution of sound sources was a secondary consideration, and the choice of directions from which sounds were to come was to be entirely at the discretion of the directors, musicians and technicians.

The story of the development of Fantasound and its evolution through numerous experimental forms beginning in 1937, was told by Garity and Hawkins,[333] with further reports by Garity and Jones,[334] and by E. H. Plumb.[335] Garity and Hawkins reported from tests that if a sound source (from loudspeakers) was to seem to move smoothly from one position to another, the output power from the two speakers should be held constant. This condition is not necessarily met by having the actual source move from near one microphone to near the other, but it can be met when the gain is reduced to one speaker and increased to the other by means of a knob or control tone.

The animated picture was designed specifically for the music, which was taken from great classics. In the initial orchestral recordings many microphones and separate recording channels were used. Recordings were selected or mixed in the re-recording to obtain desired effects such as predominance in turn of various orchestral groups (strings, brass etc.). Sound and picture were on separate films. The final sound film carried three 200-mil push-pull variable-area soundtracks, and three superimposed variable-amplitude control tones on a fourth track. The amplitude of the several control tones was determined by manual adjustments.

The theater equipment consisted of three loudspeakers at the center and to the sides of the screen and additional speakers at the sides and back of the auditorium. The latter could be brought into operation by relays responsive to notches in the edge of the film. They were used effectively for various sound effects and for the music of a large chorus. Abundant sound power and volume range were employed, the volume range being readily obtained by use of the control tracks.

The final Fantasound equipment was designed by RCA engineers. A special optical printer was used to print sound from separate negatives onto the multitrack positive, and special film phonographs in which a single system illuminated all four tracks, the transmitted light being received by four independent double-cathode photocells.

Fantasia was enthusiastically received but was not a financial success because of the heavy expense not only of its production but of "road-showing" with such elaborate equipment. The advent of World War II hastened its withdrawal, but Disney had performed a great service to the industry and art by pioneering in a sound-effects field which is now finding important applications.

Recent Multiple-Channel Systems.[336–342] During 1952 and 1953 three new systems of presenting pictures were introduced, known as "3-D" (Three-Dimensional), "Cinerama" and "CinemaScope." All of these represent more elaborate and expensive picture-projection systems, and with them would logically go whatever could be offered in the way of more impressive sound. The principles of stereophonic sound, plus the surround speakers distributed around the auditorium (as used in Fantasound), have been applied.

In the 3-D system two projectors are required, and a third synchronized machine, a film phonograph, is added for the sound. The sound system is stereophonic and uses three 200-mil magnetic tracks.[370,371]

The CinemaScope system[339] (developed by Twentieth Century-Fox) presents a much wider screen picture than does the

* Exactly, in terms of timing, but not necessarily fully restoring the 30 db of compression range.

standard system, and therefore presents an excellent opportunity for the use of stereophonic sound since the screen speakers are distributed over a large enough distance to make the shifts in the position of the sound source noticeable and needed for realism. The sound system developed to go with CinemaScope uses four magnetic stripes or tracks, two just inside the sprocket holes and two outside. To make more room for the tracks and leave as much as possible for the picture, sprocket holes of new shape have been designed. In the new perforation no valuable feature is believed to have been sacrificed, and the film will still run on standard sprockets. Three of the tracks provide the regular stereophonic sound (three speakers behind the screen) and the fourth carries sound effects for transmission by the surround speakers. For multitrack magnetic reproducing equipment see references 108–110.

Cinerama[340] (developed by Fred Waller and Hazard E. Reeves, and commercialized by Cinerama Productions Corp.) carries the wide-screen principle much further, employing three projectors to project adjacent edge-blended pictures on a curved screen. For the sound six magnetic tracks are used, and five speakers behind the screen, while the sixth track feeds a set of surround speakers.

The surround speakers, wherever these are used, are of the direct-radiator type, much less bulky than the screen speakers and with more limited frequency range.

Recent Multiple-Speaker Systems With Photographic Track.[339] A simpler multispeaker (or sound-placement) system has been developed by Robert Fine[342] and named "Perspecta Sound." Mention was made under the heading "Control Tones," of the use of control tones of subaudible frequency. In the Fine system there is only one soundtrack (variable-area, photographic) in the standard position, but three loudspeakers behind the screen, fed through separate variable-gain amplifiers. Three control tones, superimposed on the sound recording and separated in reproduction by filters, control the gains of the three amplifiers so that the apparent source can be made to shift across the screen, and the total sound level may be varied as desired to increase the dynamic range. The Perspecta-Sound recording if reproduced on a standard system (not equipped to make any use of the control tones) would, except for a slight reduction in level, be indistinguishable from a standard recording. M-G-M and Paramount have been particularly interested in Perspecta Sound and have equipped numerous theaters with it.[342]

Another sound-placement system was developed by the Dorsett Laboratories of Norman, Okla., and has been installed in a number of theaters in Texas and Oklahoma. It is described in the May 1954 Progress Report[339] as using a standard optical track, but with provision for shifting the sound from the center speaker to either of two screen speakers to right or left, or to peripheral (surround) speakers. This is accomplished by "switching cues in the form of a binary code marked into both sprocket-hole areas," and optically scanned. "Standard single-track optical release prints are cued for use with this system by the Dorsett representatives." (Quotations are from the Progress Report.)

Sound and Color. Since in color pictures the silver is removed from the emulsion, special handling of the soundtrack is required. In the Technicolor imbibition process the soundtrack is printed in the usual way, the remainder of the film is then cleared of all silver, and the pictures produced by dye transfer from relief masters.

With the multilayer color films such as Kodachrome, Kodacolor, Anscocolor and a number of more recent types it would be possible to expose the track with white light so that all three dyes contributed to the density, or with colored light so that the sound image would be principally in the top layer, and reproduce with a filter of the complementary color. The principal problem with this procedure is that existing projectors are nearly all equipped with caesium photocells whose sensitivity extends well into the infrared, in which range all of the dyes in use are transparent.[343] Substitution of phototubes of other types would mean an objectionable loss of sensitivity. In May 1946, A. M. Glover of RCA reported the development of a blue-sensitive phototube which could replace the caesium tubes in projectors without loss of output.[344,345] However, by this time the makers of color film had begun the use of edge-development processes that form a track of silver or of a metallic salt (opaque to infrared) not removed by the bleach which was part of the picture processing.[346] In one system the silver is in the top layer only, and the dyes in the other two layers contribute to the opacity. The metallic track became general in the handling of sound on color films.[347–350]

Sound on 16mm Film. I have confined my story to developments in the 35mm field in the belief that the general principles and practices which solved problems or led to improvements in one case were applicable in the other. It is probably a gross injustice to pass over the valuable work of engineers whose efforts were devoted to 16mm sound, but it seems to be a necessity.

From the start, the recording of sound at 36 instead of 90 ft/min. presented great difficulties. Only the fact that standards were much less exacting made the project practicable. But with each advance in the resolution of high frequencies in 35mm recording, the corresponding principles were applied to 16mm. One factor at least was in the favor of the low film speed, namely the providing of adequate exposure. By the time of the outbreak of World War II sound on 16mm film had improved to the point which made it acceptable for a great number of military applications.[351]

Recording sound on black-and-white reversal film was not too satisfactory, but years later when color films came into wide use, it again became necessary to put the sound on what was essentially a reversal type of film. Particularly successful for this purpose is recording on the individual prints or electrical printing. (See the section with that heading, and the December 1950 paper by J. G. Frayne.[323])

Black-and-white prints, with original sound recorded either on 16 or 35mm films, formed the great bulk of the product before and during the war. Fortunately, fine-grained emulsions could be used. Cost considerations dictated for the most part the use of 16mm negatives and contact prints, and unhappily nearly all of the printers were of the sprocket type. One laboratory adopted 1 : 1 optical printing as its standard.* Much study was given to the possibilities of recording direct positives. Still more development work was devoted to direct optical reduction from 35mm negatives, and this certainly helped resolution and high-frequency response,[239] but in the case of area tracks, neutralization of image spread in the positive by spread in the negative was not easily achieved.[276] The same factor made difficulty in the recording of direct positives, which had had advocates since early in the era of sound pictures. Since 35mm negatives for optical reduction, or 35mm rerecording positives to be used for making 16mm negatives give best results if recorded with different degrees and kinds of high-frequency pre-equalization, the organizations producing these masters have worked together to establish standards of recommended characteristics.[352]

Adding sound to 16mm films by use of a stripe of magnetic material promises to become of great popular and commercial importance.[353]

Drive-in Theaters.[354] The drive-in theater was first proposed and advocated by R. M. Hollingshead, a businessman of Camden, N.J., not affiliated with motion-picture or electronic interests. The first such theater was built near Camden in 1933. In the earlier experiments with the system effort was made

* Precision Film Laboratories, New York, operated by J. A. Maurer.[240]

to put out enough sound power from a screen speaker to enable patrons to hear satisfactorily in their cars. This presented great technical difficulties, and also would have restricted theaters to locations where the noise would not be too objectionable. Several arrangements were tried, one with loudspeakers distributed over the field so that each speaker provided sound for two cars side by side. This was a great improvement from the noise standpoint, and the theaters previously equipped with screen speakers were converted. However, these "out-car" speaker arrangements still left something to be desired on the score of general noise. The "in-car" speaker, introduced by RCA in 1941, provided sound which was much more satisfactory to patrons and practically eliminated the neighborhood-noise problem. In the design of "in-car" speakers, the qualities of ruggedness, conveniently small size without too much sacrifice of sound quality, and immunity to damage by weather were design objectives.[355] The amplifier and audio-power distribution system had to be such that the individual levels would not be too much affected by the number of speakers in use. During the 1930's a number of drive-in theaters were built in New England, in the South, and (through the efforts of Philip Smith) in Indianapolis, Cleveland, Detroit, Milwaukee, St. Louis, Kansas City and Pittsburgh. Building activities were practically at a standstill during the war, but after its close the number increased rapidly. Underhill[356] gives the number of drive-in theaters at the end of the war as about 60 and four years later as 1000. He attributed the rapid growth just after the war in part to the greatly increased number of cars on the road, especially after the end of gasoline rationing, and in part to the shortage of building materials which made the construction of indoor theaters relatively difficult and expensive. The May 1954 Progress Report puts the number of drive-in theaters at the end of 1953 at 4000, and estimated that six months later there would be 4500.

The most serious problem of the drive-in theater is the provision of sufficient light for the large screen, a consideration, however, which lies outside the scope of this paper.

Magnetic Recording

The principle of magnetic recording was demonstrated in 1900 by Valdemar Poulsen, who called his device the "Telegraphone."[27,357] About 1917 the American Telegraphone Co. marketed a dictation machine under that name which performed well by existing standards but was complicated and could not compete commercially with cylinder machines. Recording was on 0.010-in. "piano" wire, contacted from opposite sides by a pair of offset steel pole-pieces. Erasure was by a saturating d-c field, and a d-c bias was combined with the recording-voice current in sufficient magnitude to maintain all the recorded magnetization of the reversed polarity.

An alternating magnetic field has for years been the accepted means of demagnetizing magnetic materials, and it seemed a paradox that a superimposed alternating current would assist in, rather than obliterate, recording. However, it was found in 1921 by W. L. Carlson and G. W. Carpenter, then working on a government project of recording telegraph signals, that a bias current of supersonic frequency could be very advantageous in magnetic recording of audio-frequency signals.[358]

The development of magnetic recording was carried on by the Bell Telephone Laboratories during the 1930's. A thin steel ribbon about $\frac{1}{8}$ in. wide was found better than wire, and alloys of superior magnetic properties were developed. Direct current erase and bias were used in the equipment.

The developments and publications of Marvin Camras[359,360] of Armour Research Foundation aroused widespread interest in magnetic recording and the results obtainable with high-frequency bias. The essential difference between a recording made with d-c bias, and one made with high-frequency bias is that with the latter (1) modulation is through zero, with resultant increase in maximum recordable amplitude, and (2) there is no remanent magnetism when the modulation falls to zero. The second feature is the condition for low background noise. The comparison is analogous to that between a Class B push-pull photographic record, and a unilateral recording without ground-noise reduction.

There was much developmental activity in wire recording just before and during the war, with numerous applications for the armed services. The extreme compactness of recordings stored as magnetized wire plus the ruggedness of the system with respect to mechanical injury made it of especial value for military uses. Better wires were developed, 4- to 5-mil diameter sizes being widely used. The Brush Development Co. developed a compound wire in which an alloy of superior permanent magnetic properties was plated on a brass core.[357] The National Standard Co. of Niles, Mich., developed a successful stainless-steel recording wire.

S. J. Begun[357] quotes an article in *Machinery* of January 1917 about the Telegraphone in which mention is made of a stripe of powdered iron to be painted on a motion-picture film to provide synchronous sound. It was more than 30 years later before use was made of this principle — one of the many examples of development in which the basic concept is only a small part of the invention, and the real contribution to progress the result of laborious experimentation and wise application of refinements and better techniques. Not until a sound quality was attained in magnetic recording surpassing that of any other known system did it become of great concern to motion pictures.

Development of magnetic coatings on paper or other base materials was undertaken by the AEG in Germany about 1928, but up to the outbreak of war nothing of outstanding quality had appeared. At the close of the war the American occupying forces brought back samples of a new German magnetic tape and equipment. The magnetic material was a finely divided iron oxide, mixed with a binder and coated on a thin cellulose base (total thickness about 0.002 in.). In the recording magnet a supersonic bias current was superimposed on the audio current. Magnetization was longitudinal, produced by C-shaped magnets of high-permeability alloy, with very short gaps where they contact the tape. Reproducing magnets were similar. In cleanness of reproduction, low ground noise and volume range the German system set a new high standard.

A period of intensive development followed the demonstrations. Some time was required before American firms could match the quality of the German tape, especially with respect to freedom from noise. Numerous papers were published describing basic properties of magnetic materials,[361,362] analysing the action of the supersonic bias,[363,364] and reporting tests on various tapes to determine optimum bias, relation of distortion to recorded amplitude, and amount of residual noise.[365] Among the first in this country to produce acceptable tapes was the Minnesota Mining & Mfg. Co.[361] Experimenters tried the magnetic black oxide (Fe_3O_4) in powder form and found it capable of producing higher output levels but noisier than the red oxide used in the German tapes. The red oxide (Fe_2O_3) in a certain crystal form ("gamma phase") is magnetic. Grinding to a particle size of about 1 μ or less was found essential, and prolonged mixing. Many tape-recorder-reproducer equipments were developed, both for amateur and professional use, the latter principally for broadcast stations.

Advantages of the Magnetic System. The compactness and portability of the magnetic-tape equipment, its freedom from dependence on laboratories, the immediate playback, the small storage space required, the relatively small cost of recording stock, plus the ability to reuse tape when the recorded sound on it is no longer wanted, the ability to work in daylight, and finally the excellent sound quality and dynamic range, combined to make the magnetic system a great advance from both the economic and performance standpoints.

Uses in the Motion-Picture Industry of Nonsynchronous Recording. The prompt interest of motion-picture producers in magnetic recording was shown in two lines of activity. The Basic Sound Committee of the Motion Picture Research Council held meetings in *1946* to which prospective suppliers of magnetic-recording equipment and record materials were invited.[366] The purpose was to formulate the requirements of the motion-picture industry in order that developments might be better directed toward meeting these requirements. The other activity was making experimental use of the nonsynchronous thin-tape recording equipment which was the first to be developed.[200] While the most important use which might be made of the magnetic system would be for the original synchronous recordings, there are numerous operations for which the lack of exact synchronism of magnetic tape would not be too serious an obstacle, such as for immediate playback after rehearsals, for training singers and actors, and for recording of music and sound effects which do not have to synchronize exactly with the picture. In musical numbers the picture is often secondary to the sound, and in many cases the practice had been followed of recording the sound first, without picture, and subsequently fitting the picture to the music. For this, initial recording on tape was applicable, the sound being re-recorded to film while musicians or vocalists performed synchronously for the camera.

Papers on Progress in Magnetic Sound. At the October 1946 convention of this Society Marvin Camras described and demonstrated synchronous magnetic sound, using 35mm film coated at Armour Research Foundation. However, the coated film was not offered commercially. At the same meeting H. A. Howell[362] of Indiana Steel Products Co. gave data on several magnetic materials and described a coated-paper tape which could be perforated if desired. While paper offered certain advantages which commended its use at the time, it has not been possible with coatings on paper to attain the quality and low noise that are realized with bases of clear plastic.

In February 1947 the Du Pont Co. furnished RCA with samples of coated 35mm film base. A conversion kit was developed so that a standard RCA photographic recorder (PR-23) could record and reproduce magnetically. The November 1948 issue of the *Journal* contains a description of the kit by Masterson,[367] measurements of the properties of the Du Pont film reported by O'Dea,[368] and bias studies by Dimmick and Johnson[365] of $\frac{1}{4}$-in. thin tapes made by Du Pont and by Minnesota Mining & Mfg. Co. as compared with one of the German tapes. The commercial version of the conversion kit was described by Gunby[369] at the October 1948 convention. In the June 1949 *Journal* Mueller and Groves[200] describe experiences at Warner Bros. Studios with various uses of nonsynchronous magnetic recording, and such experience as had been had up to that time with synchronous magnetic recording. The practice of re-recording from magnetic to direct-positive photographic tracks is mentioned. This has sometimes been called "electrical printing," and soon became the prevalent method of providing a sound film to be edited and then re-recorded to the final release negative. The January 1952 paper by Carey and Moran[322] states that the practice of re-recording from a magnetic original to a 200-mil push-pull variable-area direct positive for editing had been followed by Universal International Pictures since January 1951.

The Progress Report of May 1951 shows RCA synchronous magnetic recording equipment, designed to make one, two, or three tracks on the film.* This was being used by Columbia, the sound being re-recorded to direct positives for editing. The same report tells of Westrex portable synchronous magnetic-recording equipment, suited (optionally) to 35mm, $17\frac{1}{2}$mm or 16mm film, describing this equipment as in wide use in this country and abroad. Triple-track Westrex equipment is described by Davis, Frayne and Templin[371] in the February 1952 *Journal.*

Portable magnetic-recording equipment (the complete channel weighing less than 100 lb) using $17\frac{1}{2}$mm film was described by Ryder[372] at the April 1950 convention. The May 1951 Progress Report states that since April 1, 1950, all Paramount production recording had been done on this equipment.

The Progress Report[373] of May 1952 states that by the end of 1951 approximately 75% of the original production recording, music scoring and dubbing in Hollywood was being done on magnetic-recording equipment.

Editing. While it is entirely possible to edit magnetic recordings with the help of quick-stop reproducers, sound-film editors have come to depend in part on the visibility of modulation in a photographic track. This is probably one of the chief reasons for the retention of photographic-sound records for this intermediate function. Push-pull recording is usual, and in order to add as little ground noise as possible, preferably wide-track. The use of direct positives saves time as well as printing losses. When the editing is completed, the negative for release printing is made by another re-recording operation.

To provide the visual advantages of the photographic track for purposes of editing while retaining the quality advantages of the magnetic system, an arrangement has been tried which registered by an ink line on the magnetic film the amplitude of the modulation being recorded.[372] Another expedient, described by Frayne and Livadary,[374] is to make simultaneous tracks on the film to be edited, one magnetic and the other photographic variable-area, the magnetic to be used for the re-recording.

A system in which both pictures and sound can be backed up at any time without loss of synchronism is described by George Lewin[377] of the Signal Corps Pictorial Center. This makes it possible for a narrator to correct or change his speech, erasing portions of the previous record as he substitutes the new.

Synchronous Thin Tape. While use of perforated film afforded the necessary synchronism, the thin tape has the important advantages of reduced size and weight of equipment, smaller space required for storage, lower cost, and better contact between magnet and record surface because of its greater flexibility. A number of systems have, therefore, been developed to drive tape in strict synchronism. These have for the most part used the principle of recording a tone on the tape in addition to the audio modulation and of controlling the speed of the driving system so as to hold within limits the phase relation between the reproduced tone and a reference frequency, usually the 60-cycle power which drives the camera. The recorded tone may be 60 cycles[375] (excluded from the audio by a high pass filter) or a tone slightly above the audio range for example 14,[376] 15[377] or 18[378] kc, and modulated at the 60-cycle rate.

An optical tone on the tape, as by stripes on the back of the tape would have certain advantages (one of which is that full voltage can be developed from standstill), but this has to the best of my information not been made commercial.

Experiments have indicated that with a suitably designed mechanical system, perforations and sprockets are not out of the question, even with tape as small as 0.002 in. thick by $\frac{1}{4}$ in. wide.[379]

Striping. While magnetic sound has been thus far used mainly in the preliminary operations of making sound pictures, and release prints are still

* The use of three tracks on a 35mm film was begun by Columbia in November 1950. In single-channel recording the three tracks could be used in succession, or in recordings calling for combined voice, orchestra and sound-effects these could be independently and simultaneously recorded and later mixed for desired balance.

optical, there are some exceptions, for example the films for the CinemaScope system, on which the sound is all-magnetic. This calls for applying stripes of magnetic coating on the photographic film which carries the picture. There are also numerous applications, especially with 16mm films, for which it is desirable to add sound to an existing picture film, and other uses for which the stripe is applied to the unexposed film.

The application of the magnetic material in stripes of closely controlled width, position and thickness is no simple problem. The April 1953 *Journal*, Part II, carries a series of papers dealing with problems of magnetic recording. Striping is discussed by representatives of Reeves Soundcraft Corp.,[380] Minnesota Mining and Mfg. Co.,[381] Eastman Kodak Co.[382] and Bell and Howell.[383] The Minnesota Mining and Mfg. Co. developed a method of application of a stripe by transfer from a temporary supporting tape. Only heat (no solvent or wet cement) is required for the transfer. The Reeves engineers also have papers on the preparation of the magnetic material,[384] and the study of the minute surface irregularities which tend to lift the tape from the magnet causing sound "drop-outs."[385] In spite of the utmost effort to prevent the formation of such high spots they are not entirely eliminated, and polishing operations are helpful. Other papers in the group deal with wear on magnets,[386] measurements of magnetic induction,[387] and standardization.[388]

The May 1954 Progress Report mentions new high-output magnetic-oxide coatings introduced in 1953 and 1954 by Minnesota Mining and Mfg. Co., greatly increased use of striping, new machines for applying the stripes, and several designs of theater soundheads (to be mounted above the projector head) for reproducing multiple-track magnetic sound.

A Sound Committee Report by J. K. Hilliard in the June 1953 *Journal* tells of arrival at agreement for a standard of track positions for triple 200-mil magnetic tracks on 35mm film, of projects for standardizing theater magnetic-reproducing characteristics, and plans for making available various magnetic test films, corresponding to the long-used photographic test films.

Theater reproducing systems for magnetic tracks are designed to be mounted on the tops of projectors, and do not interfere with the optical reproduction.

New Safety-Film Base.[280,389] For years the motion-picture industry struggled to minimize the fire hazard of nitrate film. Safety-film base had early been developed and used for certain purposes for 35mm film, and was mandatory for amateur equipment (16mm), but the stability and mechanical properties of the safety base were so inferior to the nitrate base that it was not a satisfactory substitute.

The film companies worked long and diligently on the problem of improving film-base stock. In 1937 the Eastman Co. adopted an improved safety base,[390] and in 1948 announced a new safety base which combined the needed properties to replace the long-used nitrate base, being superior to the nitrate in heat resistance and low shrinkage. It is described by Fordyce[391]. With these virtues the new film has rapidly supplanted nitrate.

The improvement in sound quality due to reduced shrinkage may not be noticeable to the average listener, but it must inevitably mean better performance especially in the action of contact printers. The importance of this new base can hardly be exaggerated.

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APPENDIX

Development of High Vacuum Amplifier Tubes from the Audion

A brief account of the improvement of the audion by Dr. Arnold of the Western Electric Co., and of the subsequent patent interference and litigation, appeared in *Jour. SMPE, 17:* 658–663, Oct. 1931. In view of the vital part played by the electronic triode, it seems appropriate to tell something more about the parallel developments at the General Electric Co. The results, in terms of practical, high-vacuum amplifier tubes, were attained independently and at very nearly the same time at the two laboratories. The Telephone Co. had immediate use for audio amplifiers and promptly put them to use on a large scale, whereas, at the General Electric Co., the work was much more nearly a pure research.

Study at the Research Laboratory of the General Electric Co. of the relation of "Edison Effect" current to residual gas was an outgrowth of incandescent lamp development. Because of serious effects in some cases of the minutest traces of impurities or of certain gases or vapors, the techniques of producing high vacua had been developed to a high degree. In the early days of the Fleming valve and the de Forest audion the opinion was widely held that these depended for their conducting properties on the presence of some gas. Experiments in 1907 by Prof. Soddy[395] of the University of Glasgow lent support to the belief that the space current would become zero if a true vacuum were obtained. On the other hand, the English scientists J. J. Thompson (who first proved that there was such a thing as an electron) and O. W. Richardson believed that high temperature would cause a conducting body to throw off electrons into the adjacent space, without dependence on the potent effects (in releasing electrons) of impacts on the cathode surface by positive gas ions. It was the question which of these theories was right that enlisted the interest of Dr. Irving Langmuir. By using the known techniques for driving occluded gases from glass and metal surfaces, the Gaede diffusion pump, and adding a liquid-air cooled trap in the exhaust line, Dr. Langmuir exhausted his experimental tubes to about the highest possible vacuum. He showed that (with adequate temperature of the tungsten cathode) a pure electron space current flowed, and that this current followed the theoretically predicted 1.5 power relationship to the anode potential.[397]

With high enough anode voltage to carry over all the electrons emitted by the cathode ("saturation current") Langmuir was able to verify O. W. Richardson's prediction ("The electrical conductivity imparted to a vacuum by hot conductors," *Phil. Trans. 201:* 497, 1903) that the rate at which electrons are "boiled" out of the cathode bears a similar relation to temperature that vapor pressure does in the case of an evaporating substance. The presence of small quantities of ordinary gases (other than the "noble" gases) was found to "poison" the tungsten surface and greatly reduce emission, but this effect disappeared at high enough temperatures.[397]

These studies were begun in August 1912, and continued through that year and the following. Three electrode tubes exhausted to high vacuum were found to be free from the voltage limitations and erratic behavior of the previous audions.[398] Another important outcome of the development of the pure electron discharge was the Coolidge X-ray tube (hot-cathode, high-vacuum type) in which the electron velocities at the anode (and thereby the frequency or penetrating power of the X-rays) could be accurately and reliably controlled, and carried to much higher values than had been possible in the previous tubes where gas ionization had limited the effective anode voltage. The use of chemical "getters" for improving the vacuum in sealed-off tubes was also much advanced by work at this time at General Electric. In October 1913, a patent application was filed for Langmuir on "Electrical Discharge Apparatus" (triode) in which conduction is entirely by electrons, the effects of gas ions being negligible.

The audions which de Forest supplied for radio reception broke into a glow discharge if anode potentials of more than 20 to 40 were applied, and all control by the grid then vanished. The very limited output with low-voltage operation was not serious for radio detectors, but made the

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tubes of little or no use as amplifiers. During the years 1909–1912 de Forest was employed by the Federal Telegraph Co. of California. The company wanted amplifier tubes and de Forest ordered some made with better vacuum, calling in some cases for re-exhaust, so that by August 1912, a tube was being used at 54 v and by November, one at 67½ v. This was held in some of the later court actions to be a clear indication of the direction from which improvement in the audion could be expected and thus, so far as invention or discovery goes, an anticipation of possible patent claims by others, directed to improving the audion by employing higher vacuum.

At the time that the work just described was going on, the Telephone Co. was making plans to establish transcontinental telephone communications in time for the opening of the San Francisco Panama-Pacific Exposition in 1915. There had been a long-felt need for a voice-current amplifier, much effort had been expended on the project, and devices based on various principles tried.

For the 3000-mile transmission the possession of amplifiers would be imperative and they must have low distortion to permit cascading. According to the accounts by Lovette and Watkins,[48] and by Wm. R. Ballard,[393] a visit by de Forest in October 1930 served to direct attention to the possibilities of the audion, other devices of promise having till then claimed the research efforts. De Forest gave demonstrations and left a sample for tests and study. The demonstrations were repeated next day for the benefit of research engineer Dr. H. D. Arnold, who was quick to recognize the potentialities of the audion, the requirement for high vacuum and the role of space charge in limiting and controlling electron current. He expressed entire confidence that an amplifying tube which would meet the requirements could be developed from the audion, and he was assigned the task. Progress was rapid, and tubes with much higher vacuum were quickly available, but vacuum of the desired value was not achieved until a Gaede molecular pump, which was ordered from Germany, arrived. Long-lived cathodes were of great importance for telephone applications, and cathodes of the Wehneldt oxide-coated type were developed to replace de Forest's tungsten cathodes.

More details about the developments at the Western Electric Co. will be found in the references already cited.[48,393] Doubting the patentability of the improvement brought about by higher vacuum, Arnold and his attorneys did not file any application until they learned that an application based on a similar development had been filed by the General Electric Co. The prolonged interference which followed is summarized in the footnote on page 657 of the October 1931 *Journal*, "After various conflicting opinions by successive tribunals, U.S. Pat. No. 1,558,436 was issued to Langmuir in 1925."

In 1926 the General Electric Co. brought suit for infringement against the de Forest Radio Corp. Again there were decisions, appeals, and reversals, ending with the ruling of the Supreme Court, May 25, 1931, that the patent did not involve invention.

Some light on the questions at issue may be found in opinions written by the successive courts.

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Errata

In the second installment of this paper, published in the July *Journal,* the titles appearing under Figs. 8 and 9 should be interchanged; in the title to Fig. 14, "variation" should read "various"; and the title to Fig. 16 should read: "Horizontal cross section showing sound passages of folded low-frequency horn."