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(FOUNDED IN 1925 – INCORPORATED IN 1932)

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PRINCIPAL CONTENTS

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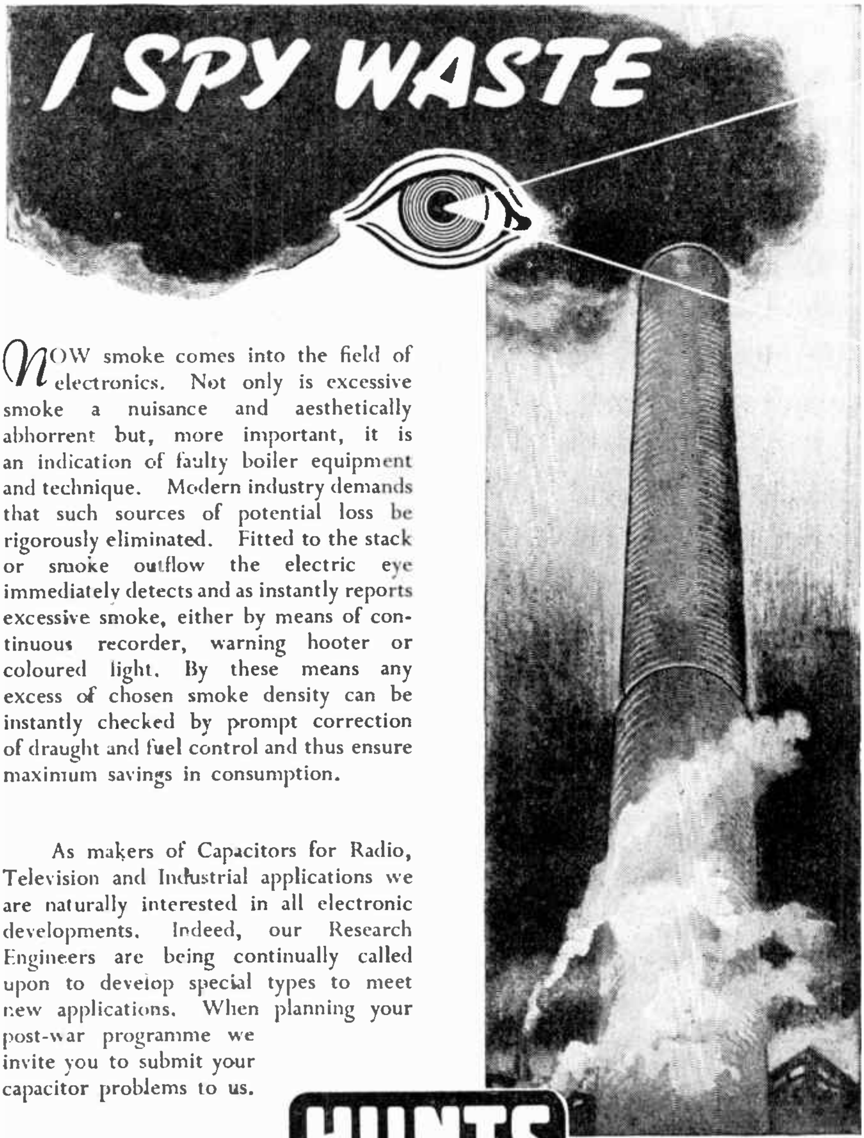

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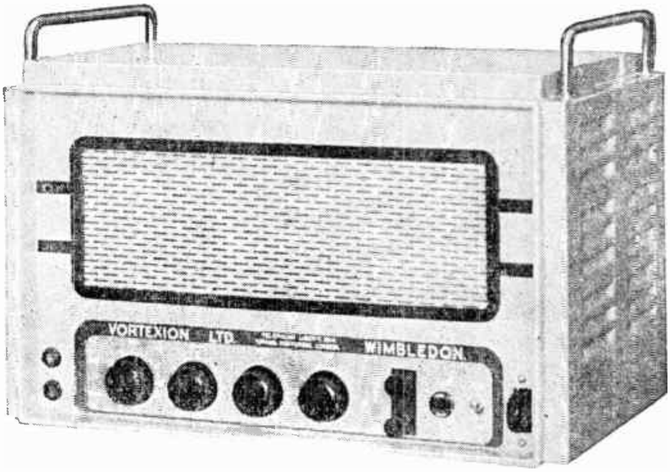
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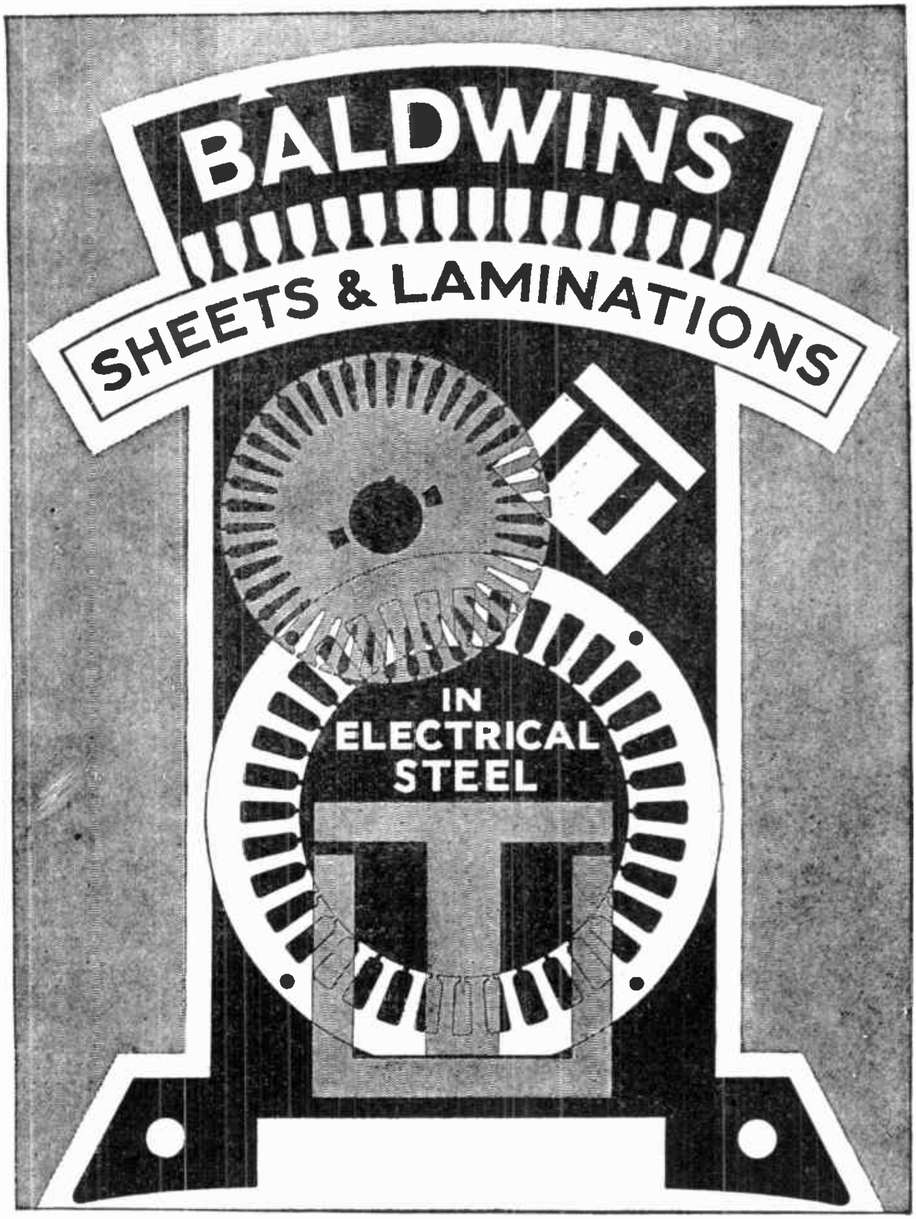
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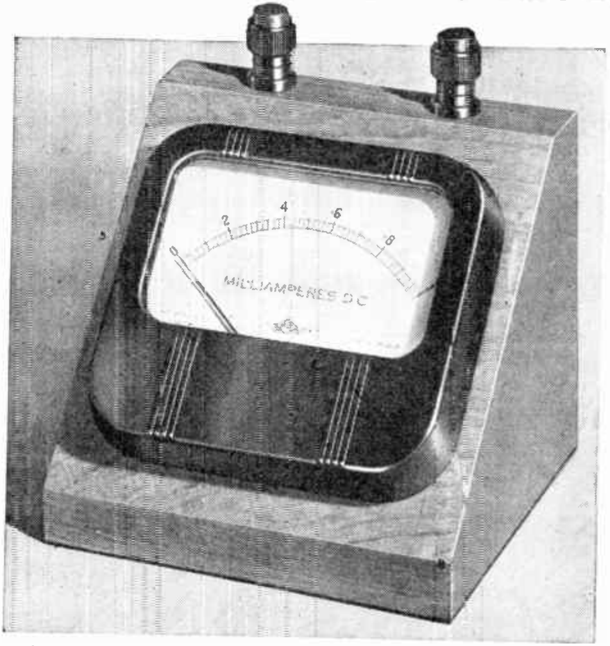

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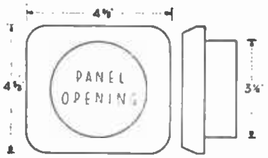

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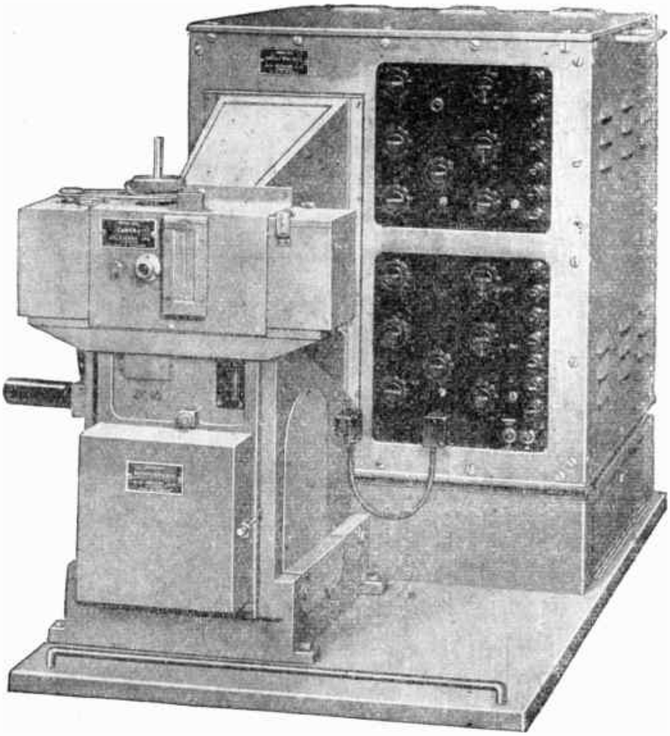

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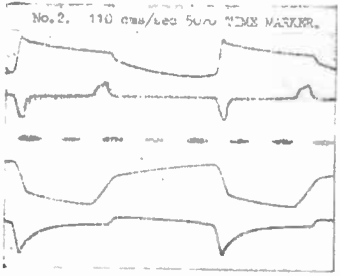

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JOURNAL OF

The British Institution of Radio Engineers

(FOUNDED IN 1925—INCORPORATED IN 1932)

"To promote the general advancement of and to facilitate the exchange of information and ideas on Radio Science."

Vol. 5 (New Series) No. 5

OCTOBER-DECEMBER, 1945

ANNUAL GENERAL MEETING OF THE INSTITUTION

The TWENTIETH ANNUAL GENERAL MEETING of the Institution (the twelfth since incorporation) was held at the Institution of Structural Engineers, London, S.W.1, on October 5th, 1945, commencing at 6 p.m.

Mr. Leslie McMichael (President) took the Chair and was supported by a number of members of the retiring Council.

1. Minutes of the Annual General Meeting held on October 19th, 1944

On the proposal of Mr. G. L. Hamburger, seconded by Mr. L. Grinstead, the minutes of the last Annual General Meeting, as reported in the December 1944 Journal, were approved.

2. Minutes of the Extraordinary General Meeting held on March 23rd, 1945

Mr. McMichael referred to the fact that many members present also attended the Extraordinary General Meeting and that the alterations then carried out to the Articles of Association had since been approved, but the Institution was still waiting Court approval to the Memorandum of Association.

On the proposal of Mr. E. A. W. Spreadbury, seconded by Mr. P. Adorian, the minutes of the Extraordinary General Meeting were approved.

3. Annual Report of the General Council for 1944/5

The President referred to the Annual Report given in the August-September 1945 Journal, but before asking for comment, Mr. McMichael said that one of the disadvantages of an annual report was that for various technical reasons it could never be considered by the membership until some months after the end of the Institution's year, by which time the Council were well launched into another year. So far as membership was concerned, the total number of proposals received and the total number of elections made during the first six months of the current year were already within 50 or so of the complete totals for last year. The number of entries for examinations now totalled 250 compared with 202 for the whole of last year. The Institution had now had a first conference with the Ministry of Education to discuss the training of radio engineers, but as these discussions were still proceeding, it was not possible to go into great detail, other than to say that the proposals put forward by the Institution were being most seriously considered.

A special vote of thanks was due to the Papers Committee, under the Chairmanship of Mr. L. Grinstead, who had done so much to keep up the standard of meetings of the Institution, notwithstanding war-time restrictions.

Mr. J. A. Sargrove suggested that the pre-war committee on radio therapy, which had not functioned during the war, should be reappointed. Mr. Sargrove indicated the scope of such a Committee's work and its immediate value to the Institution.

Mr. J. Tanton stated that notices of the Institution's general meetings were at one time included in the Journal of the Royal Society of Arts and proposed that such notices should be sent to the Royal Society of Arts in future.

The President promised to refer Mr. Sargrove's suggestion to the General Council, and the Secretary was requested to follow the suggestion made by Mr. Tanton in regard to circulation of notices of the Institution's meetings.

Proposing the adoption of the Annual Report of the Council, Mr. W. E. Miller said that the Annual Report seldom reflected the enormous amount of work which had to be done before such a report could be compiled. Apart from Council meetings and Committee meetings—of which there were many—there were numbers of individual interviews, deputations, etc., which had to be attended to either by the Council or by Committees, or even by individual officers of the Institution. The report, of course, was highly condensed. Paper shortage, for one thing, prevented a complete report of the activities of the Council and Committees, and, therefore, the report did not cover many of the minor activities of the Institution which, nevertheless, were very important. However, it was sufficiently full to show that the Institution was now on a very solid foundation, a foundation which had been largely built up during the difficult years of the war. On that foundation he believed they would build up an ever-growing superstructure in the years of peace which it was hoped were now ahead.

Mr. J. A. Sargrove seconded the proposal, and the Annual Report of the Council was then unanimously adopted.

4. Election of President of the Institution

The Secretary said that this was not a matter which could be dealt with through the Chair. The last and preceding issues of the Journal gave notice that the General Council were unanimous in recommending the re-election of Mr. McMichael for a second year, and on this occasion members were afforded the opportunity for showing their appreciation of Mr. McMichael's work for the Institution by heartily supporting the recommendation of the General Council.

The proposal was supported with hearty acclamation and in his response the President said that now, happily, the war was over, the Institution would have new tasks to face and he thought it a great compliment that he should have been asked to continue as President for a second year. In view of the fact that a most interesting address was being given by Air Vice-Marshal Sir Victor Tait, Mr. McMichael said he did not propose to give a long address and again expressed his thanks and assurance that he would continue to do all that he possibly could to further the objects of the Institution.

5. Election of Vice-Presidents of the Institution

Although the members had before them the unanimous recommendations of the General Council, the President thought that the meeting would wish to send special greetings to Admiral the Lord Louis Mountbatten and Air Vice-Marshal R. S. Aitken, both of whom were at present serving oversea. The President also thought that the members would support the re-election of Dr. Robinson and, in particular, would welcome the election of Mr. L. H. Bedford. Mr. Bedford would not be present at the meeting as he had just left for America, but he had served on Committees and on the Council of the Institution and well deserved the honour of his election as a Vice-President.

Mr. L. Grinstead seconded the proposals of the President, which met with unanimous approval, with a further resolution that appropriate messages be cabled to Admiral the Lord Louis Mountbatten and Air Vice-Marshal R. S. Aitken.

6. Election of General Council

The President said he understood it was unusual in that for the first time for many years it had not been necessary to hold a ballot for the election of members to the General Council. This was not only a compliment to the retiring Council for the wisdom of their nominations, but was a particular compliment to the ability and esteem in which the following members were held by the membership :—

Sir Ernest Fisk (Honorary Member) ; Mr. E. Cattanes (Member) ; Lt.-Col. J. D. Parker (Member); Mr. W. W. Smith (Member) ; Dr. G. A. V. Sowter (Member) ; Mr. H. Whalley (Associate Member) ; Mr. G. A. Taylor (Associate Member) ; and S./Ldr. S. R. Chapman, who was elected Honorary Treasurer.

The elections were approved with acclamation.

7. Auditors' Report, Accounts and Balance Sheets for the year ended March 31st, 1945

In calling upon Sir Louis Sterling to present the accounts, the President expressed appreciation for the work done by Sir Louis during his two years as Chairman of the Finance Committee.

Sir Louis Sterling said that the accounts now presented* gave less cause for worry than at any other time in the Institution's history, but that did not mean that the Institution could afford not to be careful. He was sure that it must be the wish of everybody to see the Institution with a substantial bank and investment balance, but in order to do that, income must exceed expenditure, and in the last year the first step towards this end had been achieved by an excess of income over expenditure of £330. Sir Louis referred to the contributions from industry which had been maintained during the last three years. The Institution could not be encouraged more in its work than by such a tangible means of support.

The Balance Sheet reflected, of course, the heavy liabilities incurred at the beginning of the war, and which were only now being cleared off. Sir Louis believed, however, that this year the Institution would be able to show a considerable improvement on these figures.

Sir Louis Sterling also recommended to the meeting the adoption of the accounts relating to the Special Funds. The figures shown in the last Journal were quite straightforward and it would be seen that the Benevolent Fund showed better support by members, although he thought that this Fund should receive even more support in order to give immediate help to any member who should have real need of the Institution's assistance.

Referring to the Prisoners of War Fund, Sir Louis

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*See pages 181 to 183 of the current volume of the Journal.

recommended that the small balance left in the Fund should be transferred to the Benevolent Fund. A little use had been made of the Prisoners of War Fund, but with the end of the war, he thought that this money would be more appropriately used in the Benevolent Fund.

Sir Louis moved the adoption of the accounts relating to the special and general funds.

Mr. J. Tanton suggested that "arrears of subscriptions not recovered and written off" should not be included in the income and expenditure account and the meeting agreed that this point should be referred to the auditors for future reference.

In seconding the proposal for adoption of all the accounts, Mr. J. L. Thompson expressed the thanks of members to the Finance Committee for their careful work during the past 12 months. The accounts and the auditors' reports were then unanimously adopted.

8. Appointment of Auditors

On the motion of the President, Messrs. Gladstone, Titley and Company, of 61-63 St. Paul's Churchyard, London, E.C.4. were re-elected auditors.

9. Appointment of Solicitors

The President moved the re-election of Messrs. Braund and Hill, 6 Grays Inn Square, London, W.C.1, as Solicitors and the motion was unanimously adopted.

10. Awards to Examination Prize Winners

In presenting the President's Prize to Mr. Peter Robinson, of Chelmsford, Mr. McMichael referred to the fact that the award is made annually to the most outstanding candidate in the year's examinations.

The Measurements Prize was awarded by the President to Mr. Maurice Charles Bumstead, of Hythe, Kent.

The winner of the S. R. Walker Prize for the year (Mr. William R. Luckett) was not present, and the President referred to the fact that the North-Eastern Section had held their Annual Dinner on the 28th September, when the Mountbatten Medal was presented to Mr. Robert Crawford by Vice-Admiral Sir Wellwood Maxwell, on behalf of Admiral the Lord Louis Mountbatten.

11. Other Business

The President: "It now gives me very great pleasure indeed to introduce Air Vice-Marshal Sir Victor Tait. When, early in the war, radar was known as radiolocation and still a very, very secret topic, Air Vice-Marshal Sir Victor Tait was Director of Radiolocation. He brought to this appointment a lifetime of service in the Royal Air Force and so 'pin-pointed' his targets that, in 1942, he was appointed Director-General of Signals, controlling the Directorates of Signals, Radar and Telecommunications, the latter also involving the special section which so admirably dealt with Radio Counter Measures.

"With all that background, Air Vice-Marshal Sir Victor Tait has largely contributed to developing radio science to something more than radio communication. I know that you will join with me in giving a very hearty welcome to him."

An Address by

AIR VICE-MARSHAL SIR VICTOR TAIT, K.B.E., C.B.

DIRECTOR-GENERAL OF SIGNALS, AIR MINISTRY

(*Read at the Annual General Meeting of the Institution on October 5th, 1945*)

The Annual Report of the Institution shows that your Council is well prepared for the resumption of peacetime activity. But before leaving behind the record of war I would like to give you a brief examination, as I see it, of the work that your members did for the Fighting Services during the war, and the part that I believe they can play in winning the peace.

This has been a highly technical war, especially a radio technical war, and the demands of the Services and industry for radio personnel created one of the greatest problems that this country has had to face—that of technical manpower. The Fighting Services before the war saw the need arising for an adequate supply of well-trained radio engineers and radio mechanics. The numbers even then visualised were great, and the demand was urgent if a base was to be built in the short time available on which the Fighting Services' wartime radio needs could be built.

The urgency and the size of this manpower demand for radio personnel can be realised when it is known that at one time during this war the ground radar stations of the Royal Air Force in the United Kingdom alone required the full-time employment of sixteen hundred officers and twenty thousand other ranks. The first radar station in the United Kingdom, Orfordness, was not established until 1935. In under ten years, that half-dozen radio men who first assembled at Orfordness had to expand into a force of well over twenty thousand. This rapid expansion was, of course, made possible by the active co-operation of your Institution, and I firmly believe that if institutions of this kind had not been in being well before the war, and able to give the Fighting Services the help they required, we would not have been able to obtain the radio engineers that the Services had to have for the war, and we would not, therefore, have been able to exploit to the full the radio systems which played such a vital part in our successes in defeating our common enemy. I would, therefore, like to record the valuable assistance your Institution gave to the Fighting Services in recruiting the technical personnel they required.

Your profession has played a great part in our successes in this war. Radio has become a powerful war weapon, and the force equipped with the best radio systems and with the skilled radio personnel to enable them to use them in the best tactical and strategical manner starts a battle with a great advantage. Radio has come to stay as a vital weapon of war. As air bombing developed in the last war, and then became one of the major weapons in this war, so radio, which developed as a weapon in this war, will become an ever more important weapon if we ever again have to face an aggressive foe. The development of most modern weapons, such as flying bombs, rockets, and even the means of delivery of the atom bomb, all require radio systems both in their offensive use to guide and control them on to their target, and in the defence systems against such forms of attack, where, for example, very long-range warning of attack systems can only be implemented through various radio and radar systems. I believe that if we and our Allies successfully develop radio weapons they will act as a strong deterrent to any evil aggressor, and make them think twice before committing themselves to war, and in that way radio can be a great insurance for peace. The success achieved by radio in the war to a large extent, I believe, was due to the close co-operation that was developed in this country between scientists, the radio engineer, and the Fighting Services. You will note that I have put the radio engineer between the scientist and the Fighting Services, which is their proper place. They interpret into practical ideas the results of the scientists' research, and these practical ideas give the Services the equipments in well-engineered units that they require for fighting their battles. But the radio engineer must permeate both the scientists' field and the Services' field. He must work with the scientist and behind the scientist, so that he guides him on lines which will ensure that research results can be turned into practical equipment, and he must be with and in the Services to ensure that the Fighting Services can install and maintain the equipment when they take it into use in the field. The success of this co-operation cannot be too strongly emphasised and should be continued in your peacetime activities.

The radio engineering profession has increased both in importance and numbers as the result of the great development of radio during the war years. Many young men have entered the profession and helped by their work—in the development establishments, in the radio industry, or in the Fighting Services—to win this war. I believe that, unlike many of the other trades of war which demand concentrated training from the best young men of the nation, and then, at the termination of war, throw them on to the world untrained for any peace-time occupation, the developments of radio have made its peace-time use such that there is a great field opening up for the radio engineer going back to peace-time occupation. Radio developments, such as radar and television, can, through their civil application, give great benefits to the well-being of humanity. Improved communications will result in a greater knowledge of the people of other countries which must lead to better understanding between the peoples of the world, and do much to do away with previous suspicions and doubts of our neighbours' intentions, and thus be a great contribution to world peace. Applications of radar can, and will, make travel, by air, land and sea more regular and safer. The provision of good and cheap amusement and entertainment to a large number of people such as can be provided by television can, handled properly, be a great asset to the well-being of the nation.

These are some of the fields of enterprise that are ahead of the radio engineer, and these are the fields that those of you who have been in the Services, or those of you who have been in industry meeting Service needs, now face. We have ahead of us a difficult task in re-establishing our life in the British Isles to a standard approaching that of pre-war days. British effort during this war has shown that in the field of radio we are second to none. Other countries are demanding equipments which incorporate these advanced facilities which have resulted from British radio development. In our introduction and production of radio systems to meet this world-demand for these new equipments is a great field for increasing our export trade and helping to bring back a standard of living in this country which we all want, and, indeed, must have if we are to survive.

The Fighting Services believe that they can only maintain their efficiency and lead in their arms if there is a large and healthy development section of the radio industry working for and with them. A vigorous development section of the industry is also essential if British radio is to maintain the lead in the introduction of new and advanced techniques which it established in the war. This is of great importance if we are to build up and maintain a satisfactory export trade. A plan is being formulated by the Services to make a long-term contract with the radio industry to undertake over a number of years this Service radio development work. I think it is of great importance that the Services and industry be thus linked together.

During the war we were forced to concentrate nearly all our resources for radio research and development on new weapons required for the Fighting Services. We had first to have the radar chains which gave us the vital information required when the Luftwaffe started their powerful air attacks on this country. The radar chain enabled us to win the Battle of Britain. These radar search equipments were essential in the hunt for the U-boat trying to cut our supply life-line, and finally the blind bombing radio and radar devices had to be forced ahead to enable our bomber force to destroy the war factories and communication system of Germany, and thus allow the Allied armies to invade Europe and overwhelm the German armed forces. With our limited resources the production and development of these vital war-winning weapons had to be done at the expense of the development of other radio equipments. In the radio telecommunication field we led the world for many years, but we have slipped behind in the war years ; it is of great national importance that we re-establish British supremacy in the telecommunication field and I suggest to you, this be one of your main objects in the first years of peace.

In conclusion I would like to thank you, Mr. President, and the members of the Institution, for this opportunity of expressing the appreciation of the Fighting Services for the co-operation the Institution has given to them during this war, and to say how much we hope that this co-operation will continue into the years of peace. By your co-operation in peace-time the Fighting Services can be assured of a strong radio personnel backing, and a radio industry well acquainted with Service needs. We must make sure that the Fighting Services are prepared, and by their being prepared we will have one of the best insurances for the maintenance of peace. The radio engineer played a magnificent part in the war. He has a great field before him in helping to win the peace, and I am sure he will maintain his war reputation in the difficult years now ahead of us.

Mr. **Paul Adorian** (Member of Council), proposing a vote of thanks to "the Chief Engineer of the world's finest radio organisation," said that unquestionably the R.A.F. had used radio in a bigger and more efficient way than anybody before. This applied to radio-communication, radio-location and other radio navigational methods., In the efficient use of these services the R.A.F. had set an example to all other Services and our Allies, and even the enemy had tried to copy our methods.

In all major radio developments the R.A.F. had held the initiative for the last decade. It was this initiative which had been instrumental in the defeat of the enemy, and Sir Victor could claim a large share of the credit for maintaining the initiative of the Royal Air Force, for he had been closely associated with the policy of making radio one of the most important tools of the R.A.F.

The address showed that Sir Victor Tait appreciated the importance of co-operation between the Services and professional engineers. His reference to radio engineers in general, and the Institution in particular, was most gratifying, whilst the description of some of the achievements of the past and problems for the future clearly confirmed Sir Victor's contention that co-operation between the Services and radio engineers was absolutely essential. The Institution, on the other hand, was most anxious to continue in peace the co-operation which had existed in war.

Mr. Adorian therefore proposed that the Institution accord a vote of thanks to Sir Victor for his address, and the proposal was carried with acclamation.

HIGH FIDELITY REPRODUCTION OF MUSIC

(A Discussion Meeting of the London Section of the Institution held on March 10*th,* 1944)†

The Chairman (Dr. G. A. V. Sowter): We are to discuss this evening the subject of the quality reproduction of music, and we are honoured to have with us Dr. Malcolm Sargent. It would be presumption on my part to attempt to introduce him, for we all know him as a conductor of international repute, and we are particularly favoured to have him with us.

We are well aware of what is necessary in connection with amplifiers, microphones and loud speakers, and that side of the art is fairly well known. This evening we will approach the problem of reproduction from an entirely new angle, involving factors which hitherto have not been measurable. Progress in quality reproduction demands co-operation between the artist and the engineer.

In order that we might first direct the minds of engineers beyond the realms of engineering we have asked our Member, Dr. Partridge, to open the discussion. He has written a very excellent work on distortion,* and he is also something of a musician; so that he can discuss the subject from the points of view of both engineer and musician.

Dr. N. Partridge: In order that we may reap the greater harvest, I propose to emphasise in my introductory remarks that certain of the Institution's activities appear to fall outside the legitimate scope of science. That audio frequency engineering is not an entirely scientific pursuit may not be accepted without argument, and therefore I will first justify my contention.

Science depends for its success upon the exclusive employment of recognised facts concerning the objective world. It is shy of personal opinion and can find no real use for those sensations and emotions that are the essence of conscious experience but which, by their very nature, can never be treated objectively. It follows that a strictly scientific study of the reproduction of music will take no account of the human significance of music or of the sensations of sound experienced by a conscious mind. Instead, the problem will be defined wholly in terms of the physical conditions existing in the medium external to the listener. Hence, if audio frequency engineering were wholly scientific in all phases of its practice, then total deafness would be no bar to the profession.

Let us consider the viewpoint of a deaf engineer engaged upon the development of a sound system for the reproduction of music. He can readily learn all that science has to teach. Having mastered the relevant techniques, he will no doubt become preoccupied with microphones, amplifiers and such like pieces of equipment. This will occasion no special difficulty since it is only a matter of wave-forms, amplitudes and frequencies, all of which are examined by means of instruments and not by one's ears. But what kind of system as a whole will our deaf colleague devise? For him the problem is to reproduce at the ears of a distant listener exactly those physical conditions existing at the ears of a local listener. He will probably employ two separate channels, substituting a pair of microphones for the ears of the local listener and applying earpieces to the ears of the distant listener. Satisfactory or not, such a system would be amenable to design in the true sense, and its success would be judged by precise measurement.

Now note the change of view that takes place with the possession of a pair of normal ears. A typical sound system to-day will certainly employ only a single channel. As likely as not, this channel will be fed from two or three microphones strung about the concert hall. It should be observed, firstly, that a single channel cannot cope simultaneously with the two distinct sets of conditions existing at the ears of a listener. Secondly, since no one has yet been known to listen with one ear divided into three widely distributed parts, it is evident that no attempt is being made to simulate anything objectively associated with the experience of listening to a concert. What, in fact, is being attempted, is to induce in the distant listener a subjective conscious experience having a significance similar to that associated with the act of listening within the concert hall. By thus changing the terms of the problem we have crashed right through the boundaries of science and landed heavily within the field of art. Rarely is the misdemeanour so blatantly admitted. Nevertheless, the success of our system is no longer judged by impartial measurement but by personal opinion based upon the simple art of listening, and the wisdom of such a judgment must depend upon the artistic appreciation of the judge and not upon the extent of his technical education.

I am now going to suggest that we, as engineers, pay far too little attention to the distinction between the sound of music and the significance of music.

Consider the implication of the following imaginary episodes:—

Episode 1. When a popular and well-"plugged" dance tune is being performed, ask a friend to pay special attention to it. Afterwards play a gramophone record of a dance band playing *similar* music and

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* "An Introduction to the Study of Harmonic Distortion in Audio Frequency Transformers." *Journal Brit. I.R.E., vol.* 2 *(new series).*

† Publication of this report was delayed by the death of Dr. Norman Partridge in June, 1944

follow it by a record of a piano arrangement of *the same piece* as originally heard on the radio. Now the sound of a piano bears less resemblance to the sound of a dance band than does that of another dance band. But the friend will unhesitatingly declare the piano record to be identical with the radio performance. In other words, he automatically listens to the music and pays but little attention to the actual sounds of individual notes.

Episode 2. Take a friend for a walk and pass within earshot of a man playing an accordion. Ask what the man is playing. The answer will be, for example, " Land of Hope and Glory." Later call the friend's attention to the strains of a piano and again ask what is being played, and again assume the answer to be " Land of Hope and Glory." Now the sound of an accordion is not like the sound of a piano, and neither of them is the least like the sound of Elgar's original orchestration. Nevertheless, the significance of all three is unanimously " Land of Hope and Glory."

Episode 3. Recall the early days of the cinema and try to remember the accompanying music played on a piano. Later a quartet was employed ; later still, a full orchestra ; and more recently a Wurlitzer. No one will dispute the difference in sound between a piano, a quartet, a full orchestra and a Wurlitzer, but each was able to convey to the audience the same gamut of emotional suggestions.

Episode 4. Go to a recital and hear a great artist, say Leon Goossens, playing his oboe. Invariably the chief topics of discussion afterwards are the merits of the performance and the merits of the composition. Tentatively enquire if Goossens' tone quality is wholly and typically oboe-like. You will learn that his tone is far more beautiful than that of the average player and that, on occasions, it scarcely sounds like an oboe at all ! What can an engineer make of this ? The musician is evidently not looking for a precisely defined standard of tone quality but for an elusive feature called beauty. How can we, as engineers, ensure the transmission of this quality while we remain without apparatus for measuring it ?

The object of the foregoing examples is to show that in everyday life the attention is directed upon the significance of music and not upon the mere sound of the music. Play a few notes on a violin to the average man and he will not be able to say if the tone is strictly standard violin quality. Play " The Bluebells of Scotland " before the same man and he will have a decided reaction, one way or the other, to the performance as a whole.

When we are asked to produce a sound system for the high fidelity reproduction of music, we should do well to note that the request contains a possible ambiguity. Are we required to reproduce with high fidelity the *sound* of the music or the *significance* of the music ? Science has no option but to accept the former interpretation, and therefore it is the cue to which our technical training inevitably directs us. But I have shown that common sense and everyday usage invariably assume the latter interpretation. Is it not possible, therefore, that to some extent we may be barking up the wrong tree ?

In conclusion, I will propound a series of questions for Dr. Malcolm Sargent. These questions coupled with their answers should indicate to the engineer something of the practical importance of the distinction between sound and significance in music. At the same time, the questions will show the musician the kind of advice that will be most helpful to us.

Question 1. For a variety of reasons we are unable exactly to reproduce at the ears of a distant listener precisely those physical conditions existing at the ears of a local listener. This being so, we have to concentrate upon making the reproduction sound like a true copy in spite of the known imperfections. If there be any truth in what I have already said, we should attempt to preserve the significance of the music rather than the mere tonal quality of the instruments. What are the factors governing the significance of music or, alternatively, upon what features must we concentrate in order to preserve the significance ?

Question 2. When dealing with high fidelity equipment we come up against the problem of background noise in one form or another. With the gramophone there is needle scratch, with the radio side-band twitter and whistles. To eliminate these extraneous noises we have to modify the tone quality to a certain extent. Which is the more tolerable, a well-nigh perfect tone quality with background noise or a slightly impaired tone quality with a silent background ?

Question 3. For technical reasons it has been found very desirable to reduce the range of volume normally associated with big orchestral works. This is done by making the soft passages less soft and the *fortissimo* passages less loud. Is this very detrimental to the significance of the music, and would it be a great advantage to restore the full range of extremes ?

Question 4. When using " straight " amplifier equipment it is necessary for the sound intensity at the listener's ear to appproximate to that in the concert hall in order to obtain a sense of intimacy and realism. In the case of radio and gramophone, this necessitates a rather considerable noise in the home. If the volume be turned down the orchestra recedes into the distance and the tone balance is upset. By " cooking " the response of the amplifier the intimacy and balance can be restored even at very low volume level, but we have now produced something that does not exist in real life, namely, a symphony orchestra in miniature. Is this legitimate or must we aim at life-size volume ?

Question 5. Lastly, in how far do we succeed in reproducing music, and what are our most obvious shortcomings from the musician's point of view ?

Criticism should be with reference to the best examples of our work and not with reference to cheap commercial sets in which the performance is limited by price considerations.

Dr. Malcolm Sargent : For a very long time it has been my wish that the musician and the practitioner (the physical engineer) should come together so that, by combining our ideas, we could achieve the unity which I feel is possible, but which we have not yet achieved. I could not take it upon myself to call a meeting and I was therefore delighted to be invited to this meeting. I am not expecting a contest, but I hope to assist in coming to some definite form of agreement, something which will be useful to our combined art.

I do not propose to tackle Dr. Partridge's questions one by one ; but my remarks may cover some of them.

There are two different languages which must be spoken as between the scientist and the artist. We have the science of acoustics, involving something which can be measured against definite standards and expressed in figures. Then we come to the science of æsthetics. Since the days of Plato, and even further back, there has been a controversy as to whether æsthetics can be considered a science, whether we can set up a standard which will remain true in all cases for art, for beauty, for æsthetics.

Thus, at the start we are up against a difficulty. As Dr. Partridge has said, high fidelity reproduction should include beauty. But what is beauty ? We know that Pilate asked what was truth, and waited for the answer ; it has not come yet. Truth is not beauty. There may be beauty in truth ; but truth itself is not large enough to contain within its walls standards of beauty.

We may argue that beauty begins where utility ends ; and that is an interesting point. This line of demarcation is interesting and important. There comes a moment when we get beyond utility and fidelity to something which we call beauty. We cannot define it ; but we must accept it as something we must endeavour somehow to get into our reproduction—unless we decide just to make for sounds, the right ratios of vibrations, and so on.

It is a shock for us to realise the artistic axiom that we must avoid high fidelity reproduction if we wish to create beauty. All the great artists say that the one thing we must never do in art is to imitate or to have two sides exactly alike. If we have two sides of a picture exactly alike, we are introducing some measurement. Nature never does that. Again, the two sides of a statue are not the same ; the eyes are not the same, one leg is in front of the other, and so on. The poised figure absolutely dead straight is inartistic and not true to nature ; it would not look like a human being, for no human being is dead straight, having two sides about a centre line. When nature wishes to be beautiful, it avoids high fidelity. Again, in architecture a succession of gargoyles are not all alike. It is only when the machine comes into play that faithful reproduction is either possible or desirable.

It is interesting that nature avoids high fidelity reproduction, and the artist has always avoided it. He avoids copying his picture ; he employs someone else to do that. In cases where pictures have been painted two or three times they have never been exactly the same. Symmetry in art is not for the purpose of making two things identical, but to ensure that it has a seemliness of pattern.

The art of the composer is to write on paper his dots and dashes and lines, and the work of the artist is to reproduce those dots and dashes and lines as a work of art in music which can be enjoyed and understood. So that from the start we are dealing with reproduction and, strangely enough, when we are recording we are reproducing a reproduction. Should we reproduce the significance of the music as written by the composer or the significance of the performance, the tonal values, as given by the artist ? In recording a Kreisler performance of a Beethoven sonata the reproduction should be as performed by Kreisler. If the tone of the fiddle as produced by Kreisler is not given, do not label it as a reproduction of a Kreisler performance, because in effect it is a sonata as played by the fellow who turns the knob ! We produce gramophone records, but we have never yet decided just to reproduce music. We always reproduce a performance of music. The idea of using reproduction as an art form in itself is interesting, and it has been tried to some extent ; it is something which can be exploited, and I think it will be exploited.

But that is not what we are dealing with, for we are concerned with the reproduction of a performance. The standard must be absolutely high, in order to reproduce every form of gradation, the complete range which is possible by the original artist.

Should there be any link at all that is movable between the artist who puts it on to the wax and the wax itself ? Or in the case of a broadcast, should there be any link which is adjustable between the artist who is playing a piano and the listener ? The artist will know that there should be none at all. There should not be a middleman who can touch any machine which can alter the gradation, the volume and the tonal values, because the moment that is done the performance is *not* being reproduced.

In discussion, therefore, I should use the following points in answer to the five questions propounded by Dr. Partridge :—

Question 1. The significance of music must be directly perceived. It cannot be explained, described or taught, although its appreciation can be encouraged by training. The question therefore cannot be answered directly. But a very useful negative answer can be given. The significance of music will not be achieved merely by the precise mechanical performance of the composer's score. Thus the tempo may be varied—conductors vary considerably in the speed at which they take even standard works; the pitch can be changed—Bach, Haydn, Mozart, etc., have been played at a variety of pitches at different periods and places; the loudness can be altered—there is a decided difference in this respect between front and back of a concert hall; the tone quality can be modified—solo artists are often recognisable by their characteristic tone quality; and so on. It is this great variability that makes so many interpretations possible without loss to the essential meaning.

The important conclusion is that concentration upon the perfect reproduction of any one feature (tone quality for example) will not necessarily lead any nearer to capturing the significance or beauty of the composition.

Question 2. Is it better to have one's room papered with beautiful wallpaper having sundry grease spots and ink splashes on it, or to have a slightly inferior paper without blemish? The question is of this type and the answer will depend to some extent upon the viewpoint taken. If we are considering the enjoyment of the music in the broadest sense, then needle scratch is a distraction and greatly reduces the enjoyment. Its removal coupled with slight impoverishment of tone will greatly increase the comfort of listening and will do little to affect the significance of the music. On the other hand, if a record is purchased for the special purpose of reminding oneself of the unique tone quality of a particular artist, then, of course, needle scratch must be tolerated.

The latter interpretation is a rather special one. In the broader view, extraneous noise should be removed even at the expense of tone-quality—assuming the price not to be exorbitant.

Question 3. In view of the great trouble the instrumentalist takes to acquire a wide range of power, it seems discouraging to vitiate his work. But, at the same time, providing the volume compression is undertaken systematically, the significance of the music will not suffer a great deal. By "systematically" is meant that a definite law must exist between change of volume in the original and in the reproduction—the variation must not be capricious. The mood calling for a crescendo, for example, is usually expressed in other ways, such as by a rising phrase, increasing complexity of harmony, increasing tempo, etc., all of which will remain and will of themselves maintain the significance of the passage. It is not essential to restore the original range of volume, but it would clearly be advantageous to do so.

But there is a type of volume control that is wholly intolerable. When a soft movement is immediately followed by a bold tutti it is not unusual for the volume control to be abruptly turned down. The same thing is done when a solo passage (concerto cadenza) is followed by a sforzando entry of the full orchestra. This sudden changing of the volume relationships renders the passage meaningless and even ridiculous. The effect is similar to being instantaneously transferred from the front of the stalls to the back of the hall. The mind requires time to adjust itself to its new position and while this is going on the significance of the passage has been missed. Any change in the range of volume must retain something of the original relationship.

Question 4. Without a knowledge of technicalities one would expect a perfect reproduction to sound identically the same as the original music. But if, for technical reasons, this is not to be expected, then surely the relation between the reproduction and the original should be something of the nature of the relation between a picture of a person and the person himself. For example, all varieties of pictures of Mr. Churchill (and cigar) have appeared from miniature line cartoons to oversized posters. None is truly like Mr. Churchill in the sense that it might be mistaken for him in person, but all bear the significance "Mr. Churchill." The picture chosen for any particular purpose will obviously be the one most suited to that purpose. So it should be with reproduced music, assuming it to be other than a true copy. All varieties of reproductions should be possible from oversized sounds for the football field and cinema to undersized varieties for invalids in hospital. None will be the same as the original, but all must carry the same essential significance. For the home fireside, full volume does not seem desirable, but intimacy and tone balance are highly desirable features.

To express this in another way, in the absence of an orchestra a musician can enjoy much of a composition by reading the score in silence. Artificial reproduction should go one better and present directly to his consciousness all the material necessary to enable him to appreciate much of the meaning and beauty of a composition. Any "cooking" necessary to this end would seem not only legitimate but essential.

Question 5. This is wholly personal—no suggestions can be offered. Criticism should be from the artistic angle—engineers are only too well aware of the technical shortcomings from the scientific viewpoint, but I do feel that no matter how small the interference by the machine, to that extent the reproduction of the performance is imperfect. The ideal at which we should aim should be to do away with any interference. We should say that we will not be content until we have absolutely expunged the middle-man who controls anything between the producer of music and the receiver in the home.

Obviously we have not yet reached that stage. Therefore, what should be done? Having decided that we will never accept the present situation as the ultimate, what can we do in the present circumstances?

First of all, it is possible to establish complete collaboration of ideals and ideas as between the artist and the engineer. The latter is the man between the producer and the receiver. Under present conditions there should be at least every possible form of artistic and practical collaboration.

First, then, we must assume that the control room engineer is there in case anything goes wrong with the adjustment of the equipment. We must also assume that the musician is a man of intelligence, able to conform with conditions which may be essential for the time being.

I should like to see collaboration between engineer and musician established to a much greater extent than we have it to-day. It seems quite possible, and it is something I have longed for in connection with broadcasting and gramophone recording, for the conductor or the performer to have before him a dial to record the volume, and having danger spots marked on it, so that he can work his crescendos in line with it. By that means the conductor or the artist could see, long before he reached a climax, whether that climax would be within the required range, and he could ensure that it would be within that range. I know the dangers of sudden outbursts of sound, such as a crash on the drum, and so on. I would like to be able to see, at the rehearsal, how much drum I dare put on. I believe that any intelligent person could watch such a dial and could adjust the volume; that would be far better than to have an adjustment which is effected arbitrarily by someone else.

Again, in connection with recording and in broadcasting, the conductor asks that there should be very frequent tests; we do not have enough. The artist wants time to hear his performances, just as the listeners hear them, so that he can make his own adjustments. In broadcasting we seldom have a chance to hear them; there is not time. But if we are really out for high fidelity reproduction, that is the first thing on which I insist, so that the artist has the opportunity to adapt his art to the job in hand, be it broadcasting or gramophone recording.

Does the music actually go out of a hall faithfully? By that I mean, is the microphone the equivalent of a human ear? A point which has been raised, and which interests me, though I cannot answer it, is whether one microphone can do the work of two ears. Do the ears really work stereoscopically? Is the distance between them important, in the same way as the distance between the two eyes is important in providing a sense of exactness? If one microphone is not enough, the answer is not necessarily that there should be three or four in a room; you might have two, the distance between them being the same as between two human ears.

There is one simple test, but I have not yet seen it applied. I would say that a microphone is doing its job absolutely right if you can place it in a room and, when standing beside it, you can listen to the music with the ear, and then put on earphones from the microphone and hear the music exactly as before. If the results are identical in both cases you can say that the microphone is faithfully putting over to the wax the sounds received by the ear. That is an ideal which we have not yet approached.

It might be possible also, when testing microphones in a hall, to move a microphone about and to find out where there is the least difference between the sounds received by the earphone and the human ear. You may move the microphone up or down or sideways and you may find one spot where there is the least difference. Then you can adjust. The orchestra may be too large, and you may have to reduce it. I remember an occasion on which the basses were too resonant, and I told four of the eight that they could go home. There was a terrible shemozzle! They came back again, but I told them that so long as they did not play I should be perfectly satisfied. They had a grand time, doing nothing at all; and the results were very much better!

I am not the sort of musician who insists upon broadcasting under concert conditions; I do not think that is the best way. Ideally it is the best way; but until you can produce microphones which are in effect human ears, it is not the best way.

Having decided that the music does not come out of the hall faithfully because the microphone is very different from the human ear, we have then to decide whether or not it goes on to the wax faithfully. Here again, in recording one sometimes wonders what is taking place in the van. I have occasionally come across troubles with the intonation of soft wood wind chords, which I am certain is due to the fact that the turntable is not absolutely correct. In watching needles on turntables, both in vans and elsewhere, one can always see a slight movement. If there is any vertical movement at all, the wax is not taking the sound accurately; it should be dead still, in order that the sound should come through without being alternately accelerated and slowed up in certain parts. That is one of the problems the solution of which will help towards high fidelity in recording.

It may be thought that by placing microphones in various parts of a hall the balance obtained is absolutely perfect; but it is strange that the near microphone gives an entirely different idea of concert recording. I remember a very curious example, when I first went to see the film " Fantasia." From outside the hall I was listening to the Nutcracker Suite, and I thought I could hear female voices singing; I presumed that it had been re-orchestrated. But when I entered the hall I found that the sound which I had thought to be due to female voices was simply due to the playing of the strings; the harmonics were so changed that I had thought the sound was vocal.

Again, in " La Gioconda " I heard a most miraculous sound of flutes, as full as the sound of trombones. It was wonderful, but it was not a sound which had ever been heard in an orchestra. I get it sometimes when a flautist plays near me, and it can be reproduced like the sound of trombones. It is very striking, but it is not the sound which the composer intended when he wrote the flute solo. Flutes can be used that way if we decide that the music has been written for recording or for a film and should be used as such; I think the modern composer can produce some wonderful sound effects by placing microphones near to instruments which we are not accustomed to hear. He can make a chord on the clarinets give a blast louder than that from the Albert Hall organ. But that is not what we are dealing with in high fidelity reproduction; it is high " infidelity."

In broadcasting insufficient trouble is taken with the placing of the microphone. I have not seen the B.B.C., which could well afford to do it, use the first night of the Proms experimentally. Even when using the Albert Hall it could be stated that the first night of the Proms is an experimental night; the B.B.C. could then hang dozens of microphones and could spend the evening trying out the best combinations for producing the right effects over the air. That can be done only when the hall is full. The result should be much better than anything we have ever had.

In fact, however, suddenly I am asked to broadcast a choral concert. The problems of a choir with an orchestra are many. The experts arrive at the hall and sling up a couple of microphones, listen to the results in an empty hall, with no choir there at all, but only the orchestra, and they seem to consider that that is sufficient. It seems to me that every concert hall in Great Britain which is to be used for broadcasting should be registered with the necessary information as to the best method of broadcasting from it. There should be an experimental session. It would be quite easy, without disturbing the concert, if the microphones were slung in many places, to switch them on and off or lower them between items. We should be very glad to co-operate in this work, for we should then have a setting for a concert which would always give us good reproduction. At the moment the problem is a nightmare. Even the best of concerts that come over from choral societies, and so on, ought to be much better reproduced than they are. We have always to make allowances for the broadcasting.

I should like to ask your opinion on another matter. I have discussed it with doctors, but have never received a satisfactory answer. The ear is less understood than the eye. If I hold up my finger before my eyes I can look at it and see it quite clearly, or I can look through it and see the door of the room behind it, by focussing. I am convinced that we can focus with our ears also. I can decide to hear the second bassoon, by focussing the ear to it. I believe the ear must have a control system which is really minute and has not been studied fully. When you enter a machine room you cannot at first hear your friends speak, but later the ear becomes dull to certain sounds and you tune in to voices. In a restaurant one perhaps tries to hear above other voices a remark by someone who is, comparatively speaking, a long way away. Once you catch the tone of the voice you want to hear, you can hear what is being said.

The point has been raised that a conductor does not really hear a concert as the audience hears it, and therefore, perhaps he is not the best representative to make a decision about recording. I must tell you that a conductor cultivates a curious sort of hearing which becomes instinctive; but he does not decide on a performance exactly as *he* hears it. It is particularly noticeable in a piano concerto, the piano being much louder to him than to anybody in the hall, and he becomes accustomed to that. I do know—and that is why I believe in the focussing of the ear—the amount of volume from a 'cello, because I can see the amount of bow.

Just as, in recording, one would turn down the knob to take a loud chord, the conductor would turn up the knob after the loud chord, because if a loud chord is followed immediately by pianissimo the ear is not ready to accept it. Therefore, an orchestra will play louder (mezzoforte) immediately after a loud chord, and it will sound pianissimo. The conductor's job is to play for effect. We play the written note in order to produce the effect upon the hearer; we are not there to please ourselves, but actually to get the result over to the listener. You would be amazed to find how often composers make errors of judgment. What they write could not give the complete effect intended. This balancing is something which any sane conductor is accustomed to do, and it is not beyond his powers to do without our friend with the knob and perhaps to obtain better results on the wax.

What I have said will convince you that there is at least one musician who is intensely interested in your part of the job, because he knows it to be of vital importance, and who will be only too happy if you will allow him to learn some of your secrets and to collaborate with you, so that the results of that collaboration will benefit humanity in general.

Mr. P. G. A. Voigt: In recording work, a loudness dial on the conductor's desk can and has been provided. I was once concerned with recording an organ which had a particularly objectionable note and which no gramophone would record. A connecting lead was ran out from the amplifier, a meter was placed on the organist's desk, and he played the passage concerned until we found the needle going hard over. Then I asked him to hold that note—which is quite easy in the case of an organ—and we moved microphones all over the place until a spot was found where the note was not so serious. That became the standard spot for the microphone when recording that organ.

Regarding the alleged deficiencies of microphones and gramophones, Dr. Sargent is perfectly correct in his contention that if you put your head near the microphone and listen through headphones you should be able to hear exactly what you hear when you take off the headphones. But not only have the microphones to be perfect. The headphones also should be perfect ; but perfect headphones are few and far between.

One way of making a test is to have the artist and the microphone in one room and a speaker in another room. The speaker will reproduce the sound, which will set up echoes in the second room ; and since the microphone will pick up part of the reverberation of the first room, the reproduction will contain two sets of echoes. Therefore, it cannot be exactly the same as the original. But it can be very near to the original. By means of that test it is possible to discover deficiencies.†

One of our difficulties is that the average member of the public has never heard what can be done with high quality apparatus under the best conditions ; and those best conditions, I am afraid, are a microphone connected through amplifiers and a direct line to the loud speaker. Under those conditions a very high standard can be achieved. The gramophone disc and the radio introduce certain difficulties which, by good technique, can be made very slight. Microphones should be far apart and pass their output through a single amplifier over one radio transmitter or through one record groove ; for binaural listening it is necessary to have two separate transmitters and two separate grooves.

Binural listening has been achieved academically, and it is most interesting. The impression is given that the orchestra is all around the listener. But to preserve binaural it is essential to have double channel, and synchronisation must be absolutely spot-on ; the nearest substitute would be to have two spaced loudspeakers and two suitable spaced microphones.

The middle-man is always getting into trouble. When I was making gramophone records I endeavoured not to touch the knob whenever I could avoid it. But if the artist were given a choice between leaving in a top note so loud that it would shut down the transmitter and having that note slightly modified, I do not think there is any question as to the choice he would make.

Then there is the problem of arranging the differences musically. Is the sound of a drum which is hit as hard as one can hit it, and with the volume control turned half-way up, the same as a drum hit half-hard and with the volume control left fully on? I do not think it is the same ; but I will not argue as to which is preferable.

I believe than when the equipment is perfect, when all the imperfections of which the engineers are conscious can be eliminated, the music through a loud speaker will be of such quality that it will sound to an audience as though the orchestra is in a studio adjoining the room, there being no wall between the room and the studio.. We shall not be conscious of any intervening link of any kind.

I cannot agree with the view, however, that in order to obtain that effect the sound should be doctored by the engineers. In eliminating engineering imperfections it is possible to lose some of the beauty of the music.

It is often suggested that engineers should alter the quality of the music as received on the radio or record. The musical instrument manufacturers, however, have been engaged for several centuries in making musical instruments, and no doubt they have made those instruments to sound as good as they know how. For a technician to introduce treble cuts and bass boosts, and what not, in order to improve the quality of the music from those instruments is by way of being an impertinence. If it is done in collaboration with the musician in order to achieve certain definite artistic effects it is justifiable ; but that is not high fidelity reproduction, and it is not the technical problem of conveying a sound as it was produced.

One of the reasons for the difficulties that arise as between artists and engineers is that to some extent they speak different languages. When I was trying to convince a recording department of the need for electrical recording I talked about harmonics. My colleagues looked very wise ; and I discovered later that "harmonics" was a special way of playing a violin ! What the engineer calls "harmonics" the musician calls "overtones." Perhaps Basic English will put that right !

The problem of reproducing pictures has been mentioned by way of analogy. Analogies are always very dangerous. But if I wanted to purchase a copy of a Rembrandt, for example, I would object to the use of a photographic process which was arranged to give something artistically more desirable. All the imperfections of that Rembrandt should be reproduced, if the copy is to be a faithful one.

Multiple microphones have been attacked on technical grounds. I prefer to use one microphone, though we can use several. If one imagines that half way between two microphones there is a completely reflecting wall, then the introduction of multiple microphones produces a fictitious state of affairs, the walls reflecting some sounds but not others.

Dr. L. E. C. Hughes : It was my privilege to deliver a lecture to the members of this Institution about 18 months ago,* and I tried then to show that practically all the scientific factors involved in the reproduction of sound were known and could be controlled. The discussion to-night is concerned mainly with the defects; we are arguing along the lines of least resistance and

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† See also "Sound Reproduction," by P. G. H. Voigt, *Journal Brit.I.R.E.*, Vol. 1 (new series), p. 74.

* "The Technical Basis of Sound Reproduction," November, 1942.

complaining about the ignorant criticisms of musicians who perhaps do not know what they are required to listen for. I hope the discussion to-night will clear up the point that there is a standard of objective assessment of quality. But it is not the final one ; the final one must be the purely subjective.

The way in which the engineer attacks the problem differs from that indicated in the first remarks of Dr. Sargent. Artistically, it is the business of the conductor to give us the best example he can of what the composer had in mind. If the conductor deviates, that is his responsibility. It should then be possible for the engineer to compare the original with the reproduction ; however, this has to be staged especially, and the suggestion by Dr. Sargent that he would be willing to experiment with the telephones points one way out. It must, however, be borne in mind that ordinary telephones distort, so that special high quality telephones would have to be used. The best solution would appear to be to have the conductor in a glass box, where he could not hear the orchestra directly, but could hear the reproduction.

" Fantasia " in its orginal form must give, I think, the finest reproduction ever attempted. The film with its three sound channels was shown in America, and it was reported that audiences were very excited about it. The point is that Stokowski himself recorded the three channels from the original microphones ; it was therefore Stokowski himself who sanctioned what the public should hear. If there is anything wrong with the music it is his reponsibility, not that of the engineer.

We have a glorious opportunity to ask for Dr. Sargent's good offices to educate the public to appreciate high quality reproduction. We have been talking about it for 20 years with no result whatever, and it can be done only by great artists, such as Dr. Sargent, arguing our case.

Patric Stevenson : Dr. Sargent obviously appreciates the fact that music now reaches many more people as reproduction than as a real performance in the concert room ; the more time given by musicians to discussing the problems to which reproduction gives rise, the better for all concerned. For this is a somewhat neglected field, and the æsthetics of reproduction is in danger of falling between two stools, being, on the one hand, too exclusively concerned with qualitative æsthetic theory for the technical press, and on the other hand, too technical for consideration in publications devoted to the art of music. Nevertheless, it is of vital importance, and liaison between musician and the engineer should be encouraged, as an ever-increasing part will be played by the latter in the sphere for so long dominated by professional musicians.

I wish to deal to-night with the subjective, perceptual aspect of the reproduction of big ensembles, with a view to finding what principles, if any, can be deduced to guide us in our attitude towards sound-reproducing systems.

Means and Ends

Assuming, for the moment, perfect reproduction to be an eventually attainable aim, we should never forget that broadcasting is a *means*. When used as the vehicle by which the performance of a world masterpiece is heard, it behoves us to look into the question from the æsthetic point of view. For a great musical composition possesses intrinsic value in and for itself—it is an *end*, not a *means*—and our method of distribution must interfere as little as possible with the ends entrusted to its care.

What then, in terms which concern the sound engineer, is an orchestral concert ? It is a sequence and combination of sounds of varying pitch, volume, timbre, and "transiency"[1] produced by a large number of different instruments.

Five Conditions of Performance

The following are some of the elements—acoustical, environmental, physical or physiological—which will condition an actual symphonic performance :—

1. A large number of instrumentalists will occupy a lot of space, and play in a closed auditorium seating, perhaps, 2,000 people. Hence there will be considerable variations in the distances between each player and any given listener. This path difference will give rise to varying phase differences at the listener's ears.

2. The human eardrums, being located apart (average distance 21 cm.), are capable of detecting differences of phase over certain frequencies, thereby giving us a sense of direction of the sound source.[2]

3. The loudness-sensitivity of the ear varies over the frequency range so that, other things being equal, bass and extreme treble will be louder relative to the middle notes when near the orchestra, and softer when farther away.

4. All sound is affected by the reverberation period of the hall. The walls cause reflections, and interference patterns are set up.

5. A range of the order of 50 db. will normally be covered in dynamics.[3]

All these conditions modify the result before the final concept of, let us say, Beethoven's *Fifth Symphony* becomes apprehensible to the mind of an average listener. Moreover, all these factors must have played their part in creating the conception of the symphony in Beethoven's brain. He did not conceive the music

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[1] Using the word in its technical sense the meaning is "transient content."

[2] Beatty, R. T., "Hearing in Man and Animals." G. Bell & Sons, 1932.

[3] " Cathode Ray," " Loud Speaker *versus* Orchestra." *Wireless World*, March 10th, 1938.

as emanating from a nine-inch diameter "point-source" in a bijou villa sitting-room: the size and space inseparable from performance were inherent factors.[4] "The music," as Terman says, "exists in terms of musical instruments. Moreover, it exists in terms of the place and occasion of its execution."[5]

Bearing in mind the above five conditions of performance, let us see what broadcasting technique would give the listener a perfect replica of the original.

Approaching the problem from the point of view of transporting one individual to the concert hall, the arrangement will be as shown in Fig. 1. Two microphones, each having the same directional properties as a human ear, and situated in the same mutual physical relationship are suspended at A in the auditorium.[6]

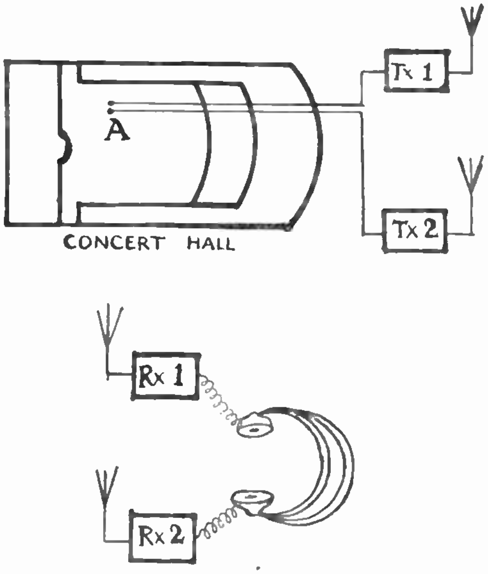

Fig. 1.—The listener is transported to the concert hall.

Two separate transmitting and receiving channels convey the vibrations to the respective ear-pieces of a pair of high fidelity 'phones. The listener adjusts the volume so that the intensity at his eardrums is the same as the intensity he would hear in the hall. This exemplifies binaural or stereophonic broadcasting.

So much for theoretical perfection; what have we in reality? Fig. 2 illustrates existing monaural practice which strikes an unsatisfactory compromise between attempting to take the listener to the concert hall and bring the orchestra into his home. Several microphones, A,A,A, are placed throughout the hall. (This would of itself produce abnormal sense perception). Their output is mixed and fed via the balance and control panel—which includes volume compression—to a single-channel transmitter. Assuming that the receiver volume control is set to give an approximation to the average intensity at the ear in the hall, what the listener hears will further depend on home conditions, i.e. (i) his position B; (ii) the placing of the loud-speaker; (iii) the acoustics of his room.

Even assuming the as yet unattained perfection of each link in the broadcasting chain, it is obvious that the result will be unlike anything which a single individual could hear in the hall. The five conditions of performance, whose subtle fusion exercises such a potent influence on direct listening, are absent—or present but singly or piecemeal—in the reproduction. That the loud-speaker should sound as pleasing as it does is partially explained by the fact that the ear is a very accommodating organ, accepting as natural the result of interference effects, and obligingly supplying a fundamental when harmonics only are present. Furthermore, the aural memory of most people is of extremely short duration. A deeper, psychological reason is due to the mind's renunciation of the judgment that the reproduction is not the reality. We do not judge it to be unreal; hence the resulting negative reality is fairly convincing.

I conclude, therefore, that distortion is inevitable and a facsimile of the broadcast impossible.

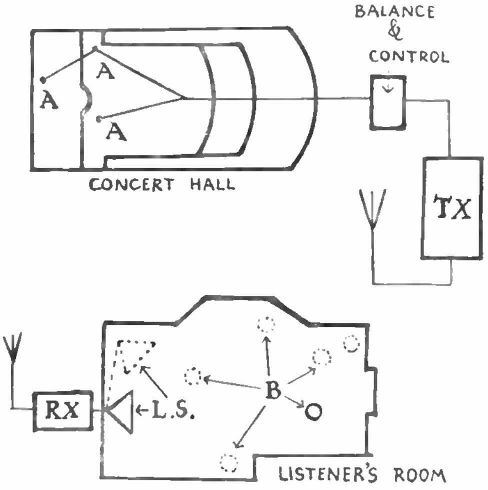

Fig. 2.—A compromise is struck between taking the listener to the hall and transferring the orchestra to the sitting room.

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[4] "Reverberation in Orchestral Recording." *Gramophone*, October, 1941.

[5] *Radio Engineering*, p. 192.

[6] They must be suspended in mid-air, as no mechanical device, devoid of will power, can be expected to discriminate against extraneous noise in favour of the music.

Existing Schools of Thought

The attitude of those who have studied the philosophy of sound reproduction can be classified under three schools of thought.

The first school, the Purists, believe as ultimately attainable what I have just shown to be impossible, viz., absolutely distortionless reproduction. They therefore hold that broadcasting is simply a means of sound transmission, and no distortion can be tolerated. Our aim is not achieved, they say, until the vibrations at the listener's ears are identical with those which would impinge upon them at the actual performance.[7] Let us hear Mr. J. R. Hughes, a doughty champion of this school, on the question of volume levels :—

> " The loudness of a symphony is part of the symphony ; if we change it, no amount of 'tonal balance ' can resurrect the murdered original."[8]
>
> " Scale, size or loudness—these are inherent factors. A miserable, puny undersized reproduction of a great symphony is no more capable of exciting the deepest emotions than is a vest-pocket photograph of the Matterhorn."[9]
>
> ". . . by no natural means is it possible to hear music softly and yet preserve the same 'tonal balance' as exists when it is heard loudly. Why, then, should we try to introduce this unreal condition into our 'high fidelity' radios? . . . 'Tone correction' is always wrong. If we must have our music softly, then let it sound like real soft music."[10]

The views of the *second school, the Pragmatists*, may be summarised as follows. Broadcasting is a universal means of home entertainment and instruction. Although the Purists' ideal may be the counsel of perfection, the conditions of its attainment are seldom, if ever, capable of realisation in practical life. We agree that all juggling with frequency-response curves is *ipso facto* wrong, but maintain that the power to produce a touched-up version of broadcast music, more suitable for a home environment, should not be denied to the ordinary listener.

Mr. P. G. A. Voigt would seem to be an adherent of this school. He has written :

> " Reproduction is possible at any volume level, and a faithful replica of the sound anywhere between these extremes of loudness can be high fidelity. Faking the volume control so as to boost the bass at low-volume levels is, therefore, inadmissible from a quality point of view.
>
> . . . While I dislike the faked volume control, I do not condemn normal correction circuits . . . When characteristics are known, compensating circuits can be evolved intelligently. When they are unknown . . . a variable adjustment is often of immense value."[11]

The *third school, the Subjectivists*, realising that distortion is inherent in present systems of broadcasting, claim that reproduction is a purely subjective affair. The home listener must be given full control to get his music the way he wants it. There is no right or wrong in the matter ; it is entirely a question of personal taste.

Mr. R. C. Harris is a typical Subjectivist. He writes :

> " Mr. Hughes appears to have the psychology of listening all wrong. When we listen to the reproduced version of an orchestra we want to be able to hear the correct proportions of the original . . . After all, what is the criterion of good reproduction ? When we can sit back . . . and can say that it was magnificent. Does it really matter if it was not quite like the original ? "[12]

Dealing, as I am, with the reproduction of music which possesses inherent artistic value, the contentions of the third school would seem impertinent and untenable. Has the composer no right to say how *he* wants his music heard ? If not, why has he been so meticulous in adding expression marks to his score ? What would Beethoven or Brahms have said if told that the mere fact of using a radio entitled the listener to hear *their* music just as *he* wanted ? Why, too, should the exquisite and laboriously rehearsed balance of a Beecham or a Sargent be at the mercy of the irresponsible knob-twiddling of John Brown ?

Well, the fact is that we are committed to scientific progress giving the man in the street a steadily-increasing control over his broadcasting. What, however, are we to do when Beethoven emerges with everything altered (except, possibly, pitch and *tempi*) from the devious channels and filters of our friend's amplifier ? I can only answer with one word, educate. Education, and the development of a collective artistic conscience must be the means by which we fit the ordinary listener for the onus and privilege of becoming, in a certain sense, a co-interpreter of great music. When Berlioz writes an unusual *diminuendo* on the final chord of his Rakoczy March (which responsible conductors like the late Sir Hamilton Harty observe in performance), we must rely on the general musical culture of the listener restraining him from turning up the volume control for the last few beats under the mistaken impression that the effect is due to the B.B.C.'s "playful habit of compressing the peaks of the finale."[13]

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[7] ". . . It cannot be too strongly, or too often emphasised that an ideal receiver must reproduce *at the listener's ear*, exactly the same intensities and exactly the same range of intensities as would exist *at the listener's ear* if he were seated in his favourite seat in the concert hall."—Letter from J. R. Hughes, *Wireless World*, January, 1943.

[8] *Wireless World*, April 13th, 1939.

[9] *Wireless World*, February, 1942.

[10] *Wireless World*, August 10th, 1939.

[11] *Wireless World*, August 24th, 1939.

[12] *Wireless World*, August 31st, 1939. See also the article " New American 'Quality' Receiver," March 23rd. 1939, and letter in issue dated May 18th, 1939, both by Pacent and Likel.

[13] *Wireless World*, March, 1942.

Similarly, when Schubert, Brahms, Berlioz or Sibelius indulge in a passage of contrary dynamics[14] (let us say the treble getting louder with a simultaneous diminuendo in the bass) we must again fall back upon the education and artistic integrity of John Brown, who by nature likes his orchestral items with plenty of bass, preventing him from manipulating his tone controls so as to annul the intended effect.

Whilst admitting the necessity for education, we may ask is there any principle to guide us through the chaos of "loud-spoken" sound ? I think there is. Starting from the fundamental truth that imperfections will always remain in the broadcasting of music as we know it, we see the futility of trying to make our home reproduction a *copy* of reality. Our true aim should be not a *copy* but an *imitation*. Looseness in linguistic usage may obscure this point ; it can best be illustrated by extracts from Coleridge's " Lectures on Shakespeare."[15] Coleridge is discussing the stage and stage illusion. To make these passages applicable to our subject, the italicised words have been substituted for the original terms.

> " *Reproduced music* . . . is not a copy, but an imitation of the *actual performance*. This is the universal principle of the fine arts. In all well laid out grounds what delight do we feel from that balance and antithesis of feelings and thought ! How natural ! we say—but the very wonder that caused the exclamation implies that we perceived art at the same moment . . . And so it is in *sounds* known to be artificial, which appear to be natural.
>
> . . . All reproductions are to produce a sort of temporary half-faith, which *the listener* encourages in himself, and supports by a voluntary contribution[16] on his own part, because he knows that it is at all times in his power to hear the thing as it really is . . . the suspension of the art of comparison, which permits this sort of negative belief is . . . assisted by the will.
>
> The true *illusion of reproduction* . . . consists not in the mind's judging it to be *an actual performance*, but in its remission of the judgment that it is NOT *an actual performance* . . . For not only are we never absolutely deluded—or anything like it, but the attempt to cause the highest delusion possible, to beings in their senses sitting *at home* is a gross fault."

I submit that these quotations embody a principle which should determine our attitude to sound reproduction. Since our loud-speakers cannot produce a *copy* of reality, we must aim at an *imitation*, and thus learn to treat broadcasting as an *art* in itself. Imperfections and limitations preclude its being relegated to the category of a mere means ; in some degree it becomes an end in and for itself.[17] Regarded in this light, electrical reproduction is raised to the status of an auxiliary interpretative art, and shares in some measure the artistic responsibility which falls on the performer.

Some of our best critics have pointed out that we hear more accurately by radio than in the concert hall.[18] The merciless way in which the microphone shows up technical and imaginative faults makes a broadcast a much more rigorous test of the *inner* value of a performance than listening as a member of the audience. For one thing, what Ernest Newman calls "The monstrous fake known as 'personality' or 'personal magnetism' " makes no *extra*-musical appeal to the disinterested microphone.

More recently[19] Newman has suggested how the development of a new wireless technique could enable us to realise the spatial effects which Berlioz had in mind when writing such works as *The Requiem* and *Te Deum*, effects which fail to "come off" under present concert conditions. Elgar, that great champion of the gramophone, demonstrated on at least one occasion his delight in the possibilities of enhanced expression provided by science. In Basil Maine's Life[20] we read :

> " *Falstaff* was played on the gramophone and the music was followed with the manuscript full score . . . Elgar, not content with having conducted the performance for the records, proceeded to control the gramophone version of that performance. By continuously twisting the control that increases and decreases the volume of tone, he obtained sharper and more sudden contrasts than are possible in the concert hall, and was delighted with the discoveries he made in the heightening of effects. When there came the Gloucestershire Interlude[21] he turned the control so that the music

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[14] Examples of contrary dynamics :—

Schubert ; Unfinished Symphony, 1st movement, bar 178 *et seq*. (wind and timpani *decrescendo*, 1st and 2nd violins and violas *crescendo*).

Brahms ; Tragic Overture, bars 44-47 and 48-51. (Woodwind rise from *poco f* to *f* while strings reduce to *p*.)

Berlioz : The Corsair, Overture, bars 44-45 and 50-51. Double basses and 'cellos *poco f* to *p*, violins and violas *p* to *f*).

Berlioz : Symphonie Fantastique ; Marche au Supplice, bars 34, 36, 42 and 44. ('Cellos, violas, double basses *crescendo*, 1st and 2nd violins *decrescendo*).

Sibelius ; 7th Symphony, last two bars, trumpets, trombones, and timpani hold a chord *dim ff* to *mf*, while strings and horns rise from *f* to *ff*, woodwind holding an *ff* chord the whole time.

Sibelius ; 7th Symphony, bar before letter E, oboes, horns and bassoons, *dim. f* to *p*, strings cresc. *p* to *mf*.

[15] *Everyman's Library* or *World's Classics*.

[16] The "voluntary contribution" from the mind of a trained musician is so great that it makes him oblivious to distortion which would be insufferable to ordinary intelligent listeners. Hence one reason for the observed fact that many musicians seem to be quite content with inferior reproduction.

[17] Art is limitation even before it is imitation.

[18] E.g. Ernest Newman, writing in the *Sunday Times*, especially articles entitled "Listening by Wireless," September, 1934. For an expression of the opposite point of view see the second of two articles by R. H. S. Crossman entitled "Listening to the B.B.C.," the *New Statesman and Nation*, January 15th and 22nd, 1944. Crossman says : "Classical music . . . is not pure radio, but something far better heard and far better enjoyed in the concert hall."

[19] *Sunday Times*, December 19th, 1943.

[20] G. Bell & Sons, 1933.

[21] Maine may have meant the First Interlude rather than the scene in Shallow's Orchard. It is in the former that Sir John dreams that he is once more " a boy and page to Thomas Mobray, Duke of Norfolk."

did indeed appear to recede to a dream environment. Wonder and awe were in his eyes as he listened to the unreal effect."[22]

Here we have an instance of electrical *imitation* coming closer to the composer's intentions than ordinary performance.

Mr. H. A. Hartley : I cannot help feeling that the audio frequency engineer can act only as an audio-frequency engineer, working to formulae and equations. When it comes to judging the performance of a piece of audio frequency equipment which purports to reproduce what was sent into the microphone, the decision rests with the musician only, because he is the only person competent to deal with it.

The engineer should, however, endeavour to acquire musical judgment in such a way that he begins to do things to the flat response which will result in the reproduction of a sound as pleasant as the musical sound. In records, films, and that which we conveniently call the ether there are factors interposed between the original performance and the reproduction, and they introduce distortion. In the case of a record there is surface noise ; in the film there are other things which are the result of the photographic properties of the emulsion ; and in the case of the ether there is interference of one type or another. But the ear is capable of reproducing certain sounds by virtue of its own mechanism. So that I think we are entitled to mutilate the sound, provided we so mutilate it that the natural mechanism of the ear can reconstruct what has been taken out. I maintain that is possible.

The so-called middleman must be the guide, philosopher and friend of the musician. The musician will say what he wants, and the middleman will tell him how to achieve it.

It is certainly important that, in broadcasting, the conductor must be able to make the necessary disposition of his orchestra.

Dr. Partridge : According to most speakers, the great source of trouble is the middleman, and it would be a good idea to get rid of him. If we could get rid of him, or of the effects of him, and at the same time remove a lot of background noise, it would be a good idea. After considering what one does in a television set, the ordinary gramophone set is very simple, and it would not complicate it to put in another channel. If we make the signal in this channel in some way proportional to the knob-turning of the control man, we could always record at a fairly high amplitude, and we could control or re-expand by means of this second channel signal very precisely and exactly, thus obtaining our full range of volume and, at the same time, possibly doing away with a lot of background noise.

Dr. Malcolm Sargent : With regard to the remarks of Dr. Hughes, it seems that I did not express myself properly with regard to the "Fantasia" film. I heard it six times, for I enjoyed it so much, particularly the music. I have actually heard it in England, with whatever reproduction is here, and which, I am told, is not the right one. But the sounds I heard in the Nutcracker Suite were not the sounds one hears from the orchestra. They did not represent a faithful reproduction ; they were very much better. The flutes were five times as loud as I have ever heard elsewhere. The music was arranged by Stokowski and sanctioned by Levinski, and they were after effects which were really suitable to a highly coloured picture. That emphasises that we must reach the point at which music is written entirely with a view to reproduction. That is all-important.

In my reference to the Albert Hall I was not pleading that that particular hall should be made a perfect place for reproduction. All I want to stress is that in regard to any hall in England not always is sufficient trouble taken to ensure that microphones are hung where they should be hung, and that the conditions generally are right for a broadcast.

The worst people to give judgment on performances are composers ; they listen with their own feelings, and a composer, after listening to some of his own music, will say : "That was lovely," because it was the part he enjoyed composing. Again, with regard to performers, in college I endeavour to make the students listen to what they play, instead of just feeling it. I impress upon them that it is not what they feel, but what they make other people feel, that matters, and that when they really listen they will not feel so happy about their performance.

The loudspeaker in itself is, to my mind, an unfortunate thing. When I go to a music or concert hall I see people walking about on the stage carrying something into which they speak. It is a new technique, but horrible. In the old days the performers could make their voices reach the back of the gallery ; they had to, in order to make a living. Let us get down to the rebuilding of the halls, but let the performers do their work so that speech shall be audible in the ordinary buildings, straight from the vocal chords to the ears.

In moving a vote of thanks to Dr. Sargent for attending the meeting, Mr. G. D. Clifford referred to the frequency with which, over the past few years, the Papers Committee had arranged meetings for discussion of the problems of high fidelity reproduction. It was an innovation to invite an eminent musician, and Dr. Malcolm Sargent had certainly proved the desirability of there being co-operation between the conductor who interprets the composer, and the engineer. The large attendance proved the interest of radio engineers in the subject, and would, in itself, convey to Dr. Sargent the Institution's appreciation of his attendance.

A vote of thanks to Dr. Malcolm Sargent was then heartily acclaimed.

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[22] *Op. cit.*, p. 268

TRANSFERS AND ELECTIONS TO MEMBERSHIP

The following elections and transfers were recommended by the Membership Committee at their meetings held on July 31st, September 18th and October 15th, 1945. At these three meetings the Committee considered a total of 94 proposals for transfer or election to Graduateship or higher grade membership.

Transferred from Associate Member to Full Member

CHAPMAN, Sydney Ronald, Sqdn./Ldr.	Bishop's Stortford
HUMPHREYS, Thomas Denis	High Wycombe
MARTIN, George Henry Randolph, Lt./Cmdr.	Morden, Surrey.

Transferred from Associate to Associate Member

GARSTANG, Fred	Ilford
RODGERS, Eric Hugh	Colombia, S. America

Transferred from Student to Associate Member

SANDERSON, Albert King	Norwood, S.E.25

Transferred from Student to Associate

ALTMANN, Helmut Nachman	Palestine
DUNLOP, John	Kilmarnock
FIRTH, Frederick William	Brockley, S.E.4
GWILLIAM, Alfred Lionel	Worcester
HEDGE, William Criswell	Northampton
MURPHY, Kevin Anthony	Dublin
OLIVER, Leo Francis	London, W.13
PERRY, William Edward	Wembley, Mddx.
PORTER, Ernest George	Northwood
RAYMOND, Anthony Miles	Langley, Bucks.
RIDGERS, Charles Edward Sydney	London, N.W.9.
SLY, Roland John	Slough, Bucks.
THOMPSON, Charles Leslie	Scunthorpe, Lincs.
TURNER, Cyril	Manchester
UNDERDOWN, Percy James	Upminster, Essex
WAREING, Cecil William	Bournemouth

Transferred from Student to Graduate

ANDREW, Alexander Miller	Larbert
BRODIE, William David, B.Sc.	Farnborough
CROCKER, Norman Joseph	Enfield, Mddx.
FREAN, Peter Frederic	Reading, Berks.
KIRKMAN, Dennys	Haslemere, Surrey
MILLS, Kenneth Douglas	Reading, Berks.
STANLEY, Thomas John Harvey	Bristol, 8
WOODS, John Frank	Tarrant Rushton

Elected to Full Member

COOPER, William Charles, Air/Cmdre., M.A.	London
MEYER, Leslie William, W/Cmdr.	London, S.E.7

Elected to Associate Member

BURROUGHS, George Edward Richard, B.Sc.	Canterbury
DAVIES, Wilfred Llewellyn, F/Lt.	Whitchurch
EDWARD, Reginald Charles	Belvedere, Kent
EVANS, John Harold	Cambridge
EVANS, Meurig Hill	Leeds, 6
GEOGHEGAN, Gerald Robert Holme, S/L, M.A.(Cantab.)	Tunbridge Wells
GODDEN, Alec William, B.Sc.(Eng.)	Ealing, W.3
KAY, Fred, M.A. (Cantab.)	Bolton, Lancs.
KEEN, Arthur William, S/Ldr.	Cowley, Oxford
KRAUSE, Vivian Rupert	Johannesburg
LOWE, Francis Cyril, S/Ldr.	Sleaford, Lincs.
MAITRA, Krishna Chandra, B.Sc., M.Sc.	Bilston, Staffs.
MAUDSLEY, Benjamin	Blackburn, Lancs.
MORPHET, William Henry, B.Sc. (Hons.)	Burnley, Lancs.
MORTON, John Robertson, Capt., B.Sc.(Eng.)	Edinburgh, 8
MUNRO, Angus	S. Rhodesia
PENTON, William Arthur, Lieut.	New Zealand
SWANN, Eric Dennis	Highgate, N.5
WEECH, Charles William Thacker, Major	Huddersfield
WILLDER, Kenneth Burnett Shelton, W./Cmdr., B.Sc.	Staines, Mddx.

Elected to Companion

ROBBINS, Richard Arthur	Abergavenny,

Elected to Associate

CHAKRAVARTI, Brahman Mohan, Capt.	India
CRAWFORD, Robert	Aberdour, Fife
CRITCHLOW, Philip Sydney	Tipton, Staffs.
DRIFFELL, Joseph	Swindon, Wilts.
HARES, Walter	Coalville, Leics.
HODSON, Edwin, Lieut.	Manchester
JARDINE, Roy	Aberdeen
JOHNSTON, Warren George	Weybridge
KERSHAW, James, B.Sc.	Derby
KNOWLES, Kenneth John, B.Eng. (Hons.)	Wallasey
LAYZELL, David Robert Rayner	Sutherland
LEWIS, Geoffrey, Capt., B.Sc. (Hons.)	Christchurch
MOLONEY, John Lawrence	Aldershot
SCOTT, Alfred, Lieut.	London, W.2
SHEAD, William Percival	Greenford, Mddx.
SUDERSHAN, Raj, B.A., M.Sc.	Hyderabad Dn.

Elected to Graduate

FREEMAN, Peter, B.Eng. (Hons.)	Cornwall
KENNY, Vincent	Dublin

STUDENTSHIP REGISTRATIONS

The following were Registered as Student members of the Institution at meetings of the Membership Committee held on July 31st, September 18th and October 15th, 1945. At these meetings, the Membership Committee received a total of 114 proposals for Registration as Student members.

AGIUS, Peter Joseph Vermont	London, E.C.
ALLEN, Maxwell George	South Australia
ALLISON, John	Ayr, Scotland
ASKEW, John Edmund	Bolton, Lancs.
AVERY, Leslie Henry	Brighton
BAGLEY, Aubrey Stephen	Queensland, Aust.
BAMPFIELD, Geoffrey	Huddersfield
BARRETT, Wilfred, Lt.	New South Wales
BENNETT, Albert Gordon	Queensland, Aust.
BETTS, Charles Anthony Blundell	Birmingham, 30
BLIZARD, Duncan	Liverpool, 13
BULMAN, Reginald Verne	Tasmania, Aust.
BUTCHER, Albert Norman	Kirkwall
BUTCHER, Walter Sidney	Coventry
BYRNE, David Brian	Plymouth, Devon
CHING, Frederick Douglas	Auckland, N.Z.
CHRISTIAN, Robert Gregory	Billericay, Essex
CLARK, Stanley Tulloch	Aberdeen
COOPER. Wallace George	London, N.4
CRAIG, David Alfred Finch	New South Wales
CRYER, Frank Stanworth	Liverpool 23
DAVIS, Harry	Birmingham
DAYNES, Herbert Cecil	Manchester
DICKMAN, Matthew Colin	Johannesburg
DILL, Robert Munro	Glasgow
DIXON, Graham James	Epping, Essex
DOUGHTY, George William Edward	Highley, Worcs.
EAST, Alexander Maurice	Grays, Essex
ECCLES, Claude Llewellyn	Paignton
ELLERTON, George	Liverpool
ELLIS, Donald John	Swindon, Wilts.
FRANKLIN, Roger John F.	Richmond, Surrey
GILL, Owen John	London, W.14.
GOLDSTEIN, Morris	Winnipeg, Canada
GREENE. Robert Emile	Newcastle-on-Tyne, 3
HALL, Thomas Charles	Canberra, Aust.
HARRIS, Philip Arthur Lester	Paignton
HAUGHEY, Patrick Joseph	Co. Armagh
HELM, Frank	Harrogate
HEMMING, William Charles	Liverpool, 11
HEYS, Eric	Stretford, Lancs.
HIGGINS, Thomas Francis	Birmingham, 21
HINDLEY, Frederick Gilbert	Northwich, Ches.
HONIATT, Robert William Roy	Hounslow, Mddx.
HORWOOD, Albert William, F/Lt.	Edgware, Mddx.
INGOLDSBY-BROWN, Frederick Searle	New South Wales
INSTONE, Allan Arthur	Cheltenham
KEMSLEY, John William Herbert	Hastings
KRAICER, Alec	London, N.W.3
LAKE, Francis Murray	Bedford
LAPIN, Joseph	Port Elizabeth.
LEES, Geoffrey Noel	London, N.W.1
MACKAY, Archibald John	Glasgow, S.4.
MAJOR, Richard James	Bridport
MANN, Francis Charles	Leigh-on-Sea
MARRIOTT, Martin George	Totteridge, N.20
MIDDLETON, Eric John	Johannesburg
MORRIS, Douglas Arthur	Birmingham
MORRIS, John Bernard	Newbridge, Mon.
MOUNTJOY, Vaughan Briscoe	Auckland, N.Z.
MURTAGH, Patrick Joseph	Co. Cavan
NADLER, Joe	London, N.W.11
NAWIESNIAK, Jau Augustyn	London, N.19
OLDFIELD. Roy Eric	New South Wales. Aust.
O'REILLY, Gerald Gabriel	Dublin
PARTRIDGE, Jack Edward	Wellingborough
PATERSON, John	Alloa, Scotland
PATERSON, John Lindsay	Scopwick, Lincs.
PEARCE, Richard John	Shrewsbury
PELOW, James George	Dublin
PETRIE, Albert Bruce	Glasgow, W.3
PITTENDRIGH, Lenus Walter Duff, S/Ldr.	Edgware, Mddx.
PRIOR, Reginald Howard William	Sturry, Kent
PROCTOR, Antony Charles	London, N.W.9
PUGH, Jonathan Edward T.	Llanidloes, Mont.
RIDGWAY, Harry	Oswestry, Salop
ROBILLARD, Philippe A., Lt.	Montreal, Canada
ROSENBERG, Louis Jack	Victoria, Aust.
ROWE, Harry Shaw	Dalton-in-Furness
ROWLES, Arthur Leonard	Colchester
RUTTER, Frank	Coventry, War.
SAMUELS, Lloyd Phillip	Jamaica, B.W.1
SCHOFIELD, Jack	Retford, Notts.
SCOTT-SMITH, Harold Michael	Hexham, Northumberland
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ENGINEERING METHODS IN THE DESIGN OF THE CATHODE RAY TUBE

by

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SUMMARY

This paper discusses the application of the general theories of scale, dimensional homogeneity and energy conservation to cathode ray tube designing. From these simple bases it is shown that many important deductions can be made about the general form which the tube geometry should assume. There is no appeal to advanced electron-optics, and the approach should therefore commend itself to the engineer.

LIST OF PRINCIPAL SYMBOLS USED

e = Electronic charge.

m = Electron mass.

k = Constant of scale (linear size or voltage).

K_1 and K_3 = Initial velocities in axial and radial directions respectively.

K_2 and K_4 = Co-ordinates of point of emission.

V = General symbol for potential on bounding electrode.

ϕ = General symbol for potential at any point in space.

$\bar{\phi}$ = Height of negative potential hump necessary to just suppress emission.

V_c = Negative grid bias necessary to just cut off beam when anode voltage is V_a.

$V_c{}^*$ = Negative grid bias necessary to just cut off beam when anode voltage is zero.

V_1 = Potential at crossover point.

V_2 = Potential at image point.

A, B = "Constants of potential," functions only of the space co-ordinates.

λ = Scanning angle, i.e. angle between deflected ray and axis.

θ = Half angle of beam subtended by final anode hole at screen.

n_1 = Refractive index of crossover point.

n_2 = Refractive index of image point.

z = Distance measured along beam axis.

r = Distance measured from beam axis.

t = General symbol for time.

y_1 = Size of crossover.

y_2 = Size of image.

v = Distance from plane of equivalent focusing lens to image.

u = Distance from plane of equivalent focusing lens to object, i.e. crossover.

M = Geometrical magnification, i.e. v/u.

ρ, ρ' = Space charge densities.

x, y, z = Space co-ordinates.

X, Y, Z = Space co-ordinates in transformed system.

DEFINITIONS

Deflectional discrimination—

the ratio $\dfrac{\text{Sensitivity of deflection}}{\text{Spot diameter}}$

Electron-*gun*—That portion of the electrodes excluding the deflector system.

PART 1

FOUR BASIC RULES IN CATHODE RAY TUBE DESIGN

1.1. Principle of Voltage Similitude.

1.2. Principle of Geometrical Similitude.

1.3. Spot Size/Crossover Size Relationship.

1.4. Dependence of Crossover Size on Voltage on Crossover forming Electrode.

1.1. Proof of Voltage Similitude Principle.

1.2. Proof, etc.

1.3. Proof.

1.4. Proof.

1.5. Spot Size and Deflection Defocusing.

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PART 2

APPLICATION TO SPECIFIC PROBLEMS

General.

In the design of almost any scientific instrument there are two distinct lines of approach. The first consists of evolving a complete theory of the mode of operation of the device. This is the comprehensive way, which will yield the maximum of information, and will enable all aspects of designing to be done with rigour and exactitude. But the task of evolving such a theory is often difficult and, moreover, much of the information it will yield belongs more properly to the field of development and research than to routine design work. If one is content to deal with the latter only, much can be done by far simpler methods. These methods are not peculiar to any particular branch of scientific designing, but are based on quite general theories of scale, energy and dimensional homogeneity. One of their interesting features is that they require only a most rudimentary knowledge of the theory of the particular device to which they are being applied.

A very striking instance of this, familiar to most physics students, is the derivation of Poiseuille's equation relating to the flow of viscous liquids through pipes. Without any knowledge whatever of hydrodynamics, and by purely dimensional methods, it is readily shown that the volume of liquid discharged/unit time through the pipe is given by $V = K.p.r^{4+\beta}/l^{1+\beta}.\eta$, where p is the pressure difference, r is the pipe radius, l its length and η the coefficient of viscosity. An intelligent guess or simple experiment gives $\beta = 0$, whereas the derivation of this law from hydrodynamical principles is quite difficult. On the other hand, such an analysis yields the value of the constant K as $\pi/8$, about which the dimensional method gives no information at all. But the value of the constant could be easily determined by a *single* experiment following the dimensional analysis, so the power of the latter method is evident.

A very similar position occurs in cathode ray tube design. The methods which we shall now treat do not alone give any information as to how a design should proceed, but taken in conjunction with experimental investigation and prototype tubes, they do provide an easy basis for further designing. This approach is a useful complement to, but not a substitute for, a complete theory of the tube.

PART 1.

FOUR BASIC RULES IN CATHODE RAY TUBE DESIGN.

The following four rules form the basis of the "relaxation" methods of cathode ray tube design. The first three "rules" are really laws, and are quite rigorous within their limiting postulates. The fourth is merely a rule, which has some theoretical justification, but for which the main support is experimental.

1.1. Principle of Voltage Similitude.

In any electron optical system, in which space charge is neglible, *and in which the electrons start from rest*, the electron trajectory is unaltered by multiplication of *all* electrode potentials by a constant factor (k). The transit time between any two fixed points in the system varies as $\frac{1}{\sqrt{k}}$.

1.2. Principle of Geometrical Similitude.

In any electron optical system in which the total current flow is constant, the *shape* of the field and of the electron trajectory is unaltered by multiplication of the size of *all* the bounding electrodes by a constant factor (k). The transit time between corresponding points in the two systems is proportional to k.

1.3. Spot Size/Crossover Size Relationship.

If the crossover and spot are formed in regions of the same potential, then

Spot size = crossover size × geometrical magnification (M).

More generally, if V_1 is the crossover potential, and V_2 the spot potential, then

Spot size = crossover size × M × $\sqrt{V_1}/\sqrt{V_2}$.

1.4. Dependence of Crossover Size on Voltage on Crossover forming Electrode.

To a close approximation, in any system where the space charge is negligible, the crossover diameter is inversely proportional to the square root of the potential on the crossover-forming electrode.

The proofs of these four principles are discussed below.

1.1. Proof of Voltage Similitude Principle.

The proof of this principle is in two parts. Firstly, we prove in Appendix 1 that the *shape* of the field bounded by any electrode system is independent of the absolute magnitude of the potentials on the bounding electrodes, and depends only on their *ratios*. Note that this is true only when space charge is negligible. Since the *size* of the electrode system is postulated as constant, it immediately follows that the electric field strength, at any point, is proportional to the voltages on the electrodes.

Next, in Appendix 1 by integrating the equations of motion of an electron in an axially symmetrical field, it is shown that the *shape* of the trajectory is independent of the potentials on the electrodes. Note particularly that the theorem is true generally only when the electrons start from rest, since only then are the constants K_1 and K_3 equal to zero. A special case corollary, of importance in connection with deflector-plate theory, occurs when both K_1 and K_3 are proportional to k, for the theorem still holds in that case. (Physically speaking, this is the case where the "injection" volt velocity of an electron is raised in proportion to the rise of potential on the subsequent electrodes.)

Finally, from Appendix 1 we note that the transit time of an electron between any two fixed points is inversely proportional to $\frac{1}{\sqrt{k}}$, where k is the "scale" factor. Thus for instance, a multiplication of all electrode potentials by four results in a reduction of the transit time to one half its previous value. This result is of interest in connection with design problems at ultra high frequencies.

1.2. Proof of the Principle of Geometrical Similitude.

Again the proof of this principle is in two parts. Firstly, we establish in Appendix 2 the invariance of the geometrical *form* of the field shapes with change in the scale of the bounding electrodes. This principle holds even when the space charge is present, and is thus of extreme generality. The proof is based simply on the invariance of Poisson's equation with change of scale, provided $\rho' = \rho/k^2$, where, as usual, k is the scale factor. The condition $\rho' = \rho/k^2$ is merely an assertion that the *current* in the rays is constant.

Secondly, in Appendix 2, a transformation of the equations of motion into the enlarged co-ordinate system shows the identity of the transformed system, provided the new time scale is multiplied by k. Hence the transit time between corresponding points on the two systems is proportional to the scale constant k.

1.3. Proof of the Lagrange Law.

This law is also sometimes attributed to Abbé. A proof is given in Appendix 3. The only important point to note is that it holds only for paraxial rays. In point of fact this restriction is of far less consequence in electron-optics than in the light optical case for which the law was originally derived, since electron beams are in general far thinner, and make smaller angles to the axis.

1.4. Dependence of Crossover Size on Voltage.

This relationship is in no sense a law, but is a rule which appears to have useful accuracy over a wide range of voltages, and which appears to be largely independent of the form of the electrode system used to produce the crossover.

In Appendix 4 is given a justification for this form of relationship. Another justification, based on quite different reasoning, has been given by Langmuir[1] in his fundamental paper, as has been discussed by the present author.[2]

The primary evidence for the truth of this relationship is, however, experimental. Careful measurements have been made in these laboratories, over the range 900 to 4,000 volts, which show that the spot diameter varies as $1/\sqrt{V}$ to a close approximation. The spot diameter is here defined as that diameter corresponding to a current density of 1/5 that on the beam centre. The current distribution in the spot was measured by the method of slit scanning, first described by Jacob.[3]

1.5. Spot Size and Deflection Defocusing.

Before passing on to discuss the application of these principles to specific problems, we shall treat briefly some aspects of spot size and deflection defocusing.

Firstly, as regards spot size only, it is necessary to point out that any apparent inconsistency between principles 1.1 and 1.4 is resolved by the fact that the electrons from the cathode do not start from rest. If the initial emission velocity were zero, then principle 1.1 relating to voltage similitude would hold ; the crossover and spot sizes would be quite independent of anode potential, and this would be at variance with 1.4. In fact, however, the electrons have a Maxwellian velocity spread on emission, which means that both crossover (and therefore spot) sizes are finite, and are dependent on the accelerating potential in the way indicated in the analysis in Appendix 4 and elsewhere.[1, 2]

When the spot is deflected, it suffers distortion, the form of which varies widely. In all cases, however, the spot increases in area. This increase in area is due to the *distortions of the deflecting field*, i.e. to the geometry of the deflecting region. Hence, to this part of the deflected spot size, the principles of geometrical and voltage similitude hold. Thus, for instance, the *increase* in spot size on deflection (through constant angle) is not affected by anode potential. Hence, a tube with severe deflection defocusing is not improved by operation at increased anode voltages. Only the central focus is improved.

Appendix 5 expresses these facts in symbolic form.

PART 2.

APPLICATION TO SPECIFIC PROBLEMS

2.1. Elementary Applications of Principle of Voltage Similitude 1.1.

The following two very well known properties of the cathode ray tube are direct results of the principle of voltage similitude.

(1) If the *final* anode potential is multiplied by k, then the deflector plate voltages for equal spot displacements are also multiplied by k.

(2) If, in any electrostatically focused cathode ray tube, the potentials of *all* the accelerating electrodes except the focusing anode are multiplied by k, then the focusing anode potential must also be multiplied by k to maintain focus. In practice some *slight* deviation from this may be detected, and this is due either to space charge effects or possibly to shift of crossover position with variation of grid bias.

2.2. Applications of Principle of Voltage Similitude 1.1.—Prediction of Relative Triode Performance, Conditions at Cut-off.

Some prediction of, and justification for, the behaviour of the triode portion of the electron gun is given by application of voltage similitude. Caution is necessary, however, since the two basic postulates—namely, absence of space charge, and zero starting velocity for the electrons—are not wholly satisfied.

Consider, for example, the question of variation of cut-off voltage with variation of first anode potential. We know that the electrons are emitted with a Maxwellian velocity distribution, so that on an average they have some initial velocity. Hence it is reasonable to suppose that the emission will be suppressed by the creation of a small *negative* potential barrier in front of the cathode. Suppose that a potential $-V_c$ on the grid cuts off the triode when the anode potential is V_a, this cut-off being due to a small negative potential hump of height $-\bar{\phi}$. What can be predicted about the value of the grid bias necessary to cut-off the tube when the first anode potential is $k.V_a$? By voltage similitude a grid voltage of $-k.V_c$ will now create a negative barrier of height $-k.\bar{\phi}$. Now k is inherently positive, and if, furthermore, $k > 1$, then it follows that $-k.\bar{\phi} < -\bar{\phi}$, so that the triode *must* be cut-off under the new conditions. Thus it is *certain* that if a tube is just cut-off with the first anode voltage V_a and grid voltage $-V_c$, then it will be cut-off for all *higher* anode voltages, for which the modulus of the grid voltage is raised in proportion.*

We can, however, carry our predictions considerably further, as indicated by the following analysis. It is fundamental in potential theory that however complex a field may be, the potential at any fixed point in it is linearly related to each of the potentials existing on the bounding electrodes. Thus it follows that the potential at some fixed point on the beam axis in front of the cathode surface can be expressed as

$$\phi = A.V_g + B.V_a \qquad \text{.....(1)}$$

where A and B are constants depending only on the electrode geometry and the position of the point at which the potential is ϕ. Now suppose that the critical potential $\bar{\phi}$ necessary to just cut-off the triode is created by a grid potential of $-\bar{V}_c$ and an anode potential of $\bar{V}_a$. Then from (1)

$$\bar{\phi} = A.\bar{V}_c + B.\bar{V}_a \qquad \text{.....(2)}$$

We next multiply the anode potential by k, and we wish to determine the new grid potential which will maintain the same critical retarding potential $\bar{\phi}$ (and hence presumably will just cut-off the triode). Clearly, if V_c is this grid potential,

$$\bar{\phi} = A.V_c + B.k.\bar{V}_a \qquad \text{.....(3)}$$

and by equating (2) and (3) we readily obtain

$$V_c = \bar{V}_c - \frac{B}{A}.\bar{V}_a(k-1)$$

whence, dividing both sides by $\bar{V}_c$

$$\frac{V_c}{\bar{V}_c} = 1 - \frac{B.\bar{V}_a}{A.\bar{V}_c}(k-1) \qquad \text{.....(4)}$$

It will be noted that this last equation (4) incorporates the principle of voltage similitude. For if the required critical retarding potential $\bar{\phi}$ to just cut-off the triode were zero, then from equation (2) it follows that $A.\bar{V}_c = -B.\bar{V}_a$, whence substituting this latter relation in (4) yields $V_c/\bar{V}_c = k$. This, of course, is merely a direct application of voltage similitude, and could be predicted immediately without the analysis given.

The value of the full analysis incorporating both the principle of voltage similitude and the linearity concept of potential, as exemplified by (4), is that it permits a deduction to be made about the extent of the departure of V_c and V_a from proportionality, in terms of the grid voltage necessary to cut-off the triode when $V_a = 0$. For, dividing (2) throughout by $A.\bar{V}_c$ gives

$$\frac{B.\bar{V}_a}{A.\bar{V}_c} = \frac{\bar{\phi}}{A.\bar{V}_c} - 1 \qquad \text{.....(5)}$$

and using this relation (5) in (4) yields

$$\frac{V_c}{\bar{V}_c} = 1 - \left\{\frac{\bar{\phi}}{A.\bar{V}_c} - 1\right\}(k-1) \qquad \text{.....(6)}$$

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[*] We are here assuming no perturbations due to contact potentials.

Now consider the position when the first anode voltage V_a is zero. Let V_c^* be the negative grid voltage then required to suppress emission. Thus, from (2), putting $V_a = O$ gives

$$\bar{\phi} = A.V_c^* \dots\dots (7)$$

since in all cases regardless of the actual potentials on the grid and anode, the only criterion of cut-off is the creation of the same negative potential barrier of height $\bar{\phi}$. Substituting from (7) into (6) yields

$$\frac{V_c}{V_c} = 1 - \left\{ \frac{V_c^*}{V_c} - 1 \right\} (k - 1) \dots\dots (8)$$

Equation (8) is a remarkable deduction from such simple postulates. It shows that the V_c/V_a relation is uniquely defined, once the value of grid bias for cut-off without applied anode voltage is known. The only assumption made in its deduction is neglect of space charge. In view of the cut-off conditions this would seem quite reasonable.

Fig. 1 shows a sketch of the form of V_c/V_a the curve, deduced from equation (8). Direct experiment† has shown that this type of relation is followed in practice so closely that no deviations are detectable, within the measurement accuracy as limited by the difficulty of deciding when the triode is actually cut-off.

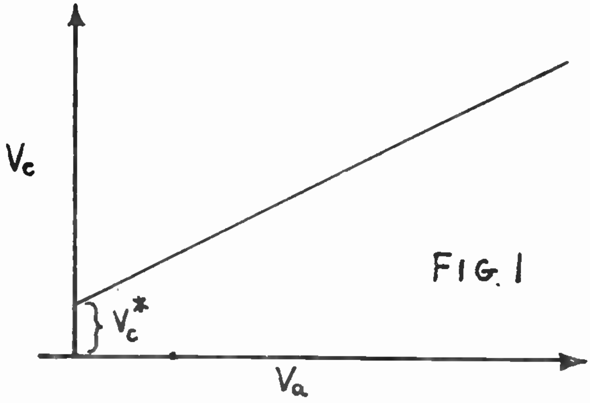

FIG. 1

2.3. Extended Applications of Voltage Similitude—Prediction of Relative Triode Performance—Conditions near zero Grid.

It is important to have some knowledge of the way in which the cathode current of any C.R. tube depends on the first anode voltage, for a specified grid potential. For the moment we will restrict the investigation to the case when the grid potential is zero.

The usual method of computing the form of the required relation is to solve the reduced Poisson's equation, as was first done by Childs for the case of the planar diode. In this case, and also in one other of practical importance—namely, the cylindrical diode—the problem is relatively easy, since the reduced form of Poisson's equation presents no difficulty. But in our problem the position is much more serious, for we are confronted with the difficulty of solving a three-dimensional form of the equation in which the only simplification lies in the fact that the field distribution possesses rotational symmetry. In fact the equation is

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}.\frac{\partial V}{\partial r} + \frac{\partial^2 V}{\partial z^2} = 4.\pi.i\sqrt{\frac{m}{2.e.V}} \dots\dots (9)$$

which is not very hopeful.

But consider the following chain of reasoning. From the fundamental definition of potential we may write

$$\phi = \underset{\text{volume}}{\int \frac{\rho d\sigma}{r}} + \underset{\text{anode}}{\int \frac{\sigma dS}{r}} + \underset{\text{grid}}{\int \frac{\sigma dS}{r}} + \underset{\text{cathode}}{\int \frac{\sigma dS}{r}} \dots (10)$$

(10) merely expresses the fact that the potential ϕ at any fixed point in the field of the triode is equal to the sum of the potentials due to the volume distribution of charge, and to the surface distributions on the three bounding electrodes. Now consider the position when no space charge is present, when the anode potential is V_a and the grid potential zero. From equation (1) we see that the potential is then expressible in the form $\phi = B.V_a$. But under these conditions a certain charge distribution exists on the bounding electrodes, and the resulting potential is expressed by the sum of the last three terms of equation (10). Hence we may rewrite (10) in the form

$$\phi = \underset{\text{volume}}{\int \frac{\rho d\sigma}{r}} + B.V_a \dots\dots (11)^*$$

At first sight this does not seem helpful, but we now recollect that in all these derivations of the saturated emission/voltage law, we make the fundamental postulate that the mechanism of the emissive process is such as always to maintain zero potential gradient at the cathode surface. Differentiating (11) therefore with regard to z, and equating to zero gives

$$O = \frac{\partial}{\partial z}\int \frac{\rho d\sigma}{r} + B_1.V_a \dots\dots (12)$$

Note that voltage similitude is the justification for the form of the second term in (12). This latter equation indicates proportionality between ρ and V_a, for zero cathode gradient. Hence the important conclusion—*in any space charge limited device in which the cathode potential gradient is zero, the total space charge is proportional to the anode voltage.*

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* Experimental evidence to be presented in author's paper, "The Electron Gun of the Cathode Ray Tube," Part 2. See Fig. 14. (See Vol. 6, *J.Brit.I.R.E.*)

* This equation is interesting because it is homogeneous in V_a and ρ. Thus if both V_a and ρ are together multiplied by k the potential at any fixed point is also multiplied by k. This can be regarded as an extension of the principle of voltage similitude to the case where space charge is present. Cf. Appendix 1.

By application of the energy equation, $mv^2/2 = e\phi$ it immediately follows that the electron velocity at any fixed point in the field is proportional to the square root of the voltage, provided the electrons start from rest, or at most with relatively negligible velocities. Thus the current, which is the product of the space charge density and velocity (under steady state conditions), must vary as the 3/2 power of the anode potential.

Thus finally

$$I_c = K.V_a^{3/2} \quad (V_g = 0) \qquad \ldots\ldots (13)$$

where I_c is the total cathode current. This reasoning has not involved any special assumption as to the shape of the bounding electrodes.

2.4. Extended Applications of Voltage Similitude—Prediction of Relative Modulation Characteristic.

The conclusions that the cathode current varies as the three halves power of the anode voltage, and that the cut-off voltage is fairly closely proportional to the anode voltage have been adequately confirmed by experiment. Thus multiplication of the anode voltage by k also multiplies the cut-off by k and the cathode current at zero grid voltage by $k^{3/2}$. From this it immediately follows that for geometrically similar points on the grid base, the cathode current varies as $k^{3/2}$. By geometrically similar points is meant points which divide the grid base between zero and cut-off in the same ratio. Thus if the grid voltage were maintained constant, while the anode voltage were multiplied by k, the cathode current would certainly not increase by $k^{3/2}$, except in the special case where $V_g = 0$.

Table 1 summarises the main conclusions of the principle of voltage similitude as applied to the C.R. tube. The last row in the table follows immediately from energy conservation.

2.5. Application of the Principles of Geometrical Similitude.

Let *all* the dimensions of a C.R. tube be multiplied by k, while the operating voltages remain constant. Then by principle of geometrical similitude 1.2. the current remains constant, and the whole scale of the trajectories is multiplied by k.* The crossover diameter and spot diameter are multiplied by k; their density falls to $1/k^2$, as does also the cathode emission density, since the same current is being extracted from an area k^2 times as large. This last result can also be regarded as a consequence of the principle of dimensional homogeneity when applied to the system.

Table 2 summarises these questions.

2.6. Relaxed Geometrical Similitude—1.

More important applications of these ideas on scale theory involve what may be termed "relaxed" similitude, in which only certain portions of the tube are changed. This type of computation is exceedingly rapid, and frequently leads to conclusions of a general sort about the form a tube should take to meet a specified demand.

Table 3 shows a specific example, which shows in general the superiority of the large tube, at least so far as the performance towards the screen centre is concerned, We might further generalise by now imagining that the screen diameter is kept constant. Then the new (longer) tube has a much smaller scanning angle, so the increase in deflection defocusing is avoided, and the longer tube has a clear increase in deflectional discrimination for the same cathode loading and operating voltages. But there is a limit to this process, since Table 3 assumes small space charge at the screen. If this does not obtain, so that the spot size is dominated by space charge swelling, then the spot size is a linear function of the scale factor k, and the conclusions of Table 3 are invalid. This question was discussed very fully in another paper by the author[2] to which close reference should be made.

2.7. Relaxed Geometrical Similitude—2.

Table 4 illustrates a similar type of problem, from which we may draw the important conclusion that the performance of any tube in which deflection defocusing is small is continuously improved by reduction in the scale of the triode portion. The price paid is an increase of cathode loading. This process has been applied in practice during the war to obtain a very high performance tube, without increase in length or operating voltage.

2.8. Relaxed Geometrical Similitude—3.

In this section we investigate the general effect of keeping the form and size of all the tube between anode and screen constant, but multiplying the linear scale of the remainder by k. The anode hole diameter is also kept constant. Table 5 illustrates the results, and the following is the reasoning involved.

All dimensions of the triode are multiplied by k, hence the crossover size is also multiplied by k. But unlike Case 2.7, the crossover/anode distance is also multiplied by k, so that the magnification between crossover and spot is multiplied by $1/k$. Hence the undeflected spot size is unaltered.

Application of the principle of geometrical similitude also shows that for constant electrode voltages the total current is unaltered. But the anode hole has been postulated as being of constant size. Hence the beam current (i.e. current emerging from anode hole) is down to $1/k^2$ (approx.), assuming that the gun size is always sufficiently large to make the beam more than fill the anode hole. But again the cathode area is up k^2 times for the same cathode current. Hence the cathode loading is down $1/k^2$, i.e. in the same ratio as the beam current. Thus the net result is no gain in

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* The scale of the potential field is also multiplied by k, as can be seen from equation (11). For at corresponding points in the two systems the second term $B.V_a$ is constant. Let primed symbols refer to the transformed system. Since the current is constant, $\rho' = \rho/k^2$. Also $r' = k.r$, $d\sigma' = k^2.d\sigma$. Hence the first term in (11) is also constant, and thus ϕ is constant.

overall performance.* The focus conditions at the edge of the screen are clearly unchanged since the whole geometry of the deflecting region has been postulated constant.

At this stage it is desirable to issue a warning about drawing conclusions which are more far reaching than the postulates justify. Taken at its face value the foregoing reasoning would appear to imply that if the deflecting geometry of a cathode ray tube is maintained constant, then the actual size of the remainder of the gun has no effect, provided the gun size is adequate to fill the anode hole. But this conclusion has been based on certain postulates, one of which is that aberrations in the gun are independent of the physical size of the electrodes of which it is made. This is certainly not true without qualification. Experimental evidence shows that in general for a fixed final anode hole diameter, the aberrations of the final focusing lens decrease as the size of the lens increases, up to a certain point, at which further increases in size have little effect. Having regard to this fact, the practical conclusions of this section may be stated thus :

In any cathode ray tube of fixed deflecting geometry in form and size, an advantage is gained as the size of the *gun* section alone increases (final anode hole diameter constant), up to the point when the anode hole is fully filled *and* reduction of lens aberrations is negligible. Further increases in size have then no useful effect.

2.9. Relaxed Geometrical Similitude—4.

This illustrates the important effect of keeping the size and form of the whole electron gun (including focusing portion and deflector plates) constant, and multiplying the geometry of the screen end of the bulb by k. More accurately, the tube neck diameter is kept constant, and the derived tube is formed by merely slicing off the bulb, and thus multiplying the anode to screen distance by k. (Refer to Table 6.) Thus the new spot density at the screen centre is multiplied by $1/k^2$ for the same cathode loading, since the gun conditions are unchanged. If, as a usually justifiable first approximation, the relatively small distance between the anode and the centre of deflection is ignored, then for the same scanning angle the derived tube has a screen diameter multiplied by k.

Now consider the deflection defocusing. A direct application of geometrical similitude is inadmissible, since the deflecting region of the derived tube is not a scaled down replica of the prototype. But consider the following chain of reasoning, based on dimensional homogeneity.

Let R be the radius of the anode hole, d the anode to screen distance, and λ the scanning angle. For constant deflector plate size and geometry, the linear increase in spot size on deflection (refer to section 1.5) must be a function of R, d and λ. Thus

$$\text{Linear increase in spot size} = K.R^a.d^b.\lambda^c \quad \ldots. \quad (14)$$

But λ is a pure numeric without dimensions, and since the left hand side must have the dimensions of a length, it follows that $a + b = 1$.

In the present problem, the only variable is the anode to screen distance d. Hence the linear increase in spot size is proportional to d^b.

It is obvious that $a > 0$, and $b>0$. Thus $0 <b<1$

Thus if the anode to screen distance is multiplied by k, the linear increase in spot size on deflection through a constant angle is multiplied by k^b.

But here $0 < k < 1$. Therefore $k < k^b < 1$.

It is therefore certain that there will be some improvement in deflection defocusing. This improvement will tend to zero as $b \rightarrow 0$, and will tend to k times its original value as $b \rightarrow 1$.

A sensible first approximation would put $a = b = 0{\cdot}5$, so that the increase in spot size on deflection is multiplied by $\sqrt{k}$. This has been done in Table 6, which summarises the position.

The tube with the smaller screen size has a very marked superiority in central focus performance. The *absolute* quality of the edge focus *must* also be better than on the original tube. The relative quality of the edge focus *must* at best be slightly worse than on the original tube.

2.10. "Philosophy" of Design—the "Optimum" Tube.

While all the statements in the foregoing sections are correct within their postulates, they do not form a very coherent pattern, and it is difficult to see in what way they point so far as the "optimum" tube is concerned. This is natural enough, since a cathode ray tube is a perfect example of "co-ordinated compromises" in which improvements in one feature appear to involve loss of performance in some other. But we shall now show that there is in fact a general "pattern" which leads to the best type of design for most purposes.

The following postulates will be made, and it will be noted that these are essentially reasonable and practical.

(*a*) The cathode loading and final anode voltage are both fixed.

(*b*) The overall tube length is fixed.

(*c*) The screen diameter is fixed.

It has been clearly established that the general performance of a given *form* of tube improves as (*a*) and (*b*) are increased,[2] and as (*c*) is reduced. Our problem is to find the optimum form, in general terms.

Ultimately the design compromise breaks down into a contest between the central focus and spot density, and the permissible degree of deflection defocusing. In another paper by the present author[2] discussing the

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* For, by driving the tube more heavily the spot density would be restored.

fundamental work of Langmuir[1], it was emphasised that when space charge is negligible the undeflected electron spot density is proportional to $\sin^2\theta$ where θ is the semi-angle of the electron beam converging on the screen. Hence constant θ should ensure constant density.

Let R be the radius of the final anode hole, and let d be the anode to screen distance. Then since θ is very small. $\theta = R/d$. So far, therefore, as the central spot density is concerned, the designer has freedom to put the final anode in any position provided that R/d is constant. What deduction, if any, can be made about its optimum position ?

The whole answer to this question turns on the extent to which deflection defocusing varies with the scanning angle. Formal reasoning gives no answer to this last point ; $-\lambda$ in equation (14) is a pure numeric, so that nothing can be deduced from dimensional considerations about c. But common experience shows that deflection defocusing rises very rapidly with scanning angle, so that if deflection defocusing were expressible as a simple power function of the scanning angle, then $c > 1$. But is has been shown that $a + b = 1$. From this it immediately follows that multiplication of R and d by a constant (k) (so as to preserve constant θ), with corresponding reduction of the scanning angle λ to λ/k, results in reduced deflection defocusing.

Hence the general design procedure should be to make the anode to screen distance as large a fraction as possible of the total (fixed) tube length, and make the final anode hole as large as possible consistent with deflection defocusing.

Applying now the principles treated in section 2.8, the electron gun proper should be made sufficiently large to avoid aberration in the final lens.

Finally, applying the principles treated in section 2.7, the triode section of the gun should be reduced in scale to achieve the desired spot size.

These are the general principles behind the design of all-electrostatic cathode ray tubes of high performance and fixed length. It will be observed that this design technique not only ensures greatest focus uniformity, but also gives maximum deflector plate sensitivity and deflectional discrimination. The only exception to this principle would appear to be the case of high current, low voltage tubes which might become severely space charge limited at the screen.[2,4]

2.11. Application to the Problem of Projection Tubes.

Initial design investigations on the possibilities of projection tubes afford an interesting application of the various methods discussed. All the foregoing ideas are used, and the analysis is an excellent example of the scope and limitations of the methods.

Insert 1 on Table 7 shows the essential dimensions of a typical 15-inch direct viewing television cathode ray tube. This tube is regarded as the prototype. A justification of its form is irrelevant here—the dimensions have been arrived at by long experience as representing a satisfactory compromise. The operating figures are similarly the result of experience. It has been stressed that all the ideas in this paper deal with *relative*, not absolute, performance. Therefore we must start from some existing design. What inferences can be drawn about the dimensions and operating conditions of derived projection tubes which will give the same final picture quality ?

The essential point about the projection tube is that it is smaller, and thus avoids the fragile, rather expensive, and even dangerous large glass envelope. Hence the first obvious derived tube to investigate is a proportionally scaled down replica. Insert 2 shows this with a three to one linear reduction. which seems reasonable. For practical reasons the base only is not scaled down.

The first step is to decide on the postulates. It will be assumed that the cathode loading remains constant, which is quite reasonable. From this it immediately follows that the beam current in the scaled down tube can be only 1/9 of that of the prototype.

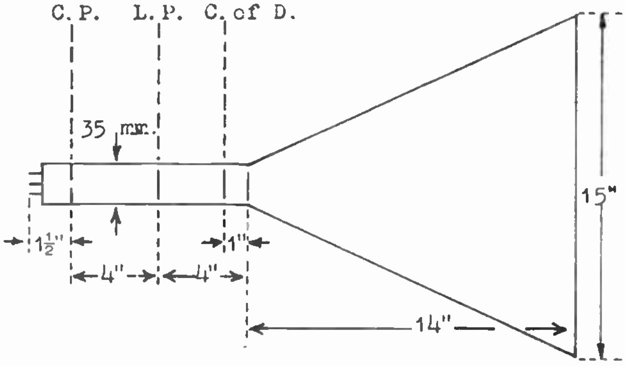
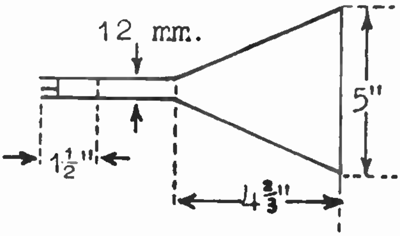
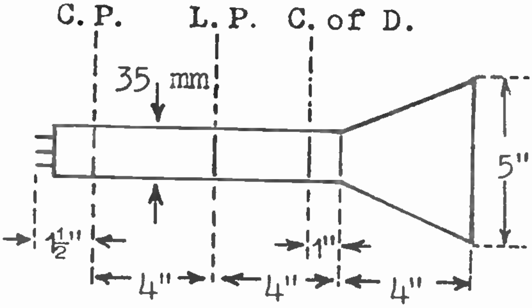
Next, in order to ensure equal *final* projected picture brightness, some assumption as to the efficiency of the projection lens system must be made. A figure of 20 per cent. is assumed, which can be achieved with a well designed Schmidt mirror system. Then if V_p, I_p are the beam voltage and current respectively in the projection tube, and V and I those of the direct viewing tube, the requirement of equal final picture brightnesses gives

$$.2\, V_p^2 . I_p = V^2 . I \qquad (15)$$

The screen brightness is here assumed to be proportional to the *square* of the beam voltage, which is a good working approximation. In (15) only V_p is unknown—its value works out at 54 k.V.

Next we investigate the picture definition. By geometrical similitude it immediately follows that if the anode voltage were unchanged, then the definition must also be unchanged. However, the anode voltage has been changed, and from section 1.4 it follows that the new spot size is multiplied by $\sqrt{\frac{8}{54}}$. Hence the scaled down replica will not give the constant picture quality required.

A solution involves application of the principles of section 2.7 and Table 4. The spot size is restored by multiplying the scale of the triode by $\sqrt{\frac{54}{8}}$. This then means that the cathode loading is only $\frac{8}{54}$ of that on the prototype. This suggests the current could be increased for the same cathode loading, so that the extreme voltage increase might be avoided.

	Final picture illumination	Efficiency of optical system	Anode voltage	Beam current	Cathode loading	Beam power	Screen loading	Scanning power	Final picture size
				Full white					
 1. 15″ DIRECT VIEWING TUBE	10 e.f.c.	100 per cent.	8 kV.	150 μA.	·35 Amp./cm.^{2}	1·2 watts	1·6 mW/cm.^{2}	18 watts	12 in. × 9·6 in.
 Triode portion only ⅔ scale. See text. 2. ⅓ SCALE PROJECTION TUBE	10 e.f.c.	20 per cent.	28·4 kV.	60 μA.	·35 Amp/cm.^{2}	1·7 watt	20·6 mW./cm.^{2}	21·3 watts	12 in. × 9·6 in.
 Gun section not reduced in size. 3. PRACTICAL PROJECTION TUBE	10 e.f.c.	20 per cent.	18 kV.	150 μA.	·35 Amp. cm.^{2}	2·7 watts	33 mW./cm.^{2}	40 watts	12 in. × 9·6 in.

C.P. = Crossover Plane. L.P. = Lens Plane. C. of D. = Centre of Deflection.

Defined performance in case (2) and (3) achieved in practice by alteration of cut-off voltage and grid drive. Cut-off voltage changed by change in cathode to grid spacing only. To be discussed in subsequent paper.

TABLE 7

To solve this problem, let *k* be the linear multiplying factor for the triode portion only. The remainder of the tube is, as before, multiplied by 1/3.

Inserting the values in Table 7, insert 1, the following equations will be found to obtain :

(1) Energy balance

$$.2\,V_p^2.I_p = 8^2 \times 150 \quad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

(2) Constant cathode loading (postulate)

$$I_p = 150.k^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

(3) Constant spot size

$$3.k = \sqrt{\frac{V_p}{8}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

Solving this system gives $V_p = 28.4$ *k*.V., $I_p = 60$ μA., k = 0.63. Thus, although the tube is reduced to one-third size, the triode portion is reduced only to approximately 2/3 of its previous value.

The remaining columns in Table 7, insert 2, are fairly obvious. The last column but one relating to scanning power depends on the fact that the latter varies direct as the anode voltage and neck diameter.

Another interesting solution for a derived tube begins with the method of section 2.9 and Table 6—by slicing off the bulb of the direct viewing tube. This approach is suggested by the large resulting increase in spot density without loss in spot size/screen size ratio. Although the final tube must be larger than that derived from a complete scaling-down, since the neck dimensions are unchanged, this does not matter much, because the major bulb volume is in the conical portion.

The reasoning to obtain the values shown in Table 7 is as follows.

Since the gun and deflector system is unchanged, a constant cathode loading requires the beam current to be unchanged. An energy equation as (15) then gives $V_p = 18$ *k*.V.

To investigate the definition, suppose for simplicity that the crossover size of the direct viewing tube were unity. Then the undeflected spot size of the latter would be 4.5. But the crossover size of the projection tube is down to $\sqrt{\frac{8}{18}}$ by section 1.4. The magnification of this tube is 2—thus the spot size on the screen is $2.\sqrt{\frac{8}{18}}$, and magnifying this three times by the projection lens gives the final picture spot size as

$$3 \times 2 \times \sqrt{\frac{8}{18}} = 4$$

This difference between 4 and 4.5 is hardly noticeable. Hence the definition at the screen centres is substantially the same.

The *relative* definition at the edges of the projection tube will be slightly worse by the reasoning given in section 2.9. It would be appreciably worse if the deflection defocusing on the prototype direct viewing tube were bad. In this case the calculations give only a very rough estimate of the position.

Acknowledgments

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APPENDIX 1.

1.1. PRINCIPLE OF VOLTAGE SIMILITUDE.

When space charge is absent, the potential at any point in space must satisfy Laplace's equation

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

or briefly

$$\nabla^2(V) = 0$$

Suppose that $V = f(x,y,z)$ is a solution of (1). Then it is clear that $V = k.f(x,y,z)$ is equally a solution, since

$$\frac{\partial^2 (kV)}{\partial x^2} = \frac{k.\partial^2 V}{\partial x^2} \text{ etc.}$$

Thus, $\nabla^2(kV) = k.\nabla^2(V) = 0$
since $\nabla^2(V) = 0$ by hypothesis

Note that this does not apply when space charge is present, since in this case Poisson's equation holds, and

$$\nabla^2(V) = 4.\pi.\rho$$

If this equation is satisfied by $V = \psi\,(x,y,z)$ it is not in general satisfied by $\phi = k.V$.

When space charge is negligible, the two fundamental equations defining the motion of an electron in an axially symmetrical field are

$$\frac{d^2 z}{dt^2} = \frac{e}{m}.\frac{\partial V}{\partial z}, \quad \frac{d^2 r}{dt^2} = \frac{e}{m}.\frac{\partial V}{\partial r}$$

If *all* electrode potentials are multiplied by k, these equations become

$$\frac{d^2z}{dt^2} = \frac{e.k.}{m}\frac{\partial V}{\partial z}, \quad \frac{d^2r}{dt^2} = \frac{e.k.}{m}\frac{\partial V}{\partial r} \quad \ldots\ldots\ldots(1)$$

Integrating each equation twice, *w.r.t.*, to obtain the displacements gives

$$z = \frac{e}{m}\iint k.\frac{\partial V}{\partial z}\,dt\,dt + K_1.t + K_2 \ldots\ldots\ldots(2)$$

$$r = \frac{e}{m}\iint k.\frac{\partial V}{\partial r}\,dt\,dt + K_3.t + K_4 \ldots\ldots\ldots(3)$$

K_1 and K_3 are the initial velocities in axial and radial directions respectively. Provided these are zero, $K_1 = K_3 = 0$. K_2 and K_4 are merely the co-ordinates of the starting point. They may be eliminated by shift of origin effected by writing $Z = z - K_2$, $R = r - K_4$. Making this substitution, and dividing (2) by (3) then gives

$$\frac{Z}{R} = \frac{f(t_1)}{\phi(t_1)} \text{ which is independent of } k.$$

$$t = \sqrt{k}.\, t_1$$

Hence the shape of the trajectory and its scale are independent of k.

APPENDIX 2.

1.2. PRINCIPLE OF GEOMETRICAL SIMILITUDE.

In general the potential at any point in space must satisfy Poisson's equation

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 4.\pi.\rho \quad \ldots\ldots\ldots\ldots(1)$$

Now suppose that the dimensions of all the bounding electrodes are multiplied by a factor k. Then any point (x,y,z) becomes transformed to a corresponding point (X,Y,Z) where $X = k.X$, $Y = k.y$, $Z = k.z$.

Transforming (1) then gives

$$k^2\left\{\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2} + \frac{\partial^2 V}{\partial Z^2}\right\} = 4.\pi.\rho \quad \ldots\ldots\ldots(2)$$

so that provided the new density $\rho' = \rho/k^2$ it follows that (1) and (2) are identical. Now suppose that electronic device being considered comprises some ray or beam, and that we twist the reference axes so that the beam axis lies along the z dimension. Then the condition $\rho' = \rho/k^2$ merely means that the *density* of the beam at right angles to its length has been reduced to $1/k^2$ of its original value. But the cross sectional area of the beam has increased by k^2 times. Hence the condition $\rho' = \rho/k^2$ implies that the total current in the ray has been kept constant. This proves the invariance of the field *shape* with change of electrode scale.

Next consider the fundamental equations of motion of an electron in an axially symmetrical field. Taking only the z-directed term gives

$$\frac{d^2z}{dt^2} = \frac{e}{m}.\frac{\partial V}{\partial z} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

using the transformation $Z = k.z$ as above, converts (3) into

$$\frac{1}{k}.\frac{d^2Z}{dt^2} = \frac{e}{m}.k.\frac{\partial V}{\partial Z}$$

which may be re-expressed

$$\frac{d^2Z}{dT^2} = \frac{e}{m}.\frac{\partial V}{\partial Z} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where $T = kt$. (3) and (4) are identical in form so that the trajectories are geometrically similar, but with a transit time k times as large in the transformed system.

APPENDIX 3.

1.3. LAGRANGE'S LAW.

Applying Snell's law to the ray YOY^1 (sketch) gives

$$\frac{\sin\theta}{\sin\alpha} = \frac{n_2}{n_1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

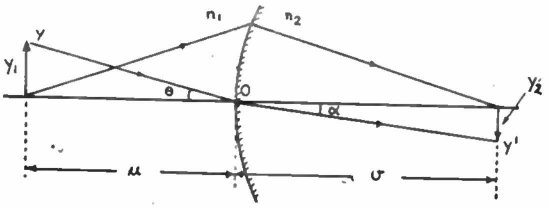
Again, since θ, α are small we may write

$$\sin\theta = y_1/u$$
$$\sin\alpha = y_2/v \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Substituting from (2) into (1) gives

$$y_2 = y_1 \cdot \frac{v}{u} \cdot \frac{n_1}{n_2} = y_1.M.\sqrt{\frac{V_1}{V_2}}$$

Note Postulate position of pole 0 fixed.



APPENDIX 4.

1.4. DEPENDENCE OF CROSSOVER SIZE ON VOLTAGE.

When space charge is negligible, the two equations of parametric form defining the electron displacement have been shown to be

$$z = \frac{e}{m}\iint \frac{\partial V}{\partial z}\,dt\,dt + K_1.t + K_2$$

and ....(1)

$$r = \frac{e}{m}\iint \frac{\partial V}{\partial r}\,dt\,dt + K_3.t + K_4$$

Here, K_1 and K_3 are the initial emission velocities along, and at right angles to, the beam axis respectively. K_2 and K_4 are zero if the origin of co-ordinates is taken to coincide with the point of emission. For the very high voltages used in cathode ray tubes,

$$\iint \frac{\partial V}{\partial z}\,dt\,dt >> K_1.t$$

Again, for an electron starting on the beam (z) axis, $\frac{\partial V}{\partial r} = 0$ initially, and since its distance (r) from the beam axis is always small, it is perhaps justifiable to write

$$\iint \frac{\partial V}{\partial r}\cdot dt\,dt << K_3.t$$

Hence, equations (1) degenerate into

$$z = \frac{e}{m}\iint \frac{\partial V}{\partial z}\,dt\,dt \quad \text{......................(2)}$$

$$r = K_3.t \quad \text{..............................(3)}$$

If we now assume that $\partial V/\partial z$ is constant over the very short axial distance involved, we may put $\partial V/\partial z = k.V$, where V is the voltage on the crossover-forming electrode. Integrating (2) then yields

$$z = \frac{e}{m}.k.V.t^2/2$$

whence for constant z (fixed cathode-crossover distance), $t = K/\sqrt{V}$ and thus substituting in (3) $r = K/\sqrt{V}$ at the crossover.

APPENDIX 5.

1.5. SPOT SIZE AND DEFLECTION DEFOCUSING RELATIONS

Effective magnification between crossover and spot

$$= M.\sqrt{\frac{V_1}{V_2}}$$

where M is the "geometrical magnification" and equals v/u. Thus if y_1 is the crossover size, the size of the undeflected spot is

$$S_{undeflected} = y_1.M.\sqrt{\frac{V_1}{V_2}} \quad \text{................(1)}$$

But we have shown that $y_1 = K/\sqrt{V_1}$. Thus substituting in (1)

$$S_{undeflected} = k_1/\sqrt{V_2} \quad \text{..................(2)}$$

By experiment we find that when the spot is deflected it increases in size, and also that this increase in "size" is a function of the deflecting geometry (G) and the angle of deflection (λ). Thus we may write for the deflected spot size

$$S_{undeflected} = k_1/\sqrt{V_2} + k.f(G,\lambda) \quad \text{.........(3)}$$

where k is a constant of scale. Note that $(G,\lambda) = 0$ when $\lambda = 0$. Note that only the first term of (3) is a function of anode voltage. Hence if $k.f(G,\lambda) > k_1/\sqrt{V_2}$ (severe deflection defocusing) little improvement is made by raising V_2.

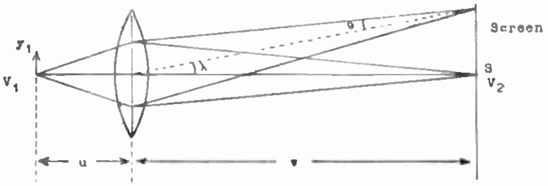


TABLE 1

APPLICATION OF VOLTAGE SIMILITUDE

All Anode Voltages on Tube Multiplied by *k*

Total cathode current and beam current (zero grid or at corresponding point on grid base)	$\times\ k^{3}/^{2}$
Cathode loading, ditto	$\times\ k^{3}/^{2}$
Beam power	$\times\ k^{5}/^{2}$
Screen loading (watts/cm.²)	$\times\ k^{5}/^{2}$
Crossover and undeflected spot size	$\times\ 1/\sqrt{k}$
Increase in spot "size" on deflection	$\times\ 1$
Ratio of new to original deflected spot size	$\dfrac{f(G,\lambda) + a/\sqrt{k}}{f(G,\lambda) + a}$
Current density in undeflected spot	$\times\ k^{5}/^{2}$
Sensitivity of deflection (mm. per volt	$\times\ 1/k$
Deflectional discrimination	$\times\ 1/\sqrt{k}$
Electron transit time	$\times\ 1/\sqrt{k}$
Screen brightness assuming screen powder has square law response to voltage, and linear response to current density	$\times\ k^{7}/^{2}$

Note that although the magnification ($M = v/u$) is constant, the ratio, current density in undeflected spot/cathode loading, has increased k times. This corresponds exactly to the optical analogue—image brightness = object brightness multiplied by the ratio of the squares of the refractive indices of image and object spaces.

Note also the rapid increase in raster brightness with anode voltage.

TABLE 2

APPLICATION OF GEOMETRICAL SIMILITUDE

All Dimensions Multiplied by k

Beam and cathode currents	$\times\ 1$
Beam power	$\times\ 1$
Cathode loading	$\times\ 1/k^2$
Crossover size	$\times\ k$
Magnification (M)	$\times\ 1$
Undeflected spot size	$\times\ k$
Increase in spot size on deflection	$\times\ k$
Ratio of new to original deflected spot size	$\dfrac{k.f(G,\lambda) + k.a}{f(G,\lambda + a} = k$
Current density in spot	$\times\ 1/k^2$
Screen size (linear)	$\times\ k$
Sensitivity of deflection	$\times\ k$
Deflectional discrimination	$\times\ 1$
Electron transit time	$\times\ k$

Note there is no fundamental gain in performance. The spot density and cathode loading are equally affected, and there is no gain in deflectional discrimination.

TABLE 3

RELAXED GEOMETRICAL SIMILITUDE—1

Suppose that in any cathode ray tube, the triode portion is maintained of constant size, but that *all* remaining dimensions are multiplied by k. Determine the main features of the new tube.

Beam and cathode currents at same grid voltage	$\times\ 1$
Beam power	$\times\ 1$
Cathode loading	$\times\ 1$
Magnification (M)	$\times\ 1$
Crossover size	$\times\ 1$
Undeflected spot size (space charge at screen assumed small)	$\times\ 1$
Increase in spot "size" on deflection	$\times\ k$
Ratio of new to original deflected spot size	$\dfrac{k.f(G,\lambda) + K}{f(G,\lambda) + K}$
Screen size (linear)	$\times\ k$
Sensitivity of deflection (mm. per volt)	$\times\ k$
Deflectional discrimination (near screen centre)	$\times\ k$
Screen brightness for same relative scan	$\times\ 1/k^2$

Provided that the deflection defocusing on the original tube was small, we conclude that the derived tube will have a resolution k times as large.

TABLE 4

RELAXED GEOMETRICAL SIMILITUDE—2

Suppose that in any cathode ray tube the dimensions of the triode portion are multiplied by k, all other dimensions remaining constant. Determine the main features of the new tube.

Beam and cathode currents at same grid voltage	$\times\ 1$
Beam power	$\times\ 1$
Cathode loading	$\times\ 1/k^2$
Crossover size	$\times\ k$
Magnification (M)	$\times\ 1$
Undeflected spot size	$\times\ k$
Increase in spot size on deflection	$\times\ 1$
Ratio of new to original deflected spot size	$\dfrac{f(G,\lambda) + a.k}{f(G,\lambda) + a}$
Screen size	$\times\ 1$
Sensitivity of deflection	$\times\ 1$
Deflectional discrimation (near sceen centre)	$\times\ 1/k$
Screen brightness	$\times\ 1$
Current density in undeflected spot	$\times\ 1/k^2$

Provided deflection defocusing in original prototype tube is small, the overall performance of the new tube improves continuously as the triode is reduced in size. Limit set by permissible cathode loading and mechanical tolerances.

TABLE 5

RELAXED GEOMETRICAL SIMILITUDE—3

All dimensions of the *gun* only in a cathode ray tube are multiplied by k, except for the anode hole which remains of constant size. The deflector plates, anode to screen distance, screen diameter, etc., remain unchanged. Determine the main features of the new tube.

Cathode current at same grid voltage	$\times 1$
Beam current ditto (see text, section 2.8)	$\times 1/k^2$ (approx.)
Beam power	$\times 1/k^2$ (approx.)
Cathode loading	$\times 1/k^2$
Crossover size	$\times k$
Magnification (M)	$\times 1/k$
Undeflected spot size	$\times 1$
Increase in spot size on deflection	$\times 1$
Ratio of new to original deflected spot size	$\times 1$
Screen size	$\times 1$
Sensitivity of deflection	$\times 1$
Deflectional discrimination	$\times 1$
Screen brightness	$\times 1/k^2$

Conclusion.—Within the postulates set out in the text (section 2.8), no fundamental improvement gained by increasing *gun* size beyond the point where the anode hole is filled.

TABLE 6

RELAXED GEOMETRICAL SIMILITUDE—4

A cathode ray tube is derived from an established design by moving the plane of the screen only, so that the new anode to screen distance is k times that on the original. Determine the main features of the derived tube.

Beam and cathode currents at same grid voltage	$\times 1$
Beam power	$\times 1$
Cathode loading	$\times 1$
Crossover size	$\times 1$
Magnification (M)	$\times k$
Undeflected spot size	$\times k$
Increase in spot size on deflection (see text)	$\times \sqrt{k}$
Ratio of new to original deflected spot size	$\dfrac{\sqrt{k}.f(G\lambda,) + a.k}{f(G\lambda,) + a}$
Screen size (linear, for same scanning angle)	$\times k$ (approx.)
Sensitivity of deflection	$\times k$ (approx.)
Deflectional discrimination (near screen centre)	$\times 1$
Current density in undeflected spot	$\times 1/k^2$

Conclusions.—Large increase in spot density without corresponding increase in cathode loading, effected by reducing anode to screen distance and screen diameter. *Absolute* focus quality *must* improve over *whole equivalent* screen area. Relative focus quality unchanged at centre, and may not be *appreciably* worse at edges if deflection defocusing is small. Indicates the merit of correctly designed tubes of small screen diameter.

LONDON DISCUSSION

Mr. J. Sharpe (communicated): Dr. Moss's survey of the methods used by C.R.T. designers in deriving tubes from an existing prototype contains many statements with which I disagree, but some of these are not concerned with the topics of similitude and dimensional homogeneity, and not all will be considered here.

Section 2.9, however, requires consideration from both of these aspects.

In equation 14, from which Dr. Moss has derived the whole of his argument on deflection defocusing variation with scale, the constant K has been assumed to be a pure numeric. Unfortunately, this constant includes the parameters of the actual deflectors under consideration, even though they are being kept constant in the particular equation. A simple consideration of the mechanism of defocusing with electrostatic deflectors shows that K has the dimensions (Length)$^{-1}$; $a + b$ then equals 2, and the simple theory shows that a and b are both equal to 1. The argument in the concluding paragraph 2.9 then falls to the ground. The ratio of derived to original spot size is then equal to k, whether deflected or not, and the definition is identical in the two cases.

The argument above is valid only on the basis of the assumption mentioned in the first paragraph of 2.9, namely, that the anode to screen distance is large compared with the distance from anode to centre of deflection. The deductions become precise, however, if the symbol R in equation 14 is made to refer to the beam radius at the deflectors.

The author has carried the assumption mentioned above into his derivation of the projection tube in Fig. 3 of Table 7, where it is not justified. As a result, the deflection defocusing characteristics of the tube will be very different from the prototype. The reason for this is quite different from that advanced by Dr. Moss, based on 2.9, from which he deduces that the prototype will be better than the derived tube. In actual fact, due to the larger angle of convergence of the beam in the shorter tube, the beam diameter in the deflecting region is *ca* 25 per cent. smaller than in the prototype, and the deflection defocusing (increase in spot size/screen diameter) will be better than the original.

In practical applications of similitude, the manipulation required to scale the tube up or down, while preserving the definition of the trace (spot size/screen diameter) constant at corresponding points of the screen, is rather more complicated than Dr. Moss has indicated. This will be dealt with in a forthcoming paper by Mr. Jesty and myself, in more detail than is possible here.

I have recalculated the projection tube shown in Fig. 3, Table 7, of the paper, to give a picture almost identical with the prototype. The lens plane is shifted to 1 in. from the centre of deflection, maintaining constant lens to crossover distance, so as to keep the beam width constant at the centre of the deflecting system, and preserve the same relative deflection defocusing. (There may still be a residual difference due to the fact that the width at the entrance to the deflectors will be *ca* 12 per cent. larger, and at the exit *ca* 14 per cent. smaller, than the prototype.)

The tube parameters now come out as follows :— Va 13·6 Kv. instead of 18 Kv., beam current 250 ua. instead of 150 ua. The triode is scaled up by a factor of 1·3, to keep the definition and current density constant. The beam angle from the triode is kept the same as in the prototype, so the cut-off voltage and drive are both increased by a factor of $\left(\frac{250}{150}\right)^{2/3}$ to allow for the increased beam current. The brightness, definition, defocusing and current density are the same in the prototype and in the picture projected from the derived tube.

(Incidentally, the fact that the definition comes out about right in the author's example seems to be fortuitous, as spot size does not enter into his calculation of voltage.)

The tube calculated above has the lens rather close to the coils, and in practice one would make a further modification. The lens could be pulled back to 3 in. from the centre of deflection as in Fig. 3, Table 7, and the triode, still scaled up by 1·3, would move to 5⅓ in. from the lens plane. A larger lens would probably be necessary to accommodate the wider beam without aberration. Other variations of the parameters are, of course, possible to suit practical conditions.

It will be seen that the differences due to the more precise evaluation are considerable.

Apart from the above, which bears directly on the similitude problem, there is one further point requiring mention.

In 2.2, equation 8 is stated to define the $\frac{Vc}{Va}$ relation from a single measure of cut-off without applied anode voltage. This appears to me to be attempting to define a line from a single point. Surely a further measurement of cut-off with anode volts applied is necessary to define the slope of the line in Fig. 1.

Dr. Van Den Bosch : Does ion bombardment of the cathode upset, in a practical sense, any of the calculations shown by Dr. Moss?

Mr. G. L. Hamburger : I have a question about the ion bombardment of the screen, which has very noticeable effects.

Owing to the heavier mass of the ion, magnetic deflection does not deflect the ion to the same extent as the electron and a patch forms in the screen centre. The spot is very circular with a beautiful rim and I should like to know why this spot is so very well defined.

Mr. J. Sharpe : The author mentioned early in his lecture the question of space charge. That is certainly one of the fundamental things to determine. It involves the aberration of the triode lens and to that extent can only be dealt with practically.

In connection with the measurements mentioned in section 1.4, which was kept constant — the beam current, the current density or the voltage ratios?

Mr. Shelton : I think the author might have made it clearer in his lecture that where the various " V "s occur, they are the volt velocities of the electrons at the cross sections considered, and not necessarily the electrode potentials. In attempting to assign some meaning to the voltage at which the crossover is formed, one must refer to the volt velocity of the electrons in that region. In some experiments I have made I find that the crossover is formed about halfway between the grid and the first anode.

The author has suggested that the brightness of the screen increases as the square of the voltage and linearly with the current. I should like to know over what range that was assumed, because published data do not quite agree with that.

With regard to experimental observation of deflection defocusing, I should like to describe an interesting technique which permits its examination without involving actual beam deflection. Suppose a 50-cycle voltage is applied to the X plates. You observe the width of the line and then connect both Y plates to one of the X plates. It is thus possible to superimpose deflection defocusing due to the Y plates on the X plate deflection without deflecting the beam within the Y plates.

REPLY TO THE LONDON DISCUSSION

Dr. Moss (communicated reply to Mr. Sharpe): I thank Mr. Sharpe very much for his contribution, and especially for his discussion on my working in section 2.9.

It is difficult to make a full reply, since I have not had the advantage of seeing Mr. Sharpe's own analysis of these problems. His forthcoming paper with Mr. Jesty is awaited with great interest. In the meantime I am a little worried as to how rigorous is his reasoning by which he deduces that $b = 1$. I give here further investigations on this point which appear to show that this is a reasonable value, so that since $a>0$, $K \neq 0$, and I am definitely in error in section 2.9. However, rigour is lacking as will be seen below.

Consider the deflecting system of Fig. 3 (*a*). It will be assumed that the deflectors are short in relation to their distance from the screen. 2R is the beam width in the deflectors, and *d* is the distance between their centre and the screen. (In the main body of my paper, R was defined as the anode hole radius or beam radius at the anode, and *d* as the anode to screen distance, because the working ignored the anode to deflector distance. However, there is here no reason so to restrict the theory.)

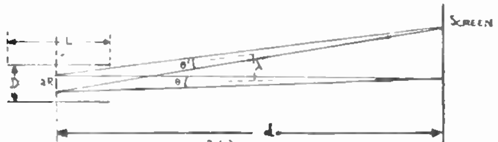


FIG. 3(a)

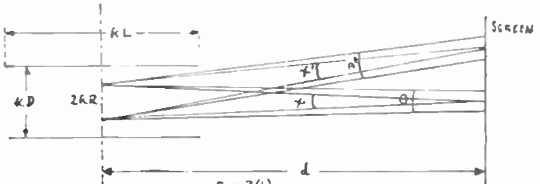


FIG 3(b)

Using the notation in Fig. 3 (*a*), the corrected equation (14) becomes

$$\text{Linear increase in spot size} = k.\mathrm{L}^{\alpha}.\mathrm{D}^{\beta}.\mathrm{R}^{a}.d^{b}.\lambda^{c} \quad (14a)$$

(In this equation we introduce the terms L and D, the deflector plate length and spacing, since we now no longer assume, a priori, that $\alpha + \beta = 0$.)

From (14a) it immediately follows that

$$\alpha+\beta+a+b=1 \quad \ldots\ldots\ldots\ldots (18)$$

Now suppose that every dimension *except d* in Fig. 3 (*a*) is multiplied by *k* (Fig. 3 (*b*)). Then since in geometrically similar figures the angles are preserved constant, it follows that the angles θ and θ' are unchanged. But to a close approximation the increase in spot size on deflection is clearly $(\theta \sim \theta').d$, and since *d* is constant, it follows that the deflection defocusing is also unchanged.

So far the argument is rigorous. But unfortunately the conditions described above are not quite those which obtain in practice. For, on scaling up the deflector region and maintaining *d* constant, we should have to alter the convergent angle of the beam to preserve focus. This is shown in Fig. 3 (*b*). The new convergent angles of the beam become (say) ψ and ψ', and the new increase in spot size is $(\psi \sim \psi').d$. *If now we assume that* $(\psi \sim \psi') = (\theta \sim \theta')$, then the deflection defocusing is unchanged by scaling up everything except *d*. Hence from (14*a*) and (18) it follows that $\alpha + \beta + a = 0$ and $b = 1$.

I shall be extremely interested in noting whether Mr. Sharpe's full analysis on the value of *b* avoids this assumption. It hardly appears possible, or otherwise we should have the remarkable result that the variation in the " dispersion angle " is independent of the angle of the beam on entry to the deflectors. Indeed, the identity of Mr. Sharpe's view seems contained in his sentence (" There may still be a residual difference due to the fact that the width at the entrance . . . etc.")

With this assumption, then, we reach the important conclusion that for constant scanning angle and deflector to screen distance, no increase in deflection defocusing occurs by widening the beam in the deflectors, *provided the deflectors themselves are scaled up in proportion.*

The argument in section 2.10 is substantially unaffected, except that as the deflectors are moved away from the screen their size is scaled up in proportion to the increase in beam width.

Finally, the seventh and eighth line of Table 6 becomes simply *k*. To avoid confusion, this table is repeated:

REVISED TABLE 6

RELAXED GEOMETRICAL SIMILITUDE—4

A cathode ray tube is derived from an established design by moving the plane of the screen only, so that the new anode to screen distance is *k* times that on the original. Determine the main features of the derived tube.

Beam and cathode currents at same grid voltage	× 1
Beam power	× 1
Cathode loading	× 1
Crossover size	× 1
Magnification (M)	× *k*
Undeflected spot size	× *k*
Increase in spot size on deflection (see text)	× *k*
Ratio of new to original deflected spot size	× *k*
Screen size (linear, for same scanning angle)	× *k*
Sensitivity of deflection	× *k*
Deflectional discrimination	× 1
Current density in undeflected spot ..	× $1/k^2$

Conclusion.—Large increase in spot density without corresponding increase in cathode loading, effected by reducing anode to screen distance and screen diameter.

It is to be carefully noted that Table 6 is based on the assumption that the deflectors are very close to the focusing lens so that variations in beam width can be ignored. Mr. Sharpe points out that this postulate is not always justified in practice, and although there is nothing wrong with my working for the derived projection tube (when the deflection defocusing conclusion in the final paragraph of 2.11 is modified by the foregoing reasoning) Mr. Sharpe's derivation is certainly preferable as being more exact. (Incidentally, the "coincidence" he refers to in my working is due to my having deliberately chosen values which fit. The full working is similar to that given in connection with No. 2 example of Table 7, and was not repeated on that account).

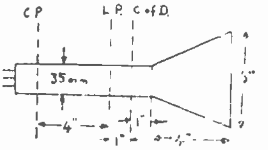


FIG. 4

I think it worth while to show the full reasoning which was probably used by him. Fig. 4 shows his derived tube geometry.

Following the notation used in section 2.11, we have

Energy balance

$$\cdot 2\, V_p^2 \cdot I_p = 8^2 \times 150 \quad \ldots\ldots\ldots\ldots (19)$$

Constant cathode loading

$$I_p = 150\, k^2 \quad \ldots\ldots\ldots\ldots (20)$$

Constant definition

$$\frac{4\cdot5}{3 \times \sqrt{8}} = \frac{1\cdot5\, k}{\sqrt{V_p}} \quad \ldots\ldots\ldots\ldots (21)$$

The solution of this system gives the values obtained by Mr. Sharpe, viz., $V_p = 13\cdot6$, $k = 1\cdot3$ and $I_p = 250 u$A.

Equations (19), (20) and (21) are exactly analogous to (15), (16) and (17) ; (21) differs from (17) merely on account of the change in magnification between crossover and spot.

It is desirable to say something about the way in which the performance defined by equations (19) to (21) can be realised in practice. It should be appreciated that the operations performed on the prototype tube described by the solution given, do not automatically enable the derived tube to give the desired performance. This can be seen by the following reasoning.

Suppose that the prototype 15-in. tube operates at a grid bias of $- V_g$ when giving the performance set out in Table 7. Mr. Sharpe's derived projection tube operates at anode voltage 13·6/8 times as high as that of the prototype. Since the beam width in the deflectors has to remain constant, it follows by voltage similitude that the grid bias for the derived tube would have to be $-\frac{13\cdot6}{8}\cdot V_g$.

(It will be noted that the scaling of the *whole* triode by the factor 1.3 does not alter the beam angle.) But by section 2.4, the current in the beam would now be $\left(\frac{13\cdot6}{8}\right)^{3/2} \times 150$ *u*A., whereas we require the current to be 250 *u*A. in order to satisfy equations (19) and (20).

The solution of this problem involves one fact which does not appear to belong to the province of similitude. If any two triodes identical in *all* respects, *except* in their cathode to grid spacings, are operated at different first anode potentials so that their cut-off voltages are identical, then to a close approximation their modulation characteristics, both in current delivered and in beam angle, are identical. Applying this fact to the problem we adjust the cathode to grid spacing of the derived tube so that the cut-off voltage at 13·6 kV. is $\left(\frac{250}{150}\right)^{2/3}$ times that of the prototype at 8 kV. The grid drive from cut-off is also multiplied by the same factor, so that the new current (section 2.4) is 250/150 of the original, for the same beam angle. This justifies Mr. Sharpe's reasoning. This additional property of the triode will be better appreciated after reference to my forthcoming paper on the "Electron Gun of the Cathode Ray Tube, Part 2." Suitable adjustment of cut-off by variation of cathode to grid spacing has also to be made for the derived tubes shown in Table 7.

This last paragraph tempts me to make one general comment. It is not desirable to try to base too much on the four rules outlined in this paper. I repeat my remarks at the beginning of the paper : "They are no substitute for a complete theory of the tube." Their real strength is apparent only when they are combined with a more detailed theory, and this will be attempted in my forthcoming paper.

The final point raised by Mr. Sharpe is due to a slip. The sentence he objects to should read : " It shows that the form of the *Vc*/*Va* characteristic . . . etc."

From the remarks of Dr. van den Bosch and Mr. Hamburger, it appears that I may have given the impression that the paper was more comprehensive than is in fact the case. It is intended as a survey of elementary design methods, but it was not intended to discuss how or whether the designs could be realised in practice. That is the second, and quite distinct, half of the problem. Until computations of the type discussed are made it is not possible to say whether any practical difficulties are going to arise. This fact adequately justifies the division of the subject of design into theory and practice.

The objections of Dr. van den Bosch and Mr. Hamburger are entirely valid, but do not belong to this part of the subject.

The circular ring due to ion burn mentioned by Mr. Hamburger is most probably a shadow of some masking aperture in the gun, or of the tube neck. It could also arise, although perhaps not quite so sharply, in the absence of any such shadowing, since the natural shape of the ion and electron beams emitted from the triode must be axially symmetrical and has a fairly well defined boundary.

Mr. Sharpe has stressed the necessity of remembering that in most of the reasoning involved, the space charge is ignored. I agree fully, and admit that caution is necessary in applying these methods in some types of problem. In connection with the experiments briefly mentioned in section 1.4, it was the beam current that was kept constant. I do not wish to enlarge on this here, for it is a very involved question and belongs to Part 2 of my paper on the " Electron Gun of the Cathode Ray Tube."

I thank Mr. Shelton for his remarks and agree about the significance of the " V "s. With regard to the screen brightness and its variation with impact velocity and current, I agree that one cannot always assume that the laws are as stated, although I think they are good engineering approximations, at any rate for sulphide materials, over the range 1-7 kV. I was mainly concerned, however, with illustrating the method. Equation (15) can be altered to suit any particular case if more accurate data is available.

I am interested in his method of observing deflection defocussing, but I think he will agree that it is a rather dangerous technique without further investigation, since the beam trajectory in the " Y " plate is quite different from that which obtains in practice. It would seem that it would be a little difficult to relate the results of his method to what actually happens.

Mr. T. D. Humphreys : It is a very great pleasure to me to be able to propose this vote of thanks. It has been my good fortune to have been associated with Dr. Hilary Moss and I was disappointed that during the discussion so many people have regarded the paper as being essentially associated with practice. I may be wrong, but I view it as being very largely a dimensional and geometrical consideration of cathode ray tube design. However, this does not detract from the excellence of the manner in which the lecture has been given, nor does it suggest that Dr. Hilary Moss is not equally aware of these unfortunate practical limitations.

NORTH-EASTERN SECTION DISCUSSION

The Chairman (Mr. H. Brennan) : I would like to congratulate Dr. Moss on his excellent lecture and the clear way he has shown that from simple bases important deductions can be made regarding the geometry of the cathode ray tube.

Mr. H. Armstrong : Could the general principles set out in the author's paper be applied to ordinary thermionic valves? If not, could they be applied to gas-filled valves, sometimes called thyratrons? Does the author believe that these dimensional methods can be applied by someone who is unfamiliar with the details of the particular device?

Mr. J. Moore : A brief description of Laplace's equation will, I feel, be of reference value in studying this paper.

The Chairman : What would be the highest electrode voltage that could be used in tubes without ion attack on the cathode becoming sufficiently serious to upset practical calculations? The second question is with regard to space charge. I am rather interested to know how to determine the degree of space charge, and can it be assumed as negligible? What is meant by origin distortion, and what are the remedies for it?

Mr. J. Hare : I understand that deflection defocusing was due to beam length, and that was why manufacturers shape the end of the screen as they do.

Mr. L. Parsons : I should think a curved screen would be better than a flat one. What is the advantage the Americans claim for a flat screen? What is the best size of television tube for direct viewing? I should also like to know what are the smallest clearances possible in the triode before its manufacture becomes uneconomic.

Mr. J. Bolam : What are the relative economics of projection and direct viewing systems?

Mr. E. Watts : Dr. Moss mentioned the fact that the spot size decreases in a small tube. A statement has been made that the spot size does not increase with screen diameter and that better definition can be obtained in larger tubes.

Mr. J. Finlay : I would like to ask some questions on the subject of trapezium distortion, particularly as explanations which have been given differ considerably amongst themselves.

Fleming-Williams[1] says that " the sensitivity of the plates nearest the *gun* (Y plates) is modulated by the potential applied to the other pair (X plates) but *the converse does not occur.*" He illustrates this point by a diagram of a television-type raster for a symmetrically applied scanning waves on both plates, in which, instead of a rectangular figure being obtained, the top and bottom edges slope towards the more positive X plate.

This would suggest that, providing the X plates

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[1] Fleming-Williams : " Trapezium Distortion in Cathode-Ray Tubes." *Wireless Eng.*, Feb., 1940 (17) 61-4.

were worked symmetrically, it would be immaterial whether the Y plates were supplied with a symmetrical signal or not. If this is true, then in tubes not specially corrected for trapezium distortion it would be good practice to apply a symmetrical time base to the X plates (nearest the *screen*) and allow of either type of working from the signal on the Y plates.

Parr[2] gives an example of trapezium distortion for the same conditions, but the shape is markedly different from that described by Fleming-Williams, and suggests that the sensitivity of *both* pairs is affected. Could Dr. Moss suggest under what conditions these differences arise?

It is sometimes stated that the effect of trapezium distortion is less in gas-focused tubes than in high-vacuum types because of the lower deflecting potentials used. Since, however, the anode voltage is correspondingly lower (thus giving the increased sensitivity), the ratio of deflecting to anode potentials is of the same order throughout, and this ratio is surely the critical factor. Is there not some other fundamental reason for the alleged lower distortion in gas-tubes?

REPLY TO NORTH-EASTERN SECTION DISCUSSION

Dr. Moss: I am not a valve designer and therefore hesitate to commit myself too definitely, but it is fairly certain that similitude and dimensional methods are very applicable to valve and thyratron design. With regard to Mr. Armstrong's next point, I think that the *calculations* themselves are easily made by relatively inexperienced engineers, but the interpretation and translation of the results into practice does require a wider background.

It is a little difficult to answer Mr. Moore concisely. In physics and engineering, we frequently study field problems in which a certain vector quantity (such as electric field strength, temperature gradient, stress in a medium, etc.) varies in some assigned manner over a region. In many problems of this type, the vectors describing the " field " have no " sources " or " sinks " *within* the field and Laplace's equation is a mathematical statement of this fact. For example, we are accustomed in elementary electrostatics to think of lines of force connecting point charges. The direction of the lines of force is the direction of the field, and the number of lines of force/unit area at right angles to their direction is proportional to the field strength. If we consider any element of volume within such a field, but so placed as to contain no charges, then no lines of force can originate or terminate within the volume. On expressing this fact in symbols we immediately obtain Laplace's equation.

In reply to the Chairman, I should not like to make any definite statement as to the highest voltage which can be used without involving severe ion attack on the cathode. There is no well defined limit. It is far more important to pump the tubes very " hard."

It is often quite easy to justify the neglect of space charge effects in these computations, although correction for their influence may be quite difficult. These points are discussed in my paper on the " Electron Gun of the Cathode Ray Tube," Part 1, and also in the *Wireless Engineer* for July, 1945.

Origin distortion is the name given to deflectional non-linearity in gas-focused cathode ray tubes. It can be remedied by a form of split deflector plate construction which is described in standard texts.

The old question of deflection defocusing and curvature of the screen face has arisen again. These things are not significantly related. Deflection defocusing is principally due to distortion of the beam in the deflectors, not to variation of anode to screen distance, because the depth of focus of the lens is very large. The curved screen is used mainly to provide mechanical strength.

This leads to Mr. Parsons' question. The Americans presumably prefer a flat screen because they consider it gives a better looking picture. I don't personally feel very strongly on this matter so far as television is concerned.

For direct viewing purposes in an ordinary sized living-room I think a picture about 12 × 9 in. is the optimum on the present 405 line system. Anything larger involves too great a viewing distance for domestic convenience.

With regard to triode clearance, this depends on the mechanical design employed. In our tubes we regard cathode/grid spacings of about 0·1 mm. as the minimum limit in view of the close tolerance involved.

Mr. Bolam raises a very big question, which cannot be adequately treated here. In any case, it is hardly fair to compare the economics of projection and direct viewing systems for pictures of larger size than about 13 × 10 in., since it is scarcely feasible to produce such images by direct viewing systems. In fact, if you do require a much larger picture size, the projection scheme is the only possibility, so that no question of comparison can arise. However, referring to my Table 7, which discusses the use of projection tubes to give final picture sizes equal to those obtainable on about the largest practical direct viewing tube, I think in general at present such a projection system would be far more expensive. In fact, almost the only point of the projection system of this miniaturised type lies in avoiding the large glass envelope of the direct viewing tube.

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[2] Parr: "The Cathode-Ray Tube" Chapman & Hall, 1943.

I am not very clear about the comments of Mr. Watts. My Table 3 appears to agree with his statement, but I must stress that a more exact definition of what factors are being varied is necessary before his comment has a very definite meaning. For example, on his statement my Tables 2 and 3 would appear to be mutually inconsistent, whereas in reality both are quite correct, only are based on different assumptions. It is hardly possible to stress sufficiently strongly that conclusions on the effect of geometrical changes on a cathode ray tube must never be separated from the postulates which attend the changes. Failure to appreciate this fact causes endless misunderstanding, even though there may be no real difference of opinion as to the underlying scientific facts.

I think Mr. Finlay is not quite correct in interpreting the article by Fleming-Williams as he does. Distortion of the *raster* shape may not be much improved by symmetrical working on the Y plates, but the spot distortions are thereby considerably minimised, or alternatively for an assigned amount of distortion a wider beam can be used. The great importance of this factor was discussed in my recent paper in this journal.

If, however, the signal voltage must be unbalanced to ground, then it is best to use the deflector plates in the way Mr. Finlay suggests. Unfortunately, for reasons of economy in commercially built oscillographs, the time-base voltage is frequently unsymmetrical and in this case it is immaterial from the point of view of trapezium distortion as to which way round the plates are connected.

I am quite unable to account for the shape of the raster given by Parr in his book. I have since learnt from him that he regards this diagram as due to an anomalous tube and therefore without special significance.

The assertion about reduced trapezium distortion in gas-focused tubes is new to me and I am not aware of any authority for this statement. Mr. Finlay is certainly correct in supposing that it is the ratio of deflecting potential to anode potential and not the absolute magnitude of these potentials which defines raster distortions. The raster shape and size are dependent on this ratio and not on the absolute magnitude of the voltages. I can suggest no reason at all why in general a gas-focused tube should possess less trapezium distortion than a high vacuum one, and I doubt the correctness of such a statement.

BOOK REVIEW

Radio Receiver Design, Part Two. By K. R. Sturley, Ph.D., B.Sc., M.I.E.E.

The second part of the author's book now completes a full and comprehensive work on radio receiver design.

The subjects discussed are: "Audio Frequency Amplifiers," "The Power Output Stage," "Power Supplies," "Automatic Gain Control," "Push-button, Remote and Automatic Tuning Control," "Measurement of Receiver Overall Performance," "Frequency Modulated Reception," "Television Reception." All these are treated in great detail, both the theoretical and the practical view points being well represented.

The last two chapters which alone cover 175 pages will be particularly welcome, as information on the technical aspects of frequency modulated reception and of television reception is not readily available.

Complicated formulae which, in our opinion, occur somewhat too frequently in Part One are used sparingly here.

The book should be extremely useful to the designer, without being too technical for the student.

E. Z.

A REPORT ON AERIAL AND EARTH FACILITIES FOR THE RECEPTION OF SOUND BROADCASTING IN PREFABRICATED HOUSES

Prepared by the Technical Committee*

Summary

The reception of sound broadcasting by radio depends upon the field strength of the required signal, the magnitude of any " static," the sensitivity of the receiver, and the efficiency of the aerial system.

For reception at " entertainment level " a high signal to noise ratio is required. This can more easily and more cheaply be obtained by the aid of a good aerial than by any other means.

In prefabricated houses as standardised by the Ministry of Works, the type of aerial system is dictated by structural considerations and cost. The two types of houses proposed are :

(a) Non-metal or metal framed houses.
(b) Metal-clad houses.

For the first type (a) the occupier must provide his own aerial facilities. An indoor aerial 15-20 ft. long has been found to be satisfactory.

For the second type (b), metal-clad, an external aerial is essential. For these houses, the Ministry of Works propose a 6 ft. rod aerial with an unmatched screened lead connecting the aerial to the receiver. Quantitative tests show that this unmatched lead introduces very considerable loss. It is thought that this loss will more than offset any hoped for advantage against " man-made static."

It is felt that an unscreened lead would give a better signal to noise ratio, but this can only be decided by more extensive tests.

Introduction

(1) Radio reception of sound broadcasting in the home is now taken as an essential part of social and cultural life by all classes of the community irrespective of wealth or geographical position. There can now be hardly a home in the country that has not some form of equipment for radio reception of sound broadcasting.

(2) This report is primarily concerned with radio reception in temporary houses. Suggestions are also made as to the lines which further investigation should follow in order that such reception should be satisfactory.

Controlling Factors in the Reception of Sound Broadcasting by Radio

(3) Satisfactory radio reception is mainly dependent upon the following four factors :

(*a*) The field strength of the required station in the particular area.

(*b*) The ratio, at the receiver input, of the required signal voltage to the voltage of any radio frequency interference.

(*c*) The sensitivity of the receiver to be used.

(*d*) The efficiency of the aerial system used, i.e. the height of the aerial ; its freedom from screening by buildings, trees, local topography, etc., its insulation from earth and the correct matching of the aerial system to the receiver.

Field Strength

(4) The field strength of any signal in any specified area is dependent upon many factors : distance, topographical and geographical position, meteorological conditions, etc., which are outside the control of the listener and the scope of this report.

Noise Interference

(5) The magnitude of any "noise" interference reaching the aerial is the factor that limits the useful sensitivity of the receiving set. It consists in part of static, that is, of radio frequency waves produced by natural causes, as, for example, storms, atmospheric disturbances, etc. The remainder of the "noise" received by way of the aerial consists of "man-made static" which produces radio waves or induces radio frequency voltages into the aerial system. Such "noise" is produced in many ways : by the opening and closing of switches in electrical circuits, by the sparking of commutators in electrical machinery, and in such

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* In December, 1944, the Council of the Institution gave the following terms of reference to the Technical Committee :—

(1) To examine the facilities provided for radio reception in temporary houses, in particular, the installation of aerial and earth facilities.

(2) To make recommendations as to the type and installation of such aerial and earth facilities as may be considered necessary.

During the course of their deliberations, the Committee paid visits to the temporary housing exhibition in London, organised by the Ministry of Works, to whom the Council wish to express their thanks for helpful co-operation.

domestic equipment as vacuum cleaners, hair driers, refrigerators, etc., and is especially strong in densely populated areas.

(6) Such interference is distributed more or less evenly over the whole of the normal broadcasting channels, and although certain valve operated devices have been developed to minimise such interference, the average broadcasting receiver is unable to discriminate between such interfering signals and the desired signal. Much can be done by suppressing such interference at its source, but until legislation is introduced to make such suppression compulsory, only the listener's own equipment can be so treated. The use of a screened lead from the aerial proper to the receiver confers a certain amount of benefit, but unless such a lead is correctly matched, both to the aerial and to the receiver, not only the noise but the required signal also is greatly attenuated.

Receiver Sensitivity

(7) The ultimate sensitivity of the receiver is limited by the "noise" that appears in the receiver output in the form of "hiss" (known as "random noise") when a completely interference free signal is applied to the input (i.e. with the receiver operating in a screened room and fed from a standard signal generator). It is the lumped total noise due to thermal agitation of the electrons in the input circuit "shot effect" in the plate of the input valve and the "noise" produced by the frequency changer.

(8) The magnitude of the noise in the receiver output is dependent upon the degree of amplification following the various "noise" producing networks. For a given sensitivity this noise output will vary according to the design and the circuit arrangement, being less when part of the total amplification is obtained prior to the frequency changer, i.e. when the receiver incorporates a high frequency amplifier stage.

(9) The use of a high frequency amplifier ahead of the frequency changer is not common practice so far as normal broadcast receivers for use with an outside aerial are concerned. This is due partly to the technical design difficulties involved, partly to economic reasons—a high frequency stage adding several pounds to the receiver selling price, but mainly because a good aerial system will provide signal input voltage to the frequency changer equal to, if not greater than, that provided by a high frequency amplifying stage fed from a poor aerial.

(10) In all cases, however, it holds true that for any particular receiver the noise increases as the receiver sensitivity is increased. Most of the receivers manufactured since 1935 incorporate some form of automatic volume control. By this means, the sensitivity of the receiver, and thus the noise, decreases as the strength of the input signal increases. In certain cases the receiver is so designed as to remain quiescent until the input signal reaches certain predetermined amplitude, thus ensuring a low level of output noise.

Aerial Efficiency

(11) The importance of the aerial system can now be appreciated. The more efficient the aerial the greater is the desired signal voltage applied to the receiver input, and consequently the lower is the amplification necessary for a given output. Not only is the "random noise" thereby decreased, but the interference output due to "static" (man-made or otherwise) is also decreased.

(12) *A good aerial system is therefore desirable, far more as a means of reducing the noise background to a received signal than as a means of increasing the range of the receiver.*

(13) Efficient aerial systems are not synonymous with the unsightly rows of poles and masts that disfigure so many residential areas. The structure of the normal house lends itself in many ways to an aerial installation, either indoor or outdoor, that is of reasonable efficiency without offending æsthetically.

Aerial Installations in Prefabricated Houses

(14) In the all-metal prefabricated houses such as the Portal, the Phœnix, the Spooner and the Airoh, some form of outside aerial is essential. Structural considerations impose serious limits on the weight that can be supported, and hence the height of such an aerial, whilst due to the density of grouping, poles or masts in the garden are debarred on æsthetic grounds.

(15) The Ministry of Works have therefore decided to equip such all-metal houses with a 6 ft. rod aerial mounted at the side of the house at the apex of the barge boards. A screened lead approximately 20 ft. long (also built in) connects the base of the aerial to an outlet socket which is located on a small panel adjacent to the power outlet socket at the side of the fireplace in the living-room. This screened lead is unmatched both to the aerial and the receiver. (Specified as Telcon type PT 1M, which has a capacity of approximately 20 ρF/ft.)

(16) An earth socket is also provided on this same panel connected to the earth pin of the three-point power outlet socket adjacent. This point is some 15 ft. from the true water pipe earth. It is noted that no lightning arrestor is fitted at the base of the rod aerial.

(17) In the non-metal or metal-framed houses, no aerial and earth facilities are being provided, and such arrangements are the concern of the occupier.

Tests

(18) The fact that with the rod type aerial a screened feeder cable is used, unmatched both to the aerial and to the receiver, gave rise to some doubts as to the efficiency of such a system, and quantitative tests were therefore carried out at a particular site in North London.

(19) The results of these tests are tabulated in the appendix.

(20) These figures show that the use of the unmatched, earthed screened feeder cable reduces the possible efficiency of the 6 ft. rod aerial over the medium wave band by an average of 20 db., and that the indoor aerial is better by an average of 6 db. over the medium wave band when compared to the most efficient performance of the specified rod aerial.

(21) It is emphasised that the figures given are the results of quantitative tests at one particular site with one particular receiver. It is, however, thought that they are indicative of the general behaviour of the two types of aerial tested. The loss due to the unmatched earthed screened lead will vary with the particular type of aerial input circuit incorporated in the receiver to be used and may, in some cases, be worse than the results quoted. It is considered doubtful whether any domestic receiver will show a material improvement upon these figures.

Conclusions

(22) It is understood that the production quantities of all these all-metal houses will run into many tens of thousands, and as it is considered that the present efficiency could be obtained at a lesser cost or that a considerable improvement could be obtained at the same cost, it would appear desirable for further investigation and measurement to be made into alternative positions and forms of aerial and an alternative method of connecting the aerial to the receiver. Possible lines along which such an investigation might proceed are given under the paragraph " Proposals for Further Investigation."

(23) Presumably, the screened lead has been specified to guard against interference due to "static" arising from the electrical equipment installed in the house and in adjacent premises. Taking into account the 20 db. loss in input signal voltage that results from the use of this screened unmatched lead, it is considered doubtful whether any such advantage will, in fact, be obtained. Indeed, it is not improbable that such interference will be found to have worsened.

(24) The method of obtaining an earth connection for the receiver from the earthy power supply conduit is also open to criticism on the grounds of the possibility of the common impedance causing interference. A direct connection from this earth socket direct to the earthed water pipe is to be preferred.

(25) In the non-metal or metal framed houses the conventional indoor aerial should, in general, be satisfactory. This aerial can conveniently take the form of an insulated wire some 15-20 ft. long attached to the beading at the junction of the wall and ceiling. The position of the receiver in the living-room of these houses is governed by the position of the power outlet sockets, of which there are two : one adjacent to the fire and one adjacent to the window. For the earth connection it may be possible to use the earthed conduit of the power supply, but in cases where this common impedance coupling introduces "noise" a lead should be taken to the nearest water pipe or direct to earth.

(26) *In the metal-clad houses, the proposed rod aerial and unmatched screened lead is considered unsatisfactory.*

Proposals for Further Investigation

(27) Investigations should be confined to a more efficient overall aerial system *within* the limits dictated by the structure and with due regard to the question of cost.

(28) With the specified design of rod aerial, an alternative form of aerial lead-in should be investigated ; an unscreened but insulated lead from the base of the aerial could be supported in the loft, passing into a conduit only for the run down the wall from the loft to the outlet socket.

(29) The degree of "man-made static" with these two types of lead-in should be investigated at least so far as the installed electrical equipment is concerned. If any particular piece of equipment is found to generate excessive "static," then the inclusion of a simple capacitative filter should be investigated. The cost of such a filter might easily be met by the saving due to the difference in cost between the screened and the unscreened lead.

(30) Alternative forms of aerial should be investigated as, for example, a straight wire parallel to, and, say, 3 ft. above the ridge of the roof, an unscreened lead-in being used, as suggested in paragraph 28.

(31) The technical and economic aspects of communal aerials for groups of prefabricated houses should be examined.

(32) It is desirable that all the above proposals should be investigated quantitatively in a typical metal-clad house surrounded on each side by one or more such houses. The local screening effects of adjacent houses might otherwise invalidate the performance figures taken in respect of alternative forms of aerials.

APPENDIX

QUANTITATIVE TESTS ON AERIAL EFFICIENCY TAKEN ON A SITE IN NORTH LONDON

These tests were carried out in North London in May, 1945. Measurements were made with four types of aerial system.

(*a*) A vertical rod aerial 6 ft long, the base being 7 ft. 6 in. above ground level, and connected to the receiver measuring set by 15 ft. of earthed screened cable having a capacity of 20·4 pF/ft.

(*b*) The same rod aerial at the same base height but connected to the receiver measuring set by 15 ft. of earthed screened cable having a capacity of 14 pF/ft.

(*c*) The same rod aerial at the same base height but connected to the measuring set by 15 ft. of unscreened but insulated cable.

(*d*) An indoor aerial approximately 15 ft. long, constructed in the form of an inverted L, Supported at a height of 6 ft. 9 in. above ground level and arranged clear of the walls and ceiling.

The above systems were not tested in metal-clad houses.

The receiving set consisted of a normal superheterodyne broadcast receiver fitted with automatic volume control (A.V.C.). The receiver was earthed in all the tests.

A meter was placed in the "earthy" end of the A.V.C. diode load resistance reading the rectified diode anode current and was calibrated in terms of the input voltage fed to the receiver input terminals from a standard signal generator.

Throughout the tests, the B.B.C. 668 kc/s and 877 kc/s programmes were used for measuring the relative efficiencies. This was considered a more practical method than energising the aerial under test from a local oscillator and less liable to error. The test results are tabulated below.

Types of Aerial System used	Equivalent Input Signal 877 kc/s	Relative increase db. Aerial A. taken as reference	Equivalent Input Signal 668 kc/s Service	Relative increase db. Aerial A. taken as reference
(*a*)	3·9	0	3·3	0
(*b*)	5·1	2·32	4·6	2·9
(*c*)	29·0	17·40	38·0	21·2
(*d*)	52·0	22·50	96·0	29·2

The figures given above represent subjective tests on one receiver only and in one locality. It is desirable that more comprehensive tests be carried out, particularly as regards the distribution of the total loss, i.e as to how much of the loss is due to the capacity potentiometer effect of the aerial and the aerial lead-in, and how much is due to the detuning effect of the first tuned circuit by the larged lumped capacity of the screened lead that is reflected into it.

Report on miniaturisation of radio sets and valves, and uses and possible applications of miniature equipment

The Technical Committee have now been requested by the General Council to draft a report under the above heading, and members of the Institution with special experience or knowledge of miniature radio equipment are invited to collaborate with the Committee. Comments and drafts should first be addressed to the Chairman of the Technical Committee, c/o the Institution.

NOTICES

Honours

Council congratulates Air Vice-Marshal R. S. AITKEN, C.B.E., M.C., A.F.C., on his appointment as a Companion of the Most Honourable Order of the Bath. Prior to this honour, Air Vice-Marshal Aitken had been mentioned in despatches and has been especially congratulated on his having been awarded the American Legion of Merit Medal for "exceptionally meritorious conduct in the performance of outstanding service."

Obituary

Council record with deep regret the death of Kenneth Ernest CLIFTON, of London, N.13 (Registered Student). Cfn. Clifton had served with R.E.M.E since 1942, and was killed in an Army accident on September 17th last. He was 24 years of age and recently succeeded in part of the Graduateship Examination of the Institution.

Overseas Members

Many members from overseas are now in England or are contemplating visits to Great Britain in the near future.

It would be appreciated if these members would communicate with the Secretary stating the date of their probable arrival or visit to the Institution as soon as possible after their arrival.

Such an arrangement will enable overeas members to receive full information regarding meetings of the Institution whilst they are in England, and in other ways take advantage of facilities which can be offered by the Institution and its members.

December Meetings

Programme cards giving full details of all meetings of the London and North-Eastern Sections up to and including May, 1946, have already been circulated to members in the respective areas. Further copies of these programme cards may be obtained on application to the Secretary. Other Section meetings for December are :—

Scottish Section : December 11th, 1945, at the Heriot Watt College, Chamber Street, Edinburgh 1, at 7 p.m.—a Paper by Professor M. G. Say, Ph.D., M.Sc., on "Ultra High Frequency Technique."

Midlands Section : December 14th, 1945, at the Birmingham Chamber of Commerce, New Street, Birmingham, at 6.15 p.m.—a Paper by S. G. Button on "U.F.H. Aerial Technique."

(Preprints of this Paper are available to members attending the meeting.)

GRADUATESHIP EXAMINATION

PASS LIST—MAY, 1945 (2nd List)

Passed Entire Examination

ZELINGER, Geza	Palestine
ORRIN, John Noel	Liverpool

Passed Parts 1, 2 and 4 only

CANNON, Charles W.	Clacton-on-Sea

Passed Parts 1, 2 and 3 only

ASKHAM, Leslie	Leeds

Passed Parts 1 and 2 only

BROWNE, Colin	Leigh-on-Sea

Passed Part 2 only

LIGHT, Thomas	Rochdale
SANDS, James Cunningham	London, S.W.15

Passed Part 3 only

MENZEL, Raoul	Tel-aviv
SEHPOSSIAN, Haig	Heliopolis

Extraordinary General Meeting

It is necessary to hold another Extraordinary General Meeting in connection with the proposed revisions to the Memorandum of Association. For the purpose of the special resolution necessary, an Extraordinary General Meeting will be held at the Institution, 9 Bedford Square, London, W.C.1, on December 21st, 1945.

Corporate members only are entitled to vote at the Extraordinary General Meeting, and notices have been circulated accordingly.

Subject and Author Index, 1939/1945

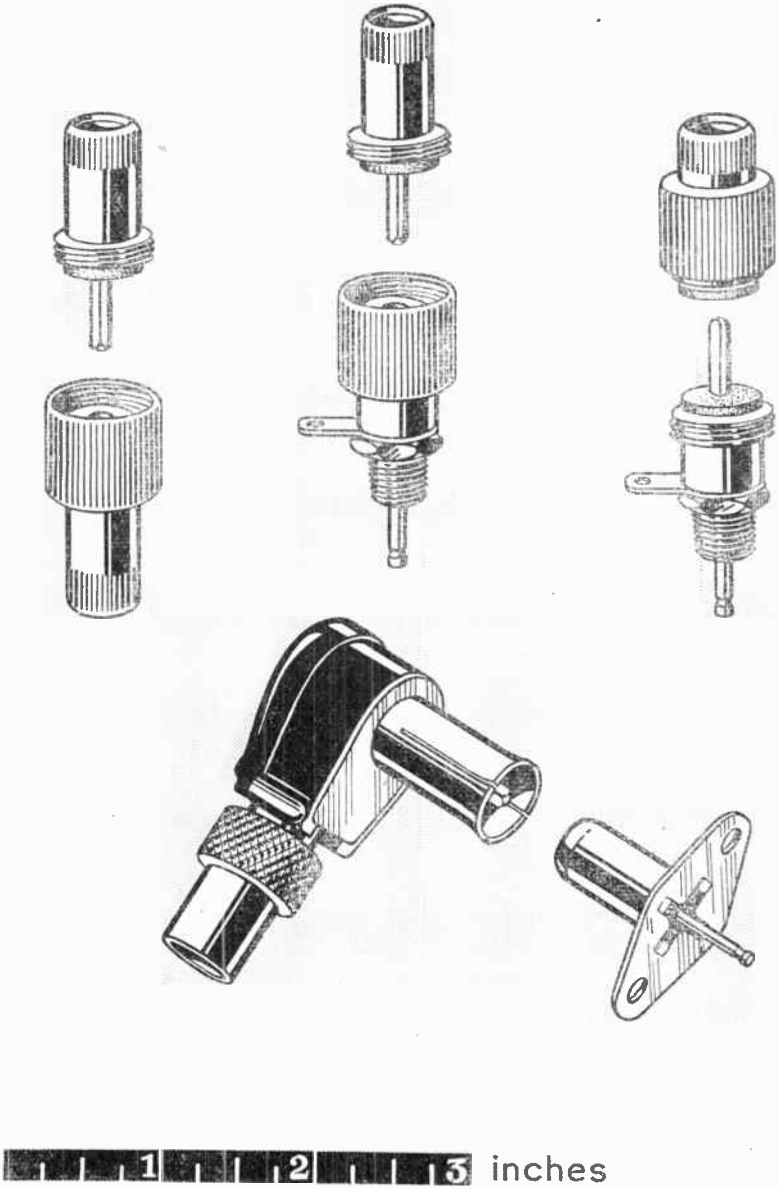
The Library Committee are publishing a Subject and Author Index covering all issues of the Journal since the outbreak of war, and this will be available to all members of the Institution in December.

This issue of the Journal is the last of the present volume, and members wishing to have the volume bound should return all five issues of 1945 to the Secretary with a remittance of 10s. 6d.

1946 Year Book

A revised Year Book is now being prepared for press and will include all new elections and changes of addresses up to the end of December, 1945. All grades of members are particularly requested to advise the Secretary of any Honours or other distinctions awarded during the year of which advice has *not* already been sent to the Institution.

Changes of address should only be in respect of permanent addresses and not temporary addresses.



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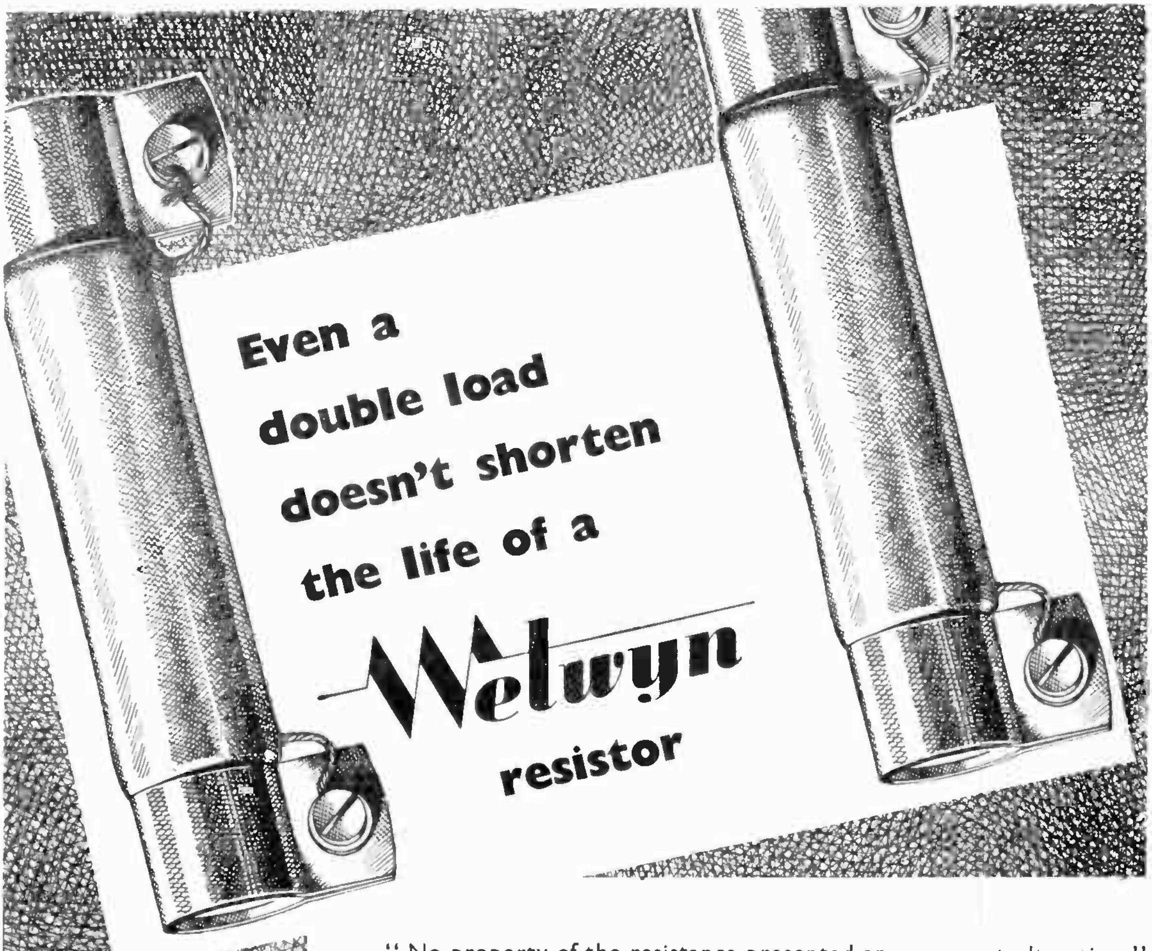
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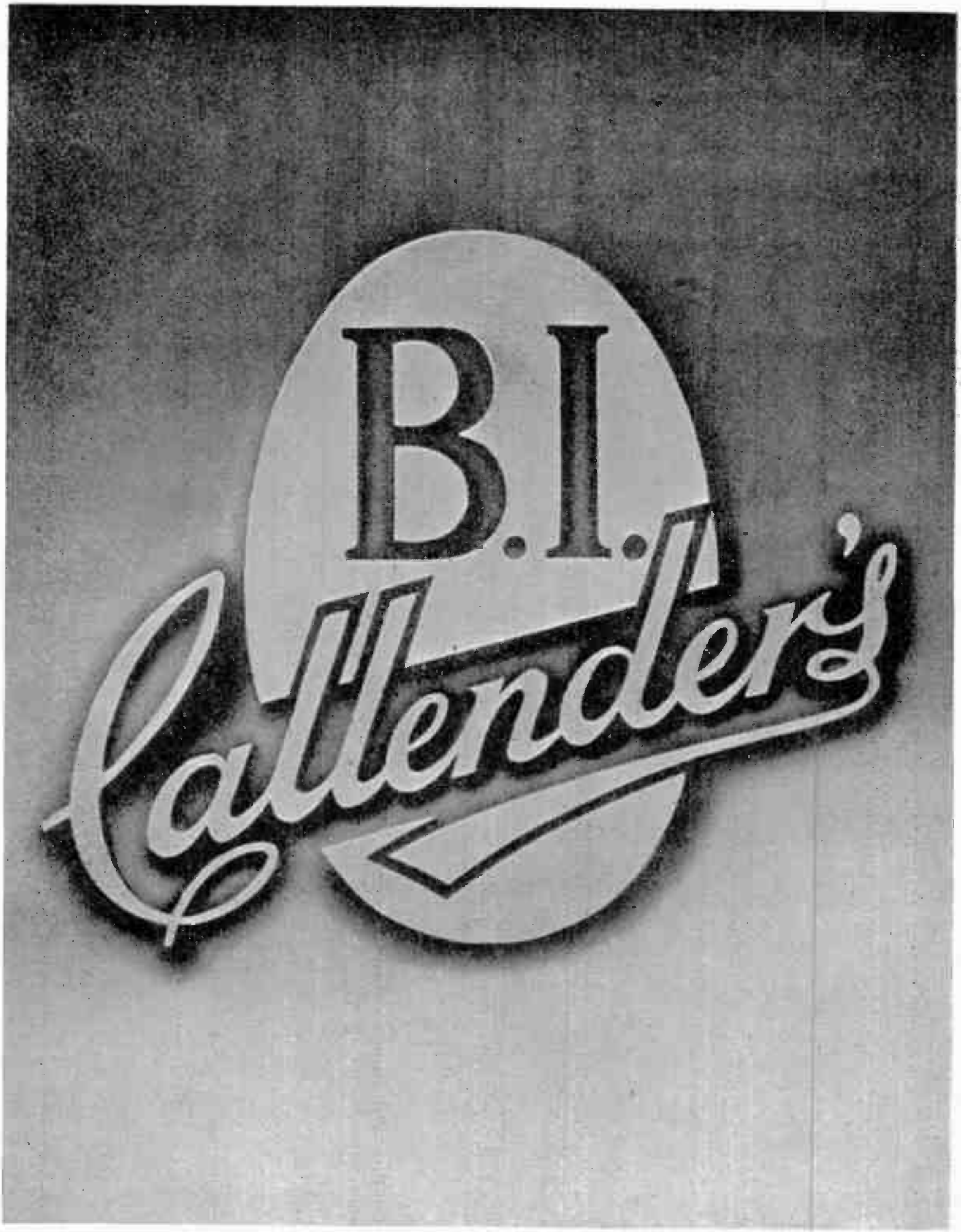
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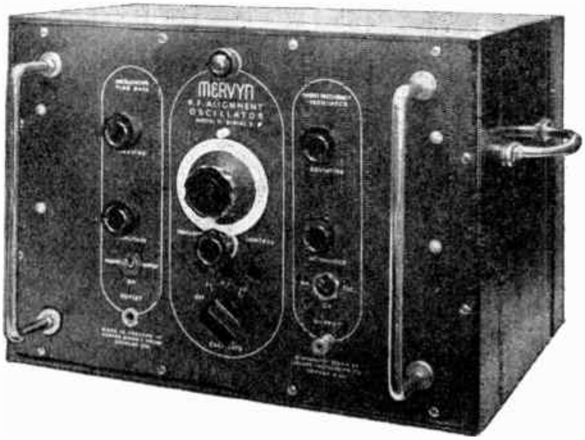

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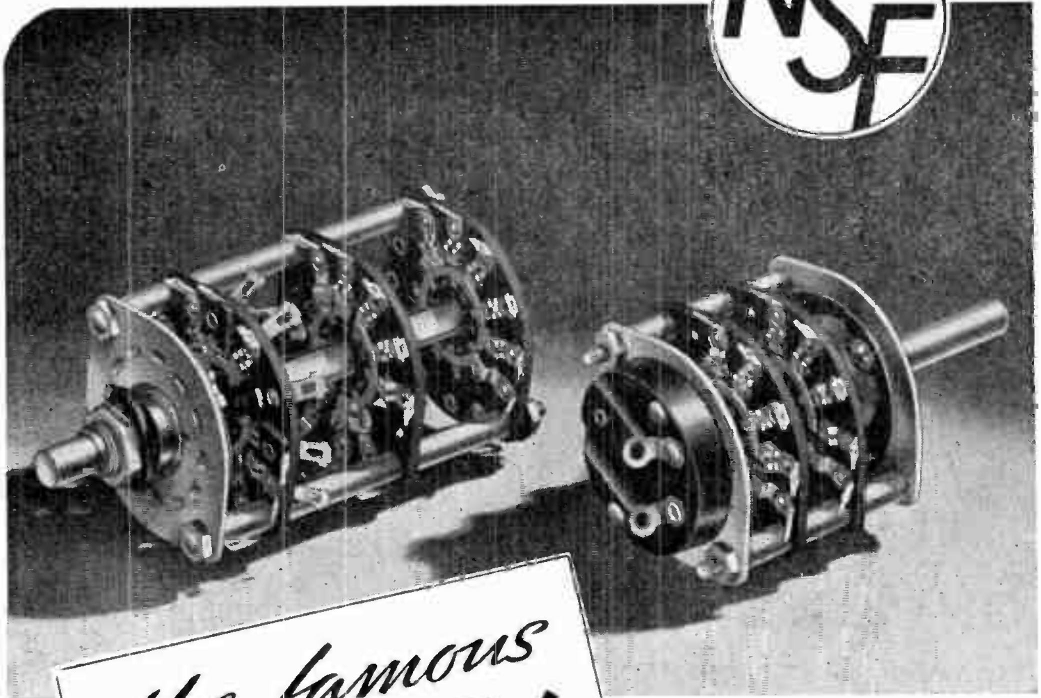

1922

2 LO first came on the air and, later in the same year, I was associated with the promotion of my Company to manufacture Insulated Instrument Wire and provide immediate - personal-attention to the multifarious requirements of a rapidly progressive science.

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> " In the spring of 1922 a rival to Writtle appeared in the field at uncertain intervals. This was a station known as 2 LO, a 100-watt set contained in a small teak cabinet, and housed in the cinema theatre on the top floor of Marconi House, London. This set, which was of a number of standard transmission products, was used for demonstrations .... "

Close co-operation with Radio Research and development, linked with rapid production methods and prompt service, have been for 23 years and will remain the policy of my Company.

> " In the summer of 1922 there came indications of a changed attitude towards broadcasting by the English Post Office, the Government mouthpiece in wireless affairs. At once the Marconi Company's engineers commenced work in the designing of what they considered would be the Government's idea of a British broadcasting station. Valves and condensers .... "

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World Radio History

THE JOURNAL OF

The British Institution of Radio Engineers

(FOUNDED IN 1925 – INCORPORATED IN 1932)

VOLUME 5 (new series) MAY—JULY, 1945 Number 3

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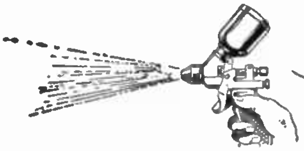

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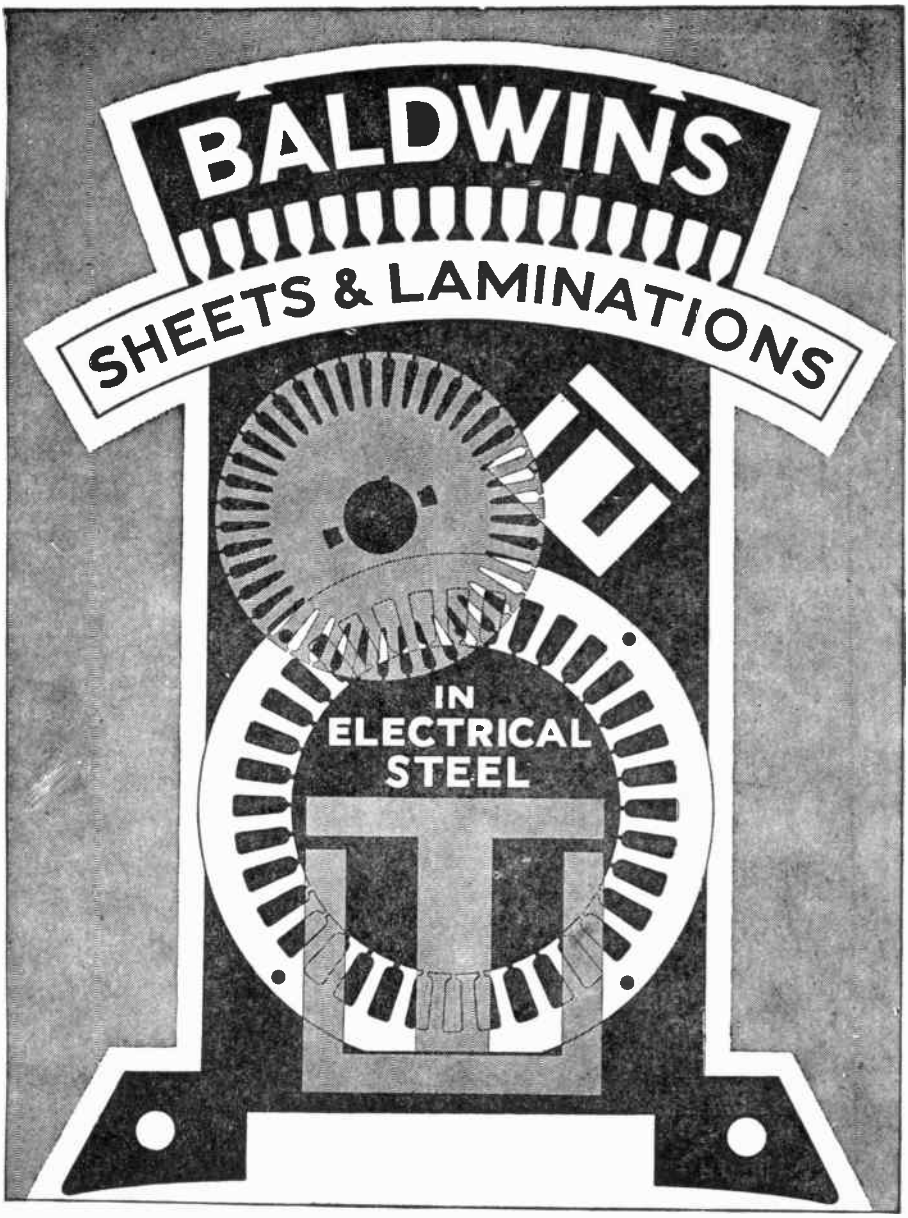
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In the House of Commons :

Mr. EVELYN WALKDEN asked the President of the Board of Trade why 120-volt Exide Batteries which are sold at 11s. 1d. are in short supply and other 120-volt batteries of less reliable make, and sold at 15s. 6d., only are available . . .

Mr. DALTON : Wireless batteries are now in short supply, owing to the heavy demands of the Services, and it is necessary, therefore, to make use of the output, although small, of the higher cost producers. Prices are controlled under the Price of Goods Act, 1939, and those charged for both classes of battery referred to by my Hon. Friend have been investigated and approved by the Central Price Regulation Committee.

Mr. WALKDEN: While appreciating what my Right Hon. Friend has said, is he not aware that batteries are used largely by people in small homesteads who cannot understand why good batteries cannot be obtained while there is a plentiful supply of inferior ones. . . ?

Mr. DALTON : I am very anxious to get a fair distribution of whatever supplies there are, but the best batteries are required for the Services in a very great and increasing quantity. . . .

(Extracts from Hansard, Jan. 16)

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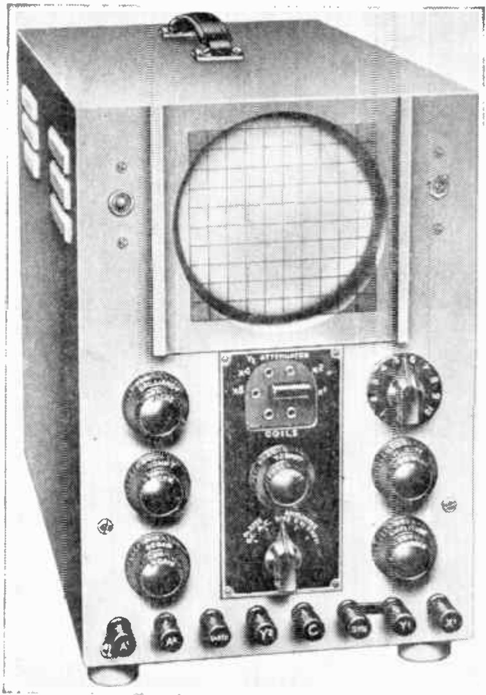

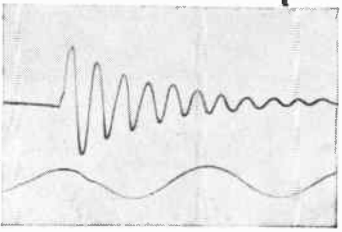

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"To promote the general advancement of and to facilitate the exchange of information and ideas on Radio Science."

Vol. 5 (New Series) No. 3 MAY-JULY, 1945

WAR AND PEACE

Although the war against Japan has still to be won, radio engineers may look back with satisfaction on the part they played in the efforts of the nation between September 3rd, 1939, and May 8th, 1945.

The full technical story of the war-time advancement of radio science may not be completely revealed for some years, and it is therefore worth remembering that the experience gained during the first Great War was largely responsible for the development of radio communication: subsequent progress demanded co-operation between engineers engaged in the applications of radio science, and it is largely due to this fact that the Institution was founded. Thus, dissemination of knowledge was not only encouraged between radio engineers, but also between members of the Institution and engineers engaged in other branches of engineering; subsequently, the need for courses and training in radio engineering was advocated by the Institution—although this recommendation was not fully implemented until the demands of war necessitated urgent measures.

Recommendations of the 1939/40 Council

In the latter connection, the Journal records that in September, 1939, Sir Arrol Moir advised co-operation with kindred bodies and continuation of the Institution's educational work since "... the advancement of the science will be as rapid during war as in peace, although on specialised lines during the former." Subsequent alterations to the Graduateship examination syllabus gave opportunity for securing recognition of specialist ability. In another paper, Mr. J. F. Paull stated that the Institution's "... examinations are assisting in the laying down of a definite standard of knowledge, and we rightly insist that all applicants for membership shall be up to this standard." A perusal of the lists of elections during the war years shows rigid adherence to this standard; indeed, although the exigencies of war-time training in all spheres have tended to ease tests, the qualifications required for membership of the Brit.I.R.E. are, in fact, higher to-day than ever before.

War-time Work of the Standing Committees

Keeping pace with the advancement of radio science has, in the matter of membership of the Institution, given a great deal of work to the Education and Membership Committees. Attendance at any kind of meeting has been difficult, but it is encouraging to note that during the war these two Committees between them held 95 meetings. Their work will have a great influence upon the peace-time progress of the Institution.

Space does not permit of reviewing here the work of the other Committees, but the objects of the Institution have also been constantly examined by the Council and the appropriate Committees. In 1941, Dr. C. C. Garrard outlined the comparative position of the Brit.I.R.E. with other engineering Institutions; that co-operation between the Institutions would help in preventing abuse of the title "Engineer" was also advocated by Sir Louis Sterling in his Presidential Address in 1942. The value of the work done in these directions cannot yet be measured, but is reflected in the purpose of the Extraordinary General Meetings held during the past three years in order to alter the Institution's Memorandum and Articles of Association.

Extension of the Sections

Subsequent papers have referred to the Institution's desire for co-operation—achieved in many directions, and notably with the Australian Institution of Radio Engineers. Considerable progress has also been made both at home and abroad in securing better facilities for members of the Institution to meet and read papers, and in other ways disseminate knowledge. By these and other means, an invaluable contribution is made towards advancing the science.

Notwithstanding the difficulties of war-time, therefore, the Institution has been very much alive to the problems that peace will bring. Good will inside and outside the membership, officially and unofficially, should ensure that on the conclusion of hostilities against Japan the Institution will be able to regard the years of war as not having been entirely wasted, but very much in keeping with the development of radio science.

MAGNETIC DUST CORES

by

E. R. Friedlaender (*Member*)*

(Read before the Institution in London on November 27th, 1944, *and repeated before the Midlands Section on February 28th,* 1945, *and the North-Western Section on May 4th,* 1945)

SUMMARY

Magnetic dust cores for inductances operating above power frequencies are manufactured from very finely divided magnetisable material, each metal particle being insulated from all its neighbours. The metal powder is of such a fine subdivision that it is commercially known as metal dust. Dust cores for radio work, until recently known as High Frequency Iron Cores, are dealt with in detail, while dust cores for telephone work are omitted unless their treatment is essential for the tracing of development trends and theories. The historical development is outlined and the need for planned research on metal dust and core problems is stressed. Permeability and loss analysis are discussed, and the need for standard test specifications stated. The relative value of the mathematical loss calculation and the graphical loss analysis methods based on the calculations are reviewed and their accuracy examined.

The application of different radio core types is set out and a table of preferred applications is given and discussed. The influence of magnetic dust core developments in connection with i.f. filter design and push-button tuning is described, together with practical implications of permeability tuning. The technological aspect is considered and plant used for the production of dust cores mentioned. The mechanical and electrical tolerances are stated after a survey of suitable metal dusts indicating their useful application.

History

Very few radio engineers had heard of magnetic dust cores in the early 1930's. It took a great deal of convincing to introduce the cores into wireless receivers and other electronic appliances. Yet dust cores were first described by O. Heaviside[1] in the *Electrician* of May 14th, 1886. It does not seem out of place to recall that his experiments were extremely successful in establishing the reduction in eddy current losses and hysteresis losses.

Heaviside's experiments and his mathematical treatment of the problems of long distance telephony had an acknowledged influence on the work of two American scientists, Pupin and Stone, who laid the foundation for the mass application of Heaviside's dust core in its modern form.

Pupin's early experiments led to the famous patent of 1899[2] on the loading of telephone lines by lumped inductances in regular, calculated intervals. The question of small, compact inductances for submarine cables was solved by the application of iron cored coils, the patent describing the following advantages : compactness, low ohmic resistance, low eddy current and hysteresis losses and constant permeability in weak fields for coils with "a carefully designed core." The danger of increased losses due to bad core design were realised and the following core specifications issued : Ring-shaped (toroidal) cores were formed by stacked discs of ·005 in. thickness. For further subdivision Pupin suggested the winding of the discs from ·004 in. diameter wire, the disc now taking the form of a spiral.

Inspired by Heaviside's work in one direction, he overlooked the experiments on dust cores, and also Currie's work[3]. Production methods for dust cores were nevertheless patented as early as 1901[4, 5], but the wire core high permeability and its lower losses were against the dust cores at this stage. A promising avenue of development on dust cores and dust core materials was discontinued due to lack of sustained and planned long-term research.

The wire position became critical during the early part of World War No. 1[6]. The United States were cut off from their supplies of Continental diamond dies, which were required for the drawing of the very fine and hard wire needed for the cores, as well as from all supplies of finished wire for this purpose. The search for an immediate substitute led to the intensification and large-scale reopening of the dust core research in 1915, and Elmen, Speed and Woodruff put the dust core for telephone work on a commercial basis. Concentrated effort soon gave it a performance superior to that of the best wire cores. Electrolytic iron powder was replaced by hydrogen reduced material in 1916, and silicon iron powder in 1919. The development of Permalloy powder in 1921 gave the cores increased permeability and performance.

Radio cores were developed quite independently. John Stone Stone was the first to realise the possibilities of dust cores for "space telegraphy" in 1902.[7] A year later, acknowledging Heaviside's influence, Stone applied for a British Patent[8] covering inductance coils and h.f. transformers employing dust cores.

Iron dust cores were developed by the Marconi Company in 1904[9] and subsequently used for intervalve transformers of their A 55 amplifier at a fre-

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* J. G. Smithson & Co., Ltd.

quency of 3 Mc/s. This development was not followed up, and it is necessary to explain the disappearance of radio dust cores up to their reintroduction in the early 1930s.

The first cores were made from crude, irregular filings, using wax as an insulator and binder. Neither of these materials lends itself to mass production and close mechanical and electrical limits. Other components of the tuning circuit promised an easier development, and there was no demand for the improvement of the coil performance until, e.g., the condensers had reached such a performance that the further improvement of the receiver circuits was held up by the low performance figures and instability of the coil design.

Scattered and unco-ordinated research continued over the whole of the period, and wax was replaced as insulator by thermoplastic binders. The advent of the mains receiver presented new problems to workers experimenting with dust cores, and no further developments could take place until thermo-setting materials replaced the thermoplastic binders.

Powder production also made progress and carbonyl powders made their appearance in 1927. Production methods were gradually improved and the necessary mechanical and electrical limits came nearer to those envisaged for mass production. The names of Polydoroff in U.S.A., and Vogt and Nissen in Germany, are linked with this early commercial period. The latter two both claim to have first produced the small cored coil as we know it to-day.

The improvements in production methods and performance gradually convinced the designers, and radio dust cores were used by the million when war broke out. Electrical and mechanical limits now confirmed to standards which were acceptable for the mass production aim of interchangeability. Most cores were made from carbonyl iron powder, for which Germany had a virtual monopoly, or were imported from that country. The Salford Electrical Instruments, Ltd., were the only firm in this country which was ready with a substitute powder.

World War No. I brought the loading coil dust core, a substitute which came to stay. It took World War No. 2 to stimulate the production of suitable powders in the countries of the United Nations. When war broke out, Germany had to all purposes a monopoly for the radio core raw material. Who will see to it that such research is not again left in the hands of interested parties alone? Will this be a subject for the proposed Radio Research Institute?

Patents

The historical survey shows that no "master patents" can be in existence with regard to the manufacture or application of magnetic dust cores. All the early patents have expired long ago. Hundreds of patents have been granted in this, and other countries, covering the manufacture, the raw materials, the shape of magnetic dust cores, the design of the cored inductances and filters and their application in circuits.

An interesting position has arisen with regard to patents covering the manufacture of magnetic dust cores. According to the latest conception—core manufacture must be considered as part of the art now known as powder metallurgy. This is not only by virtue of the fact that the cores are manufactured from metal powder, but also by consideration of its production methods, which have developed closely akin to those used in many branches of the new art. The new classification and attitude has a curious effect on the value of certain patents, for which the patentees applied in good faith, convinced that they had made a true invention. A general knowledge of production methods used in powder metallurgy would have shown them that in practice they have done nothing else but "found a new application for a known method, which could be expected of everyone versed in the art" which latter term stands here for the art of powder metallurgy.

Should a patent be granted for such applications of known facts to new fields? The blame cannot be put on the Patent Office examiners, who follow their routine search. Shall we say that the Patent Office has not proved itself flexible enough to adapt itself readily to these new groupings? A Royal Commission is now considering the whole of Patent Legislature, and it must be hoped that implications as the ones mentioned, will not escape attention.

Theory

The Dust Core Losses

Dust cores were first designed to reduce eddy current losses in cored inductances at, say, higher than power frequencies. Eddy current losses can only be reduced, and not eliminated, by the fine sub-division of the magnetisable material, and still represent the major portion of the total losses of dust cores subjected to an alternating field. The proportion of the losses directly attributable to eddy currents becomes more and more prominent with the increase of the frequency at which the core is employed.

The magnetisation curve of ferro-magnetic materials is not simply reversible, and forms the hysteresis loop, the area of which is a measure of the hysteresis loss for every cycle of the alternating current creating the field. While this loss component is not of very great importance in high-frequency work, it is of major importance in telephone work.

Analysis of the loss measurements has shown that a further loss component must be present. Very little is known about it, and for want of a better name, it has in this country been termed "the residual loss."

The core has to be subjected to an alternating field to measure these losses, which can only be done by providing the dust core with a coil winding. This coil, in its turn, is not lossless, and as some of the coil winding losses have the same cause as those of the core, an accurate loss analysis cannot be carried out by one or two simple measurements. This difficulty, in conjunction with the desire of the production people to have one measurement giving direct results for the performance of the whole cored coil, has given growing popularity to the factor Q.

The Q Factor of an Inductance Coil

In mass production the production control wants to know the electrical performance of the coil assembly at a given frequency and checked against an agreed standard. For this purpose they measure the magnification factor Q, sometimes called " figure of merit."

$$Q = \omega L/R \qquad (1)$$

where R represents the equivalent resistance for the losses in the coil winding and the core, ω the angular velocity and L the inductance.

In considering the usefulness of this figure we must always remember that it includes the performance of the whole coil assembly. Some years ago, when large scale employment of radio dust cores in the industry commenced, core manufacturers issued beautiful Q curves, showing the performance of their cores at different frequencies. These curves quickly disappeared as they led to endless disagreements; the test coils had not been specified!

Nowadays core manufacturers and users agree on test coils and test frequencies, at which the core has to have a specified performance (Q value) in a given coil. This is very unsatisfactory and leads to a chain of private standards. The author feels certain that an attempted standardisation would at least restrict the multitude of private standards to a minimum.

Losses in the Cored Inductance

It has already been stated that the loss resistance R in the Q value represents two parts

$$R = R_m + R_w \qquad (2)$$

where R_m represents the core losses and R_w the losses in the coil winding. The previous statement that these two loss groups cannot be readily separated needs some more investigation, and the total loss R is for this purpose divided into losses according to phenomena by which they are caused, viz.:

1. Ohmic loss.
2. Eddy current losses.
3. Hysteresis losses.
4. Residual loss.

1. *Ohmic Loss*

This loss is introduced solely by the d.c. resistance of the coil winding. It will depend on the length of wire, its gauge, and conductivity of the material. Its reduction is one of the advantages of the dust cored coil, and is due to the core permeability and the small diameter of the cored coil winding. The permeability cannot be increased beyond a certain value as the choice of the permeability is a compromise between the useful reduction of ohmic resistance in the coil winding and increase of harmful losses, due to the methods of obtaining a higher permeability.

2. *Eddy Current Losses*

The introduction has shown that one of the main stimulants for the development of dust cores was the reduction of eddy current losses, which increase with the square of the frequency. They also increase with the square of the particle diameter and the permeability of the core. The losses will further increase with an increased packing factor for the magnetisable material, and reduce with an increased resistivity of the dust particles.

The alternating field will set up the following conditions in a cored inductance:

(*a*) Eddy currents will form in each metal particle in the core. Given big enough particles and relatively strong fields, the eddy currents will produce a "shielding" effect, thus apparently reducing the particle permeability.

(*b*) Microscopic examinations of dust cores show that it is impossible to insulate every particle perfectly while still maintaining a satisfactory core permeability. Particles will group together and remain in direct electrical contact, even before the mixture of metal particles and binder is submitted to the moulding pressure. The latter pressure may also damage the particle insulation in the case of irregular metal particles with sharp corners being used. An unsuitable insulator and/or binder will produce the same effect. It will break down under the moulding pressure, and the metal particles will again be in contact; eddy currents will form over the whole area, giving the appearance of a coarser sub-division of the magnetisable material, by giving the same performance as coarser metal particles under better insulation conditions. These eddy currents can under circumstances set up a noticeable field in opposition to the main field.

(*c*) The insulator and/or binder has a very definite resistance which will depend on its general physical properties. The finished core will therefore have a measurable resistance across its section, i.e., at right angles to the lines of force, in which plane eddy currents over the whole cross section can be set up. The resistance of cores per cm^3 varies between 50 ohms and over 10 megohms, according to manufacturing processes and application requirements.

(*d*) Most insulators and binders have also dielectric properties, and the magnetisable particles can be considered as the plates of minute condensers with the binder as dielectric, thus enabling displacement currents to flow in the core cross section.

(*e*) A capacity is also formed between the dust core and the coil winding due to the dielectric properties of the coil former. This fact very often decides the wall thickness and the material of the bobbin.

(*f*) Eddy currents will be set up in the wire of the winding, and will produce a skin effect. This is counteracted by a fine sub-division of the wire into strands.

(*g*) Further eddy currents will be induced from one turn of the winding to the other, and will give cause to the proximity effect.

(*h*) Screening cans can add to the losses by eddy currents in their material. They are mentioned here because they will influence the Q figure of the whole produced unit or filter. Analysis measurements for core losses can usually be carried out without the can.

3. *Hysteresis Loss.*

It can be shown that the hysteresis loss represented by the hysteresis loop per cycle, increases linear with the frequency, and also with the flux density and, therefore, with the current in the coil winding causing the flux.

Hysteresis losses cause wave distortions, particularly in the third harmonic, which make the application of dust cores for certain telephone work difficult, and require special treatment of the powder for the manufacture of loading coil cores.

The hysteresis loss drops considerably with further sub-division of the material. At radio frequencies the sub-division has reduced the permeability so far that the hysteresis losses become negligible as compared to the total losses.

4. *Residual Loss*

Various theories have been developed to explain this loss component, which increases linear with the frequency, is not affected by field alterations and does not cause wave distortions. It is very difficult to separate it from the hysteresis loss. Jordan introduced the term "Nachwirkungs-Verlust" which has been translated as "after-effect" (lagging effect may be a more correct translation), because he assumed that it is due to a time lag between induction and field. Its independence from flux density makes it akin to eddy current losses, while its linear increase with increased frequency, makes it possible to try to account for it by an additional member to the Rayleigh equation. An improvement in residual losses of material by heat treatment seems to indicate internal stresses.

It must not be forgotten that this residual loss contains elements of all known losses as these are only separated according to an analysis which contains many approximations, as will be seen further below.

The above analysis of conditions prevailing in a cored inductance enables us to allocate certain portions of the losses to either the coil winding (R_w) or dust core (R_m), while others will be common and cannot readily be separated.

Permeability

The permeability of a magnetic dust core can be expressed in two ways :

(1) the permeability specific to a given core material, which is called the specific permeability, and

(2) the permeability effective on the particular core under observation.

In the case of a toroidal core the external leakage field will be so small that the effective permeability becomes the specific permeability for all practical purposes, and in this case the ratio between the inductance of the coil winding on the toroidal test core and the inductance of the coil winding only is called the specific permeability. The specific permeability of dust cores lies between 10 and 140 for general purposes. Core materials for special purposes have occasionally been designed with specific permeabilities outside the figures mentioned.

The accuracy with which the value of the specific permeability will be approached by the measurement of the toroid permeability will partly depend on the design of the core. Legg[11] and Welsby[12] have dealt with this problem on the theoretical side without, however, going so far as to suggest definite dimensions which could be used as a basis for a standard test specification. It is in the interest of manufacturers and users of dust cores alike that such standards shall be discussed by a suitable committee at the earliest opportunity and in the presence of the powder manufacturers, so that the recommendations of the committee can be made binding to all parties.

This specific permeability figure refers to the material as pressed in this particular toroidal core. It does not refer to the insulated metal powder as such, and it can easily be shown that the permeability of a core can be increased by increasing the moulding pressure and compressing a larger quantity of the insulated powder into a given volume. With the alteration of the core density other characteristics of the core will alter too, e.g., for some time the Q figure of the test inductance may increase, and decrease with further increase of pressure. Some of these additional losses may be due to a breakdown of the insulation on account of excessive pressure. The specific permeability as such, does not tell us anything about the other electrical characteristics, and it seems, therefore, obvious that a link-up must be arranged in some way.

So far, specifications on the indicated line have unfortunately been private arrangements between manufacturer and user. A new value has in this connection been suggested by Neighbours[13], who does not only give a detailed description of his test core dimensions and procedure, but also introduces the term "resistancy." This term is defined as the ratio between the h.f. resistance of a single layer coil on the toroidal magnetic dust core, and a similar coil wound on a toroidal core made from insulating material to the same dimensions as the dust core. Measurements are to be made at 1,000 kc/s. This suggestion does not, of course, take into account the losses introduced by the insulating material core. The American term "apparent permeability" used in this reference corresponds exactly to our term "specific permeability."

The value of the specific permeability as characterising a pressed core material, becomes still more doubtful when considered in relation to the peculiarities of some radio cores. Some of the more common types are of uneven cross section in press direction, and microscope examinations show zones of different density, low permeability zones alternating with high permeability zones. It is believed that the only practical value of the specific permeability is for the examination of powders as supplied to core manufacturers, provided that a test insulation and procedure can be agreed upon.

The radio designer is usually interested in core types other than toroids, and wishes to know what *de facto* figure he can obtain for his core permeability. This is established as :

$$\mu_{\text{eff}} = L_{\text{core}} : L_{\text{air}} \qquad \dots\dots\dots\dots (3)$$

Even this simple measurement cannot be carried out without agreement of the parties concerned as to procedure, and a simple experiment will illustrate this. A cylindrical core is first placed into a coil, which covers the middle third of the core length only. Next the same core is placed into a winding of the same inductance but now covering the whole length of the core, resulting in a considerably higher effective permeability than in the first case. Agreement should be reached on test procedure for the most common types without much trouble—once the parties get together.

One more point is of interest. The permeability in an alternating magnetic field can be represented by the equation :

$$\mu = \frac{B}{H} \qquad \dots\dots\dots\dots (4)$$

in which B represents the instantaneous flux density, and H the instantaneous field. From this relation it follows that the permeability will depend on the form of the hysteresis loop and that a very flat loop, approximating a straight line, is essential to obtain a constant permeability in fields with a larger ratio of alteration in the intensity of the magnetising force. Kersten[14] mentions toroidal cores in which the remenance is not greater than 3×10^{-6} of the maximum flux density.

Measurements and Calculations

Several methods are known to measure the coil performance. The large scale commercial production of the Q-meters has made this method the most convenient as the instrument allows direct readings of the magnification factor over a large frequency range. The basic circuit of a Q-meter is shown in Fig. 1.

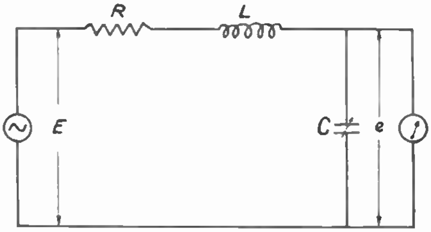

Fig. 1

The test coil L with its magnetic dust core is connected in series with a low loss condensor C and a high frequency supply source. The resistance R is the equivalent loss resistance for all energy losses in the circuit. E is the injected voltage and e is the voltage across the capacity C, measured by a high impedance input valve voltmeter.

In this circuit

$$E = I\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \qquad \dots\dots\dots\dots (5)$$

At resonance this will become

$$E = IR \qquad \dots\dots\dots\dots (6)$$

The current I will produce across C or L a potential difference

$$e = I\omega L = \frac{I}{\omega C} \qquad \dots\dots\dots\dots (7)$$

Relating e to E we can now write

$$\frac{e}{E} = \frac{\omega L}{R} = \frac{1}{\omega CR} = Q \qquad \dots\dots\dots\dots (8)$$

Suitable choice of components can make the losses in the meter circuit so small in comparison with the coil losses that the observed Q-value can be used without correction factor for all practical purposes. The necessary data for correction at higher frequencies are usually provided by the manufacturers.

The observed Q-values do not give any indication as to the contribution of the winding loss resistance R_w and the core loss resistance R_m to the total resistance R. The use of the Q measurement for the purpose of checking the performance of a magnetic dust core requires an agreed test coil and agreed test-frequencies if the measurement shall have binding value between contracting parties.

The reciprocal value of Q is sometimes quoted as the power factor of the coil. This is slightly confusing until it is remembered that the loss angle δ is still smaller than 3° for as low a Q as 20. The substitution of sin δ for tan δ only involves an inaccuracy in the fourth decimal, and as sin δ is equal to cos θ, the term power factor is justified.

A further performance check can be arranged at the same time as the Q measurement : the effective permeability can be checked when the Q value is established.

The Q meter is, however, not suitable for a detailed analysis of the components making up the loss resistance R. This is done on an A.C. bridge for which different designs have been described by several workers together with the methods of approach and formulæ. Legg's method of loss analysis[11] has now largely been accepted in English speaking countries and will be quoted here.

Toroidal cores lend themselves particularly to the mathematical treatment and to the graphical analysis based on these calculations. They have, therefore, been chosen as standard cores for such measurements. The mathematical treatment itself is based on the assumptions that the core consists of magnetisable particles which are all sufficiently insulated from each other, evenly spaced by the insulation and moulded to a uniform density, thus guaranteeing uniform flux density. It is acknowledged that this ideal state cannot be obtained with present day methods and that, therefore, the analytical work can only give approximate results. It has not been possible to account for the ununiform character of the dust core by correcting members to the formulæ which would account for the deviations. This is an inherent weakness of the analysis as such, which makes a 30 per cent. to 40 per cent. approximation between calculated and measured losses look quite satisfactory.

Consideration must now be given to the separation of the winding loss resistance R_w from the core loss resistance R_m. It has been shown that the separation causes difficulties. The various ways open to overcome it can now be described :

(1) The toroid can be wound with a very thin single layer of evenly distributed stranded wire and R_w can be neglected, assuming that it will be very small compared to R_m.

(2) The winding on the toroid can be repeated on a core from insulating material with good h.f. characteristics. R_w can then be measured and will give a good approximation value.

(3) Cage windings have been suggested[14] which can be measured with and without core, allowing comparative measurements of several test cores with exactly the same winding.

(4) An attempt can be made to calculate the value for R_w with sufficient accuracy.

Legg states that the method according to (1) gives such small values that the analysis becomes difficult and inaccurate, and develops a formula for a restricted inductance value at which R_w will only introduce a permissible small error at the highest test frequency.

This highest frequency is limited by the fact that the eddy current losses increase with the square of the frequency and tend to swamp the other loss components, making them so small in comparison that the analysis can become valueless. Most loss analysis measurements are carried out at audio frequencies, and all below 100 kc.

New investigation methods have recently been described by Oddie[15] who reports measurements of the specific permeability on cylindrical cores at frequencies up to 40 Mc/s. The inductance change of a straight wire was measured with and without a cylindrical core co-axially arranged. The lines of flux were in this case at right angles to the usual direction and were not interrupted by any airgaps outside the core.

The success of this method originally suggested by Glaisher and its reproducibility encouraged Oddie to undertake measurements of eddy current losses in the same way. While these results were also easily reproducible, they did not agree with the losses calculated according to Legg's formula.

It would be interesting to examine the influence which different production methods can have on these results. It is feasible that the press direction will have an influence on the findings.

According to the usual practice the inductance L for the toroidal core is measured on an A.C. bridge as well as the loss resistance R. The permeability of the core can then be calculated, after correction of L

$$\mu_m = \frac{\quad_{m}\quad}{4\,N^2\,A} \times 10^9 \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

where L_m = inductance due to the magnetic core.

μ_m = permeability corresponding to L_m.

N = number of turns of the winding.

A = core cross section.

d = effective magnetic diameter.

The D.C. resistance of the winding is measured next and deducted from R together with the a.c. resistance of the winding, if the latter is too large to be neglected. The remaining value is R_m. By neglecting the interaction of eddy current losses and hysteresis losses in the core, and treating each of the loss components separately Legg arrives at the formula

$$\frac{R_m}{\mu_m L_m f} = a B_m + c + ef \quad \ldots\ldots\ldots\ldots \quad (10)$$

in which *a* represents the hysteresis loss coefficient, *c* the residual loss coefficient, and *e* the eddy current loss co-efficient. These coefficients are material factors determined by material charactertistics which are very difficult to establish in practice. For example, the eddy current coefficient will depend on the mean particle diameter as well as resistivity of the core material, while one of the components of *a* is the initial permeability which is very difficult to measure.

The only coefficient for which a detailed definition is not available is c. The physical causes for the residual effect are unknown, and its introduction tries to compensate for the presence of this loss.

The left side of equation (10) now consists of known values, while only one member of the right side varies with f. Measurements of R_m at different frequencies and constant field can thus be plotted against $R_m/\mu_m L_m f$ and will result in a straight line with an intercept at zero frequency. This intercept gives the value for $a\,B_m + c$ for the given field.

Repetition of the measurements for different flux densities give several intercepts which can be plotted against B_m. The resultant points do not lie on a straight line, thus showing deviations from the Rayleigh equation. A straight line drawn through most of the points will give an intercept on the $R_m/\mu_m L_m f$ axis which will give a value for the residual loss coefficient c. This intercept can only be obtained reasonably accurately if readings are taken with great care with very low currents.

The number of readings to be taken clearly depends on the purpose of the analysis. Routine examinations will be satisfactory when two or three readings for each curve fall all within the limits. In investigations of other nature five or six measurements for each curve are essential.

Jordan, Deutschmann and Kersten as well as Legg and Welsby base their calculations on the assumption that Rayleigh's equation for the hysteresis losses in magnetic materials at low flux densities is valid for magnetic dust cores. Accordingly they assumed that the hysteresis coefficient is constant for all flux densities encountered in telecommunication work. Rayleigh found empirically[16] the independence of the coefficient from B and that in this case the hysteresis loop can be represented by two parabolas. It is generally assumed that the equation is valid for all cases in which the initial permeability does not change more than 10 to 20 per cent. The inaccuracies described above came more and more under observation, and Kornetski[17] took the inconsistence of the Sen-dust hysteresis co-efficient at very low flux densities as an example to investigate the problem.

He investigated two equations. One is a variation of the original Rayleigh equation, using a hysteresis coefficient h which is related to the Rayleigh equation by

$$h = 7{\cdot}5\,\frac{v}{\mu_a} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

where μ_a is the initial permeability. The second formula is Deutschmann's equation[18]:

$$h_w = h\left(\frac{\mu_{wa}}{\mu_a}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

for dust cores. h represents the hysteresis coefficient of the undivided ferro-magnetic material with an initial permeability μ_a, while h_w is the coefficient for the sub-divided and insulated core material with the initial permeability μ_{wa}. The equation indicates also a coefficient value independent of flux density. The coefficient is also assumed to be independent of flux density.

Measurements have shown that this is not so, and that actually the values of coefficients for core material vary considerably with flux densities. Two curves from Kornetzki's paper are reproduced in Fig. 2 representing the coefficient measured on carbonyl powders E and H, the former of which is mostly used for radio cores; h_{wa} represents the value of h_w for $H_a = 0$ and cannot be measured. Its graphical determination would suppose a well-known relation between h_w and H_a which obviously does not exist. Its mathematical determination must be based on assumptions and approximations.

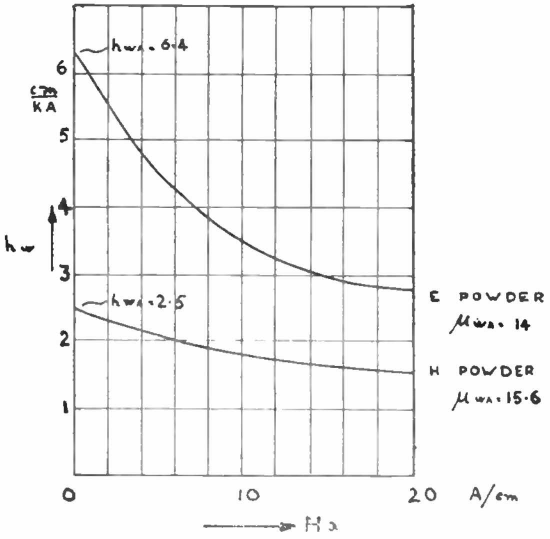

Fig. 2.

Kornetzki nevertheless tries a strictly mathematical solution, and proves that the Rayleigh law cannot be valid for any core material if the magnetic material before the subdivision followed the law. Taking Kornetski's paper in consideration we must now come to the conclusion that our graphical solution is incorrect, and that the value for the residual loss coefficient c thus found, is wrong.

Kornetski's further mathematical treatment did not bring him much nearer to his experimental figures, and he concludes his paper by saying that he did not expect it at this stage.

Having seen that the loss analysis cannot be correct with regard to the separation of hysteresis and residual loss components, we must with renewed interest review the evaluation of the eddy current loss coefficient. In this connection Kornetzki and Weiss have done much theoretical work[19]. We cannot, however, overlook Oddie's recently published experimental work in this direction[15]. One of his experiments refers to the formula represented by the eddy current coefficient e in Legg's formula which has been used above. Legg's actual formula reads as follows :

$$e = \frac{1{\cdot}24 \times 10^{-3} t^2}{\rho \times r^{1/3}}$$

in which ρ is the resistivity of the magnetic powder in ohm-cm. and t the mean particle diameter in cm. The only variables for any given powder are r which represents the volume fraction of magnetic material in the core and the coefficient e. The product $e \times r^{1/3}$ should be constant. It is nothing like constant. In considering this discrepancy it should, however, be kept in mind that any mathematical treatment is based on the untrue assumption that all particles are evenly spaced and well insulated from each other.

Nevertheless, it can readily be seen that the above methods of loss analysis have only very limited value and that they are used in core investigations as strictly comparative measurements until a better method can be devised. Any attempt to use them as basis for advance calculations of core characteristics must be futile, and the method as existing now can be of value only to core manufacturers, and in connection with certain audio frequency cores for which a relative standard for the loss components must be established.

The criterion for radio dust cores will, for a long time to come, be the Q measurement which will gain much in value once its procedure is standardised.

This section would not be complete without mentioning Welsby's design of an improved A.C. bridge for loss analysis[22] which has overcome many of the difficulties inherent in the measurement itself.

Application

The Two Core Groups

Different requirements for different core applications have been mentioned, and two main groups were easily recognisable in the historical survey. The division into two groups has in general been maintained during the further development. Border-line cases have arisen with the extended application of cores, and the division is not now as sharp as it once was.

Magnetic dust cores were developed to keep eddy currents down, as they represented the highest loss component in cores, without the extremely fine subdivision of the dust cores. These losses do not only increase with the square of the frequency, but also with the square of the mean particle diameter. Loading coils for telephone work require a high inductance at a relatively low frequency. Particle diameters are therefore large, and the insulating film between the particles is sometimes kept as low as 0·5 micron (0·0005 mm.). The largest particle size which can be employed for the purpose will be determined by the size of the permissible eddy current losses, and cannot go beyond a compromise point. Toroid permeabilities between 60 and 140 are common in this core group.

Employment of dust cores at, say, 30 Mc/s on the other hand will make toroidal cores unsuitable, due to the low inductance required. Eddy current losses will be of first importance, as they lead to a low all-round performance of the cored coil, also producing a heavy magnetic skin effect at such high frequencies. The particle size will have to be very small, and the resulting larger surface of magnetisable material will have to be insulated with a thicker layer of film. The very fine subdivision of the core particles and the small pack factor of the magnetisable material in the core volume will keep the permeability down as well as the hysteresis losses. Materials of this second group have a specific permeability of between 10 and 20. These figures are still reduced for special purpose cores.

These few observations indicate that the core material must be developed to suit the performance which is expected of it. This point has not been put strongly enough until now. Radio manufacturers still try occasionally to "standardise" the core types employed at their factories, and in other cases the mechanical design has influenced the specification unduly. Collaboration and frankness is often missing between customer and supplier.

The first group of cores, requiring high and constant permeability, low hysteresis and eddy current losses at relatively low frequencies, is not the main subject of the paper, which is more concerned with the second group, commonly called radio cores. Filter cores for telecommunication work are borderline cases, which have also been omitted. They have been specially considered by American workers and recently by Polgreen[23].

Core Types and Shapes

Toroidal air-cored coils led to the development of toroidal cores (Fig. 3.1) and this remained the only core

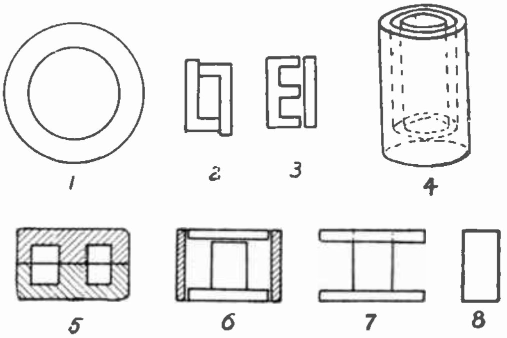

Fig. 3. Core types.

type for many years. Both Heaviside and Stone mentioned the cylindrical core (Fig. 3.8), which was not commercially produced until much later. Vogt copied the L-core (Fig. 3.2) and the E and I core (Fig. 3.3) from the normal technique for laminated transformer cores, and found these shapes particularly suitable for his first radio core material.

It was soon discovered that cores with angular cross section require more wire per turn for a given inductance than cores with a circular cross section, and the L as well as the E and I cores have lost their importance with the improvement of core materials. Polydoroff's first core design is shown in Fig. 3.4. It is of interest as it illustrates Polydoroff's early attempts to replace the condenser in an oscillatory circuit by a magnetic dust core sliding over a single layer coil. The cumbersome and expensive cores made the "permeability tuner" uneconomical.

The current radio core design is represented in the next four illustrations, and all core variations can be traced to one of these main types. Fig. 3.5 shows the pot-shaped or ironclad core, which forms a closed magnetic circuit round the coil. The difference from the toroidal core is that the complete winding is inserted into the split core while it has to be wound on to the toroid core. The permeability is greatly reduced as compared with the toroid core. Its cheaper production makes a high quality performance coil a commercial proposition. Its effective permeability is 3·5—5.

The next core (Fig. 3.6) can be considered as a variation of the pot-shaped or the reel-shaped core. It consists of two mushrooms, or a mushroom and a disc, surrounded by a dust core return cylinder.

The "reel" core type (Fig. 3.7), gets its name from the resemblance to a cotton reel. This core only surrounds the winding partly and its effective permeability is lower than that of a pot-shaped core (3 to 4). The gap in the magnetic circuit is outside the winding. The centre of the coil and the two cheeks are filled with magnetic material.

The last type (Fig. 3.8) is the cylindrical core. It is the oldest mentioned radio core type, and the most commonly employed core. It is manufactured in many variations, and fills only the centre of the coil winding. Its effective permeability is normally up to 3, but special cores with high effective permeability are used for special purposes.

Inductance Adjustment.

Permeability tolerances on cores were plus/minus 10 per cent. when cores first became a commercial product, and it was fairly obvious that inductances could be matched only in two ways :

(1) By winding the coil to a high inductance and then taking turns off until the desired inductance was reached, or

(2) By adjustment of the core permeability.

The first method is still in use for certain air-cored coils. The second method is one of the advantages of the dust cored coil.

Again we can define certain basic methods of adjustment. In practice there will usually be a combination of two or more of the undermentioned methods. Different arrangements have been devised to obtain specially formed adjustment curves, by combining the following features :

(1) Introduction of an adjustable air-gap into the magnetic path. Such adjustments can be made according to Fig. 4.1, which illustrates the method for different core types.

(2) Alteration of the magnetic cross section as illustrated by the E and I core in Fig. 4.2.

(3) Alteration of the length of the magnetic path (Fig. 4.3). This method is also known for laminated cores, and was first employed for L-shaped cores. Later reel cores were adjusted in this way and gave very good adjustment curves.

(4) The last method can in certain aspects be considered as a variation of method 2, as it also varies the magnetic cross-section, but in another way, viz., by the movement of a cylindrical core in the coil winding centre (Fig. 4.4). This cylindrical core may be the only ferro-magnetic material present in the centre of a coil, or it may move inside another fixed core already partly filling the coil centre cross-section.

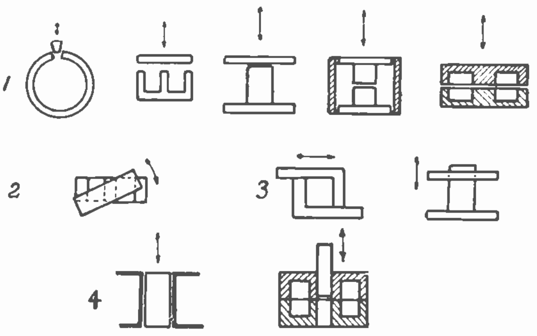

Fig. 4. Permeability adjustment.

The Cylindrical Core and its Variations.

The cylindrical core in its original form (Fig. 5.1) has a diameter of approximately ·375 in., and a length of ½ in. to ¾ in. for the m.f. range. The core diameter may, however, vary as much as from ·2 in. to ·75 in., and the length between ¼ in. and 2 in. in the extreme. This core type is usually fixed into a coil winding and does not lend itself readily to permeability adjustments, with the exception of the very long cores which are used as permeability tuners in circuits of American design.

Cylindrical cores can be provided with centre bores (Fig. 5.2) without much loss of permeability. The bore is either used as location for the whole coil assembly or it may be used as location for a cemented-in brass screw. The core can be shifted in relation to the fixed coil winding by means of the screw, thus adjusting the coil inductance. The introduction of the brass stem does not influence the permeability of the core materially and this fact has been made the basis of a calculation by Professor Howe[20], in which he proved that this phenomenon is due to the imperfect insulation of the dust particles.

Cores to Fig. 5.2 have to be cemented very carefully to obtain the necessary concentricity between the core and the screw, which permits frictionless turning in the coil former without excessive clearance. To improve the concentricity, brass stems are also moulded into cores (Fig. 5.3). A core type separating the core and the screw by a moulded insulator, to improve the magnification factor of the coil assembly, was developed by the author in 1937.

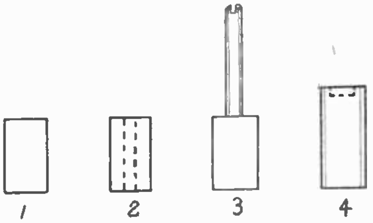

Fig. 5. The cylindrical core and its variations.

While brass stem cores became very popular with the introduction of push-button tuning, they met with strong competition for the application in i.f. filters. A screwed core (Fig. 5.4) was developed in Germany, which has electrical advantages, particularly a good electrical performance at medium frequencies. The effective permeability of this core is equivalent to that of a cylindrical core of slightly more than root diameter of the screwed core, and it is further reduced by the necessary thread depth and wall thickness of the former—which spaces the core from the coil winding. The mechanical tolerances for such cores are also wide. Production methods for screwed cores have improved but the fight for predominance is not yet decided.

The Choice of Core Shapes for H.F. Work

The different core types find their most suitable application in quite different ranges. In many cases electrical considerations have been set aside and the costing department has decided the choice by fixing a cost price which does not allow for a better quality core. Development in electronics is governed by the cost of vital components and the policy of their producers, which thus influence the trend of development not only in countries but often in whole groups of countries.

German designers choose the cores mainly from the electrical aspect, counting every avoided small loss as an advantage. Designers in this country balanced the additional price for a more efficient core against the improved performance of their appliances and decided, in the majority of cases, in favour of the less efficient and cheaper cylindrical core. The United States put up with cores of very low electrical and mechanical performance. Production has recently developed considerably in that country, and high quality cores are available in mass production quantities.

Table 1 represents the different applications possible for the discussed core types[12]. It will be noticed that the commercial choice varies considerably from the best choice in the majority of frequency ranges.

The employment of dust cores in i.f. filters is a classical illustration of the clash between the two interests. I.f. filters are usually employed as anode loads of valves. The gain of the stage largely depends on the dynamic resistance.

$$R_d = \frac{L}{C\,R} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

TABLE 1.

Frequency	Best Choice	Second Choice	Commercial Choice	Remarks
< 150 kc/s	Reel core with outside cylinder	—	Reel core with outside cylinder	Chosen on account of high permeability to reduce copper losses in winding. Material which increases Q of coil not wanted
150–400 kc/s	Cylindrical core	—	Cylindrical core	—
I.F. (450 kc/s)	Pot core	Reel core	Cylindrical core	—
600-1,500 kc/s	Reel core	—	Cylindrical core	—
> 1·5 Mc/s	Cylindrical core Reel core with outside cylinder	— —	Cylindrical core Reel core with outside cylinder	Specially designed shapes and reduced permeability to reduce losses. Reel core for screening with outside cylinder. Cylindrical core mostly for trimming (threaded core)

A combination of high inductance, low capacity and low loss resistance will thus ensure high gain. The capacity cannot be reduced too far without reducing the selectivity and making the change in valve capacity due to AV.C. bias noticeable. The choice of the core for the filter coil will have a marked influence on the dynamic resistance as the loss resistance of the coil is an appreciable component of the total loss resistance in the circuit.

As far as the 450 kc. range is concerned this can best be obtained by application of pot-shaped cores with their high effective permeability. The cores have also the advantage to allow close screening.

Unfortunately, they are the most expensive radio cores, due to the amount of magnetisable dust required for their manufacture, and to certain production difficulties. Permeability adjustment over the range of 8 to 10 per cent. can easily be arranged. The price of the core is still considered too high for domestic purposes, and cylindrical cores are employed in this country instead. The latter are considered to give sufficient value for the money spent.

It is interesting to note that the advent of the magnetic dust core, in conjunction with the introduction of mica-silver condensers, revolutionised the filter tuning arrangements. Condenser trimming was used throughout the industry until approximately 1938, when it was realised that the magnetic dust core allowed much finer tuning and higher stability than previously known, particularly when put into a filter with low loss mica-silver or ceramic-silver condensers.

The commercial influence can also be observed with regard to tuning coils in the medium frequency range (600-1,500 kc/s). The reel core gives a performance superior to all other core types in this range, and also allow for very close screening. Following the previously mentioned trend the reel core is considered the only suitable core for m.f. in Germany. The total quantity of reel cores manufactured in this country for m.f. was always negligible, and as a result the author has not been able to compile comparative curves at the moment, due to the lack of suitable cores.

To give, however, some impression of the relative position of the Q curves the following illustration[27] has been produced (Fig. 6).

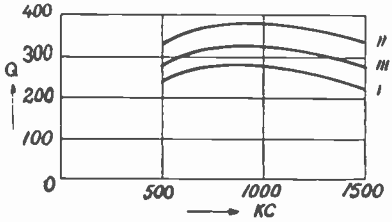

Fig. 6.

Curve No. 1 represents the Q of a coil with a cylindrical core, No. 2 the coil with a reel core, while No. 3 represents coil with a pot-shaped core. All coils are wound to 0·2 mH on four-sectioned formers with 20 × 47 S.W.G. litz wire.

Dust Core Push-button Tuning

It seems somewhat out of place to discuss push-button tuning in the fifth year of war—when the only receivers produced for domestic consumption are utility receivers. A large number of dust cores had been used for this purpose just before war broke out, and the quantities were steadily increasing. The subject shows also some interesting points for designers.

Push-button tuning made a come-back in 1937-38. The first push-button receivers were built and marketed as early as 1928, and relied on condenser tuning. They were unsuccessful as the padding condensers did not stay put, and the design was scrapped. The first British design used the same principle, but condenser production had been developed so much in the meantime that stability was assured. One disadvantage of the condenser employment was that the trimming condenser used for the final tuning had a capacity of not more than 10 to 20 μμF. It was really a pre-set circuit which was selected by the push-button, and the trimmer of which only compensated for production tolerances. The faults of this design were shown up in a very peculiar way. Radio Normandie changed its frequency pretty radically just after the introduction of the sets, and all sets in private hands had to be returned to the dealers for a replacement of the padding condensors.

Leaving aside motor and purely mechanical push-button tuning, which stop the ganged main condenser at a predetermined point, and do not provide any additional circuits for push-button selection, we are left with the possibility of replacing the factory pre-set circuit by channel tuning, which allows the listener to tune to any station within the channel and alter the setting himself as frequently as he wishes. Proper choice of the channels will allow the tuning—even of stations which are at neighbouring frequencies. Conditions for this type of push-button tuning are stability, fine adjustment made sufficiently easy, and reasonably wide channels for each button. The dust cored coil meets the conditions, and brass stemmed cores with an effective permeability of 2 to 3 are considered satisfactory.

Most sets in this country being superhets, the listener had to go back to the good old days of primary and secondary tuning when adjusting his push button circuit to a new station. The ganged condenser pointed the way and ganged permeability tuning was introduced. It set some problems to designers, and a number of ingenious designs had been marketed when war broke out.

A pre-selector circuit of a superhet covers the frequencies between 500 kc/s and 1,500 kc/s for the m.f. range. Assuming an i.f. of 455 kc/s, the corresponding oscillator circuit will have to tune from 955 kc/s to 1,955 kc/s, the frequency ratio being 3 : 1 in the pre-selector and 2.05 : 1 in the oscillator. Permeability tuned push-buttons cannot easily cover the whole range, but even for smaller, overlapping channels the rate of inductance change must be different for the two circuits. Both circuits must track at as many points as possible of the adjustment curve over the whole channel width, and follow the ideal curve as closely as possible on all other frequencies. Many methods are known[20] to overcome this difficulty, and the first ganged permeability tuners were imported from the States. The arrangements fall into two main groups :

(1) Ganged tuners with cores parallel and ganged by means of a cross bar, thus avoiding the presence of a brass inside the tuning coil ; and

(2) Tuners with cores sitting co-axially on one adjustment screw, which passes through each coil.

The problems with regard to the inductance change are the same for both groups, and by way of an example an arrangement of the second group shall be illustrated in Fig. 7. Designers did not seem averse to accepting the low "Q" value of the cores resulting from the continuous presence of the brass screw in the coil winding. Manufacturing tolerances could be compensated by altering the distance between the two dust cores. Due to the rubber tubing this could be done after assembly. This first adjustment provided also the first tracking point.

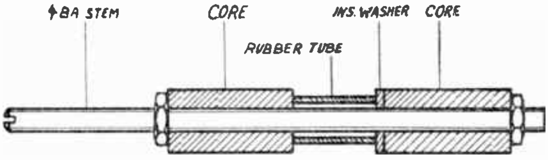

Fig. 7.

It is interesting to observe in which way the different workers obtained the two rates of inductance change. In most cases the coil and the core for the pre-selector were standard, the core being of high effective permeability. If this was the case, the oscillator coil had to have a lower rate of inductance change, which could either be obtained by providing dust cores of the same physical dimensions but lower effective permeability, by cores of different physical dimensions but manufactured from standard core material (longer or smaller in diameter), or by variations in the coil arrangement (diameter, length or irregular winding).

With all these arrangements the dust cores had to be to close specifications. In one case the pre-selector core had an effective permeability of 3, which was diluted to 1.2 for the oscillator core. The manufacturing problem was to obtain either very homogeneous cores, or, if this was not possible, a controlled variation of the density. In the latter case the core had to be coded on one side to make sure that the tuner would track on the specified points.

The Brass-stemmed Cylindrical Core

It has just been stated that the radio engineers accepted the presence of a brass screw in the core centre. Actual figures may be of interest, and are tabulated in Table 2, for a core similar to Fig. 5.3, and made from iron dust. The core diameter was ·365 in., and the length ·5 in., while the stem was threaded for 4BA. The coils were wound on four-section polystyrene formers and consisted of 100 turns 9/45 stranded wire for the 1 Mc/s test and 4 turns 22 s.w.g. enamelled wire for the 20 Mc/s test. The 1 Mc/s coil was $\frac{7}{16}$ in. long, while the 20 Mc/s coil covered only approximately the centre $\frac{1}{4}$ in. of the core.

TABLE 2.

	1 Mc/s $\mu_{eff} \sim 2{\cdot}1$		20 Mc/s $\mu_{eff} \sim 1{\cdot}4$	
	C_{pF}	Q	C_{pF}	Q
Test Coil only ..	234	112	118	128
Core without Stem in Coil	110	185	84	131
Core with Brass Stem	108	163	83	132
Core with Brass Stem $\frac{1}{4}$ in. separated	110	171	84	130
Core with Steel Stem	109	105	83	125

The cores were first tested without a stem, then with brass stem and with steel stem. An additional test was carried out in which the stem was separated from its usual position by approximately $\frac{1}{4}$ in. in axial direction. This measurement would be equivalent to the measurement of a core separated from its stem by an insulator of very low losses. While the tests were purposely made at both frequencies, with the same core material, this must not be taken as indicating that the same core material would necessarily have been recommended for both applications. The results of Table 2 are best checked against the main points raised previously in this paper.

Technology

Metal Powders for Magnetic Dust Cores

Metal powders for magnetic dust cores have to be developed towards characteristics which will meet the electrical requirements. Mathematical formulæ have been a great help and have indicated the general direction in which development work has to proceed. Attempts to calculate in advance the properties of a dust core made from a particular powder, or the powder characteristics required to produce a specified dust core, have so far been without success. The discrepancies between calculations and experimental results have been obvious for some time. The uneven particle distribution in the dust core and the failure to insulate and space the dust particles sufficiently, make accurate calculations impossible.

The mathematical treatment shows the influence of the following powder characteristics :

(1) The core volume, and with it, losses in the coil winding and production costs are reduced by a high initial particle permeability of the powder.

(2) The fineness of the sub-division and the constancy of the particle size distribution will influence the eddy current losses and production uniformity.

(3) Increased resistivity will also reduce eddy current losses.

(4) Tolerable production tolerances depend on constant particle permeability and density.

(5) The particle shape and, to a certain extent, the particle size, will decide the volume percentage and type of the core insulation.

The first iron powder production for dust cores on a commercial scale followed the electrolytical process. The low density and resistivity led to the development of more efficient hydrogen reduced powders, while silicon, originally added to improve the mechanical pulverisation, increased the resistivity and general electrical performance.

Elmen, who was so actively engaged in the production of the first commercial dust cores for loading coils, was also responsible for the development of permalloy powders which became the standard material for this type of cores in the 1920s. The most general grade of this material contains 81½ per cent. nickel and 28½ per cent. iron, and required an annealing process after disintegration and before moulding. The heat treatment stage is characteristic for all permalloy materials, and on its proper execution depends the electrical performance.

The highest permeability obtained with specially annealed iron powder is 60, while permeabilities up to 140 can now be obtained with standard permalloy grades. With the increased permeability go lower hysteresis losses and a better permeability stability. Such improvements were balanced by certain disadvantages, such as the extremely critical cycle and temperature of the second treatment after the moulding process. Only very careful observation of process procedure gave the required performance.

General metallurgy experience in alloying was of help, and the addition of Cr and Mn made the heat treatment cycle less critical. The latest developments resulted in an addition of 2 per cent. of molybdenum[24], and it is claimed that either the permeability of a toroidal core can be increased by 50 per cent. for a given volume or the volume reduced by 60 per cent. for equal permeability. The new material does not retain a change of permeability of more than ·5 per cent. within three minutes after a heavy superimposed D.C. magnetisation.

The dust particles of all the above mentioned powders are of irregular shape, very often sharp cornered. Their size will vary with the purpose for which the powder is developed. In most cases perfectly round particles would have been preferable and attempts were made early to produce such a powder with a small particle size, which would make it possible to develop good dust cores for h.f. The introduction of carbonyl iron powder met these requirements, and the I.G. Farben Gesellschaft which developed the process had at one time a virtual monopoly for core powders for radio frequencies. Carbon monoxide is in this production passed over a spongy metal, forming in our case the liquid pentacarbonyl, which will decompose at elevated temperatures, freeing carbon monoxide for recirculation and producing a very fine powder which can then be wind sifted into different particle grades. The material forms perfect small spheres which are built up from laminations of extremely pure iron with a particle diameter of less than 10 microns and with a majority of particles about the 1 micron range ($10\ \mu =$ 0·01 mm. = ·0004 in.). The largest particles of carbonyl iron powder are annealed and used for loading coils, while the finest particles are used for radio frequency work.

The high costs of carbonyl powder and the monopoly position lead to the employment of substitutes, and ground magnetite (Fe_3O_4) was used in Canada and America with little success. German firms tried to reduce the costs with as little reduction in performance as possible, and used Fe_3O_4 and other oxides for the return cylinders of pot-shaped cores and flanges of reel cores while retaining carbonyl for the more important part inside the coil winding.

Carbonyl iron powder is now produced in many countries in sufficient quantities, but the search for cheaper powders continues. The reduction of production costs has reached a new importance with increased tonnage required for other branches of powder metallurgy, and the U.S.A. Government has set aside $600,000[10] for the successful development of a cheap iron powder production method. While such a powder must not necessarily be suitable for dust core purposes, it will no doubt influence development in this direction as well.

The discussed powder grades can in the main be allocated to our two dust core type groups. Large particle size, high initial permeability, low hysteresis losses and high resistivity are essential for telephone loading work, while a very fine subdivision will be the main consideration for radio work. Permalloy answers the requirements of the first group, while carbonyl iron powder is chiefly used for the radio work. There is no sharp division, and a special grade carbonyl powder is used for loading coil core purposes in Germany (due to the nickel shortage), while the finer grades of permalloy are used for medium frequency cores in certain instances.

The question of the latter employment has recently been discussed by Welsby[25], and the author[12]. The accompanying Fig. 8 is a reproduction from Kersten's paper[14] illustrating the basis for the contention that an increase in initial particle permeability (identified by μ_{wahr}) would not lead to an increased core permeability μ for radio cores. The curves are drawn for the different volume percentages of insulating material and the permeabilities are given as multiples of the permeability of vacuum, designated as μ_0.

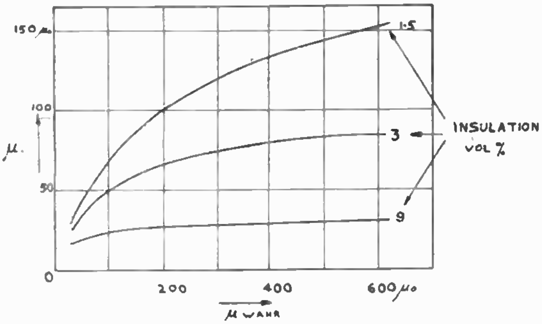

Fig. 8.

The curves were drawn as illustration for one of Kersten's formulæ, which is only valid for cases in which the volume percentage of the insulation is very much smaller than 1. No limits are given and the curves are calculated and not experimentally established. When considering the illustration it should be kept in mind that the initial particle permeability has been given as 150 for carbonyl powder[17], and 220 for molybdenum permalloy[24].

TABLE 3.

Test Core	Spec. gr. gr/cm³	1 Mc/s		20 Mc/s	
		μ	Q	μ	Q
Commercial	4·62	2·15	192	1·58	131
Material A	4·52	2·15	190	1·58	136
Material B	4·14	2·15	185	1·58	105

Test core dimensions : ·375 in. diameter and ·5 in. long.

Test coils: 1 Mc/s—100 turns 9/45 on 4-sectioned former ; 20 Mc/s—4 turns s.w.g. on 4-sectioned former. The 1 Mc/s coil covered $\frac{1}{16}$ in. length of the core and the 20 Mc/s covered the middle $\frac{1}{4}$ in. only.

Core materials : A was a carbonyl iron powder with small spherical particles, and B a nickel iron alloy powder with larger, irregular shaped particles. Both were insulated in the same way but slightly different from the commercial test core chosen.

Experience differed from this interpretation and some measurements were made which are tabulated in Table 3. It was decided to prepare h.f. cores from carbonyl iron powder (core A) and permalloy powder (core B) according to the same recipe and process. To make sure, the permeability was checked against a commercial core, the insulation process of which is not known. Its performance suggests that it is made from carbonyl iron powder.

The permeability and Q figures for all cores can be considered as corresponding at 1 Mc/s, while the specific gravity values vary considerably. Nickel iron alloys in itself have a higher density than iron, and the low specific gravity at standard permeability for core B indicates that less metal is present. Actually cores of a density of 4·63 were pressed from the B material and showed an increased effective permeability coupled with a slight increase in Q at 1 Mc/s. The figures for 20 Mc/s show that the permalloy, probably due to its coarseness, is not suitable for higher frequencies.

The above figures prove the value of permalloy powders for medium frequency cores with increased effective permeability. Carbonyl iron powder can be employed for cores up to 30 Mc/s, and reports from the U.S.A. mention special alloys[26] which have been employed with advantage at frequencies of 150 Mc/s. Nothing is, however, known about the alloy which would indicate to what features the good properties are attributable.

The specific permeabilities of cores produced from the above powder groups are generally as follows :

Radio cores, 10-20.

Loading coil cores from carbonyl powder, 60.

Loading coil cores from permalloy, 90-140.

The Insulation

The metal dust has to be insulated in such a way that as many particles as possible receive an independent insulating film which is hard enough to withstand the pressure. The insulated dust must also easily be moulded into the required shape and to close tolerances. The rust proofing of iron dust powder brings up a further problem.

The insulating process is again entirely different for radio cores and loading coil cores. Even if every small particle in a radio core is covered with a film, the problem of binding the insulated particles together into a homogeneous body has to be tackled. The processes vary therefore considerably, and some manufacturers employ separate insulators and binders, while others prefer the binder to do both jobs at the same time, trying to obtain the insulating and binding properties by process manipulation.

Loading coil toroids present a different problem. Only less than 5 per cent. of the core volume are filled by insulating and binding material. Due to the very high permeability required, the insulator has to withstand much higher pressures as the specific gravity of the pressed toroid comes very near that of the solid material. The particle size and the volume distribution only allows for insulating films in the neighbourhood of 0·5 μ, which distance can just only be detected by optical microscopes. It is, therefore, scarcely astonishing to see the variety of insulators which have at various times been suggested for this purpose: they range from sour milk to sugar, from acids to toxic chemicals, and steam.

The binder for radio cores is in nearly all cases a synthetic plastic material. Both hot and cold moulding is practised with more and more emphasis on the latter. Injection moulding of cores has also been practised in certain cases, but results in cores of relative low permeability. The type of plastics employed also governs the further heat treatment and stabilising process. The metal dust does not require treatment, and the stoving is only essential for the stabilisation of the core.

The binder problem for toroidal cores of high permeability has different aspects. Since the introduction of permalloy type cores, the heat treatment after the moulding was required for strain relief and annealing purposes, and has to be carried out at temperatures which at least char organic substances. Refractory materials were therefore indicated and ceramic insulations have gained ground.

Plant

Considerable attention was paid to the plant question from the beginning of commercial production. It was, however, found that even the real mass production output in this country did not allow the employment of specially designed machinery, and most of the plant consists of adopted machinery originally designed for the plastics industry. It can easily be seen from the aforementioned points that the mixing process is of greatest importance. No new revolutionising mixing methods have, however, been developed, and it seems that this will be one of the greatest handicaps for the core manufacturers.

Radio cores with their large content of binder and an average porosity of 10 to 15 per cent. require relatively small pressures, which will be influenced by core material, core shape and the electrical properties of the metal dust. The cross sections are small and, in spite of pressure variations from 6 to 30 tons/sq. in., mechanical presses are used in preference.

Toroidal cores with their larger areas under pressure, and their high specific permeability, have from the start been subjected to pressures of approximately 100 tons/sq. in. The equipment for these cores is essentially of the heavier hydraulic type.

Where the plant was modernised and more closely adapted, the development has followed the general outline indicated by other branches of powder metallurgy which also influenced the furnaces for the heat treatment.

The Tolerances of Radio Cores

Core manufacturers are handicapped by the fact that the core material will not readily flow under moulding pressure and yet retain its structure. Slow and patient development was essential to obtain the mechanical and electrical tolerances to which the designer is used to-day. The permeability limits have been brought down to plus/minus 2 per cent. from the original plus/minus 10 per cent. Permeability tolerances of plus/minus 1 per cent. can be achieved with additional care. The mechanical limits have been reduced to plus/minus ·005 in. in general with ·002 in. on bores. The concentricity between brass stem and cylindrical core is of great importance and a concentricity of ·003 in. has been guaranteed in special cases. Cores are often subjected to heavy strain and e.g., screw cores are regularly submitted to strength tests, most of which are private arrangements between customer and manufacturer.

Radio cores age slightly during the first few days, but this process is completed before the cores reach the consumer. Special cores with negative and positive temperature coefficient have been developed to compensate circuit members of opposite temperature coefficient value.

Acknowledgment

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LONDON SECTION DISCUSSION

E. Cole : Can the author state the cause of breakdown of dust cores ? Is breakdown due to mechanical vibration of the particles or to some other reason ?

J. A. Sargrove : Reference has been made to the benefits to be derived from standardisation. Successful standardisation is usually reflected in the cost of the article, a fact which frequently is lost sight of by the customers in their reluctance to abide by standards suggested by manufacturers. Nevertheless, I would plead with the radio designer to standardise not only with regard to iron cores, but for all radio parts. I suggest that more thought should be devoted to that problem.

Has the iron dust core industry a real conception of what types of standards would be desired, and could it put forward recommendations which the British Institution of Radio Engineers, or some other body, could make known ?

J. Driscoll : In connection with standardisation we should not overlook the existence of the British Standards Institution, which has co-operated with various bodies from time to time in specifying standard methods and tests and materials for conducting tests. I remember that it has dealt, for instance, with the measurement of incremental permeability of some transformer materials ; and I suggest that the British I.R.E. should request the convening of a committee on standards for cores.

E. Cattanes : As to the technique of powder metallurgy, particularly when using the carbonyl type of iron, do the core manufacturers use a lubricant of some sort to prevent packing ?

Are the pot cores intended to be closed and sealed permanently, and if so, what method of sealing is used ?

Judging from Mr. Friedlaender's survey of the whole position it seems that it has not changed very much during the last ten years. Mr. Colebrook made a very extensive survey of iron cores for the Radio Research Board in 1934, and published it under the title of "Magnetic Materials at R.F." It would appear that the uncertainty as to the quantitative determinations of both the design and utilisation of cores which existed then still persists. But Mr. Friedlaender's concluding statement seems to indicate that we are verging on the point at which this state of affairs will resolve itself into the ability of the core manufacturers to make something to within very close tolerances.

Coming to the historical side of the subject, I know Nissen personally, and I am very sorry that he was not referred to as being the man who introduced the present-day technique of core manufacture. His work was mentioned by Mr. Friedlaender, but he was not given credit for the modern form of iron cored coil ; that explains the delay in using those coils in the past. To my knowledge he used first the carbonyl powder and insulated it with Trolitul ; he was the first to produce the coils, and all modern core manufacture seems to derive from his work or his technique. He had a research laboratory in Berlin, but being a Jew he had to escape from Germany, and he went to Paris.

Reference has been made in the paper to the effective permeability. In that connection, does Mr. Friedlaender take into account the reduction of effective field due to the eddy currents ? There are two values of effective permeability.

With regard to sealing cores, it is known that the German Neosid Company granted a manufacturing licence to a firm known as Ragaunot in France. They were the first to seal cores permanently by the method of polymerization of the plastic binder and insulator. All other seals and cores have an ageing factor by which is meant the effect due to the change in gap due to setting of the adhesive used. As ageing factors were not mentioned, I am wondering whether the practice of using adhesives still obtains.

W. F. Randall : I am interested in the reason for the residual losses in the cores. I would ask whether the magnitude or proportional magnitude of those losses is the same in the case of carbonyl iron as in nickel iron.

Secondly, have trials been made or has any improvement been effected by the magnetic directionalisation of particles.

The residual losses may be due to a slipping effect, for the particles are enclosed in a fairly unyielding matrix and the magnetisation will set up extensions which may cause stresses, increasing the losses within the particles.

Further, figures have been shown indicating that the permeability is improved in the case of nickel iron as against carbonyl iron. That would not apply in the case of cores having only 40 to 50 per cent. metal in them, I gather, because dust particles may be spaced at a distance of four or five times their diameter from each other by insulation and I should not imagine that the overall permeability would be increased.

H. L. Ranson : One of the many arguments against the use of the more complicated forms of core construction was that cost ruled them out. A second argument was that the higher Qs which academically were available were useless in practice in the ordinary commercial set, where the shunt resistance of the circuit discounted all the gain from the high Q coil. That point must be stressed, because in the radio industry, in so far as it is concerned with the ordinary broadcast receivers, we have to scale down the price. Therefore, I think we shall have to wait a long time before the ordinary bar core will disappear from the r.f. or i.f. side.

I feel that in this country insufficient attention has been devoted to the crude methods of manufacture applied, such as the use of single impressing tools to pressing out the cores. The costs are proportionately higher and, as one would expect, the quality is variable as the result of crude methods of production.

Can we rely on negative coefficients from the molybdenum-containing cores to which Mr. Friedlaender has referred ?

Secondly, as one who has had experience in the tropics of the peculiar performance of iron cores, I wonder if Mr. Friedlaender can say anything about the phenomenon of rust, which was very common until a few years ago in material used in Northern Australia, New Guinea, and so on.

S. R. Wilkins : I was very interested in the remarks made about the presence of a metal rod in close proximity to the core, but was disappointed that the author did not take his figures a little higher. I have made some measurements in this connection. Mr. Friedlaender's permeability figure and the loss figure, due to the presence of the metallic rod, went hand-in-hand to about 25 Mc s ; then there was a point between 25 and 35 Mc s at which the brass rod became very effective, and that coincided with the point at which the core had an effective permeability of less than 1. There seemed to be a relationship between the presence of the brass rod and the effective permeability of the core. Has he succeeded in producing h.f. cores having an effective permeability up to 35 or 40 or even 55 Mc/s to give some reasonable variation of inductance ? It may have something to do with the distribution of the particles giving rise to very distinct losses.

By removing the iron dust core completely and leaving the metallic rod, purely by eddy current changes the change in effective inductance was the same, showing that the effective permeability of the rod was practically nil. Have there been more recent developments which allow iron dust cores to give high effective permeabilities at the high frequencies ?

Have they been used effectively ?

Dr. G. A. V. Sowter : In 1932 or 1933 I was very interested in dust cores, and developed a core with a Q of about 450, and I was wondering what improvements have since been made. I would add that when this inductor was used in a commercial wireless set, the associated condenser was so bad that it was decided that the improved Q was not justified. As a result of this I am interested to know whether there is a limit to the value of Q which is desirable, and what actual values are obtainable with modern technique.

Reference has been made to Sendust. I have some slight experience of it, but only on a few Japanese samples which must have been especially good. An initial permeability of the order of a few hundred was obtained, and I am curious to learn whether the use of Sendust has been considered for later applications.

I notice that resistivity is an important factor in the function associated with loss under h.f. conditions. Have the advantages of a high resistivity alloy, such as Rhometal, been explored ?

Further, can Mr. Friedlaender say anything more about ceramics, which have been given a passing mention in his discourse ?

Finally, I recollect a statement in the Press that in certain German equipment which has been captured, dust cores have been incorporated in very small loop aerials. I should like to know whether that sort of device can have post-war application.

G. L. Hamburger : I am puzzled as to why radio manufacturers want Q values higher than 100. If you have an I.F. of 460 and a Q of 100 it gives 4 kc/s. What is the use of aiming at Qs higher than 100 ? You do not want to operate a receiver at 1 k.cs bandwidth.

J. Chamberlain : Mr. Friedlaender has described various devices for comparing the inductance of a coil with and without its paramagnetic core. He describes a "cage" in which the core is enclosed and its inductance measured. The cage is then opened, and the core taken out so that the inductance of the cage may again be measured when the permeability of its interior is that of free space. I have great difficulty in imagining such a cage, for it must have dimensional stability and must comprise a continuous metal spiral of low resistance in which the mechanical division of each turn is possible. I should be very interested to have further particulars of this device, and should be glad if Mr. Friedlaender would indicate the manner in which the above difficulties are overcome.

In addition, I would welcome information concerning the temperature coefficient of inductance of dust cores with some indication of the magnitude and sign of this quantity.

I am particularly anxious to obtain material with high permeability, high saturation value and, most important of all, high specific resistance. This is for the construction of small A.C. electromagnets and relays, and would have the great advantage that the magnetic circuit of such instruments could be enormously simplified by being made solid instead of laminated. Such a material would banish the undue eddy current losses and skin effects which are inherent in all materials at present available when used for the purpose indicated above.

Would it not be possible to produce such a material by the methods of powder metallurgy which Mr. Friedlaender has described? An additional use for such a material would be in the manufacture of small transformers. The core would be moulded solid in two sections, which procedure would very greatly simplify and cheapen the construction of this type of apparatus.

REPLY TO LONDON SECTION DISCUSSION

Mr. E. R. Friedlaender (replying): As Mr. Cole may be aware, breakdowns in finished cores are very rare. During the production they can be due to the irregular, sharp-cornered shape of metal particles piercing the insulation film. Round particles will slide over each other and pack better into the cavities

It is often assumed that this type of breakdown is due to excessive pressure. I am investigating whether this assumption is correct. It seems to me that it may largely depend on the binder used.

The special interest with regard to standardisation lies in its application to test specifications both for the finished core and the metal powders required. Once the tests are standardised, many difficulties will disappear. The help of the British Standards Institution and our Institution would be very valuable.

A word of warning must, however, be said with regard to standardisation of cores as suggested by Mr. Sargrove. While standardisation can, and will, cheapen the core, it has its limitations. There is a certain danger that cores are used for other purposes than those for which they are designed, and the core manufacturer is told that the core does not come up to expectations. Very often, the application or circumstances of the experiments are not even mentioned. On the other hand, core designers may not always take the trouble to question the customer sufficiently about the proposed application before submitting samples.

Mr. Cattanes brought up several interesting points. Lubricants for carbonyl iron powder are not used in the powder metallurgical sense, since the powder is mixed with a binder which normally contains some plasticiser. Much depends on the method of moulding, hot or cold.

The method of sealing the pot cores is usually left to the designer of coils and is not specified by the core designer. In many cases, the core halves are pressed together by mechanical means. The main point is that the centre bosses of the two halves meet, as an air gap at this point would affect the effective permeability. Permanent sealing is of importance only in very specialised cases.

Ageing is a very important characteristic, and we have found that cores age shortly after the manufacture. This ageing takes place within the first week and usually before the core has reached the coil manufacturer. It produces small changes both in permeability and Q. The ageing effect may vary between different brands of cores, as I am convinced that it is a factor of the heat-treatment of the core.

I agree that there have been no revolutionary changes in the dust core industry during the last ten years. It has been a period of very hard development work which has made the dust core a commercial mass-production proposition. If it is thought that the development is so small, it would be advisable to consider that plus/minus 1 per cent. tolerances on effective permeability can be guaranteed to-day, if required.

There is a suggestion that I did not give sufficient credit to Nissen. There is something of a fight between Vogt and Nissen, both of which claim to have invented the iron-cored coil of modern small dimensions. As both put the coils forward at about the same time, I have avoided mentioning this question.

Effective permeability is measured by putting the core into a coil and measuring the inductance with and without the core. The relation between the two gives the necessary information. This figure includes, of course, the reduction of the effective permeability due to any eddy current shielding.

The percentage increase of effective permeability produced in radio cores by the substitution of permalloy for carbonyl iron powder is nothing like its increase in audio-frequency cores, where the highest permeability on toroidal cores is only 60 for carbonyl iron powder, as compared with 150 for permalloy powder types. This is partly due to the fact that for these lower frequencies the loss coefficients are lower and the resistivity higher.

It is very difficult to give Mr. Randall an explanation for the residual loss. Our approximations in calculating and/or graphically determining the eddy current and hysteresis losses will account for a varying percentage of this residual loss. It often appears to me that this loss is called " residual " because it contains the residue of all our approximations and mistakes.

Directionalisation of powder particles has been used by Vogt and others. It had its origin in the crude and irregular powder particles employed and had no importance once the better powder types were developed.

I think it rather unfair to blame the core manufacturers for the high cost of the cores. Unfortunately, there is no getting away from the fact that powder prices dominate the cost of powder metallurgy.

The high " Q " coil is certainly not lost in an ordinary set if and when properly employed. As an example for Mr. Ranson, I would point out that the Germans employ ceramics in coil formers. If you use a good core and sacrifice the benefits to be derived therefrom by badly designing the set in which it is used or try to save on the former, then money is wasted. There is now a different attitude to design, and we may hope for better design and performance.

Criticism has been directed to the crude methods by which powder cores are manufactured, e.g. the use of single impression tools. It is quite possible to design machines, giving an output of, say, 500 cores per minute. These machines are very costly to design and build if the cores shall still be subject to the now usual limits. These machines which Mr. Ranson envisages can only be employed when long runs at this production rate become feasible.

I had no opportunity to test the latest toroidal cores containing molybdenum and can only refer to American papers.

The rust proofing has been a source of considerable trouble. At the moment I am awaiting independent results on rust proofing work which I trust will be satisfactory.

Mr. Wilkins raises a point which is much influenced by the conditions of the experiment. Our cores are effectively used in the 30 Mc s range, and this seems to be contradictory to his experience. Cores have in the States been used up to 150 Mc/s. I have had no opportunity to examine such cores, and have been very much surprised.

I gather that our Chairman has developed a cored coil with a "Q" of 450 at 1 Mc/s. I personally should be very glad to produce such a core commercially. Shortly before the war, a customer told me that he had obtained a " Q " value of 450 to 500 with our cores, but I am very sceptical. Discounting these high values, we are always trying to improve the commercial core. The chain of problems is endless, and improvements will not be revolutionary unless the metallurgists supply us with an entirely new set of suitable powders. Other improvements will be small and gradual, and may include modification of core shapes.

I am not in the position to give more details on ceramic insulations, but have to refer to the material published in the *Bell System Technical Journal.*

In reply to Mr. Chamberlain, I would point out that the cage for measuring toroidal corex permeability is described in the proceeding of the Siemens Works, but no details are given. I imagine that it is an arrangement of very fine tubes which is flexible enough to yield without altering markedly the spacing of its winding. The temperature coefficient of radio dust cores will vary from manufacturer to manufacturer and will in many cases not have been measured for the simple reason that it seems to have been satisfactory enough for the users. Mr. Chamberlain's suggestions for small transformers are very interesting, but I am afraid that, due to the very distinct subdivision of the magnetic material in dust cores, the permeability obtainable is too low for such purposes and that for the time being the solution must be sought in other directions.

MIDLANDS SECTION DISCUSSION

Mr. D. E. Head : With reference to loading coils, I should like to emphasise the importance of the dust core. Prior to its introduction, the loading pots in telephone cables often weighed over a ton and were inserted in the cables at every 2,000 yards. With the advent of the dust core, particularly of the modern type, the size of the core has been reduced by some 70 per cent., with the result that nowadays the loading coil pots are very much smaller and much more convenient. Carrier work having been introduced into telephony, loading has been obviated, but again the dust core has entered very considerably into the design of filters for carrier working. It would be interesting to know to what extent the inductance of these coils varies in frequency.

In the design of a complete coil the advantages of the modern core, I take it, are very much linked up with the copper losses of the coil, and I am wondering to what extent the manufacturers of the cores have trouble with people buying coils. That is to say, do the manufacturers of the cores manufacture them as a whole or are the cores sold as separate components and to what extent is there co-operation between core designers and coil designers?

As to specific permeability, for optimum specific permeability I assume that there are definite proportions of nickel and iron. I believe that in the case of ordinary nickel-iron laminations the figure of optimum permeability is something like 78 per cent. nickel. Does that apply in dust cores ? I take it that the heat treatment which is so necessary with ordinary nickel-iron cores is obviated altogether in the manufacture of the dust core.

Mr. A. Shipton : Some time ago I had some standard high frequency sets which we had taken a great deal of trouble to make. There were three stages of amplification and ordinary commercial dust cores were used. Over a period of two years the cores appeared to have aged considerably. I should like to know whether that is a normal effect. It has been suggested that it might be due to the iron piling up mechanically and becoming cohesive.

Mr. G. F. Knewstub : In my experience it is quite usual for the Q to fall off after a comparatively limited time—perhaps eighteen months or a couple of years—and the matter of changing the cores does not, as a rule, effect any particular improvement. In my personal opinion we must look for the cause in chemical changes in the properties of the former on which the coil is wound. Another important matter is that of insulation. I should like to ask what effect, if any, the use of magnetic dust iron cores has on the signal to noise ratio.

Mr. W. T. Warnock : Until listening to Mr. Friedlaender's interesting paper on "Magnetic Dust Cores" I had not realised that so much detail was available for their construction. I believe that one of the first attempts to arrive at something like a dust core was made by Heaviside.

Reference has recently been made to synthetic resins, and I should like to know whether that is the usual separative in magnetic dust cores.

Quite a bit of cross modulation in receivers can be caused in the transformers. Will dust cores alleviate that or leave the possible cross modulation in transformers just as bad as ever? Mr. Friedlaender has once again shown the need for co-ordination, not only in radio research, but research as a whole. Very often members of the research laboratories make discoveries which, if pursued, might yield something far-reaching. Unfortunately, however, due to other considerations—costs, manufacturing procedures and so on—they are not pursued, with the result that, too often, developments which really make history come from the other side of the Atlantic. Now that we have the project from the Brit.I.R.E. on radio research, I think we should, if possible, try to overcome that deficiency.

Mr. F. H. Alston : How does one of the first commercial iron cores for high frequency work of about 1930 compare with the more modern dust cores? How does the magnetic dust core effect ultimate optimum magnetic length?

Mr. W. Finn : With reference to losses mentioned which were, of course, of primary importance, could Mr. Friedlaender give the meeting any idea of the magnitude of the relative losses under the headings *a*, *c* and *e*? With regard to metal alloys, most of them showed a considerable reduction in permeability when subjected to mechanical stress. It would be interesting to know whether, in pressing up the cores, this point was kept in mind.

REPLY TO THE MIDLANDS SECTION DISCUSSION

Mr. Friedlaender : Radio cores are usually sold to radio manufacturers to wind their own coils, but the matter is different with telephone contracts. The manufacture of cores is not always determined by maximum specific permeability and is very often a compromise between optimum permeability and other requirements. The nickel-iron alloy for cores contains mostly 81 per cent. nickel and for this type of cores for telephone work heat treatment is highly essential, while radio dust cores are only heat treated to stabilise the core binder.

The stability of cores will of course depend on the manufacturing methods and the year of manufacture. Modern cores will be more stable, but I wonder whether any corrosion has been observed which could account for some frequency drift, but scarcely for a large drop in Q.

It must be remembered that the performance of cores is not only dependent on the performance of the core, and with regard to stability I can only speak for the dust core. The influence of cores on the signal to noise ratio is therefore a bit of a poser, as it really comes under receiver design and will be governed by a multitude of influences, independent of cores.

Heaviside's pioneer work is unquestionable, and I have always stressed it, as it tends to be overlooked. Synthetic resins are to-day used as binders for radio dust cores, but not for telephone cores. Sometimes insulators are used in addition, but in some cases the resin serves both purposes. The influence of cross modulation again depends on so many factors that the receiver designer is more qualified to answer.

Considerable temperature changes do not often occur, but they can be compensated for if the temperature change is so large that it would affect the permeability of a standard core. Quite recently cores have been developed using a nickel-iron alloy powder containing 2 per cent. molybdenum. If this percentage is increased to 12 per cent. the Curie point will occur at room temperature and the material will become non-magnetic at room temperatures. In certain cases negative temperature coefficients can be obtained.

The first cores for radio purposes rather differed from to-day's. Long paper bands were sprayed with a resin and iron filings were dropped on to the paper. Sometimes the filings were magnetically orientated. The paper layers were stamped into shape and the necessary number of layers consolidated under pressure. This method was soon stopped due to instability and inaccuracy.

Applications of dust cores are so many that it is difficult to speak of optimum magnetic length. In the case of permeability tuning the length of a coil is determined by the ratio of change of inductance which we want to obtain, and to obtain this ratio other performance characteristics must often be sacrificed. Maximum permeability and maximum Q for radio cores do not fall together.

For a core with a specific permeability of 11·7 the following coefficients were obtained :—

$$a = 2{\cdot}7 \times 10^{-5}$$

$$c = 8 \times 10^{-5}$$

$$e = 0{\cdot}51 \times 10^{-9}$$

The reduction of permeability due to mechanical stresses is due to the high pressure used, for example, for toroidal high permeability cores. The previously mentioned heat treatment leads to stress relief, and this is one of the reasons why it is so critical.

TRANSFERS AND ELECTIONS TO MEMBERSHIP

Since April 1st, 1945, the Membership Committee have considered 24 proposals for transfer to a higher grade of membership and 44 proposals for direct election to Graduateship or higher grade membership. The following transfers and direct elections were recommended by the Membership Committee at their last three meetings, and have now been confirmed by the General Council.

Transfers

From Associate Member to Full Member

HUDSON-DAVIES, John	Khartoum

From Associate to Full Member

MAZDON, James Frederick Sq. Ldr., M.B.E.	London, S.W.9

From Associate to Associate Member

BROOM, Ronald Sherwood	Paignton
HANNAM, William Harold	Leominster
IRONMONGER, John Edward	Putney, S.W.15
JACHESS, Denis Godfrey, B.Sc.	London, N.W.11
WATKINS, Francis James	Rutherglen, Lanarks.

From Student to Companion

AUSTEN, Frank Henry	Margate, Kent

From Student to Associate

CAMERON, James Dalziel	Larkhall, Lanarks.
JONES, John Elfed, B.Sc.(Hons.)	Hull, Yorks.
LUCKETT, William Roy	Hereford
MORAN, Robert Roy	Earls Croome
TITMUSS, Walter Ernest	Sutton Scotney
WARD, Leslie	Preston, Lancs.
WHITE, Hubert Percival, B.Sc.	Poole, Dorset

From Student to Graduate

FALLON, Francis Rooney	Glasgow

Direct Elections

To Full Member

CORDINGLY, Norman Charles, W Cmdr., M.B.E.	London, N.W.11
McMENEMY, William, W/Cmdr.	Falkirk
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DIELECTRIC HEATING BY THE RADIO FREQUENCY METHOD

by

L. Grinstead, M.I.E.E. (*Member*)*

(Read before the Institution in London on February 28th, 1945, and repeated before the Midlands Section on March 28th, 1945, and the North-Eastern Section on April 18th, 1945.)

Summary

After a brief reference to some of the applications of radio-frequency energy to the heating of dielectric materials, the general theory of the method is outlined.

The heat and power relations governing all such uses are discussed in some detail with special reference to sources of electrical and thermal loss in the generator and the work. It is shown that, for minimum losses and a reasonably good temperature distribution, fast heating is desirable. A family of curves is included enabling relative performances of various generators in terms of power and time to be rapidly determined.

The basic circuits for dielectric heating equipments are briefly reviewed and the need for correct loading of the transmitting valves is explained.

Two of the more usual load coupling circuits are analysed so that the effects on loading and efficiency of varying circuit parameters may be studied. It is shown that the series-capacitance type of circuit can, under certain conditions, maintain nearly constant power in the work during a heating cycle. For transformer circuits, the conclusions reached show that a proper value of coupling coefficient is desirable in the interest of circuit efficiency.

TABLE OF CONTENTS

Introduction.

For many years it has been a well-known fact that any insulating material placed in an alternating electric field experiences stresses acting in the direction of the field. The resulting strain, whether due to electronic, atomic or molecular displacement involves cyclic expenditure of energy which is recoverable only when the material is perfect, i.e., there is no lag between stress and displacement.

All present known materials absorb some of the displacement energy and thereby become heated. From this is derived the concept of power factor which is really the non-recoverable energy expressed as a percentage of the total stored energy. For electrical purposes, stress and displacement are expressed in terms of volts and amperes respectively. The product of these multiplied by the power factor defines the absorbed energy per cycle which is the dissipated power.

Until comparatively recent times, the heating effect just outlined was regarded only as a nuisance by engineers since such an unwanted energy loss naturally detracted from the overall efficiency of any piece of electrical or radio equipment.

To-day, the need has arisen for essentially uniform heating of electrically non-conducting materials such as wood, plastic materials and various less well-defined chemical substances, all of which are poor heat-conductors. Thus the effect mentioned above can be turned to account and forms the basis of dielectric loss heating, now being adopted in many industries. As this new method depends solely on generation of heat

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* Philips Lamps, Ltd.

within the mass of the material, it enables operations of a nature hitherto impracticable with older methods to be performed successfully.

The use of radio frequency apparatus for dielectric heating has already been exploited, particularly in America, for such diverse purposes as the preheating of bakelite powders and pellets, prior to compression moulding, the drying of timber and tobacco, the spot welding of veneers and thin sheets of plastic material, the glueing of wood,[2] the manufacture of plywood and high density boards of fabric or wood veneers and the dehydration of various foodstuffs.[3]

A great many articles have been written during the past two years on the subject of radio frequency heating, largely concerned with processes and the characteristics of particular materials, but few technical papers have dealt with the matter from the point of view of engineering a complete equipment to meet specified requirements.

Apart from a number of detailed problems dependent on the exact requirements of a particular heating operation there are two main questions to be solved in every case. The solutions to them both will decide whether or not a project is practicable from the technical and economic aspects. These immediate problems are :—

(*a*) To determine the total power which must be supplied in terms of heat generation to carry out the required process in a specified time.

(*b*) To provide suitable electrical circuits to permit the power density indicated by solution of question (*a*) to be attained.

So far as the first problem is concerned it can be said that in principle there is always a technical solutiont, but not necessarily an economic one. The factors concerned are considered in some detail in section (3).

The second problem is often difficult of technical solution where irregular objects require to be heated and especially so where a range of work is envisaged. Some of the methods employed are discussed in section (5).

(2) Principles of Dielectric Heating

No dielectric yet discovered is perfect in that all cause some dissipation of power when stressed by an alternating electric field. In practical heating applications advantage is taken of this fact by employing the non-conducting material as the dielectric of a condenser which frequently takes the conventional parallel plate form. This is understandable when it is realised that uniformity of heat production demands a uniform electric field, i.e. a constant value for electric stress throughout the material to be treated.

The equivalent circuit for dielectric heating is thus illustrated by Fig. 1 where R represents the effective resistance responsible for the power dissipation.

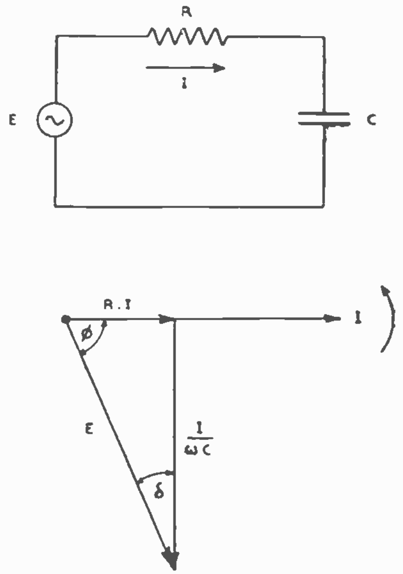

Fig. 1.—Equivalent circuit for dielectric heating and vector diagram for derivation of power factor.

Generally, however, the quality of the dielectric is expressed by its power factor cos ϕ or, more conveniently, by tan δ whenever the reactance is sufficiently high to ensure the condition $1/\omega CR > 10$ being met.

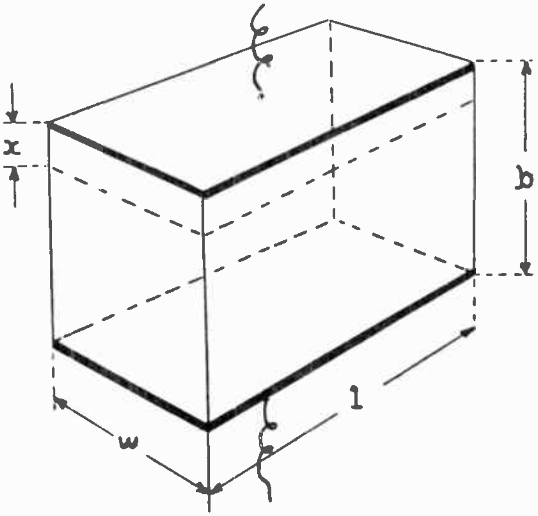

Fig. 2.—Rectangular block of dielectric material. The temperature distribution is determined for various planes, parallel with the electrodes, distant x from one of the electrodes.

As the reactance of the condenser X_c is given by $1/\omega C$, the current resulting from an applied voltage E at radio frequency, when R is small, is :—

$$I = E\omega C \times 10^{-6} \text{ amperes} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where E = generator voltage.
$\omega = 2\pi f$.
f = frequency in Mc/s.
C = capacitance in pF.

The product of I and E gives the stored energy per cycle of the system expressed in volt-amperes, and when multiplied by the power-factor of the condenser leads to the following expression for power dissipated in the dielectric :—

$$W = E^2\omega C \tan\delta \times 10^{-6} \text{ watts} \quad \ldots\ldots\ldots (2)$$

It is clear that the power loss in a given dielectric varies directly as the frequency and as the square of the applied voltage. As it stands, however, equation (2) is not convenient for practical work, and a modified form is developed in the appropriate section of the paper.

The relation does however show that, in principle, there is no limit to the amount of heat that can be generated by the radio frequency method. In fact, practical considerations of valves and circuits put an upper limit to the value of $E^2\omega$, and this limit is not unrelated to the load capacitance concerned which itself is governed by the shape and physical properties of the material to be heated.

(3) Heat and Power Relations

In order to raise any body to a given temperature in a specified interval of time a certain minimum quantity of heat energy is required, and this is directly related to the expenditure of power. Consider the block of material pictured in Fig. 2. The heat required is :

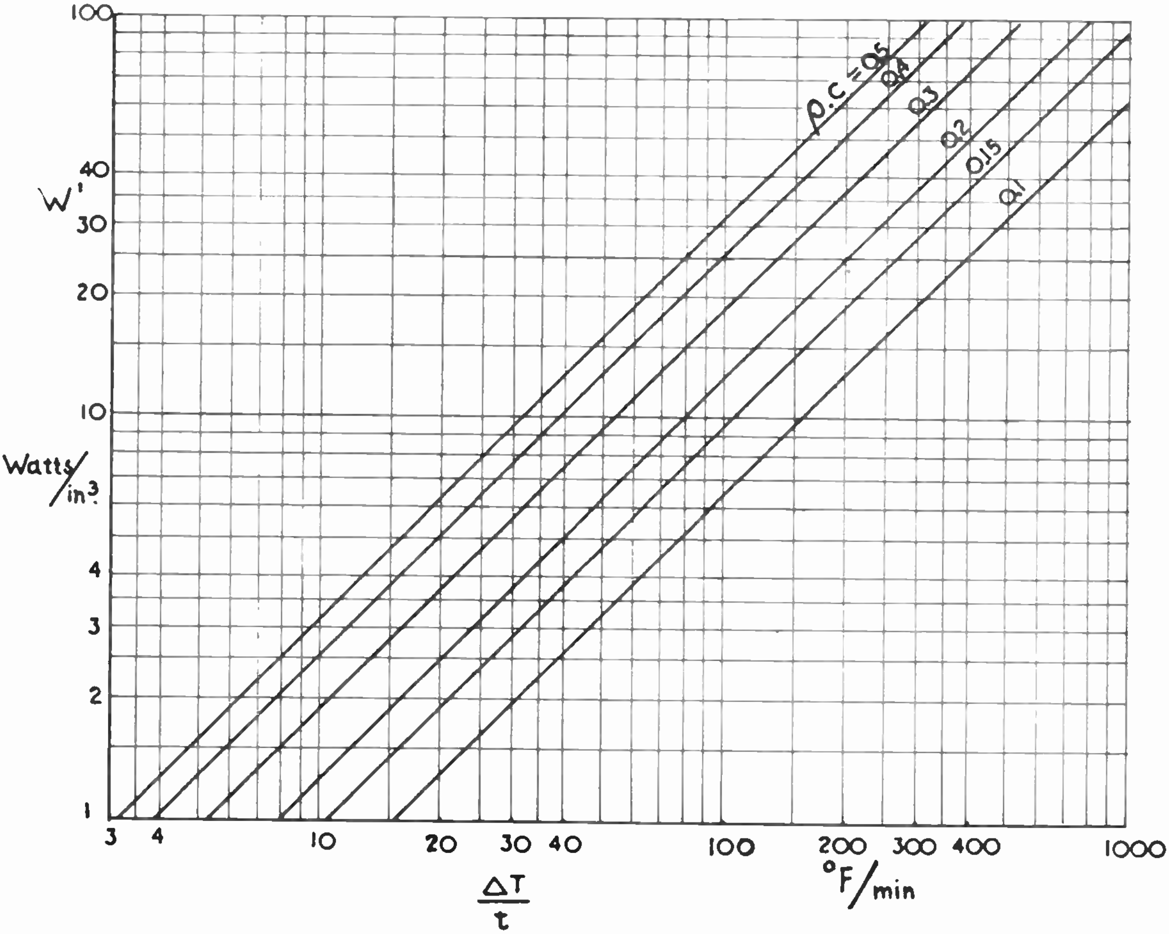

Fig. 3.—Power concentration necessary with various materials to secure a specified rate of temperature rise.

$H = \rho.c.v.\ \Delta T$ grm. calories .... (3)

where c = specific heat (cal. per grm.per deg. C.)

ρ = specific gravity (grm. per cm.^{3})

v = volume (cm.^{3})

ΔT = temperature rise (deg. C.)

The power required to produce this minimum quantity of heat in the given time t (sec.) is :

$W = 4{\cdot}18\,\rho.c.v.\ \Delta T/t$ watts .... (4)

For practical calculations it is usually preferable to work in terms of power density in the material under treatment, and in many industries units of minutes, inches and deg. F. are in common use. Equation (4) is then changed to :

$W' = W/v = 0{\cdot}637\,\rho.c.\ \Delta T/t$ watts/in^3 .... (5)

This relation is shown in graph form in Fig. 3, where W′ is shown as a function of $\Delta T/t$ with the product $\rho.c.$ as a parameter. It is clear that dense materials of high specific heat require a high power concentration which increases directly in proportion to the rate of temperature rise required.

An important point to remember is that the power calculated by the use of equation (5) is the net power required without reference to losses in the radio frequency generator, discussed later in this section, and it does not take into account heat losses by radiation, convection and conduction. The heat lost by conduction is not usually negligible in practical arrangements, and the convection and radiation losses can be appreciable in some circumstances. In connection with conduction-loss, G. H. Brown[4] has recently developed some interesting equations as solutions to thermal problems encountered in the heating of wood blocks, which are capable of wider use with suitable amendments to certain constants. In his analysis of heating by the dielectric loss method he shows that the temperature reached at selected planes of a rectangular block after a given period of time may be expressed as*

$$T(x) = \frac{4\,H^1 b^2}{\pi^3 k}\left[(1 - e^{-\pi^2\alpha^2 t/b^2})\sin\left(\frac{\pi x}{b}\right) + \frac{(1 - e^{-3^2\pi^2\alpha^2 t/b^2})}{3^3}\sin\left(\frac{3\pi x}{b}\right) + \frac{(1 - e^{-5^2\pi^2\alpha^2 t/b^2})}{5^3}\sin\left(\frac{5\pi x}{b}\right)\ldots\right] \quad (6)$$

where $T(x)$ = temperature at a plane distant x cm. from one electrode (deg. C.).

H^1 = rate of heat generation (grm cal. per sec. per cm.^{3})

b = thickness of block (cm.)

k = thermal conductivity of block $\left(\frac{\text{cal./cm}^2\text{/sec.}}{\text{deg. C/cm.}}\right)$

α^2 = $k/\rho c$ = thermal diffusivity.

t = time (sec.)

Before simplifying this relation to analyse conditions affecting conduction loss it is of interest to note that the temperature variation throughout the material is intimately connected with the time interval of heat generation and the block thickness. This is well brought out in Fig. 4, which expresses equation (6) generalised in respect of time and material thickness for two values of thermal diffusivity. The units employed for dimensions and time are inches and minutes respectively.

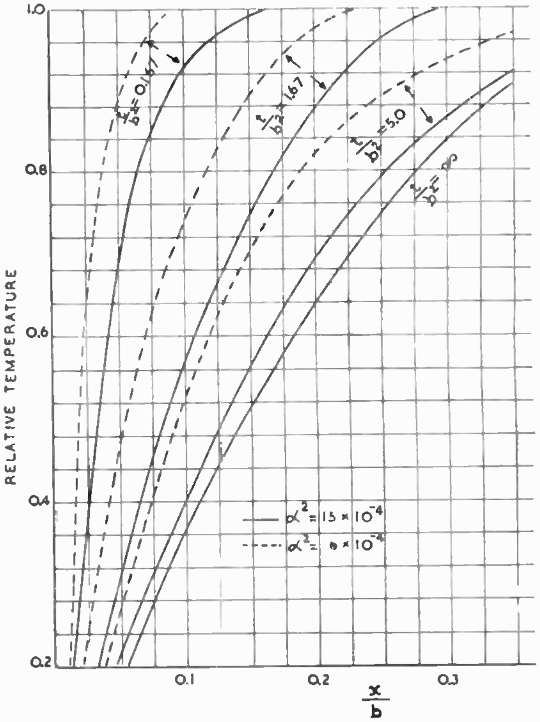

Fig. 4.—Temperature distribution throughout a rectangular block generalised with respect to time and thickness of the block.

It will be noted that for reasonable uniformity of temperature the factor t/b^2 should not be much more than 0·2 for values of α^2 in the range 6 to 15 × 10^{-4}. This implies high power concentration in the work and a short heating cycle which leads to economy in energy consumption, but a high capital cost for the equipment and a poor load-factor. However, it is often possible to supply heat to the electrodes by means of electricity, hot water or steam, to equalise the temperature distribution in the material concerned.

In the absence of such additional heating, thermal loss to the electrodes will occur, and this will modify the power requirements for any given operation.

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* Equation (6) is based on the assumptions that heat is uniformly generated within the material and that the electrodes remain at ambient temperature due to infinitely high thermal capacity.

First, the loss of heat will mean that for each application there is a minimum power which must be supplied to afford a specified temperature rise no matter how long the heating time may be. This may easily be shown by inserting the condition $t = \infty$ into equation (6). As the main interest is in the highest temperature, which is at the centre of the work, the substitution $x = b/2$ is also made. Equation (6) then reduces to the form :

$$W' \text{ (min)} = 47{\cdot}4\, k\Delta T/b^2 \text{ watts/in.}^3 \quad \ldots\ldots\ldots\ldots (7)$$

where k = thermal conductivity of block
b = depth of block (inches)
ΔT = temperature rise (deg. F.)

Fig. 5 shows the relation just derived for various values of b and the product $k \cdot \Delta T$.

Second, the heat loss by conduction means that a power density in excess of that calculated by equation (5) must be employed. For this case the temperature at the centre of the block is again used, permitting the substitution $x = b/2$ to be made, but the series within the brackets of equation (6) has to be summed for various values of α^2 and t/b^2. The additional power required can then be calculated from the relation :

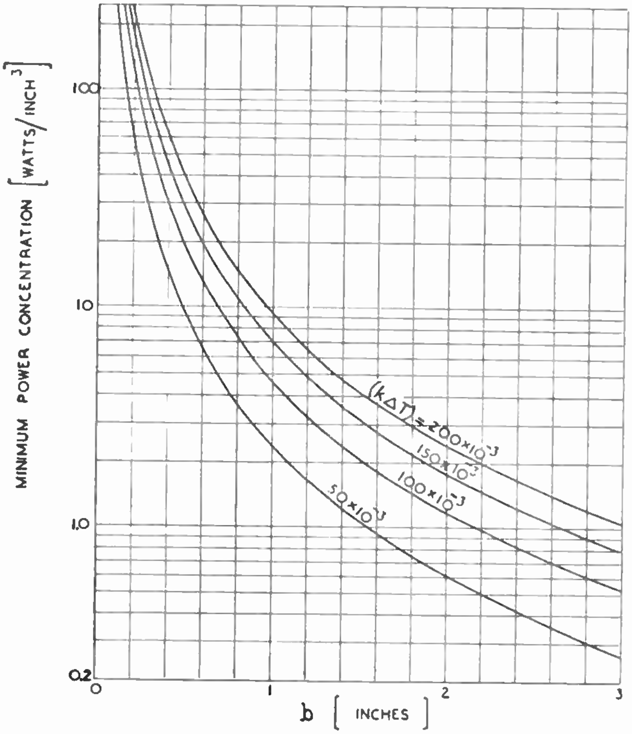


Fig. 5.—Minimum power concentration required with various materials to secure a given temperature increment.

$$\frac{\text{Power with losses}}{\text{Power without losses}} = \frac{72\,\alpha^2\, t/b^2}{\left[\left(1 - e^{-9{\cdot}3\beta t/b^2}\right) - \dfrac{1}{27}\left(1 - e^{-83{\cdot}7\beta t/b^2}\right)\ldots\right]} \quad (8)$$

where t = time (minutes)
b = depth of block (inches)
$\alpha^2 = k/\rho c$
$\beta = \pi^2\alpha^2$

Equation (8) is shown graphically in Fig. 6, which indicates clearly that for high values of thermal diffusivity much additional power is necessary to make good thermal losses unless the value of t/b^2 is kept low.

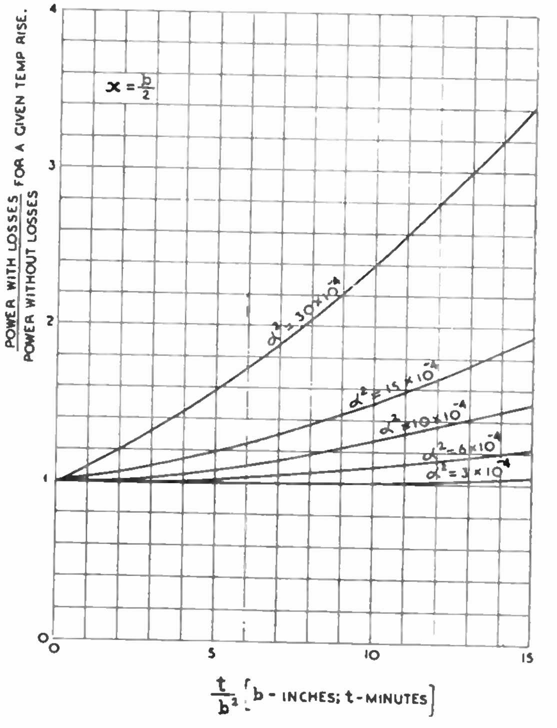


Fig. 6.—Ratio of power required with materials of different thermal diffusivity for a given temperature rise in the presence and absence of electrode conduction loss.

It is often helpful to be able to estimate the reduction in power that can be allowed for a given heating operation if the duration of the heating cycle be extended. Ideally, the reduction in power would be inversely proportional to the increase in time allowed, but in the presence of heat losses this relationship does not hold. In the extreme case of the original power concentration being only just over the minimum specified by equation (7), a substantial reduction of power would mean that the required temperature would never be attained by the work. For intermediate conditions a solution for relative powers for different time intervals can be obtained by evaluating equation (8) with unity substituted for the numerator. This results in Fig. 7, the use of which is best illustrated by an example.

Suppose that by the use of Figs. 3 and 6 it has been determined that a power of 50 kW is needed to raise the temperature of a given block of wood 1 in. thick by a given amount in three minutes. Assuming $\alpha^2 = 10 \times 10^{-4}$ for the wood, Fig. 7 shows that reducing the power to one-third of its former value will necessitate increasing the heating cycle by 3·6 times, while one-quarter of the original power will involve a period 6·7 times as long. The flattening of the curves of Fig. 7 for high values of t/b^2 (they are asymptotic to a relative power of $32/\pi^3 = 1{\cdot}03$) clearly shows that for the case considered the power could not be reduced to one-fifth and still raise the temperature by the required amount, even with an infinite heating time as the minimum power concentration required by Fig. 5 would not then be reached.

Apart from the conduction loss, which has been shown to be more important with thin work specimens, heat loss by radiation from the open ends of a block of material will be of more account where large cross-sections are concerned. It can easily be calculated* that for wood raised to a temperature of 350 deg. F. the radiation loss is about 1·16 watts per square inch.

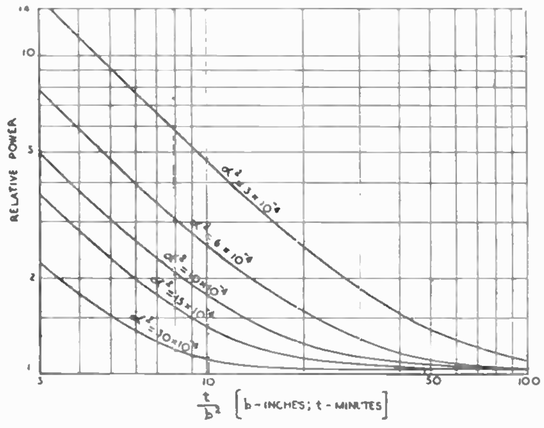


Fig. 7.—Power-time relations for determination of relative performance of a given equipment with materials of varying thermal diffusivity.

Heat loss by convection is more difficult to estimate, but is customarily of the same order as that due to radiation. However, it must not be overlooked that many materials have appreciable water content, the reduction of which at elevated temperatures by evaporation leads to further power demands on account of the high latent heat of evaporation of water (about 600 grm. calories per grm.).

There will, of course, be electrical losses in the generator itself to add to the thermal losses before an estimate of the total power requirement can be made. These are principally to be found under the headings :

(*a*) Power loss in coupling circuits (see section 5).
(*b*) Anode and grid dissipation in the oscillator valves.
(*c*) Power lost in the rectifier unit.
(*d*) Power for filament heating and control circuits.

The major item is undoubtedly the second one, as anode conversion efficiencies of transmitting valves on high frequencies are likely to be in the range 65 to 70 per cent. for frequencies of a few Mc/s and perhaps 55 to 65 per cent. over the frequency band 15 to 40 Mc/s.

Of the true power taken from the mains, therefore, only some 40 to 50 per cent. will be available at the output terminals of the valve generator. The power-factor of the equipment as a whole is high, the nature of the load being essentially resistive. The apparent power-factors of generators incorporating the more popular rectifier arrangements are :—

Single phase full wave (C/T transformer)	0·875
Single phase full wave (bridge connection)	0·875
Three phase half wave (single Y)	0·80
Double three phase half wave (double Y)..	0·925
Three phase full wave (bridge connection)	0·925

Generally for equipments of moderate or high power, for example, upwards of 3 kW output, polyphase rectifiers are installed.

(4) General Electrical Relations

Before studying actual circuits for the production of radio-frequency voltages across the desired load condenser, it is of interest to note certain general relations which arise from the occasional necessity to have additional capacitance in series with or in shunt to the load capacitance. Even when this additional capacitance is loss free (i.e. $\tan \delta = O$) the assemblage will reflect a lower useful power-factor than that of the load itself. Consider the series arrangement of Fig. 8a, and suppose that R_1 has an appreciable value, then :

$$\tan \delta_{(eff)} = \frac{\omega C_1 C_L (R_1 + R_2)}{C_1 + C_L} \quad \ldots\ldots\ldots\ldots(9)$$

By putting C for $C_1C_L/(C_1 + C_L)$, the effective circuit capacity, and expressing $\tan \delta_1$ as $1/\omega C_1 R_1$ and $\tan \delta_L$ as $1/\omega C_L R_2$, a short manipulation gives :

$$\tan \delta_{(eff)} = \frac{C}{C_1} \tan \delta_1 + \frac{C}{C_L} \tan \delta_L \quad \ldots\ldots\ldots(10)$$

---

* By means of the Stefan-Boltzmann relation :

$W/in^2 = 36{\cdot}8\ K\ (T^4 - T_0^4) \times 10^{-12}$

where K = a constant (0·90 for average wood)
T = final temperature (deg absolute)
T° = ambient temperature (deg. absolute)

The first term obviously vanishes in the case of a perfect series condenser C_1. Normal air-dielectric condensers will have a negligible power factor, and it is worth while noting the ratio of supply voltage to load voltage with this condition. This is :

$$\frac{E}{V} = \frac{\dfrac{1}{j\omega C_1} + \dfrac{1}{j\omega C_L} + R_2}{\dfrac{1}{j\omega C_L} + R_2} = 1 + \frac{C_L}{C_1\,(1 + \tan\delta_L)} \qquad (11)$$

The parallel case of Fig. 8b is easily solved, the two capacitances C_1 and C_L practically forming an effective capacitance Cp with an effective power factor :

$$\tan\delta_{(eff)} = C_L \tan\delta_L / Cp \ \ldots\ldots\ldots\ldots\ldots (12)$$

In practice the case frequently arises where the output circuit efficiency must be considered since the inductive branch of the resonant circuit will itself cause an unwanted power loss. For convenience the power-factor of the coil, 1/Q, is expressed as $\tan\delta_1$. Then, at resonance :

$$X_1 = X_2\,X_L/(X_2 + X_L)$$

where $X_1 = \omega L$, $X_2 = 1/\omega C_2$ and $X_L = 1/\omega C_L$. Reference Fig. 8c.

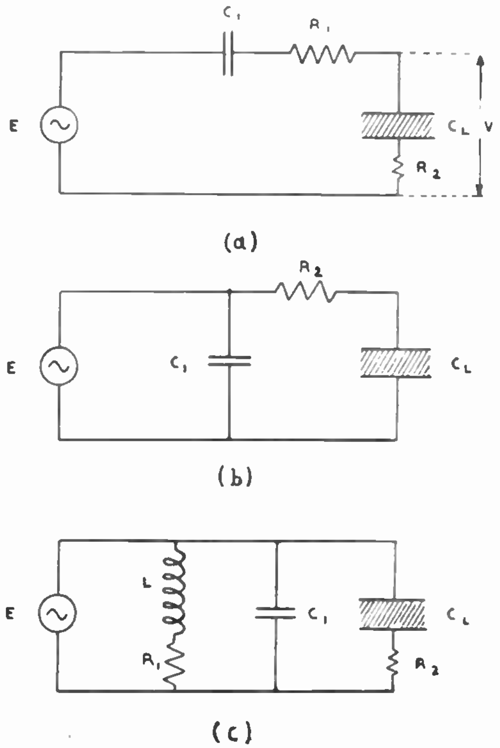


Fig. 8.—Basic load circuits used in analysing effective power factor for dielectric heating calculations.

With an applied voltage E the total power dissipation is :

$$E^2\,(\tan\delta_1/X_1 + \tan\delta_2/X_2 + \tan\delta_L/X_L)$$

Only the last term in this expression represents useful power, from which the efficiency is determined as :

$$\eta = \frac{\tan\delta_L}{\left(1 + \dfrac{X_L}{X_2}\right)\tan\delta_1 + \left(\dfrac{X_L}{X_2}\right)\tan\delta_2 + \tan\delta_L} \qquad (13)$$

Since the reactance-resistance ratio Q. for the capacitance C_2 will normally be from 1,000-2,000 with well designed air-dielectric condensers, the second term in the denominator of equation (13) may be ignored. The effect of the parallel condenser on the efficiency of the assemblage is best shown by Fig. 9, where η is plotted as a function of $\tan\delta_1/\tan\delta_L$ with the ratio C_2/C_L as a parameter.

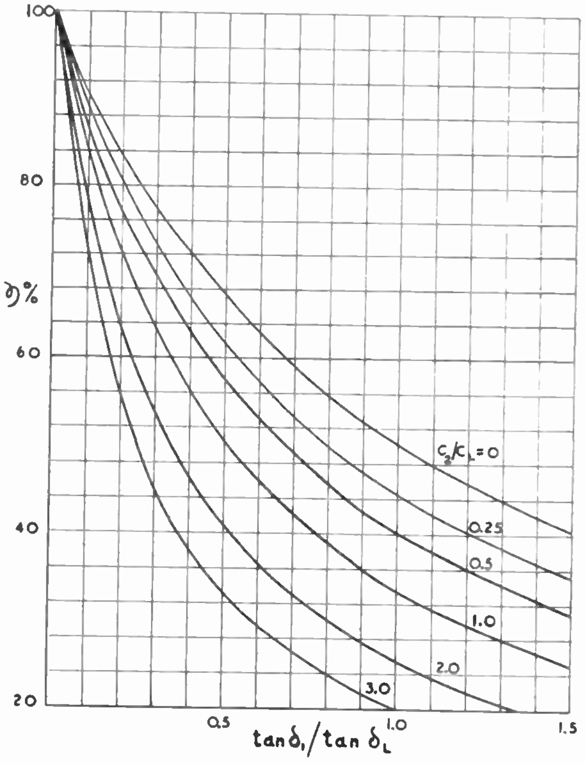


Fig. 9.—Efficiency of the parallel resonant circuit of Fig. 8 (c) showing influence of the condenser C_1 and the coil loss resistance.

It was pointed out in section (2) that equation (2) could be modified to be more useful in practice, and this is advisable if only to render clear the function of frequency of the applied R.F. energy and to correlate the power concentration determined by equation (5) with an equivalent power density determined by the electrical requirements of the work.

Accordingly E may be substituted by $F = E\,b$, the voltage gradient in volts per inch, and $\epsilon A/b$ may be written for C where $A = \omega \times l$ reference Fig. 2. It follows that :

$$W \propto F^2 f \tan \delta . Ab \qquad (14)$$

Noting that Ab is the volume of the material and inserting the necessary constants for the units chosen :

$$W' = 2{\cdot}24\, F^2 f \epsilon \tan \delta \times 10^{-13} \text{ watts/in}^3 \qquad (15)$$

In order to render this equation more simple for graphing, it is preferable to consider a fictitious power concentration W'' such that

$$W'' = W'/\epsilon \tan \delta = 2{\cdot}24\, F^2 f \times 10^{-13} \text{ watts/in}^3 \quad (16)$$

The relation expressed by equation (16) is graphed in Fig. 10, where W'' is shown as a function of frequency with the voltage gradient as a parameter. The voltage gradient and frequency necessary to achieve a power concentration in the work determined by equation (5) in section (3) are thus found by using as an ordinate in Fig. 10 the value of W'' obtained by dividing W' by the product $\epsilon . \tan \delta$.

It will be seen that the higher frequencies permit of lower electric stress in the material which is of importance where thick materials are being treated. However, in general, the use of high frequencies implies, in the absence of special correction stubs, a limit to the length of the work in order to avoid unequal heating brought about by the standing wave effect. Methods of surmounting this difficulty have been described in a recent paper by Bierworth and Hoyler.[5]

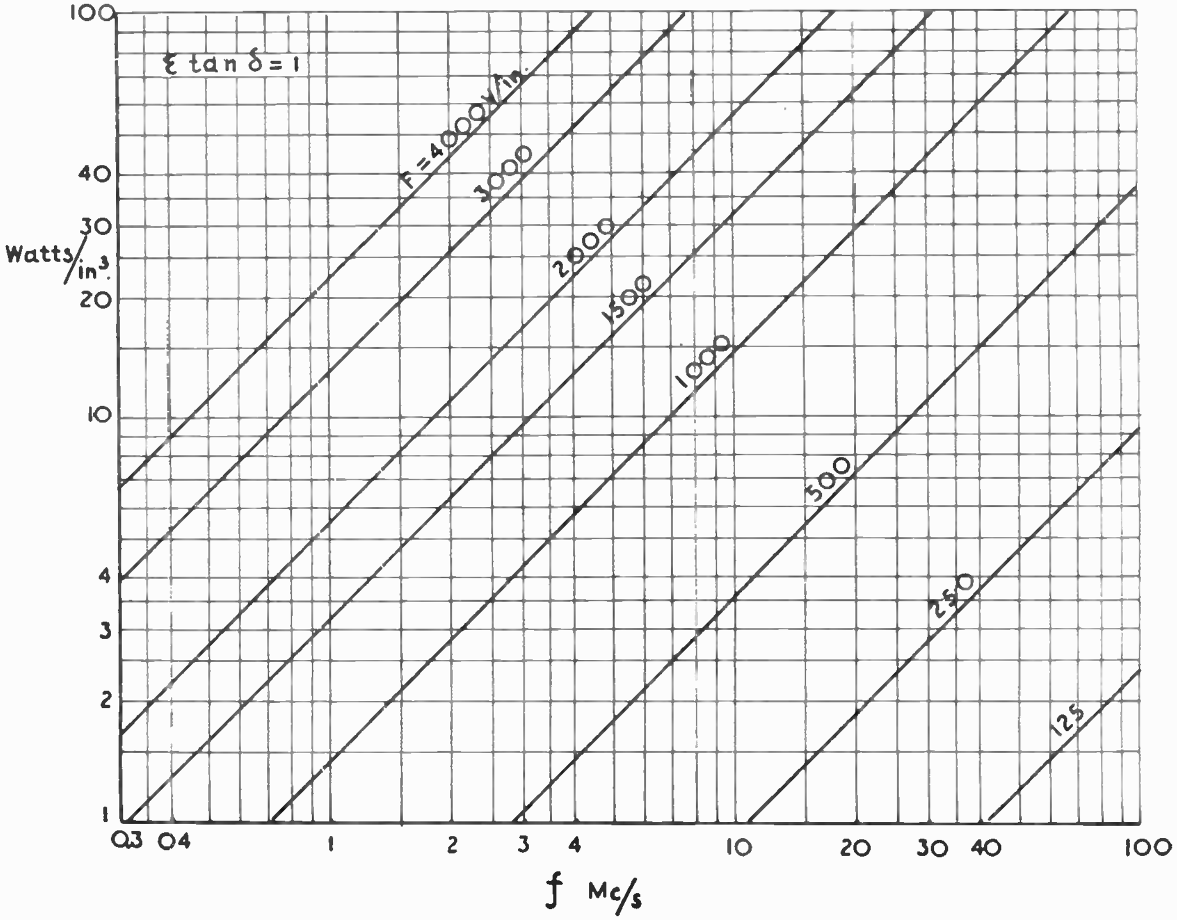


Fig. 10.—Variation of voltage gradient with operating frequency for a given power concentration based on unity power loss factor.

There are, however, other disadvantages in employing unnecessarily high frequencies due to the fact that generator outputs for given transmitting valves are less than at the lower frequencies, and the efficiency of conversion is, moreover, lower; this is on account of restrictions on anode voltage and, ultimately for the highest frequencies, transit time dephasing causing losses which are no longer negligible.

Occasionally the necessity arises to heat together uniformly and equally, two materials of different physical properties. This is possible only when a particular condition can be secured, as can easily be demonstrated by combining equations (5) and (15) to yield an expression for the rate of temperature rise in terms of voltage gradient, frequency, and the physical properties of the specimens, i.e. power-factor, dielectric constant, specific heat and density. This is:

$$\frac{\Delta T}{t} \propto \frac{F^2 f \epsilon \tan \delta}{\rho c} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

As the frequency is not concerned in any relation connecting the ratio of heating rates it may be omitted. Provided the power-factors are low (e.g. $< 0{\cdot}1$) the voltages across the two condensers formed by the specimen practically add up to an applied voltage E. Using subscripts 1 and 2 to denote the two differing materials the voltage gradient for the former is evidently:

$$F_1 = \frac{V_1}{b_1} = \frac{E}{\left(1 + \frac{C_1}{C_2}\right) b_1} = \frac{E\epsilon_2}{(\epsilon_2 b_1 + \epsilon_1 b_2)}$$

Similarly $F_2 = \dfrac{E\epsilon_1}{(\epsilon_2 b_1 + \epsilon_1 b_2)}$

The respective voltage gradients are evidently inversely proportional to the dielectric constants concerned. Equal values of $\Delta T/t$ for the two materials therefore necessitates realisation of the following relation:

$$\epsilon_2 \rho_2 c_2 \tan \delta_1 = \epsilon_1 \rho_1 c_1 \tan \delta_2 \qquad \ldots\ldots\ldots (18)$$

(5) Circuits for Dielectric Heating

(5.1) *Valve Oscillators*

The valve oscillator for high or very high frequencies does not differ in principle from one operating on medium frequencies in that the same design problems exist to ensure a correct value of anode load to obtain full output from the valves, and sufficient grid excitation in antiphase to the anode alternating voltage to enable the rated peak anode current to be drawn from the H.T.D.C. supply, together with a proper value of negative bias for the grid to ensure high conversion efficiency.

In practice, however, there are not many circuits that can be considered reliable for industrial use, and they are generally variants of two basic types. The first is the Hartley circuit for frequencies up to 10 or 15 Mc/s, dependent on the size or the oscillator valve, anode and grid seal arrangements and values of interelectrode capacitance. The second is a type of Colpitts circuit, relying on interelectrode capacitances and essentially lead inductances only, to form the oscillatory circuit. The latter arrangement is useful for the generation of frequencies in the range 20 to 70 Mc/s.

Apart from load coupling arrangements considered in a later section of the paper, the Hartley circuit is sufficiently well known not to require description here. There are, however, special features of the modified Colpitts circuits which need consideration, particularly from the aspect of grid excitation requirements.

In the circuit shown in Fig. 11a the oscillatory circuit comprises an inductance L and the three interelectrode capacitances of the valve. When this circuit

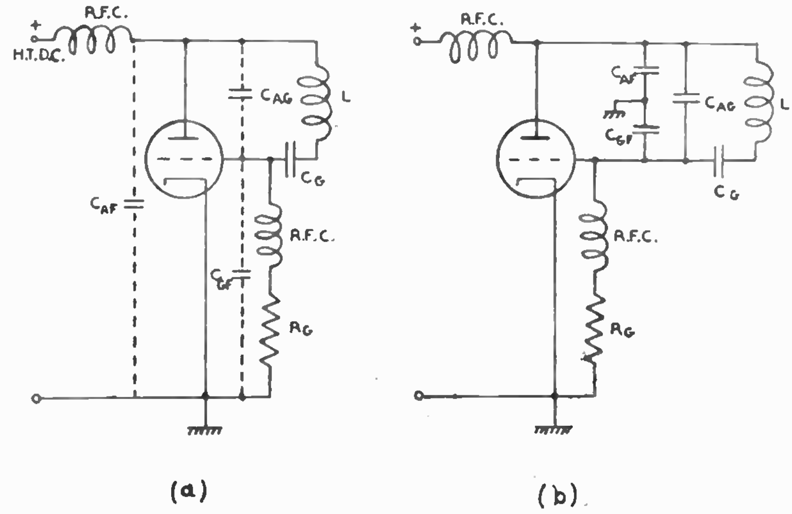
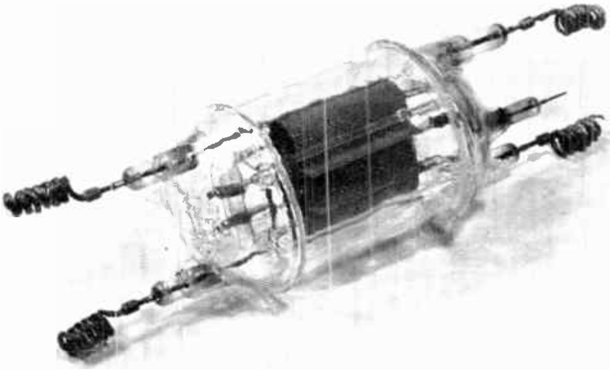


Fig. 11. — Modified shunt-fed Colpitts circuit (a), redrawn to show valve capacitances forming the oscillatory circuit (b) for analysis of grid excitation conditions.



Oscillator type TY 2-300 used in mobile dielectric heating equipment preceding. Maximum rated output is 350 W on frequencies up to 50 Mc/s with anode voltage 2,000 V. Higher frequency operation with reduced output is possible with lower anode voltage.

Oscillator type TXS 10-4,000 *for which dynamic characteristics are given in Fig.* 14. *Maximum rated output is* 6 *kW on frequencies up to* 12 *Mc/s with anode voltage* 10 *kV. Operation at* 15-18 *Mc/s is possible at* 8 *kV with reduced output.*

SILICA TRANSMITTING VALVES

(By courtesy of the Mullard Wireless Service Co., Ltd.)

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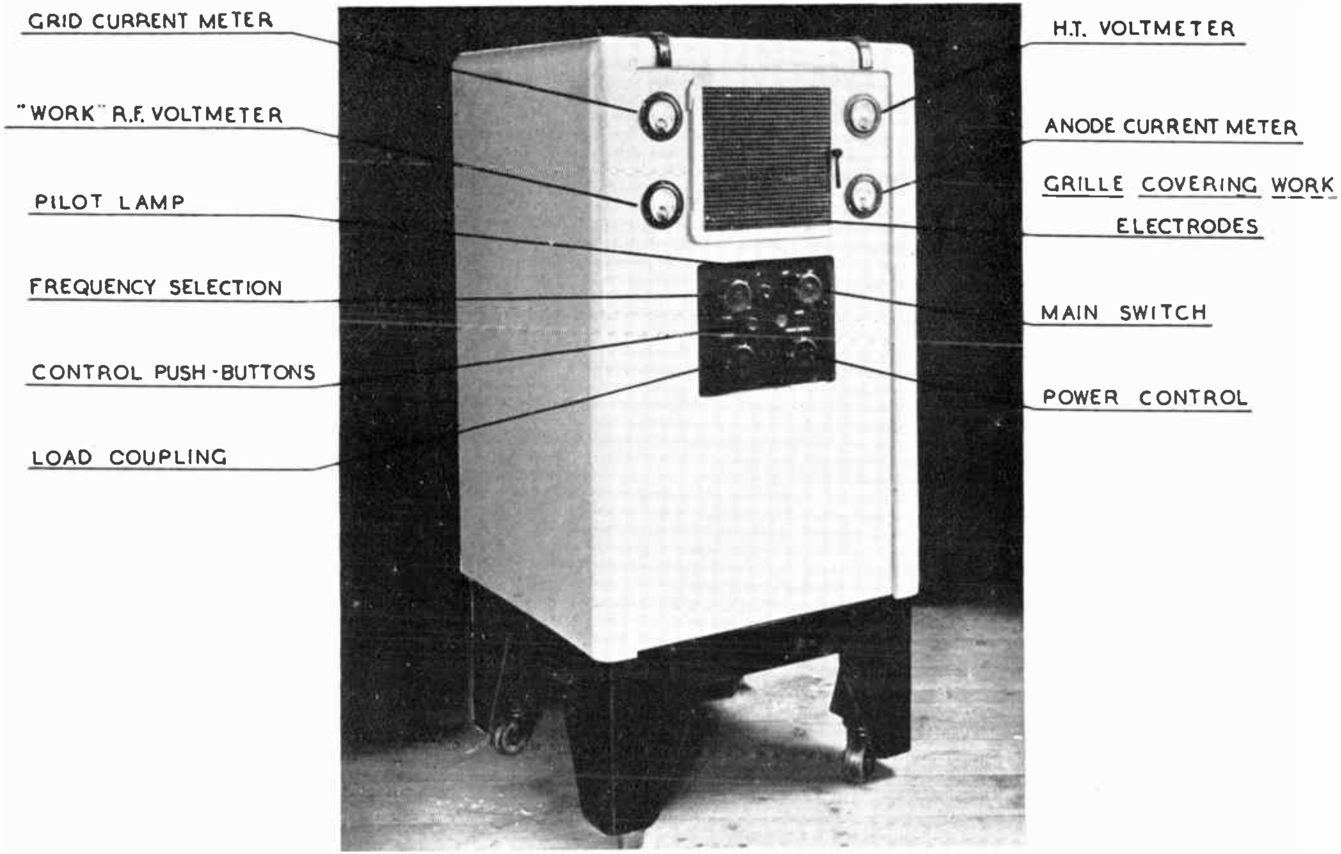

Mobile dielectric heating equipment with internal "work" electrodes. The power output is 350 W over a frequency range of 30-40 Mc/s. A coupled output circuit is employed.

is redrawn as in Fig. 11b it is seen that the grid excitation voltage is derived from a potential-divider formed by the anode-filament and the grid-filament capacitances, although stray capacitance to earth from the anode end of the circuit will augment the former. With normal valves, C_{gf} will often be five or more times the value of C_{af}, so that a proper ratio of anode to grid alternating voltages (commonly required to be 2 to 3) is not secured. This generally results in low conversion efficiency, but the effect can sometimes be avoided by connecting an additional condenser between anode and filament. This remedy will not be wholly satisfactory if the leads of the shunt-condenser are long, with a resulting reactance which is not negligible compared with the reactances of the capacitances concerned.

For the reasons given above, the circuit of Fig. 12a will often be found preferable to that of Fig. 11a, in that some control of grid excitation may be exercised in the design stage. From the equivalent circuit shown in Fig. 12b it is clear that when the radio-frequency choke in the grid resistor circuit is removed* the grid exciting voltage is derived from the oscillatory circuit by a species of mixed Hartley and Colpitts connections. The ratio of anode-filament alternating voltage to that between grid and filament is not now governed solely by the valve capacitances but is dependent also on the tapping point chosen by the inductances. This will be clear by reference to Fig. 13 which illustrates the relation.†

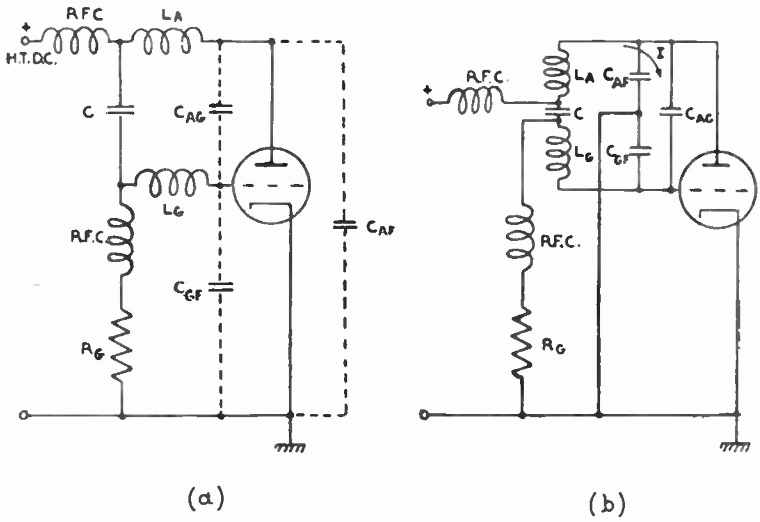

Fig. 12.—Modified series-fed Colpitts circuit (a) redrawn to show valve capacitances forming the oscillatory circuit (b) for analysis of grid excitation conditions.

$$\frac{V_{af}}{V_{gf}} = \sqrt{\left[\frac{\beta^2(1+\alpha)^2 + \alpha^2\delta^2}{(1+\alpha)^2 + \delta^2}\right]} \quad \ldots\ldots\ldots(19)$$

where α is controlled by the tapping point on the inductance, β expresses the ratio of grid-filament capacitance to anode-filament capacitance and δ is the ratio of the reactance of this latter capacitance to the grid leak resistance R_g.

It will be observed that only by using relatively low values of grid resistor can reasonable excitation conditions be secured, but a limit will be reached when the grid bias voltage decreases to a value too low for efficient operation of the valve.

A further type of oscillator is available for frequencies in the range of 80 to 300 Mc s, in which the normal lumped reactances L and C of the oscillatory circuit are replaced by lines a quarter-wavelength long, the connections being essentially similar to those of Fig. 12a. Because of the increasingly adverse effect of electron transit time on conversion efficiency as the frequency rises, valves of small physical dimensions must be used with inherent reduction of power output. For this reason very high frequency valve generators are limited to a few specialised applications, such as the spot-glueing of plywood, or the seam-welding of plastic seams, where the heat treatment is severely localised and the power demand is accordingly small, usually of the order of 100 to 150 watts.

In all the arrangements discussed in this section it will have been noted that no mention has been made of frequency stabilisation. Since practically all dielectrics show some variation of physical properties when heated, it is to be expected that any oscillatory circuit of which

---

* This is quite feasible as the grid filament return circuit is connected to a low radio-frequency-potential point on the inductance L_a, L_g.

† Derived in Appendix (8.1).

they form part will undergo changes of resonant frequency and of effective resistance. The valve self-oscillator is probably unique in adapting its operating frequency to meet changed conditions which would cause adverse if not dangerous conditions with the power-amplifier type of valve generator in the absence of automatic tuning devices. Mainly for this reason the power amplifier system has not been much used for dielectric heating equipments, while there is the further deterrent of neutralising circuits to be considered. Multigrid transmitting valves, in particular pentodes, with moderate interelectrode capacitances and specially low lead inductances to render them suitable for use at the higher frequencies could, however, be employed at power levels of a few kilowatts.

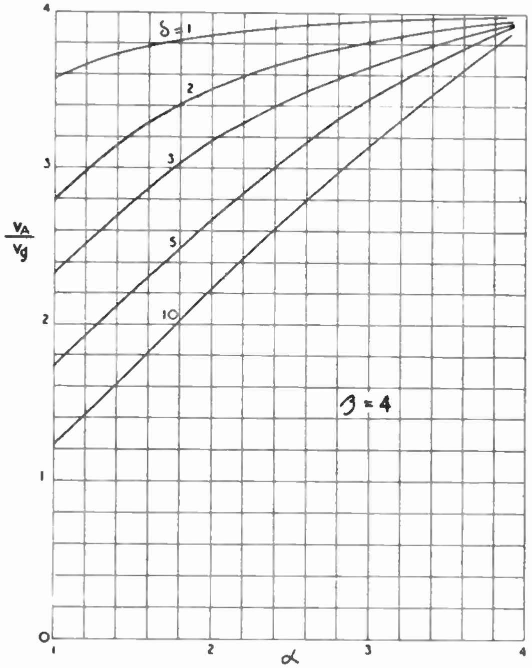

Fig. 13.—The effect of varying the grid resistor and coil tapping point upon the ratio of alternating components of anode and grid voltage for the circuit of Fig. 12 (b), when the grid-filament capacitance is four times the anode-filament capacitance.

(5·2) *Load Coupling Circuits*

It is well known that the transmitting valves only deliver their rated output power with good efficiency when the anode circuit looks into a load impedance of a particular value governed by the anode H.T.D.C. voltage and the cut-off grid voltage conditions selected.[6] For any given valve and anode voltage there is not a large range of load impedances permissible as will be evident from Fig. 14, which illustrates the dynamic characteristics of a silica valve having a nominal output rating of 5 kW. These curves have been calculated under conditions of fixed minimum anode voltage and maximum grid voltage, and rated peak anode current, the variation of output power, anode dissipation and mean anode current being evaluated for various angles of anode current flow controlled by the alternating and steady components of the grid voltage.

It is evident that output circuits for dielectric heating oscillators should be designed to meet the requirements of the transmitting valves to be used, and therefore a few typical arrangements in common use will be discussed. At the same time the efficiency of the coupling circuits themselves, which also is of importance in maintaining high over-all efficiency, will be considered.

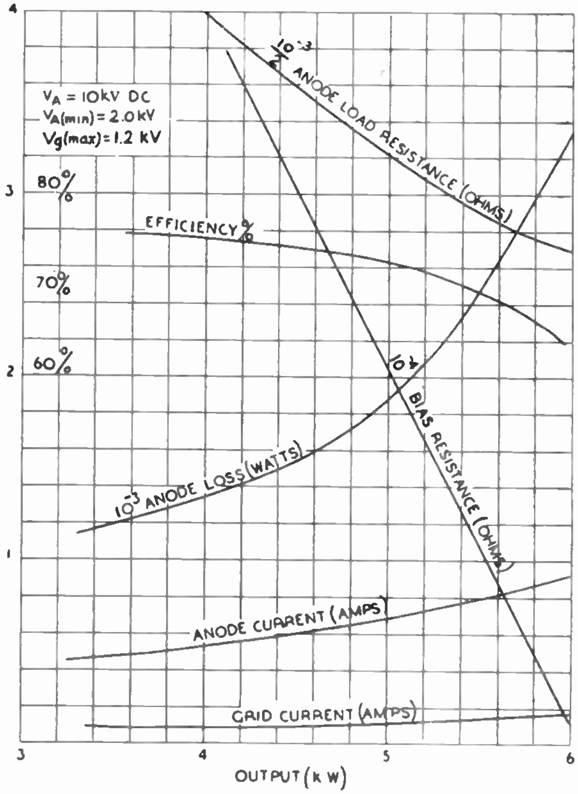

Fig. 14.—Dynamic characteristics of a 5 kW silica valve with fixed values of minimum anode and maximum positive grid voltages.

(5.2.1) *The Series Capacitance Circuit*

The series capacitance circuit shown in Fig. 15 is frequently used where long lines from the generator to the work are avoidable and the operating frequency is comparatively low, e.g. 1 to 10 Mc/s.

The main part of the oscillatory circuit comprises the anode-filament (plus stray) capacitance C_1 and the inductance L across which is shunted the load control condenser C_2 in series with C_L and R, the load represented by the work.

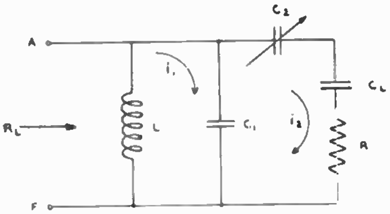

Fig. 15.—*The series capacitance output circuit. The valve loading can be adjusted by variation of condenser* C_2.

The derivation of the effective load resistance R_L is given in appendix (8.2) and results in the simple relation:

$$R_L = \frac{K}{\tan \delta_L}\sqrt{\left(\frac{L}{C_1}\right)} \times 1{,}000 \text{ ohms} \quad \ldots\ldots(20)$$

where K is purely a function of the ratios C_2/C_1, and C_L/C_1, L and C_1 being expressed in units of micro-henries and micro-microfarads respectively. Generally it is required to ascertain suitable values of C_2 and C_L when selection of a transmitting valve has already established the values R_L must have and C_1 will probably have. With this end in view the relation between K and tan δ_L for various values of L is shown in Fig. 16. The determination of the range of load capacitances (with a fixed value of tan δ_L) and the required maximum and minimum values of the controlling capacitance C_2 is aided by reference to Fig. 17, where K is plotted as a function of C_2/C_1 and C_L/C_1. It will be observed that the frequency has not been explicitly stated in these relations; but nevertheless, it has been fixed since it is implicit in the function K. This being the case it is desirable to check the resulting value for voltage gradient over the work by reference to Fig. 18. Here the ratio of load voltage to anode-filament alternating voltage is given as a function of both C_2/C_1 and C_L/C_1; it is derived from equation (11) with tan δ_L ignored as its effect is generally small in practice.

There is one point of special interest with this circuit. When K can be chosen of low value, e.g. around unity, Fig. 17 shows that variations of capacitance C_L have little effect as K is almost constant when $\alpha > 4$ and $\beta >> 7$. This implies nearly constant loading of the transmitting valve and hence reasonably constant dissipation of power in the work, which is advantageous for materials liable to vary considerably in dielectric constant during the heating cycle unaccompanied by severe changes in power-factor. Where changing power factors are encountered the loading may be corrected by adjusting C_2.

(5.2.2) *Coupled Circuits*

(5.2.2.1) *Short Lines*

In many cases the work to be considered does not call for the use of long lines between it and the generator, but requires a rather more flexible circuit than the one just described, in particular one with the possibility of obtaining higher voltages than are available with any form of direct inductive or capacitive coupling.

This last requirement implies a step-up transformer arrangement which, in practice, involves coupled tuned circuits because of the necessity for neutralising secondary reactance where low values only of the coupling coefficient *k* are possible. This is inevitable on account of the severe limitation imposed on coil dimensions at radio frequencies of 1 Mc/s and above.

The practical arrangement is shown in Fig. 19, where C_L is the load condenser representing the work.

It is easily shown that the load presented to the oscillator valve is :*

$$R_L = \frac{\tan \delta_L}{k^2}\sqrt{\left(\frac{L_1}{C_1}\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(21)$$

Thus the loading may easily be adjusted over a wide range by variation of the coupling between L_1 and L_2

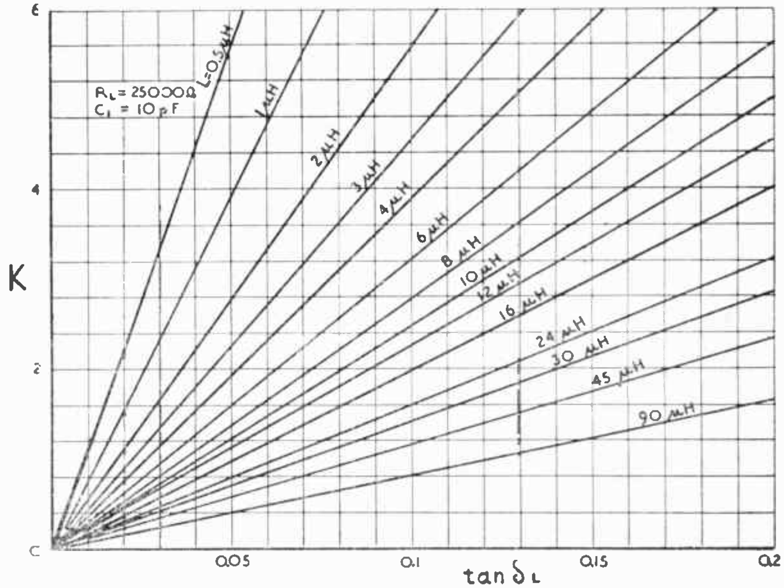

Fig. 16.—*Determination of the loading factor K of equation* (20) *for the series capacitance circuit, with a given transmitting valve, showing the influence of inductance L and power-factor of the work* (*tan* δ_L).

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* For derivation of this relation refer to appendix (8.3.1).

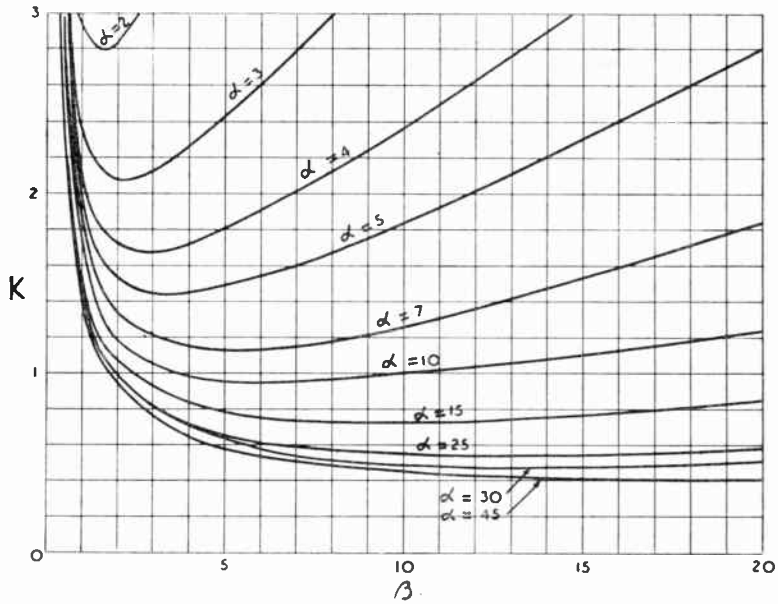

Fig. 17.—Determination of the capacitance range of condenser C_2 *for the series capacitance circuit. The curves illustrate the factor K as a function of* C_2/C_1 *and* C_L/C_1 *reference Fig. (15).*

while further adjustment is available by variation of the inductance-capacitance ratio for the primary circuit. Moreover, in principle, there still remains the possibility of working at various frequencies, always adjusting L_2 for resonance with particular load capacitances.

In practice, as all these variables are not independent, the range of variation of R_L is not quite so large as might be supposed from the foregoing remarks, particularly when the voltage across the work is considered.

The ratio of secondary to primary voltage* is expressed by :

$$\frac{V_2}{V_1} = \beta\sqrt{\left(\frac{L_2}{L_1}\right)} \quad \ldots\ldots (22)$$

where
$$\beta = \frac{k}{(k^4 + \tan^2 \delta_L)^{\frac{1}{2}}} \quad .. (23)$$

Equation (23) is graphed in Fig. 20 for ranges of power factors and coupling coefficients which are likely to be met in practice. It will be seen that voltages substantially larger than that of the primary circuit are possible when the load power factor is low. This is convenient since materials of low power-factor are more difficult to heat when the working frequency is not very high. As will be clear from equation (2) in section (2) a given percentage increment in voltage increases the power dissipation in the material far more than the same percentage increment in frequency. As the coupling employed markedly affects the voltage ratio of coupled circuits, so that a free choice of this factor is not always possible, it is necessary to consider the influence of coupling on circuit efficiency.

An analysis* of the circuit of Fig. 19 results in the following expression for the efficiency :

$$\eta = \frac{k^2}{\left(1 + \frac{Q_L}{Q_2}\right)\left[\frac{1}{Q_1}\left(\frac{1}{Q_2} + \frac{1}{Q_L}\right) + k^2\right]} \quad \ldots\ldots\ldots\ldots (24)$$

where k = the coupling coefficient for the inductances L_1, L_2.

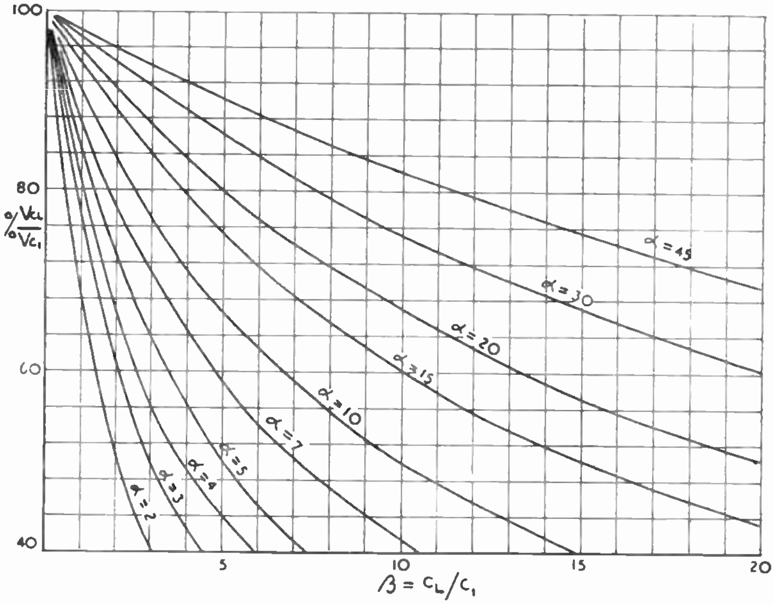

Fig. 18.—Variation of load voltage for the series capacitance circuit in terms of the capacitance ratios C_2/C_1 *and* C_L/C_1.

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* The derivation of this relation is given in Appendix (8.3.2).

* Reference should be made to Appendix (8.3.3).

Q_1 = reactance/resistance ratio for the primary coil.

Q_2 = reactance/resistance ratio for the secondary coil.

Q_L = reciprocal of power-factor of load = $1/\tan \delta_L$.

This relation is shown graphically in Fig. 21 for few typical values of Q_1, Q_2 and k. It will be observed that weak couplings are not conducive to the attainment of high circuit efficiency and that even where this can be achieved with high quality inductances for L_1 and L_2 it can only be sustained over a small range of load power-factors.

(5.2.2.2) *Long Lines*

In many situations the use of long lines from the generator to the work is unavoidable and this gives rise to problems peculiar to the case, the chief of which concerns matching the line to the work and to the generator valves.

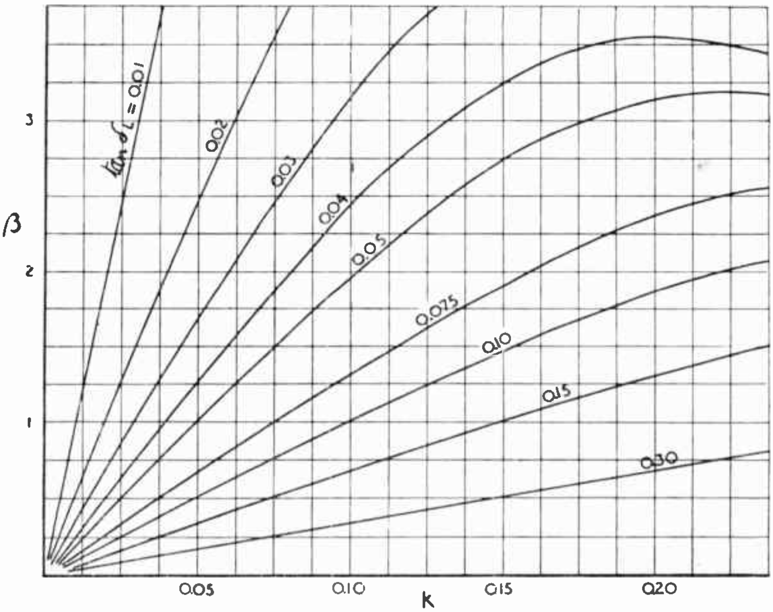

Fig. 20.—Variation of the voltage factor β of equation (23) *for the coupled output circuit showing influence of load power-factor and coupling coefficient. Multiplying this factor by* $\sqrt{(L_2/L_1)}$ *gives the secondary/primary voltage ratio.*

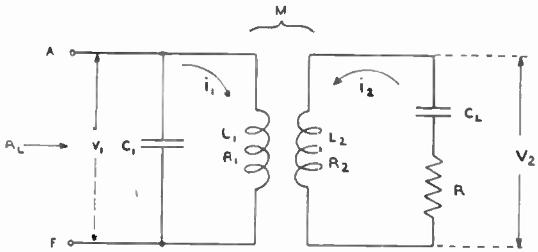

Fig. 19.—The coupled output circuit comprising two tuned circuits. An analysis of input impedance, voltage ratio and efficiency is made in Appendix (8.3).

In order to avoid standing waves on the line, it is necessary to arrange for the line load termination to be resistive and of value closely that of the characteristic impedance of the line.

As the load is capacitive and normally of low power-factor the first condition can be secured by tuning the load to the desirable operating frequency by means of a shunt inductance at its terminals which usually takes the form of a short-circuited stub line. Because of the second requirement, the operating frequency must be chosen so that a practical value of line characteristic impedance results, e.g. 30-100 ohms for concentric lines or 200-600 ohms for open two-wire lines. The concentric line is to be preferred if only on the score of prevention of unwanted radiation.

In principle such a matched line could be of any convenient length but the physical properties of the work will almost certainly change during the heating cycle with the resulting condition of mis-match. Unless the line is $\lambda/4$ or $\lambda/2$ long the change in the resistive component of input impedance will be accompanied by a reactive component (previously zero) of either positive or negative sign dependent on whether the ratio of "tuned" work resistance to line characteristic impedance is greater or less than unity.

Frequently the line will be shorter than a quarter-wavelength, but it can be artificially increased by addition of a T section network to avoid the above effect. This is mentioned in a paper by Bierworth and Hoyler[8], who also have devised the scheme of supplying the compensated line via a high reactance to minimise the effect of load variations on the oscillator valves.

(6) Acknowledgments

The author has to thank the directors of Philips Lamps, Ltd., and Radio Transmission Equipment, Ltd., for permission to publish this paper based on investigations carried out in their laboratories during the past year.

Thanks are also due to my colleague, Mr. K. A. Zandstra, who undertook the production of the lantern slides, for helpful criticism and advice during preparation of the paper.

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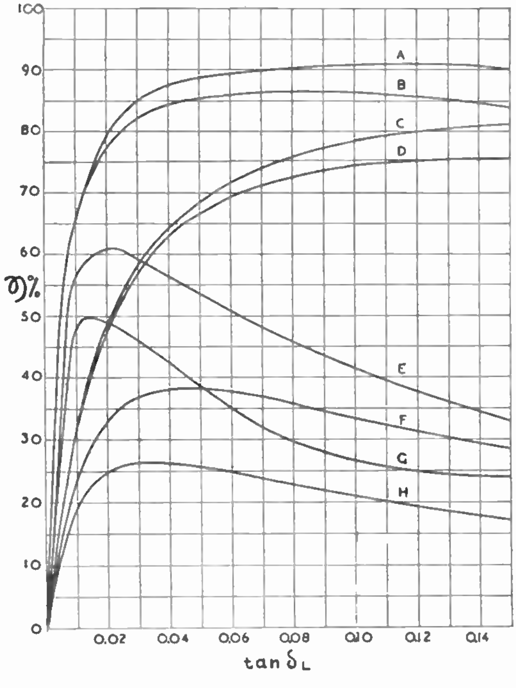

Fig. 21.—Efficiency of coupled circuits as a function of coil quality, coupling co-efficient and load power-factor.

k = 10 per cent.			*k = 2 per cent.*		
Curve	Q_1	Q_2	*Curve*	Q_1	Q_2
A	200	200	*E*	200	200
B	100	200	*F*	200	50
C	200	50	*G*	100	200
D	100	50	*H*	100	50

(8) Appendices

(8.1) *Anode and Grid Alternating Voltages for the Modified Series-fed Colpitts Circuit*

The circuit of Fig. 12b being of the multi-mesh type makes an accurate analysis somewhat laborious. With a view to simplification it should be noted that the oscillatory circuit has two capacitive branches, one of which, that of the anode-grid capacitance, will normally possess far the higher susceptance. The major part of the circulating current therefore traverses this path, and will accordingly divide the total alternating voltage from anode to grid into two parts dependent on the ratio of La to Lg.

It is convenient, therefore, to consider an equivalent circuit where *La*, *Lg* and *Cag* are omitted, the inductances being replaced by generators having relative voltages (for a circulating current of I amperes) of $La\omega I$ and $Lg\omega I$ equal to V_1 and V_2 respectively.

The arrangement is that of Fig. 22 and is easily analysed by employing a theorem due to Millman.[7] Putting $Y_1 = j\omega C_{af}$, $Y_2 = j\omega C_{gf}$ and $Y_3 = 1/R_g$, the voltage across the grid resistance is

$$V_{OF} = \frac{V_1 Y_1 - V_2 Y_2}{Y_1 + Y_2 + Y_3} \quad \ldots\ldots\ldots\ldots\ldots\ldots(25)$$

or if the tapping point on the inductance is chosen so that $V_1 = \alpha V_2$:

$$V_{OF} = V_2\left(\frac{\alpha Y_1 - Y_2}{Y_1 + Y_2 + Y_3}\right) \quad \ldots\ldots\ldots\ldots\ldots(26)$$

also $V_{AF} = V_1 - V_{OF} = \alpha V_2 - V_{OF}$ ....(27)

$$V_{GF} = -V_2 - V_{OF} = -(V_2 + V_{OF}) \quad \ldots\ldots(28)$$

substituting equation (26) into (27) and (28) gives the voltage ratio as :

$$\frac{V_{AF}}{V_{GF}} = -\frac{\alpha Y_3 + Y_2(1 + \alpha)}{Y_3 + Y_1(1 + \alpha)} \quad \ldots\ldots\ldots\ldots(29)$$

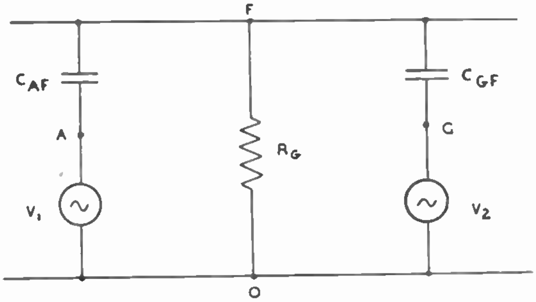

Fig. 22.—Equivalent circuit of Fig. (12b) for analysis of anode and grid alternating voltage ratio.

Let $C_{gf}/C_{af} = \beta$ so that $Y_2 = \beta Y_1$ and $1/\omega C_{af} R_g = \delta = jY_3/Y_1$ so that $Y_3 = -j\delta Y_1$; the relative magnitudes of the two voltages can then be expressed :

$$\frac{V_{AF}}{V_{GF}} = \sqrt{\left[\frac{\beta^2(1+\alpha)^2 + \delta^2\alpha^2}{(1+\alpha)^2 + \delta^2}\right]} \quad \ldots\ldots\ldots(30)$$

So far, the effect of grid current on the division of voltage has been ignored. Its effects can, however, easily be studied by estimating the effective shunt resistance R and writing in equation (25), $Y_2 = j\omega C_{gf} + 1/R$.

(8.2.) *Effective Resistance of the Series-Capacitance Tuned Circuit*

In determining the load resistance presented to an oscillator valve by a circuit of the series-capacitance type a simple method is to determine the effective resistance R' and the effective reactance Xc' of the assemblage of condensers C_1, C_2 and C_L in Fig. 15, and then to use the well-known relation $L/C'R'$ to find R_L.

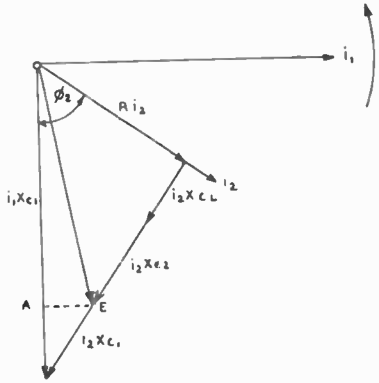

Fig. 23.—Vector diagram for the capacitive branches of the circuit of Fig. (15).

The vector diagram of Fig. 23 shows the voltage and current relations of the capacitive assemblage neglecting, for the moment, inductance L. The current ratio ι_2/ι_1 can immediately be written down by inspection of Fig. 23 as :

$$\frac{\iota_2}{\iota_1} = \frac{Xc_1}{Z_2} \text{ where } Z_2 = \left[R^2 + (Xc_1 + Xc_2 + Xc_L)^2\right]^{\frac{1}{2}}$$

The effective reactance of the assemblage is clearly given by OA on the diagram, so that :

$$Xc'\iota_1 = Xc_1\,\iota_1 - Xc_1\,\iota_2 \sin\phi_2 \quad\ldots\ldots\ldots\ldots(31)$$

The effective resistance can be seen to be represented by AE on the diagram, or :

$$R'\iota_1 = Xc_1\,\iota_2 \cos\phi_2 \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots(32)$$

In the great majority of practical cases the reactance of the secondary circuit will be far greater than the resistance so that the following approximations may justifiably be made :

$$\sin\phi_2 = 1$$
$$\cos\phi_2 = R/Xc$$
$$\iota_2/\iota_1 = Xc_1/Xc \text{ where } Xc = Xc_1 + Xc_2 + Xc_L$$

Equations (31) and (32) may then be rewritten :

$$Xc' = Xc_1 - \frac{Xc_1^2}{Xc} = \frac{Xc_1\,(Xc_2 + Xc_L)}{Xc} \quad\ldots(33)$$

$$R' = \frac{Xc_1^2\,R}{Xc^2} \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots(34)$$

If the reactance of inductance L is now designated X_L the load resistance is given by :

$$R_L = \frac{L}{C'R'} = \frac{X_L\,Xc'}{R'} \quad\ldots\ldots\ldots\ldots\ldots(35)$$

and on insertion of equations (33) and (34) this produces

$$R_L = X_L\left[\frac{Xc\,(Xc_2 + Xc_L)}{Xc_1\,R}\right]$$

or in terms of inductance and capacitance only :

$$R_L = \frac{L}{R}\left[\frac{(C_2+C_L)\{C_1\,(C_2+C_L)+C_2\,C_L}{C_2^2 - C_L^2}\right] \ldots(36)$$

For convenience R is best replaced by $Xc_L \tan\delta_L$ or, after making use of the relation

$$\omega^2 L\left[C_1 + \frac{C_2\,C_L}{(C_2 + C_L)}\right] = 1$$

by

$$R = \frac{\tan\delta_L}{C_L}\sqrt{L\left[C_1 + \frac{C_2C_L}{(C_2+C_L)}\right]} \quad\ldots\ldots\ldots(37)$$

Equation (36) can further be simplified by inserting the conditions $C_2 = \alpha\,C_1$ and $C_L = \beta\,C_1$ and then yields the solution :

$$R_L = \frac{(\alpha+\beta)^{\frac{3}{2}}(\alpha+\beta+\alpha\beta)^{\frac{1}{2}}}{\alpha^2\,\beta\tan\delta_L}\sqrt{\left(\frac{L}{C_1}\right)} \quad\ldots\ldots(38)$$

The coefficient of $\dfrac{1}{\tan\delta_L}\sqrt{\left(\dfrac{L}{C_1}\right)}$ in equation (38) is expressed by K in equation (20) and graphed in the form $K = f(\alpha, \beta)$ in Fig. 17.

(8.3) *Tuned Radio Frequency Transformers*

(8.3.1) *Input Impedance*

In considering the circuit of Fig. 19 it will be assumed throughout the analysis that the condition $\omega^2 L_4 C_1 = \omega^2 L_2 C_L = 1$ is true, as it very nearly is, in practice. Also the coupling between the two coils will be regarded as weak, i.e. $k = M/\sqrt{(L_1\,L_2)} << 1$ and that $L_2 > L_1$.* Further, R_2 will be considered negligible in comparison with R.† The voltage and current relations for this circuit, ignoring for the moment C_1 are given in Fig. 24 where, in order to secure clarity the secondary reactance voltage vectors are purposely made short by comparison with that for the resistive drop.

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* Neither of these conditions is essential to the treatment, but it is more convenient to adopt a definite arrangement for investigation.

† Where R_2 cannot be ignored $\tan\delta_L$ should be increased by an amount $1/Q_2$ (see section 8.3.3).

Noting that the current ratio, ι_2/ι_1, is given by $\dfrac{\omega M}{Z_2} = \dfrac{\omega M}{R}$ for the resonant secondary circuit the equivalent reactance and resistance can be expressed by :

$$X' = \omega L_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(39)$$

$$R' = \omega^2 M^2/R = k^2 \omega L_1/\tan\delta_L \quad \ldots\ldots\ldots(40)$$

Since $R = \tan\delta_L/\omega C_L$ and C_1 is in parallel with the equivalent series reactance and resistance just determined, the input or load resistance is given by :

$$R_L = \frac{L_1}{C_1(R_1 + R')} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(41)$$

On the assumption that R_1 will be made small compared with R' in the interests of efficiency, it will be neglected. Then insertion of equation (40) into equation (41) and elimination of ω enables the load resistance to be expressed as :

$$R_L = \frac{\tan\delta_L}{k^2}\sqrt{\left(\frac{L_1}{C_1}\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots(42)$$

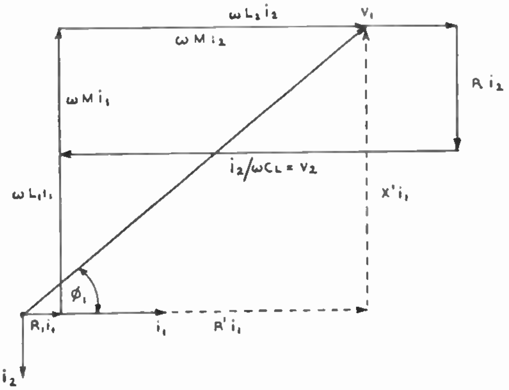


Fig. 24.—Vector diagram for the circuit of Fig. (19) *omitting condenser C_1.*

(8.3.2.) *Secondary/Primary Voltage Ratio*

The voltage developed in the secondary circuit, V_2, can be seen from Fig. 24 to be :

$$V_2 = \iota_2/\omega C_L = \omega M\iota_1/\omega C_L R \quad \ldots\ldots\ldots\ldots(43)$$

The primary current is strictly of value $V_1/(R_1 + R' + j\omega L_1)$, but again as R_1 must be kept low it is better written :

$$\iota_1 = \frac{V_1}{R' + j\omega L_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(44)$$

Substituting (44) into (43) immediately gives the voltage ratio of the transformer as :

$$\frac{V_2}{V_1} = \frac{\omega M}{\omega C_L R\left(\dfrac{\omega^2 M^2}{R} + j\omega L_1\right)} \quad \ldots\ldots\ldots\ldots(45)$$

As the relative magnitude only* of these voltages is required equation (45) can be transformed into :

$$\frac{V_2}{V_1} = \frac{\omega M}{\omega C_L R\left(\dfrac{\omega^4 M^4}{R^2} + \omega^2 L_1{}^2\right)^{\frac{1}{2}}}$$

or
$$\frac{V_2}{V_1} = \frac{\omega M}{\omega^2 L_1 C_L R\left(1 + \dfrac{\omega^4 M^4}{\omega^2 L_1{}^2 R}\right)^{\frac{1}{2}}} \quad \ldots\ldots\ldots\ldots(46)$$

The relations $M = k\sqrt{(L_1 L_2)}$, $\omega = 1/\sqrt{(L_1 C_1)}$ and $R = \tan\delta_L/\omega C_L$ can now be employed to simplify equation (46) which then reduces to :

$$\frac{V_2}{V_1} = k\sqrt{\left[\frac{L_2}{L_1(\tan^2\delta_L + k^4)}\right]} \quad \ldots\ldots\ldots\ldots(47)$$

With a given pair of inductances then, the voltage ratio will be governed only by the coupling between them and the secondary circuit power-factor. These two factors are best taken together so that equation (47) then becomes :

$$\frac{V_2}{V_1} = \beta\sqrt{\left(\frac{L_2}{L_1}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(48)$$

$$\text{where } \beta = \frac{k}{(k^4 + \tan^2\delta_L)^{\frac{1}{2}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(49)$$

Equation (49) is plotted in Fig. 25 for a large variation of k and a range of values for $\tan\delta_L$. At the start, when $k^2 << \tan\delta_L$, $\beta = k/\tan\delta_L$ and the curves are straight lines of slope $1/\tan\delta_L$.

They reach maximum values when $k^2 = \tan\delta_L$ as can be seen by inspection of the denominator of equation (49), such that $\beta\ (\max) = 1/(2\tan\delta_L)^{\frac{1}{2}}$. Finally, as k is increased to the point where $k^2 >> \tan\delta_L$ all curves become asymptotic to the hyperbola $\beta = 1/k$.

In practice such a large variation of k is unnecessary, and therefore equation (49), which is also equation (23) in section (4), has been graphed in Fig. 20 for values of k up to 0·25 maximum in order to secure a more open scale for β.

(8.3.3) *Efficiency of Coupled Circuits*

Again considering the circuit of Fig. 19 and the conditions laid down in (8.3.1), but ignoring a supposedly small loss for condenser C_1 a further equivalent circuit could be drawn comprising three resistances R_1, R_2 and R' in series traversed by the current ι_1.

The current ratio is now $\omega M/(R_2 + R)$ and R_1 and R_2 are given by $\omega L_1/Q_1$ and $\omega L_2/Q_2$ respectively. The transferred resistances R_2' and R' are obtained from R_1 and R_2 by multiplication with the square of the current ratio. The efficiency is then expressed by :

$$\eta = \frac{R'}{R_1 + R_2 + R'} = \frac{\omega^2 M^2 R}{R_1(R_2 + R)^2 + \omega^2 M^2(R_2 + R)} \quad \ldots(50)$$

---

* Fig. 24 gives the phase relation of the two voltages. When the diagram is drawn to scale V_2 will be seen to be practically in antiphase to V_1.

On dividing through by R and substituting the appropriate values for Q, Q_L being obtained from $1/\tan\delta_L$:

$$\eta = \frac{\omega^2 M^2}{\left(1+\frac{Q_L}{Q_2}\right)\left[\frac{\omega^2 L_1 L_2}{Q_1}\left(\frac{1}{Q_2}+\frac{1}{Q_L}\right)+\omega^2 M^2\right]} \quad \ldots(51)$$

The relations $\omega^2 = 1/(L_2 C_L)$ and $M^2 = k^2 L_1 L_2$ can now be substituted in equation (51) yielding:

$$\eta = \frac{k^2}{\left(1+\frac{Q_L}{Q_2}\right)\left[\frac{1}{Q_1}\left(\frac{1}{Q_2}+\frac{1}{Q_L}\right)+k^2\right]} \quad \ldots\ldots\ldots(52)$$

It will be useful to consider the requirements for peak efficiency with specified inductances for L_1 and L_2.

If the differential coefficient of equation (52) with respect to $\tan\delta_L$ (or $1/Q_L$) be equated to zero a maximum value of η is obtained when

$$\tan^2\delta_L = \frac{1}{Q_2^2} + k^2\frac{Q_1}{Q_2} = \frac{1+k^2 Q_1 Q_2}{Q_2^2} \quad \ldots\ldots(53)$$

As $k^2 Q_1 Q_2 >> 1$ generally, it is convenient to write:

$$\tan\delta_{(opt)} = k\sqrt{\left(\frac{Q_1}{Q_2}\right)} \quad \ldots\ldots\ldots\ldots\ldots(54)$$

Substitution of equation (54) in equation (52) gives the maximum efficiency attainable with given quality inductances as:

$$\eta_{(max)} = \frac{k^2}{\left(1+\frac{1}{k\sqrt{Q_1 Q_2}}\right)\left[\frac{1}{Q_1 Q_2}\left(1+k\sqrt{Q_1 Q_2}\right)+k^2\right]} \quad \ldots\ldots\ldots\ldots\ldots(55)$$

The conditions for high efficiency of power transfer are clearly seen to be tight coupling of the circuits combined with a high value for the geometric mean Q of the whole transformer and the optimum value for load power-factor.

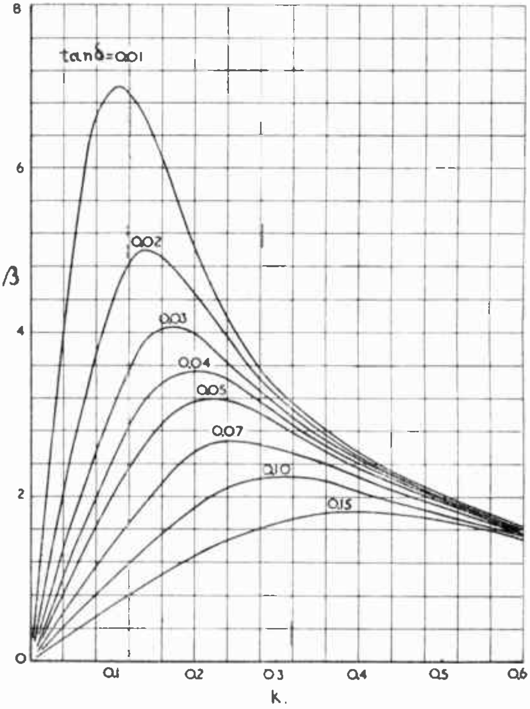


Fig. 25.—The voltage factor β of equation (49) *as a function of load power factor and coupling coefficient.*

LONDON DISCUSSION

Dr. G. A. V. Sowter: The preparation of this paper has clearly involved considerable labour, and the data presented should be extremely valuable to designers and others dealing with this class of equipment. Most articles in the technical press have avoided giving any details of the radio frequency generating system, and the author is to be congratulated on including data covering this aspect of dielectric heating in his paper.

In connection with the tuned circuits of these valve oscillators, would the author say whether water cooling of the inductance portion has been found necessary, as in the case of induction heating equipments?

Many of the formulæ given in the paper require a knowledge of the dielectric constant of the material involved, but no mention has been made of the change of this constant with varying temperatures.

Mr. C. E. Tibbs: The author has covered ground which is new to most of those present. There have been numerous papers on applications of radio frequency heating but few which are of interest to the radio engineer. It is valuable to find that the author has stressed the conduction losses arising from the slow heating of dielectrics, because these losses can be substantial. In this connection, the curves in the paper will be of great assistance to those engaged in the design and use of radio frequency heating equipments. The author has mentioned a method of inserting the load condenser directly into the oscillatory circuit, but in my experience there are certain difficulties associated with that arrangement. One is, that the presence of long conductors might easily lead to inductive reactances greater than the terminating capacity reactance with consequent peculiar results. In practice there is a definite point beyond which it is not possible to make the load form part of the tuned circuit. With ½ kW or ¼ kW sets for example, 30 Mc/s is the highest permissible frequency for such an arrangement.

Mr. Swain : I should be glad to know when it would be advisable to make the work condenser form part of the oscillator tuned circuit.

Mr. Dalton : In recent publications it has been stated that the greatest heating is obtained at certain definite frequencies for particular substances. Has any work been done on bakelite or celluloid to ascertain these optimum frequencies ?

Mr. Pallett : Would the author inform us whether any work has been done on the subject of percentage change in dielectric constant due to increasing the temperature of a material ?

Mr. Thwaite : With reference to some experimental work I have done in connection with plywood curing, I have found it advantageous to use two valves in a push-pull circuit operating from unrectified A.C. supply, so that each valve operated per half-wave, enabling a higher peak voltage to be used. The change of dielectric constant of glue as it dries is very pronounced, but it can be overcome by using a tuned circuit having large capacitance in parallel with the plywood unit. This increases the stability of the circuit by reducing the overall change caused by the curing of the glue.

One other interesting feature is that on first switching-on there is obviously a very high current density in the glue. As this dries out, the current drops down ; this is of little consequence as the tendency toward the glue being over-cured is avoided automatically. As regards screening, the apparatus used was a screen in itself, one live electrode being used between two earthed platens of a press so that two plywood units were being cured together requiring a power of approximately 150 watts. The apparatus was used next door to a radio dealer's premises without complaints of radio interference. Has the author derived any simple formula for assessing the power densities in a compound dielectric such as interleaved wood and glue ? I have found it rather difficult to make calculations of that kind.

Mr. Parker : I should like to ask the author how the old spark gap method of radio frequencies generation compares in overall efficiency with valve oscillator methods. The spark gap method might be the less efficient, but this disadvantage might be outweighed by lower basic cost.

Capt. W. C. Gee : As one primarily concerned with radio communication, I should like to ask the author whether precautions are taken in designing and installing radio frequency heaters, to prevent or at least minimise unwanted radiation particularly under different conditions of loading.

Mr. Bazin : Engineers engaged in this type of work will be helped by the very interesting and valuable information given in the paper, but one aspect not stressed is the question of the high voltages necessary to heat large articles, particularly in wood, as well as the related question of unequal voltage distribution in such cases. Can the author give us any ideas about the voltage distribution in that connection ? It might be interesting to mention, in connection with the curing of large parts for aircraft, that the unequal voltage distribution can be utilised to advantage to cure glue in large joints in certain parts of spars requiring a high power concentration at the same time as the treatment of smaller ioints in other parts is being effected.

Mr. J. A. Sargrove : Would the author tell us how many hours life is to be expected from silica valves used in these heating equipments ? I feel that some figure distinct from the maker's normal guaranteed life would be of interest.

Mr. Ranson : In the paper the author has mentioned only silica valves as oscillators. Could he inform us whether any work has been done on high powered valves with steel cases for these equipments ?

Mr. J. Thompson: It is to be hoped that more publicity will be given to the engineering aspects of this form of radio heating in order to counterbalance the rather optimistic views many people have of the uses of the method. I am glad that the author has stressed the relations between load capacity and frequency from the point of view of the complete output circuit, so that a proper output from the valves would be secured. This is of importance, as many people appear to think that the sole criterion of effectiveness of a radio frequency heater is the highest frequency at which it will work.

REPLY TO THE LONDON DISCUSSION

Mr. L. Grinstead : With reference to Dr. Sowter's query concerning the necessity for water cooling the oscillatory circuit inductances in these generators, it can be said that this requirement does not normally arise since the circulating currents involved rarely exceed a few tens of amperes even with output powers of 10 to 15 kW. Should industrial equipments of much higher power come into use, no doubt provision of water cooling (alternatively air-blast cooling) will be essential.

Mr. Tibb's remarks on the direct connection of the load capacitance to the oscillatory circuit endorse the author's view, implied in section (5.2.1), that this method can only be considered good practice in the absence of long lines from the generator to the work and/or a high operating frequency. There is, therefore, a frequency range, between approximately 10 Mc/s and 30 Mc/s for low powered sets, where discretion must be used before adopting the direct connection scheme in the absence of calculations or practical tests. As Mr. Tibbs rightly added, the upper limit of 30 Mc/s may well be reduced for equipments of higher power. Mr. Swain's query can only be answered in these general terms.

In the author's opinion the statement mentioned by Mr. Dalton needs qualification. Evidence published so far shows that there are no sharp optima of frequency for the majority of plastic substances or, indeed, for many kinds of wood. As the rate of heating depends on the power which can be dissipated in the material, it is of greater importance to select the working frequency to secure proper matching of the load to the oscillator, a point stressed in the paper.

A good deal of information has been published in various technical journals concerning change of dielectric constant with temperature, a point referred to by Dr. Sowter and Mr. Pallett. Variation of this constant can be appreciable, as Mr. Thwaite has stated ; increases of 50 per cent. up to 100 per cent. are not uncommon at temperatures in the neighbourhood of 100 to 120 deg. C. In cases of materials possessing high initial water content, the dielectric constant usually has a high initial value and here a reduction will be observed as increasing temperature accelerates water evaporation.

Mr. Thwaite also referred to the operation of push-pull valve oscillators direct from an H.T A.C. supply. Although high voltages can be obtained in this way there remains the disadvantage that the valves are not utilised to their best advantage. As the peak anode current is fixed for a given type of valve, A.C. operation necessitates limitation of the mean anode current to 70 per cent. of the value normally permitted with D.C. operation. This in conjunction with instantaneously varying anode voltage leads to a reduction of approximately 50 per cent. in possible output power. The saving of cost by eliminating the rectifiers is liable to be outweighed by the loss in available output while the radio interference bandwidth is extended by virtue of the "half-sine" modulation, an undesirable feature.

The other problem put by this speaker is a difficult one. In principle calculations of relative initial power concentration are possible along the lines indicated in sections (3) and (4) of the paper, but a complication arises from the transfer of heat from one material to the other unless the heating time is short. It is a matter of doubt whether figures derived from the formulæ would be useful other than as a rough guide to conditions obtaining in the work.

With reference to the remarks of Mr. Parker, the overall efficiency of spark gap systems is essentially of the same order as for valve generators, provided the spark gaps are carefully maintained Against the lower capital cost, however, it must be remembered that owing to a poor power-factor, intrinsic with the spark method, the kVA required from the supply for a given useful output power is much higher than for valve sets. The running costs may, therefore, be considerably higher, and there is the added technical disadvantage that spark systems have, so far, not been developed to operate satisfactorily on frequencies higher than about 800 kc/s.

Capt. Gee raises the question of interference with communication services. To minimise unwanted radiation it is usual practice to screen entirely the generator itself, and often the complete load circuit. There are, however, some applications, a small percentage of the whole, where complete screening is difficult if not impossible. There remains the possibility of choosing a non-interfering frequency and stabilising it. How serious the stray radiation field will be must depend on the particular application involved, and so will vary from case to case.

The author did not include a treatment of voltage distribution under the conditions referred to by Mr. Bazin, as this subject has been discussed in some detail already by R.C.A. engineers (see reference No. 5). As Mr. Bazin points out, a non-uniform voltage distribution is not always a disadvantage.

The question raised by Mr. Sargrove cannot be answered definitely, as valve life differs from type to type, and is, moreover, not independent of the conditions of use. Certainly the actual lives experienced will be greater than those guaranteed, but it is not possible to indicate the margin for the general case.

Mr. Ranson raised a question concerning the possible use of steel-cased valves. The author is not aware of any technical reason why such valves should not be used in high-powered equipments when desired, but, so far as is known to him, only demountable types are available in this country. Present practice indicates a preference for sealed-off valves on the part of most equipment manufacturers.

It is heartening to have Mr. Thompson's endorsement of the author's view that an engineering approach to dielectric heating problems is necessary for proper development of this new technique. It is to be hoped that this paper will be followed by further papers as development of equipment progresses and industrial operating experience becomes available.

MIDLANDS SECTION DISCUSSION

Mr. D. E. Head : I have heard dielectric heating referred to as electronic heating, which appears to me to be incorrect, as one usually associates the movements of electrons, as a cause of heating, with metals and not dielectrics.

Mr. Beecham : Can the author tell us whether radio-frequency dielectric heating is cheap in comparison with other methods ?

Mr. S. G. Button : With the high powers and high frequencies mentioned in the paper, it is almost impossible to prevent radiation of energy by screening, and I would like to know what precautions are usually taken to ensure that the energy radiated does not affect the health of operators.

Mr. W. W. Smith : The author is to be congratulated on the wealth of detail which he has managed to compress into so little space. Many new problems are raised with this new heating technique, and I think it would be helpful if the author could give us some idea of the " work " voltages involved in practice.

Mr. L. H. Pinkiss : I would like to mention some practical points arising out of my experience of high frequency dielectric heating of plastic preforms under production conditions.

There has been some discussion of the use of very high voltages across the load. There are practical limitations to the voltages which may be used, due to standing arcs causing breakdown of the insulating supports for the electrodes. The heating chamber is a stout earthed metal cage, and there is no danger to the operator.

It would be very interesting to know if the author has any practically determined figures to correspond to the gradients shown for the temperature distribution through the load and, if so, to know how he obtained them.

I have made a few such measurements, not, of course, during heating, for the concentration of field by an inserted thermo couple would give quite false results, but by using piles of flat pellets between the electrodes, stopping the heating at a suitable stage, and quickly inserting a thin flat thermocouple between two of the pellets in a given pile.

I have found some large temperature gradients towards the outside surface, as might be expected. This matter of temperature difference is of considerable practical importance.

It is desirable to raise the average temperature of the work to a convenient high level. If there are large differences of temperature, a limitation is placed on the maximum average temperature which can be attained, for no part of the work may reach a temperature which would cause pre-curing of the material, and consequent faulty mouldings.

Such considerations lead to a comparison of conditions with other methods of pre-heating. The benefit of H.F. pre-heating over other methods depends on a more uniform and rapid heating of the material. There are serious limitations to the rate of heat transfer in other types of pre-heating. For again, over-heating of surface layers, and consequent pre-curing of mouldings, must be avoided and these materials in pellet or powder form have notoriously low thermal conductivity. These limitations in turn reduce the effective thermal efficiency of the pre-heating oven.

Thus, although a 50 per cent. efficient conversion of electrical energy into heat in the load for the H.F. method may seem low, it compares most favourably with the efficiency of other methods of pre-heating. In fact, the running costs for a given heat input for high frequency pre-heating are considerably lower than for other methods. The capital cost of equipment is, however, high and must be taken seriously into consideration of the economics of the process.

In general terms, the method has the advantage of greatly increased output per moulding press, particularly of mouldings of heavy section where curing times are normally long.

Mr. L. L. Langton : I notice that no mention has been made of fringing of the electric field, which affects the uniformity of heating. This is purely a matter of relative size and disposition of the electrodes and the work. Another point which occurs to me in connection with coupled circuits is that some expressions and curves are developed in the paper which apparently depend upon the secondary circuit being in resonance with the primary. In practice the condition implied cannot be exactly realised, and I think this may invalidate the conclusions reached.

Dr. C. C. Garrard : I should like to ask the author whether there is any possibility of attaining a higher overall efficiency than 50 per cent. which, to electrical power engineers, is regarded as an extremely poor figure. The question of possible detrimental effect to the health of operators is important. These generators are usually tested inside a screening-cage of the type specified by the Post Office, and the operator has, of necessity, to go inside. Is there really any danger at all of his health being affected by stray radiation ? On the question of nomenclature, I think the process is properly described as radio frequency heating. The great advantage of the method is that it often renders possible the successful treatment of things which are practically impossible to heat except at great cost and inconvenience in any other manner.

Dr. E. A. Hanney: It appears from the paper that there are a great number of variables concerned with circuits for dielectric heating, and I should like to know whether this implies that the method is only suitable for long runs where the set-up is determined by the manufacturer of the equipment rather than the user of it.

Mr. Galitia : It would be interesting to have the author's views on the question of rating industrial radio frequency generators. At the moment there appears to be no standardisation in this connection, and with their increasing use I feel that this matter needs attention.

Mr. E. Leyton : With reference to the previous speaker's remarks, many engineers are tending to the specification of the power available from the transmitting valves into a non-reactive resistance of a value which just loads the equipment fully. This appears to be the only method available in view of the variation of circuit losses with work specimens of different power factor.

Dr. W. W. Wilson : There is no doubt that dielectric heating has a great future. At the moment it is impossible to set limits upon the applications of high radio frequencies, and the present paper is timely in focussing attention on the many electrical and thermal relations which require study before an effective application of the method to a particular process can be made. After the war we shall again be faced with the difficulty of green timber. Those who can recall the conclusion of the last war will remember the troubles that arose from lack of seasoned timber. The author has mentioned that in America this method is in use for the seasoning of timber, so it would appear to be economical to carry on the process on a large scale.

REPLY TO MIDLANDS SECTION DISCUSSION

Mr. L. Grinstead: Mr. Head raises a point of nomenclature. Strictly, the term electronic heating should be confined to those methods wherein displacement of electrons with respect to positive nuclei is concerned and, with frequencies normally covered by the term radio, this is not the case with dielectrics. However, this strict definition would not separate the cases where direct conduction currents are concerned, e.g. ordinary resistance heating, and hence the description electronic heating has become general for those methods based on the electronic art as distinct from normal electrical practice.

With reference to Mr. Beecham's question, much depends on the application in view. It is unfortunate that the overall efficiency of these equipments is rather low, although frequently operation times can be drastically shortened, as evidenced by Mr. Pinkiss in the field of bakelite pre-heating, so that this disadvantage is outweighed from the point of view of running costs.

Concerning the point raised by Mr. Button, it should be remembered that electrode systems commonly used are comparatively poor radiators, and the field strength necessary for adverse physiological effects is far above that allowable when possible interference with communication circuits is considered. So far as I am aware, no cases have been recorded of operators of these equipments experiencing difficulties, and even with larger powers, which no doubt will be necessary in future, elementary screening precautions can be expected to remove all danger.

Mr. Smith referred to actual " work " voltages used in practice. In general, the tendency is to keep the radio-frequency voltage as low as possible in order to avoid excessive gradients which lead to internal sparking or external flashover. Values of 1,000 to 2,000 volts per inch are common so that the work voltage may vary, with different specimens, from a few hundred volts to an upper limit of perhaps 12,000 volts. Higher voltages than this with frequencies in the " megacycle " range lead to considerable difficulty in providing reliable insulation and freedom from excessive stray field, especially when the available radio frequency power is of the order of tens of kilowatts. In laboratory work, however, it is possible to operate equipment of 200 or 300 watts with electrode voltages of 15,000 to 20,000 volts without difficulty.

Referring to a point mentioned by Mr. Pinkiss, no attempt has yet been made to correlate practical temperature gradients with those determined by calculation in view of the difficulties expected. With the plastic pellets he mentions the temperature gradients will undoubtedly be less with radio frequency heating than with other methods, and these gradients will be considerably reduced when the pellets are placed between heated platens. As he rightly points out, an attempt should be made to realise as even a temperature as possible during pre-heating, and the calculations are useful in showing that high power concentration combined with a short heating time is essential. The other remarks of Mr. Pinkiss, of a most practical character, support the general conclusion that radio frequency heating has many applications which can be undertaken with economy, and form an additional reply to Mr. Beecham.

The question of fringing electric fields referred to by Mr. Langton was deliberately omitted from the paper as a good deal of information has already been published about it. In connection with his remarks on the derivation of the input impedance of coupled circuits, the approximate method was adopted for greater speed and clarity. Strictly, the frequency condition to secure a purely resistive input is $\omega^2L_1C_1 = (1\text{-}k^2)\,\omega^2L_2C_2 = 1$ and its adoption leads to an equation of the same form as (21) with an added multiplier in the numerator of $(1\text{-}k^2)$. Since, in practice, k is unlikely to exceed 12 per cent., equation (21) gives a value within 2 per cent. of that obtained by the more formal solution.

Dr. Garrard mentioned the low overall efficiency of radio frequency generators. Unless some entirely new technique of valve generation is discovered, it is very unlikely that efficiencies appreciably higher than those stated in the paper will be realised. In connection with personnel operating these equipments, no difficulties are likely to arise within the screening cage (provided the generator itself is also screened by reason of its usual closed metal cabinet) as the work condenser electrodes in such circumstances would generally not be of large physical dimensions and the stray field would accordingly be low.

Although, as mentioned by Dr. Hanney, a good many variables are concerned in dielectric heating the curves included in the paper should be helpful in determining rapidly the conditions necessary to secure good results with a particular generator on varying types of work. Most manufacturers of these equipments provide flexible output circuits capable of adjustment for a range of specimens of a given type, but it should be clear from the analyses in section (5.2) that their are limitations to this flexibility ; it is frequently impossible to treat materials of physical properties and dimensions vastly different from those originally intended for the given equipment.

Both Mr. Galitia and Mr. Leyton called attention to the need for a proper system of rating radio-frequency generators for industrial purposes while appreciating certain difficulty in its formulation. From the point of view of the user the main interest is in the useful output power available, and the author feels that this should be specified, in kW or BThU as desired, rather than the D.C. input to the valves or the output they give without reference to circuit losses. The difficulty, however, arises that circuit losses will depend on the power-factor of the work so that the useful power, under conditions of proper matching, is not constant. To specify the power when the load jointed to the generator output terminals is purely resistive, at least is useful for purposes of check, but leaves the user in doubt when the work-piece concerned is only of the customary low power factor, e.g. 2 to 10 per cent. It would appear more desirable to quote the output for a definite power factor based on the type of material the generator has been designed to treat. Even then it is important to consider the probable thermal losses which diminish the real " heat " output but are more properly the concern of the user.

NORTH-EASTERN SECTION DISCUSSION

Dr. E. Williams : In the design of Class C amplifiers for ordinary communications work there are not only the limitations imposed by the valve emission and permissible anode dissipation, but also there must not be undue harmonic generation. Many designers arrange that the effective Q of the total load circuit does not fall below 10. Has the same value of Q been chosen for the curves of Fig. 14 and, if not, what considerations were used in deciding upon the value of Q ? I have two questions about high frequency transformers. The first concerns the author's simplifying assumption that $\omega^2L_1C_1$ and $\omega^2L_2C_2$ were each equal to unity. Presumably in making that assumption he assumed that the small differences from unity which those quantities take up in normal oscillators would not affect the result. But do not small differences from unity affect the result profoundly because of the selective nature of the circuit ? In many cases I find that a very small departure from unity makes a very big difference to the equations as a small change of frequency from the natural resonant frequency of the circuit usually means a big change in the reactance. Again, the expression for the voltage ratio has been much simplified and does not contain any frequency-dependent term. Usually the voltage ratio of a transformer does depend physically upon frequency where the coupling coefficient is not close to unity.

Dr. Craig : Many of the author's equations appear to be based on the assumption that dielectric heat is uniform between the plates. Is this actually the case in practice ?

Mr. Fleming : Referring to equations 20 and 21 governing loading conditions, is it a fact that tan delta does remain substantially constant throughout the heating process or are there occasions when variations occur which may upset the matching of the load to the oscillator ?

Mr. Prouch : If tan delta varied during heating there would be a change from the condition of critical coupling one way or the other. If the coupling became greater than the critical coupling one would get the normal double-hump tuning and presumably a change in the natural frequency of the oscillation of the generator. I should like to know whether such changes of frequency can be followed so that the whole system remains matched.

REPLY TO NORTH-EASTERN SECTION DISCUSSION

Mr. L. Grinstead : With regard to Dr. Williams' first question, the value of Q does not enter into the relations depicted in Fig. 14 although a minimum of 10 is necessary for stability of the circuit. Within this limitation any value of Q is permissible which makes the effective resistance of the oscillatory circuit the desired amount, but high values lead to high circulating current and consequent high power loss in the circuit.

Concerning radio frequency transformers, the simplification of the frequency condition is justified where first order effects only are being studied as self-oscillators possess the property of automatically adjusting the generated frequency so that the load circuit is non-reactive. With reasonable values of effective Q for the primary circuit the frequency may, under certain conditions, have a value such that $\omega^2L_1C_1 = 1$ or $(1 - k^2)\,\omega^2L_1C_1 = 1$. If the secondary circuit is to be "operative" it must be tuned, but whether one takes the resonance condition as $\omega^2L_1C_1 = 1$ or a more involved one including the effects of secondary Q, the principal quantity concerned (the resistive component reflected into the primary R′) remains essentially the same in magnitude. This point may easily be demonstrated by redrawing the vector diagram of Fig. 24 with $\omega L_2 i_2$ made a few per cent. larger than $i_2/\omega C_L$; the current i_2 now lags i_1 by a little more than 90 deg. and the angle ϕ_1 also decreases. When the quantities $\omega L_2 i_2$ and Ri_2 are properly drawn to scale it will be seen that the alteration in length of the intercept $R'i_1$ is very small. The voltage ratio expression to which Dr. Williams refers has been developed only for the condition of resonance and not for the general case. Accordingly, the effect of leakage reactance, which for the "untuned" case would be greatly dependent upon frequency under the practical condition of low coupling factor, is nullified by compensating capacitive reactance; there is hence no explicit frequency term in equations (22) and (23).

In connection with Dr. Craig's query, it must be admitted that the assumption has been made throughout the paper that uniform generation of heat within the material between electrodes is secured. This is probably true in the majority of applications when care can be taken to arrange the electrodes so that the electric field between them is uniform.

Mr. Fleming can be assured that variation in power factor of the load during heating will almost invariably occur. Frequently the change will be large enough to necessitate rematching of the load to the generator. This does not give difficulty with the series-capacitance type of circuit but may be troublesome where coupled circuits are used.

It is doubtful whether practical circuits would, as Mr. Prouch implies, be operated under "critical coupling" conditions; rather higher coupling factors are usual so that sudden discontinuous changes of matching are not normally met. Under such circumstances it is possible to design equipment which automatically corrects the load matching during the heating cycle.

BOOK REVIEW

Worked Examples in Electrotechnology. By W. T. Pratt, B.Sc.(Eng.) Lond., A.C.G.L.

This excellent book can be recommended as a useful aid to both teachers and students. With its help much valuable classwork time can be saved. It is impossible to cover all the ground required in Part I of the I.E.E. Associate Membership Examination, the City and Guilds Examinations in Electrical Engineering Practice, and the Ordinary National Certificate within the range of approximately 200 examples, but the author has made a very praiseworthy attempt. Notably, alternating current machines and thermionic valves have not found a place, but present-day restrictions on space must lead inevitably to some omissions. Many of the examples, but not all, have been worked by your reviewer and a number used in classwork by his colleagues, but no fundamental errors were found. There is an obvious printer's error on page 169, example 141, where it is stated that the average value is equal to the maximum value of a half-wave rectified sinusoidal current. For the example given, the symbol π should, of course, be inserted in the space provided under " maximum value."

It is a sign of the times that this book should be priced at 12s. 6d., but when it is considered that each worked example costs the student approximately ½d., the result does appear to represent good value for money. Perhaps subsequent impressions will work out even cheaper and place the book within the reach of most students in the subject.

The work is well arranged, and includes a complete Index to Problems. Pages 8-12 give Definitions of Terms and Definitions of Units, and are in a very concise form. These will prove useful between the covers of such an invaluable assistant to the student as this book undoubtedly will become. G. A. T.

NOTICES

Honours

Council has tendered congratulations to the following member on his inclusion in the Birthday Honours List (1945) :—

Wing-Commander Rudolph Francis Tibbey (Associate Member) was appointed an Officer of the Military Division of the Most Excellent Order of the British Empire.

Congratulations are also again extended to **Wing-Commander H. J. Barton-Chapple** (Member), who has been Mentioned in Dispatches for a second time in recognition of distinguished services.

Obituary

Council record with deep regret the presumed death of **Angus John MacGregor**, of London, S.E.5 (Registered Student).

First of all reported as missing since November 7th, 1944, the Air Ministry now states that the death of **A. J. MacGregor** must be assumed from that date, when he was on operation with an R.A.F. Radar Unit.

Registered as a Student of the Institution in April, 1941, Mr. MacGregor had already succeeded in part of the Institution's examination and but for the war would by now have completed his candidature. He was posted as missing soon after his 23rd birthday.

Annual General Meeting

Corporate members of the Institution are requested to note that the Twentieth Annual General Meeting of the Institution will be held in London on Friday, October 5th, 1945, at 6 p.m. Further advice and details will be circulated to Corporate members in due course.

In the meantime, attention is drawn to Article 32 :—

> " Article 32. Not later than the 16th day of August in each year the Council shall send to each corporate member a list of duly qualified persons whom they nominate for the vacancies about to occur in the offices of President, Honorary Treasurer, and Ordinary Members of the Council on the 30th day of September next following. After the issue of the Council's lists and not later than twenty-one days after the date of such issue, any ten corporate members may nominate any other duly qualified person to fill any such vacancy by delivering such nomination in writing to the Secretary, together with the written consent of such person to accept office, if elected."

Scottish Section

The Council have approved the formation of a Scottish Section of the Institution which, during the ordinary session, will hold meetings alternately in Glasgow and Edinburgh.

Suggestions for papers and other information regarding the Section may be obtained from Mr. H. G. Henderson (Member), 5 Muirburn Avenue, Muirend, Glasgow, S.4, who has been appointed Honorary Local Secretary of the Section.

North-Eastern Section Annual Dinner

The Guest of Honour at the North-Eastern Section Dinner to be held on September 28th at the Royal Station Hotel, Newcastle-on-Tyne, will be Sir Louis Sterling (Immediate Past President).

Applications for tickets cannot be accepted after the 1st September, and it would be appreciated if members made application as quickly as possible to the Local Honorary Secretary, Mr. H. Armstrong, 69 Osborne Road, Jesmond, Newcastle-on-Tyne.

Graduateship Examination

The Pass List for the May, 1945, examination will be published in the next issue of the Journal.

The next examination will take place on November 16th and 17th and will be held, as usual, in approved centres both at home and overseas. Application to write the November examination must be lodged, on the appropriate form, not later than October 1st.

Copies of papers set in May, 1945, and preceding examinations may be obtained for 2s. 6d. per set, post free.

Correspondence on Past Issues of the Journal

Although previous notices have been published regarding the availability of past issues of the Journal, enquiries are still being received for copies of Proceedings which are no longer available. Copies of all Journals from 1925 to 1938 inclusive and Volume 2 (new series), 1941/42, *and* Volume 3 (new series), 1942/43, are now out of print ; single numbers of the Journals in these volumes are also no longer available except on loan from the Library of the Institution.

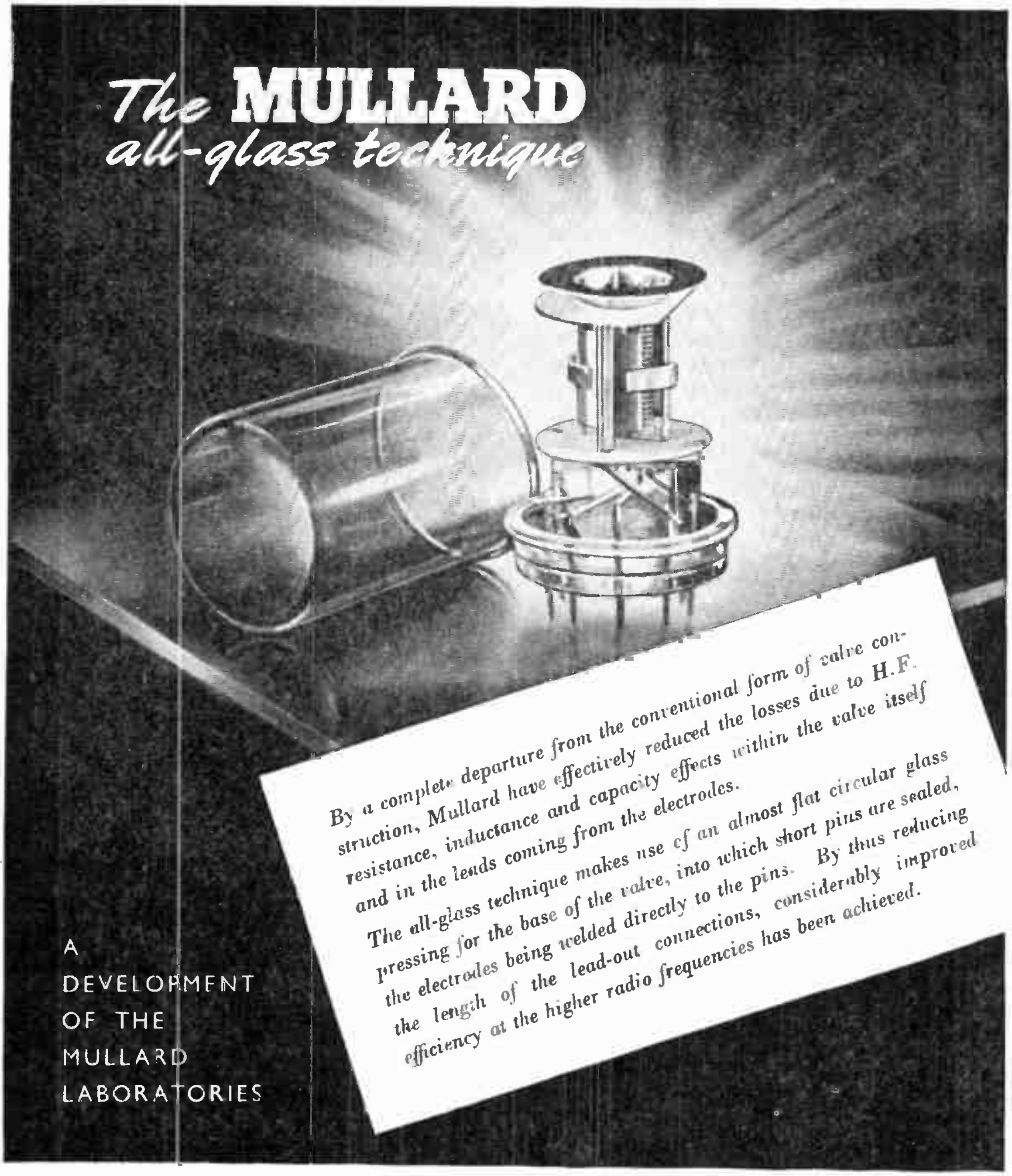
A few complete issues (bound) of Volume 1 (new series), 1939/40, are still available at 10s. 6d. each, post free. Complete bound issues of Volume 4 (new series), 1944 are available at 12s. 6d., post free.

Separate copies of Journals published in 1944 and 1945 may also be obtained by members for 5s. each, post free (7s. 6d. to non-members).

Year Book

A new issue of the Year Book will be published about December next.

The work of compilation will be considerably helped by all grades of members advising the Institution of any changes in their *permanent* addresses.



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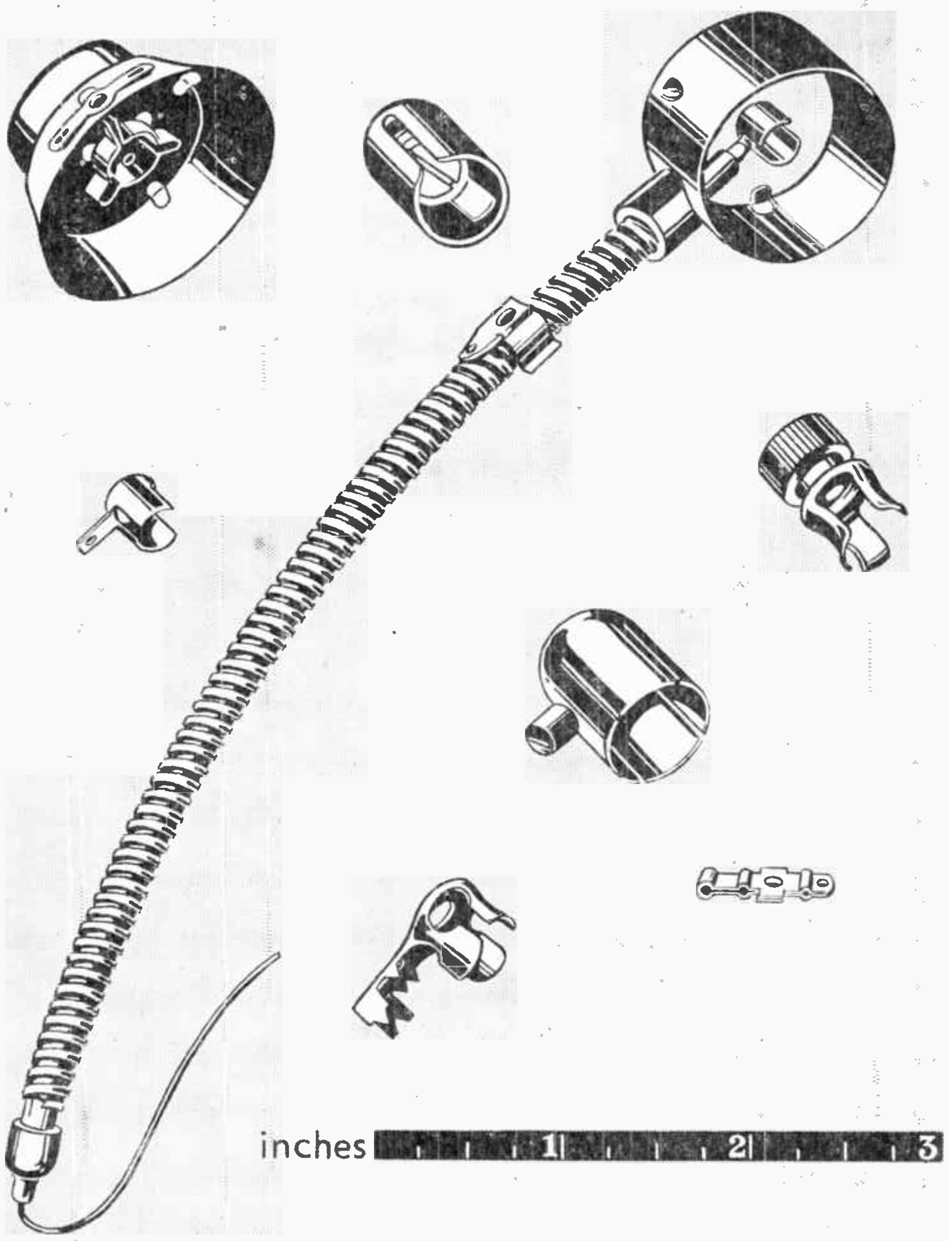
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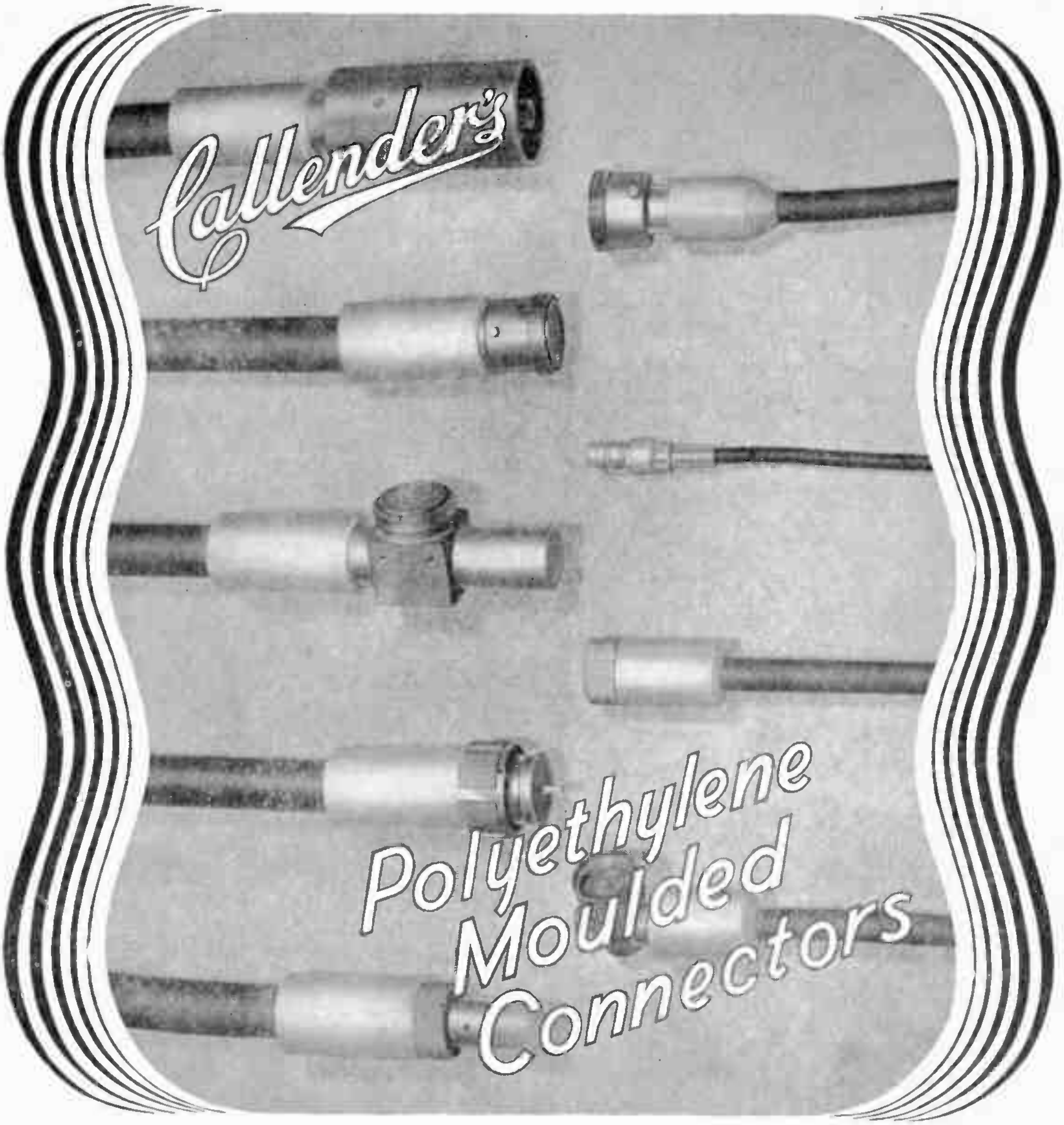

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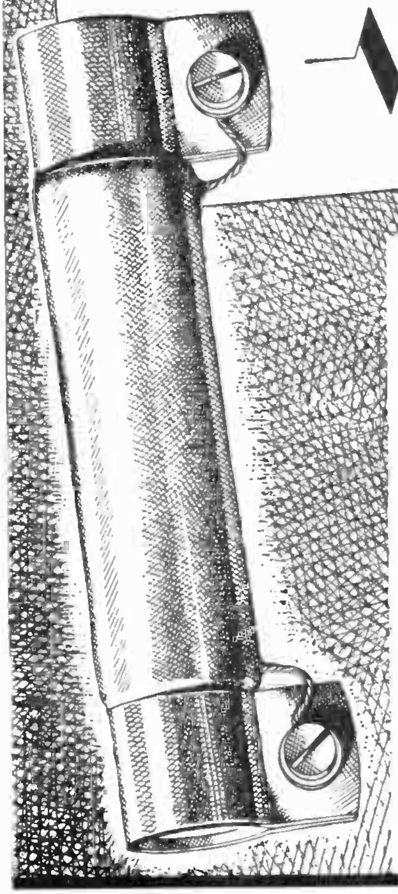

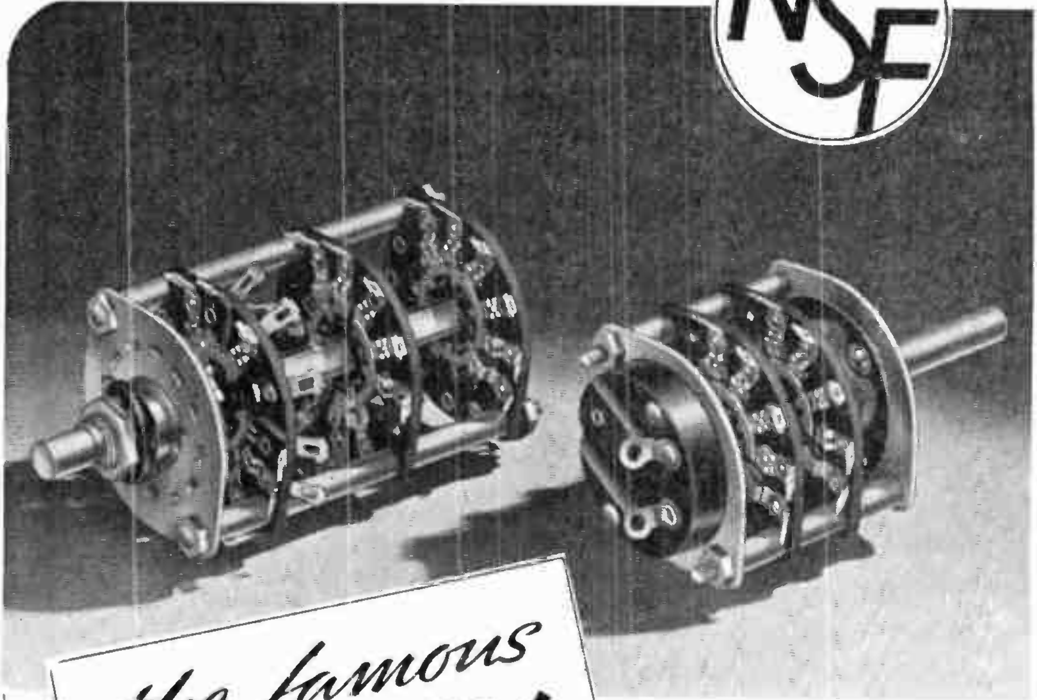

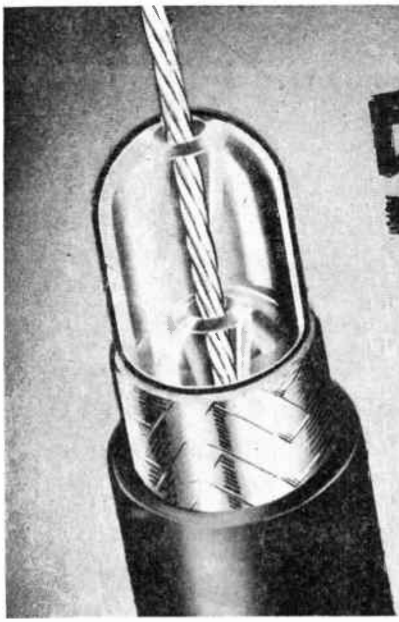

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(FOUNDED IN 1925—INCORPORATED IN 1932)

VOLUME 5 (new series) MARCH—APRIL, 1945 Number 2

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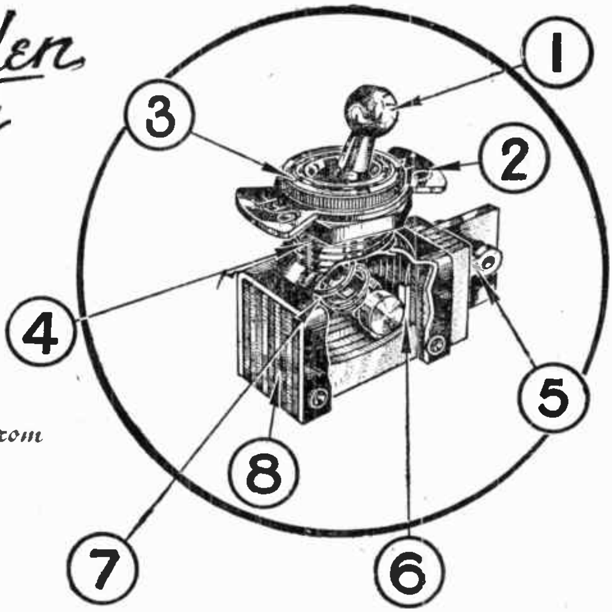

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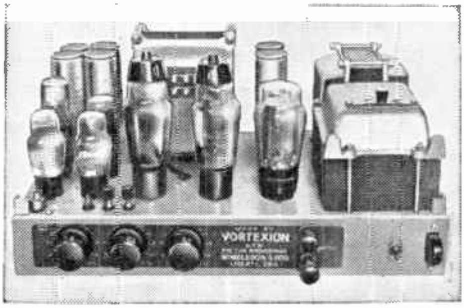

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Mr. DALTON : Wireless batteries are now in short supply, owing to the heavy demands of the Services, and it is necessary, therefore, to make use of the output, although small, of the higher cost producers. Prices are controlled under the Price of Goods Act, 1939, and those charged for both classes of battery referred to by my Hon. Friend have been investigated and approved by the Central Price Regulation Committee.

Mr. WALKDEN: While appreciating what my Right Hon. Friend has said, is he not aware that batteries are used largely by people in small homesteads who cannot understand why good batteries cannot be obtained while there is a plentiful supply of inferior ones. . . ?

Mr. DALTON : I am very anxious to get a fair distribution of whatever supplies there are, but the best batteries are required for the Services in a very great and increasing quantity. . . .

(Extracts from Hansard, Jan. 16)

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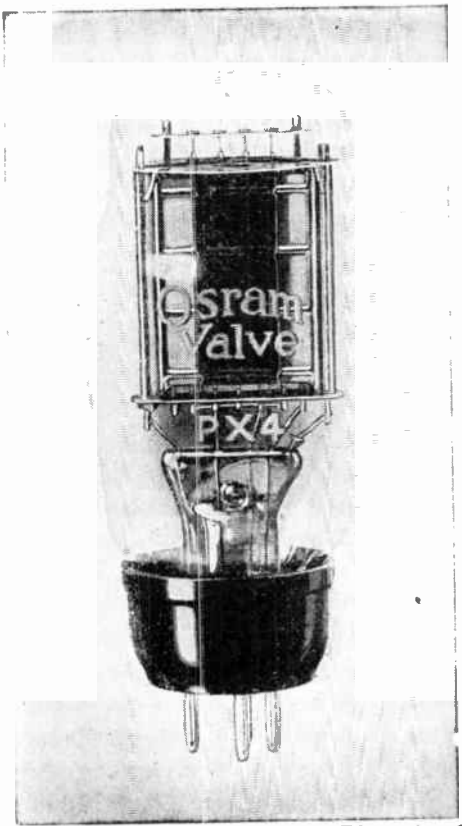

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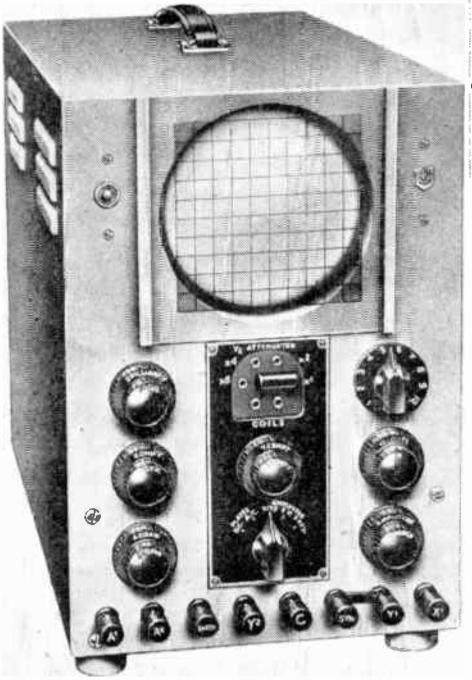

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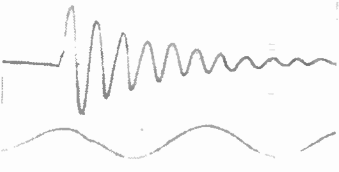

The British Institution of Radio Engineers

(FOUNDED IN 1925 - INCORPORATED IN 1932)

9 BEDFORD SQUARE, LONDON, W.C.1, ENGLAND.

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INSTITUTION MEETINGS

The Committees of the various Sections of the Institution, in conjunction with the main Programme and Papers Committee, are now preparing for the 1945/6 session of meetings which, in all Sections, will commence in October, 1945. The new session, therefore, commences in the twentieth year of the Institution and should be marked by increased activity in all the Sections after six years of wartime restrictions.

It is intended to publish for each Section a Programme Card, and this part of the work of the Programme and Papers Committee will be considerably assisted by members lodging well in advance manuscripts of the papers offered for reading before various Sections. The following provisional arrangements have already been made :—

NORTH-EASTERN SECTION

(All Meetings commence at 6 p.m. and are held in The Neville Hall, Westgate Road, Newcastle-on-Tyne.)

September 28th, 1945 :

6 p.m. Annual General Meeting of the Section
followed by
The Annual Dinner at 7.15 p.m.,
at
The Royal Station Hotel,
Newcastle-on-Tyne.
(Tickets on application to the Local Secretary.)

October 10th, 1945 :

A Paper by
J. Hare and J. C. Finlay
on
" Review of Industrial Electronics."

November 14th, 1945 :

Paper to be arranged.

December 12th, 1945 :

A Paper by
H. Armstrong
on
" Ships' Distress Automatic Alarm Apparatus."

January 16th, 1945 :

A Paper by
Dr. R. T. Craig
on
" Deaf Aid Systems."

February 13th, 1945 :

A Paper by
G. Dobson
on
" Reproduction from Sound on Film."

March 13th, 1945 :

Paper to be arranged.

April 10th, 1945 :

A Paper by
G. Phillips
on
" Short Wave Matching"

REMAINING MEETINGS—1944/5 SESSION

MERSEYSIDE SECTION

May 2nd, 1945, at 6.15 p.m.

Meeting at :—
The Central Hall, Renshaw Street,
Liverpool, 1.
A Paper by
T. H. Turney, Ph.D.,
on
" Wave Guides."

LONDON SECTION

May 17th, 1945, at 6 p.m.

Meeting at :—
Institution of Structural Engineers,
11 Upper Belgrave Street, S.W.1.
A Paper by
F. Jones, B.Sc.(Hons.) and R. Sear,
B.Sc.(Hons.)
on
" The Measurement of Cable Characteristics at Ultra-High Frequencies."

NORTH-WESTERN SECTION

May 4th, 1945, at 6 p.m.

Meeting at :—
College of Technology
(Reynolds Hall),
Sackville Street,
Manchester, 1.
A Paper by
E. R. Friedlander
on
" Magnetic Dust Cores."

JOURNAL OF

The British Institution of Radio Engineers

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"To promote the general advancement of and to facilitate the exchange of information and ideas on Radio Science."

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PHYSICS AND RADIO

by

Professor E. N. da C. Andrade, D.Sc., Ph.D., F.R.S.

(*A lecture delivered before a joint meeting of the Physical Society and the Institution in London on October* 31*st*, 1944).

The British Institution of Radio Engineers draws its members from that large body of technicians who are now professionally concerned with what may be shortly termed "Radio." They are specialists of a new kind, familiar with all the intricacies of valve circuits, which are still somewhat of a new magic to the academic physicist. It would often seem that the most that the ordinary physicist can hope to do is to know what can be achieved by the new methods, the complexity of which is increasing every day, and to ask the youngsters of the new era, who have been brought up in constant familiarity with the new technique, to carry out the details when, as often happens, need for the new instruments and their adaptation arises in the physics laboratory. Although radio is only an application of ordinary physical laws, the development of radio engineering has called for specialised study of the generation of radio waves, e.g., the launching of radio waves into space and their behaviour when launched, the influence of frequency on their propagation, aerial arrays, and so on—all of which are now the fields wherein radio engineers specialise.

A situation arises then where physics and radio science seem to be drifting apart, and I am afraid that the scope and significance of many of the fundamental laws of physics are unknown or unfamiliar to some radio physicists; they tend to explain everything in terms of their own specialised rules and by-laws rather than in terms of the general laws of physics. Radio science is, however, derived from these fundamental laws and so, of course, is the explanation of any new phenomenon which may come their way. But very often, instead of going to the common source when they want to explain the new phenomenon, they try to make a short cut across the unknown, not always with happy results.

I suggest that the radio engineer, marvellous as are his achievements in his specialised fields, needs to be really familiar with the fundamental laws of physics, not only when it comes to making advances in new directions, but also quite often in his daily work. On the other hand, the physicist needs a knowledge of the general achievements of radio engineering, for there is to-day scarcely any laboratory technique where radio methods may not be wanted at any minute. It is most desirable, then, that physics and radio science should not drift too far apart, and I welcome this joint meeting of the Physical Society and the Brit.I.R.E., since personal contacts like this often lead to an interest in one another's problems.

In so dwelling on the relations between physics and radio, I wish to show how radio has grown out of physics, and how the physicist has often already worked out those fundamental problems which grow naturally out of the development of radio. I propose to run quickly through the history of certain developments, starting right at the beginning and coming up to the present time. If sometimes I seem to be straying a long way from radio I beg you to be patient with me, for I will show that I have not forgotten my theme.

Newton was the first man to treat waves in an exact manner. He not only had a clear conception of the mechanism of simple harmonic wave, and of frequency, wavelength, velocity and the relation connecting them, but he worked out the velocity in terms of the elasticity and density of the medium obtaining the familiar formula $v = \sqrt{\frac{e}{\rho}}$ where v is the velocity, e the appropriate elasticity and ρ the density. This work of Newton's put the study of waves on a sure footing, and Laplace, who completed Newton's work on the theoretical velocity of sound by pointing out that it was the adiabatic, and not the isothermal, elasticity that was in question, referred to his work on waves as a monument to his genius, and said of his deduction: "La manière dont il y parvint est un des traits les plus remarquables de son génie." I think, then, that any discussion, however sketchy, of the history of electromagnetic waves should begin with a brief tribute to the founder of modern mathematical physics.

The electromagnetic theory may be said to have started with Faraday, who could not reconcile himself to action at a distance. It is very hard to get any physical idea of how one body can act on another across empty space. The mathematicians who followed Newton were not much worried by the question of *how* gravity acted : they were content to know the quantitative laws of gravitational force and to leave any machinery by which the force acted as a mystery. Early electricians spoke of an electrical effluvium, supposing that an electrified body was surrounded by a mysterious vapour which produced the effects of attraction and repulsion. Faraday regarded the medium between two electrified bodies as the seat of the action. In the case of a dielectric he supposed that the electric force produced in it a state of polarisation, that is, a partial separation of the positive and negative electricity which it contained in equal quantities, a change in the distribution of electrical forces. He made much use of lines of force, both electric and magnetic force, which he assumed to have a tension along them and a repulsion of one another laterally. He was not very happy about vacua, for he liked always to talk of intervening particles. He supposed that when a magnetic force acted these particles were in a particular state which he called the electrotonic state.

About this time those dealing with other branches of physics, especially with the propagation of light, were deeply concerned with considerations of empty space. Light was acknowledged to be a transverse vibration, and, since light travels across space void of matter, the question was, what could be vibrating? To explain this difficulty space was held to be filled by an ether, and this ether had the properties of an elastic solid. Thus the whole theory of elasticity and elastic vibrations was involved in the study of light : nobody could be versed in the theory of light unless he were familiar with the mathematical theory of elasticity. Most of the great names of nineteenth century physics play a prominent part in the history of elastic ethers—Fresnel, Cauchy, MacCullagh, Neumann, Green, Kelvin, Stokes, Larmor, for instance. I am often asked whether there is an ether or not. If you take the ether to be nothing more than a subject for the verb "to vibrate," it may be said to exist, or to be a convenient word in conversation. The moment that you try to give it any material properties, even a position, much less density or elasticity, it fails and leads to contradiction. It is rather like one of the bright creations of the politician—very good and comforting until you strive to attach some precise meaning to them, when they vanish in a cloud of inconsistencies, leaving merely names behind them !

Do not think that ether seems remote from radio waves. In 1855 Maxwell wrote : "By a careful study of the laws of elastic solids, and of the motion of viscous fluids I hope to discover a method of forming a mechanical conception of this electrotonic state adapted to general reasoning." He used Faraday's term for the state of the intervening space which arose when it was the seat of electric and magnetic forces. He gave a mathematical form to Faraday's thoughts, introducing what mathematicians call a "vector potential" which could be taken as a measure of the electrotonic state. The magnetic lines of force were thought of as something possessing mass rotating about their axes which gave them the properties of striving to shorten and to expand sideways, just as Faraday had conceived. This meant that the intensity of the medium had to be identified with the permeability μ. It is strange to think that to-day a similar theory is applied to material bodies, for the elasticity of rubber is being explained by the rotation of chains of molecules which tend to contract by virtue of their rotation.

Further, Maxwell extended Faraday's thoughts on dielectrics. Faraday had attributed the properties of dielectrics to a displacement of charges within the insulating substance, a displacement which disappeared as soon as the force was cut off, just as if each charge was bound by springs to one spot, but could be moved from it by a force, the distance through which it was pushed being proportional to the force. This meant that $D = \epsilon F$, where D is the displacement, F the force and as ϵ the dielectric constant. Maxwell thought of this displacement of charge as constituting a momentary current, just as the continuous movement of charges through a wire can be thought of as constituting the current. There is no current where F is constant, since then the charges do not move, but any change of F which leads to a movement of charges constitutes a displacement current. Further, Maxwell imagined the same kind of displacement current in empty space, where $\epsilon = 1$, and not, of course, zero.

Without any mathematics, we would expect this to lead to waves. The medium has density μ and elasticity $\frac{1}{\epsilon}$ since elasticity $= \frac{\text{stress}}{\text{strain}} = \frac{F}{D} = \frac{1}{\epsilon}$ The velocity should be, by Newton's reasoning, $\sqrt{\frac{e}{\rho}} = \frac{1}{\sqrt{\mu\epsilon}}$ This is precisely what Maxwell's elaborate calculations gave.

The scaffolding which Maxwell used to build up his equations no longer expresses our methods of thought on these subjects. Elastic ethers with mechanical properties are out of fashion for good, superseded by more precise, if more remote, conceptions. Maxwell's theory is Maxwell's equations, says the science of the day. But I thought it worth while to show you how they grew out of the physics of the time, out of Faraday's thoughts and out of a mechanical elastic ether.

Let me try to contrast simply Maxwell's electrodynamics with the older views. Consider an iron ring with a close winding, through which an alternating current passes. On the older views the magnetic field would be confined to the iron, where it would vary periodically. On Faraday's views there would be a varying electric field surrounding the ring, since there is a magnetic flux through any circuit looped round the ring. On Maxwell's views this field would constitute a varying displacement current, which must be accompanied by a varying magnetic force, since any change of electric force is equivalent to a current, which is proportional to the rate of change of the force.

Maxwell knew nothing of electromagnetic waves such as radio deals with. He showed that from his equations it followed that electromagnetic waves—that is waves in which both electric and magnetic force varied periodically—must be propagated with the velocity of light : $\frac{1}{\sqrt{\mu\epsilon}} = 3 \times 10^{10}$ cm/sec. in empty space if we choose the right units. Hence he concluded that light was an electromagnetic disturbance, and he and his immediate successors brought much supporting evidence to this theory. Now this is fundamental for radio, for it means that all the laws of optics, suitably modified for the difference of frequency, must apply to radio. Much of what I have to say hereafter will be concerned with this transference of work done on light to the field of radio waves.

I must mention the work of Hertz, who first produced the long waves with which radio deals. Hertz was at one time a German hero, but his Jewish parentage has led to the disappearance of his name from German scientific literature. All German scientists in Germany to-day say " it was shown," and not " Hertz showed." Nevertheless, he is still one of the heroes of science, and it is a great pleasure to read his wonderful papers. I am grateful that this address sent me back to them.

Hertz was convinced of the correctness of Maxwell's equations and saw that it should be possible to produce electromagnetic waves by electromagnetic means, but the difficulty was to detect them. It was known, as a result of the work of Kelvin and others, following the lines already worked out by mathematical physicists for material pendulums—another example of the interdependence of the different branches of physics—that the discharge of a Leyden jar was oscillatory. Hertz realised that the strength of the wave must depend on the frequency ; Maxwell's equations show that the effects are proportional to the rate of change of the electric force. Hertz pointed out that the frequency of ordinary Leyden jar discharges was about 10^6 per second. What he did in effect was to make an oscillatory circuit with a very small capacity and consequently a very high frequency, of the order of 10^8 per second, and to demonstrate the use of a broken ring as a detector, a spark passing across the very small gap when a wave traversed the ring. With this apparatus he established the existence of the waves and showed that they obeyed the laws of optics—reflection, refraction and polarisation. The waves that he used were of metre wave length. Radio science was founded on a sure basis. Just as Roentgen founded the study of X-rays so thoroughly that for twenty years after his discovery no fundamental advance was made, so Hertz did his work so well that nothing really essential was discovered for ten years after his papers appeared. Then Marconi's discovery of a new sensitive detector was the starting point for fresh advances.

To return to optics, once it had been definitely established that light was an electromagnetic disturbance all the optical properties of material bodies had to be explained on an electrical basis. The discovery of the electron and the establishment of its properties by J. J. Thomson and his school and by Continental workers had convinced everyone that matter was electrical in structure, and the optical properties of matter had clearly to be worked out on the basis of the interaction of the forces of electromagnetic waves with the electrons in matter. The rapidly varying electric forces act on the electrons, and the electrons themselves emit, and so react on the waves. We are at once met with two cases : the electrons may either be practically free, and act merely as particles with inertia on which periodic forces act, or they may be bound with quasi-elastic forces, so that if moved from their equilibrium position they are urged to return by a force proportional to the displacement. Free electrons correspond to metals, bound electrons to insulators, for if we apply a steady electric force to free electrons they will drift steadily along, and constitute a current, but if we apply it to an insulator the electrons will be displaced by a given amount from the centres of positive charge, and the material will become polarised. In the case of the insulator the behaviour will depend upon the forces binding the electrons, that is, upon the period with which the electron would vibrate if left to itself, as compared with the period of oscillation of the electric forces, i.e. with the frequency of the wave. We are dealing with the case of a forced oscillation with damping. If the free and forced periods agree, we have resonance, to which corresponds a very strong effect on the wave, leading to absorption and anomalous velocity. If the frequency of the wave is a little less than that of the bound electrons with which it interacts, the velocity of the wave is much less than the normal velocity in the material, that is, than the velocity of waves whose frequency is far removed from that of the bound electrons ; if the frequency of the waves is a little greater, the velocity exceeds the normal velocity. On the basis that all optical effects are due to the periodic displacement of charges in the material body, the waves from the moving charges combining with the wave as it would be in the absence of the material, Lorentz and others worked out all the optical properties of insulators. The optics of metals were likewise worked out, but here the subject offers peculiar difficulties, on account of the frequent collisions which the free electrons make with the atoms of the metal, leading to strong absorption.

I have said that near the region of resonance, the region of absorption—that is, in the region of so-called anomalous dispersion—the velocity of the wave may exceed the normal velocity in the material, this normal velocity being, of course, less than the velocity in free space. However, the velocity may even exceed the velocity in free space; with sodium vapour, for instance, the velocity of a wave of length 5889·6 Å (there is a sodium emission line at 5889·96) is notably greater than that of light in free space, the refractive index being 0·614 only. How is this possible? You have all been told that the theory of relativity implies that no signal can be sent with a velocity greater than that of light, or, if you like, that a packet of energy cannot travel with a velocity greater than that of light. This is true. In a dispersing medium, however, that is, in a medium in which waves of different frequencies travel with different velocities, we can have simple harmonic waves which travel with velocities above that of light, but in such media we have the peculiar phenomenon of wave groups.

As a simple example, consider ripples on the surface of a pond, the velocity of which varies with the wave length. The effect of a stone dropped into the water is a group of circular wavelets running out. By watching carefully one of the minor wave crests towards the back of the group, we shall see it catch up the centre of the group, overtake it and then die down to invisibility, to be followed by another wave crest. It is clear that the wave trains which build up the group alone travel faster than the group itself does. At the highest crest of the group—that is, at the centre of the group—crests of the various wave trains of different frequency that make up the group coincide. If all the frequencies travelled with the same velocity, this central crest, and the whole group, would also travel with the same velocity, but since the different frequencies travel with different velocities, as they pass through the group they soon find themselves at some spot in front of the main crest, in such phase relationships that they cancel out, so that they appear to run through the main crest and vanish. Similar considerations hold for any kind of waves that show dispersion. Now the energy can be shown to travel with group velocity and not with the single wave velocity or phase velocity, as it is called.

The question may be asked, why not send a signal by one single frequency, by monochromatic radiation? The answer is that it is impossible: monochromatic radiation must stretch out in an infinite train in both directions. One has only to take up a pencil to try to draw it to see that a monochromatic train cannot be started from nothing. Any signal starting from nothing and building up to an approximately monochromatic train must necessarily contain a range of frequencies, particularly prominent in this important initial part. If there is no dispersion they will all travel with the same velocity, and these considerations do not arise, but in a dispersing medium the signal travels with the group velocity. Discussion of this point arose when the velocity of visible light was being considered: the full theory of group velocity first appeared, however, in Lord Raleigh's "Sound." The application to radio will appear later.

Fundamental for the radio engineer is the great body of physical research on the electron carried out by J. J. Thomson and his school at the Cavendish laboratory in Cambridge, by such men as J. S. Townsend, who is here to-night, and by such workers abroad as Millikan, Langevin, Lenard, Wien and many others whose names will readily occur to you. They established the general laws of the conduction of electricity through ionised gases at different low pressures, in terms of the rate of production of the ions, their coefficient of recombination and their mobilities; the motion of electrons in magnetic fields; the effect of ultra violet light in producing ions in gases; and the laws of the emission of electricity by glowing metals, with which the name of O. W. Richardson is particularly connected. All these matters seemed very remote from any practical end when the fundamental researches on them were being carried out. I need hardly remind you that the work on thermionics and on the electrical behaviour of gases at very low pressures lies at the basis of the wireless valve, so that an understanding of them should be part of the equipment of everyone who deals with the generation and reception of waves.

I want now to turn to something a little less obvious, perhaps, and show how an understanding of Lorentz's work on optics, of Rayleigh's work on wave and group velocity, of the properties of gaseous ions and their generation by ultra violet light is essential to those who concern themselves with the passage of the waves between transmitting and receiving stations.

One of the great sensations of the early days of wireless was the establishment of wireless communication between England and America by Marconi, in 1901. Attempts were made to explain this passage of the waves round the curvature of the earth on the lines of classical optical theory, as diffraction, the earth being regarded either as a perfect or a partial conductor, but Lord Rayleigh and others showed that the effect of diffraction was far too small. The optical analogy would be a point of ordinary light extremely close to the surface of a sphere a few centimetres in diameter: you know how little of the light would get to a point 20 or 30 degrees away, let alone to the antipodal point. Shortly after Marconi's achievement Kennelly and Heaviside independently proposed to attribute the effect to a reflecting layer, consisting of ionised air, spread parallel to the earth's surface and acting as a roof, keeping the rays from escaping. It was not until well over 20 years after this suggestion that Appleton and his collaborators, followed by Breit and Tuve in America, established the existence of such a layer; Appleton, in fact, proved that there was more than one layer. Let us consider, very briefly, the physics of this remarkable effect.

The nature of the effect was investigated by Appleton by two methods, the first being to measure the angle at which rays from a given source returned by the upper atmosphere reached the ground again, and the second, which has been much more extensively used and proved very fruitful, to observe the effect at a distant receiving station of varying continuously the frequency of the waves emitted by the sending station. The general principle of this matter is very simple, being that of the so-called Lloyd's interference fringes in ordinary optics, which are produced by the interference of a direct wave with a ray from the same source reflected from a mirror. There is, of course, the difference that in the Lloyd's fringes the frequency is constant and the fluctuations occur in space, whereas in Appleton's method the frequency varies and the fluctuations occur in time at a fixed spot. There is a third method, originated by Breit and Tuve, which consists in transmitting a very short pulse of given frequency and recording the arrival of both the ground ray and the ionospheric ray. This has proved very fruitful and gives the same kind of information as the interference method.

If the ionosphere could be taken to consist of a sharp reflecting surface, exactly analogous to a mirror in ordinary optics, the matter would be very simple. The ground ray and the reflected ray would travel at practically the same velocity and the rate at which the path difference, expressed in wave-lengths, changed with frequency, as revealed by the interference effects at the receiving station, would give the path difference and hence the height of the layer. Our problem is not, however, so simple; the layers of ionised air are thick and have no sharp boundary. Simple physics provides us with a picture as to how the E layer is formed. The ionising agent is the ultra-violet light of the sun, which brings us back to the work in the physics laboratory on the production of ions by ultra-violet radiation and its dependence on wavelength. The production of ions means absorption of the radiation, so that the nearer we approach the earth, the feebler the effective radiations become. On the other hand, the nearer we approach the earth the more molecules we have in a given volume, which would lead to an increase in the number of ions. The two effects work against one another so that we should expect a maximum effect at a certain height, with little production of ions very remote from the earth, where the radiation is strong, but there are few molecules to encounter, and little production of ions near the surface of the earth, where there are plenty of molecules, but little effective radiation left.

To explain the effect fully we have to take into account the recombination of the ions and electrons. Chapman has also taken into account the effect of the rotation of the earth, and obtained very satisfactory agreement of calculation with observation for the E layer. The complex F layer offers many difficulties, but is also accessible to theoretical explanation based on the general physics of ionising radiation. There is no doubt that radiation from the sun is the agent which produces ionisation, the evidence being derived from the variation of the height of the layer with time of day, in particular the contrast between day and night, and from the variation with sun spot activity, which is correlated with ultra-violet emission. It will be seen, therefore, that the radio engineer cannot afford to neglect the physics of the sun. We shall also see that the earth's magnetic field has a very important part to play, so that geophysics as well as solar physics claim our attention.

Consider, then, the interaction of electromagnetic waves with a wide layer containing free electric charges. This is just what Lorentz treated in his theory of the effect of matter, of dielectrics, on ordinary light. The earth's magnetic field must also be taken into account, as just mentioned. Although the charges are free our analogy is not the optics of metals, where the absorption is very high, but the optics of dielectrics when the frequency of the incident waves is very far from the frequency of any resonators in the dielectrics; very far, that is, from the free period of bound electrons. In such a case the binding forces have little effect.

Just a word on the effect of a magnetic field. When an electron is moved in a magnetic field it experiences a force which tends to push it at right angles both to its motion and to the direction of the transverse component of the magnetic field. Thus, if the magnetic field is entirely along the direction of motion, there is no effect; if it is entirely at right angles to the direction of motion, and both are in the plane of the paper, the force is normal to the plane of the paper. At the magnetic equator we have precisely this effect for a vertical beam, for the magnetic force is entirely horizontal, and waves with polarisation parallel to the magnetic force are reflected at a different level from those polarised transversely to the force.

The force is proportional to the strength of the field and to the velocity, but the tendency of the electron to persist in a straight line is proportional to the square of the velocity. The result is that, in a given field, the faster the electron moves, the larger the circle into which it is forced by a normal field. A result of this is that the time taken by an electron to go once round, or its frequency of revolution, called its gyro-frequency, will be independent of its speed, but will depend on the strength of the field (and on the charge and mass of the electron). The electron, then, has a kind of resonant frequency in the field.

Working out the optics of the waves passing through a cloud of free electrons, without magnetic field for the moment, we find that there is dispersion, that is, that the velocity depends on the frequency of the wave, and also on the density of electrons, since clearly if there are no electrons present there will be no effect. We are confronted at once with the problem of phase velocity and group velocity, but the student of optics will have no difficulty here. He is not surprised to find that the refractive index of the layer is less than unity, which means that the phase velocity is greater than that of light, while the group velocity, which is what is measured, is less than that of light. The refractive index also depends on the frequency, as it does in the ordinary optics of transparent media. But if the refractive index of the layer is less than unity we shall get total reflection, as when light passes from glass to air.

Considering now the magnetic field, and supposing it to have a component at right angles to the direction of travel of the waves, we are confronted with two cases. The electric vibration lies in the plane at right angles to the direction of travel, and the magnetic field also lies in this plane. If the two directions coincide, the magnetic field will have no effect ; if the two are at right angles, the field will have a maximum effect. The wave will behave differently, therefore, according to its plane of polarisation. Waves polarised in one direction will be unaffected and will correspond to the ordinary ray in crystal optics : waves polarised in a direction at right angles will be affected and will correspond to the extraordinary ray in crystal optics. The absorption of the two rays will be different ; in fact, one may be so strongly absorbed that only the other is received. The analogy in optics is shown by the crystal herapathite, the substance used in making polarised films. This strongly absorbs one of the rays, so that the light that comes out is plane polarised. All our textbook optics is repeated with small variations only.

Appleton applied all these considerations to the reflection of wireless waves from the ionosphere. He showed that while a high frequency beam will penetrate the ionosphere if the angle of incident is small, it will be reflected if incident at an angle exceeding a certain limit depending upon the frequency. The way in which the reflection of a beam incident obliquely on the ionosphere leads to a "skip distance" is well known. We have only to remember that the ground ray dies off rapidly when waves of medium length are in question. This is perhaps the most important effects for purely practical considerations. The structure and height of the ionosphere is, however, of the greatest theoretical interest, and one of Appleton's chief contributions is to show how radio waves can be made to give detailed information on these points. One of the main discoveries is that, with a fixed angle, say vertical incidence, as the frequency is increased, a value is reached at which the waves penetrate the ionospheric layers. Reflection takes place when the appropriate refractive index is reduced to zero, and theory shows that, neglecting minor complications, this zero refractive index is reached when

$$\frac{N}{m} = \frac{\pi f^2}{e^2}$$

where N is the number of electrons per unit volume (the "electron density"), e and m the charge and mass of the electron and f the frequency, supposing that, as appears to be the case, only electrons, and not charged atoms, are responsible for the refraction. Higher frequencies than that given by the formula will penetrate the layer. Hence the greater the electron density, the greater the frequency required for penetration, and, whatever the density, a sufficiently high frequency will be transmitted right through the layer. Appleton found that waves exceeding a certain frequency have a much greater height for the reflecting layer, which simply showed that the waves had penetrated the ordinary E, or Heaviside layer, and been reflected at a much higher, the F or Appleton, layer. Still greater frequencies penetrate the F layer and so give no reflection. Appleton was also able to trace the influence of magnetic field on the polarisarion of the waves, in accordance with the theory already indicated. He further measured the density of electrons in the two layers, by the simple considerations just indicated. A vast amount of work has been done on the variation of the heights of the layers with hour and season. What I wish, however, to emphasise is that the whole of the work is optics on a large scale of wave length ; the theory is a skilful application of the results obtained years before by Lorentz and others working our problems in the electromagnetic theory of light.

There is one trifling illustration of the theory of dispersion to which I should like to refer before leaving the subject. An essential feature of this theory is the strong absorption that takes place if waves of a certain frequency traverse a medium containing bound electrons that would of themselves vibrate with this frequency if disturbed—resonators, as it were. Now it has been found that when signals are sent across London a marked absorption of certain frequencies occurs, due to the various tuned aerials operating in the built-up area. They take up the energy of their own particular frequency and remove it from the signals. They must also lead to dispersion, but I have not heard that the effect of this has been actually measured.

A different aspect of the application of optical theory is afforded by the arrays used to-day for beam wireless. In the transmission diffraction grating familiar to students of physics we have a large number of openings, spaced at about a five-thousanth of a centimetre from one another, and we are dealing with wave lengths of a few hundred thousandths of a centimetre. If the grating is illuminated normally by parallel light, each slit will act as a line radiator, all the radiators being in the same phase. The effect due to any number of parallel equidistant slits—sources, that is—has been worked out for the purpose of spectral analysis. In the wireless array we are usually dealing with waves of length of some metres, and the elements of the aerial array are usually effectively spaced at half a wave length apart. In any case, the whole problem of the distribution of the resultant radiation—the so-called polar diagram—is exactly the same as the problem of the distribution of light from an optical diffraction grating, whether a single Franklin aerial is in question, where the elements are in a vertical line, or whether several aerials are placed side by side to concentrate the beam in a horizontal as well as in a vertical direction. The wave length is, however, some tens of million times that in question in optical experiments.

I may say that I have heard proposals to use very fine gratings of parallel wires, kept white-hot by an electric current, as the optical analogy of the wireless array. This proposal shows a misunderstanding of the situation. In the wireless case the phase relationship of the oscillations in the different component aerials is carefully governed by the circuits ; in the ordinary diffraction grating the phase relationship is governed by illuminating the rulings with a beam of parallel light from one line source. With glowing wires there would be no phase relationship—no coherence, as it is called—and no interference effects.

The use of very short, centimetre, waves has brought in further examples of optical diffraction. Every student of light knows that when a reflector or obstacle is of anything like the size of the wave length diffraction effects take place—we cannot use the results of geometrical optics, which assume that light can be considered as travelling in straight lines. A concave mirror, to give a good parallel beam, must be many tens of wave lengths across, or even larger, if great accuracy is required. This is sometimes forgotten in radio. For instance, I am told that in certain short wave experiments when the mirror was only twelve or fifteen wave lengths across, considerable trouble was taken to get a parabolic rather than a spherical mirror, but actually the spreading due to diffraction was so large that this added refinement was not worth while. We may usefully keep in mind the Rayleigh criterion given for the optical case, but valid here, that variations of the surface by one-quarter wave length from the ideal form do not signify. The size of an optical mirror bearing the same relations to the wave length as do radio mirrors would be microscopic.

My last example of how old physics turn up in new radio is the wave guide. Many difficulties, which are well known to most of you, attend the generation of very high frequencies, sometimes called hyper-frequency radiation or centimetre waves. The inductance and capacities of the leads into the valve are not negligible for such frequencies and problems of matching become very grave. These troubles are avoided by the use of the so-called wave guides, the simplest form of which consists of a copper tube of circular or rectangular cross section, an inch or a few inches in diameter, according to frequency. The generating valve is placed inside the tube, so that we have perfect shielding from electric disturbances, and simple and robust construction, among other advantages. The mathematical conditions governing the waves generated in this enclosure are different from those for waves in free space, since we have the condition at the metal surface that the component of electric force parallel to the surface must be zero. It so happens that these conditions were worked out by Lord Rayleigh in 1897, long before the subject seemed to have any practical interest. He established the existence of the two classes of possible waves, namely, those which have no component of magnetic force parallel to the axis of the tube, the so-called E waves, and those which have no component of electric force parallel to the axis, the H waves. He also showed that there was a certain lowest frequency for the propagation of periodic waves inside a hollow conducting cylinder and found an expression for this lowest frequency in the case of both a rectangular and a circular cross-section. The critical or cut-off frequency depends on the dimensions of the cross section and on the dielectric in the tube, if there is one. In the course of his paper he refers to work done in his *Theory of Sound*, which shows how general is the application of physical work done on vibrations. These wave guides can be used as generators of waves, and as resonators, that is, tuned receivers. The analogies with sound are very striking, the emission of waves from the end of the guide being, for instance, very like the emission of sound from the end of a tube provided at the other end with a vibrating diaphragm, with which I personally have been concerned. We also meet again with the question of phase and group velocity : at frequencies near the cut-off frequency the phase velocity may greatly exceed that of light. In the wave guide electromagnetic theory, optical theory and the theory of sound all meet in harmony.

There is much talk to-day to the effect that all scientific research should be carried out with a practical end in view ; that the only object of science should be to minister to the material needs of humanity. I am far from agreement ; the sublime curiosity that pushes a Faraday or a Rutherford to find out, to search by patient thought and experiment for reasons and meanings in nature's vast complexity, is a thing to be encouraged, whatever may come of it, just as great art is a thing to be encouraged—a manifestation of the nobler side of our mixed nature. Remember that, no matter how little the abstract scientific worker, the poet of the laboratory, may have practical ends in mind, he often founds vast industries and initiates advances which bring the material prosperity which some say he should deliberately seek. Newton, Faraday, Maxwell, Hertz, J. J. Thomson, Owen Richardson, H. A. Lorentz, Lord Rayleigh—these men had no practical end in view when they carried out their researches. Without their labours, however, the science of radio, if it existed, would be much the poorer. My attempt this evening has been to show how pure physics underlies all aspects of radio. My examples have been few, but I hope that I may have stimulated you to search for yourselves and to regard a knowledge of physics not as a polite accomplishment, but as a fundamental need of the radio engineer.

A vote of thanks, proposed by Dr. James Robinson, was most heartily accorded to the author for his paper.

PROPOSALS FOR TELEVISION AND BROADCASTING TRANSMISSION SYSTEMS

by W. A. Beatty (*Member*)

A paper read before the London Section of the Institution on February 16*th*, 1944, *and repeated before the North-Eastern Section on March* 14*th*, 1945.

SUMMARY

Proposals are made for Television and Broadcasting Transmission Systems. These proposals visualise television standards and Transmission methods different from those previously used. It is proposed that :—

(*a*) Two polarisations be used for television transmission, vision signals using vertical and sound signals horizontal polarisation, both transmissions sharing a common frequency spectrum.

(*b*) Interference between the vision and sound transmissions be combated by the introduction of an antiphase sound signal into the vision signal, and by the use of a time modulated pulse transmission for sound. A method of combatting interference between sound and synchronising by having some synchronising between the different pulse trains used for sound transmission and synchronising is suggested.

(*c*) Each transmitted picture has 640 lines due to a three-way interlacing, and that provision be made in the transmission for increasing the line structure up to 1,280 lines per picture.

(*d*) Two methods of frame synchronising be available, one due to a difference in duration between line and frame synchronising pulses, and the other due to the changing of the basic carrier frequency during the frame synchronising period. It is further proposed that frame synchronising makes provision for automatic colour phasing in an experimental colour transmission system.

(*e*) The time modulated pulses used for sound transmission have a repetition frequency of 32 kc/s, and that these pulses retain up to the ninth harmonic of the pulse repetition frequency. The signal to noise improvement as compared to amplitude modulation is discussed ; an improvement, as compared to amplitude modulation of 29·2 db. in the case of random noise, and 34 db. in the case of car ignition noise is claimed.

By the adoption of three ranges of service area for different services, two polarisations, and a time modulated pulse system with a repetition frequency of 20 kc/s for local sound services, it is shown that one television transmission with stereophonic sound, and 21 broadcast sound transmissions can be provided in any one location.

It is shown that the number of frequency channels or spectra required to give adequate television programme coverage to a large area of country can be decreased by increasing the frequency ; this decrease being due to the greater attenuation beyond the horizon for higher frequencies.

In order to avoid interference between transmissions in different areas served by a common television programme, it is suggested that if frequencies in the neighbourhood of 42 Mc/s were used, seven channels would be required, as against five channels when using frequencies in the neighbourhood of 250 Mc/s.

It is pointed out that there may be advantages for local sound services in covering an area by the use of a large number of low power transmitters, rather than by a smaller number of higher powered transmitters. The author suggests that the existing air raid syren poles and power supplies could form the basis of such a low power transmission system.

INTRODUCTION

The first broadcast radio post-war requirement is the design of ordinary receivers. During this initial period engineers can re-group themselves into well integrated teams capable of carrying out in a satisfactory fashion the design of television equipment meeting improved standards of transmission.

The author wishes to emphasise the fact that he does not consider that the proposals which follow offer a satisfactory solution to the problems of post-war television and sound broadcasting on short wavelengths, he is also of the opinion that none of the groups of proposals recently put forward by individuals or sponsored by professional bodies offer practical solutions to the television and broadcasting problems.

Because of these and many other valid reasons which can be brought forward, it seems desirable that we resign ourselves to the fact that it will not be practicable to restart television for at least three (3) years from the cessation of hostilities with Germany.

This interim period offers an opportunity for investigation into the questions of the most satisfactory television standards and methods of transmission. The proposals which follow are being put forward mainly with the idea of stimulating discussion, and it is hoped that such discussion will demonstrate the undesirability of fixing now or in the immediate future any post-war television or broadcasting standards.

The author is further of the opinion that the question of fixing television standards and methods of transmission should be deferred until such time as competent radio engineers can devote the major portion of their activities to these problems. Any final standards should be arrived at as a result of open discussion between representatives of the radio industry, the B.B.C., Government services, and professional bodies.

Prior to the war, the B.B.C. operated a television transmitter from Alexandra Palace, London, the vision and sound transmission using adjacent frequency spectra in the neighbourhood of 45 Mc/s. Amplitude modulation, with double side bands, was used for vision, synchronising, and sound, the transmission being vertically polarised. The transmitted vision signal comprised 25 complete pictures per second, made up of 50 interlaced frames, each frame having 202·5 lines, giving 405 lines per complete picture. White in the vision signal was given by a signal of positive sense, relative to a black level, given by 30 per cent. of the peak picture signals. Synchronising signals were transmitted in the level 0 to 30 per cent. of the peak picture signal.

It has been suggested elsewhere that it would be a good plan to resume television transmission as soon as possible after the war, using the pre-war standards of transmission. The standards for the pre-war B.B.C. television transmission were fixed by E.M.I. about 10 years ago, and since that time many developments have taken place in television and allied transmission systems, which make it desirable that the whole question of television and broadcast transmission should be reviewed.

No doubt various other television transmission systems can be put forward, and recently ([1,2]) there have been discussions regarding such other systems. With a view to stimulating discussion on the subject, a television and broadcasting transmission system is proposed which, in all its main features, differs considerably from the pre-war B.B.C. standards of transmission.

The fact that definite proposals are being made should not be taken as an indication that these proposals either individually, or together, are considered to be the best compromise which can be taken on the subject of television standards, and ultra short wave broadcasting.

Briefly stated, the proposals are :—

1. That the frequency used for transmission shall be such that there is no danger of effective interference due to ionospheric reflections, or other causes from other transmissions working on the same frequency.
2. That vision signals be transmitted with vertical polarisation.
3. That sound signals be transmitted with horizontal polarisation, but using a frequency spectrum within the frequency spectrum taken by the accompanying vision signals.
4. That interference on the vision signal due to the sound transmission be combated by introducing into the vision signal a further signal which can be termed "An anti-phase sound signal."
5. That interference on the sound signal due to the vision transmission be combated by the use of a wide band time modulated pulse transmission for the sound signals.
6. That interference with synchronising signals, due to the sound transmission, be combated by having some synchronisation between the synchronising pulses and the time modulated pulses used for sound transmission.
7. That a vestigial side band transmission be used for the vision signal.
8. That vision white be given by a signal of negative sense relative to the vision black signal level, and that synchronising signals are given by a signal of positive sense relative to the vision black signal level, said black level being 84 per cent. of the combined vision and synchronising peak voltage level.
9. That the vision signal be comprised of 16⅔ interlaced frames per second making a total of 50 pictures, each frame having 213⅓ lines giving a total of 640 lines per complete picture.
10. That the shimmer due to the picture speed of 16⅔ lines be combated by an auxiliary interlacing giving an effective line structure of 1,280 lines per picture.
11. That the aspect ratio of the viewed picture be in the ratio of 4–5, vertical to horizontal dimensions, the frame synchronising and blanking interval being 7 per cent. of a frame period, and the line synchronising and blanking interval being 15 per cent. of a line period.
12. That line and frame main synchronising pulses be of the same constant amplitude, and that two types of frame synchronisation be available.
13. That the first type of frame synchronising be due to pulses in the frame synchronising period, having a duration which is four times that of the line synchronising pulses.
14. That the second type of frame synchronising be due to pulses transmitted at a period when the basic carrier frequency of the transmitted carrier has been changed. These pulses to be known as F.M. Pulses.
15. That frame synchronising makes provision for automatic colour phasing with a view to the subsequent adaptation of the system to a medium grade experimental colour television system.
16. That the sound transmission be due to the time modulation of a train of pulses of constant amplitude, having a repetition frequency of 32 kc/s per second, i.e., three times the frequency of the line scanning frequency.
17. That the slope of the edges of the time modulated sound transmission pulses be characteristic of

pulses retaining up to the 9th harmonic of the pulse repetition frequency.

18. That provision be made for stereophonic transmission of sound on the television service. The transmission channels necessary for this service using horizontal polarisation and sharing the same spectrum with the vision signal.
19. That two wide band pulse modulated high quality sound transmission channels with horizontal polarisation be allocated frequencies within each guard spectrum between the vision spectra.
20. That additional high quality wide band sound channels in any one area be provided by pulse transmissions with horizontal polarisation, these transmissions sharing spectra with vision transmissions in other areas.
21. That further, medium quality wide band sound transmission channels in any one area be provided by pulse transmission with vertical polarisation, these transmissions having a limited service area, and sharing spectra with vision transmissions in other areas.

The various proposals can now be dealt with in greater detail.

It is well known that at various times the B.B.C. television signals on 7 metres were picked up at places located considerably outside what was considered to be the normal service area, transatlantic reception even being claimed. These long ranges could only have been due to signals reflected from the ionosphere. Such reflections can well be expected under certain sun-spot conditions, since on occasions communication on wavelengths as low as 5 metres has been achieved over distances over several hundreds of miles. It is probable that there will be international agreement on one or more frequency spectra to be used for television, and it is desirable that the frequency spectra agreed upon preclude the possibility of interference due to reflected signals from other transmissions.

The minimum acceptable signal to interference for vision is apparently 46 db.(³). This means that when amplitude modulation is used for the vision signal, any interfering signal should be less than 0·5 per cent. of the voltage of the vision signal given by a change from black to white, peak voltages being assumed in both cases.

It may be that when using a wavelength of 7 metres for television, the interference due to reflection would, because of ionospheric attenuation and other causes, have such a low field strength in all cases that effective interference would not be caused. It is reasonable to suppose that much more is now known of ionospheric reflections than was the case in 1933, and those who are well experienced in this aspect of radio propagation will be able to advise which frequencies can be safely adopted for a general television service.

No definite proposals are being made here regarding any particular frequency to be used for a television service. Attention is, however, drawn to the fact that it is desirable that the question of the most suitable frequency for general television service be reviewed in the light of modern experience.

Apart from the interference due to reflections, the possibility of interference due to direct propagation either within the line of sight, or over the horizon, should also be considered. Factors which influence the degree of interference likely to be experienced by transmissions on the same frequency are the heights of the transmitting and receiving antennæ, the distance between transmitters and receivers together with the frequency and power used. The heights of the transmitter and receiver antennæ determine the line of sight or what can be termed the " horizon " distance.

In an article entitled, " The Service Range of Frequency Modulation," (⁴) by Murray G. Crosby, there is derived from previously known formulæ, an equation for the field strength of ultra short wave transmissions, given by :—

E (r-m-s microvolts per meter) =

$$\frac{0{\cdot}01052\ ahf\ D_h{}^{(n-2)}\sqrt{W}}{D^n} \qquad \text{...........} \quad (1)$$

where W = effective watts radiated = power in antenna times antenna power gain over a one-half wave dipole.

a = receiving antenna height in feet.

h = transmitting antenna height in feet.

D = distance in miles.

D_h = distance to horizon in miles = $1{\cdot}22\sqrt{h} + 1{\cdot}22\sqrt{a}$

f = frequency in Mc/s.

n = 2 for distances within the horizon, and varying with frequency, is taken from a curve for distances beyond the horizon (for instance $n = 3{\cdot}5$ when $f = 42$ Mc/s and $7{\cdot}25$ when $f = 250$ Mc/s.

The equation given by (1) may be re-written as :—
E (r-m-s microvolts per meter) =

$$\frac{0{\cdot}01052\ ahf\ \sqrt{W}}{\left(\frac{D}{D_h}\right)^n \times D_h{}^2} \qquad \text{..............} \quad (2)$$

When $D = D_h$ the above equation gives the field strength at the horizon.

It can also be seen from (2) that the field strength at places other than the horizon varies relative to the horizon field strength as

$$\left(\frac{D_h}{D}\right)^n \qquad \text{...} \quad (3)$$

This variation in field strength can be shown in decibels as

$$20\ n\ \log_{10}\left(\frac{D_h}{D}\right) \qquad \text{.............................} \quad (4)$$

If $D = 0{\cdot}5\ D_h$ the increase in field strength given by (4) is $+ 6$ db. when $n = 1$.

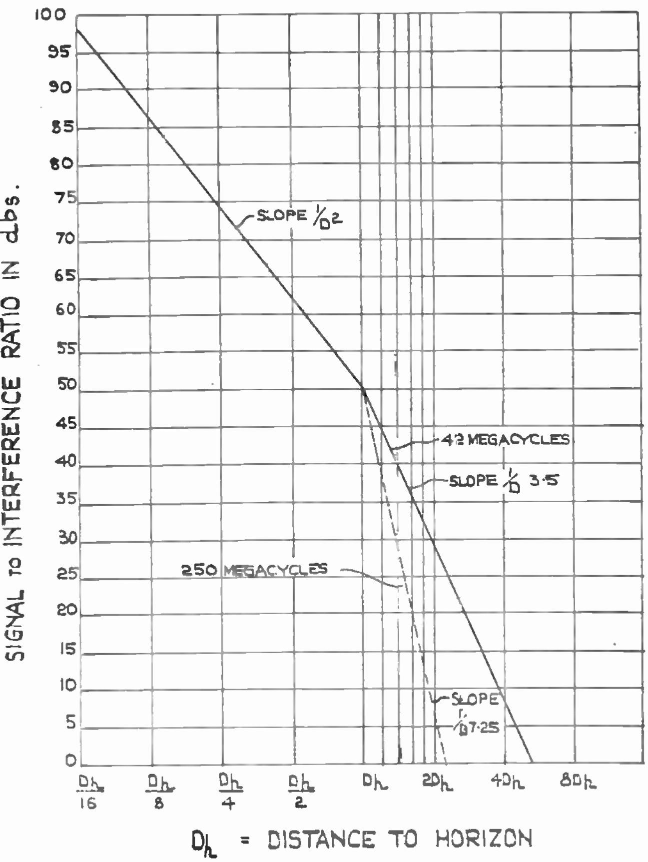
or if $D = 2\ D_h$ the decrease in field strength will be $- 6$ db. when $n = 1$.

The change in field strength relative to the horizon field strength can therefore be given as

+ 6 n db. for each progressive halving of distance inside the horizon and — 6n db. for each progressive doubling of distance outside the horizon. ...... (5)

Fig. 1 shows curves for field strength in decibels against distance, within and without the horizon, when $f = 42$ Mc/s and $f = 250$ Mc/s, the distance scale being logarithmic. Since $n = 2$ for distances inside the horizon, each halving of distance gives an increase in field strength of 12 db. for both frequencies.

FIGURE. I.



However, outside the horizon, doubling the distance gives an attenuation of $6 \times 3{\cdot}5$ db. $= 21$ db., in the case of 42 Mc/s, and $6 \times 7{\cdot}25 = 43{\cdot}5$ db. in the case of 250 Mc/s.

In Crosby's article, entitled " The Service Range of Frequency Modulation," the type of curve shown in Fig. 1 is made subject to a correction which allows for variations in field strength both within and without the horizon, these variations being due to fading, reflections, and other causes. These variations in field strength, when allowed for, can modify the curves shown in Fig. 1. These curves should, therefore, be regarded as being representative of an approximation of the mean field strength likely to be encountered in practice.

The method of deriving the attenuation relation given above for distances beyond the horizon was empirical, and may not be justified on theoretical grounds.

Theoretical consideration indicates that the relation of field strength and distance is of exponential form. This attenuation relationship has been discussed by M. Katzin(5).

If in practice it is found that field strength beyond the horizon varies exponentially with distance, the number of spectra required so as to avoid interference may have to be greater than that which would be the case where field strength varied as a negative power of distance.

Referring to the curves on Fig. 1, there is shown a signal to random noise level of 50 db. at the horizon. If a frequency of 42 Mc/s is used, and one considers the interference likely to be experienced between two similar transmitters, the first of which is one D_h unit of distance and the second four D_h units of distance from the receiver, it will be seen that the signal to interference level is 42 db. Similarly, if a frequency of 250 Mc/s is used, the signal to interference level will be 44 db., when the second transmitter is only two D_h units of distance from the receiver. This difference in attenuation of signals with change of frequency should have a considerable bearing on the number of adjacent frequency spectra allocated to a television service, so that adequate geographical separation can be achieved between transmitters working on the same frequency spectrum.

If it were desired to give complete television coverage to a large thickly populated area such as, for instance, the north of France, Belgium, and Holland, there would be required at least seven different frequency spectra when using frequencies in the neighbourhood of 42 Mc/s, so that adequate separation can be achieved between transmitters using the same frequency spectrum. When using spectra in the vicinity of 250 Mc/s, only five different spectra would, however, be required. Equal omni-directional propagation is assumed in both cases. However, if specially beamed antenna were used it would probably be possible to reduce the number of spectra required to five and three in the cases of 42 and 250 Mc/s.

Frequency spectra can be made available more readily on 250 than 42 Mc/s, and therefore, apart from interference considerations due to ionospheric reflections, there may be arguments in favour of using for the post-war television service frequencies much higher than those used by the B.B.C. prior to the war.

Proposal (2) that vision signals be transmitted with a vertical polarisation and sound signals with a horizontal polarisation can conveniently be considered together.

The successful use of vertical and horizontal polarisations for transmissions on the same frequency depends upon the amount of discrimination due to polarisation which can be obtained between the transmissions. Prior to the war, some rough tests were made on the B.B.C. television sound transmission, at a location in the Cray Valley, at a distance of 13 miles from the transmitter and out of the line of sight between the transmitting and receiving antennæ.

The receiving antenna was located inside a building which was surrounded by trees. The receiving conditions, therefore, could not by any means be considered as ideal.

It was found that by swinging the antenna from the vertical to the horizontal position, the discrimination as judged aurally was at least 20 db., and probably much better than that.

A discrimination of 20 db. only would not be sufficient for satisfactory operation of either the vision or sound transmissions, but if means can be found to improve upon this initial discrimination then there would be advantages in using two polarisations and a common frequency spectrum for the vision and sound transmissions.

The whole of the spectrum allocated to a television service could be used for vision transmission, and as this spectrum would be much greater than that required for any practical type of sound transmission, more than one sound transmission could be accommodated within the spectrum, giving rise to the possibility of having a stereophonic effect on the television sound transmission.

In addition, wide band transmission systems can be used for sound transmission, such transmissions being either due to frequency modulation or time modulated pulses, with the advantage that a large measure of freedom from interference due to car ignition and similar causes can be achieved.

In considering what type of polarisation should be allocated to each transmission, the following observations may be helpful. It was noticed with B.B.C. television transmission that when interference from car ignition was experienced, the sound transmission could tolerate much less interference than the vision. When the sound transmission was completely unintelligible there would still be a reasonably good picture. This leads to the conclusion that if car ignition interference shows a tendency towards one polarisation more than another, then the sound transmission should use the polarisation least favoured by the car ignition interference.

Some time before the war, the British Electrical and Allied Industries Research Association carried out an investigation(6) into the polarisation of the interference due to car ignition. It was found that the average interference tended to have a greater vertical than horizontal component of polarisation.

This leads to the conclusion that for minimum interference from car ignition the sound transmission should be horizontally polarised. If two polarisations are to be used, the vision transmission would preferably be vertically polarised.

Proposals (4, 5 and 6) dealing with methods of combating mutual interference between the different types of signals can conveniently be considered together.

The vision and synchronising signals transmitted with vertical polarisation comprise a complex signal with amplitude modulations for vision, while pulse signals to be used for sound transmission are signals of constant amplitude. It is well known that if one has an initial discrimination of about 6 db., against interference in the case of constant amplitude transmissions, such as frequency(36) or pulse modulation, then by virtue of the special characteristics of the transmissions the discrimination against interference can be improved, the amount of improvement being dependent upon the bandwidth required for the transmission.

With amplitude modulation transmissions on the same frequency a discrimination of 40 db. is normally considered necessary for satisfactory operation. As far as is known there have not previously been proposals which would allow of any improvement being obtained on the initial discrimination existing between two amplitude modulated transmissions working on a common frequency. A method whereby additional discrimination can be achieved between two amplitude modulated transmissions on the same frequency will now be described.

If one assumes a discrimination of 20 db. between two transmissions on the same frequency, one of the transmissions being vertically and the other horizontally polarised, the mutual interference between the transmissions can be combatted by mixing with either transmission, a signal which is the "Anti-phase signal" of the other, and 20 db. down on the original signal. This can be more readily understood by referring to Fig. 2, where two simple types of pulse transmissions are shown.

Referring to Fig. 2, assume that the pulse train A curve 1, of constant voltage V, is characteristic of a signal used to modulate a vertically polarised transmission, while the pulse train B curve 3 of similar constant voltage is used to modulate a horizontally polarised transmission, having an output similar to that of the previous transmission.

If one assumes that at the receiver there is only 20 db. discrimination between the two polarisations, the received signals will be characteristic of the curves 5 and 6, i.e., either signal will have the other 20 db. down, superimposed upon it.

Instead of transmitting the pulse signals A and B as shown in curves 1 and 3, there is derived from these signals the anti-phase pulse train *a* curve 2, having a voltage of $^{1}/_{10}$ V and the anti-phase pulse train *b* curve 4, also having a voltage of $^{1}/_{10}$ V and these anti-phase signals are combined with the original signals, as shown in curves 7 and 9. Curve 7 shows the original signal A, combined with the anti-phase signal *b*, while curve 9 shows the original signal B with the anti-phase signal *a*. The signals shown in curve 7 are now transmitted with vertical polarisation while the signals shown in curve 9 are transmitted with horizontal polarisation.

At the receiving location, signals characteristic of curves 7 and 9 will be received on adjacent vertical and horizontal antennæ. In addition the vertically polarised signal will suffer interference from the horizontally polarised signal to the extent shown in curve 8, while the horizontally polarised signal will suffer interference from the vertically polarised signal to the extent shown in curve 10.

The combination of the signals shown in curves 7 and 8 gives a resultant signal as shown in curve 12. It will be seen that the signal shown in curve 11 is characteristic of a signal having an amplitude 99 per cent. of the amplitude of the signal B, curve 3.

It can thus be seen that at the expense of a small loss of power in the transmitters, the mutual interference between the two transmissions can be cancelled.

In the example taken, the anti-phase signals were introduced at the transmitters, but if required, the mixing of the in-phase and anti-phase signals can be performed at the receiver. This, however, may complicate the receiver somewhat, and it may be more practical to carry out the mixing at the transmitters. The example taken is a simple example of what may be termed "Anti-phase discrimination."

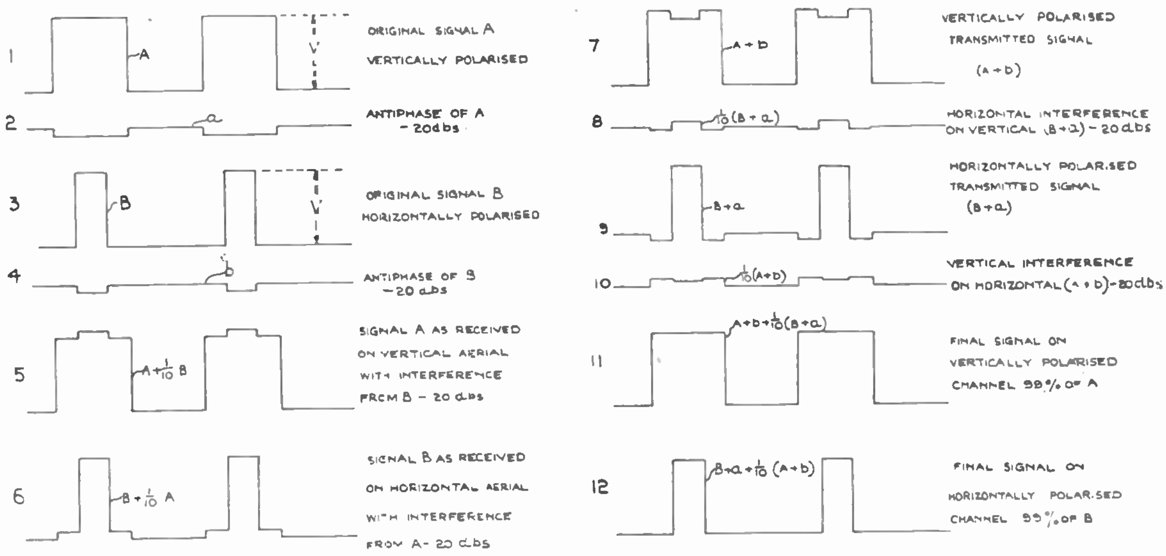
If the sound transmission is due to a time modulated pulse train, anti-phase time modulated pulses of the correct amplitude and phase can be introduced into the vision transmission, with the result that mutual interference between the transmissions at the receiving terminal can be reduced. It would be necessary first to ascertain what would be the maximum amount of interference likely to be obtained between the two transmissions. The level of anti-phase signal introduced into the vision transmission would be dependent upon the maximum amount of mutual interference which would be experienced. This maximum would, due to scattering and reflections, probably occur at the limit of the service area. In order that a satisfactory balance between the in-phase and anti-phase signals be obtained at locations where the mutual interference is less than that allowed for as a maximum, it would be necessary to increase the mutual interference to that obtained as a maximum. This could be done by alignment of antennæ, or by coupling in the early stages of the receiver.

It should not be necessary to introduce anti-phase vision signals into the sound transmission, since the special features of the pulse transmission will give sufficient discrimination against interference.

Although the basic principles of time modulated pulses for the purpose of transmission had been disclosed as long ago as 1924, by R. A. Heising,(7) and although there have at intervals since that time been references in the patent and other literature (8-26) to this pulse

FIGURE 2

ANTIPHASE TRANSMISSION SYSTEM



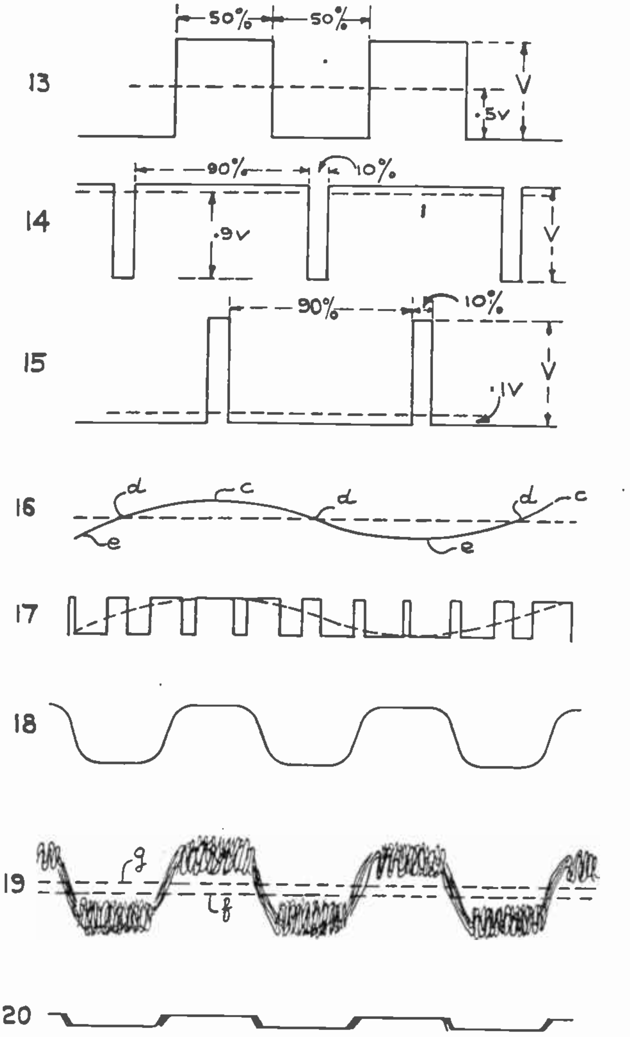
transmission system, the basic principle is not well known to workers outside this specialised field, and a short description of the system in its simplest form would probably be not out of place here.

Fig. 3 shows a series of curves which will serve to illustrate the description.

Referring to Fig. 3, curves 13, 14 and 15 show three trains of rectangular pulses, the first having a switched-on duration of 50 per cent., the second 90 per cent. and the third 10 per cent. of the periodic time. If the pulses all have the same constant voltage V, the average voltage level of the three trains will be 0·5 V, 0·9 V, and 0·1 V, as shown in the curves. It can therefore be seen that if means are available for time modulating a pulse train in accordance with a signal voltage, the mean voltage level of the pulse train will be characteristic of the modulating signal voltage.

FIGURE.3

TIME MODULATED PULSE TRANSMISSION



For methods of time modulating pulse trains, reference should be made to the patent literature (7,10,11,14,15,21,22).

Curve 16 shows the waveform of a signal used to time modulate the pulse train shown in curve 17. The pulses shown in curve 17 have a mean duration of 50 per cent. of the pulse periodic time when the waveform shown in curve 16 has its mean voltage at the times indicated as *d*, while the pulses have their maximum duration at the time *c*, and their minimum duration at the time *e*. The dotted line in curve 17 shows the mean level of the pulse train. It will be seen that the waveform given by the dotted line is substantially similar to that given by the curve 16. For practical working it is desirable that the repetition frequency should be at least five times that of the highest fundamental tone which it is desired to transmit. For high quality music transmission, these conditions can be met by making the pulse repetition frequency not less than 30 kc/s.

Under practical conditions, the transmitted pulses will not be rectangular in waveform as shown in curves 13, 14, 15 and 17, but will have a definite slope to their edges as shown in curve 18, the slope of the edges being dependent upon the harmonic content of the pulses. This will be discussed in greater detail at a later stage.

Curve 19 shows the same train as shown in curve 18 but with an interfering signal added. If the signal plus interference shown in curve 19 is applied to the input of an amplitude filter, having a lower cut-off voltage as indicated by the level *f*, and an upper cut-off voltage as indicated by the level *g*, the output from such a filter will have a waveform similar to that given by curve 20, which it can be seen is substantially similar to that given by curve 18. The interference which was superimposed upon the pulse train has been largely eliminated, the only effect of the interference being to advance or retard slightly the time of occurrence of the leading or trailing edges of the pulses. This advancing or retarding of the time of occurrence of the edges of the pulses can be regarded as a time modulation of the pulse train due to interference.

The greater the slope of the edges of the pulses, the smaller becomes the amount of time modulation due to interference. The slope of the pulses increases in accordance with pulse harmonic content, i.e., bandwidth required, and it can thus be seen that any improvement in signal to interference is obtained at the expense of a greater band width. For satisfactory operation, the minimum harmonic content for the pulse train is the retention of all harmonics up to the fifth. Since the repetition frequency of the pulse train must be at least twice that of the highest frequency of the modulated signal, the retention of the fifth harmonic as a minimum means that, for satisfactory operation with time modulated pulses, the pulse train must contain frequencies up to ten times that of the highest frequency of the modulating signal.

It can, therefore, be seen that a time modulated pulse transmission is essentially a wide band transmission system, and can only be recommended in certain cases. It is not proposed to discuss here in great detail the signal to noise improvement to be obtained with time modulated pulse transmissions, but some reference to this improvement will be made later when discussing the details of standards for the proposed television and broadcasting systems.

It is possible to make either the leading or the trailing edges of the time modulated pulse train occur at fixed intervals of time. Such edges are usually referred to as fixed edges. By using this expedient it is possible to make a fixed edge of one train of time modulated pulses to occur at the same time as the leading edge of the pulses used for line synchronisation, with the result that the interaction between the two transmissions is a constant at the time of line synchronising, thus giving line-synchronisation free from interference. The effect of interference on frame synchronisation can be made very small and will be discussed later.

Proposal (7) that a vestigial side band system be used for vision signals. The arguments in favour of this system can be summed up by saying that it is working effectively in the U.S.A. and gives a satisfactory vision service with economy of bandwidth as compared with a double side band system.

Proposal (8) that vision white be given by a signal of negative sense relative to the vision black signal level and that synchronising signals are given by a signal of positive sense relative to the vision black signal level, said black level being 16 per cent. of the combined vision and synchronising peak voltage level.

This proposal suggests a sense for the vision signal the opposite of that adopted by the B.B.C.; the synchronising level suggested is about 0·5 of that used by the B.B.C.

The main advantages arising from having picture white given by the negative signal are that the synchronising pulses give a peak signal of constant amplitude and this peak signal can be used for A.V.C. purposes.

The provision of A.V.C. for the vision signal may be important if the frequency adopted for transmission be such that signals are subject to variations in strength, due to any causes, either inside or outside the horizon.

The B.B.C. television system had a synchronising signal level of 30 per cent. of the combined synchronising and vision peak signal level. An examination of the requirements for accurate synchronisation lead to the conclusion that a synchronising level of 30 per cent. is too great.

Assume that a smaller level, such as 1/11 of the combined synchronising and vision signal level, is allocated to synchronising. Under such circumstances the effective signalling portion of the synchronising signal would be 20 db. down on the vision signal. It was previously pointed out that for satisfactory operation the vision signal should be 46 db. up on interference, so if satisfactory operation is being obtained the synchronising to interference level would be 26 db. If the slope of the edges of the synchronising pulses is such that each pulse rises and falls from approximately 12·5 per cent. to 87·5 per cent. of its peak amplitude in ·5 micro-seconds, the amount of time modulation given to the edge of a pulse by an interfering signal 26 db. down would be very small, and would not be noticed under practical conditions.

The effect of such interference will be dealt with in greater detail at a later stage.

Greater freedom from interference can be achieved by making the slope of the synchronising pulses as great as possible. The slope described above would require a bandwidth of approximately 1 Mc/s for one side band, and the system about to be proposed will require a bandwidth of approximately 4·6 Mc/s for one vision side band.

Proposals 9 to 16, dealing with the various standards of the proposed television system, can be considered as the details of the system are given.

Before considering the details of the standards for a television system it is desirable that there be established a convenient formula which will make possible easy analysis of all factors dealing with picture detail and the frequency spectrum involved.

It is desirable that in fixing any standard for definition equal time be allocated to vertical and horizontal definition. With the spot size and shape limitations of present-day electron cameras and cathode ray tube reproducers, it is not possible to obtain equal horizontal and vertical definition with an equal time allocation to these definitions. However, the allocation of equal time for horizontal and vertical definition allows for any advantages likely to be obtained by improvements in the operation of electron beam scanning devices.

A convenient formula which allows for equal time being allocated to vertical and horizontal definition(3) :—

$$f_v = \frac{1}{2} \cdot \frac{\beta}{\alpha} \cdot r \cdot f_p \cdot n^2 \text{ cycles per second} \quad \ldots\ldots \quad (6)$$

where f_v = fundamental frequency obtained by scanning the picture, referred to here as the vision frequency.

b = width of visible picture.

h = height of visible picture.

r = aspect ratio = b/h.

n = total number of lines.

n_p = number of lines in visible picture.

$\alpha = \dfrac{\text{time taken to scan visible part of line.}}{\text{total periodic time of each line.}}$

$\beta = n_p/n$.

f_p = number of pictures per second.

The formula given by (6) was derived as the result of considering a picture having an aspect ratio in which the width was greater than the height. The formula does not hold for pictures having aspect ratios in which the height is greater than the width ; however such aspect ratios are not usual, and can be neglected for practical purposes.

It is realised that there is some difference of opinion as to what are the factors determining overall vertical and horizontal definition. Some of these factors are discussed in a paper entitled "A Determination of Optimum Number of Lines in a Television System" by R. D. Kell and others(35). In that paper the relationship between optimum number of lines and frequency spectrum requirements is determined by a formula somewhat different to that given by (6).

It should be noted that f_v the vision frequency refers to the frequency of the vision signal prior to modulation of a high frequency carrier signal ; therefore, with full double sideband amplitude modulation, the spectrum required for transmission will be 2 fv.

If $n = 640$

$\alpha = \cdot 85$

$\beta = \cdot 93$

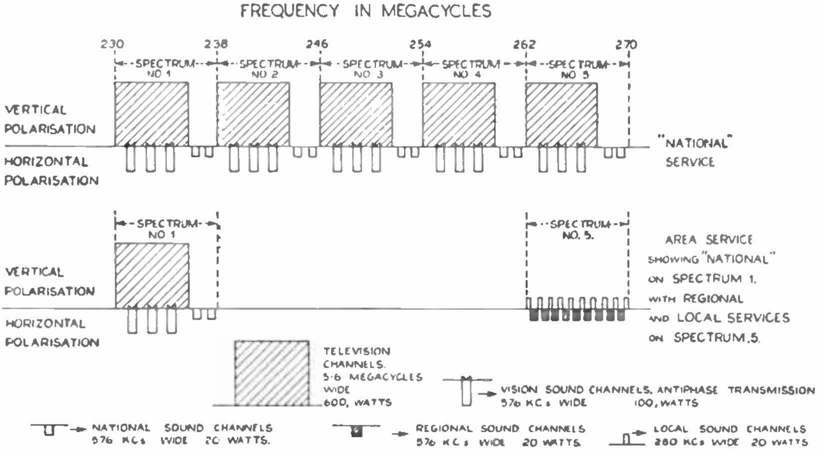
$f_p = 16\frac{2}{3}$

$r = 1{\cdot}25$

then f_v given by (6) = 4·6 Mc/s.

If a vestigial sideband system is used for transmission, allowance should be made for approximately 1 Mc/s for the vestigial sideband, and accordingly the system with the standards given above will require an overall spectrum of approximately 5·6 Mc/s.

FIGURE 4.



In Fig. 4 there is shown a diagrammatic arrangement of 5 spectra, each spectrum being 8 Mc/s wide, giving an overall spectrum of 40 Mc/s, centred on 250 Mc/s.

The hatched spectra above the horizontal dividing line refer to 5·6 Mc/s wide channels used for vision and synchronising transmission, with vertical polarisation.

Sound channels, each 576 kc/s wide, are shown below the horizontal dividing line, all these sound channels being allocated to horizontal polarisation. The 576 kc/s wide channels can each accommodate a double sideband pulse transmission, the pulse repetition frequency being 32 kc/s, with up to the ninth harmonic being retained.

In each 8 megacycle spectrum, three of the sound channels share a common frequency spectrum with the vision transmission. These three channels are allocated to the sound side of the vision programme, and the anti-phase method of transmission would be adopted on the vision transmission. The provision of three sound channels makes it possible for a stereophonic transmission to be adopted for vision sound.

Two other sound channels are shown in the 2·4 Mc/s interval spectrum allowed between each vision channel. These interval channels can be allocated to programmes which are independent of the television transmission.

The vision and sound channels, as shown in Fig. 4, could be allocated to the main service in a country. At first sight it might seem that the number of channels provided would be inadequate, but it will be shown that with proper choice of frequency and service ranges of transmitters, it would be possible to accommodate any demand for sound channels likely to arise in practice.

In Fig. 5 there is shown a diagrammatic arrangement of an area completely covered by vision transmissions shown by large circles using frequency spectra numbered 1 to 5. Each transmitter is assumed to have a omnidirectional propagation characteristic. The edges of the circles indicate the horizon distance plus 10 per cent. from the transmitter, the transmitters using frequencies allocated so that areas using a common frequency spectrum will not suffer from mutual interference. The vision sound, and the two transmissions in the interval spectra, would have the same service area as the vision transmission. The letters V and H in the diagram refer to vertical and horizontal polarisation respectively.

There is also shown an area indicated by a circle having two-thirds the radius of the large circles, this circle being shown in dotted outline. This dotted outline circle covers portions of areas served by spectra 1, 2, 3 and 4, and preferably has its centre at a location where the horizon distances of the various television transmitters tend to coincide. The area within this dotted circle can be served by sound transmissions horizontally polarised and using channels within spectrum 5. Nine 576 kc/s wide channels with guard bands of 280 kc/s wide can be accommodated within an 8 Mc/s spectrum, so by this arrangement of frequencies nine further channels can be allocated to a given area.

AREAS SERVED BY FIVE SPECTRA, USING VERTICAL AND HORIZONTAL POLARISATIONS

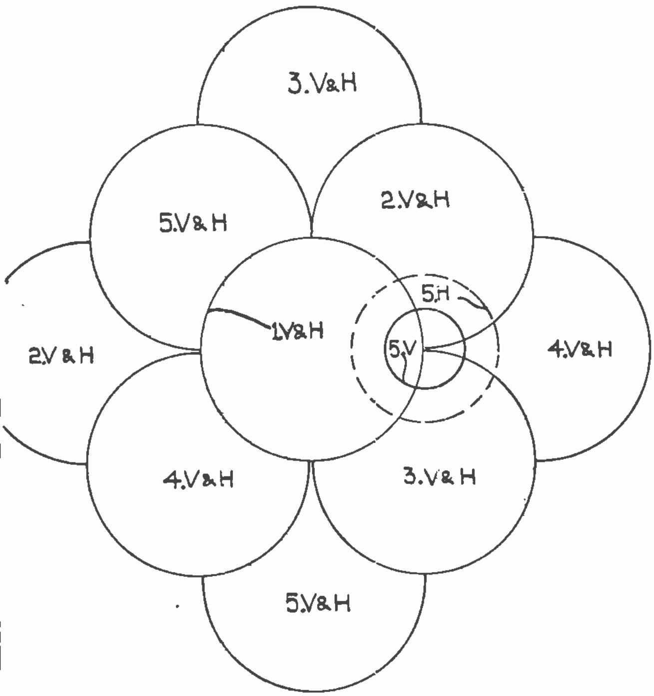


FIGURE 5

A still smaller circle, having one-third the radius of the largest circles and having the same centre as the circle shown by the dotted line, also covers portions of the areas served by spectrums 1, 2, 3 and 4. The area within this small circle can be served by sound transmissions vertically polarised, and using channels 280 kc/s wide within spectrum 5, these 280 kc/s wide channels being the guard bands used for the 576 kc/s wide channels of the horizontally polarised transmissions in spectrum 5. Ten such guard bands can be accommodated within each 8 Mc/s spectrum.

The 280 kc/s wide channels can be allocated to time-modulated pulse transmissions, the pulse repetition frequency being 20 kc/s with harmonics up to the seventh being retained. A transmission having these characteristics would be capable of giving quality which, for all practical purposes, would be up to the standard normally transmitted by the B.B.C. Transmissions of this type would be suitable for local services.

Since pulse transmissions, like frequency modulated transmissions, are of the constant amplitude type, a discrimination of only 6 db. is necessary between different transmissions, in order for the special signal to noise improvement features of the system to be realised. The separation between working frequency bands shown above is more than sufficient for the purpose of giving the necessary 6 db. discrimination.

The arguments for allocation and use of frequency spectra can be summarised as follows:—Because of propagation attentuation characteristics, it would be necessary to allocate at least five spectra for television services, so that complete coverage could be obtained. These spectra must of necessity be separated from one another by guard bands, so as to give selectivity discrimination in areas where the services overlap. Anti-phase transmission makes it possible for vision and sound to share a common spectrum in the television transmission. The economy in bandwidth due to the sound and vision sharing the common spectrum makes possible a greater picture detail in the bandwidth available.

Since 5 spectra must be allocated for vision, reserving for this service a frequency spectrum of 40 Mc/s it is possible by a proper choice of polarisation and service range to make available numerous sound transmission channels in any part of the areas served by the television service.

In the worst case, which is obtained when there is an overlapping of four television service areas, it should be possible to provide the allocation indicated below.

One television vision channel with bandwidth of 5·6 Mc/s.

Three television stereophonic sound channels with bandwidths of ·576 Mc/s.

Two broadcast sound channels with bandwidths of ·576 Mc/s.

These transmissions, which could be referred to as "National," should have a service range of approximately 33 miles radius from the transmitters, which preferably should be served from the same location.

Nine broadcast sound transmitters with bandwidths of ·576 Mc/s.

These transmitters, which can be referred to as "Regional," could have a service range of approximately 22 miles radius from the transmitters.

Ten broadcast sound transmitters with bandwidths of ·280 Mc/s.

These transmissions, which could be referred to as

" Local," would have a range of approximately 11 miles radius from the transmitters.

The above allocations give one television transmission with stereophonic sound, and 21 broadcast sound transmissions in any one location.

The number of local transmissions could be increased very considerably if the service range of each transmitter were further reduced. For instance, if the service range was reduced to about two miles, it might be possible to give a multi-channel local service, using the existing air raid warning siren supports as transmitting sites. The transmitters required could be very small and be remotely controlled. The power supply now available for each individual siren is much greater than that which would be required for small, time-modulated pulse transmitters.

If the service range of 33, 22 and 11 miles taken above are considered to be the horizon distance plus 10 per cent., these distances will be given by assuming a receiving aerial of 25 feet high, and transmitting aerials of 400, 150 and 25 feet approximately in the cases of the National, Regional and Local transmissions, respectively.

The power requirements for the various services would vary somewhat with local conditions, but rough calculations indicate that a television transmitter having a mean radiated power of 600 watts and sound transmitters having mean radiated powers of 100 watts in the case of the television sound and 20 watts for the other sound transmitters would give adequate service over the ranges specified, when using frequencies in the vicinity of 250 Mc/s.

In designing receivers for the above types of transmissions it would probably be found more convenient to use a single stage of superheterodyne frequency changing for the vision signal, using an I.F. of about 45 Mc/s. For the sound transmissions, a double stage superhet could be used, the first I.F. being the same or nearly the same as the vision I.F., while the second I.F. could be in the region of 4 Mc/s.

Provision could also be made in receivers for switching antennæ with either vertical or horizontal polarisation to the input of the sound receiver as required, when receiving sound transmissions which are independent of the television transmission.

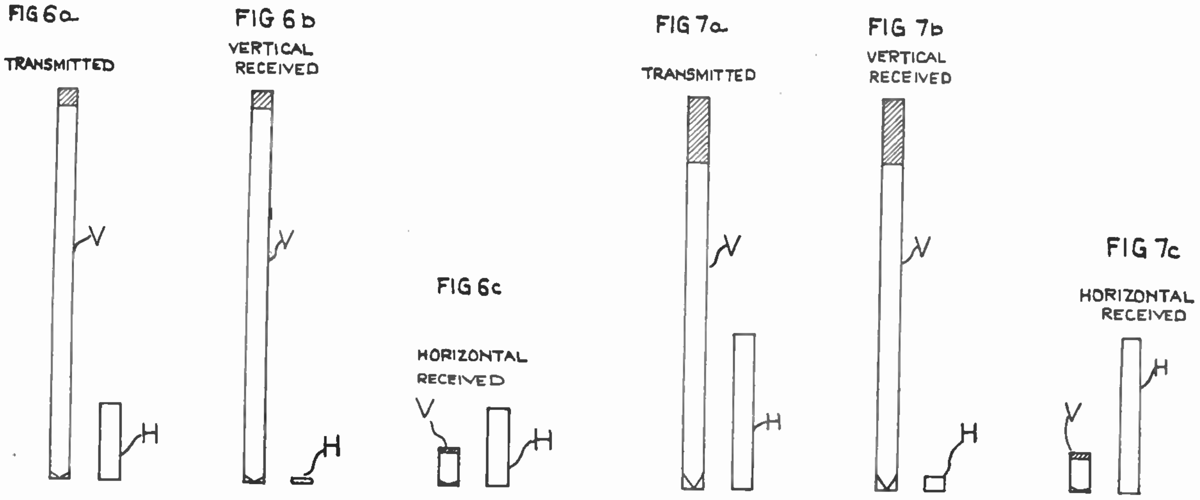
Before considering the details of the television transmission, it is necessary to discuss the relative amplitudes desirable between the sound, vision, and synchronising signals.

The signal to noise improvement features of the sound transmission can be effected with a signal to noise ratio of 6 db. Since a discrimination of 20 db. can be obtained by means of polarisation, the peak voltage of the vision plus synchronising signals could be 14 db. up on the peak voltage of the sound signal, both peak voltages being constant. This can be more readily seen by referring to Figs. 6a, 6b and 6c.

Fig. 6a shows the voltage levels of vision plus synchronising signals, transmitted with vertical polarisation,

TRANSMITTED AND RECEIVED SIGNAL LEVELS

FOR VERTICAL AND HORIZONTAL POLARISATION
WITH ANTIPHASE TRANSMISSION OF HORIZONTAL
ON VERTICAL POLARISATION DISCRIMINATION 20 dbs



POLARISATION: VISION AND SYNCHRONISING, VERTICAL (V) SOUND, HORIZONTAL (H) and sound signals transmitted with horizontal polarisation. The sound signals have a voltage level which is 20 per cent. of that of the peak vision plus synchronising signal.

The synchronising signals have a voltage level which is 20 per cent. of that of the sound signal level, i.e., it is 4 per cent. of the peak vision plus synchronising signal.

Fig. 6b shows the relative amplitudes of the two transmissions as received on a vertical aerial, when a polarisation discrimination of 20 db. is allowed for; it will be seen that the sound signal is now 2 per cent. of the peak vision plus synchronising signal, and that the synchronising signal has an amplitude which is twice that of the sound signal.

Fig. 6c similarly shows the relative amplitudes of the two signals as received on a horizontal aerial, the polarisation discrimination of 20 db. reducing the vision plus synchronising signal to an amplitude which is half that of the sound signal.

In the example taken above, the synchronising signal level of 4 per cent. would be too small for practical working, while a voltage ratio of only 2 : 1 in favour of the received sound programme, while practicable, is rather too close to the limit for comfortable working.

In Fig. 7a there is shown another arrangement of signal levels, and this latter arrangement is suggested for practical working. The sound signal is 40 per cent. and the synchronising signal 15 per cent. of the peak vision plus synchronising signal.

When polarisation discrimination is allowed for, the vision signal as shown in Fig. 7b has an amplitude of over 20 times that of the sound signal. The sound interference can be further reduced by the use of anti-phase transmission. An anti-phase sound signal having an amplitude of 4 per cent. of the peak vision plus sound signal can be introduced into the vision transmission, with the result that for all practical purposes the sound interference will be eliminated from the vision signal.

In Fig. 7c the signals as received on a horizontal antenna are shown. The sound signal has four times the amplitude of the vision plus synchronising signal. This signal to interference ratio of 12 db. is more than sufficient for comfortable working of the system. The final signal to interference ratio obtained by the use of the time-modulated pulse transmission will be discussed later.

Having fixed upon a reasonable value of synchronising signal level, it will now be possible to consider other details of the television signal.

With a picture having 640 lines and 16⅔ pictures per second, the scanning frequency will be 10·67 kc/s per second. This gives a duration of 93·75 micro-seconds per line, there being 213⅓ lines in each frame, if a three-way interlace with 50 frames per second is adopted.

In Fig. 8 there is shown diagrammatically portions of seven consecutive frames giving some details of the proposed signal.

The first frame shows portion of the vision signal, and this frame is assumed to finish at the end of 213⅓ lines. The black level is 84 per cent. of the peak vision plus synchronising signal level, vision signals being negative and synchronising signals positive relative to this level.

Each line having a duration of 93·75 micro-seconds has a synchronising and blanking period of 14 micro-seconds, this being 15 per cent. of the periodic time.

The line synchronising and blanking periods are made up as follows. At the end of each line there is an equalising period at black level for 1·5 micro-seconds, followed by a line synchronising pulse having a duration of 6·25 micro-seconds, followed by a period at black level for another 6·25 micro-seconds.

If line synchronising is assumed to occur on the leading edge of the synchronising pulse there will be a time allowance of approximately 13 per cent. for fly-back time.

Each frame has a blanking and synchronising signal period of 15 lines, this being approximately 7 per cent. of a frame period.

Two independent methods of synchronising are offered by the synchronising system which is proposed. The first method is due to pulse duration discrimination, as was done in the B.B.C. system, while the second is due to frequency modulated pulses.

Each frame and synchronising signal period of 15 lines is made up of signals as follows.

First line, three equalising pulses having durations of 6·25 micro-seconds, and intervals of four times their duration, i.e., 25 micro-seconds.

Second line, three synchronising pulses having a duration of 25 micro-seconds with intervals of 6·25 micro-seconds.; i.e., each frame synchronising pulse has a duration which is four times that of a line synchronising pulse.

The third line is similar to the first line.

Fourth line has one equalising pulse, similar to those in previous lines, followed by two or three, as required, frequency modulated synchronising pulses. The frequency modulated pulses referred to as F.M. pulses have a repetition frequency which is six times that of the line frequency. Each F.M. pulse has a duration of 6·25 micro-seconds, and the first pulse in the series commences one-sixth of a line after the previous equalising pulse in the case of odd frames, and one-third of a line after the previous equalising pulse in the case of even frames. Each three consecutive frames has a series of two F.M. pulses in two of the frames, while the third frame has a series of three F.M. pulses. The frequency deviation can be of the order of 2 Mc/s within the spectrum used by the vision transmission.

Fifth and remaining lines up to a total of 15 lines have line synchronising pulses of 6·25 micro-seconds with intervals of 87·25 micro-seconds.

All synchronising pulses will have a slope such that the pulses rise and fall between the limits of 15 per cent. and 85 per cent. of their levels in 0·25 micro-seconds.

If frame synchronising is given by the pulse duration method, that is to say, synchronising is given by the second line of pulses, the fly-back time allowed will be 6 per cent. If frame synchronising is given by the F.M. pulses the fly-back time allowed will be 5 per cent.

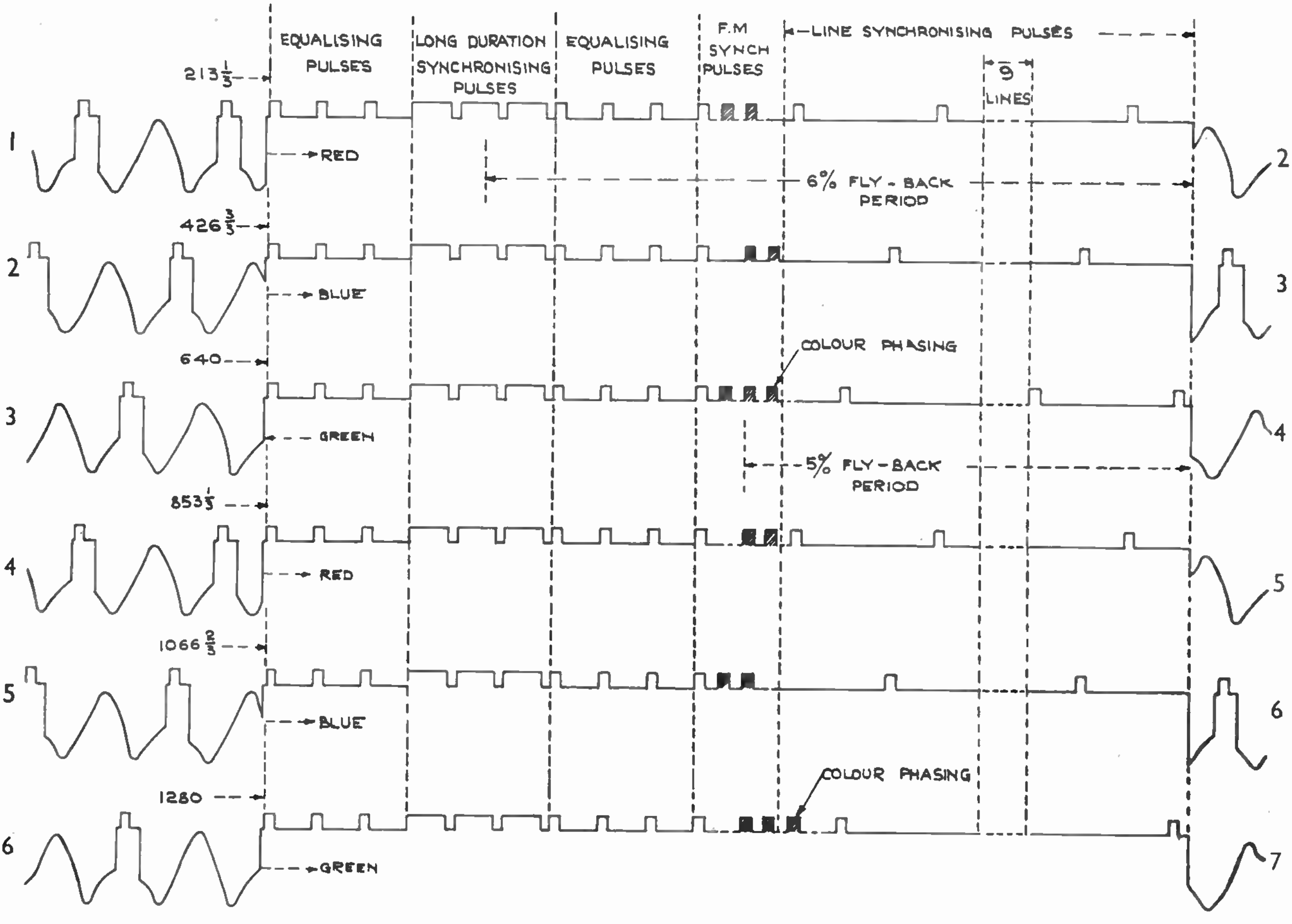
The special advantage to be obtained by the F.M. method of synchronising will now be considered. F.M. pulses for synchronising and other purposes in television transmission have previously been suggested (27-30), and it is only proposed here to consider the special timing aspects of the proposed system.

Considering the first frame shown in Fig. 8. This frame ends when $213\frac{1}{3}$ lines have elapsed, i.e., it ends when one-third of a line has taken place. The first F.M. pulse which follows occurs $3\frac{1}{6}$ lines after the end of the first frame. Therefore, the first F.M. pulse in the second frame occurs when one-third plus one-sixth of a line period has elapsed, i.e., at 0·5 of a line period.

Considering the second frame shown in Fig. 8. This frame ends when $426\frac{2}{3}$ lines have elapsed, i.e., it ends

FIGURE 8

1280 LINES, WITH 6 WAY, AND 640 LINES, WITH 3 WAY INTERLACING



LINES PER FRAME $213\frac{1}{3}$; PICTURES PER SECOND $16\frac{2}{3}$; FRAMES PER SECOND 50

LINE SCANNING FREQUENCY 10·6 K.C DURATION OF LINE 93·75 MICROSECONDS,

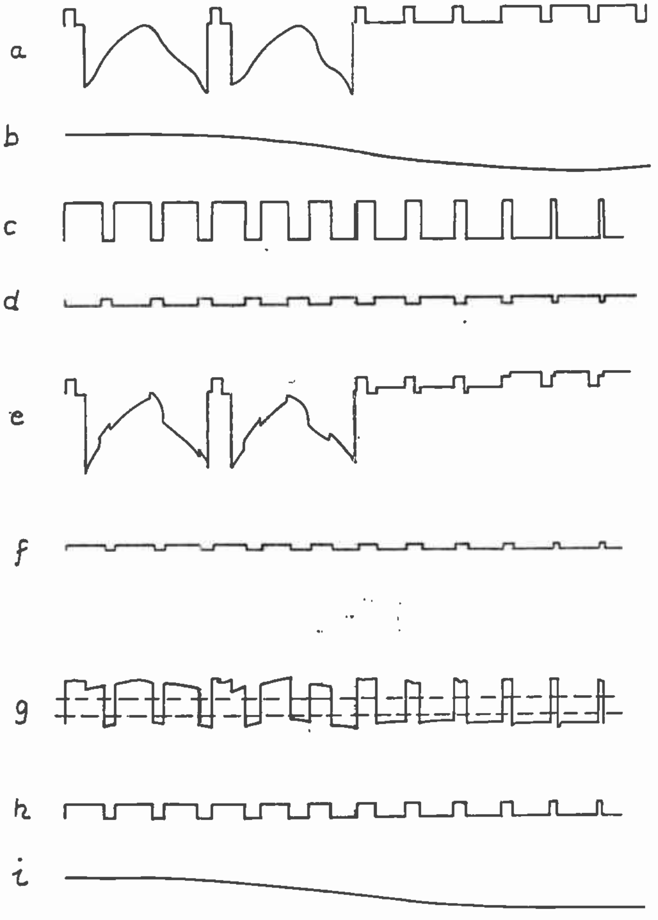
LINE SYNCHRONISING & BLANKING 15% OF LINE PERIOD; FRAME SYNCH; & BLANKING 7% OF FRAME PERIOD when two-thirds of a line has taken place. The first F.M. pulse which follows occurs 3⅓ lines after the end of the frame. Therefore, the first F.M. pulse in the third frame occurs when two-thirds plus one-third of a line period has elapsed, i.e., at the beginning of a line period.

Consider the third frame shown in Fig. 8. This frame ends when 640 lines have elapsed, the first F.M. pulse which follows occurs 3⅙ lines after the end of the frame. Therefore, the first F.M. pulse in the fourth frame occurs when one-sixth of a line has elapsed.

Consider the fourth frame shown in Fig. 8. This frame ends when 853⅓ lines have elapsed, i.e., it ends when one-third of a line has taken place. The first F.M. pulse which follows occurs 3⅓ lines after the end of the frame. Therefore, the first F.M. pulse in the fifth frame occurs when one-third plus one-third of a line period has elapsed, i.e., at two-thirds of a line period.

FIGURE 9

VISION AND SOUND SIGNALS AS TRANSMITTED AND RECEIVED



Consider the fifth frame shown in Fig. 8. This frame ends at 1,066⅔ lines. The first F.M. pulse which follows occurs 3⅙ lines after the end of the frame. Therefore, the first F.M. pulse in the sixth frame occurs when two-thirds plus one-sixth of a line period has elapsed, i.e., at five-sixths of a line period.

Consider the sixth frame shown in Fig. 9. This frame ends when 1,280 lines have elapsed. The first F.M. pulse which follows occurs 3⅓ lines after the end of the frame. Therefore, the first F.M. pulse in the seventh frame occurs when one-third of the line period has elapsed.

It will be seen that the six-way interlacing is achieved by advancing each alternate line by one-sixth of a line period with reference to a three-way interlacing system.

Frame synchronising at the transmitter can be made dependent upon the pulse duration method, or the F.M. method.

Preferably frame synchronising at the transmitter should be dependent upon the F.M. pulses. When this is done receivers synchronised by the F.M. pulses would receive a picture having a detail given by 640 lines, with a vertical line structure of 1,280 lines, while receivers dependent upon the pulse duration method of synchronising would receive a picture with a detail of 640 lines, each alternate picture being displaced by 0·5 of an element of detail from that actually scanned by the transmitter. This small displacement of detail would probably not be observed by viewers.

In addition to giving a vertical line structure of 1,280 lines, the six-way interlacing method may have other advantages. Even when pictures with the B.B.C. system were known to be interlacing perfectly, a viewer could get the impression that correct interlacing was not taking place. This was due to the fact that when the viewer changed his angle of vision in a vertical direction, a stroboscopic effect was obtained between the different sets of scanning lines on alternate frames, or submultiples of such alternate frames.

The greater irregularity introduced into the scanning by the method proposed may make the setting up of the stroboscopic effect more difficult. This could probably only be tried out in a practical case. Should an improvement be obtained in this connection the method described would have useful application to large-scale television as shown in cinemas, more especially when considering viewers close to the screen.

The amplitude of the shimmer or interline flicker is dependent upon the number of lines in a frame. The visible picture would have nearly 200 lines in each frame, this being slightly greater than in the pre-war B.B.C. transmission. With the system proposed the amplitude of the interline flicker would be approximately 1/200th of the vertical height of the picture. The flicker would be characteristic of a picture frequency of 16⅔ and 8⅓ pictures per second.

With the pre-war B.B.C. system the amplitude of the interline flicker was approximately the same as would be obtained with the proposed system. The flicker was characteristic of a picture frequency of 25 pictures per second.

Practical tests would probably be necessary before one could decide which standard would prove the more acceptable. The higher definition of 640 lines would be achieved at the expense of interline flickers having a lower frequency than was obtained with the pre-war B.B.C. system.

In Fig. 8 each third frame is shown as having a series of three F.M. pulses. These groups of three pulses can be used for obtaining automatic colour phasing in a colour television system. The necessity for having such automatic colour phasing has previously been discussed in the patent literature (16,28) and elsewhere (31). There are known methods of making a pulse dependent upon the occurrence of a series of pulses having discreet spacings, the more useful of these methods being dependent upon the use of delaying circuits(32,33). Using one of these known methods, a pulse can be derived from the third pulse in each series of three F.M. pulses. This derived pulse can be used for synchronising apparatus giving automatic colour phasing in a colour television system.

In Fig. 8 each series of three frames is shown allocated to the sequential transmission of the colours red, blue and green, and colour synchronising is shown as taking place on the frames transmitting green.

This colour synchronising system should not be taken as a proposal for an immediate introduction of colour television, but it does indicate a method of providing for automatic colour phasing on what is normally a monochromatic system, in such a manner that the later introduction of colour would not affect the synchronising of receivers adapted to receive monochromatic pictures.

It is realised that the straightforward adaption to colour of the monochromatic system described does not offer the best solution for colour television, but this subject can be considered in much greater detail when finally fixing monochromatic and colour television standards.

It will be seen from Fig. 8 that each alternate frame synchronising pulse when the F.M. pulses are used for synchronising is advanced by one-sixth of a line period from a normal three-way interlacing. This introduces a time error of one-sixth of a line in 213⅓ lines, which equals 1 part in 1,280 in each alternate frame. An error as small as this will not affect accurate triggering of frame scanning signal generators, and it can be neglected for all practical purposes. The error introduced into the automatic colour phasing can also be neglected.

The special sequence of pulses shown in Fig. 8 is more complex than that normally employed, but the generation and keying-in of the various pulses should offer no difficulties to those who are skilled in the art of pulse generation. In fact, various methods of generating and keying the desired pulses can be suggested. It is not proposed, however, in this paper to deal with the subject of pulse generation, except to emphasise that all the pulses required can be obtained by well-known methods.

The relative amplitudes and mixing of the vision and sound signals as transmitted and received is shown in Fig. 9, curves *a* to *i*.

Referring to Fig. 9, curve *a* shows the vision signal with synchronsiing signal added.

Curve *b* shows the sound wave to be transmitted.

Curve *c* shows a train of time modulated pulses with a repetition frequency of 32 kc/s, the time modulation being characteristic of the sound wave-form shown in curve *b*. The leading edge of each third pulse is fixed in phase with each line synchronising pulse, the leading edges also being synchronised with the leading edges of the equalising pulses.

Curve *d* shows a train of pulses which are the anti-phase pulses of the train shown in curve *c*.

Curve *e* shows the vision and synchronising signals mixed with the anti-phase sound signals.

Curve *f* shows the sound signal as received on a vertical antenna, this signal being 20 db. down on what would be received on a horizontal antenna.

The mixing of the signals shown in curves *e* and *f* gives a resultant which is similar to the vision and synchronising signals shown in curve *a*.

Curve *g* shows the sound signal as received on a horizontal antenna with an interference 20 db. down from the vertically polarised vision transmission. The dotted lines drawn through curve *g* indicate the upper and lower amplitude limits of an amplitude filter, so adjusted that it accepts the mean value of the complex signal and rejects amplitudes subject to vision interference.

Curve *h* shows the pulse output given by the amplitude filter.

Curve *i* shows the wave-form due to the integration of the pulses shown in curve *h*. It will be seen that this wave-form shown in curve *i* is similar to the original sound wave-form shown in curve *b*.

Signal to Noise Ratio and Mutual Interference between Signals

The discussion which follows on signal to noise improvement, to be obtained with the various transmission arrangements proposed, is not to be taken as a rigorous treatment of the signal to noise improvement aspects of time modulated pulse systems. This is a subject which is outside the scope of the present paper. The discussion must be regarded as a simple approach to the problem as exemplified by special conditions.

Up to the present very little has been published on the subject of signal to noise improvement obtainable with time modulated pulses. Some aspects of the subjects have been dealt with by previous workers in 1935(9), and in this discussion it is not intended to enlarge greatly upon previously published information.

The envelope of a square-shaped wave-form of constant amplitude can be resolved into a Fourier series, as is well known, thus :—

$$f(p) = \frac{2}{\pi}\left[\frac{\alpha}{2} + \sin\alpha\cos pt + \frac{\sin 2\alpha\cos 2pt}{2} + \frac{\sin 3\alpha\cos 3pt}{3} + \dots\dots\dots\right]\dots\dots\dots \quad (8)$$

where α equals one-half of the pulse duration in angular measure, and p equals the angular velocity of the pulse repetition frequency.

In Fig. 10a there is shown a curve derived from the formula given by (8), when the pulse duration is 50 per cent. of the pulse repetition period, and harmonics up to the ninth are retained. Only a portion of the wave-form dealing with the edge of the pulse has been plotted as this is the portion mainly concerned with signal to noise improvement.

FIGURE 10a

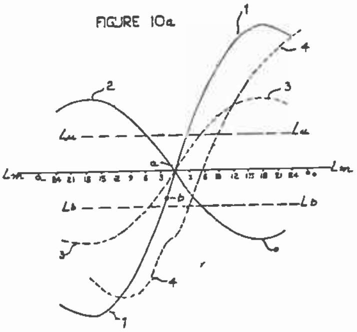


FIGURE 10b

FIGURE 10c

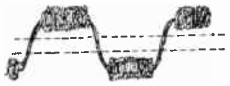


Fig. 10b shows the type of pulse usually generated in time modulated pulse systems. This pulse has a constant amplitude between its edges, whereas the pulses derived according to (8) have periodic variations of small amplitude between the edges, the periodicity of the variations depending upon the number of harmonic terms retained. However, the curve shown in Fig. 10a is near enough, to what is used in practice, for the purpose of considering signal to noise improvements and mutual interference between the various transmissions.

Interference of Sound Programme on Vision

It has been stated that if anti-phase transmission is used, the interference due to the sound programme on vision can be eliminated. This assumes that the anti-phase signals have an exact anti-phase relationship to the sound pulse signals. There may be difficulties in obtaining an exact anti-phase relationship, and it is desirable that the tolerable limits for phasing be determined.

It was previously shown that with the standards adopted, the interference of the sound on the vision signal would have a level which is 4 per cent. of the peak vision plus synchronising signal. The vision signal has an amplitude 84 per cent. of the peak vision plus synchronising signal.

The amplitude of an interfering signal which can just be observed as an interference on the vision signal is 0·5 per cent. of the amplitude of the vision signal, that is to say, with an interfering signal 0·4 per cent. of the peak amplitude (i.e., 10 per cent. of 4 per cent.), there will be a just observable interference on the vision signal.

Referring to Fig. 10a, the point *a* on the curve indicates the mean amplitude of the signal given by the wave-form, and at this point the curve has its maximum slope. The point *b* on the curve indicates where the amplitude of the signal is two-fifths of its maximum, that is to say, it is 10 per cent. less than that given by the point *a*. The time taken for the signal to change from *a* to *b* is approximately 1/200th of the pulse repetition period.

Since the repetition frequency of the sound pulses is 32 kc/s, the pulse period is 31·25 micro-seconds, and 1/200th of this period is 0·15 micro-seconds.

From the above it should be obvious that if the anti-phase pulses depart by more than 0·15 micro-seconds from being exactly out of phase, interference is liable to be noticed on the vision signal.

The phasing of the anti-phase pulses can be very accurately adjusted at the transmitter, and any out of phase at the input of the receiver would be due to difference in the transmission paths for the vertically and horizontally polarised signals.

Assuming that correct phasing of the anti-phase pulses was achieved at the transmitter, a path difference in transmission of 45 metres would give a phasing error of 0·15 micro-seconds. If the vision and sound antennae were mounted vertically above one another on the same mast structure, the vertical and horizontal antennæ could be separated by a distance of 45 metres, and with receivers directly under the antennæ, the phase difference of 0·15 micro-seconds would be obtained.

It should not be necessary to have the vertical and horizontal antennæ separated by as much as 45 metres, and the further the receiver was located from the transmitter the less would be the difference in the lengths of the transmission paths. It would, therefore, seem that in this respect the anti-phase methods of transmission would prove satisfactory. Other factors not considered here, such as reflections from buildings and difference in field strength for the two polarisations, may arise in practice and experimental proof of the working of the system would be desirable.

Signal to Interference Aspects of Pulse Transmission

For satisfactory operation of a time modulated pulse signal, the signal to interference ratio should be 6 db. as a minimum. Receivers have been operated with a signal to noise interference ratio of 4 db., but this latter ratio cannot be regarded as practicable.

With pulse modulation receivers the bandwidth of the

I.F. circuits must be twice that of the highest frequency in the pulse transmission, but subsequent to final R.F. detection, the pulse signals can be passed through a low-pass filter adapted to pass only frequencies up to the highest frequency retained in the pulse signal. Passing the pulse signal and interference through such a filter prior to the pulse amplitude filter, ensures that the slope of any interference is not greater than the slope of the pulses.

Certain types of interference, as for instance that due to car ignition, may have slopes less than that of the pulses(34), but random noise and interference due to the vision signals can be assumed to have initially slopes which are greater than the slopes of the pulses. However, since all sound pulse signals would, in the case under consideration, be passed through a low-pass filter passing up to 288 kc/s, i.e., the ninth harmonic of the pulse repetition frequency, the slope of the interference due to random noise and vision signals would be the same as the slope of the pulses.

The effect of an interference signal 6 db. down on the pulse signal will now be considered. Such a signal plus interference would appear on an oscilloscope screen somewhat as shown in Fig. 10c. The dotted lines indicate the amplitude filter levels, and it can be seen that the interference during the constant amplitude portions of the pulse is eliminated. The effect of the interference on the sloping edges of the pulse is to advance or retard the time of occurrence at these edges, relative to the amplitude limits set by the amplitude filter.

It has previously been shown that the passing of the combined signal plus interference through the amplitude filter has the effect of cutting out the interference which may be present during the constant amplitude periods of the pulse. Therefore, the only time when interference can affect the pulse is during the times taken for the pulse to rise and fall between its constant amplitude conditions, i.e., during the times of occurrence of the pulse edges. It should be obvious that the less time taken for the pulse to change, between one constant amplitude condition and the other, i.e., the greater the slope of the pulse edges, the less will be the time during which noise can affect the edges of the pulses. The slope of the pulse edge can be increased by the retention of a higher harmonic content in the pulse, this entailing a greater bandwidth.

Referring to Fig. 10a there are shown, in addition to the curve 1, indicating the pulse edge, three other curves numbered 2, 3 and 4.

Curve 2 shows the wave-form of an interfering pulse having half the amplitude of the pulse signal shown in curve 1. The interfering pulse is in anti-phase with the pulse signal.

Curve 3 shows the wave-form of a signal derived by the addition of the wave-forms shown in curves 1 and 2.

Curve 4 shows the wave-form of a signal derived by the addition of the wave-form shown in curve 1, and a wave-form similar to that shown in curve 2, but being led by the pulse edge by a time period of

$$\tfrac{1}{3}\,t \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

where t is equal to the periodic time of the highest harmonic, i.e., the ninth, of the pulse repetition frequency.

The limits of the amplitude filter are indicated by the dotted lines L_b and L_u, which refer to the lower and upper amplitude limits respectively.

The mean amplitude of the amplitude filter and of the pulse signals is given by the dotted line L_m.

An examination of the various curves shows that the wave-form given by curve three passes through the mean level of the amplitude filter at the same time as the wave-form 1 given by the pulse signal. Therefore, when the interfering pulse is in exact anti-phase with the pulse edge, the amplitude filter gives its mean output at the same time as when no interfering signal is present. The same condition will also hold when the interfering pulse is exactly in phase with the pulse edge. Therefore, there will be no time modulation of the pulse signal when the interference is exactly in phase, or in exact anti-phase with the pulse edge. The slope of the edge of the pulse given at the input of the amplitude filter will vary with interference such as that considered above, but the noise output given by this change of slope is very small, and for practicable purposes can be neglected.

Consider now the waveform given by curve 4. This wave-form was derived as a result of combining the wave-form given by curve 1, with a wave-form similar to that given by curve 2, the latter wave-form being lead by the pulse edge by a time equal to $\frac{1}{3}$ t.

It will be seen from an examination of curve 4 that it passes through the mean level L_m at a time which is later than would have been the case if no interference were present. This difference in the normal time of occurrence of the mean amplitude of the pulse is on examination of the curves, shown to be nearly

$$\tfrac{1}{6}\,t \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

This time of one-sixth t is the time modulation of the pulse, due to one condition of interference, i.e., when there was a particular phase relationship between the pulse and interfering signals. If the interfering signal is given different phases it will be found on examination that the time of $\frac{1}{6}$th t is approximately the maximum time modulation due to noise which can be given to the pulse for the signal to noise conditions taken.

An examination of the effect of the random phase of the noise on the time modulation of the pulse train due to noise can be made by considering the pulse edges to be fixed in phase, and the noise pulses to have variable phase relative to the pulse edges.

If a number of curves are derived in a manner similar to that in which curve 4, Fig. 10a, was derived, an approximation of the effect of random noise will be given by considering random phase of noise over a period covering a large number of signal pulses. During half the period, the time modulation due to noise will tend to average $\frac{1}{6}$th t, during one-quarter of the period will tend to average $\frac{1}{12}$th t, and during the remaining quarter of a period will tend to average $\frac{1}{24}$th t.

If a time modulation of one-sixth t over one-quarter of the period is considered to be one unit of time modulation, the time modulation due to noise over the period taken will be given by $1 + 1 + \frac{1}{2} + \frac{1}{4}$.

If the noise power due to the maximum time modulation of one-sixth t is regarded as being one unit of noise power, the total noise will be given by

$$1 + 1 + \tfrac{1}{4} + \tfrac{1}{16} = 2\tfrac{5}{16}$$

whereas if throughout the whole period the time modulation due to noise has been at a maximum, the noise power would be unity for the whole period, and would equal 4. Therefore, the random phasing of the noise has the effect of approximately reducing the noise power in the ratio of $2\frac{5}{16}$ to 4, which equals 1 to 1·7, as compared to maximum time modulation for the whole period.

A power ratio of 1·7 equals 2·3 db., and accordingly the final signal to noise ratio can be arrived at by calculating the signal to noise for maximum time modulation and adding a figure of 2·3 db. to account for random phasing.

The time t was taken as being equal to the periodic time of the highest harmonic as retained in the pulse, and in the case under consideration the ninth harmonic is being retained; therefore, the periodic time for the pulse will be given by

9 t .... (11)

Each sloping edge requires a time t, therefore the time available for modulation due to the signal will be given by

7 t .... (12)

It was shown that the maximum time modulation due to peak noise was one-sixth t, (10), therefore the time modulation due to the signal relative to the time modulation due to the peak noise is given by 7 over one-sixth equals 42 times, i.e.,

S/N for peak noise = 32·4 db. .... (13)

The final signal to noise when considering one edge of the pulse can be obtained by adding 2·3 db. to allow for the random phase of noise, and a further 10 db. to allow for the effective noise due to its random amplitude, giving

32·4 + 2·3 + 10 = 44·7 db. .... (14)

The second edge of the pulse will introduce an equal amount of noise power; therefore, the figure of 44·7 db. given by (14) must be reduced by 3 db., giving a final signal to noise ratio of

41·7 db. .... (15)

The final S/N of 41·7 db. given by (15) was obtained when the initial S/N ratio of the pulse signal to noise was 6 db. The improvement in signal to noise obtained, therefore, is given by

41·7 − 6 = 35·7 db. .... (16)

Comparisons with Amplitude Modulation

It is interesting to compare the special case taken for the time modulated pulse transmission with an amplitude modulated system. Consider first the case of random noise.

Assuming that frequencies up to 15 kc/s audio-frequency were present in the modulating signals for both the pulse and amplitude modulating systems. The pulse receiver requiring a bandwidth of 288 kc/s prior to the amplitude filter would have a bandwidth requirement of 18 times that of the audio output stage of the amplitude modulated receiver. With random noise, the peak value of the noise increases as the square root of the band-width.

Thus, with the case taken, the peak noise increases by

$\sqrt{18}$ times = 12·5 db. .... (17)

However, with amplitude modulation 50 per cent. of the main transmitter power is taken by the modulating stages, whereas with pulse modulation practically the whole of the main transmitter power can be allocated to the final output stage. This gives a power gain of 3 db. A further gain of 3 db. is due to the fact that the average pulse duration is only 50 per cent. Thus, there is a power gain of 6 db. to offset against the loss of 12·5 db. due to the increase of bandwidth in the pulse transmission system. Therefore, there is an initial loss in the pulse system of

6·5 db. .... (18)

The improvement given in (16) is 35·7 db. for the pulse system, so that allowing for the loss of 6·5 db. given in (18) the particular pulse system taken gives an improvement of

29·2 db. .... (19)

as compared to an amplitude modulated system.

This improvement would be obtained when the signal to noise ratio was 6 db. When allowance is made for the initial loss of minus 6·5 db. given by (18), the improvement would be obtained at a distance from the transmitter where the S/N ratio of an amplitude modulated transmitter radiating one-half the power of the pulse transmitter was

12·5 db. .... (20)

Consider now the case of car ignition noise. One of the most troublesome sources of interference with television programmes was that due to car ignition. It is more difficult to assess what the final noise due to impulses of the car ignition type would be, with the pulse system taken, than it is for random noise.

This difficulty arises from the fact that the slopes of the noise pulses varies with different cars, being generally much less than the slope of the pulses taken in the particular pulse transmission system. In addition, the periodicity of the car ignition varies with different types of cars and variations in engines speed.

The type of car ignition noise investigated by G. K. Jansky[34] can, however, be taken as an example. This noise had characteristics such as that increasing the bandwidth above 90 kc/s did not add appreciably to the peak amplitude of the noise. From this it follows that the car ignition noise had a maximum slope which was characteristic of a filter having a pass band of 90 kc/s, i.e., about one-third of the pass band required for the pulses having frequencies up to 288 kc/s. Therefore, the slope of the car ignition noise would be one-third that of the pulses.

The audio bandwidth is again taken as 15 kc/s, and the increase in car ignition peak noise voltage will be six times, i.e., 90/15 kc/s. The noise voltage increasing directly with bandwidth.

A voltage increase of six times equals 15·4 db., and this must be offset against the power gain of 6 db., giving an initial loss of

— 9·4 db. .... (21)

The effective value of the car ignition noise will increase as $\sqrt{6}$ times for a band-width increase of six times, equals

7·7 db. .... (22)

A signal to peak noise ratio of 6 db. will be given when the amplitude modulated transmission has S/N of

9·4 db. + 6 db. = 15·4 db. .... (23)

In the case of random noise previously taken the S/N ratio at the limit of the service range was 12·5 db. for the amplitude modulated transmitter. Therefore, in the case of the particular car ignition noise the initial S/N requirement is

15·4 — 12·5 = 2·9 db. .... (24)

higher than for random noise.

The effective noise increases as the square root of the bandwidth, i.e., it increases in the same manner as random noise. If the effective noise had shown no falling off in increase of voltage up to 288 kc/s, the increase in effective noise voltage would have been $\sqrt{18}$ times equals 12·5 db. instead of the 7·5 db. obtained as a result of increasing the bandwidth by six times. Therefore, the improvement of the pulse modulation over the amplitude modulation will in the case of car ignition, as compared to random noise, be increased by the ratio of

12·5 — 7·7 = 4·8 db. .... (25)

The final improvement in S/N in the case of random noise for the pulse as compared to the amplitude modulation was given by (19) as 29·2 db., therefore the final improvement for the comparison in the case of car ignition noise will be 29·2 db. given by (19) plus 4·8 db. given by (25) equals

34 db. .... (26)

Owing to the fact that the initial S/N of 6 db. would be obtained at a distance from the transmitter, which gave an increase in field strength of 2·9 db. given by (24) as compared with the case of random noise, the service range would be slightly reduced as compared to that obtainable under random noise conditions for a transmitter having equal power.

Interference of Vision Signal on the Sound Programme

It was shown earlier that when an allowance of 20 db. has been made for polarisation discrimination the received sound pulses will have a voltage of four times that of the interfering vision signal. Therefore, the initial signal to noise is 12 db. The vision plus synchronising signal can for practical purposes be considered wholly as a signal of random occurrence. This initial improvement in signal to noise of 12 db. gives 6 db. greater final S/N as compared with the figure of 41·7 db. given by (15), i.e., a final S/N of

47·7 db. .... (27)

20 kc/s Pulse System

With the 20 kc/s pulses retaining up to the seventh harmonic, signal to noise improvements can be calculated in a manner similar to that shown for the 32 kc/s pulses with the ninth harmonic retained. It is not proposed to give here details of these calculations, except to state that as compared to amplitude modulation, a final improvement of approximately 28 db. could be obtained for S/N conditions similar to those taken in the previous example. It will, therefore, be seen that the low power of 20 watts for the local transmitters would give a service comparable with that given by 13 kilowatts using amplitude modulation.

Film Transmission

So far nothing has been said regarding the transmission of films. With 16⅔ pictures per second this would be more difficult to arrange than when 25 pictures per second were being transmitted. There have, however, been various suggestions made previously for the obtaining of television pictures from films, where the number of pictures per second given by the films do not coincide with those given by the television signal. For instance, alternative film frames can be scanned twice. It is not proposed here to discuss in any detail the subject of film transmission, within the standards proposed. No doubt various satisfactory solutions to the problem can be put forward.

It should be realised that the main object in presenting this paper is that of promoting discussion, so that the whole question of post-war television standards and broadcasting methods as applied to short waves can receive the attention it deserves.

Since the original preparation of the above paper, there has been a publication of patent literature referring to anti-phase discrimination[37].

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LONDON DISCUSSION

J. A. Sargrove (*Member*): In order to enable the more reliable and less costly separation of the synchronising pulses from the signal I suggest that the television carrier should be frequency modulated during the synchronising periods. Quite a small frequency deviation would suffice; say 5 kc/s for the line sync. and 10 kc/s for the frame.

This can be handled by the broad band signal amplifier and picked up at the end by "ringing" coils, and these used to trigger the scanning mechanism.

Secondly, whatever line and frame standard is adopted do not let it be so ambitious that even with the best available spot size C.R. tube it still cannot be followed; rather limit the standard to a somewhat less ambitious level at which the improved mechanical-optical systems can follow it. This way the cinemato-

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**Refer to anti-phase receiving methods* graph industry, which will at least partially adopt this technique, can receive and reproduce topical items directly from the B.B.C. transmissions. This would be a contribution from the radio industry towards the cinematograph industry which may result in a reciprocal contribution whereby the pre-war limitation on televising films would be removed, to the very great benefit of both industries.

Lastly, whatever standards are adopted they should be such that the recently developed systems of " signal converter " for producing the scanning waves in the receiver can be efficiently used, as these are likely to improve materially the reliability of the receiver and also are potentially less expensive.

Mr. O. S. Puckle : First I would like to emphasise that this paper shows considerable thought, together with the existence of a mind which is certainly not "hide bound." As the author himself states, none of the principles suggested are new, but the applications are, in many cases, original. As the paper is so full of new ideas and there is little time to spare, I shall spend it on a criticism of those ideas with which I am not in agreement.

With regard to the author's suggestion for anti-phase discrimination : the loss in transmitter power should be avoided if possible on grounds of economy, and this can be achieved by carrying out the principle at the receiving end. This method will also take into account any variations in the dipole discrimination which will not always be 20 db. as suggested. Furthermore, it is not likely that this scheme will function in practice when selective fading is present unless the anti-phase signal is inserted at the receiving end.

It is, in any case, very doubtful whether the use of the same frequency for vision and sound provides a worth-while reduction in bandwidth in view of the difficulties involved in anti-phase cancellation of interference.

The author suggests that a transmission of high quality music by the time-modulated pulse method requires a pulse repetition frequency of not less than five times the highest modulating frequency. He also states that this results in a pulse repetition frequency of 30 kc/s per second. This assumes a high frequency limit of 6,000 cycles, which is quite insufficient. The limit should certainly be raised to 12 or 14 kc/s for the sound portion of a television programme, giving a repetition frequency of 60 kc/s to 70 kc/s.

A statement is made that equal times are required for horizontal and vertical definition. This is quite untrue since, if there are 500 elements in a line, the time for the vertical definition is 500 times greater than that for the horizontal definition without allowing for the synchronising period. If the latter is, say, 10 per cent. of the line period, the ratio is increased to 550.

It is doubtful if stereophonic sound reception is required, especially in view of the fact that it is only effective when the acoustics of the listening room are the same as those at the transmitting end, and when the microphone and loudspeakers are in equivalent positions. This cannot occur in practice except in one or two very isolated instances. The cost of the transmitter and receiver will each be increased by something of the order of 25 per cent. to 50 per cent., and the advantage accruing is likely to be of a negligible order.

The power to be radiated seems to be on the low side, especially for the vision transmitter. It will be remembered that the B.B.C. employed 17 kW at 45 Mc/s and obtained a service range of approximately 35 miles. The author expects to get the same service range for 600 watts at 250 Mc/s.

Mr. Sargrove made a suggestion, during the discussion, which I consider to be most unfortunate ; he stated that television would gain in value and achieve a reduction in programme costs if films could be transmitted, and that the cinema industry might provide these films in return for permission to give to their patrons television programmes of direct transmissions of outside events. Such a scheme would be a welcome addition to the existing news reels where the time of the external event enables it to be fitted into the cinema programme. So far so good. I agree with Mr. Sargrove entirely in this respect, but he went on to say that, since the limitations upon the mechanical methods of television presentation are greater than upon the electronic methods, the television standards to be adopted in the future should be kept within those limits which it is possible for mechanical television to reach. Now, I consider this to be an *extremely dangerous* policy. Television cannot, and must not, be fettered by any arbitrary decisions of this nature. While no one desires to throttle mechanical television presentation, mechanical television cannot be allowed to limit the development of television as a whole. It is particularly important to remember, as Mr. Sargrove himself pointed out, that television is not just an interesting development for the engineer, it is a means of entertainment and education for the general public, and the public must be given the best possible service. The public is interested only in obtaining the best possible picture with the widest variety of programme distributed all over the country at the cheapest possible price, and it is quite uninterested as to whether that service is provided by mechanical or electronic means. They will not tolerate any reduction of quality or service because engineers, or some of them, wish to use a system in which (according to Mr. Sargrove) there are greater limitations than in another system, thus producing an artificial limitation to the quality of the results obtainable.

Mr. G. Wikkenhauser : We should question whether the public was satisfied with the pre-war picture or not. The picture itself certainly needed some improvement. Whatever we do we shall have to use lenses, and lenses do not give unlimited definition when using ordinary light. Due to these lens limitations the cinema picture does not have a definition higher than

650 or 700 lines. When I say lines I do not mean television lines, but interlaced scanning running to a great number of dots.

I believe the introduction of colour to be essential, since it adds to definition, but we must not forget the difficulties of programme presentation. The programme is rather a difficult matter, but if colours can be introduced, greater variety of subjects would be immediately available for transmission.

I feel that the size of the picture given by the majority of pre-war receivers was not large enough, and if the public is to be satisfied, larger pictures are essential.

Dr. Van den Bosch : Regarding colour television, if as is anticipated, new standards for monochromatic transmission are adopted, a spectrum sufficiently wide should be allocated to each transmission, so as to incorporate at some later stage a colour transmission. It would not be necessary to use the whole of the allocated spectrum for the initial monochromatic transmissions.

Another feature to be remembered about colour television is that the human eye is not equally sensitive to all the colours of the spectrum. In a three-colour system special precautions may have to be taken in transmission, so that unequal times are allocated to the transmission of red, green and blue, in order to compensate for the fact that the human eye is more sensitive to blue light than to red. Experiments which have been carried out in the United States by the Columbia Broadcasting System show not only the possibilities, but also the relative efficiency of a three-colour resolution television system.

It is essential that a single television programme should not be restricted to a small area, but should cover the whole country by means of relay stations. In my opinion radio relays are preferable to transmission over special cables. Television as we knew it before the war was restricted to the London area, and the reaction of the public as a whole was confined to the few Londoners who could afford, or chanced to buy a receiver. Thus, there was no factual television industry as a national industry. The adoption of a relaying system, making nation wide television coverage possible, is an essential requirement for the establishment of a truly national television industry.

It is worth noting that the Americans have allocated for television six bands, between 50 and 300 Mc/s, each having a band width of 6 Mc/s, but they propose using relay stations at 500 Mc/s. They must have reasons for this, but I fail to see why we could not use the main transmitter and the relay stations at the same carrier frequency.

Mr. G. L. Hamburger : I should not be surprised if negative modulation and one or two synchronising pilot frequencies of relatively stronger power would give, even with heavy motor car interference, a steadier picture with a countable number of black picture points as visible interference instead of the well-known intolerable "snowball" display.

I am strongly in favour of continuing the suspension of television transmissions for a limited period after the war. If only a fraction of the efforts up to now directed towards the development of war weapons would be used for the evolution of television, frequency and pulse modulation, radio links, etc., it should be possible to come to decisive conclusions within a relatively short time. The public—actually those 20,000 set owners—has been deprived of television for such a long time that, I feel, it could not be considered as a particular hardship to extend this period by a limited time. As a reward the public would have a really good system which may then be considered as essentially final, and once again may place Britain first in the art of television. Any further progress could then be fitted within the framework of a wisely chosen post war television standard.

To emphasise my point, I should like to refer to the gramophone industry. Owing to the huge investments in ordinary disc-recording technique any new system offering technical and economic advantages was, and most probably will *a priori* be condemned to a laboratory existence or at most to some very spasmodic application. It would be unwise to provoke a similar position in the art of television by a rash re-opening of a service with essentially a pre-war standard. Incidentally I feel sure that the radio industry is bound to be amply engaged in satisfying the needs of sound broadcasting as soon as the war will be over, thus bridging the gap to the new television boom.

Mr. K. I. Jones : I wish to emphasise the importance of starting a television service immediately after the war. The benefit to the radio industry of an early resumption of television cannot be over-emphasised. It might be agreed that at the outbreak of the war only 20,000 television receivers were in use, and, therefore, the service had not been accepted by the public. I do not think that was true ; those who possessed television receivers appreciated the high entertainment value to be obtained from the service. It is possible that the small number of receivers in use was due to a general feeling of technical uncertainty.

We should not be satisfied after the war with the pre-war system, or something as good, but something better, incorporating proved technical advances which can be utilised without causing delay. Post-war standards, whatever they may be, should not be liable to frequent changes, but should be guaranteed for a long period.

Mr. D. A. Bell : I think Mr. Puckle's suggestion that the compensation between vertically and horizontally polarised transmission should be made at the receiver is valuable.

I am doubtful regarding the practicability of a time modulated pulse transmission for sound. I have been personally concerned with some frequency modualtion developments, and I am surprised that claims are being made for pulse modulation which appear to make that system slightly better than frequency modulation. If we are to build up a system quickly we had better adopt something which is well known.

REPLY TO LONDON SECTION DISCUSSION

Mr. Sargrove suggests that frequency modulation be used for synchronising. While agreeing with him that this method of synchronising should be more reliable and less costly than the pre-war amplitude modulation and time discrimination system, I cannot agree with his suggestion that satisfactory synchronising would be achieved with a small frequency deviation of 5 or 10 kc/s.

For satisfactory line synchronising, the waveform of the effective synchronising signal should be substantially independent of picture brightness, and should have a slope such that the maximum error under normal interference conditions would not give a misalignment of detail greater than one-half of one scanned unit. In practice this would require the transmission of synchronising signals having a slope at least half that required for the minimum definition of the vision signal.

The minimum bandwidth required for the transmission of such synchronising intelligence, whether by means of amplitude or frequency modulation, will be the same, i.e. approximately half that required for the vision transmission.

Frame synchronising requirements are not so rigorous as for line synchronising. For good two-way interlacing the effective synchronising signal should have a wave front such that the maximum error in synchronising consecutive frames is not greater than 10 per cent. of a line period. In practice this would require the transmission of a synchronising signal having a slope approximately ten times as great as the slope of a sine waveform having a periodic time equal to the line scanning period. Such a waveform cannot be satisfactorily derived from a "ringing" coil tuned to 10 kc/s

Mr. Puckle suggests that a repetition frequency of 60 to 70 kc/s would be required for high quality music transmission. Practical experience has shown that this is not so, the suggested repetition frequency of 32 kc/s is quite adequate.

With time modulated pulses the modulating intelligence can have frequencies up to one-half of the pulse repetition frequency, therefore a 30 kc/s pulse frequency will allow for modulating frequencies up to 15 kc/s. A characteristic of time modulated pulses of the type mentioned in the paper is that at sub-harmonic frequencies of the pulse repetition frequency, intermodulation beat frequencies are generated under modulation conditions. The lower the sub-harmonic the greater the degree of intermodulation. With sub-harmonics greater than the fifth the intermodulation can be ignored, but at a frequency of one-fifth the pulse repetition frequency, the intermodulation beat frequency will be about 2 per cent. when the time modulation is approximately 60 per cent. At one-half the pulse repetition frequency the intermodulation beat frequency will be about 10 per cent. for the same degree of modulation.

Consider now the case of music transmission: one-fifth of 30 kc/s is 6 kc/s, i.e. a frequency higher than the normal fundamental tone of any orchestral music. Of course, tones higher than 6 kc/s are present in music, but these tones in general are overtones having an amplitude less than that of the fundamental tone. If one considers a musical note having a frequency of 2 kc/s, the third harmonic (mathematically) of this is 6 kc/s, i.e. one-fifth of the pulse repetition frequency. The modulation due to the overtone would be much less than 60 per cent., and the intermodulation beat due to this would be much less than 2 per cent. of the main modulation. In practice any beat frequencies due to the time modulation of the pulse train by overtones are entirely masked by the main time modulation.

With time modulated pulse transmission the quality of the transmission tends to improve slightly as the modulation frequencies are reduced. In this respect pulse modulation is superior to frequency modulation as with the latter, any distortion due to non-linearity of frequency discriminators is more liable to show up with heavy modulation, which generally is due to the lower tones in music.

Regarding the statement that equal time is required for horizontal and vertical definition. I agree that here the paper is lacking in clarity; however, I was not looking at the problem in quite the same way as indicated by Mr. Puckle. I was more concerned with the bandwidth requirements for equal vertical and horizontal definition. It is generally agreed that vertical and horizontal definition are equally expensive in bandwidth, and bandwidth is a function of time. The system proposed in the paper probably does not give equal vertical and horizontal definition, but it should give a flat picture free from line structure.

Mr. Puckle draws attention to the low power of 600 watts proposed for the vision transmission. The figure of 600 watts is a mean power figure, whereas the B.B.C. figure of 17 kW was peak power. The mean power of the system was approximated by considering that a frame period comprised synchronising pulses for 1/10, black level for 1/10, and a picture varying linearly from black to white for 4/5 of the total time. When allowance is also made for a lower antenna and an increase of six times in the transmitted frequency, it will be found that the field strength given by the proposed system should be very close to that given by the B.B.C. system.

Mr. Wikkenhauser has brought out an important point, when he draws attention to the fact that lenses limit the definition to 650 or 700 lines. I have proposed a definition corresponding to 640 lines, but with a line structure of 1,280 lines. If no great improvement in definition due to lenses can be visualised in the near future, it would seem that a definition of 700 lines would be the maximum likely to be obtained. That being so, we could now fix the bandwidth of the spectra required for monochromatic and coloured television services.

I agree that many pre-war receivers gave a much too small a picture. I suggest that after the war the minimum size of cathode ray tube used for television should have a diameter of 12 inches. Even this will be considered by many to be a low minimum standard of picture size.

Dr. Van den Bosch's suggestion that we now allocate spectra for colour television is useful, in that it would force engineers to consider some of the practical difficulties likely to be encountered in the transmission of coloured television. Such considerations would probably emphasise the desirability of using high frequencies for transmission, even higher than the 250 Mc/s which I suggest. We now have sufficient information to operate transmitters and receivers at these higher frequencies, and if there are no propagation disadvantages it might pay us to use these higher frequencies for the first post-war monochromatic services.

Apart from the fact that no provincial stations existed, such television industry as did exist before the war was dependent upon the continuance of one transmitter, located in a building which was built without much consideration for fireproofing. In my opinion an essential requirement for the establishment of a stable television industry is the provision of functionally designed, fireproof buildings for all the studios and transmitters.

I do not agree with Dr. Van den Bosch that it would be practical to use the original carrier frequency for relaying. In fact, when considering a number of sequential relays, the pre-war television standard for transmission to the public may not be suitable for relaying purposes. It may be desirable to consider public transmission and relaying between main transmitters as entirely different problems. Frequency or pulse modulation might with advantage be used for relaying, the signal being reconstituted at each main transmitter into something like the pre-war system.

Mr. Hamburger has indicated that he appreciates the danger of starting post-war television on the pre-war standards, since there would arise the possibility of these unsuitable pre-war standards being adopted for a long period. I agree that this danger would be present if large numbers of new receivers were manufactured to the pre-war standards.

We must face up to the fact that during the year 1939 the programme presentation of television improved enormously. The B.B.C. were beginning to reap the benefit of the experience gained since the opening of the service in 1936. As soon as possible after the war the B.B.C. could, with advantage, resume their good work of programme presentation if the old transmitters were started up without change of standards. In my opinion any such restarting of the old transmitter should be accompanied by a definite ban on the manufacture of new receivers to the old standard.

Mr. K. I. Jones stated that the benefit to the radio industry of an early resumption of television cannot be over-emphasised.

I do not agree with Mr. Jones. I think an early resumption of television on the old standards, with a very definite ban on the manufacture of new receivers, is desirable.

In the long run it is the viewpoint of the public which will matter most in television. The public in ten years' time will not thank the radio industry of the present time, if it is then found that the immediate post-war radio industry, in order to gain a temporary employment advantage, commenced large scale manufacture of television receivers to a standard lower than that which could be attained. The public eventually would have to bear the cost of changing to an improved standard.

In the radio industry three main groups of persons are concerned with television, these groups being engaged upon research, production and distribution.

The decision to adopt a new standard ensures immediate employment for a large group of research workers as soon as these workers have been gathered together from their war-time activities.

The production group can be sub-divided into radio and electronic groups. The radio group can be fully engaged for at least three years on the manufacture of ordinary domestic receivers, and even then will not have met full demands.

The electronic group can be further sub-divided into valve and cathode ray tube groups. The valve group can be fully employed for years on domestic requirements.

A delay in starting television would probably affect the cathode ray tube workers. However, it must be realised that this group of workers need not be large in order to meet any practical post-war television programme. During the war considerable progress has been made in the methods of manufacturing cathode ray tubes. At the present time 100 persons engaged upon C.R. tube manufacture could, in a few months, make all the C.R. tubes used on the 20,000 receivers manufactured prior to the war. Of these 100 persons not more than 25 per cent. need have special skill or knowledge requiring a long experience.

The small groups of highly skilled and key workers in the C.R. tube industry can no doubt be guaranteed employment on C.R. tube work in connection with the peace-time application of radar.

We can, therefore, see that in as far as employment is concerned there is no great advantage to be gained by an early resumption of television.

Mr. Jones also stated that the small number of receivers in use prior to the war was due to a general feeling of technical uncertainty.

A large-scale television industry must be served by a competent distributive service, and such a service cannot be started very quickly. Prior to the war the distributive side of the television industry was very weak, and if the position is to be improved after the war some changes of methods and types of personnel employed seem inevitable.

I agree with Mr. Jones that we should have stability in any standards which may be adopted. I suggest a minimum of ten years with six years' notice of any intended changes which are likely to affect the operation of receivers.

Mr. D. A. Bell stated that claims made for time modulated pulse transmission would appear to make that system better than frequency modulation.

It was not my intention to claim that time modulated pulse transmission was better than any other system. All the known systems of modulation have their own special useful applications. There are so many considerations when choosing a sound modulation system for television that the choice of the most suitable system will not be an easy matter. Some of these considerations are availability of bandwidth as against the signal to noise improvement likely to be obtained with a wide band system of transmission, practicable stability of domestic type receivers, propagation distortion, and freedom from interference due to reflections. I am of the opinion that when full consideration has been made to the subject of sound transmission it will be found that for a television service a time modulated pulse transmission system is somewhat better than either a frequency or amplitude modulation transmission.

NORTH-EASTERN SECTION DISCUSSION

Mr. J. C. Finlay: With reference to the mutual interference between the proposed sound and vision signals, due to the imperfect discrimination between vertical and horizontal polarisation, I note that the author suggests that a correcting anti-phase signal be added either at the transmitter or receiver, the former being, of course, the cheaper procedure. However, I presume that in any case some individual correction will be necessary at every receiver, probably by adjustable aerials. If these are used will the need for the anti-phase signal be eliminated?

If it is impossible to produce adequate discrimination in the aerial system alone, and the anti-phase signal is still required, the receiver will surely have to provide a variable in-phase (or anti-phase) signal for local balancing. In this case the whole correction might as well be done at the receiver. Is such correction likely to vary from time to time owing to tropospheric and other reflections, as this will be an important factor in determining the type of correction to be applied?

H. Armstrong: It would seem that pulse modulation can be usefully employed in certain limited fields. It would be of interest to have some indication as to what these fields are likely to be.

What are the advantages of pulse modulation as compared to frequency modulation?

Is it necessary to allow for high fidelity audio up to 15 kc/s? Would a lower fidelity of, say, up to 10 kc/s allow of the pulse repetition frequency being reduced considerably without noticeable deterioration of the transmission?

Discussion on this paper will be continued at the London meeting to be held on April 19*th*, 1945, *and will be recorded in the August Journal.*

NOTICES

Honours

The Council has tendered congratulations to the following additional members on their inclusion in the New Year's Honours List :—

Major Richard James EYNON (Associate Member) was appointed a Member of the Most Excellent Order of the British Empire (Military Division).

S/Ldr. James Frederick MAZDON (Associate) was appointed a Member of the Most Excellent Order of the British Empire (Military Division), having previously been mentioned in despatches.

Obituary

Notification has been received of the death, on active service in Italy, of Flight Lieutenant Robert Riley GREEN (Associate), of Marlow, Bucks.

Flt. Lieut. Green was registered as a Student of the Institution in May, 1938, and obtained a transfer to Associateship in June, 1942. He leaves a widow and two young children to whom Council has expressed sympathy.

Extraordinary General Meeting

An Extraordinary General Meeting of Corporate Members of the Institution was held at the Institution on the 23rd March, 1945, in accordance with the notice given in the last issue of the Journal and as circulated to Corporate Members.

A copy of the Schedule may still be obtained from the Institution ; all the revisions proposed by the General Council, both in the Memorandum and Articles of Association, were unanimously approved and came into effect immediately.

The main revision in the Memorandum covered the objects of the Institution which are now declared to be :

> 'The advancement of the science and practice of radio engineering and to afford the means for facilitating the acquisition and preservation of the knowledge pertaining to the profession of a radio engineer and to promote the general advancement of and to facilitate the exchange of information and ideas on radio science and engineering including the theory, science, practice and engineering of electronics and all kindred subjects and their applications.'

The alteration in the Articles governing election to the various grades of membership and including the new grade of Companion, are now included in the revised regulations governing membership, a copy of which will be sent to any member on request. Members wishing to obtain a transfer to a higher grade of membership are especially requested to obtain a copy of the regulations before lodging a proposal.

SCOTTISH SECTION

The President has accepted an invitation to address the Radio Industries Club of Scotland at a luncheon to be held on Wednesday, June 6th, 1945.

Members of the Institution who are not members of the Club but who wish to attend the Luncheon, should communicate with the Secretary of the Club, Mr. A. J. Couper, 149 West George Street, Glasgow, C.3.

The President will be accompanied by the Secretary, and it is intended to hold an informal meeting of members in the evening of June 6th, in order to discuss the formation of a Scottish Section of the Institution.

Personnel of Committees

Lt. Colonel J. D. Parker, M.B.E. (Member), has been appointed to the Technical Committee of the Institution, and Mr. C. Tibbs (Associate Member) has, for the time being, had to resign from the Papers Committee. These amendments should be made to the reference to Standing Committees published on page 45 of the January-February, 1945, Journal.

GRADUATESHIP EXAMINATION

PASS LIST—NOVEMBER, 1944 (2nd List)

The following Candidates Passed entire Examination	
CRAWFORD, Robert	Prisoner of War
RICHARDSON, Leonard (S)	Australia
The following Candidate Passed Parts 3 and 4 only	
STEIN, Gabriel (S)	Jerusalem
The following Candidates Passed Parts 1 and 2 only	
SEHPOSSIAN, Haig (S)	Heliopolis
THOMPSON, R.	Prisoner of War
SIMMONS, Henry	Prisoner of War
MASEYK, Norman (S)	India
The following Candidate Passed Parts 1, 2 and 3 only	
PICKERING,	Simla

1944 EXAMINATION PRIZE WINNERS

Council has approved the following awards to the most outstanding candidates appearing in the 1944 Graduateship Examinations :

PRESIDENT'S PRIZE	
ROBINSON, Peter	Chelmsford
MOUNTBATTEN MEDAL	
CRAWFORD, Robert	Prisoner of War
L.C.R. PRIZE	
LUCKETT, William Roy	Hereford
MEASUREMENTS PRIZE	
BUMSTEAD, Maurice Charles	Hythe

TRANSFERS AND ELECTIONS TO MEMBERSHIP

The following proposals and elections were recommended by the Membership Committee at their meetings held on the 14th February and 8th and 27th March, 1945. At these three meetings the Committee considered a total of 71 proposals for transfer or election to Graduateship or higher grade membership. The following list completes the elections for the year ended March 31, 1945, and makes a total of 203 elections or transfers during the year as a result of the 319 proposals lodged.

Transfers

From Fellow to Honorary Member

MOIR, Sir Arrol, Bart., B.A.	London, S.W.1

Transferred from Associate to Associate Member

BLUNDELL, Norman Howard, Capt.	London, S.E.27
COLTON, Norman Kenneth	Swansea, Glam.
PATTERSON, Stanley	Hull, Yorks.
WATTERSON, Vernon, M.A. (Cantab.), Capt.	London, W.13

From Student to Associate Member

HOLLAND, Richard Dolling	Bognor Regis
OSBORNE, John Laurence Langley	Cheam, Surrey
PATRICK, Alan Montague	Edinburgh, 10

From Graduate to Associate

BIRAM, John Graham	Hindhead, Surrey
MURFITT, Ralph Hubert	Bradford
SHARPLES, Ernest Alan	Manchester

From Student to Associate

COGHLAN, Arnold Edward	Hove
DEHN, Rudolf	Exmouth
ERDOS, George, B.Sc.(Hons.)	Loughborough
HUGGINS, Peter	London, S.W.5
JAMES, Leslie William	Rugby
MADIGAN, Henry	London, W.5
MUNDY, Everett Bernard, B.Sc.	London, S.W.19

From Student to Graduate

BUMSTEAD, Maurice Charles	Hythe, Kent

Direct Elections

To Member

MINGAY, Oswald Francis	Sydney, Australia
WARDMAN, Basil	London, N.W.3

To Associate Member

BROWN, Norman Hillier	Hayes, Middx.
DULEMBA, Boleslaw	Edgware
JACKSON, Brian Bannister, Lt.-Col.	Chislehurst
PINCHBECK, John Douglas	Swindon
SMITH, Alfred Joseph	Aldershot

To Companion

BURNHAM, Walter Witt	Blisland, Cornwall
NORMAN, Alexander John	Blundeston, Suffolk

To Associate

BLANCHARD, Allan Robin	Bury, Lancs.
DIVE, Leonard George	Sanderstead
ELLIS, Norman William Warr	London, S.W.1
GRAY, Reginald Irvan	London, S.W.1.
GREENHALGH, Wallace, B.A.	Manchester
HALLIDAY, Douglas Frank	Dumfries
HONAN, John	Dublin
JONES, Anthony Mervyn, Major	London, N.6
KNOWLES, John Hall	North Shields
KYME, Richard Cyril	Reading, Berks.
LENO, Bernard Albert	Richmond, Surrey
NICHOLSON, Philip Ian	Reading, Berks.
PUCKETTE, James Henry	London, W.C.1
REID, Oliver Walter	Cape, S. Africa
ROBINSON, Peter	Chelmsford
STURGE, Geoffrey Howard	Guildford
WINDOWS, Clifford Edgar	London, S.W.18
WRIGHT, Leonard Thomas	Bromley, Kent

To Graduate

STEVEN, Robert, B.Sc.	Hayes, Middx.

STUDENTSHIP REGISTRATIONS

The following were Registered as Student members of the Institution at meetings of the Membership Committee held on February 1st and 14th, and March 8th and 27th, 1945. At these meetings the Membership Committee received a total of 82 proposals for Registration as Student members, making a total for the year 1944/5 of 367 proposals received during the year, compared with 300 for the year 1943/4.

ARCHARD, Stanley James	Hutton, Essex
BACKHOUSE, Norman	Halifax
BARNARD, Jack Richardby	Rossington, Yorks
BATCHELAR, Robert Cyril	New Zealand
BENNETT, Charles Roy	Stockport
BROWN, Frank Ridley	Dukinfield, Ches.
BURKE, Norman William	Bromley, Kent.
CALDWELL, Jack Rowson	Australia
CECIL, David John	London, W.1
CHADWICK, Harold Sidney	Worksop
CLAYTON, Anthony	London, W.9
COCHRAN, John	Harrow
DAGNALL, Charles Sidney	Solihull
DUFFY, James	Greenford
EMERY, Trevor Munslow	Bangor, Co. Down
FORD, David	Norfolk
FORD, Edmund Alfred	Wolverhampton
FORREST, Michael Augustus	Manchester, 21
GAVIN, Kenneth Turnbull	Penrith
GENGE, Ronald George	Wimborne
GILBERT, Alan Edward F.	Dudley
GRIERSON, Francis A.	Dumfries
HAMILTON, William Ian	Newcastle, 4
HARRINGTON, Peter F. O.	Kingston
HAYES, Cornelius John	Southall
HOBSON, John Peter	Victoria, B.C.
HODGKINSON, John Thomas	Mombassa
HOPPEN, Donald Walter	London, S.W.2
HOWE, Lionel Alfred	London, S.E.15
INMAN, William John	Bristol, 6
JACOB, Robert Claud	Feltham
JOBSON, Philip Frank	Gravesend
JOHNSON, Wilfred	Scarborough
JONES, Kenneth Oliver	Upminster
JONES, Patrick Joseph	Arva, Co. Cavan
JOSEPH, Norman	Cardiff
JOYCE, Alfred Waterworth	St. Neots
KAGALWALA, Abid F.	Bombay
KENNEDY, Matthew	Renfrew
KUMAR, Krishan	Nairobi
LAYTON, Frank John	Brentford
LOWE, Philip	Birmingham, 28
MAHONEY, Douglas	Dundee
MANNING, John William	St. Albans
MARTIN, Ronald Stewart	Sydney, N.S.W.
McKENNA, Patrick, B.Sc.	Middlesbrough
McNEILL, Ian	Glasgow, E.2
MEAD, Stanley Rangi S.	Watford
MEEK, Charles	Glasgow, C.5
MORRIS, Victor	Denham
MOURAD, Abraham	Cairo, Egypt
NAVIN, Edmund	Newry, Co. Down
ORSBORNE, Charles L.	Peterborough
OVENDEN, David William	Margate
PAGE, Henry Ignatius	Sheffield, 11
PARKER, Frederick G.	Sibsey, Lincs.
PATCHER, Julius	London, S.W.9
PEPPERCORN, Albert E.	Bexley, N.S.Wales
PRESTWICK, John D.	Liverpool, 9
PRINCE, Herbert D.	Bloemfontein
QUIGLEY, George Thomas	Bromborough
QUINN, Norman Thomas	Victoria, Aust.
RAO, Perundria L. G.	South India
REA, George	Huyton, Lancs.
REED, Ronald Frederick	Bristol, 6
REILLY, James Joseph	Dublin
ROTTENBERG, Robert	Cairo, Egypt
SCOTT, John George	Slough
SEEAWN, Behari Lall	Rohtak, India
SHEARS, Philip Antony	Cheltenham
SIMMONDS, Douglas C.	Glasgow
SMITH, Basil Boyd	Homebush, N.S.W.
STANNARD, Robert	Frome
TEER, Cyril Arthur, B.Sc.	Ayrshire
TITHERADGE, John P.	London, N.19
TURNER, Lewis Edgar	Deal
VINCE, John Holistor	Hove
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SOME ASPECTS OF SPECIAL ELECTRON TUBES

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SUMMARY

A considerable amount of material has been published in recent years concerning radio tubes and other electronic devices. Much of this data has, however. been of a theoretical nature. This paper describes various specialised types of tubes and their more useful characteristics and deals with a number of types under three main headings, suitably sub-divided.

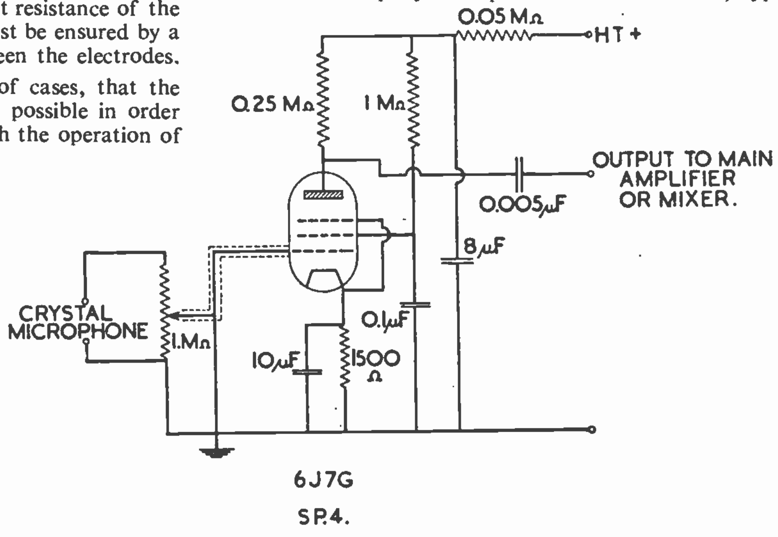
Section 1. Tubes for Voltage Amplification.

The amplifying function of the electron tube is well known, but it is proposed to deal with the less usual applications, and to endeavour to describe how certain tubes have come into being to fulfil special functions. Let us take first of all tubes for the amplification of very small voltages in the audio range. The requirements of such a tube may be tabulated as follows :—

1. A mechnical construction that is not responsive to acoustic vibration.
2. A low noise level.
3. In the case of high impedance devices, such as a crystal microphone and the photo cell (vacuum or gas-filled type), it is necessary that a high value of resistance constituting the load be used. It follows therefore that the input resistance of the tube must be high, and this must be ensured by a high degree of insulation between the electrodes.
4. It is desirable, in a number of cases, that the contact potential be as low as possible in order that this does not interfere with the operation of the circuit.

The use of triodes in a voltage amplifier will be considered in order that sufficient gain over a given frequency band be obtained to supply the input to the main amplifier. It is essential to use more than one valve, as the very best stage gain we can obtain from a triode will be of the order of 70. It will be found that the usual type of triode used for audio frequency work, etc., is subject to quite a number of troubles when used as a microphone amplifier, and perhaps the worst of these troubles is microphony, often due to the fact that the tube structure has mechanical resonances, usually situated between 1,000 and 2,000 c/s, according to the type. This may be remedied in a number of cases by the use of an anti-microphonic valveholder and acoustic damping, such as felt pads placed round the tube. However, there are many cases where the pre-amplifier must be placed near the microphone, by even using part of the microphone mounting, and in such cases space is usually at a premium.

It is quite common practice for the voltage supplies of such amplifiers to be obtained from batteries, and hence several tubes have been specially designed for the purpose. The Tungsram Company have produced an indirectly-heated tube, Type HL4G, which has a small electrode structure, and the control grid is brought out to the top of the bulb to ensure the highest possible degree of electrode insulation. This tube may be run either with A.C. or D.C. heated filament. The General Electric Company also produced a small tube, type A.537, with a special base and a non-microphonic construction. The grid connection is also brought out to the top of the bulb to increase insulation, and the



PREAMPLIFIER STAGE FOR CRYSTAL MICROPHONE.

Fig. 1.

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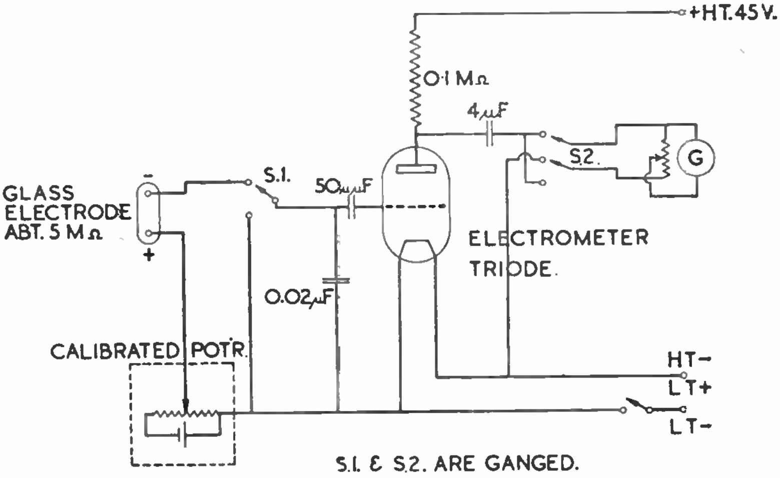
† British Tungsram Radio Works Ltd.



*p*H METER CIRCUIT USING VOLTAGE DIFFERENCE SYSTEM

Fig 3.

structure is small and rigid. This tube can only be run from batteries. The G.E.C. has, however, produced another tube, the M.H.40, which is suitable for use for A.C. filament supply, and this tube has a rigid mechanical construction with ceramic insulation to increase the input resistance. All these types are designed to have a very low background noise level.[14] It is worthy of note here that on no account should these tubes be subjected to overheating of the cathode, as this will increase the background noise, even when the tube is operated again at its normal rating.[5] It is not uncommon to find special materials used for the anodes with a view to reducing secondary emission. It is also unwise to allow the valves to operate at a reduced heater rating, as conditions[18] of temperature limited saturation, due to lowered temperature, may occur with a considerable increase in noise level.[1,3] However, as previously mentioned, the gain is low and it is quite common to use a single pentode as a pre-amplifier, and a figure of such a circuit is shown in Fig. No. 1. The fact that a high value of anode load will increase the noise level is partly balanced by the reduction of anode current, and the high magnification factor of the pentode. The screen current is also extremely limited so that the factor introduced by this electrode is quite small. Tubes which are suitable for microphone work may also be successfully used in various instruments, such as valve voltmeters and instruments for measuring galvanic pulses in biological work.

Amplifiers for use with photo-cells of the vacuum or gas-filled types require tubes with a very high input insulation resistance, as it is common to use a load in the range of 10-20 megohms. Naturally, this value is reduced by the shunting effect of the tube input impedance, and this must be kept as high as possible. A further application with specially designed triode tubes is the electrometer triode, which has an extremely high input resistance and is operated under conditions where very small current flows. This tube is specially suitable for ionization gauges, *p*H meters, etc. Fig. 2 shows an illustration of the Osram ET1, and Fig. 3 shows a common application of such a tube. It will be observed in this tube that the supporting members of the electrode are so designed that the leakage paths are very long. This is, of course, absolutely necessary if the tube is to be used with a glass electrode which may have a resistance of the order of 30 to 100 megohms.

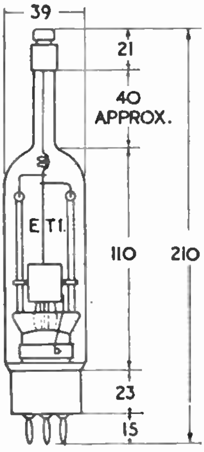


Fig 2.

Some tubes designed for R.F. amplification should now be considered. Where amplification is required for narrow band-widths, such as in the normal broadcast receiver,[15,16] one may choose an R.F. type of pentode with what might be considered average characteristics. For such purposes, the internal screening of the tube is such that the capacity between the input and output circuits is reduced to a minimum. If this is not so, voltage will be fed back to the input and oscillations will occur before the full gain of the circuit can be achieved. The capacity between the input and output of such tubes is usually very small, and of the order of ·005 *p*F. Such a value is therefore suitable for reasonably high frequencies, providing that it is not called upon to do other than amplify a signal over a narrow band of frequencies. These pentodes are high impedance devices[22] in which the object of the designer is to obtain a minimum change of anode current for a maximum change of anode voltage. A further point concerning this aspect of the tube is that the higher the impedance of the tube, the less will be the damping of the tube circuit which acts as the tube load.[12]

Some plates are shown illustrating the design of several of these R.F. pentodes (Fig. 4). From the point of view of signal to noise ratio in such amplifiers, it is desirable that the slope/anode current ratio be kept as small as possible and also that the screen current be reduced to a minimum. With the advent of the ultra high frequencies it rapidly became obvious that the ordinary types of tube were unsuitable,[38] and in the case of television amplifiers, where the magnification of a wide frequency band is essential, the high slope R.F. pentode[3] came into being. The high input and output capacities were relatively unimportant as these became part of the tuned circuit, but the high slope of 6-10 milliamps per volt gives useful amplification with the low anode load used (1,000 to 2,000 ohms) over a band of frequencies up to 2 Mc/s wide. These tubes, however, were more or less conventional in design, and degenerative effects due to lead inductance and transit time became more troublesome as higher frequencies came into use. Tubes in this class are the Mazda SP41 and the R.C.A. 6AC7. This latter tube is a single-ended pentode,[6] the object being to reduce unwanted lead inductance in the input circuit. All these tubes have the advantage that the slope to anode current ratio is as near as possible to unity and that the screen current is low (about 25 per cent. of the anode current). As a result of these characteristics, the equivalent noise resistance of these tubes is considerably reduced. This point should always be considered in the design of wide band amplifiers, as thermal noise is proportional to the square root of the band width. The reduction of screen current in relationship to the anode current has also a great effect in reducing noise, and, in this instance, attention must be drawn to tubes in which the grids are optically aligned (Fig. 5), the electrons being formed into beams, with a cross-over point which occurs between turns of the accelerator grid. In this way the screen current becomes very small, and is of the order of 10 per cent. of the anode current. A further example of the low noise R.F. amplifier is type EF8, marketed by the Tungsram and Mullard Companies, and the E.F.38 by the latter concern. These tubes are, strictly speaking, hexodes, employing aligned grids. The additional grid in these tubes assists in the function of focusing the electrons and may be used as an additional control electrode. Fig. 6 shows the principles of construction of this tube. The EF8 is only possessed of a medium slope, and it is not suitable for use in wide band amplifiers. It is an extremely useful tube for improving signal to noise ratio in short wave reception, where one can use the maximum gain.

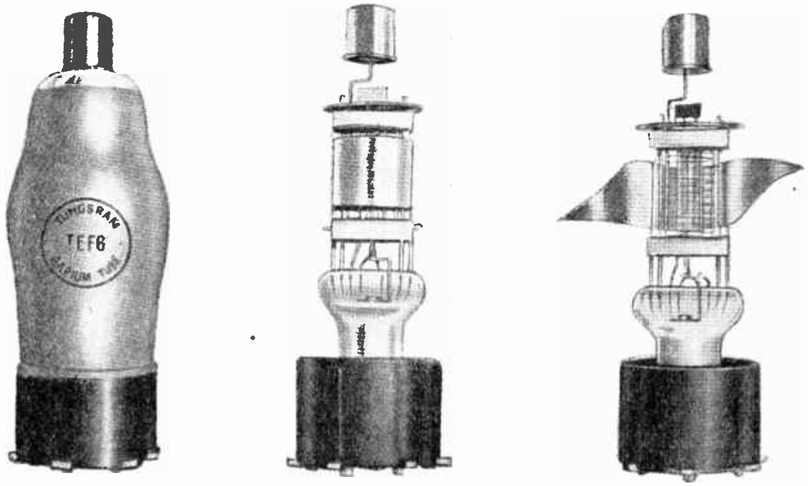


Fig 4.—Construction of R.F. Pentodes.

A great deal of reference material on fluctuation noises may be found, and in this country D. A. Bell,[2] F. C. Williams and E. B. Moullin have dealt with the matter in considerable detail. In the United States, a five-part paper by B. J. Thompson, D. O. North and W. A. Harris, entitled "Fluctuations in Space Charge Limited Currents at Moderately High Frequencies," gives a very wide review of the whole problem of tube-generated noises.

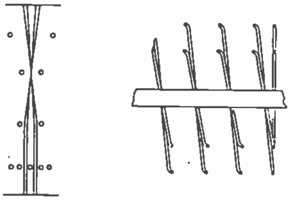


Fig. 5.—Optical alignment of EF8 grids.

A great deal of this work is carried out using as the basis for experiment and calculation the well-known Nyquist formula—

$$\overline{i^2} = 4kTg\,\Delta f$$

where

g = Mutual conductance k = Boltzmann's constant

T = Absolute temperature and Δf = band width

$\overline{i^2}$ is equivalent to the mean square of the short circuit current fluctuations.

If we keep this formula in mind it will readily be understood that the random fluctuations in currents which are an integral part of the electron stream in a tube will induce by their passage through the electrode system a corresponding fluctuation in the structure of the electrode. This question of induced currents will be dealt with later in the description of the inductive output amplifier and the Klystron tube. This phenomenon is particularly important in the case of the control grid, which will exhibit a certain value of slope for a given fluctuation. A formula has been deduced for this by D. O. North and W. R. Ferris in a paper entitled "Fluctuations Induced in Vacuum Tube Grids at High Frequencies," *Proceedings I.R.E.*, 13.1.41, published by R. C. A. Technical Service in March, 1941.

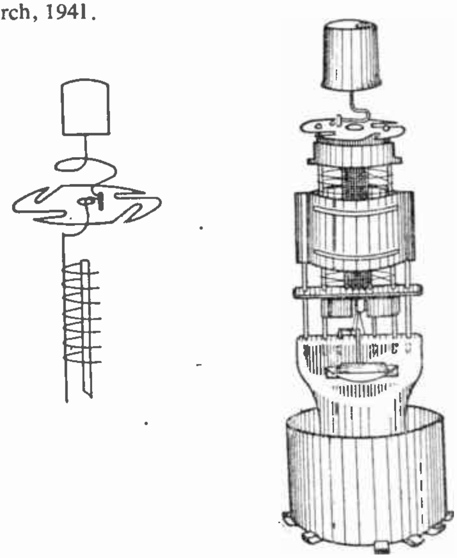


Fig. 6.—EF8 cutaway and grid fitting.

It will be seen that in addition to the normal noises generated by a tube this further effect becomes very important in ultra high-frequency tube design, and many attempts are being made to reduce the effect to a minimum.

With regard to the signal/noise ratio, in the first tube of an ultra high-frequency receiver, it will be found that the optimum aerial coupling for best signal/noise ratio is not the same as for maximum gain, and it will be found that the relative performance is considerably better if the coupling is adjusted for the best noise conditions. Considerable practical information on aerial coupling will be found in "Technique of Radio Receiver Design" by Zépler. The subject is also dealt with in some detail in the *R.C.A. Review*, Volume 6, No. 3, January, 1942.

In an attempt to improve the input impedance[25] and to reduce fluctuation noise[24] and input lead inductance, a special high slope pentode was developed in the Tungsram Research Laboratories by Zakarias. This pentode (SP.4/U1) is fitted with three cathode leads, and the control grid and one of the cathode leads are brought out to two caps at the top of the tube, thus separating the input circuit from the output circuit. In the base of the tube are the anode, heater and two cathode connections and also the accelerator grid, and in an experimental amplifier it was found that an input impedance of 60,000 ohms at 40 Mc/s was obtained. The actual point of connection of the cathode return lead is bound to be very important.

One of the most undesirable effects in frequency changing tubes at high frequencies [13,30] is the capacity coupling between the signal and oscillator grids, and owing to finite electron transit time this capacity[7,8,9] is somewhat dependent upon frequency and the relative phase angle of electrons at a given point of the cycle.[17] A considerable amount of work has been done in investigating this problem by E. Lukacs. Two papers of note are "Frequency Changing Problems," *Wireless World*, 26.1.39 and 2.2.39, and here the author discusses the various merits of types of frequency changing tubes and the steps taken to reduce capacity effects at high frequencies. This undesirable capacity coupling, particularly in the case of octodes, is mainly due to space charge influence effects, and the question of production of parasitic oscillations[39] and the dependence of gain upon frequency is dealt with in the paper by Lukacs in *Wireless World*, page 238, 17.3.38.

Combined tubes can be made to function satisfactorily up to 30 Mc/s, but for higher frequencies it is desirable to employ a separate oscillator. At these higher frequencies it is also very important to remember that the time constant of the grid leak and condenser must be arranged to prevent squegging, particularly if several wavebands are covered by switching. The simplest method here is to arrange a separate gridleak and condenser for each waveband.

A considerable amount of interesting work has been carried out by E. W. Herold, of the R.C.A. Manufac-

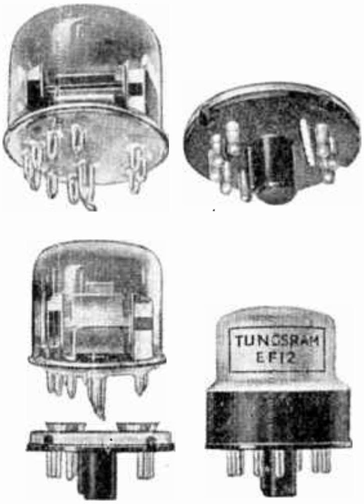


*Fig 7.—
Footless tubes.*

turing Company, on systems of superheterodyne frequency conversion, and there are several detailed discussions on the behaviour of tubes used with various methods of oscillator injection. One of the most important aspects discussed is the fluctuation noise and input resistance at high frequency for the various methods used. There is also a description of the modifications of the tube designs carried out to meet the requirements of these methods in a paper by E. W. Herold, "The Operation of Frequency Convertors for Superheterodyne Reception," *Proc. I.R.E.*, 1.10.41.

An interesting range of tubes with many possibilities in the moderately high frequency band is the so-called footless range,[26] a glass equivalent of which was introduced into this country by the Tungsram Company (Fig. 7). These valves employ the so-called optical alignment, but the electrode structure is mounted horizontally and the cathode and leads are so placed that no lead is greater than 1 in. in length and capacity coupling between the input and output of the tube is reduced to a minimum. The electrode structure is not mounted on the conventional pinch ; the electrode support wires are on the periphery of a glass disc, a procedure which reduces the glass leakage and capacities between leads due to the wider spacing and the previously-mentioned shortening of leads. The tube is fitted with a modified octal type of base with " waisted " pins which locked with the spring contacts of the valveholder. Arrangements are made for a metallic screen to be fitted in between the pins.

A high slope RF pentode which has come to the fore just recently is type EF50. The assembly of this valve is mounted on a disc seal, and the pins are extensions of the electrode wires. The whole tube is enclosed in a special metal case and the disc seal is also covered by a metal disc, while the pins protrude through holes in this disc. The tube is also fitted with a grooved spigot, which is held in the valveholder by a spring clip, thus preventing the tube from becoming dislodged by vibration or being mounted in other than an upright position.

Another tube of a similar nature is type EFF50, manufactured also by the Mullard Company, and this comprises two high slope pentodes in one bulb ; it is extremely useful for push-pull operation. Two makes of tube worthy of note are the Mazda SP41, 42 and the Osram Z62. These latter tubes are, however, fitted with normal bases and are subject to the shortcomings of such arrangements. However, they have proved very useful for wide band amplification at high frequencies.[21] As, however, higher frequencies came into use, it became obvious that considerable modifications in design would become necessary, and in this respect the Acorn tube is an example of the attempts to bring electrode lead length down to the absolute minimum, reducing the physical size, and thereby the inter-electrode capacitances, input lead inductance and transit time troubles.[23]

However, such tubes are extremely difficult to manufacture owing to their small physical size and the extreme difficulty of the glass fabrication. Acorn tubes can be successfully used in circuits employing frequencies up to 600 Mc/s, but, of course, the available power is very small (in the neighbourhood of ½ to 1 watt). One quite common application of the Acorn is its use in the probe of a vacuum tube voltmeter.[87,88] It is suitable for such instruments as it has a very small input capacitance, and if slightly under-run, the contact potential is reduced to a very small value, and this enables a very low voltage range to be covered by the meter. A very noticeable feature of modern tube design is the tendency to discard the tube cap or base and use the extension of the electrode support rods as the contact pins.[20] This feature is embodied in a recently introduced range of R.C.A. tubes in which the member supporting the electrodes is a small glass button, with the electrode support wires arranged in a small circle. These are extended through the glass to act as the contact pins. It is interesting to note that, although this button is considerably smaller than the normal pinch, the average spacing between the wires is greater than can be attained in the pinch type of supporting member, and in addition the leads are considerably shortened. At the present moment this range is confined to battery types in which the filament is rated at 1·4 volt, ·05 amp, and the types available are a pentagrid frequency changer, IR5, a variable mu RF pentode IT4, a single diode pentode, IS5, and output pentodes types IS4 and 3A4. The obvious application of these tubes is in the design of lightweight portable apparatus, and this is demonstrated by the midget personal receivers introduced in

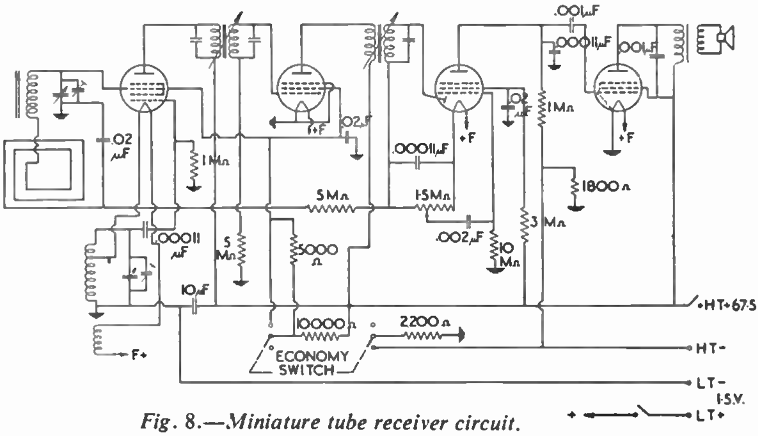


Fig. 8.—Miniature tube receiver circuit.

the States a year or two ago. The tubes are only ¾ in. in diameter, and just over 2 in. long. They can be operated on a 45 volt high tension supply, and the filaments can be supplied from a dry battery. It will be seen that, combined with the use of midget components, a very small but reasonably efficient piece of apparatus can be designed. The circuit shown in Fig. 8 is typical of the present set as used in America. It will be noted that there is no oscillator anode in the frequency changer, a cathode coupled oscillatory system being used. Fig. 9 shows a number of circuits for application to the 1R5.

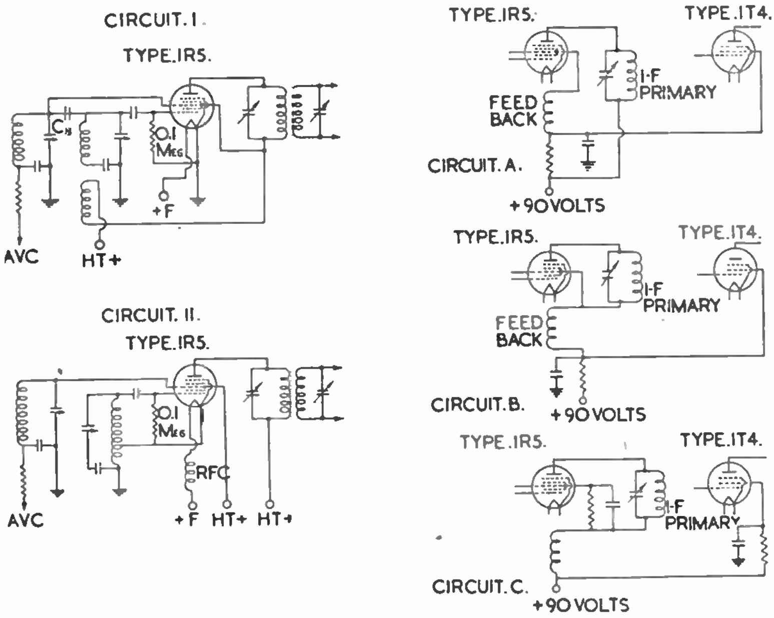


Fig. 9.—1R5 circuits.

At the present moment a considerable amount of interest is centred on the small portable type of receiver (known in the United States as a "walkie-talkie"), and it is interesting to note that the signal to noise ratio may be improved by the use of an R.F. amplifier stage even in the case of the frame aerial set. This R.F. stage may be tuned or untuned, dependent on the design of the receiver such as the Q and tuned impedance of the frame aerial, noise introduced by the frequency changer tube and the total gain from the R.F. stage itself. The main point in considering these effects in small receivers is to deduce the equivalent noise resistance of the tube (Nyquist formula), the frequency at which the improvement is required and the band width.

At present these midget tubes are not available for A.C. operation, but the R.C.A. market two pentodes and a triode in this form. These tubes are listed as the 9001, 9002 and 9003, but as these are slightly modified forms of the Acorn structure, it is unlikely that they will be used to any marked extent. A number of tubes for various high frequencies have been produced on the dish type of seal by Standard Telephones, Western Electric and R.C.A., and the 3B/250A and 4316A by the first company mentioned operate at frequencies up to 1,700 Mc/s and 700 M/cs respectively. The Western Electric Company have already introduced tubes for such frequencies and much experimental work is being carried out with hollow wave guide horn radiators, using such types. Some reference to this will be found in "High Frequency Thermionic Tubes," by Harvey.

A small triode which is designed for operation at frequencies of the order of 250 Mc/s is the HY615, made by the Hytron Company of America, and a similar tube is available in this country manufactured by the Osram Company. This type of tube has the anode and grid connection brought out to two terminals at the top, and this forms a very convenient arrangement when the tube is used as a self oscillator, as the tuned circuit can be connected directly to the tube. Another similar type of tube coming from America is the R.C.A. IC21.

Power Amplifiers

In dealing with tubes in power amplifiers, it is desirable to review the fundamental problems confronting designers, as it will be found in many cases that some of the basic requirements have been overlooked in such design work. The fundamental problem here is the conversion of an amplified signal voltage into A.C. power (Fig. 10) to be delivered to the output load, i.e. loud-speaker, relay, deflector coils for cathode ray tubes, phonic motors, recording or other devices. It is not considered within the scope of this paper to discuss these systems in detail, but the purpose of mentioning them is mainly concerned with the types of tube which have been designed to meet the requirements of these systems. After deciding what are to be the requirements of the output stage, the designer must consider what system he is going to use, and then select tubes which are most suited to this system ; the first of which to suggest itself is the single-ended output stage. In the case of audio amplifiers the single-ended output stage consists of a single triode or pentode in which the grid bias is adjusted so that the signal swing in a positive or negative direction causes the working point to travel over the straight portion of the anode current grid voltage characteristic, resulting in a change of anode current which develops a voltage across the load, thereby producing a certain amount of A.C. power. It is not necessary to describe this in any greater detail as it is fundamental in principle, but it is as well to point out that the system is uneconomic, as the ratio of power obtained to the power consumption is very low. An improvement was effected by the use of high slope tubes, which needed only a small input for maximum anode swing. Here it is as well to point out that the output pentode is not, strictly speaking, a suitable tube to use for the conversion of signal voltage to power owing mainly to its high internal impedance, and also to the fact that the pentode was originally designed for maximum voltage amplification.

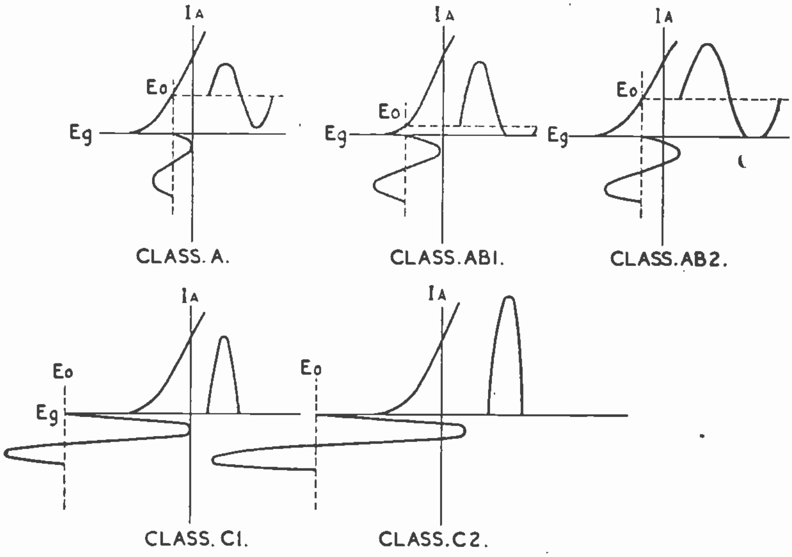


Fig. 10.—*Systems of amplification.*

About thirty years ago a patent was taken out for the use of two tubes connected in series as an amplifier. This, in effect, is the first push-pull amplifier which appears to have come into use. The arrangement was known as Class A_1 push-pull, and the working point chosen is the same as for a single tube. The use of triodes in push-pull removes, to a great extent, the even harmonics caused by curvature of the tube characteristic, and furthermore, although the output is nearly double the power consumption is also double, and the efficiency is therefore no better than the single tube. It is interesting to note that the anode loading for a push-pull stage, even of the Class A type, is not twice that of a single tube, but approximates to 1·4 times the load value for a single tube. It is governed to some extent by the permissible distortion.[34]

Other systems have been developed, and we have Class AB_1, in which the working point is situated near the cut-off point of the tube. Under these conditions twice the signal input is required, and each tube only operates over half the input cycle. This not only means that considerably more power is obtainable, but the mean anode heat dissipation is reduced. It is permissible, therefore, with a suitably designed tube, to increase the anode voltage until the dissipation is near to the rated figure, and thereby gain an additional increase in power output. These systems have approximately four times the output of the single-valve type. It will be seen that the ratio of power output to power consumption has been considerably improved, but the main disadvantages of such a system is that the percentage of harmonic content arises with reduced drive to the grids of the output tubes. In choosing tubes for this type of amplifier, it is essential that the cathode be capable of supplying the peak emission required for maximum signal swing. It will be noted that in none of the systems described has grid current been allowed to flow at any point of the input signal and this brings us to Class AB_2 amplification, in which grid current flows over part of the input cycle.

The circuit is arranged so that the input voltage swing makes an incursion into the positive grid region, and, as a result, grid current flows. This means that the tube impedance is now no longer high, and power must be supplied by the preceding stage to overcome the effects of this flow of current. A further point to remember is that power is dissipated in the form of heat at the grid of the output tube. In this system the whole of the anode current - grid characteristic is used, and a copious supply of emitted electrons from the cathode must be available. Furthermore, it must be remembered that grid current flowing through the resistance in the grid circuit develops a voltage in opposition to the grid bias, and arrangements must, therefore, be made that this voltage drop does not unduly affect the grid bias voltage when signal is applied. It is possible to obtain a power output from two tubes in Class AB_2 push-pull of 60 watts, with a drive of 1-2 watts, whilst the anode dissipation in form of heat is only of the order of 60 watts. In such an amplifier great care must be taken that the H.T. line volts are maintained with ± 10 per cent. from zero to full load, and that the grid bias regulation previously mentioned should not be greater than ± 3 per cent. If these precautions are not taken, a large increase in harmonic content in the output occurs.

The systems described deal with audio requirements, but one further system worthy of note is the Class C amplification which is used mainly in the transmission and reception of telegraphy (I.C.W.). In this system, the grid bias is set at twice the cut-off value of the tube and the signal applied swings into the positive grid region. Thus, the whole of the tube current is used, i.e., from zero to peak emission, and a large increase in power can be obtained under key-down conditions by virtue of the fact that with no signal no current flows. This results in a considerable reduction in the heat which the tube is to dissipate, and it is possible to use much higher voltages in such amplifiers and still work within the safety factor of the tube. It is obvious that this system will introduce considerable distortion into the output, but in the case of code transmissions, this is relatively unimportant in view of the increase of power output and efficiency. Fig. 10 shows the input and output wave forms of the various systems described.

Having briefly reviewed the systems of amplification, the question of tubes for the purpose should be considered. It is not proposed to deal with Class A types of tube, as this covers the main design of tubes,[31] but to commence with suitable tubes for Class AB_1, a large number may be considered suitable for this purpose, but the following precautions must be observed.

Firstly, a large reserve of emission must be available from the cathode, and an idea of this can be gained by observing the heater rating. If this is reasonably large, it can be assumed that a large emission current is available. The next point to consider is the mean current drawn from the cathode as current flowing from cathode to anode will represent a heat loss to the cathode by virtue of the kinetic energy transferred. If this represents a small percentage of the cathode wattage, the tube is equipped with a suitable emission source. This is important when increased anode voltages are used to bring anode dissipation up to its rated value, the mean heat loss being less in AB_1 if normal anode voltage is used.

In the case of directly heated tubes, the cathode return current should not exceed 10 per cent. of the filament current, otherwise uneven heating occurs due to the current distribution in the cathode. The usual phenomenon here is the development of a hot spot on the filament. The overheated metal of the core stretches under the tensioning system, resulting in a reduction of filament diameter. Thus, local overheating is aggravated, and an early failure due to fracture occurs.

A tube which is run in Class AB_1 or AB_2 conditions must also be equipped with a glass pinch (electrode supporting member) designed to give the greatest possible spacing between the anode and other electrode lead wires, and the pinch must be of ample proportions in order that the glass temperature be kept at the lowest possible level. As in the case of AB_2 it is essential that the grid be of substantial design with adequate cooling fins or other devices, in order that the power dissipation, radiated heat from the cathode and reflected and radiated heat from the anode does not give rise to grid emission current, and, of greater importance, the release of occluded gas in the metal.[40] This requirement also applies to tubes used for Class AB_1, particularly in cases where a high slope tube is used. It is as well to point out here that whilst the high slope short grid base tube can be used for Class A and Class AB_1 push-pull, it is not good practice owing to the difficulty of matching such tubes and the fact that the characteristics vary considerably during life.

It is also pointed out that such tubes, although fitted with a large capacity cathode, cannot be driven very hard owing to the large peak emission required and the inability to dissipate large amounts of heat. Lastly, the requirements of a high slope tube do not usually permit the design of a grid which can dissipate heat, and the tube is prone to develop grid emission.[41] The grid volt to anode current curve is usually rather badly curved at the grid cut off voltages, and this tends to introduce unwanted distortion if class AB_1 amplification is used. Thus the high slope short grid base output pentode should only be used where it is desired to obtain a moderately large output for a small input drive. As was pointed out in the case of Class A, it is a relatively simple matter to calculate loads[28] for a given degree of distortion from the anode volt to anode current curves, but it is to be deplored that only a few tube manufacturers publish curves suitable for this purpose.

There are some cases outside the general system described which are worthy of comment, as follows :

It is usual in the case of tubes over the 25-watt anode dissipation class to adjust the anode current of the tube[32] for the rated wattage rather than to use the actual specified grid bias, and in the case of very large tubes the filament voltage is controlled to maintain the emission supply. This has the effect of increasing tube life.[18]

WATTS OUTPUT.

Tube Type	A. Single	A.PP	A_1.PP	AB_1	AB_2	C	Watts
APP4B ..	3·6	7	10	—	—	—	—
APP4E ..	8·8	17	—	28·5	—	—	—
EL2 ..	1·2	—	—	8·5	—	—	—
EL6 ..	8·2	—	16	—	—	—	—
6V6 ..	4·25	—	—	13	—	—	—
6L6 ..	6·5	—	18·5	24·5	47	—	—
P12/250 ..	2·8	6·0	—	8·3	—	—	—
P25/500 ..	4	—	12	—	—	—	—
P26/500 ..	6·5	16	—	30*	—	—	—
P27/500 ..	5	13	18	50†	—	—	—
P30/500 ..	—	—	—	—	—	—	—
O15/400 ..	3·7	—	10	—	—	—	—
P60/500 ..	9	35‡	—	70	—	—	—
P100/1000	30	—	—	90	200	—	—
O240/2000	45	—	—	—	500	1-1·5 kW	—
807§ ..	—	—	—	—	120‡	—	—

* Low loading.
† Approximate output in experimental direct coupled amplifier
‡ Increase anode voltage.
§ Small R.F. power tetrode.

As a final point in this general review of amplifier tubes, attention is drawn to a little publicised aspect. This concerns high and low loading of push-pull output stages. It will be found on examination of the anode current/anode volts curve, of certain tubes that a given peak swing of anode voltage is obtained at maximum undistorted output with an optimum load. Now this may be within the safety factor of the physical design of the tube, but if we use Class AB_1 or AB_2 or C, the maximum anode voltage swing with optimum load may greatly exceed the capabilities of the peak insulation resulting in a flash-over between the leads and/or to rapid deterioration of the glass of the pinch due to electrolysis. This phenomenon is most pronounced in the glass at high temperatures when two polarised leads are inserted in it. The ultimate result of this trouble is that, due to denaturing, the glass becomes porous and admits air to the tube, thereby ruining it.

However, by choice of a load which will give a reduced voltage swing and an increased current swing, the compromise may be reached from the point of view of permissible distortion. This will, of course, necessitate a recalculation of the grid bias and the effective input drive voltage in addition to the calculation for a power value of load. Put in another way, low loading of a P.P. stage results in a reduction in distortion which is a net increase of power output.

Owing to the cancellation, or rather reduction of even harmonics and hum in push-pull stages, distortion is reduced, and it is permissible to reduce the load resistance to increase the output, so that more than twice the output of one tube may be obtained. This question has been dealt with in considerable detail in various other papers[13, 29, 30, 34, 35] and for purposes of calculation the system described in the R.C.A. Receiving Tubes Handbook for Power Amplifiers is also a very good practical method. Numerous methods of calculating distortion are readily available.[10, 11, 13]

It is hoped in a later paper to deal with the aspects of high and low loading in push-pull amplifiers in much greater detail.

Little has been done of recent years with Class B amplifying tubes, and such tubes are usually designed with a high magnification factor so that they may be used with zero grid bias. It must be noted that under these conditions grid current flows, and therefore the driving tube must be able to supply sufficient power to overcome these losses. In order to reduce distortion grid driving power must be considerably greater than that dissipated at the grid of the output tube.

R.F. Power Amplifiers

The same basic systems of amplification[37] apply for this purpose, but obviously the same types of tube cannot be used; hence the introduction of low loss bases, dish-type seals[42] (familiarly known as "doorknob" tubes), multiple leads for electrodes at R.F. potential,[44] and double assemblies (Fig. 11) in one envelope for push-pull operation.

When choosing tubes[36] for R.F. power amplifiers, every consideration must be given to the operating frequency. The question of lead losses is of very great importance, and electrode capacitance must be given careful consideration, owing to the large currents which flow at high frequencies, the effect of transit time on input mutual conductance, and also the variation of input impedance with varying cathode currents. Another point which receives little consideration is the fact that, due to finite electron transit time, relative phase angles are encountered in the electron stream through the tube, resulting in undesired capacity effects.

One method of reducing output capacity at very high frequencies is to apply the excitation in series with the cathode of the tube. The grid then acts as an earth shield and the output capacity is considerably reduced. It should be noted, however, that this in no way compensates for variations of input impedance due to cathode current variations. A detailed description of this system is given in a paper "The Inverted Amplifier," by C. E. Strong, of Standard Telephones & Cables, Ltd.

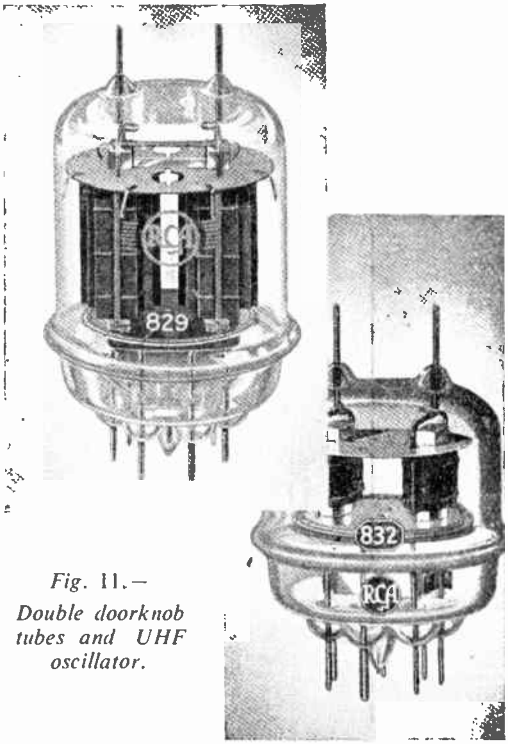


Fig. 11.—Double doorknob tubes and UHF oscillator.

Careful attention must be paid to the total available emission and the frequency at which it is desired to operate the tube. It is general for tube manufacturers to give a figure for total cathode emission[43] and/or to give several typical operating conditions (in some cases with circuit design values) (Fig. 12). It is as well to point out at this juncture that the power amplifier tubes in a transmitter have to supply energy to the tank circuit feeding the load, and the ratio of energy stored in the tank to that passed on to the load is of the order of 12 : 1. The power that the tube can deliver is, of course, also dependent on the impedance which the tank circuit displays to the anodes of the tubes at resonance (i.e. unity power factor).

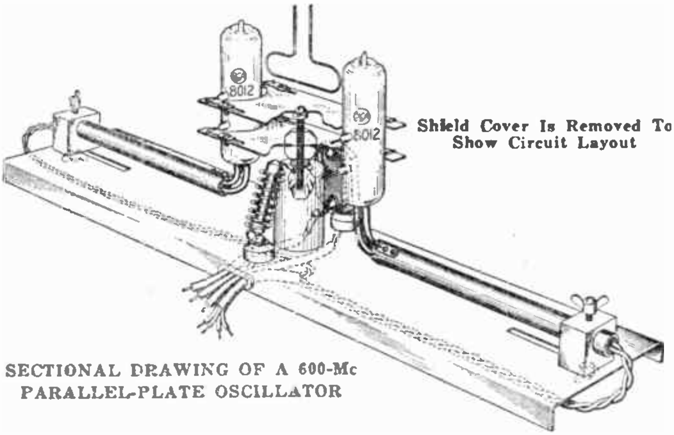


Fig. 12.—*Construction of oscillator using UHF oscillator.*

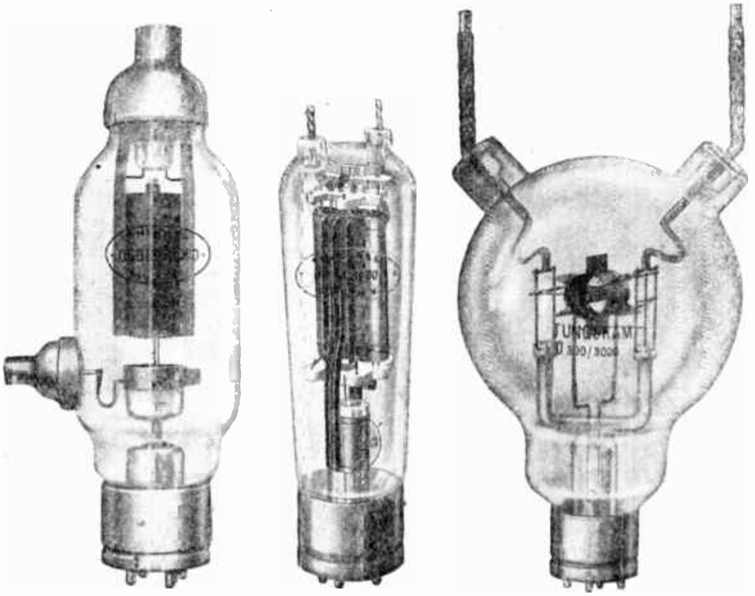


Fig. 13. *Fig.* 14. *Fig.* 15.

Examples of UHF amplifier and oscillator tubes.

Figs. 13, 14, 15 show various forms of R.F. amplifier tubes which have been developed for special purposes, and the following points are worthy of note from the constructional point of view.

The leads are well spaced and of ample dimensions, care being taken to keep them as short as possible, and in some cases the lead itself forms the connecting pin. Their location is designed for the optimum condition from the circuit point of view. In this connection it will be noted that several doorknob types of tubes which contain two identical types of structures (see Fig. 11) have been designed. This enables very efficient push-pull amplifiers to be constructed owing to the reduction in lead length and stray capacities.

Anodes are constructed of material suitable for the purpose in view; i.e., a tube which is intended to run at high temperatures owing to space limitation is often equipped with a tantalum anode which has a strong gettering effect, and will withstand extremely high temperatures. Recently, however, tubes have been manufactured with zirconium coated anodes. This metal also has a strong gettering action, and when plated on a less expensive base material tubes become more economical to manufacture without, however, losing any of their efficiency. In fact, it is possible to be more generous in the design of the anode and thereby obtain greater mechanical stability.

Carbon is used to a considerable extent, but has the drawback that it is unsuitable for ultra high frequency amplifiers because of its rather high H.F. losses. It has slight gettering action, but tends to sublime at moderately high temperatures, and to reduce the heat dissipating properties of the tube. It also reduces the effectiveness of the electrode insulators.

A system of power output measurement is shown which is of interest owing to its suitability for high frequency measurement, and consists of a tungsten filament lamp, the light output of which is measured by a S.44 selenium cell and galvanometer. (Fig. 16.)

In the particular model shown a 220-volt, 200-watt lamp is used, and by using a shutter the output range can be extended from 30 to 200 watts; the calibration of the instrument is carried out with D.C.

The design and development of three new ultra high frequency transmitting tubes was described by C. E. Haller in *Proc. I.R.E.*, 24.6.1941 : he discussed several of the novel constructional features, such as the reduction of grid emission, choice of anode material, design of mechanical structure, etc.[45]

Much consideration has been given in the design of R.F. amplifiers to "anode efficiency," in order that economy in consumption may be effected. This possibility was previously mentioned with respect to audio amplifiers, and apart from any technical aspect it is attractive from the commercial point of view, particularly in the U.S.A., where broadcasting is on a commercial basis, and amateurs are permitted the use of greater power than is the case in this country.

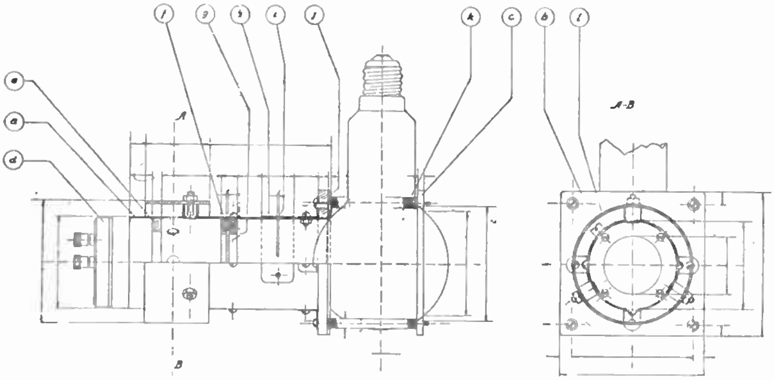


Fig. 16.—Power output meter

TABLE 1—Plate Materials.

	Graphite	Molybdenum	Tantalum
Melting-point °K.	3947*	2893	3123
Temperature of operation average °K.	600	750	900
Ease of fabrication	Medium	Difficult	Readily
Cost of finished anode	Lowest	High	As high or slightly higher
Thermal radiation constant at 900° K. in % efficiency	94	8·3	8·8
Rigidity-maintenance of inter-electrode spacing	Excellent	Both good, depending on degree of reinforcement	
Tendency to warp with heat due to crystal strains	None	Slight	Little if any
Ease of degasification†	Difficult	Hard	Slightly harder
Temperature of degasification °K	1050	1200-1500	2000-2600
Gettering action	Possibly some	None	Fairly good
Vapour pressure at a given temperature	Very low or nil	Medium	Low

* Temperature of Sublimation.

† Attempted weighted averages which take into account the requirements of equivalents, time and skill.

Secondary Emission Tubes.

Photomultipliers.

In dealing with photomultipliers it is essential to review briefly the action of the photo-cell in which light falling on a cathode coated with certain metals releases electrons which are collected by an anode maintained at a suitable potential.[46]

Here the number of electrons released in a given time is proportional to the intensity of the incident light and the maximum energy of the freed electrons is dependent on the wavelength of the light but *not* upon the intensity.

According to the quantum theory, if v = frequency or vibration per second, and h = Planck's constant ($6{\cdot}55 \times 10^{-27}$ erg seconds, then one quantum $Q = hv$ ergs. If we assume that the kinetic energy of a released electron is $\frac{1}{2}\, m.v^2$ and P is the energy given up by the action of releasing itself from the cathode, then $\frac{1}{2}\, m.v^2 = hv - P$. It will be seen here that $hv - P$ must be positive, otherwise the electron would not be released, and if $hv = P$ emission ceases. Thus if v_0 = the minimum frequency for electron emission, then $P = hv_0$ and $\frac{1}{2}\, mv^2 = H\,(v - v_0)$; v_0 is described as the threshold frequency and P is the work function of the cathode. Thus caesium, for example, has a threshold frequency of $3{\cdot}75 \times 10^{14}$, wavelength 8,000 Å, and a work function of 1·54 volts. As mentioned earlier on in this paper, it is essential to use a very high value of load, with the usual vacuum or gas-filled photo-electric cell, owing to the very small currents involved. This fact led to the use of secondary cathodes (Zworykin)[52], and to describe this action simply it may be said that electrons are caused to strike a surface specially treated, so that for each primary electron four or five secondaries are released by impact. These electrons are then directed to a collecting electrode which contains the load circuit.[49, 51, 54]

An interesting photo multiplier tube has been produced by R.C.A. and described in *Electronics*, December, 1940, by J. A. Rajchmann and R. L. Schneider.[53] Fig. 17 shows the curved targets or dynodes which are used for multiplying and directing the electron beam. A sensitivity of 10 amperes per lumen is claimed for this tube, and it has the added advantage that it is quite small, being only 2·8 in. long and 1·25 in. in diameter. This is quite an important improvement as most multipliers of this type have the disadvantage of large physical dimensions.

In Britain the Baird Television Company developed a photo multiplier in which the secondary cathodes are in the form of a fine mesh grid,[47] and the secondary emission is directed to the next stage by virtue of the penetration of the next positive field. These caesium multipliers were developed mainly for mechanical systems of television scanning, and the sensitivity of the primary cathode is 30 microamps per lumen, and the overall sensitivity is greater than one ampere per lumen. The drawback of these multipliers is the high voltage necessary for a number of stages, and also the fact that any overload destroys the secondary cathode surfaces. The final collector currents must also be limited otherwise excessive heat is developed, and in some cases will even melt the fine mesh of the grids.[50]

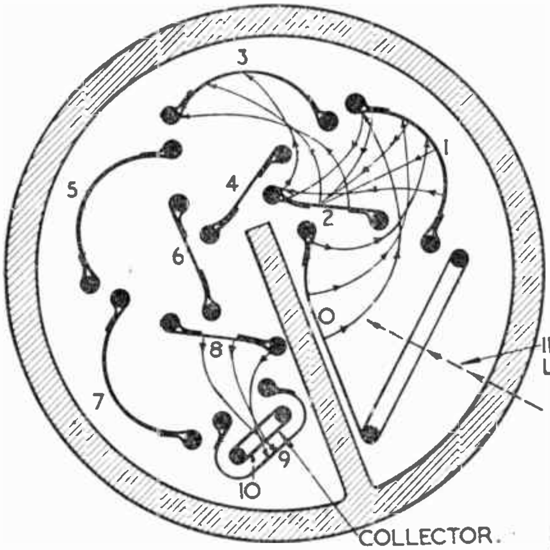


Fig. 17.—*9-stage multiplier.*

In addition to the Baird organisation thermionic and photo-multipliers have been developed in this country by Vacuum Science Products. Ltd.[48]

The secondary cathodes in these tubes are perforated discs which are coated with suitable material for secondary emission. The thermionic multiplier follows the usual practice of mounting the control grid very close to the cathode in order that a high slope may be obtained. Here again the primary cathode current is very small (10 microamps) so that a high input impedance is maintained and is not greatly affected by variations of cathode current at ultra high frequencies.

The perforations of the secondary cathodes are in the form of funnels with an angle of 60 degrees, this being the best angle of impact for the optimum release of secondaries into the accelerating field. Unfortunately, these multipliers, in common with other efforts, suffer from transit time effects at ultra high frequencies and the output conductance is a function of frequency. Investigations into this phenomenon are being carried out both in this country and in the U.S.A. (The Behaviour of Electrostatic Electron Multipliers as a Function of Frequency: Malter, *Proc. I.R.E.*, 12.3.41, and Electronics and Television. V.S.P.)

An interesting thermionic multiplier has been developed in the United States (H. M. Wagner and W. R. Ferris, *Proc. I.R.E.*, 10.1.41)[67,68] described as the orbital beam secondary emission multiplier. (Fig. 18.) This tube is designed on acorn principles and the input electrode system consists of a cathode and control grid G1, with an accelerator grid G2. The faces of the cathode joining G1 are made flat in order to obtain a beam. The electron stream from the cathode follows the path A.A. shown in the diagram, the focussing electrode J1 being at a high positive potential. When the other focussing electrode J2 is at zero potential, the electrons strike the secondary emitter K2, releasing about five secondaries for one primary electron. These secondaries are then collected by the plate P which is at a considerably higher potential than K2.

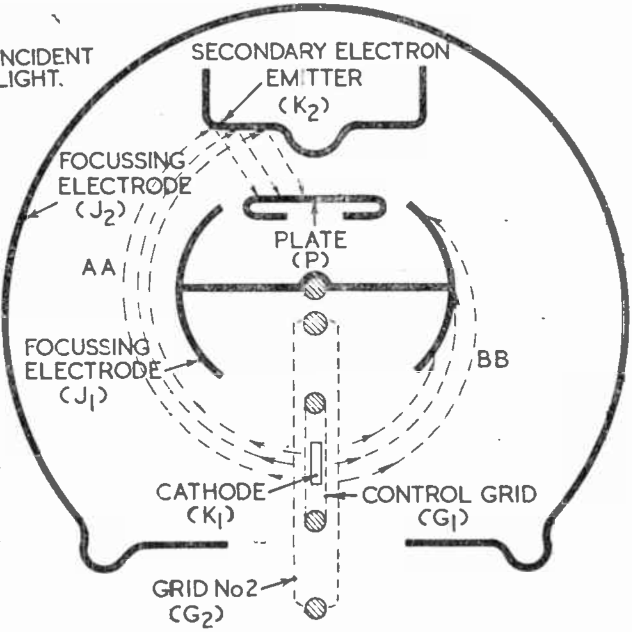


Fig. 18.—*R.C.A. Orbital beam multiplier.*

It is interesting to note that gain control is not exercised in the usual manner, i.e., by adjusting grid 1 voltage. This would cause variation of the primary cathode current with its attendant changes of input capacitance and conductance, but the path of the electrons is controlled by the potential applied to J2. Thus by making J2 negative, the electron path becomes BB, and the electrons do not strike the secondary cathode K2 but are collected by J1.

This tube has a slope of about 15 milliamps per volt, and a figure of merit (from the point of view of a wide band amplifier) of about twice that of the normal high slope R.F. pentode.

Using this tube in a 500 Mc/s amplifier, gains of seven times for 6 Mc/s bandwidth and five times for 11 Mc/s bandwidth were obtained.

Very little loss in trans-conductance was found due to the spread of emission lag (transit time effects) which is less than 10^{-9} seconds. The accelerators and focussing electrodes act as electrostatic shields reducing the capacity between input grid and output anode substantially to zero.

It has been suggested that this tube would be very suitable for repeater systems in television transmission.

It has also been found that unless the input trans-conductance of thermionic multipliers is high, the noise level compares unfavourably with ordinary tubes, and also that when this trans-conductance is high, it is difficult to stabilise the control grid voltage.

The principal advantage to be obtained from the use of multipliers is in the ultra high frequency band where input loading and capacity are important. The reduction in trans-conductance of the input system for a given overall gain which is permissible, leads to a drop of input trans-conductance (whether due to transit time or to lead inductance) and input capacity. (*See* B. J. Thomson, Voltage Control of Electron Multipliers, *Proc. I.R.E.*, 10.1.41.)

The Klystron Tube.

The klystron tube belongs to that class of amplifier and oscillator tubes where the transit time of the electrons is usefully employed instead of being a detrimental factor. It must be mentioned in this connection that the first members of this group so classified were undoubtedly the magnetron and the Barkhausen-Kurtz type of tube. But the new element embodied in the klystron is the bunching of electrons due to velocity modulation. The application of cavity resonators—fancifully called rhumbatrons in the case of klystron tubes—was not entirely new, and has, indeed, been suggested and tried out before.

For the sake of clarity, however, it is important to realise the salient features of cavity resonators, and it is proposed to give here an engineering approach to their operation. An exact mathematical analysis has so far been achieved only for hollow structures of extremely simple geometric design like spheres, rectangular boxes, etc. A resonating dipole may serve as a starting point for the following evolution. It is well known that a dipole has a very low Q—in the order of 10 depending on its thickness and geometrical shape—owing to its radiation losses ; indeed, radiation or emanation of energy is ordinarily its very purpose. If it would not radiate its Q would be very high and solely determined by the relatively small copper losses. To achieve a high Q one has, therefore, to prevent radiation. Imagine now that the dipole were bent circularly so that its ends would almost touch one another. There is no reason why this re-shaped dipole should behave fundamentally differently from its previous shape ; actually it is a better resonator than the previous. Incidentally this very type had been used by Hertz as a resonator indicator for his historic experiments on electromagnetic waves. Such a circularly bent dipole is indicated in Fig. 19, as the gapped heavy circle underneath the word "buncher." Imagine, further, that this resonating circle be rotated round the horizontal axis of symmetry thus producing a toroidal structure with a circular slot at its innermost contour. This system will still resonate, i.e., a strong alternating electric field will be set up between the two edges of the slot (the former tips of the original dipole), the magnetic field, however, will consist of closed circular lines of force existing entirely inside the toroidal enclosure, thus being deprived of any chance to escape into space. Hence no radiation can take place (the gap radiation is negligible) and, therefore, the Q of this rhumbatron, as the toroidal resonator has been christened, is tremendous, namely, in the order of a few thousand. The connection of two perforated circular discs to the two circular edges of the slot makes no difference to the resonating properties of the rhumbatron and a strong electric field now pulsates between them.

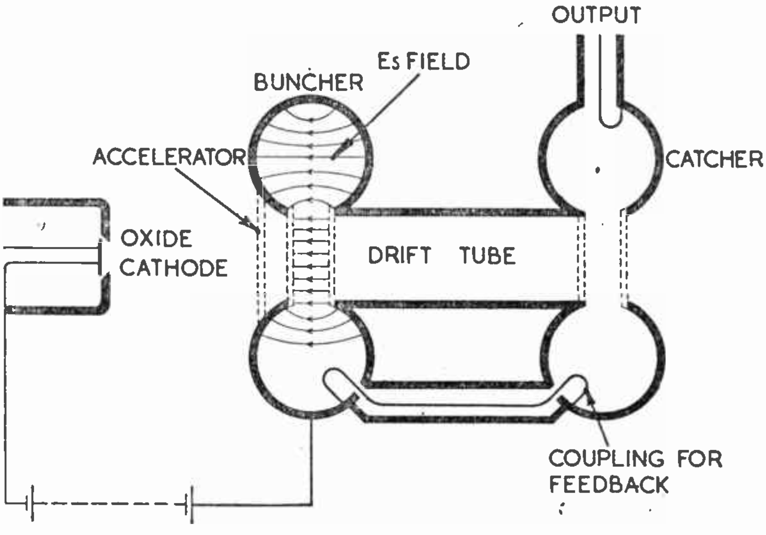


Fig. 19.—Principals of the Klystron.

Imagine now electrons of constant velocity to be shot from the gun through the perforations of the discs or grids of the oscillating rhumbatron. According to the momentary strength and direction of the electric field in the grid space they will be either decelerated, remain unimpaired or be accelerated according to whether the instantaneous field is negative, zero or positive. The first electrons will leave the resonator with a speed slower than at entering, certain later electrons will emerge with their original velocity and, therefore, catch up with the first slowed down electrons after a certain amount of drifting. Still later electrons will also catch up with the first, for they have been provided with an additional positive increment of speed. Therefore all electrons considered will meet after a certain time somewhere along the axis and form there a concentration of negative charge or a bunch of electrons the density of which is far in excess of that of the original beam. The periodic field of the resonator will therefore produce the formation of periodic bunches appearing at the certain point along the tube. For this action this resonator is called the buncher.

At the meeting place of the electrons another rhumbatron of identical shape is installed so that the highly concentrated electron bunches rush through its grid space. Imagine now that the rhumbatron also oscillates, and that the field in the grid space is just opposing the movement of the electron bunch during the short interval when the latter is within the grid space. The effect will be that the bunch will be retarded thus losing kinetic energy. The total of this loss of kinetic energy will then appear as an additional increment of electromagnetic energy contained in the resonator. This transformation of one form of energy into another is brought about by the medium of charge induction from the bunch to the metal structure of the second resonator called the catcher.

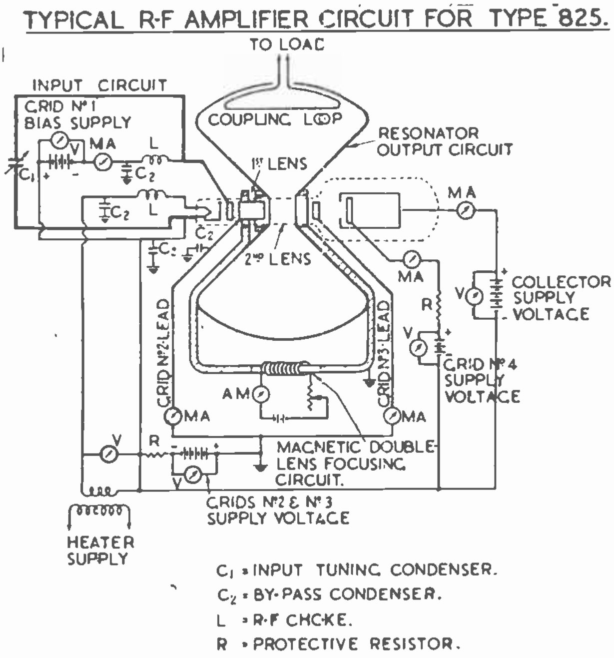


Fig. 20.—R.C.A. Inductive output amplifier and circuit.

If, then, energy is fed back from the catcher to the buncher the circle of functions is complete, i.e., the tube will oscillate continuously. Of course, the feed back has to occur at the right phase so that the bunch passing through the catcher is always being decelerated. This can be achieved by adjusting the length of the concentric feedback line.

An interesting tube which has been developed along these lines is the inductive output amplifier[59] described by A. V. Haeff and L. S. Nergaard, *Proc. I.R.E.*, vol. 28, pages 126/30, March, 1940. (See Fig. 20.)

In this tube the intensity modulation of the beam is obtained by grid control, the grid being placed very close to the cathode to reduce transit time effects, and to improve the relationship of slope to input capacity.

The output capacity which depends on the design of the resonator is of the order of 1 to 2 ρF at 500 Mc/s.

A special combined system of electro-static and electro-magnetic focussing is used owing to the fact that the size of the output electrode is determined by the cross-section of the electron beam, and a larger outer conductor is required to reduce the output circuit gap. Thus, the effects of beam divergence due to mutual repulsion of electrons, de-focussing due to electrostatic fields, and de-focussing due to high frequency electric fields are largely overcome. The latter effect mentioned is most important since electrons are required to transverse the output gap across which exists a very high potential difference which changes considerably during the time of electron transit.

The first magnetic lens compensates for accelerator divergency and the second magnetic lens compensates for the high frequency field at the gap. The gaps are made adjustable by controlling the electro-magnet current, and this prevents electrons bombarding the accelerator electrode and glass wall of the tube. It will be observed that the resonator is placed outside the glass walls of the tube, and the currents induced in it are so generated by influence through the glass walls. The collector voltage is adjusted for optimum conditions, and the electrode itself is designed so that it also suppresses and collects secondary electrons released by the impact of the primaries.

The Magnetron

It is not proposed to deal with this particular type of tube in any detail,[86,89,90,91] as a very good description of the mechanism of the tube is given in the paper entitled "Magnetron Valves for Ultra Short Wavelengths," by E. C. S. Megaw, B.Sc., D.I.C., in the *G.E.C. Journal*, vol. 7, No. 2, May, 1936.

In *Broadcast News*, December, 1935, there appeared an article by Irving Wolff and E. G. Linder describing the beam transmission of 9 cm. electro-magnetic waves. A split anode magnetron was used as a generator, in conjunction with a parabolic reflector. Transmissions were made over a distance of 16 miles and a thorough investigation into attenuation due to atmospheric conditions was made. It was found that the only effect measurable was caused by heavy rainfall which resulted in an attenuation of approximately 0·1 db. per mile.

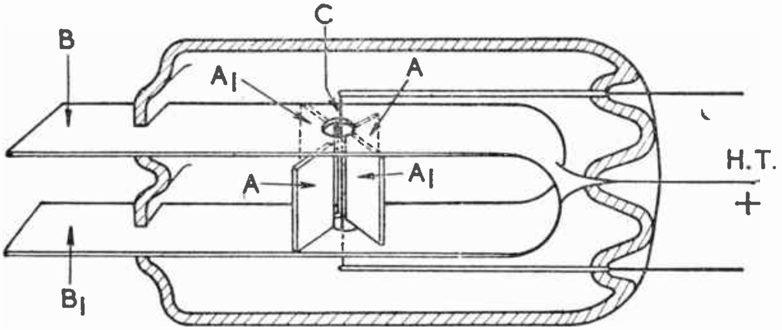


Fig. 21.—*Magnetrom with built-in resonator.*

An interesting point with this type of tube is in the life of the filament. These filaments are usually of tungsten, but due to the bombardment by emitted electrons under the action of the magnetic field, the life is reduced to about 10 per cent. of the same type of filament in a normal tube.

M. D. Guravich has published a considerable amount of useful information in an article, " New Types of Tungsten Cathode for Magnetrons."[85]

The Telefunken concern in Germany has produced a magnetron[83] in which the resonators are sealed into the tube and are connected to the alternative segments of a four-sector anode. An illustration of this tube is shown in Fig. 21.

A large section of " High Frequency Thermionic Tubes," by A. F. Harvey, deals with magnetrons, particularly in the limitation of wavelength by the magnetic field, electrode voltages and dimensions.[89, 90, 91]

Special Tubes

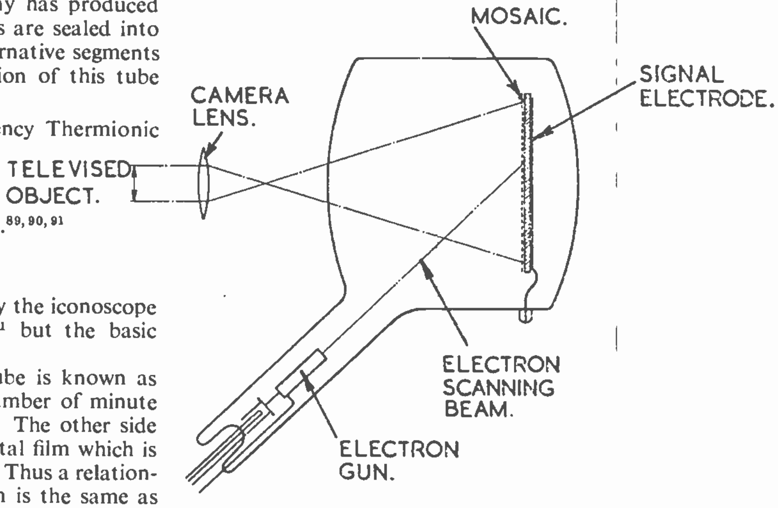
The Iconoscope.

It is only necessary to describe briefly the iconoscope tube used in the television camera,[71] but the basic principles are shown in Fig. 22.

The most important part of this tube is known as the mosaic, and consists of a large number of minute photo elements on a thin mica sheet. The other side of the metal sheet is coated with a metal film which is connected to a lead-out from the tube. Thus a relationship of the photo elements to the film is the same as that of a set of condensers with one common plate.

If an image is projected on to the photocells by means of an optical lens system, each element will produce a charge (or release electrons) in proportion to the light intensity as previously mentioned in the description of photo cathodes. Owing to the release of electrons the cathode of the cell will assume a positive charge, and in order to discharge the cell an electron beam is used as a scanning device. This induces varying charges in the metal film by virtue of the condenser effects and these charges are developed into a signal voltage across a load placed in series with the output lead. This is then followed by the conventional wide band amplifier. The drawbacks of the tube are as follows :—

1. Secondary emission produced from the photo sensitive surface by impact of the high velocity electrons in the beam falls back on the mosaic and discharges it in the vicinity of the beam. This gives rise to an apparent dark patch, sometimes known as the spurious signal. This can be compensated for electrically, but tends to leave white lines at the edges of the picture.
2. Secondary emission tends to charge the glass and reduces contrasts in the picture.
3. Owing to the two previous troubles the mosaic has a rather low storage efficiency owing to the various discharging effects, and the distance of the scanning beam anode also affects the storage capacity. Because of this trouble, the loss of definition in contrast results in an overall efficiency



BASIC ICONOSCOPE. *Fig.* 22.

of something like 10 per cent., and in addition the device is not linear from a photometric point of view.

An improvement was later made by combining the image converter with the mosaic system.

In the image converter (Fig. 23) a plain photo cathode is used, and a light image is projected upon it thus releasing photo electrons. By a system of electrostatic acceleration and a combined electrostatic and electromagnetic focussing field,^{72} these electrons are projected along parallel paths until they strike a target. In some cases this target is composed of a fluorescent material, and thus a picture or image of the original is formed.

This device was used in the image iconoscope (Fig. 24), but the fluorescent screen was substituted by the mosaic. The original photo cathode is formed on a translucent plate and the light image is projected on the back of this cathode. Thus, by making use of electrons emitted from the primary cathode, use is made of secondary emission from the mosaic to increase storage efficiency, and in addition the device has become photometrically linear. An efficiency of some ten times that of the normal iconoscope is claimed, but it still suffers from secondary emission caused by the scanning beam.

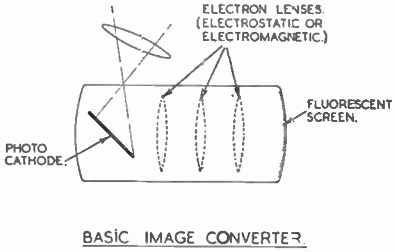


Fig. 23.

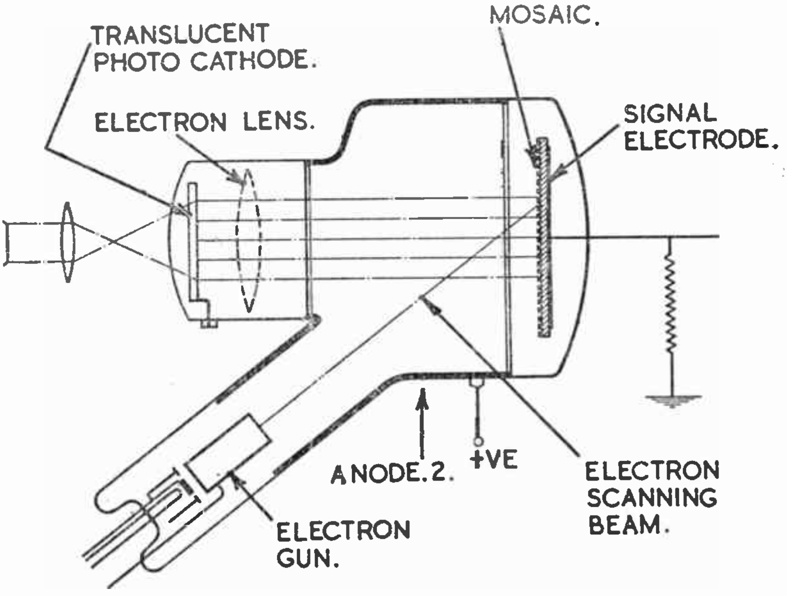


Fig. 24. IMAGE ICONOSCOPE.

A still further development introduced in 1939 by R.C.A. is the orthicon^{70} (Fig. 25), in which attempts have been made to overcome secondary emission effects by using a low velocity scanning beam, and to make it strike the mosaic perpendicularly owing to the fact that low velocity electrons are considerably de-focussed if they do not strike the mosaic in this manner. This is due to the fact that electrons tend to "skid" off the mosaic surface in much the same way as a beam of light is reflected from the surface of a mirror.

An ingenious system of beam deflection is used to prevent de-focussing by strong electrostatic and electromagnetic fields or by not striking the mosaic at right angles. The horizontal deflection is electrostatic, but the beam is made to emerge from the plates in a parallel

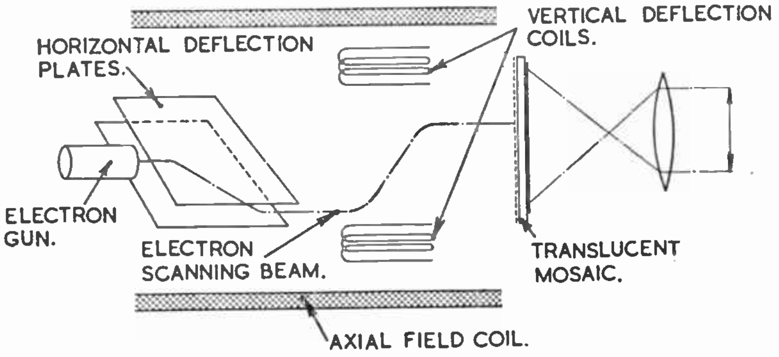


Fig. 25.—Principle of the 'Orthicon.'

path to its entry, by using a magnetic field where the lines of force are parallel with the axis of the beam (low velocity electrons will follow these lines, of course, unless otherwise interfered with). The tendency for electrons to develop a spiral or cycloidal path is prevented by a fringing field, in other words, by making the gradient of the electrostatic field gradual at the entry and exit of the deflecting plates. This is usually done by curving the edges of the plates. An electromagnetic vertical deflection system is used, such that the beam always strikes the mosaic at right angles.

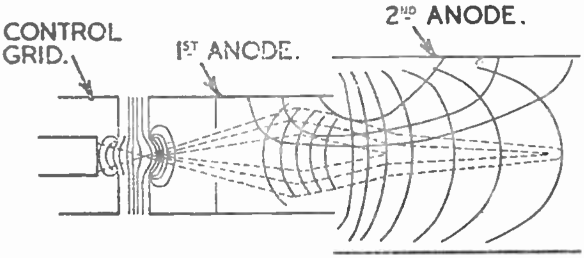


Fig. 26.—Basic cathode ray tube gun.

The mosaic is maintained at the electron gun cathode potential and, therefore, the electron beam velocities on arrival at the mosaic are so low that no secondaries are produced. Furthermore, the condition of saturated photo-emission is fulfilled as the electrons forming the beam themselves discharge the cells of the mosaic, and the signal current can, therefore, only be as great as the beam current, which is of the order of 1 microampere. This makes the tube linear from a photometric point of view, and it has the theoretical storage efficiency of 100 per cent.; more than five times as much as the normal iconoscope.

The Electron Microscope

The electron microscope is an example of the practical use of the fact that an electron beam under the influence of electrostatic and electromagnetic fields behaves in a similar fashion to a beam of light. A considerable amount of investigation into this has been carried out by De Broglie and Busch. Fig. 26 shows the cathode ray tube gun with the electrostatic field as compared with an optical system, and in the electron microscope this is used to substitute the normal light system. We then find that magnetic lenses are used as substitutes for the condenser objective and projector lenses. Fig. 27 shows the similarity of the two systems.

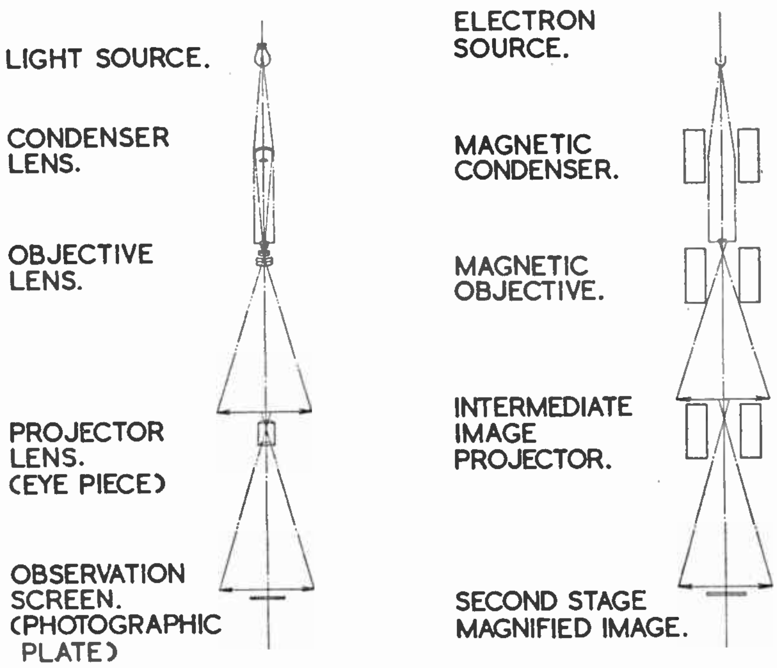
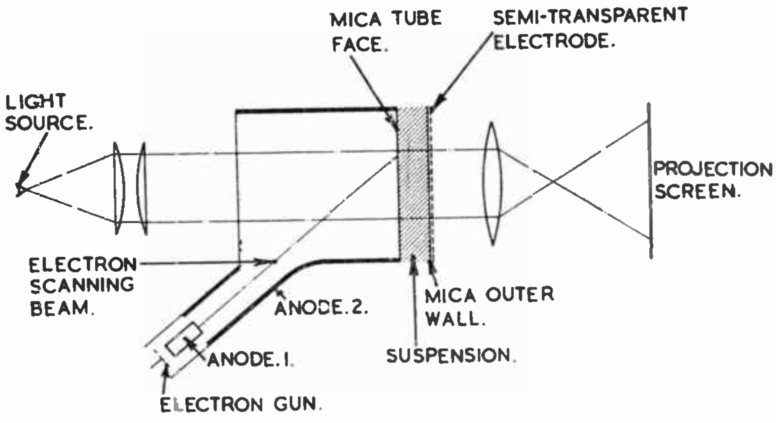


Fig. 27.—Electron microscope principles.

As the wavelength of the electrons is only at velocities between 30 and 100 kilovolts, 1/100,000 of that of light, it will be seen that the resolving power is considerably greater than that of the light microscope, and in theory will cope with atomic dimensions. Present electron microscopes have a resolving power of some 50 times that of the light microscope.[75]

High voltage power supplies are obtained from radio frequency sources which are fairly easy to screen, and somewhat reduce the problems of voltage regulation.[73] This system has been used owing to the strong magnetic fields which would be produced by high voltage supplies at mains frequency. Special airlock chambers are used for inserting specimens and photographic plates, whilst the electron lenses are controlled by the current in these coils. Any adjustments necessary after the insertion of a specimen are done by means of a bellows system.

It will be seen that as the electrons must go through the specimen, a quite different technique of specimen mounting is necessary.[74] This is achieved by using a very thin collodion film on a wire mesh holder. The



TELEVISION LIGHT VALVE.

Fig. 28.

specimens are then " fixed " on the collodion film, and the wire holder is placed in position at the magnetic objective lens by means of the airlock system already described.

Television Light Valves.

In the past many attempts have been made to solve the various problems involved in projected television with varying degrees of success. In this country Scophony have attempted to deal with this, and considerable information has been published on the diavisor[67] and the skiatron, and various experiments have been made by the Baird Company with polarised benzine cells (the Kerr cell), etc. A very recent development in U.S.A.[68,69] is a light valve consisting of colloidal graphite suspended in a solution (Fig. 28). The form of the graphite particles is that of very small flakes or plates, and if they are placed between two electrodes with a polarising voltage between them, they will assume a definite position relative to the lines of electrostatic force and dependent upon the insulating and specific characteristics of the solution used—in this case a medium viscosity oil. In the cell described the suspension is held between two glass or mica walls, one of which has a semi-transparent conducting coating on it. If the other wall is held at a potential such as would be provided by a cathode ray beam, an electric field is set up across the cell, and variations of this field will cause the particles to orient themselves accordingly. Thus we have a form of variable shutter which can be controlled by a beam modulated with the television signal, and an independent light source focussed through the cell will be modulated accordingly.

Re-orienting of the particles is obtained by the use of secondary emission, and a diagram of the tube is shown in Fig. 28. This system has considerable possibilities, but is, of course, only in the experimental stage as yet.

The Cyclotron.

Considerable interest has been aroused from time to time by various attempts at "atom-smashing." Lord Rutherford achieved some success many years ago, and opened a wide field of investigation. Since that time practically all the known elements have been transmuted by bombardment by alpha rays, high speed deuterons, etc.[76] Owing to the high positive charge of the atomic nucleus it has been found that charged particles have not been very successful when used as "bullets" to break or alter the atomic structure Electrons, even at high speed, will not penetrate far into the various orbits of an atom and are deflected outwards again at various angles, according to the nature of the atom and the velocity and charge of the electrons. This effect, however, has been found very useful in the examination of crystal structures. Heavy

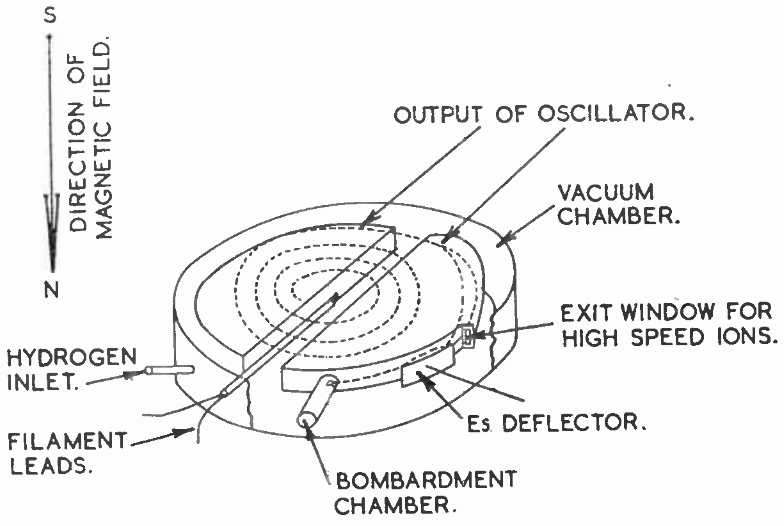


Fig. 29. BASIC PRINCIPALS OF 'CYCLOTRON.'

positive particles will not penetrate deeply into a structure, and in any case a very large repulsive force from the nucleus of the atom prevents penetration. However, in 1935 the existence of a charged particle, the deuteron (the deuteron is the nucleus of heavy hydrogen (deuterium), and consists of one proton and one neutron) was found, and these particles are themselves best suited as projectiles to be fired at atomic structures. The use of positively charged particles can be adopted if they can be sufficiently accelerated. Thus, if a positively-charged particle travels from a positive to a negative point in an electrostatic field, the kinetic energy expressed in joules is equal to the product of the charge of the particle in coulombs and the potential drop in volts.

It is at present an accepted fact that the proton (nucleus of hydrogen) has a positive charge equal in magnitude to that of the electron. This also applies to the deuteron (nucleus of " heavy " hydrogen), and it is possible to arrive at a new unit energy, one electron or similarly charged body will acquire in falling freely through a potential difference of one volt. This is given as $1{\cdot}59 \times 10^{-19}$ joule (known as the electron volt[77]). The cyclotron is an attempt to accelerate these particles to the required velocity in order that penetration may be achieved (Fig. 29). The instrument consists of two hollow semi-circular electrodes very similar to a flat pill-box cut along one of its diameters.

These electrodes are connected to the output of an oscillator which in this case operates at 12 Mc/s. In between the two electrodes is placed a tungsten filament which emits electrons. The whole of this structure is placed in a vacuum chamber which is maintained at about 1,000 volts positive with respect to the filament. Hydrogen is admitted to the chamber through a valve and considerable electron current flows between the filament and the chamber. The hydrogen ions thus released are attracted to one of the electrodes which happens to be negative at that instant. Upon entry into the cavity it is freed from electrostatic fields and is governed only by the magnetic field, the direction of which is shown in the diagram. This magnetic field causes the particles to assume a circular path, and after a time the particle will leave the cavity at that section. At this instant, however, the relative phase of the two electrodes has changed and the particle is attracted towards the other cavity, at the same time receiving a push, so to speak, from the cavity it has just left. Thus its velocity increases and the radius of its circular path will also increase. This action is repeated until the particle reaches the outer circumference, when it will leave one of the electrodes by virtue of a window provided for that purpose. Placed near this window is an electrostatic reflector maintained at 20,000 volts negative. The purpose of this electrode is to maintain the particles in a beam form. The bombardment chamber is a tube in which is fixed a very thin metal window, the rest of the chamber being open to the air. The high speed particles pass through the window and bombard any material placed in the chamber. With regard to the design of the oscillator and electrodes, it will be seen that the frequency of the oscillator can remain fixed, although the particle paths are continually increasing in length. In other words, the time required to travel at velocity v through a semi-circular path of radius r equals $t = \frac{\pi r}{v}$. Now centrifugal force due to the curved path is $\frac{Mv^2}{r}$ where M = the mass of the particle.

The centripetal force = Hev where H = magnetic field, e = the charge of particle, and from this it can be said that $\frac{Mv^2}{r} = Hev$. Thus solving for v and substituting it for t it is found that $t = \frac{\pi M}{He}$. This is constant for a given type of particle and a given H, and so t is independent of the radius of the path and the proper frequency of oscillation is found by setting t equal to one-half the period of oscillation.

U.S.A. Trade Marks.

1. Tungar or Rectigon, a low voltage high current rectifier suitable for battery-charging apparatus, etc.. This tube is high pressure gas-filled.
2. Kenotron. High voltage, high vacuum rectifier suitable for low current supply, e.g., cathode ray tubes, X-ray apparatus, etc.
3. Pliotron, any large power amplifier or oscillator tube with air or water cooled anodes.
4. Magnetron, generator of U.H.F. oscillations, the frequency of which depends on the strength of the magnetic field and electron transit time.
5. Grid-pool tube. High voltage, high current mercury pool rectifier. Striking of arc controlled by an internal grid.
6. Glow tube. Gas-filled voltage regulator, stabiliser, relaxation oscillator, etc.
7. Strobotron, gas-filled tube for photographic purposes, also strobocopic measurements.
8. Iconoscope, television camera tube, with silver mosaic screen.
9. Kinescope, television reproduction cathode ray tube with magnetic or electrostatic focussing.
10. Orthicon, television camera tube with specially corrected beam to compensate for angle of incidence on mosaic screen and suppression of secondary electrons from the screen.
11. Monoscope, small television monitoring tube.
12. Phanatron, low pressure gas tube used as voltage limiter trigger relaxation oscillator, etc.[81]
13. Thyratron, grid control gas-filled rectifier.[78,79,80]
14. The Permatron, external magnet control gas-tube.
15. Ignitron, high current high voltage mercury tube fitted with striking electrode. May be used for rectification or D.C. to A.C. inversion, frequency conversion, etc.
16. Kathetron, gas-filled rectifier, with external grid control.

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LONDON AND MIDLANDS SECTIONS DISCUSSION

G. L. Hamburger : The mechanism of electron emission from oxide cathodes is, I understand, of a rather complicated nature. It seems that the cathode should operate under its protective space charge cloud, which implies that saturation current with its consequent break-up of this space charge cloud would damage or even destroy the emission centres of the cathode. In many radio sets I have noticed the mains rectifier valve to be of the directly heated oxide coated type. Owing to the shorter time constant of a directly heated cathode the H.T. will in these cases be at full value some time before the receiver valves have reached their full emission. How seriously does this damaging effect work out in practice. Have any experiments been made along these lines, and if so, what are the results ?

Mr. J. Parry: In the orthicon a method is adopted for paralleling the beam or making the beam vertical to the mosaic, whereas in the reproducing cathode ray tube that is not the case. Would it not be as well to emit a beam at an angle to the mosaic in the one case and to the screen in the second case ?

Mr. J. Porter : Certain observations are made from time to time with regard to noise from the cathode. Is not that also the function of the rate of dissipation of heat from the glass envelope in the small pin valve ?

Secondly, what would be the order of accuracy to be expected from the photographic lamp device for measuring the anode dissipation of a valve at high frequencies, bearing in mind that photometric methods are accurate to something of the order of 5 or 6 per cent. ; and that the measurement of normal light intensities with the photo cell would be of the order of accuracy of 2 per cent. ?

Mr. R. L. West : Have attempts been made to put a screen between the heater and cathode of a valve, in the interests of noise reduction ?

Mr. Stokes : Is there any special significance in the letters EF for the EF12 ?

Mr. Alston : Why is it more difficult to exhaust a small bulb than a large one ? It seems that the reverse should be the case, since less air should be removed in less time.

REPLY TO LONDON AND MIDLANDS DISCUSSION

Mr. F. E. Lane : Replying to Mr. Hamburger, I would emphasise that the danger from full line voltage when the rest of the tubes in a receiver are under heated is not so great as is first anticipated. It must be remembered that electrolytic condensers are more prone to break down from this cause than any other component in the receiver. In any case, these condensers act as a buffer and prevent the voltage from being unduly high.

As far as the tubes are concerned, a number of manufacturers publish maximum electrode voltages under cold conditions. It is also common practice for tube manufacturers to check heating time of cathodes.

A further point is that the internal impedance of a tube is high under these conditions, and this, combined with associated circuit components, tends to limit the cathode current of the tube.

Mr. Parry doubtless appreciates the fundamental difference between the orthicon system and the cathode ray tube.

In the orthicon it is the function of the beam to discharge the individual cells of the mosaic, and therefore the velocity of the electrons in the beam should not be higher than is necessary to perform this function.

With the cathode ray tube the emission of light from the phosphor is dependent upon the velocity with which the electrons strike the material of which the screen is composed. This electron velocity is far greater than that required in the case of the orthicon, and it is not possible to control the beam in the same way as in the orthicon.

Concerning the generation of noise from the glass bulb (Mr. Porter) it appears there may be some confusion with noise generated by static charge on the glass walls. This is usually dealt with by carbonising the bulb. Metallising is also of some assistance in the case of R.F. tubes.

With regard to the accuracy of the output meter, it must be pointed out that this factor depends upon the initial calibration, human error amongst other things. No actual figures are available, but something of the order of 10 per cent. should be obtained.

Mr. West should note that if the heater is screened then the cathode cannot be heated efficiently.

The noise voltage is dependent, among other things, upon the sum of the mean squares of the random variations of the plate current. In other words the current flowing in the valve must be considered as consisting of a number of discrete particles all flowing in one direction.

If viewed as a bulk quantity a mean steady value is obtained, but the quantity varies either side of this mean level at a much greater rate than a D.C. meter could indicate, and in any case the magnitude of the variations relative to the mean level is so small that such a meter would not be sufficiently sensitive to indicate these variations.

In reply to Mr. Stokes, there is a system of coding valves on the Continent which, in my opinion, is more logical than the system used in this country. They choose the first letter to represent the filament voltage rating and the next letter determines the type of valve. The figure represents the number in the series. Obviously EF9 was the ninth of a series of RF pentodes.

Mr. Alston raises an involved problem. It is important to have the largest possible diameter piping leading to the pumps, and to know the capacity of the pumps and their ability to remove gas of a given volume in a given time. The mercury vapour pump will, if given a large enough orifice, remove gas at an enormous rate, but only if it has a pre-vacuum. In a small bulb the viscosity of the gas reduces the final degree of vacuum owing to the fact that with a large bulb there are less molecules of gas per unit volume.

NORTH EASTERN SECTION DISCUSSION

Mr. H. Clayton : Can any information be given as to the speed of orientation of colloidal graphite under the influence of an electric field in the skiatron ?

Mr. J. Hare : In the electron multiplier ; starting from the cathode one sends off, say, one electron to No. 1 anode and obtain several secondary electrons from the No. 2 anode, which is at a higher potential than the first anode, and so the multiplying proceeds. Why do they not return to the first anode ? In the R.C.A. 931 multiplier tube it appears, from one of the diagrams showing the paths of the electrons, that they miss the corner of the second anode. It is at a higher potential than the first and thus the field in the vicinity of the second anode is more intense than the first. One would expect the electrons to proceed to it. Referring to the question by the previous speaker, on colloidal graphite, I would suggest that the mass of the graphite particle would result in it taking an appreciable time to move on its axis under the influence of an electrostatic field.

Mr. A. Wolfenden : How is the photo-cell apparatus calibrated to measure power output ? With regard to noise in electron amplifiers, how does it compare with an ordinary valve ? Finally, would Mr. Lane indicate how oscillations are produced in the klystron ?

Mr. J. Finlay : With regard to the economic aspect of high frequency tubes, I am interested in the constructional differences between the acorn and glass disc seal types, particularly from the point of view of glass technique. I should like to know what practical advantage the straight through lead has to offer in valve manufacture. Perhaps Mr. Lane can also say whether he considers the adoption of plastics will assist in making special types of valves.

Mr. G. A. Hay : Am I right in assuming that in the klystron there is no such thing as grid input loss due to cathode leakage ?

REPLY TO NORTH EASTERN SECTION DISCUSSION

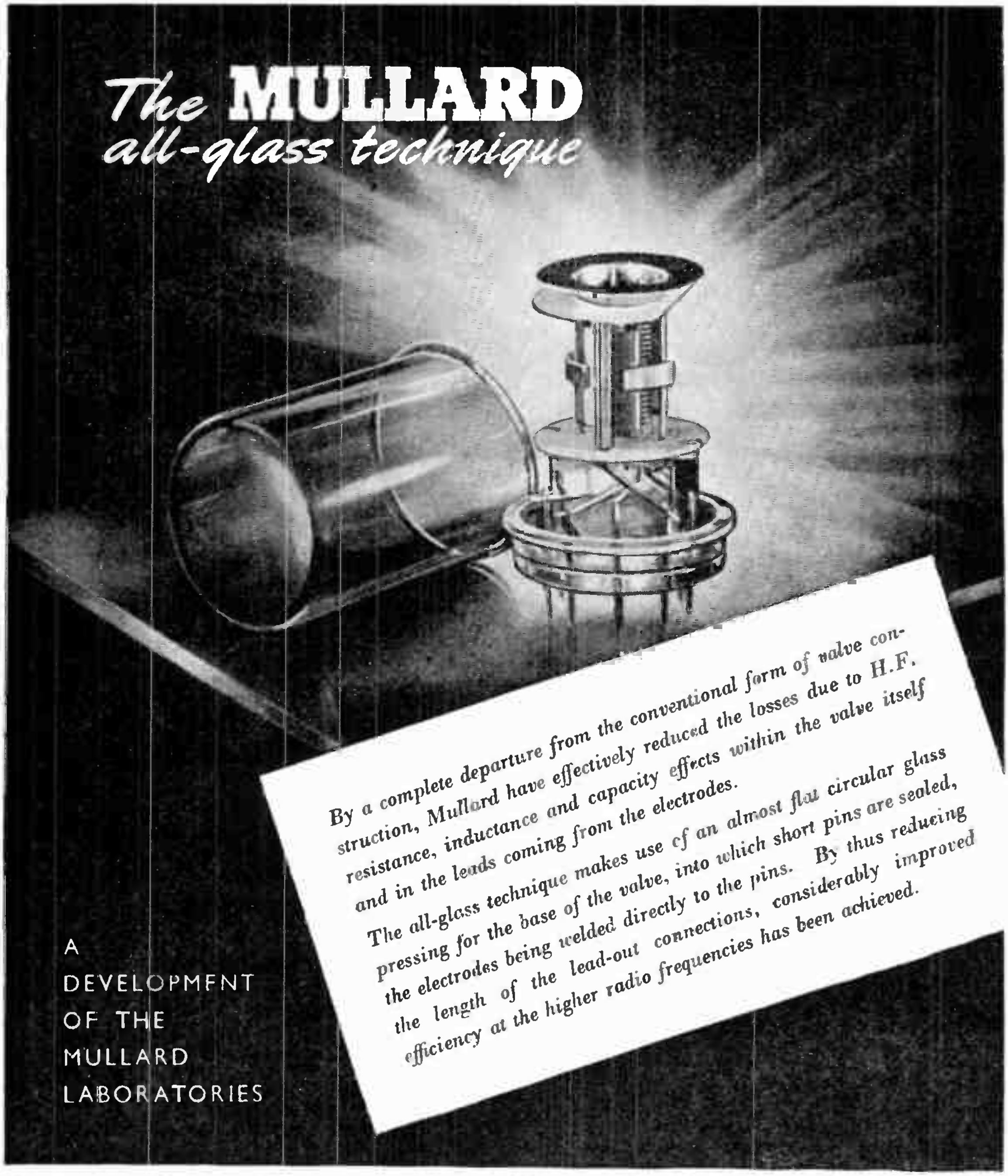
Mr. Lane : Mr. Clayton raises an interesting point concerning the skiatron. The orientation appears to depend to some extent on the viscosity of the oil and the rate of discharge of the image on the surface of the mica. One thing I am not satisfied about is whether colloidal graphite settles to the bottom of the container during the life of the tube. Nothing has been published about that aspect. The device is something quite new and it offers great possibilities, although at present it is still in the laboratory stage.

In reply to Mr. Hare, electrons have a certain kinetic energy, and the path taken is a question of field intensity. The problem was originally worked out in an electric curve trough, and as a result of the research it was found possible to design the tube to avoid the effect he mentions. With reference to his last remark, I have seen a photograph of a picture taken with this device which was not by any means perfect. However, the basic idea is good as the graphite particles can be made extremely small.

With reference to Mr. Wolfenden's remarks, a special lamp was manufactured for measurements at high frequency. It proved to be reasonably accurate, and was at that time more accurate than any other method available. An ordinary lamp can be used for measuring power outputs up to quite high frequencies before one has to use the special lamp. The question regarding noise in electron amplifiers is rather important. It is not very good unless one takes special precautions, the main requirements being very high input impedance and insulation. His last question is rather difficult to answer in the space at my disposal. I tried to give an idea of velocity modulation starting in the beam. There is the tendency for electrons to collect in individual bunches in the beam, and it is necessary to keep these bunches of electrons completely separated from each other and to give each particular bunch a high charge density. The section of the paper dealing with the mechanism of oscillation has been added to the printed paper.

Replying to Mr. Finlay, the A.E. 50 is a straight glass tube with a pinch at the bottom which is not quite the same as valves with glass disc seals. If one makes a glass seal 2 in. in diameter, one needs a certain amount of glass, in the form of molten glass or of powder ; the variation in quantity may be plus or minus 1 or 2 per cent. for satisfactory operation of the machine with suitable quality glass. If one takes a small glass seal requiring only one-twentieth of the quantity of glass in it, the supply of glass cannot be made more accurate. That is one of the biggest troubles when making tiny glass articles in a machine ; one cannot accurately control the machine, and hence the manufacture of miniature valves is uneconomic on account of this glass difficulty. Plastics have little application at the moment because of the high temperatures required in processing valves.

Mr. Hay is correct in stating that grid input loss is avoided by the klystron principle.



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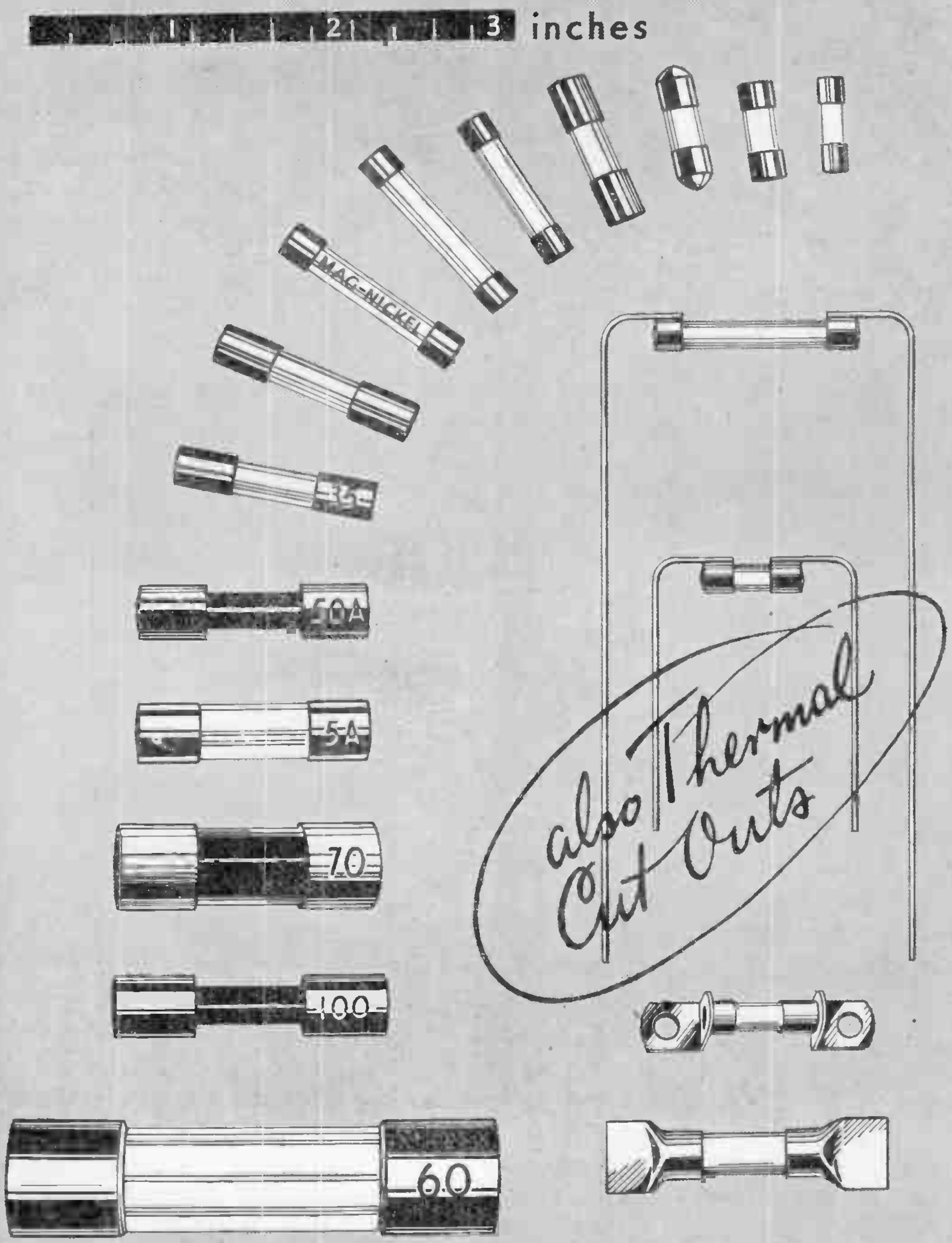
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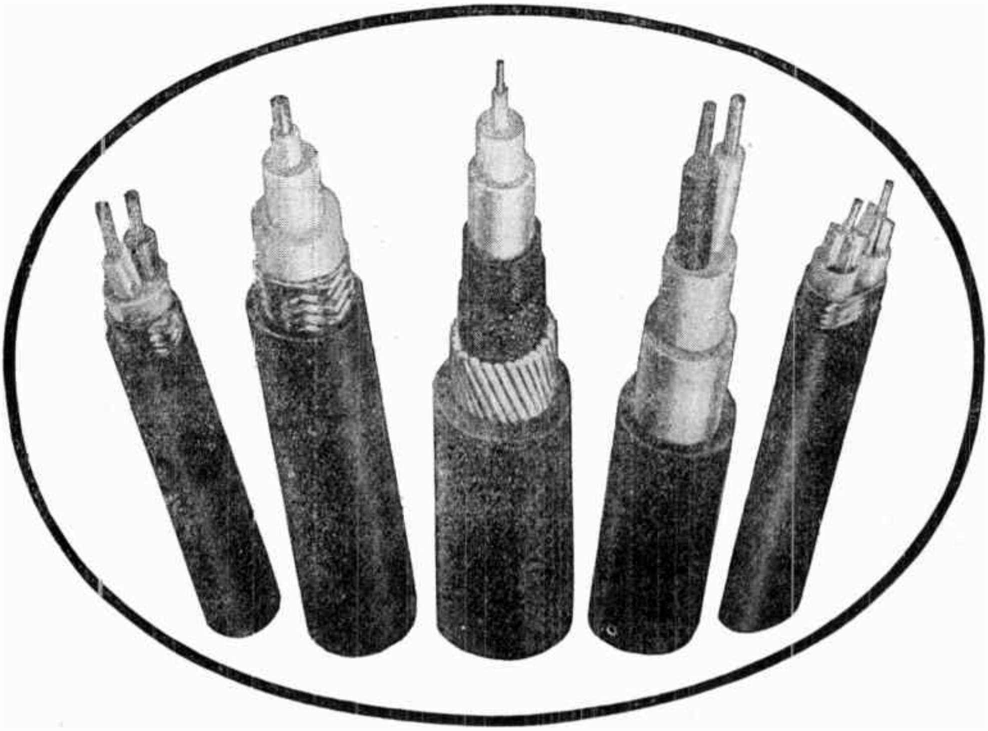


THE INSTITUTION'S ANNUAL APPEAL

Everyone grows weary of appeals ; particularly in these days, it becomes impossible to respond generously to each request. The Brit.I.R.E. has not added to the wartime burden of its membership by making frequent requests for support of the Funds ; instead, these Funds have relied almost entirely on the odd shillings or guineas which accompany a member's annual subscription.

Subscriptions are now due, and it is again hoped that as many members as are able will renew their support of the Building and Benevolent Funds, although, this year, we add an urgent request for support of the Prisoner-of-War Fund.

Brit.I.R.E. BENEVOLENT FUND

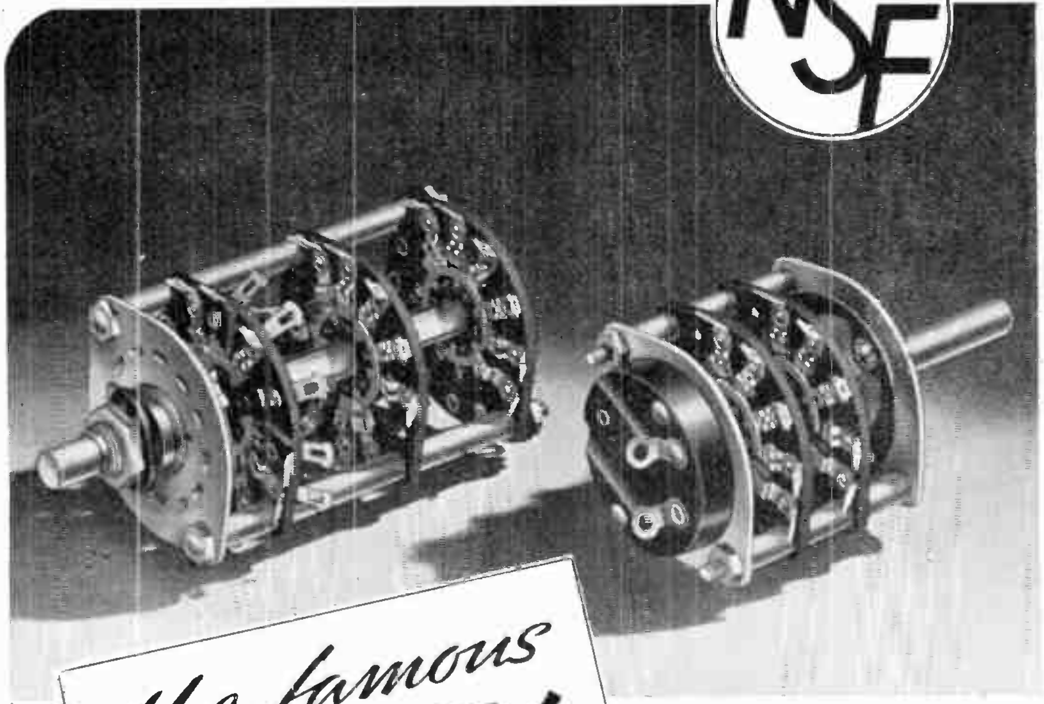
It is very probable that in the immediate future there will be a demand upon the Benevolent Fund ; the object of the Fund is to help those members of the Institution and their dependants who have suffered loss of employment through ill-health or who are otherwise passing through times of stress.

Donations may be spread over a number of years if subscribers will complete a deed of covenant for seven years, or for life (whichever is the shorter period), and thereby enable the Trustees of the Fund to recover income tax on subscriptions. Forms for this purpose will be gladly sent on request.

Brit.I.R.E. BUILDING FUND

The Institution's own post-war planning scheme envisages a building belonging to the Institution and capable of meeting the needs of members by offering all the facilities traditionally associated with a professional Institution.

Although obviously not so imperative in its need as the other two Funds, the support given to the Building Fund is of great future importance to the Institution which, in these days of high taxation and increased death duties, must inevitably rely upon the annual support of its members if a fitting building is ultimately to be acquired.



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