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THE PRESIDENTIAL ADDRESS

of

Rear-Admiral (L) Sir Philip Clarke, K.B.E., C.B., D.S.O.

Delivered at the 29th Annual General Meeting of the Institution held in London on October 27th, 1954.

During the thirty years of the Institution's life only one other serving officer has been elected to the office of President. I therefore feel it a signal honour to the Service which I represent, as well as to myself, that I should be entrusted with your confidence.

By my election you have demonstrated the policy of the Institution in promoting the association of professional engineers, whether they be in the Services, in industry, or in Government service. Indeed, it was this outlook that originally prompted my close interest in the affairs of the Institution.

During the last two years especially, I have learned that the Presidency of the Institution is no empty office, as evidenced by the activity of my predecessor, Mr. W. E. Miller. We all very much appreciate the work that he has done for us, and I am heartened in the task which I undertake by the knowledge that he continues to be a member of the Institution's Council and will, he has assured me, help in anything I undertake in your interests.

There must be specialists in every branch of science. I suggest that specialization is relative and can be as wide as the ocean—for example, you might call a sailor a specialist in maritime matters—or as narrow as the eye of a needle—the peculiar speciality of the biblical camel! In our Institution we cater for specialists in many applications of radio and electronics, but in industry and the Services all interests and talents must be co-ordinated with foresight, understanding and tolerance. Therein lie the tasks of command and administration, government and management.

Papers read at the recent meeting of the British Association emphasized the part which engineers should take in management. The specialist is not always suited to direct affairs; he may have no ambition to do so or he may feel that he can make his most worth-while contribution in his particular specialization. Management, on the other hand, calls for men who can visualize the overall importance of projects and assess how best to use the services of specialists. To quote from a paper to the American I.E.E.*: "The important point is that trying to question whether the work of an individual engineer or the work of his manager is 'more important' is like trying to answer the question whether one's heart or lungs are more important in the functioning and life of one's body."

In the Royal Navy we have been extremely well served by men who have not necessarily been specialists, but who have had the ability to appreciate scientific developments and the tenacity and often courage to ensure that full opportunity is given to new ideas. In the field of communication and radio development, Admiral of the Fleet Henry B. Jackson was an outstanding naval officer whose scientific work

* H. F. Smiddy, "New horizons for engineers," *Electrical Engineering*, 73, July, 1954, p. 590.

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was recognized by his Fellowship of the Royal Society in 1901—when he was serving as a Captain in the Royal Navy.

One particular reason why I am glad to have this opportunity of addressing you is to add a viewpoint to that most excellent illustration which Mr. Bedford gave during the course of his Presidential Address.* You may recall that after showing how Maxwell's work was developed first by Heinrich Hertz, Mr. Bedford asked "what, in fact, were the principal Marconi contributions?" We all accept the part Marconi played in what Mr. Bedford termed "the romantic phase of radio development" but the pioneer who introduced radio into the Royal Navy was undoubtedly Henry Bradwardine Jackson.

He had made a careful study of the experiments carried out by Hertz in 1886, and in 1890 (when he was 35 years of age) he suggested that an I.F.F. system could be used between capital ships and approaching torpedo-boats, but he was not then in a position to experiment. By the time he took over command of H.M.S. *Defiance*, the Torpedo School at Devonport, in 1895, the work of Bose† on coherer receivers was known and Jackson began systematic experiments, transmitting from one end of the ship to the other using improvised equipment made up on board.

In September, 1896 Jackson, who by that time had been promoted to Captain, and had developed a satisfactory system of signalling, met Marconi at a conference at the War Office. He attended trials of Marconi's apparatus and found that the principles of the equipment were similar to those employed in H.M.S. *Defiance*. As might be expected, however, the gear produced as a result of Marconi's full-time work was more fully developed and engineered than that from Jackson's own part-time effort.

(By courtesy of the Journal of the Royal Naval Scientific Service)

Henry B. Jackson, 1855-1929.
A photograph taken in 1897, when he was a Captain.

In 1897 two sets of more powerful apparatus were built in H.M.S. *Defiance* and ship-to-ship experiments carried out. The transmitter of these sets can be considered to be the first official naval wireless transmitter. These early experiments in what was then described as "signalling without wires", are carefully recorded in the contemporary Annual Reports of Torpedo Schools. Many scale drawings are still available and a replica has been made and operated.

Jackson's transmitter, consisting of a Hertz oscillator, in a hermetically sealed teak case mounted on a rain-tight teak box, contained a standard induction coil giving a 6-in spark in dry air. The apparatus was worked from the ship's mains (80 V) through a suitable resistance or from a 12-V battery, a signalling key being inserted in the primary circuit. The oscillator consisted of four 3-in solid brass balls mounted vertically, the inner balls being $\frac{3}{8}$ in apart and the outer ones $\frac{1}{4}$ in from these. The secondary terminals of the induction coil were connected to the two outer spheres, the bottom one being also connected to earth via the hull of the ship, and the top one to the aerial wire

* *J.Brit.I.R.E.* 9, January, 1949. p. 2.
†See, for instance, *J.Brit.I.R.E.*, 13, March, 1953, p.130.

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triced to the masthead. An insulated aerial was part of the equipment. The overall height of the apparatus was 2 ft 9 in.

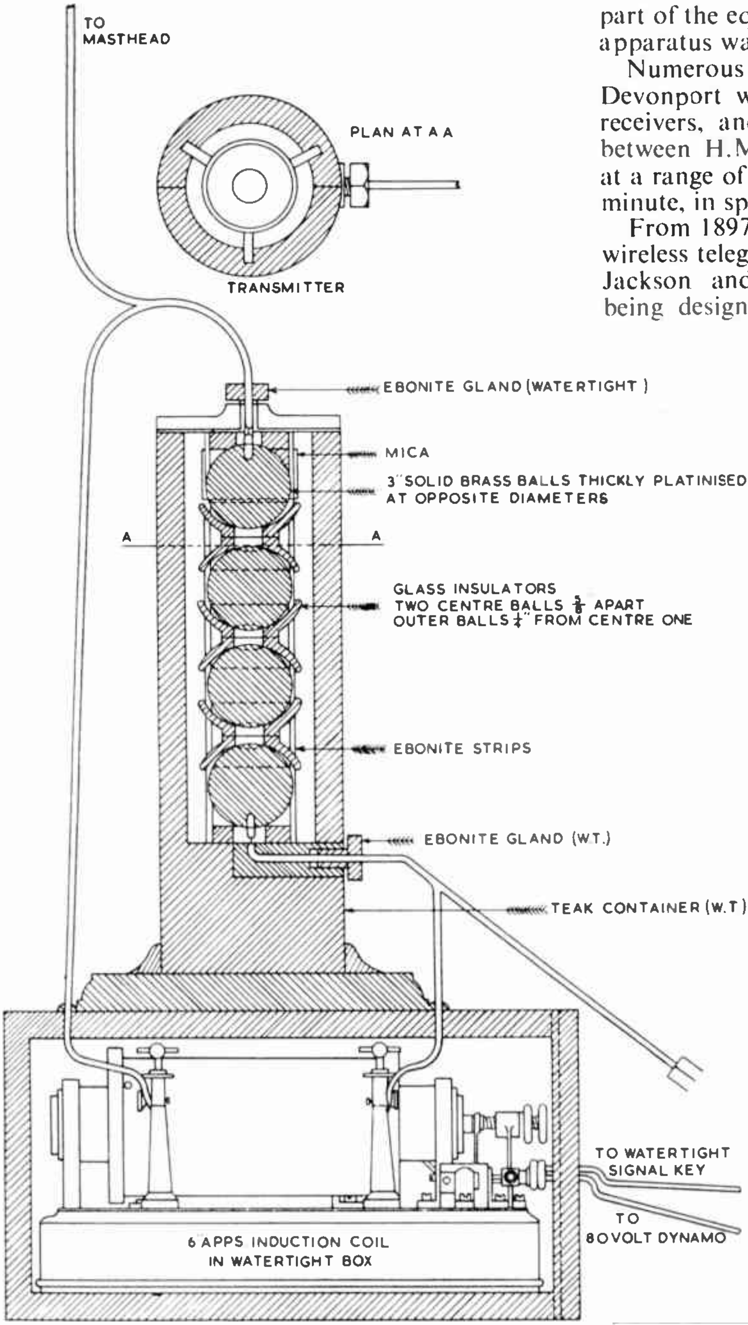
Numerous experiments were carried out at Devonport with the apparatus, using coherer receivers, and reliable signals were exchanged between H.M.S. *Defiance* and H.M.S. *Scourge* at a range of 5,800 yd at a speed of 8 words per minute, in spite of intervening hills and ships.

From 1897 to 1900 the development of naval wireless telegraphy was a joint effort by Captain Jackson and Marconi, the naval apparatus being designed and built in H.M.S. *Defiance*. By 1900, 50 ships and shore stations were fitted with naval or Marconi apparatus. After that, development was rapid.

In 1901, Captain Jackson was elected a Fellow of the Royal Society. His paper to the Society in 1902 is one of the outstanding early scientific papers on Wireless Telegraphy.*

I will not enlarge upon his appointments and work in the twelve years before the first war. He was appointed First Sea Lord in 1915 and it was largely due to his work that the chain of W/T and D/F stations was set up that led to the detection of the movements of the German High Seas Fleet and enabled the Grand Fleet to be sailed and bring them to action at Jutland in 1916.

An amusing legend has grown out of the fact that Jackson and Marconi were working independently on the same problem. It is reported that Jackson met Marconi in Italy; as a result, each realized the other was a competitor in the field and there began a race for the patent office. Jackson, returning to England in his ship, is alleged to have been injured in a deck hockey game and fetched up in Haslar instead of at the patent



SCALE 3"— 1'

(*By courtesy of the Naval Electrical Journal*)

Plan of the transmitter used for wireless telegraphy tests between H.M.S. Scourge *and H.M.S.* Defiance.

* "On some phenomena affecting the transmission of electric waves over the surface of sea and earth." *Proceedings of the Royal Society*, 70, pp. 254-272, July 8th, 1902.

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office and Marconi won. History records that the two actually met at the War Office in London and it seems likely that "the Italian gentleman," as he is referred to in con-contemporary reports, had well safeguarded his patents before approaching officialdom. Nevertheless, it is probable that had Jackson been in a position to carry out full-scale experiments in 1890 when he made his first suggestion for the use of Hertzian waves, it might well have been his name that became a household word in the realm of "signalling without wires."

In the Royal Navy we are naturally very proud of Admiral Sir Henry Jackson's pioneer work in the development of radio engineering. He became an Admiral of the Fleet in 1919 and was subsequently the first chairman of the Radio Research Board. In 1926 he was awarded the Hughes Medal by the Royal Society and died only three years later, in 1929.

Thus, my historical note emphasizes the interdependence of engineers and scientists, no matter whether they serve in the armed forces, in industry or in government departments. The Services are very much alive to the importance of radio and electronics, for to-day the success of detecting, finding, fixing and destroying an enemy largely depends on the performance and, above all, the reliability of such equipment.

Many problems of research and development, design and production, manpower and training are common to both the Services and industry. As far as security permits only good can result from a pooling of our ideas and experiences.

The work of pioneers such as Jackson should remind us that in a few years' time many of our present techniques may appear elementary. Electronics is still a young science and many important discoveries, both large and small, remain to be made. Some of these will no doubt be fostered by members of our Institution. Let us always be alert to the possibility of new discoveries and new techniques.

The resolution of new ideas into practical benefits is, of course, largely dependent upon a virile industry. In this respect we in Great Britain are fortunate for our industry is, on the whole, well organized through trade associations. These can speak on industrial policy for groups of manufacturers with common interests. Whilst, however, industry is now spending more on research and development, it must be remembered that the majority of firms are small. Many of them cannot afford to finance long-term development projects unless they have regular progress payments. Even to employ a small group of five or six research or development engineers with support and facilities costs at least £20,000 per annum. This is 4 per cent. of the turnover of a company working at a level of £½ million per annum.

For this reason, industry is increasingly encouraging the universities to devote more effort to fundamental research. Industrial grants, bursaries and fellowships are helping to finance what may prove to be very extensive research programmes.

Stemming from the scientific work of our universities we have the assistance of the Department of Scientific and Industrial Research and the Services research and development organizations. We also have the help, if necessary, of the National Research Development Corporation, and finally, the production techniques of industry.

I have not overlooked the industrial research associations, whose valuable work was referred to in detail by the late Mr. Leslie McMichael.* Their work is largely complementary to that undertaken by manufacturers themselves, and finance is provided by a particular industry supplemented in some cases by Government subsidy.

Thus, there are many sources from which new ideas in research and development may flow. We may perhaps ask ourselves whether we are making the best possible use of new discoveries. Broadly speaking it is the object of D.S.I.R. and research associations to assist in helping industry to turn new discoveries into practical use, and it is in that field that such Institutions as ours serve their principal purpose. The Institution's main object—that of stimulating the use of scientific knowledge—involves two main steps: firstly, the acquisition of scientific knowledge, and secondly, its application for the benefit of mankind.

It is of little use acquiring information if it is not disseminated among those who can make the best use of it. Our service to industry includes the publication of information and the holding of meetings and discussions so that our members may be kept up to date and en-

*J. Brit. I.R.E., 5, January, 1945, p. 2.

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couraged to use new information in their daily work. The application of new ideas often requires development of new processes and the use of new materials, as, for example, in the considerable work now being done in industry in the production of semi-conductors, transistors and printed circuits.

The speed at which this work can be done is wholly dependent on the availability and proper use of man-power. The Services share this problem with industry, and satisfactory recruitment depends on obtaining men who will find abiding satisfaction and pride in their vocation. Employment divorced from real interest becomes drudgery and only if there is enthusiasm will the utmost benefit be derived by both employer and employee.

Although never before has there been such wide public interest in science and technology we nevertheless have the paradox of a technical man-power shortage. Many reasons may be advanced for this shortage, but we might well ponder whether we do enough to attract the right sort of recruit to our professional ranks.

A very worth-while job was done by our own Radio Industry Council in publishing their booklet, in conjunction with the Ministry of Labour, on "Careers in the Radio Industry". This helps, and will I hope continue to help, recruitment to our profession. I believe that a similar valuable publication is being prepared by industry and the Ministry on the opportunities of employment and future prospects for the radio technician and mechanic.

Having obtained the interest of the younger man, the next, and probably most important, step is to give these recruits an adequate training in radio and electronic theory and engineering so that they may undertake their work with competence and with a proper understanding of what is involved.

In these matters we urgently require the full co-operation of our technical colleges. It is an understandable desire that young men wish to enter a profession where they can be assured of lifelong employment and reasonable prospects. To-day, with an ever broadening field in the application of electronics to communications, transport, industry, medicine, nucleonics, to name a few fields, as well as its increased application to the problems of defence and attack, it can safely be said that there is a certainty of the need for many more radio engineers and radio technicians.

Shortage of man-power and the need for reduced costs demand that we must make the maximum use of our engineers. There is no simple answer but much can be done by carefully matching the man to the job and not wasting qualified and experienced men on work which does not justify their skill and experience. With the co-operation of industry our Institution has done much in aiding this difficult problem of establishing a recognized system of training for the radio technician and mechanic—who is the engineer's most valuable aide. The Radio Trades Examination Board has also been of tremendous help by recognizing the eligibility of men who have been trained in the radio branches of the Navy, Army and Air Force and opening up the prospect of civilian employment when such men leave the Services. This marrying of Service and Industry's man-power requirements is of the utmost importance before and after mobilization. Whilst on the one hand the Services now offer attractive conditions for permanent employment, and we sorely need their long service, we have to consider the outlook of the man who is only a member of the armed forces either for the period of his National Service, or for a short-term engagement. Very naturally, those men want to feel that their time in the Services will be recognized as of value when they return to civilian life. I cannot emphasize too much the wide appreciation of the Services for the policy which our Institution has always pursued to try to reconcile the interests of the men in the Services with those who are engaged in industry.

Few will disagree that the development of electronics is still comparatively in its infancy. Navigational aids at sea and in the air, under-water and battlefield television, electronic armament technique, and the wider applications of industrial television are only a few of the branches being developed. Most of us have more than an academic interest in the fascinating story of the development of all kinds of electronic computers which we learned about at Oxford this summer.

Indeed, the users of electronic equipment are continually asking for it to do more and more complicated things, which in turn leads to the need for more and more complex equipment.

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In spite, therefore, of the greatly improved quality of components, and there is still much scope here, the strain on equipment is such that the standard of knowledge and skill required by the maintainers is tending to rise. But, and this is important, our quantity and quality of raw human material for maintenance are not improving at the same rate as the quantity and complexity of scientific equipment. Also the more components, the greater the likelihood of predictable and unpredictable failure. The requirements of weight and space, especially in Service equipment, most often rule out duplication. The less skill required for preventive maintenance, testing and checking performance, the better! Also the longer time that equipment can run without attention and with expectation of even 75 per cent. of optimum performance—the better. Thus, as we all know, there is a continual need for new and particularly simplified techniques.

Most advances in radio are the result of painstaking and possibly slow and laborious work in laboratories, and I do not wish to belittle the results of this important and sometimes unrewarding work. I must, however, stress the importance of encouraging all those concerned with design to be constantly on the look-out for those "neat solutions" and "brilliant simplifications" which can do so much to improve our equipment. These, together with the bold use of new techniques, can help to reduce the menace of over-complexity with all its attendant disadvantages.

Having put the case for progress, I must balance the argument by referring to the less romantic subject of standardization. Provided progress is not impeded, any measure of standardization greatly eases the user's maintenance and service burden. Standardization is always a very thorny problem but it must not be shelved on that account. With "standardization" I include "preferred components" as far as the Services are concerned—for we have to provide spares on the wide boundaries of the seven seas. As an Institution we are very glad to be represented directly on many working committees of the British Standards Institution who do such an excellent job for industry as a whole. Our own Technical Committee is always anxious to promote discussion meetings in order to secure wide ventilation of views on standardization. I think that more meetings of this character would be of great help to the B.S.I. before they set up final committees for drafting standards. In the Services, too, we are anxious to have as small a range of testing sets as possible, for we have to train each man to test and maintain a variety of equipments. Therefore, anything which can be tested with a "Common Testing Set", or a built-in testing set, is a great advantage and economy of training effort.

So far I have been making *requests* to the Radio Industry. What have the Services to offer Industry in return? First, quite a lot of money, but with some strings tied to it. Next, the opportunity of designing *up to standard* instead of *down to a price*. This is something which I think Industry should, and in fact does, value, though it brings with it plenty of headaches. Lastly, a critical but I hope a knowledgeable, and certainly an enthusiastic customer.

The new techniques becoming available and the steady advance in our knowledge provide designers with many opportunities, but it often raises the problem of "What *does* in fact, represent an improvement?" What appears to be an obvious advantage in the laboratory may turn out on balance to be a disadvantage in practice when the installation, maintenance, logistic, and financial aspects have been evaluated. The designer clearly cannot be an expert on all these matters. There are two morals to be drawn from this: one—the vital importance of close co-operation between the designer and the Service officers who *do* know what is involved in the broader Service aspects of the problem and the other—the value to all designers of getting to know as much as possible of how the equipment they design will be used, how it will be maintained, what spares can be carried—in fact, all those problems which make the difference between success and failure in use.

It might be argued that a designer's life is hard enough already without adding extra responsibilities, but I am sure that a clear picture of how the equipment that he designs will be used will make his work easier—and certainly more interesting. Speaking for the Navy, I recommend to engineers a period at sea in, say, an aircraft carrier, destroyer, or cruiser, as a most valuable experience, and many of you know that it has for long been the Navy's policy to foster such visits from engineers and

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scientists serving firms engaged in Admiralty contracts.

Similarly, co-operation between the Services and the radio industry is much helped by serving officers keeping in touch with the problems of the radio industry.

Two apparently simple technical matters will serve to illustrate my point. Firstly, there has been a great deal of discussion recently on the advantages and disadvantages of using valves with flying leads soldered direct to soldering tags, instead of the ordinary pin-based valves which are pushed into sockets. This would seem to be a fairly simple and clear-cut problem. Yet in practice it is hardly possible to take an intelligent part in the argument unless one has an almost encyclopaedic knowledge, embracing at one end the microstructure of glass, the mathematics of stress distribution and the factory techniques of glass moulding, and at the other end, the standard of skill possessed by a junior radio rating in the Navy and the amount of space available in an aircraft carrier's radio store-room!

The second example—heat dissipation in radio equipment designed for fitting in high-flying jet aircraft. Here the radio designer finds himself concerned with problems involving the meteorological conditions in the stratosphere, and with the equally unpleasant conditions found within a few inches of the blast pipe of a jet engine—while at the same time he must still not lose sight of the peculiarities of the rating who will service his equipment, and the conditions under which this work will be carried out on an airfield or in an aircraft carrier.

Certainly, the radio designer can no longer be accused of being a narrow-minded specialist. What I have said about the designer applies in many respects to everyone else concerned with the production of radio and other electronic equipment, not excluding those responsible for finally packing the equipment for transport!

In addition to the invaluable work of the British Standards Institution, to which I have already referred, there are many other committees set up by industry and government departments which help to maintain liaison on detailed technical matters. In the field of component and valve development liaison is close and good. At the Admiralty we have recently felt that there was scope for greater liaison on the general question of designing *complete equipment* for ease of maintenance. A small working party was set up in the Admiralty at the end of last year to investigate problems of electronic reliability and maintainability. Meetings have already been held on this subject with the Ministry of Supply and one of the industry associations, and I am confident that we shall derive much benefit from these deliberations. We are also to have a discussion at one of our Institution meetings in London.

A particular example of the way in which industry has benefited from Services co-operation was, of course, in the development of radar. From the use of radar on comparatively long wavelengths to the subsequent using of shorter wavelengths required knowledge gained from operational technique. At the end of the war the Admiralty made arrangements for the Admiralty Signals and Radar Establishment, then at Haslemere, to give technical advice to manufacturers to assist them in the design and manufacture, for merchant shipping, of equipment which has now been sold all over the world.

In order to gain experience in the use of equipment, the Admiralty also made available to merchant shipping Admiralty-type radar sets which had only been brought into production just before the end of the war. The A.S.R.E. has, in fact, frequently prepared prototype equipment which has subsequently been passed over to industry for full-scale manufacture. I know that, whilst I specifically refer to Admiralty co-operation, very much the same conditions apply to the research establishments of the Ministry of Supply.

There was close liaison between the Royal Naval Scientific Service and industry in the development of under-water television, combining under-water cine-photography with the research on modern television chains. Successful use of this equipment in locating the Comet aircraft lost off the coast of Italy is fresh in everybody's mind because it was news in a big way. This technique and experience should prove to be of immense advantage commercially, and to the Service, in locating and in identifying or examining and salvaging under-water objects, especially where deep water is concerned.

Similarly, the Service development of the asdic has led the way to other applications of radio acoustic work.

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I have tried to prove that the relations between the Services and the Radio Industry are already close but they must, by the very nature of the problems involved, become closer still. I am sure that the Electrical Branch of the Navy, of which I have the honour to be the Head, will play an increasingly important part in projects from inception to production, or should I say from conception to birth and maturity? The problems we must all face together are very real ones; there are no quick answers and all the solutions cannot yet be seen. I believe, however, that if radio engineers and radio physicists work together and see each other's point of view, we shall be able to exploit to the advantage of our country the great potential of our Radio Industry.

Earlier on I referred to some of the recent proceedings of the British Association on the subject of management. The executive or senior engineer or physicist requires bright ideas and suggestions from his juniors. Most of the bright ideas are born in minds which have not reached the time "when age has its compensations". Management needs to guide and coax along the junior men; delegation of responsibility encourages initiative and enthusiasm. Nice judgment and understanding are needed in applying the curb to a willing and well-trained horse!

Our standard of life and our security—indeed our daily bread—depend on our efficiency and economy in engineering production. We must export manufactured goods in order to live and we must export more to earn the money for our defence or to bargain from strength with the foreigner. Our initiative and skill in the application of science to industry and weapons can keep us a great nation and Commonwealth. Of little use our courage, our character and our good will to keep the peace of the world unless at the same time we employ our native talents to the best advantage in this time of great opportunity.

In our Institution we realize our responsibilities. Whilst we make our individual and collective contributions we may well join in the Naval Prayer said daily on board Her Majesty's Ships: "Preserve us from the dangers of the sea and from the violence of the enemy that we may be a safeguard unto our Most Gracious Sovereign Lady, Queen Elizabeth and her Dominions, that the inhabitants of our Empire may in peace and quietness serve our God and enjoy the blessings of the land with the fruits of our labours."

THE THEORY AND DESIGN OF GAS-DISCHARGE MICRO-WAVE ATTENUATORS*

by

E. M. Bradley, B.Sc.† and D. H. Pringle, Ph.D.‡

SUMMARY

The theory of the interaction between a d.c. gas discharge and an r.f. field is considered and expressions developed for the complex conductivity of the discharge. The simple Lorentz theory is shown to give values of complex conductivity not very different from those derived with more detailed analyses. Problems connected with the gas discharge including that of noise production are considered. Practical microwave attenuators developed by the authors are described in detail. Two main classes of device are considered: (a) devices with resonant structures, and (b) distributed devices.

1. Introduction

It is the purpose of this paper to give an account of the recent development of gas-discharge devices designed to provide electronically controlled attenuation of microwave radiation in waveguide structures. This development was stimulated initially by Service requirements for a means of providing automatic gain control in the 3-cm waveband, but there are other fields of application, notably crystal protection in radar receivers and modulation of microwave signals, which have recently been receiving increased attention.

The main problem in the design of such a device is to confine a gas discharge in a lossless structure, so as to obtain efficient interaction between the microwave radiation and the discharge. The gas discharge presents both reactive and resistive impedance components, the ratio of these components depending on the collision frequency of the electrons and gas molecules and on the frequency of the microwave field. The simple Lorentz theory of interaction is shown to be valid as a first approximation even though it ignores the distribution in energy and in free path of the electrons. This theory is later applied to idealized attenuator structures so that inherent design limitations may be appreciated.

Practical attenuators of two main classes have been constructed, in which gas discharges are confined (1) within a transmission cavity, and (2) within a distributed structure. The last section of this paper is devoted to devices in the development of which the authors have been concerned, and the merits and limitations of these devices are discussed.

It may be noted that the scope of this paper is restricted to gas-discharge devices which are operated without the presence of static magnetic fields. Attenuators of the latter type, which have recently been developed by Goldstein and others,[1] are divided into two classes. In the first, electron interaction is obtained by a gyromagnetic resonance phenomenon and in the second case by Faraday rotation of the plane of polarization.

2. Wave Propagation in an Electron Gas

2.1. *Unbounded Electron Gas*

The equations derived by Lorentz[2] to describe the motion of charged particles, subject to random collisions and oscillating under the action of an alternating field, can be applied to the case of a discharge plasma supporting an electron gas. One needs only to consider the elastic collisions between electrons and gas molecules to a first approximation, as electron-electron collisions are exceedingly improbable; while inelastic collisions, resulting in ionization or excitation of the gas molecules, are much less numerous. In other words, we only consider here the case where the mean electron energy is much less than the excitation potential, a condition which is known to hold in almost every region of the glow discharge.

In the absence of collisions the equation of motion of an electron in the presence of a d.c.

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†Ferranti Ltd., Edinburgh, formerly with Elliott Bros. (London) Ltd.

‡Ferranti Ltd., Edinburgh.

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field of intensity V and an a.c. field of intensity $E = E_0 \exp(j\omega t)$ is given by

$$m\ddot{x} = eV + eE_0 \exp(j\omega t)$$

Lorentz assumed that the effect of collisions is to introduce a frictional or damping force proportional to the velocity of the particles, and he was able to derive expressions for the conductivity and dielectric constant of the medium by this means. Let the damping term be represented by "$g\dot{x}$." Then

$$m\ddot{x} + g\dot{x} = eV + eE_0 \exp(j\omega t)$$

Solving for $\dot{x}$ we obtain

$$\dot{x} = \frac{eV}{g} + \frac{eE_0}{g^2 + m^2\omega^2}(g - jm\omega)\exp(j\omega t) + C \exp\left(-\frac{gt}{m}\right)$$

where C is a constant.

For free electrons it may be shown that $g = m\nu$ where ν is the electron collision frequency.

So the equation may now be written

$$\dot{x} = \frac{eV}{m\nu} + \frac{eE_0}{m(\nu^2 + \omega^2)}(\nu - j\omega)\exp(j\omega t) + C\exp(-\nu t) \quad \ldots\ldots\ldots\ldots(1)$$

The first term represents the motion under a d.c. field alone, the second term represents the in phase and out of phase components of the electron's velocity with the a.c. field and the last term is a damping term.

Now assuming an electron concentration of n electrons/unit volume we can write the a.c. conductivity $\sigma = I/E = ne\dot{x}/E$.

$$\text{Thus } \sigma = \frac{ne^2}{m}\left[\frac{\nu}{\nu^2 + \omega^2} - \frac{j\omega}{\nu^2 + \omega^2}\right]$$

$$\text{or} \quad \sigma = \frac{ne^2}{m\omega(1 + \eta^2)}\left\{\eta - j\right\} \quad \ldots\ldots\ldots(2)$$

where $\eta = (\nu/\omega)$, the ratio of the electron collision frequency to the angular field frequency.

This result assumes that all the electrons have the same energy and free path and hence that the collision frequency is constant. This, however, is not the case since the electrons will be distributed in energy and in free path and it is of interest to note two recent modifications to this theory, due to Margenau[3] and Huxley,[4] taking the energy distribution into account. Margenau derives an expression for the complex conductivity allowing for any electron energy distribution; for the particular case of a Maxwellian energy distribution, which generally obtains in the glow discharge, he finds

$$\sigma = \frac{4}{3}\frac{e^2\lambda n}{(2\pi mkT)^{\frac{1}{2}}}\left\{K_2(x_1) - jx_1^{\frac{1}{2}}K_{3/2}(x_1)\right\} \quad \ldots\ldots\ldots\ldots\ldots(3)$$

where λ = electron mean free path

k = Boltzmann's constant

T = electron temperature

$$x_1 = \frac{m(\omega\lambda)^2}{2kT}$$

The functions K_2 and $K_{3/2}$ can be expressed in terms of the exponential integral and the error function.

In equation (3) we may write

$$kT = \frac{\eta^2\pi m\omega^2\lambda^2}{8}$$

which merely expresses the mean velocity $\bar{v}$ in a Maxwellian distribution using $\bar{v} = \omega\eta\lambda$ and we obtain

$$\sigma = \frac{ne^2}{m\omega}\cdot\frac{8}{3\pi}\frac{1}{\eta}\left\{K_2\left(\frac{4}{\pi\eta^2}\right) - j\frac{2}{\pi^{\frac{1}{2}}}\frac{1}{\eta}K_{3/2}\left(\frac{4}{\pi\eta^2}\right)\right\} \quad \ldots\ldots\ldots(4)$$

Huxley derives a formula similar to that of Lorentz in which he has examined the damping term more carefully. He obtains for the a.c. conductivity

$$\sigma = \frac{2}{3}\frac{ne^2}{m\omega}\left[\frac{\eta}{1 + \eta^2}\left\{1 + \frac{1}{1 + \eta^2}\right\} - j\frac{1}{1 + \eta^2}\left\{\frac{1}{2} + \frac{1}{1 + \eta^2}\right\}\right]$$

For purposes of comparison $\sigma_r \Big/ \frac{ne^2}{m\omega}$ and $\sigma_i \Big/ \frac{ne^2}{m\omega}$ versus η are plotted in Fig. 1 and Fig. 2 respectively for each of the three theories, where σ_i and σ_r are the imaginary and real components of the conductivity.

It is seen that there is very little to choose between the three theories and the difference between the values for any given η will probably be less than the error introduced by the assumed value of η. The uncertainty in η stems from the fact that the mean free path is actually a function of electron energy.

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2.2. *Electron Gas confined in Waveguide*

The case of a uniform free electron gas confined in a waveguide may be analysed theoretically to find the order of electron density required to obtain a useful electronic interaction. While this analysis is strictly limited to an ideal case since it is impossible in practice to fill the waveguide with an electron gas of uniform density, the conditions can be approached experimentally.

It may be shown[5] that the propagation constant (γ) in a waveguide filled with a lossy dielectric such as a gas discharge is given by:—

$$\gamma = \alpha + j\beta$$

where

$$2\alpha^2 = \left|\omega\mu_0\sigma_i - \left(\frac{2\pi}{\lambda_g}\right)^2 + j\omega\mu_0\sigma_r\right| + \left\{\omega\mu_0\sigma_i - \left(\frac{2\pi}{\lambda_g}\right)^2\right\} \quad \ldots\ldots\ldots\ldots(5)$$

$$2\beta^2 = \left|\omega\mu_0\sigma_i - \left(\frac{2\pi}{\lambda_g}\right)^2 + j\omega\mu_0\sigma_r\right| - \left\{\omega\mu_0\sigma_i - \left(\frac{2\pi}{\lambda_g}\right)^2\right\} \quad \ldots\ldots\ldots\ldots(6)$$

λ_g = air filled guide wavelength.

The quantity α, expressed in neper/metre, is the attenuation, and β, expressed in radians/metre, is the phase length of the discharged filled waveguide.

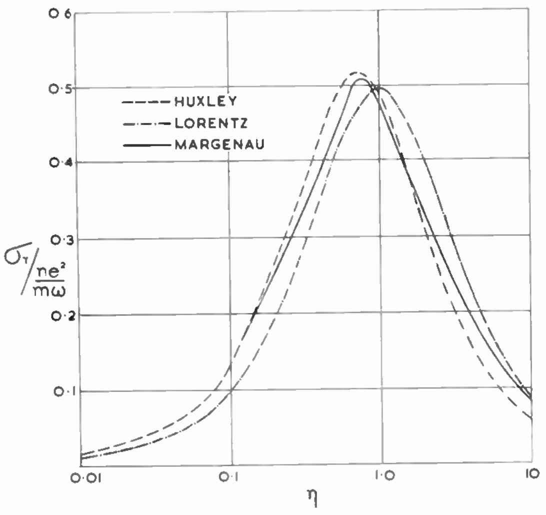

Fig. 1.—Comparison of theories for real conductivity.

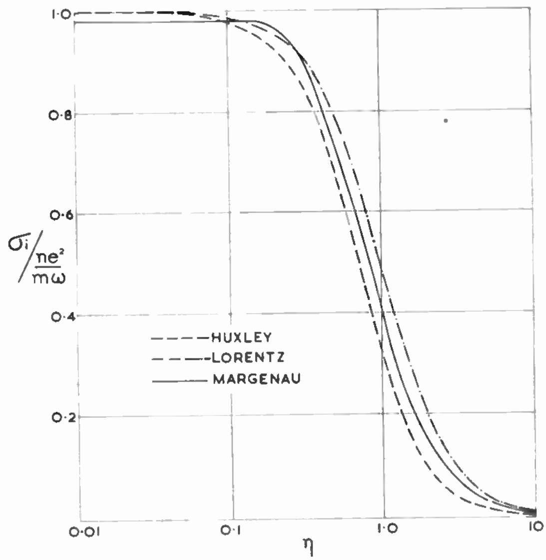

Fig. 2.—Comparison of theories for imaginary conductivity.

It will be seen that both the attenuation and the phase length may be altered by suitably controlling the complex conductivity. This may be achieved by altering the density and collision frequency of the electrons in the discharge.

Consider first the case in which it is required to know the attenuation in a discharge filled guide in which the real part of the complex conductivity is a maximum. On the Lorentz model this occurs when $\eta = 1$,

giving: $\sigma_r = \sigma_i = \dfrac{ne^2}{m\omega}$ from equation (2).

Values of attenuation, expressed in db/cm as a function of electron density, have been computed from equation (5) for a frequency of 9,350 Mc/s corresponding to $\lambda_g = 4{\cdot}45$ cm. These values are plotted in Fig. 3.

In some circuits the attenuation can be changed by altering the phase length of one component of the circuit. This can be achieved electrically by using a gas-discharge filled waveguide. However, for large attenuations to be available from the circuit, it is necessary that the attenuation accompanying the electrically produced change in phase length shall be small. An examination of equations (5) and (6) shows that if the electron collision frequency is made small compared with the applied angular frequency, i.e., $\eta \ll 1$.

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Then

$$\sigma_i = \frac{ne^2}{m\omega} : \sigma_r = 0 \text{ from equation (2)}$$

then if $\dfrac{ne^2\mu_0}{m} < \left(\dfrac{2\pi}{\lambda_g}\right)^2$

$\alpha = 0$ and β is obtained from equation (6)

i.e.,

$$2\beta^2 = \left|\frac{ne^2\mu_0}{m} - \left(\frac{2\pi}{\lambda_g}\right)^2\right| - \left\{\frac{ne^2\mu_0}{m} - \left(\frac{2\pi}{\lambda_g}\right)^2\right\} \quad \ldots\ldots\ldots\ldots(7)$$

If $\dfrac{ne^2\mu_0}{m} > \left(\dfrac{2\pi}{\lambda_g}\right)^2$ then $\beta = 0$

i.e., the waveguide is beyond cut-off and there is an attenuation given by equation (5).

The minimum phase length, i.e., the maximum change in phase length compared to that of air filled guide, occurs when

$$\frac{ne^2\mu_0}{m} = \left(\frac{2\pi}{\lambda_g}\right)^2$$

For an applied frequency of 9,350 Mc/s corresponding to $\lambda_g = 4{\cdot}45$ cm, $n = 5{\cdot}5 \times 10^{11}$ electrons/cm^3 for this condition to obtain.

With the discharge off, $n = 0$

$$\beta_0 = \frac{2\pi}{\lambda_g} = 1{\cdot}42 \text{ radian/cm.}$$

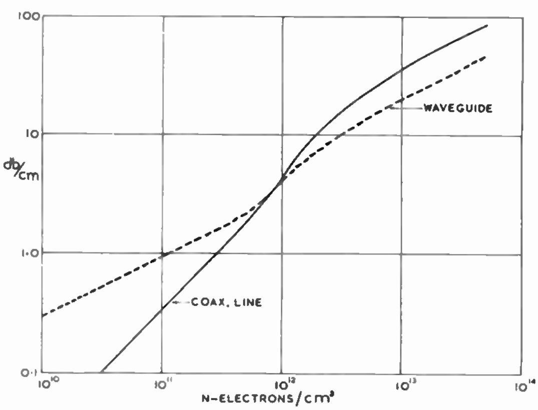

Fig. 3.—Theoretical attenuation as function of electron density.

Fig. 4 shows the complete curve obtained from the equation.

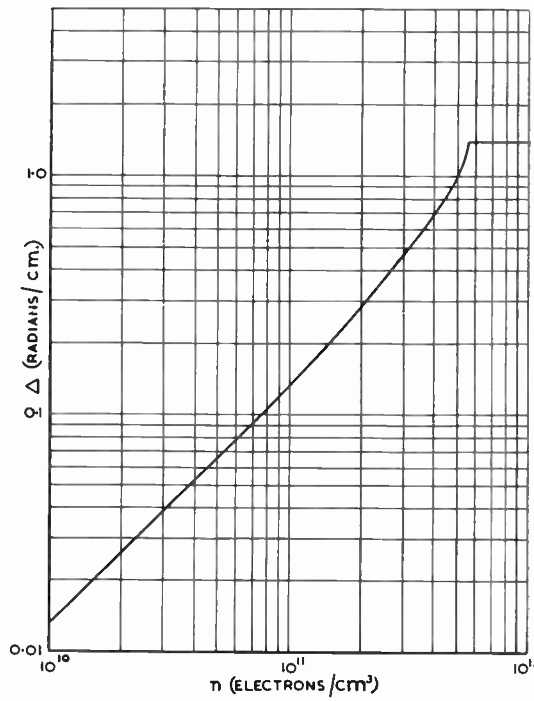

Fig. 4.—Theoretical phase shift as function of electron density in waveguide.

$$\Delta = \beta_0 - \beta$$

$$\text{or } \Delta = \frac{2\pi}{\lambda_g} - \left\{\left(\frac{2\pi}{\lambda_g}\right)^2 - \frac{ne^2\mu_0}{m}\right\}^{\frac{1}{2}}$$

2.3. *Electron Gas confined in Coaxial Line*

One of the simplest attenuator structures is the coaxial transmission line which is coupled to the waveguide circuit by means of suitable transformers and where the inner and outer electrodes are made the anode and cathode of a d.c. discharge. It is of interest to calculate how the insertion loss varies when the line is filled with a uniform electron gas.

Jackson[6] gives an expression for the attenuation of a coaxial line

$$\alpha = \left[\frac{\omega\mu_0}{2}\left\{(\omega^2\epsilon^2 + \sigma_r^2)^{\frac{1}{2}} - \omega\epsilon\right\}\right]^{\frac{1}{2}} \text{ nepers/metre}$$

which reduces to

$$\alpha = \frac{1}{2}\sqrt{\frac{\mu_0}{\epsilon_0}}\,\frac{\sigma_r}{(\epsilon/\epsilon_0)^{\frac{1}{2}}} \quad \text{when } \omega\epsilon \gg \sigma_r$$

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taking

$$\eta = 1 \text{ then } \sigma_r = \frac{ne^2}{2m\omega} \; ; \quad \epsilon = \epsilon_0 - \frac{ne^2}{2m\omega^2}$$

and

$$\alpha = \left[\frac{\omega\mu_0}{2} \left\{ \left(\omega^2\epsilon_0{}^2 - \frac{\epsilon_0 ne^2}{m} + \frac{n^2e^4}{2m^2\omega^2} \right)^{\frac{1}{2}} - \omega\epsilon_0 + \frac{ne^2}{2m\omega} \right\}^{\frac{1}{2}} \right]^{\frac{1}{2}}$$

The curve of attenuation/cm plotted against n is reproduced in Fig. 3.

2.4. *Electron Gas confined in Cavity Resonator*

Slater[7] has shown that the admittance y_d of a gas discharge contained in a microwave cavity resonator may be represented by

$$y_d = g_d + jb_d = \frac{B \int_{V'} \sigma E^2 \mathrm{d}v}{\omega_0\epsilon_0 \int_V E^2 \mathrm{d}v}$$

where E is the microwave electric field intensity, B is a coupling coefficient between the cavity and the waveguide and ω_0 is the resonant frequency of the empty cavity. V is the cavity volume and V is that of the gas discharge container.

The imaginary part of the complex conductivity gives rise to a shift in cavity resonant frequency and the real part lowers the Q of the cavity. Either effect can be used to vary the interaction loss of a transmission cavity and can also be employed as a means of determining electron density.

Rose and Brown[8] show that if $\eta \ll 1$ we obtain

$$\int_V nE^2\mathrm{d}v = \frac{8\pi^2mc^2\epsilon_0}{e^2} \cdot \frac{\Delta\lambda}{\lambda^3} \cdot \int_{V'} E^2\mathrm{d}v \quad \ldots\ldots(9)$$

where $\Delta\lambda$ is the shift in resonant wavelength from λ.

This equation can be solved for any particular cavity mode and for any density distribution of electrons. We will only treat here the case of a cylindrical TM_{010} cavity because of the simplicity of the field configuration, and the fact that experimental results have been obtained in this laboratory with such cavities in the 3-cm and 10-cm bands.

For a TM_{010} cavity

$$E_r = E_\phi = 0$$

and

$$E_z = E_0 J_0(2{\cdot}405\, r/r')$$

where E_r, E_ϕ and E_z are the radial, angular and axial components of E, E_0 is the axial field at the centre of the cavity and r' is the radius of the cavity.

Let us assume for simplicity that the electron density in the container is uniform, then we have

$$n = 6{\cdot}1 \,.\, 10^{12} \cdot \frac{\Delta\lambda}{\lambda^3} \cdot \frac{H}{h} \cdot \frac{1}{\rho^2[J_0{}^2(2{\cdot}4\rho) + J_1{}^2(2{\cdot}4\rho)]} \quad \ldots\ldots\ldots\ldots\ldots(10)$$

where H and h are the heights of the cavity and container respectively, r_0 is the container radius, and $\rho = r_0/r'$.

Figure 5 shows the effect of introducing a quartz discharge tube through the end walls of a TM_{010} cavity, resonant in the 10-cm band. In order to avoid undue disturbance of the cavity field the end holes must be kept small compared to the cavity diameter. The cavity used was 7·1 cm in diameter and 1·27 cm high and the end holes were 0·54 cm diameter, the unloaded cavity Q being about 6,000. In the figure the measured frequency shift and the electron density calculated from equation (10) are plotted as functions of distance between the cathode and inner cavity surface. Even although the density is integrated over such a comparatively large distance as 1·27 cm the results do indicate the great increase in electron density on approaching the negative glow. It is consequently an important design feature of practical attenuators that the negative glow region of the discharge be brought into the region of maximum field intensity for large interaction to take place.

3. Properties of the Gas Discharge

3.1. *Comparison of Gases*

For an efficient attenuator we require that the electron density in the gas shall be high for a given discharge current and also that η should be of such a value that efficient interaction is obtainable at suitable values of gas pressure and tube voltage. In addition it is required that the attenuation should respond rapidly to change of discharge current and that the tube should have a long life, which demands that none of the components in the tube will react chemically with the gas. In order to obtain a high electron density we require a gas in which the ionized atoms have a small cross-section for recombination with electrons. For these reasons

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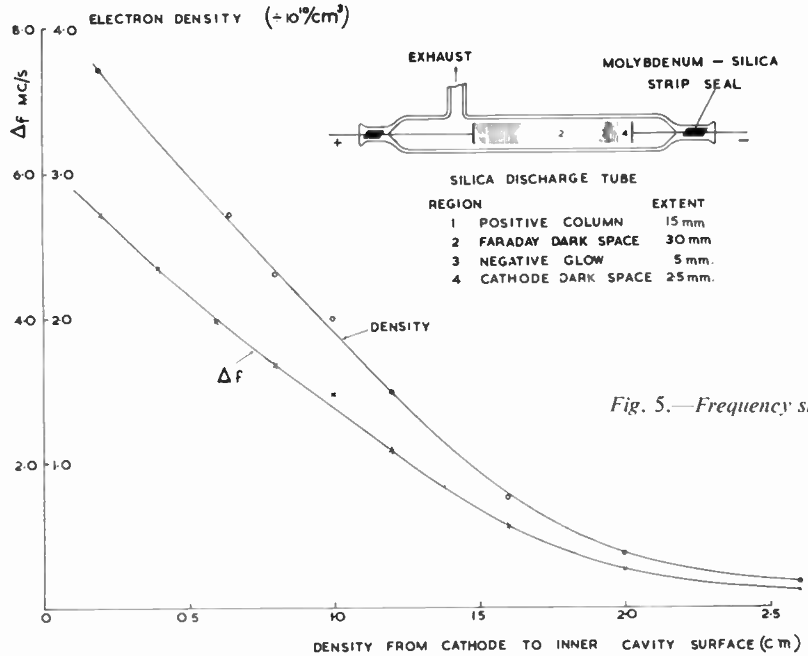

Fig. 5.—Frequency shift and electron density from cavity measurements.

the rare gases are usually chosen. Table 1 gives values for the electron temperature and mean free path in the positive column of the rare gas discharge from Knol,[9] p_x is the pressure at which $\eta = 1$ for a wavelength of 3·5 cm, λ_0 is the mean free path of the electron at gas pressure of 1 mm Hg, T is the electron temperature for pressures greater than 2 mm Hg for a discharge confined in a tube of radius 1 cm, and $\bar{v}$ the corresponding average velocity.

Table 1

Gas	λ_0 cm	T °K	$\bar{v}$ cm/sec	ν per sec	p_x mm Hg.
He	0·14	3×10^4	$1{\cdot}2 \times 10^8$	$8{\cdot}6 \times 10^8$	79
Ne	0·13	3×10^4	$1{\cdot}2 \times 10^8$	$9{\cdot}2 \times 10^8$	73
A	0·014	$1{\cdot}5 \times 10^4$	$0{\cdot}83 \times 10^8$	$5{\cdot}9 \times 10^9$	12
Xe	0·010	$1{\cdot}0 \times 10^4$	$0{\cdot}69 \times 10^8$	$6{\cdot}9 \times 10^9$	9·8

This table illustrates that to obtain efficient interaction in the positive column at pressures of the order 10 mm Hg, which is the most useful pressure range, it is desirable to use argon or xenon; although no figures are available for krypton its performance is known to be similar to these gases.

In attenuators in which it is required that $\eta \ll 1$ neon or helium should be used. Neon with a small admixture of argon (6 per cent.) gives very low breakdown voltage but the formative time of the discharge is of an order of magnitude greater than in pure neon.

An experiment was made to confirm this optimum value of pressure for the positive column of a xenon gas discharge. The discharge tube was introduced at an angle of 20 deg with the axis across the broad face of a rectangular waveguide in the 3-cm band ensuring that the discharge was well matched. The discharge current was maintained constant and the gas pressure varied between 1 mm Hg and 20 mm Hg. The interaction loss of the discharge was measured and a flat maximum was observed at 12 mm Hg as compared with 9·8 mm Hg predicted by the theory.

It is very difficult to construct a similar table for the negative glow and Faraday dark space regions owing to the non-uniformity of the electrical conditions in these regions. While the

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electron temperatures are very much lower in these cathode regions the table will give some idea of the ratio of the optimum values of the pressure for the different gases. Direct comparison of theory and experiment in practical attenuators is thus complicated by the fact that the electron density varies rapidly in the cathode regions, resulting in a varying dielectric constant.

3.2. *Noise Production*

In common with all gas-discharge devices, electronic attenuators will generate noise of large amplitude. There are present two distinct types of noise. In the first type, the r.f. energy which has passed through the device can be amplitude modulated by the unwanted noise modulation of the direct current maintaining the discharge. This will be called control current noise and is generally coherent in nature. In the second type the direct current discharge generates incoherent r.f. power of maximum equivalent noise temperature about 30,000°K. This will be called r.f. noise.

3.2.1. Control current noise

This may be divided into two classes, noise caused by (*a*) relaxation oscillations which is affected by the external circuit, and (*b*) moving striations which is independent of external conditions provided that the discharge current is maintained constant.

Relaxation oscillations are of frequency up to 300 kc/s and of large amplitude. The oscillation arises when two conditions are fulfilled: (*a*) the discharge is operating in the negative resistance region (as measured by a static current-voltage plot); (*b*) the time constant of the series resistance and the discharge impedance together with any stray capacitance is within the region of the period of oscillation in which the discharge will appear as a negative resistance. At higher frequencies the inertia of the discharge plasma will be such that the impedance presented will no longer be negative. In most of the practical attenuators described below, this problem does not arise because within the range of operating current the discharge conditions are well into the abnormal cathode fall region.

The other type of control current noise which can be either random or coherent is due to moving striations and is brought about by movements of the positive column plasma.[10] The striations can cause up to 100 per cent. modulation of the incident r.f. power at frequencies of the order of 1 kc/s. It is well known that at very high current levels (order of 150 mA) the discharge becomes quiescent and this should consequently be taken account of in the design of positive column attenuators. A device depending on interaction with the cathode regions of the discharge will not suffer from the effects of moving striations unless the tube contains a long positive column, because the striations find their origin in that region.

3.2.2. Radio frequency noise

In a gas discharge the electrons are in random motion with an approximately Maxwellian distribution of velocities. The mean electron energy is usually between 1,000°K and 40,000°K depending on the discharge region and the nature of the gas.

The equivalent noise temperature of an attenuator may therefore be as high as 40,000 °K, and this large noise output may preclude its use in a sensitive receiver circuit. However, only under certain conditions is the equivalent noise temperature equal to the electron temperature.

By analogy with the theory of heat radiation from a so-called "black body" it is seen that the noise output of the discharge will be equivalent to that given by the electron temperature only if the discharge presents a high transmission absorption. The actual noise available will be given by the equation:

$$P_A = kT_AB = kATB$$

where P_A = available noise power

T_A = apparent noise temperature at receiver

B = bandwidth of receiver

T = electron gas temperature

A = normalized power absorption coefficient.

It follows that devices depending on the change in reflection coefficient to provide attenuation and also devices depending on change of phase length that the equivalent noise temperature will be small, since the transmission absorption coefficient is small.

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4. Practical Attenuators

4.1. *Devices with Resonant Structures*

Basically these devices are modifications of transmit-receive tube, and are transmission resonant cavities. Two types of tube have been constructed (*a*) the narrow band attenuator with a high-Q cavity, and (*b*) the wide band attenuator. Both types employ a d.c. gas discharge in a rare gas at low pressure to control the microwave transmission. As the construction and operating characteristics of these tubes are quite different they are dealt with separately below. Owing to the resonant structure in which the r.f. field is very high at the d.c. discharge, the power handling capacity of the tubes is severely limited owing to the r.f. field modifying the discharge conditions.

A fuller description of these tubes appears elsewhere.[11]

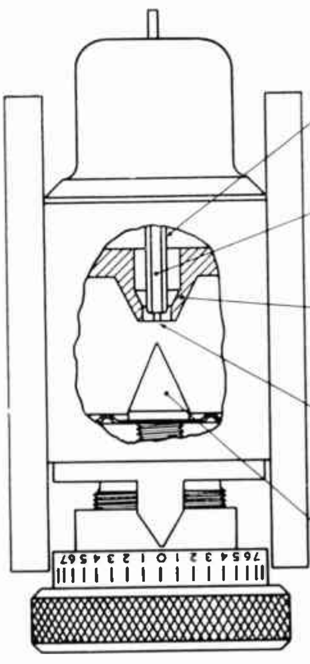

Fig. 6.—Narrow band attenuator.

4.1.1. The narrow band attenuator

An outline drawing, cut away to show the electrode design, is given in Fig. 6. The control cathode is introduced along the centre of the hollow truncated cone and is insulated so that

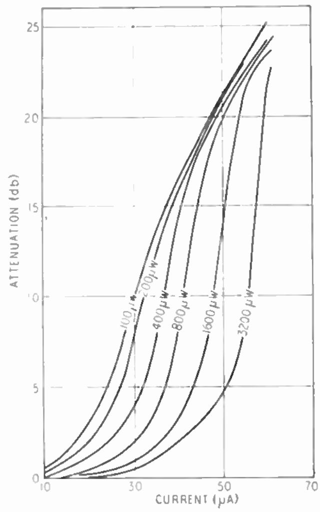

Fig. 7.—Characteristic curves of narrow band attenuator.

the discharge takes place only at the tip. The tube is a single re-entrant resonant cavity, coupled to the waveguide by means of two non-resonant windows. Tuning is accomplished by moving the solid cone, the movement being transmitted through a flexible diaphragm brazed to the wall; the tube can be tuned by this means to any frequency in the band 8,900-9,500 Mc/s. The Q of the tube is about 300.

Figure 7 shows how markedly the attenuation of the tube varies with input power; it would appear that when the power exceeds 100 μwatts the r.f. field intensity becomes comparable with the d.c. field intensity in the resonant gap. Indeed when the r.f. input exceeds 1 mW there is a gradual change in the appearance of the discharge from a typical d.c. glow with the cathode regions clearly defined, to a more diffuse uniform r.f. plasma.

The effect of passing a discharge across the attenuator gap is equivalent to introducing across the cavity a shunt impedance which changes the resonant frequency and lowers the Q. Fig. 8 shows how the apparent attenuation of the tube varies with input r.f. frequency, the attenuation being measured by the change in transmission as the discharge is switched on and off. This curve can be explained more easily by referring to Fig. 9, in which the transmission-frequency curve of the tube with no discharge is plotted, corresponding to a centre frequency f_0, in addition to the curve with the discharge on, the centre frequency now being f_0'. The apparent attenuation at any frequency is therefore given by the difference in transmission loss of the two curves; the change in Q is also illustrated by the difference in shape of the two curves.

This tube is normally filled with neon at a pressure of 10 mm Hg and using a magnesium cathode the running voltage is of the order of 200-300 volts. The recovery and build-up times are appreciable with this gas filling, and this tube can only be employed in systems where this is not important. In one typical measurement the attenuation fell from 14 db to 7 db in 20 μsec on removing the voltage maintaining the discharge, and on switching on the voltage the attenuation rose to 7 db in 200 μsec.

4.1.2. The wide band attenuator

Figure 10a is a perspective view of this tube, cut away to show the internal structure and Fig. 10b shows the electrode details. There are four tuned elements, the two windows and the cone-iris assemblies, each element being spaced a quarter wavelength apart with respect to a centre frequency of 9,250 Mc/s. The bandwidth of a typical four-element tube of this design with no discharge is 500 Mc/s with a v.s.w.r. of 1·20.

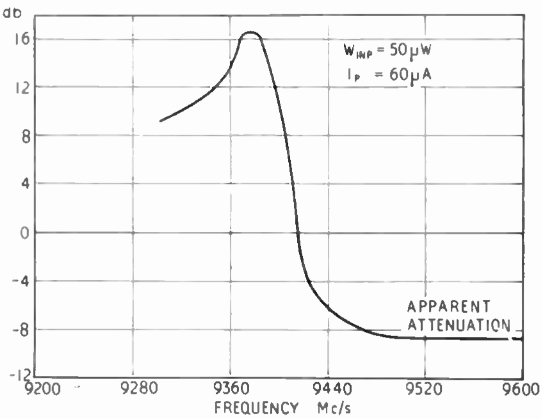

Fig. 8.—Frequency dependence of attenuation.

Typical operating characteristics of a tube filled with krypton at 5 mm Hg are reproduced in Fig. 11, the electrodes being run in parallel. By measuring the v.s.w.r. and transmission

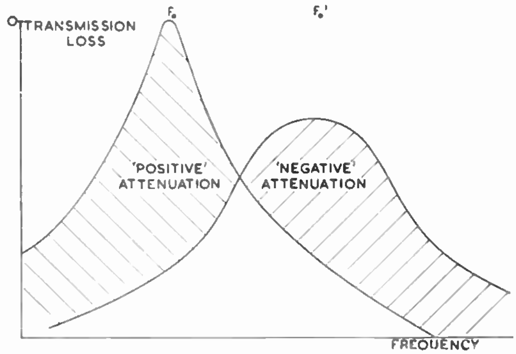

Fig. 9.

through the attenuator at various discharge currents the curves shown in Fig. 12 were obtained for the normalized power reflection and absorption coefficients ($|\rho|^2$ and $|\tau|^2$ respectively). It will be noted that the absorption coefficient is appreciable, implying that the equivalent r.f. noise temperature of the tube when attenuating strongly is an appreciable fraction of the electron temperature.

The life of a tube of this design is limited by cathode sputtering which has a serious effect on the cold transmission loss and may ultimately lead to short circuits between cathode and anode owing to the small separations. Increasing the cathode area will increase the life but the r.f. design of the tube is thereby made more difficult.

An a.g.c. circuit incorporating a wide band attenuator was demonstrated at a recent exhibition. In this circuit the r.f. output from a klystron, square wave modulated at 1,000 c/s, was fed into the tube via a variable card attenuator and a directive feed, used to display the r.f. power input to the tube. A portion of the r.f. power output from the tube was fed into a 1,000 c/s amplifier via a second directive feed and a crystal detector, and this signal used to control the discharge current and thus the microwave attenuation. With proper regulation it was possible to obtain as little as 0·5 db variation in r.f. power output for a 20-db variation in input power; the maximum r.f. input power handled was 10 mW. It may also be mentioned that the broad band electronic attenuator has been successfully employed as a microwave modulator, it being possible to obtain audio modulation with little distortion.

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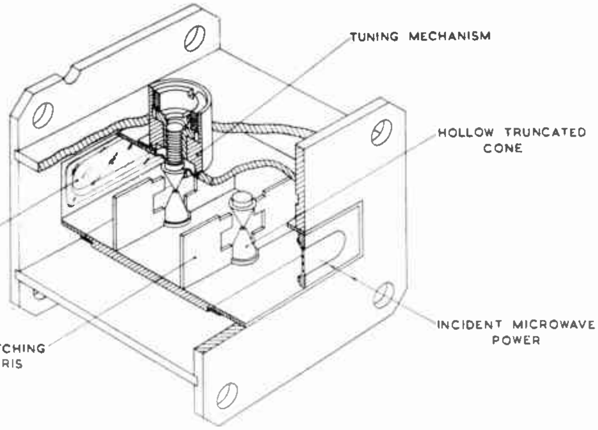

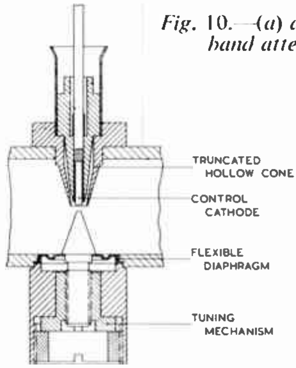

Fig. 10.—(a) and (b) Wide band attenuator.

4.2. *Coaxial Attenuator*

This device is different from those already described in that the interaction takes place in a gas discharge maintained between the inner and outer conductors of a section of coaxial line. The latter can be coupled into waveguide by means of suitable transformers.

This arrangement is particularly convenient for systems working in the 3-cm band and at longer wavelengths but the close tolerances required in the coaxial to waveguide transformers and the large loss in coaxial line propagation preclude the use of this design at shorter wavelengths.

Figure 13 is a photograph of a 3-cm band tube designed by P. O. Hawkins[12] incorporating a hot cathode. The coaxial line and the dumb-bell elements of the transformers are enclosed in a precision bore glass tube. The holder is designed so that the space between the end of the outer conductor and the shoulders of the dumb-bell projects across the waveguide, which has a terminating plunger. With this arrangement the v.s.w.r. is less than 1·2 over a 5 per cent. band with no discharge present. When the discharge is present the impedance of the co-axial line is changed resulting in a mismatch at the transformers.

Two versions of this tube have been designed having identical r.f. circuits but one having a hot cathode and the other a cold cathode. Both types of tube will control powers up to 50 mW, but no measurements have been made at higher power. The frequency response of both types of tube to modulation frequencies impressed on the anode current falls by 3 db at 5 kc/s from the value at 500 c/s. The performance of the hot cathode tube may be improved substantially by a small admixture of hydrogen. The two tubes exhibit entirely different properties and will be discussed each in turn below.

Brief reference may be made to a device due to Goldstein and Cohen,[13] which is a coaxial line attenuator but which works on a different principle. In this device the positive column of the discharge forms part of the inner conductor of the coaxial line. With no discharge, the outer tube is of such a diameter that it acts as a

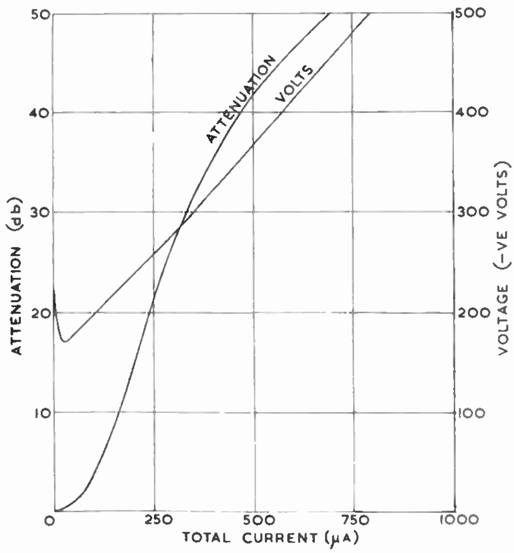

Fig. 11.—Characteristic curves of wide band attenuator.

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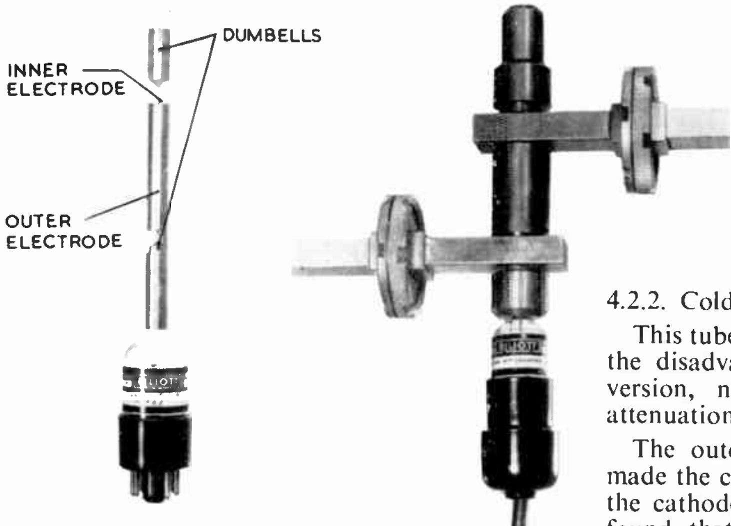

Fig. 13.—(a) Coaxial line attenuator. (b) Attenuator mounted in holder.

circular waveguide beyond cut-off. The paper by Goldstein and Cohen gives full experimental details and the theory of the device has been worked out by Rosen.[14]

4.2.1. Hot cathode coaxial attenuator

The inner conductor or cathode is made from nickel tubing 1 mm O.D. and the outer conductor or anode is 8 mm I.D. The cathode is coated with mixed barium and strontium carbonates and is indirectly heated with a tungsten filament. The tube is filled with one of the heavier rare gases to a pressure of 3 mm Hg. Fig. 14 shows the effect of varying the heater current so that the attenuation remained constant. These curves are unique without specifying the heater current since this is defined by the other three parameters. It will be seen that the attenuation depends markedly on the heater current and Table 2 shows this is another way.

Table 2

V_h (volts)	5·5	5·0	4·8	4·5	4·2	4·1	3·8
Atten. (db)	0·0	3·0	2·9	11·0	11·0	12·0	12·6

This sudden rise in attenuation at lower heater voltages can be explained as a transition from an arc discharge, in which the electron density is low, to a glow discharge. At this transition the negative glow region of the discharge collapses on to the cathode resulting in decreased attenuation. The glow discharge is unstable because the cathode coating possesses a high resistance at low temperature causing a very high field intensity which leads to breakdown in the coating.

4.2.2. Cold cathode coaxial attenuator

This tube was developed in order to overcome the disadvantage inherent in the hot cathode version, namely the critical dependance of attenuation on heater current.

The outer conductor of the coaxial line is made the cathode so that the current density at the cathode was considerably reduced. It was found that there is a large variation in the efficiency of different cathode materials, the most satisfactory results being obtained with magnesium evaporated on to the nickel outer tube. The characteristics of a tube with this cathode and with a gas filling of xenon at a pressure of 2 mm Hg together with hydrogen at 1·4 mm Hg is shown in Fig. 15. The admixture

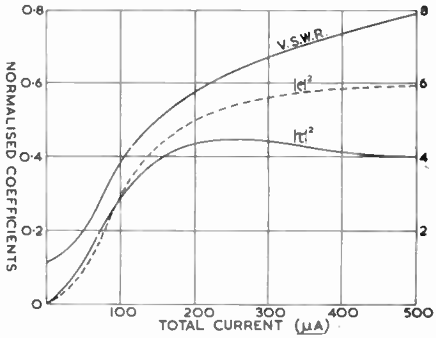

Fig. 12.—Reflection and absorption in wide band attenuator.

of hydrogen has the effect of reducing the anode current required for a given attenuation. The presence of hydrogen also makes the attenuation respond more quickly to control current impulses.

The problem of hydrogen clean-up was solved by passing a discharge in pure hydrogen during processing, which resulted in large quantities of hydrogen being absorbed by the magnesium cathode.[15] This hydrogen is re-evolved during later operation.

The r.f. noise power generated by both hot and cold cathode coaxial attenuators has a maximum equivalent temperature of about 10,000 °K, occurring at an anode current corresponding to a transmission loss of about 15 db. At higher anode currents the noise output falls gradually, because of the rapid increase of

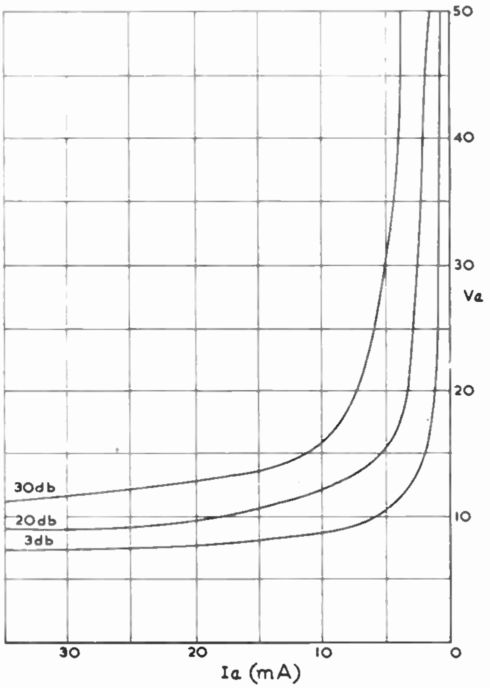

Fig. 14.—Iso-attenuation curves for hot cathode coaxial attenuator.

reflection at the coaxial to waveguide transformers and more sharply at lower currents, in accordance with our previous arguments in Section 3.2.

Life is limited by deposition of material from the cathode on the windows. This increases the cold insertion loss and the end of life is defined when it reaches some specified value, generally not greater than 2 db. The life of the cold cathode tube is of the order of 5,000 mA hours for an insertion loss of 2 db.

4.3. *Waveguide Devices*

4.3.1. Hot cathode attenuators

One such attenuator consists essentially of an oxide-coated cathode, 2 in long and 0·020 in diameter, mounted axially in a length of 0·9 in × 0·4 in rectangular waveguide which is sealed at each end by a low Q glass window. The filament is supported at each end by thin metal rods parallel to the larger waveguide dimension, the rods being taken out on the side walls of the waveguide section via glass-to-metal seals. This device depends for its operation on interaction with the negative glow region of the discharge and the most suitable gas filling employed was krypton at a pressure of 2 mm Hg. At higher gas pressures the attenuation was found to fall off rapidly.

Several interesting phenomena have been observed in the performance of this tube. It was found that the attenuation increases sharply at a

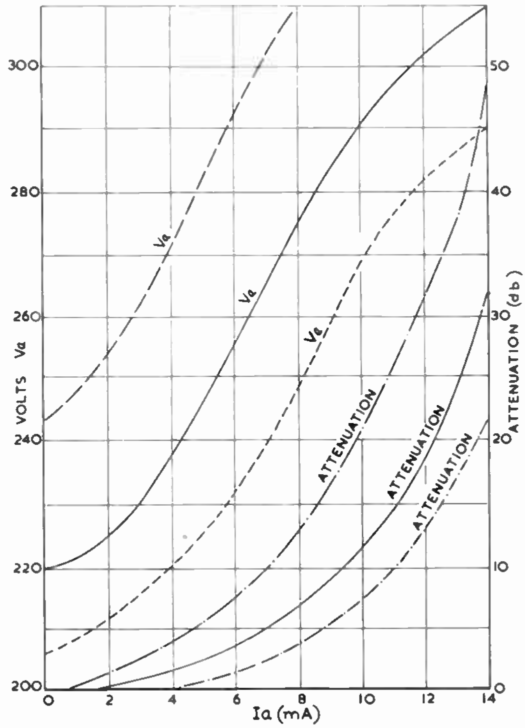

Fig. 15.—Characteristic curves of cold cathode attenuator.

certain critical value of filament current and falls sharply when this is exceeded. This sharp peak in attenuation corresponds also to a change in the discharge conditions from a normal glow to an arc. The variation in attenuation, current and voltage of the tube with filament current is

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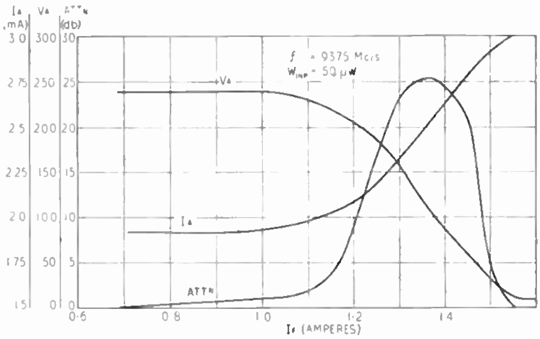

Fig. 16.—Characteristic curves of axial wire attenuator.

shown in Fig. 16. This may be compared with the results for the coaxial attenuator (Section 4.2.1); in the present case it was possible to extend the measurements into the glow discharge region because of the thinner cathode coating. The normalized power absorption and reflection coefficients when operating at the critical value of i_F (1·35 amperes) is shown in Fig. 17. The larger values of absorption coefficient imply that the noise temperature of this tube is high. The attenuation is again power dependent, the peak attenuation at the optimum filament current falling to half value as the power is increased from several hundred microwatts to 15 milliwatts and to about a quarter at 50 milliwatts.

Another type of hot cathode attenuator may be briefly described. In this tube the rectangular waveguide cross-section is reduced to 0·050 in × 0·7 in, this section being connected to the main waveguide by tapers extending over lengths of several quarter wavelengths. A cylindrical hot cathode of diameter 0·20 in is situated in the reduced section with the end face co-planar with

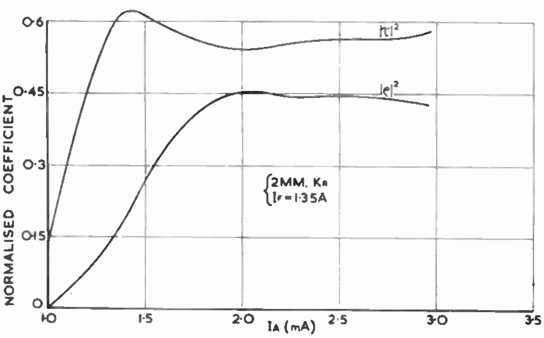

Fig. 17.—Reflection and absorption in axial wire attenuator.

the broad face of the waveguide. There is a gap of about 0·050 in between the cathode and the waveguide walls, which act as the anode of the discharge. A similar dependence of attenuation on filament current was observed and although this device gave a somewhat larger interaction with the r.f. field, the problem of obtaining a broad-band match with no discharge is more difficult than with the axial wire attenuator.

4.3.2. Split guide attenuator

This tube was introduced primarily to overcome the difficulties inherent in scaling down the cold cathode coaxial line attenuator to work at frequencies of the order of 50,000 Mc/s. The discharge is made between the two broad faces

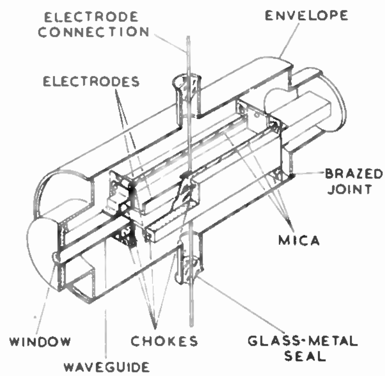

Fig. 18.—Split guide attenuator.

of the rectangular waveguide which are insulated from the rest of the waveguide circuit as shown in Fig. 18. It will be seen that the narrow faces of the waveguide are insulated from the discharge by thin mica sheets, so that the discharge will be characteristic of that between parallel plates.

As the waveguide is split along lines of current flow it is necessary to choke these joints so that they appear as a continuous r.f. circuit as shown in the figure.

The whole structure is placed in a metal envelope at each end of which is a low Q resonant window constructed in these experimental models, operating at 50,000 Mc/s, from mica sealed to metal.[16] Prior to assembly the cathode in this tube is coated *in vacuo* with magnesium as in the coaxial line tube. The tube is filled with argon at a pressure of 4 mm Hg, the most efficient pressure, which is an exact

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scaling of that at 10,000 Mc/s on the basis of electron collision frequency. The attenuation was found to be 30 db at 10 mA, but was very dependent on gas purity so that tube life was very short.

5. Conclusions

All the practical attenuator tubes developed and described above employ the negative glow region of the discharge to obtain interaction with the microwave field. The electron density in the negative glow is known to be much higher than in the positive column, and this more than offsets the disadvantage of the lower electron temperature, which leads to a lower electron collision frequency. It is, however, not possible to apply quantitatively the interaction theory described earlier in this paper to the practical tubes because of the non-homogeneous nature of the negative glow with the rapid variation in electron density and energy.[17] The position is made more difficult by the complex geometrical nature of the electrodes, particularly in the case of the transmission cavity devices.

In spite of these complications it has been felt desirable to develop the theory of microwave gas-discharge interaction for the simplest case of a waveguide filled with an electron gas of uniform density and temperature. The theory does provide an insight into the mechanisms involved and indicates the important gas-discharge parameters.

The chief advantage of the cavity-type attenuator structure lies in the low control current required compared to the distributed structure. On the other hand it is possible to control higher microwave powers with the latter type of device. Future development might include microwave attenuators which will control larger powers, have longer lives and respond more rapidly to modulation of the control current.

6. Acknowledgments

Acknowledgments are due to Ferranti Ltd. who have provided facilities for carrying out this work and have given permission for the publication of this paper. One of us (E.M.B.) wishes to thank the directors of Elliott Brothers (London) Ltd. for permission to publish information concerning the cold cathode attenuator and split guide attenuator, which were developed and made at Elliott Brothers' Research Laboratories.

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THE SCINTILLATION COUNTER IN INDUSTRY WITH REFERENCE TO STABILITY PROBLEMS*

by

J. S. Eppstein, B.Sc.(Eng.), A.C.G.I.†

A paper presented during the Industrial Electronics Convention held in Oxford in July 1954.

SUMMARY

The characteristics of scintillation counters for detection of high and low energy gamma rays are discussed. Stability problems are shown to be caused by changes in photomultiplier gain and a circuit is given for minimizing the effects of these and so making the counter suitable for industrial use.

1. Introduction

The Scintillation Counter has become in recent years one of the most important tools in the measurement of radioactivity both in the physics laboratory and in the ever widening field of tracer techniques.‡ In the industrial field, the main application of radioactive techniques has been to the measurement of weight (mass per unit area) by transmission or reflection of radiation. Most of the work up to date has been done with the aid of d.c. ionization chambers and Geiger-Müller counters, which require relatively little ancillary apparatus and which, if properly applied, can be regarded as inherently stable devices. There are, however, a large number of possible applications where these detectors have limitations, many of which may be overcome by the use of a scintillation counter.

There are two possible ways in which the scintillation counter may be used. One can measure the average (integrated) output current, or the individual pulses arising from light flashes in the phosphor. The former method leads to a relatively simple arrangement, and has been used to some extent, particularly in the U.S.A., as the basis of a sensitive detector.§ It has, however, several disadvantages, one of which is the inability to discriminate against the thermionic emission (dark current) from the photo-cathode of the photomultiplier; for most purposes it is necessary to measure the individual output pulses. Properties of the scintillation counter which may make its use desirable can be enumerated as follows:—

(1) High sensitivity to gamma radiation: use of a relatively large crystalline phosphor can result in a very high detection efficiency.

(2) Energy proportionality: by the use of suitable electronic circuitry it is possible to discriminate between radiations of different energies.

(3) Speed of response: the light decay time of the phosphors normally used is a fraction of a microsecond which makes possible a measuring system of relatively short response time.

(4) Flexibility: The detector element being a solid can easily be made any shape or size; the only limitation is the necessity of collecting as much light as possible at the cathode of the photomultiplier tube.

The scintillation counter is not necessarily an inherently stable device, and it is necessary to examine this aspect before applying it to any industrial problem where stability may well be a limiting factor.

2. Stability Problem

To illustrate the problem of stability, consider a typical arrangement for detecting gamma rays; this is shown as a block diagram in Fig. 1. The scintillation counter (A) consists of a photomultiplier tube, optically coupled to a crystal of thallium-activated sodium iodide. The high voltage for the photomultiplier tube is provided by a stabilized power supply B. The pulses from the counter are amplified in C and applied to a voltage discriminator D:

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† Isotope Developments Ltd., Beenham Grange, Aldermaston Wharf, Berkshire.

U.D.C. No. 621.387.46.

‡ J. B. Birks. "Nuclear scintillation counters." *J.Brit.I.R.E.*, **11**, June 1951, pp. 209-223.

§ H. D. Le Vine. "Logarithmic ratemeter for d.c. scintillation counters." *Nucleonics*, February, 1954.

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this gives an output pulse for every input pulse exceeding a certain voltage. The average rate is then measured in E : this may be either a scaler which counts the individual number of pulses arriving in a given time, or a ratemeter which gives a continuous indication of the average rate. The characteristics of this system with high and low gamma energies (i.e. above 1 MeV and below 500 keV) are somewhat different ; the two cases will be considered separately.

2.1. *High Energy Gamma Rays*

Figure 2 shows a typical spectrum of output pulses ("kicksorter" curve) from C, when the counter is irradiated with gamma rays from cobalt 60. This curve, due to the energy proportionality of the phosphor, is a reproduction of the energy spectrum of electrons produced by the gamma rays in the phosphor. The complexity of the spectrum arises from the fact that a large number of the electrons are liberated by the process of Compton scattering, which gives rise to a characteristic spectrum with a large spread in energy. The remainder of the electrons are produced by the photo-electric process in which the total gamma ray energy is transferred to an electron. This gives rise to the two peaks at x and y which correspond to the two Co 60 gamma ray energies of 1·1 and 1·3 MeV.

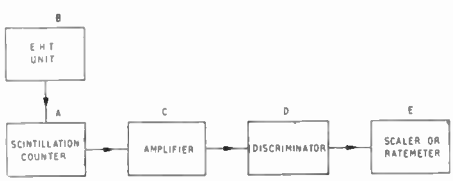

Fig. 1.—Block diagram of typical scintillation counter arrangement.

Reverting now to Fig. 1, it is instructive to observe the counting rate indicated by E as the e.h.t. to the photomultiplier tube is increased from a low value. The resulting curve of counting rate versus e.h.t. is shown as Curve A, Fig. 3 ; B is the corresponding curve for the residual background arising largely from thermionic emission. It is evident that to obtain the maximum efficiency one must work at some point such as P. At this point, however, and indeed at any other point on the curve, the observed counting rate changes very rapidly with applied e.h.t. By the same token, small changes in the threshold voltage of the discriminator or in the gain of the amplifier will give relatively large changes in efficiency. Thus, in order to obtain reasonable overall stability, it is necessary to stabilize individually the voltage to the multiplier tube, the gain of the amplifier and the threshold voltage of the discriminator.

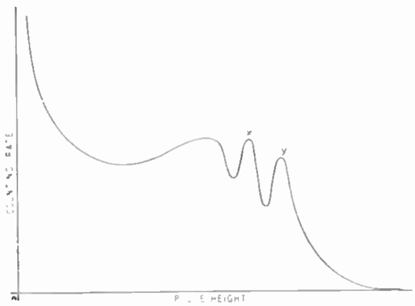

Fig. 2.—Pulse spectrum from scintillation counter: gamma rays from Co 60, sodium iodide phosphor.

In particular, the high voltage supply to the amplifier must be extremely stable, as the gain of the multiplier tube changes rapidly with changes in the high voltage. Having done this, the stability is still limited by the multiplier tube itself, which may be subject to temperature and fatigue effects. In practice, and under laboratory conditions, it is possible to obtain a daily stability figure of the order of ± 1 per cent. Under industrial conditions, however, this figure is unlikely to be attained and in fact may be worse by a very large factor.

A system of this type can be of great use in making measurements where the overall calibration can be checked between readings. An

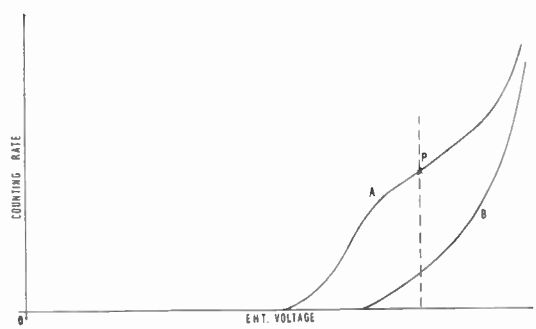

Fig. 3.—Curves of counting rate from D (Fig. 1) versus e.h.t. voltage to photomultiplier.

Curve A: Gamma rays from Co 60, sodium iodide phosphor.

Curve B: Background.

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example of this is a device developed by Putman and Jefferson of A.E.R.E. for the measurement of steel wall thicknesses by reflection of the gamma radiation. In this instrument, use is made of the direct radiation as a means of calibrating the instrument.*

There are, however, a large number of possible applications in continuous production processes where the necessity for frequent calibration may be embarrassing or, indeed, rule out this type of measurement altogether. In these cases, therefore, it is necessary to find some means of stabilizing the system. Before entering into this, however, it is worth considering the case of low energy gamma rays.

2.2. *Low Energy Gamma Rays*

So far, only the measurement of high energy gamma rays have been discussed ; in the case of radioactive beta particles, which have a large spread in energy, the problem is very much the same. The conditions which apply in the measurement of relatively low energy gamma rays (e.g. 100-500 keV) are somewhat different,

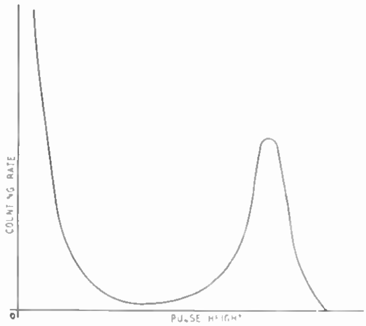

Fig. 4.—Pulse spectrum from scintillation counter: gamma rays from thulium 170, *sodium iodide phosphor.*

and can lead to a more stable system. Fig. 4 is a differential pulse height curve showing a typical spectrum of pulses obtained under the same conditions as before, but with gamma rays of about 100 keV. At this energy, the most probable mechanism of gamma ray absorption in sodium iodide is photo-electric, so that most of the electrons liberated in the

* J. L. Putman and S. Jefferson. " Tube Wall Thickness Gauge with Selection of Back Scattered Gamma Radiations." Proceedings of the 2nd Isotopes Conference, Oxford, July, 1954.

crystal receive the total gamma energy, giving rise to the peak in the curve of Fig. 4. The shape of this peak is that of a standard error curve : it represents the inherent inaccuracy of the measurement due to the finite number of electrons released from the cathode of the photomultiplier tube for each scintillation. If now we proceed as before with the arrangement of Fig. 1 and measure the change in output rate with change in e.h.t., we obtain the curve of Fig. 5. It will be seen that as the e.h.t. is increased, a point is reached where the rate changes very slowly ; this corresponds to the point where all the photo electrons are detected.

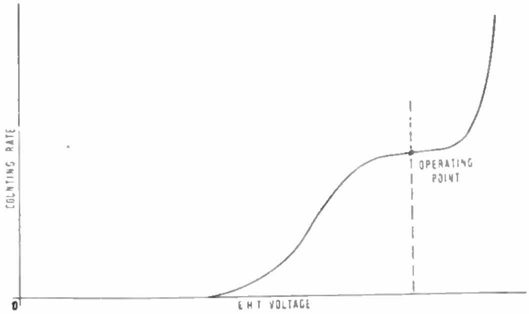

Fig. 5.—Curve of counting rate from D (Fig. 1) *versus e.h.t. voltage to photomultiplier: gamma rays to thulium* 170, *sodium iodide phosphor.*

As the sensitivity is increased beyond this point, there is a gradual increase in efficiency due to the detection of a relatively small number of electrons of lower energy than the maximum. The large increase in rate at higher e.h.t. voltages is due to the collection of small background pulses. If, now, the operating point of the system is made to lie on this " plateau," an acceptable figure of stability can be obtained without the necessity of keeping the overall gain extremely stable. Provided both source and detector are adequately collimated, the interpolation of any material which attenuates the radiation reduces the relative number of pulses measured, but does not alter the shape of the spectrum. This is because the gamma quanta detected are those which have traversed the material without interaction and so are unchanged in energy. This system provides a method of measuring weight per unit area in the region of 1 to 20 gm/cm^2 (e.g. 0·05 in to 1 in of steel).

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3. Stabilizing

As has already been seen, if one wishes to apply a scintillation counter to any continuous process involving high energy gamma rays or beta rays, some method of overall stabilization is desirable. Negative feedback techniques are not applicable to the photomultiplier tube as the source of the output signal is a photo-sensitive surface which cannot be controlled electrically in the same way as a valve amplifier. One must therefore look for some property of the output pulses from which a control signal can be derived. There are several possible ways of obtaining such a signal. For example, it is possible to produce standardized flashes of light of greater intensity than those in the phosphor at relatively long intervals, and derive a signal from the amplitude of the resulting output pulses which may be used to control the gain of the system. Provided the duration of these light flashes is relatively short, the contribution to the total number of pulses occurring at low pulse height can be made small. A system operating effectively on this principle has been used where the source of calibrating flashes is an alpha particle source irradiating a thin phosphor. This method is of limited application, and there is an alternative method of stabilization which overcomes these limitations.

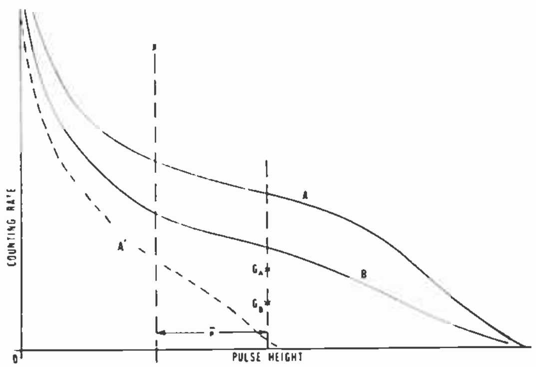

Fig. 6.—Pulse spectra from scintillation counter with organic phosphor showing invariance of mean height with absorber weight.
Curve A: beta rays of 1 MeV maximum energy with small absorber weight.
Curve A′: As A with reduced gain.
Curve B: As A with increased absorber weight.

The operation of the stabilizer depends on the fact that in many pulse distributions obtained with a scintillation counter, the average pulse size is substantially independent of the amount of absorber between the source and phosphor. This has already been seen to be true for collimated gamma radiation : in the case of beta rays, it has been found experimentally that the average pulse size remains almost constant over a wide range of absorber weight. As most of the experimental work has been carried out with beta rays, it will be convenient to describe the operation in terms of beta ray spectra, although the method is equally applicable to gamma radiation.

To illustrate this further, consider the curves shown in Fig. 6. This shows the pulse spectra obtained from beta radiation of maximum energy about 1 MeV on an organic phosphor (e.g., polystyrene loaded with tetraphenyl butadiene) with two alternative weights of absorber between source and phosphor. The abscissa corresponds to pulse amplitude, and the ordinate to the number of pulses occurring within a small voltage interval. The measuring system is biased in such a way that only those pulses are observed which occur to the right of the ordinate xx. For one weight of absorber we obtain curve A. The total counting rate is represented by the area of the curve to the right of xx, while the average pulse height corresponds to the abscissa of the "centre of gravity" G_A. If now the weight of absorber is increased, we obtain the curve B. In this case, the "centre of gravity" is at G_B and the abscissa is the same as before, i.e., the mean pulse height $\bar{e}$ above xx is unchanged. On the other hand, if the gain of the system is decreased, Curve A will move over to some position such as A′ and the average pulse height will be correspondingly reduced. Evidently, if we can find some means of keeping this average pulse height constant irrespective of rate, we will have produced an inherently stable system.

A method of doing this which has proved very satisfactory in practice is illustrated in the schematic diagram shown in Fig. 7. Positive pulses from the amplifier are fed to the grid of V1 which with V2 forms a trigger circuit. The grid of V1 is biased so that the circuit only triggers for pulses larger than a fixed threshold voltage corresponding to xx in Fig. 6. For each pulse exceeding this threshold voltage, a standard pulse of height E appears at the anode of V2. As the input

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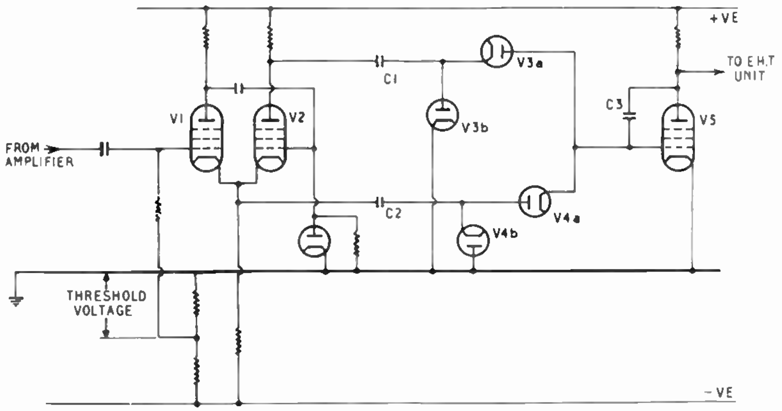

Fig. 7.—Circuit diagram of pulse stabilizer.

pulse increases above this threshold, V1 acts as a cathode follower and the excess pulse height appears at the cathodes of V1 and V2. The anode of V2 is connected to a diode pump circuit C1, V3a, V3b, while the cathodes of V1 and V2 are connected to a second diode pump circuit C2, V4a, V4b. C1, V3a, V3b are so connected that when the anode of V2 goes positive, C1 charges through V3b; on the "return stroke" C1 discharges through V3a. Thus for each individual pulse large enough to trigger the circuit, a constant negative charge is "pumped" through C1 into the Miller integrator, V5. If N pulses trigger the circuit an amount of negative charge Q_1 is "pumped" into the Miller integrator given by:

$$Q_1 = NEC_1.$$

C2, V4a, V4b are connected in the opposite sense, so that they deliver a corresponding positive charge given by:

$$Q_2 = C_2 \quad (e_1 + e_2 + e_3 + \ \ldots\ldots eN)$$

Where e_1, e_2, etc., are the heights of the individual pulses at the cathode of V1.

Now $(e_1 + e_2 + \ \ldots\ldots\ eN)/N = \bar{e}$

where e is the mean pulse height, hence:

$$Q_2 = NC_2\bar{e}$$

If the positive charge contribution is greater than the negative, the anode of V5 goes steadily negative. The anode of this valve is coupled to the e.h.t. unit feeding the photomultiplier tube which would thus tend to decrease steadily in gain, in turn decreasing $\bar{e}$. In practice, therefore, a stable position is reached where:

$$Q_1 = Q_2$$

$$\text{i.e., } NEC_1 - N\bar{e}C_2 = 0$$

$$\text{or } \bar{e} = \frac{EC_1}{C_2}$$

Thus the value of mean pulse height at which the circuit stabilizes depends only on circuit constants. To keep statistical fluctuations as small as possible the capacity C3 of the Miller integrator is made large compared with C1 and C2 so that $\bar{e}$ is effectively measured over a large number of pulses. The e.h.t. supply can be a very simple r.f. type which need have no great intrinsic stability.

The order of stability that has been obtained to date with beta particles from Sr 90 and a phosphor of polystyrene loaded with tetraphenyl butadiene is of the order of $\pm \frac{1}{2}$ per cent over periods of several days. The great advantage of such a system over any alternative pulse height stabilizing systems is that the control signal is virtually independent of rate, and is thus applicable to any measuring system where the spectrum of pulses remains constant.

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APPLICANTS FOR MEMBERSHIP

New proposals were considered by the Membership Committee at a meeting held on January 14th, 1955, as follows: 31 proposals for direct election to Graduateship or higher grade of membership and 29 proposals for transfer to Graduateship or higher grade of membership. In addition, 49 applications for Studentship registration were considered. This list also contains the names of four applicants who have subsequently agreed to accept lower grades than those for which they originally applied.

The following are the names of those who have been properly proposed and appear qualified. In accordance with a resolution of Council and in the absence of any objections being lodged, these elections will be confirmed 14 days from the date of the circulation of this list. Any objections received will be submitted to the next meeting of the Council with whom the final decision rests.

Transfer from Associate Member to Member

MADDOCK, Ieuan, O.B.E., B.Sc. *Otford, Kent.*
TARRY, Peter Albert. *Coseley, Staffordshire.*

Direct Election to Associate Member

ALBERRY, Wg. Cdr. Arthur William, M.B.E., R.A.F. *Ruislip.*
AVERY, Sqdn. Ldr. Alexander Bernard, R.A.F. *London.*
BALASUBRAMANIAN, Arunachala, B.Sc., B.E. *Chelmsford.*
HARLEY, Henry Victor, B.Sc.(Hons.). *Bangor, North Wales.*
PIDDINGTON, Vivian Henry. *Ashford, Middlesex.*
STEPHENS, Robert Bryce. *Watford.*
WILSON, Percy, M.A.(Oxon). *London, S.W.19.*

Transfer from Associate to Associate Member

BEN-HAIM, Abrahim Selman. *Haifa.*
MICHIE, Joseph Lawrence. *Southport.*

Transfer from Graduate to Associate Member

KATHURIA, Mohindar Singh, B.A. *Cholet, France.*
LONGMAN, Charles Robert. *Ickenham.*
PALMER, Edward Charles. *Harrow.*
ROSE, Frederick. *Sunderland.*

Transfer from Student to Associate Member

TOYNBEE-HOLMES, Flt. Lt. Alan, R.A.F. *B.A.O.R.*

Direct Election to Companion

IDDON, Eric St. Patrick. *Enfield.*

Direct Election to Associate

BAILLIE, Frederick. *Glasgow.*
BARROW, Leslie James. *Christchurch, Hants.*
DAVIS, R. C. James. *Hargeisa, Somaliland.*
DIKE, Albert Victor Terence. *Bramhall, Cheshire.*
EADIE, William Rowland. *Glasgow.*
KING, Leonard John. *Buckhurst Hill, Essex.*
MASON, John William Frederick. *Auckland, New Zealand.*
PARKER, Joseph Donald. *London, N.W.4.*
SPRING, Hans Paul. *London, S.E.3.*

Transfer from Student to Associate

BALDWIN, Leslie. *Plymouth.*
BECKLEY, Arthur Zuzel. *Freetown, Sierra Leone.*
FOAKES, Peter Frederick James. *Great Baddow, Essex.*
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*Reinstatement.

ELECTRONIC CONTROL OF RESISTANCE WELDING*

by

C. R. Bates (*Associate Member*)†

A paper presented during the Industrial Electronics Convention held in Oxford in July 1954

SUMMARY

After a description of the requirements of resistance welding processes the paper describes some typical electronic welding-controls. Basic circuits of timing and sequence controls are then given, together with the principles of operation of complete control units. The latest form of " all electronic " sequence timers is described. The need for synchronous control is explained, and after describing the various sub-circuits of such controls a typical complete circuit of a spot-welder synchronous control is given. The paper concludes with a brief reference to slope control of weld current.

1. Introduction

The application of electronic control devices to resistance welding has resulted in a considerable extension of the usefulness of the process. Until the development of precise control over the weld current in duration, magnitude, and in rate of change, which is only possible by electronic means, certain welding applications were considered to be impracticable. However, there are now few metals or alloys that cannot be successfully welded together, and new techniques are constantly being devised. It is worth bearing in mind that in this instance, the use of electronic control does not provide merely an improved method of resistance welding. In most cases, successful welding of almost all metals and alloys other than mild steel is impossible without the precision control afforded by the use of electronic equipment.

The process of resistance welding is one of producing a localized union of two or more pieces of metal. Current is passed through the pieces under certain conditions of mechanical pressure, and the electrical resistance to the current flow generates sufficient heat to melt the metal at a localized spot. The molten metal intermingles and a sound fusion results. There are two broad classifications, Lap welding and Butt welding. In the first case the current is passed through overlapped metal pieces by means of electrodes contacting the metal on opposite sides. The electrodes may consist either of specially shaped rods, in which case the weld is in the shape of a spot, or of discs or wheels which permit the production of a series of overlapping spot welds to make a seam. Also included in the category of Lap Welding is a process known as Projection Welding in which the path of the current is localized by projections on one or both of the work pieces. Flat-faced electrodes are used to pass the current to the work pieces, and to impart pressure to them when the metal of the projections reaches working temperature. The second classification of Butt Welding is a process of consolidating two pieces of metal held in butting contact through which current is passed under certain conditions so as to melt the metal and effect fusion.

As the electronic controls to be described are all intended for use with the Lap Welding type of resistance welding, details of the Butt Welding techniques will not be given.

2. Fundamentals

In essence the welding equipment consists of a weld transformer with a low voltage secondary winding (1 to 10 volts) capable of producing a very heavy current. Flexible arms pass the current to two electrodes which are designed to make good electrical contact with the metal to be welded. The electrodes are provided with some means of forcing them against the overlapping work pieces, and in most cases a pneumatically-operated ram is used for this purpose. At the weld point internal shrinkage of the metal usually occurs and prompt mechanical follow-up is necessary in order to ensure continued intimate contact between the electrodes and the work pieces. For this, and for several other reasons, adequate electrode pressure is essential for good welding results.

Some form of current interrupter is required and this may be electronic or mechanical. The

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electronic " contactor " consists of two ignitrons connected in reverse-parallel, or, in the case of a very small welder, two thyratrons are utilized. Magnetically-operated contactors are very commonly used with welders of mild steels, but they have severe limitations and are usually discarded where any other type of metal is required to be welded. The limitations are discussed in a later section.

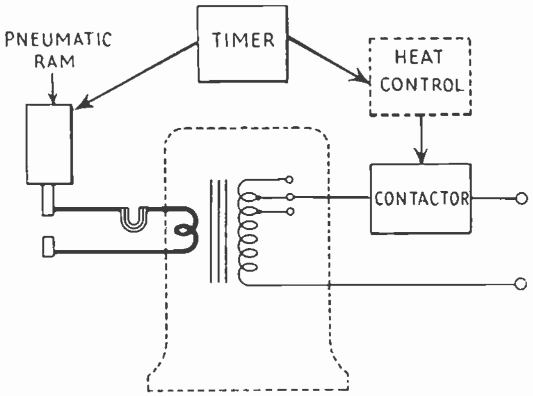

Fig. 1.—Schematic diagram of a pneumatically operated spot welding machine.

A timer to govern the operation of the contactor is also necessary and this may be of any sort from a simple " on-off " timer to a complex control also used to regulate the mechanical as well as the electrical operations in a related sequence. Coarse control of weld-heat is always provided by means of tappings on the weld transformer. However, if an ignitron contactor is used then a fine and smoothly variable control of weld heat may be obtained by phase-shifting the firing angle of the ignitrons.

Some heat is inevitably produced at the point of contact between the electrodes and the work. In extreme cases this could result in the electrodes sticking to the work, so to prevent this and to prolong the life of the tips, the electrodes are water-cooled. A pipe is passed almost down to the end of the hollow electrodes and water forced through it. Thus, a flow right down to the tip, where the amount of heat is greatest, is ensured.

A foot switch for starting the welding sequence is provided, together with a safety or weld/no weld switch, so that the operator may carry out a check on the mechanical sequence without any current flow taking place.

There are very many factors which have an important bearing on the quality of the weld but these are usually the problems of the welding engineer, the metallurgist, or the mechanical engineer. The electronics engineer is normally called upon to solve only the problems of :—

1. Controlling the current flow through the welding transformer primary.
2. Governing a sequence of operations of a simple or complex system of pneumatic or hydraulic rams operating the electrodes.
3. Controlling the sequence of both the current flow to the welding transformer (which may include the problem of varying both the value and rate of change of the current in a pre-determined manner), and the mechanical operation of the electrodes in an inter-dependent sequence.

The first two problems usually resolve themselves to that of feeding current of a pre-determined value, but of adjustable duration, to a contactor or relay. In the first case the contactor controls the electrical circuit of the welding transformer, and in the second the relay operates the air or hydraulic valves. The operating coils of the relays or contactors constitute an inductive load — a very significant factor which is often forgotten when considering electronic equipment. The effects of the inductance of the operating coils on their operating characteristics, together with the significance of the inductive nature of a weld transformer as a load, will be referred to later.

3. Controls in Common Use

To give some idea of commonly used controls, and their sequences of switching, a schematic illustration is given in Fig. 2. The rises represent current flow through the weld transformer, the height indicating the value of the current, and the width of each rise representing the duration of the flow. The first example is that of spot welding, in which the current is switched on for a pre-determined period to make a weld. The work-pieces are then removed and others substituted. Weld current flow is again initiated and another weld is made.

Seam welding is, of course, a series of overlapping spot welds made on a machine using circular electrodes. Electronic controls govern the " on " time of weld current flow and also the number of cycles of " off " time. This is usually from 1 – 25 cycles on and 1 – 25 cycles off, both being adjustable in one-cycle steps.

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Programme control, in which the weld current is reduced to a lower value after a pre-determined time without interrupting the current flow, is generally used for welding aluminium alloys. This is shown in Fig. 2c. The total weld time is usually adjustable from two cycles upwards, the time of the "initial" current and the "final" current being variable in one-cycle steps. The actual values of the "initial" and "final" currents are independently variable.

A very similar control is the "sequence" control in which there is an actual "off" time in between the initial weld current and the final current. This form of control is particularly useful for welding the high-tensile type of steels.

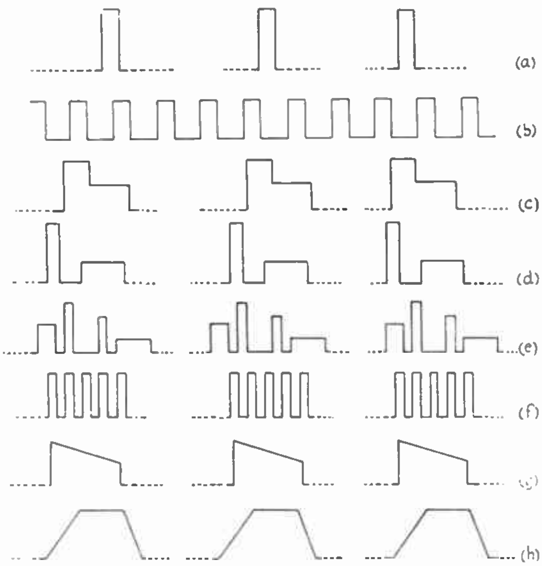

Fig. 2.—Pictorial representations of various types of welding operations. The rises represent weld-current flow.
a, Spot ; b, Seam ; c, Programme ; d, Sequence ; e, Long Sequence ; f, Woodpecker ; g, Slope ; h, Programme Slope.

Although these steels have been spot welded by non-electronically controlled machines, the spot welds are liable to fail under certain stress conditions and in the past satisfactory results have been obtained only by resorting to large numbers of welds for each joint. The present method consists of making a short weld with a few cycles of current and then allowing a very critical and definite "off" time in which the welded metal cools quickly to become brittle. A second pulse of current is then used to temper this brittle structure. The entire cycle of weld time – off time – temper time is made with one contact of the electrodes and with one setting of the control. Independently variable control over each time factor and also over each separate weld current flow is provided.

A further refinement occasionally used is the addition of a preheat, forging, and grain refinement, period. This is sometimes necessary when welding mild steel to light gauge medium-carbon, medium-alloy steel plate. The complete cycle then consists of: 1. Pre-heat. 2. Cool and forge. 3. Weld. 4. Cool and forge. 5. Grain refinement. 6. Cool and forge. 7. Temper.

In such cases the electrode pressure is usually the same for all heating periods but during the cool periods it is increased by 50 per cent. Each heating period and each cooling period, together with the value of each current flow, is independently adjustable. Because of this possible variation in current values the "sequence" and "long-sequence" control differs from the pulsation or "woodpecker" technique of welding. In this latter type, shown in Fig. 2f, a complete weld is made by using a number of impulses of current. Each impulse, which may be of anything from one to several cycles duration according to the application, is followed by a definite period of "off" time in which no current flow takes place. The woodpecker control provides, perhaps, one of the most versatile of all applications of electronic control and the process is being recognised as an increasingly important one. The advantages, which are particularly evident when a control is added to an existing machine, are that thicker material can be welded on the same machine, and that a multiplicity of thin sections may be spot welded together. Considerable improvement in the quality of the weld and extension of the life of the electrodes is also obtained because the water cooling of the electrodes is more effective. While the weld current is interrupted the electrode tips are cooled and yet with thick metal work pieces the temperature of the weld nugget is very little influenced by the water cooling in the short "off" time. This makes the spot welding of heavy sections possible and greatly extends the life of the electrodes. A typical woodpecker control allows the duration and value of the current, and the number of spots, to be set independently.

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One of the newest forms of control is " slope " control, in which the current is gradually reduced at a predetermined rate or " slope " from a maximum set value. This is a refinement of the programme control already mentioned and is particularly beneficial when spot welding aluminium. Yet a further refinement is the Programme – Slope control, in which a controlled rate of current build-up to a set maximum is followed, after an adjustable time of maximum current, by a pre-set reduction at an independently variable rate.

3.1. *Automatic Controls*

Many controls are designed so that automatic compensators for voltage or for current variations may be added. The former control makes automatic and continuous correction for variations in supply voltage, and the latter compensates, in addition, for any variations in weld current caused by the work itself. This is very necessary when welding longitudinal seams on drums or tubes, for the current will vary as the work is passed into the throat of the welder.

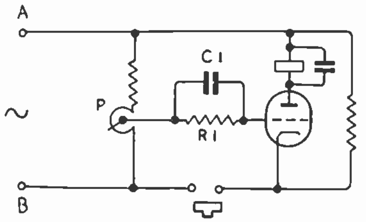

Fig. 3.—Schematic diagram of the basic time-delay circuit.

The arms of the machine, the electrodes, and the work, effectively make-up an air-cored loop which will have a certain value of inductance referred to the primary of the weld transformer. As more of the drum or tube enters the throat it acts as an iron core in the inductive loop. The eddy currents which are set up increase the magnetizing component and thus increase also the inductance of the transformer load upon the power supply. The line current and the weld current, therefore, decrease as the tube continues to be inserted into the throat of the machine.

In one example of such conditions the line current dropped from 350A to 250A, i.e. by 29 per cent. The weld heat, however, is proportional to the square of the current, or in other words, the drop in heat was 49 per cent. This is obviously unacceptable and so automatic electronic compensators were used to maintain a constant secondary current irrespective of the conditions of welding.

There are, of course, very many other types of control, and new welding techniques are being evolved almost every year. However, the controls mentioned are fairly standard and are all available commercially.

4. Electronic Timing Circuits

Many electronic timers and sequence controls are based upon the circuit shown in Fig. 3. This has already been described in detail elsewhere and so only brief references to its operation will be made. When point B is at a higher potential than A, current will flow through the potentiometer P and R1, through the grid to the cathode of the valve, and then via R2 to point A. The voltage drop across R1 will charge the capacitor C1 such that the grid is negative with respect to point B. When the start button is pressed C1 will begin to discharge and after a time, depending upon the setting of the potentiometer P, the valve will pass current and operate the relay in its anode circuit. The circuit shown acts only as delay-circuit since no operation of the valve or the relay takes place until a set time after the closure of the initiating switch. There is a disadvantage in that, once the operation has been started, any drop in supply voltage affects the delay-time. Also, the starting contacts are at the potential of point B, which might lead to difficulties under certain conditions.

4.1. *Opposing-Voltage Discharge R-C Circuit*

An interesting variation of the standard R-C discharge circuit is given where a capacitor, charged to an initial voltage V_0 is discharged by an equal voltage of opposite polarity. The voltage at any given time, v, across a capacitor C initially charged to a voltage V_0 and being discharged through a resistor R, is given by the well-known equation

$$v = V_0 \, e^{-t/RC} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

When v falls to a value V_0/n

then $\quad 1/n = e^{-t/RC} \ldots\ldots\ldots\ldots\ldots\ldots (2)$

or $\quad t = -RC \log_e 1/n \ldots\ldots\ldots\ldots (3)$

However, if the capacitor is discharged through a resistor R against an opposing voltage $-V_0$ then obviously $1/n = 1/2$ and the

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charge on the capacitor falls to zero after the time

$$t = 0{\cdot}693\ RC \quad \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Note that the time is completely independent of the initial voltage V_0.

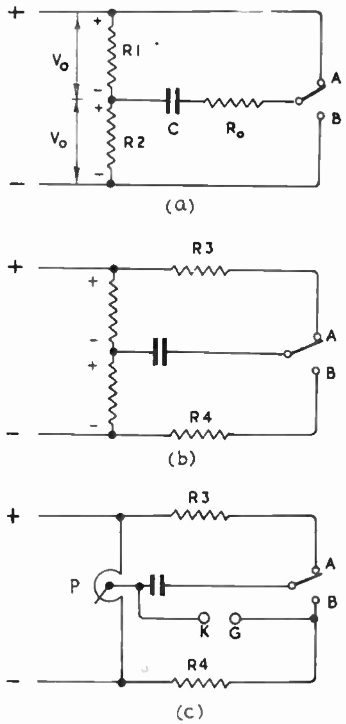

Fig. 4.—(a) Basic principle of "opposing-voltage discharge" circuit.
(b) Variation of (a).
(c) Practical arrangement of the basic circuit so as to control a valve.

A practical application of this is shown in Fig. 4c, with the circuit altered slightly and where the ratio of the charge voltages is varied by means of a potentiometer, P. The grid of a thyratron may be connected to point B, and the cathode connected to the sliding arm of the potentiometer, and thus, when the contacts are in position A the grid is negative with respect to the cathode. If the contacts change over to position B and the grid is immediately raised positive to the cathode for a time depending upon the value of R4 and the discharge voltage, which is governed by the setting of the potentiometer.

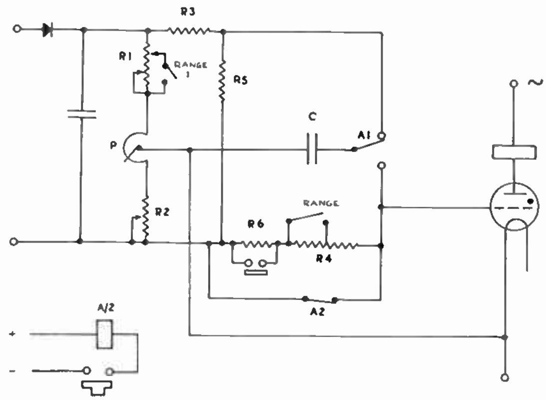

Fig. 5.—Schematic diagram of a timer based on the circuit of Fig. 4c (Brit. Pat. No. 463561).

A timing circuit in general use based on this principle is illustrated in Fig. 5. R1 and R2 are now made adjustable for setting the various time ranges, or to compensate for component variations. R5 is a bleed resistance in order to keep the load on the d.c. supply voltage constant. R6 is a high resistance which is put in series with the fixed timing resistor R4. This is short-circuited by means of contacts on the power-relay in the anode circuit of the valve. Thus, the timing period, to all practical purposes, does not commence until the relay is fully closed and R6 is shorted out. Note that the timing resistor R4 and the delay resistor R6 are normally short-circuited by contacts on the initiating relay. This is in order to prevent the grid circuit from having too high an impedance during stand-by conditions, which might lead to spurious operation of the valve from minute transient voltages either direct from the line or induced in the circuit from external radiations.

5. Sequence Control Circuits

Electronic sequence controls are often built up from the delay circuit already mentioned and shown in Fig. 3a, and the connection for a typical sequence of Squeeze – Weld – Hold – Off is shown in Fig. 6. The complete delay circuit is shown in (a) but is represented in Fig. 6b by the rectangles marked TD1, TD2, etc. Connections 1 and 3 are the supply voltage connections, and points 12, 22, 32, etc., are the connections which, when short-circuited to point 1, start the appropriate delay time. At the end of this time the relay associated with the

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circuit is energized, the contacts being shown outside the appropriate rectangle.

Closing the initiating switch S1 completes the circuit from 1 through the normally closed contact, TD3a, to energize contactor CR1. CR1c energizes the solenoid valve of the pneumatic ram which operates the welder electrodes. At the same time contact CR1a locks-in the S1 contacts, thus keeping the contactor CR1 energized even though the starting switch is released. When the normally open CR1b contact completes the circuit to 12 on TD1 time-delay relay, this starts TD1 measuring out a squeeze time so as to make sure that the electrodes have time to apply enough pressure. At the end of this time TD1 contacts complete the circuit to contactor CR2 which is usually the main power contactor for the welder. At the same instant another TD1 contact TD1b completes the circuit to 22, starting TD2 to measure out the weld-time. At the end of weld-time, TD2 relay opens its normally closed contact in the CR2 circuit which opens the weld contactor and ends the current flow through the welder.

Weld timer TD2 also closes a contact to complete the circuit to 32 and starts TD3 to measure out the hold-time, during which time the electrodes maintain their pressure on the weld spot. At the end of this hold-time TD3 opens its normally closed contact in the CR1 circuit, and this de-energizes the air solenoid valve, letting the welder electrodes separate and releasing the work. Although this also opens the CR1a contacts across the start relay the TD3 relay is still energized through its own contact in the TD3 start circuit, provided the operator still holds the starting-switch closed. However, if switch S2 is open for non-repeat welding the welder will not work again until the operator releases S1 and then re-closes it. Here S1 opens the circuit to TD3 which allows the TD3 relay to drop out and re-close its normally closed contacts in the CR1 circuit. When the start-switch is again closed by the operator a new weld sequence is commenced to make another spot weld.

If S2 is closed to give repeat welding the whole sequence is as already described up to the time when TD3 operates its contacts. While S2 is closed TD3 not only drops out contactor CR1 but another TD3 contact completes the circuit through S2 to start TD4 measuring out the "Off" time, during which the electrodes are away from the work. Another TD4 contact

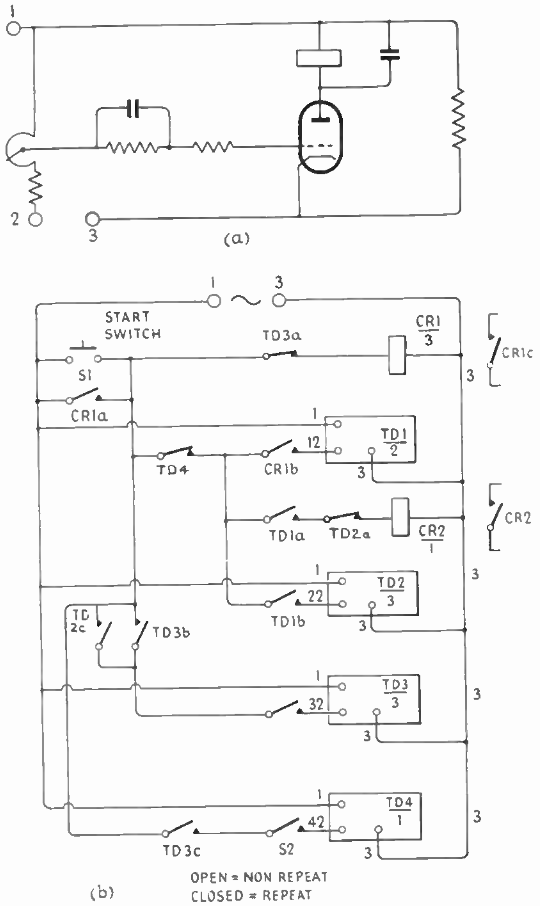

Fig. 6.—Schematic diagram of a four-stage sequence control.
(*a*) *The circuit of the time-delay unit.*
(*b*) *The relay connections of the circuit.*

is arranged to keep the circuit energized even when TD2 drops out. The complete operation will be repeated as long as the operator keeps S1 closed. If S1 is opened while the electrodes are together the electrodes will not separate until after the usual "Weld" and "Hold" times have passed.

5.1. *Double-acting Delay Circuit*

An ingenious development of the basic delay circuit already mentioned is shown in Fig. 7. Although this uses only one valve and one relay, two independently variable delay-times may be obtained. With the circuit arranged as shown the thyratron is non-conducting since

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the grid is held 90 volts negative with respect to the cathode. If the two changeover contacts are moved to position (2) then no immediate change will occur. C1, however, will discharge at a rate depending upon the setting of P1, and the potential of the grid of the thyratron will be raised until it approaches sufficiently close to that of the cathode when the thyratron will fire. If the contacts are now moved back to position 1 the thyratron will continue to conduct since C2 has now been discharged through R1 and the grid potential is temporarily held higher than that of the cathode. C2, however, will now charge at a rate depending on the setting of P2, and the grid potential will be reduced until it becomes negative to the cathode again, and the thyratron will cease to conduct once more. If two circuits based upon that shown in Fig. 5 are used, together with the changeover contacts of one circuit being controlled by the relay of the other circuit, it is possible to build up a sequence control with four independent time delays to meet the requirements of Squeeze – Weld – Hold – Off as before.

With this double-delay circuit, or the simple circuit of Fig. 3, almost any type of complex sequence may be built up. However, the problem then becomes one of sequential relay switching rather than an electronic one and so will not be discussed here.

6. "All Electronic" Control Circuits

Because of the faster operation of electronic devices, together with the absence of moving parts and the consequent reduction in maintenance, there is tendency to reduce the number of mechanical relays in sequence controls. Several interesting circuits have been developed and the principle of one of these is shown in Fig. 8. A series of thyratrons, all with common cathode connections, is arranged with each thyratron having an independent a.c. anode supply. In the circuit shown V1 is initially passing current, and the rectifying action of the valve charges C1 to a polarity which holds the grid of V2 negative with respect to its cathode. V2 is effectively held non-conducting with the result that C2 has no charge whatsoever. V3, therefore, also passes current to charge up C3. If the grid of V1 is now made negative to its cathode then V1 ceases to pass current, and C1 will commence to discharge at a rate depending on the setting of P1. At the end of this time, when C1 is fully discharged, V2 will conduct. This will build up a negative charge on C2 and cut off V3, and C3 will then commence to discharge. Thus each pair of valves constitutes a delay circuit, and it is possible to build up any sequence as required.

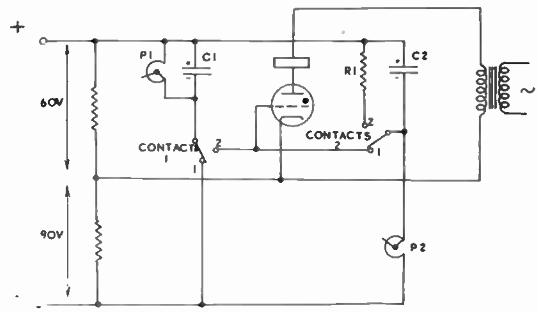

Fig. 7.—Schematic diagram of a double-delay circuit.

The complete circuit for a four-time sequence control based on this principle is shown in Fig. 9. Each valve has its own a.c. anode supply. V1 controls a magnetically-operated relay for the air-pressure solenoid and V3 governs the weld-contactor. It is possible to eliminate even these two relays if desired, but this circuit is a standard one designed to be added to existing welding machines without alteration.

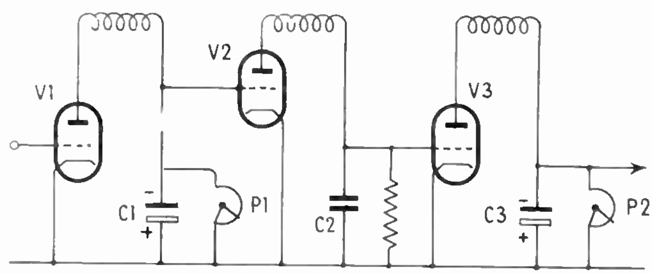

Fig. 8.—Basic principle of an "all electronic" delay-sequence circuit.

With power switched on, but before the sequence of operation is commenced, V2, V4 and V6 pass current. The negative charges on C2, C4 and C6 hold V3, V5 and V7 respectively non-conducting. Notice that all the valves have

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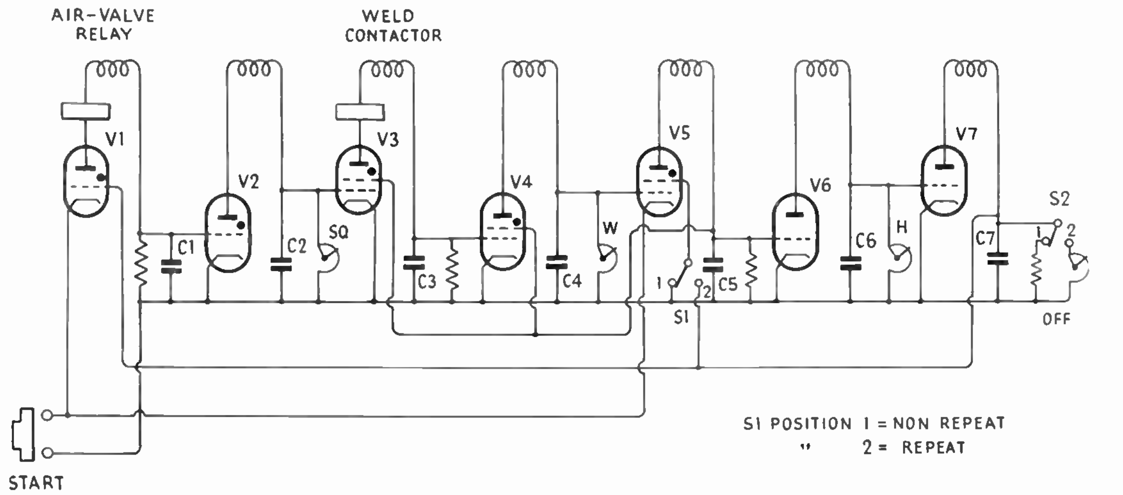

Fig. 9.—Schematic diagram of a four-stage Squeeze-Weld-Hold-Off sequence timer using the principle of Fig. 7.

a common cathode connection with the exception of V1 and V5. The reason for this will be explained later. When the start button is pressed the cathode circuit of V1 is completed and the valve will immediately pass current since its grid is held at its cathode potential while C7 is completely discharged. When V1 fires, the air-pressure solenoid is actuated, and the electrodes close on to the work. C1 will charge up and its negative potential will cut off V2. C2, therefore, will immediately commence to discharge at a rate depending on the setting of the squeeze-potentiometer. At the end of this squeeze-time V3 will pass current and initiate the weld-time by energizing the magnetic contactor. C3 will now charge up and cut off V4, which in turn will prompt C4 to discharge through the "weld-time" potentiometer. At the end of this weld-time, V5, which also has its cathode circuit completed through the start contacts, will fire, and the charge at C5, which cuts off V6, also cuts off V3. This ends the weld-time and the main contactor is now opened. When V3 ceases to pass current V4 would normally start firing again. A connection from C5, however, is also made to the screen grid of thyratron V4, which prevents it from passing current. This locks-in V5. When V6 is cut off C6 discharges at a rate depending on the hold-potentiometer and at the end of this time V7 will fire and charge C7. Notice that C7 is connected to the grid of V1 which is now cut off and the air pressure solenoid is opened. With the switch in the non-repeat position, as shown, the sequence is completed and even though the start contacts are held closed no further action takes place until the start switch is opened again. This releases the locking-out action of V5 and V1, and current is again passed by V2, V4 and V6. The circuit is now reset and ready for the next sequence of operation.

With the switch in the Repeat position, the action is exactly as described up to the operation of V7. When C7 is charged up it also cuts off V5 as well as V1. The circuit is now in the condition that V1 is cut off and V2 is passing current so as to charge up C2. V3 is cut off, both due to the action of V4 charging C4 and also to the screen grid being held negative by the charge of C7. V6 passes current since V5 is cut off, and this cuts off V7. The action of this entire sequence takes place so quickly that V7 only passes current for one half-cycle, so that although C7 is fully charged it immediately starts discharging at a rate depending upon the setting of the Off-time potentiometer. At the end of this time V1 will pass current again to operate the air-pressure solenoid and start the mechanical and electrical sequence once more. The screen grid of V5 is returned to normal and the circuit is now ready for another complete cycle of operation.

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7. Synchronous Control

As has already been mentioned, a welding transformer represents an inductive load on the power supply system and, therefore, the problem of switching-current surges assumes major importance. Considerable distortion of the current wave may occur when the circuit to the weld transformer is first closed. Theoretically the magnetic flux may be forced to double its normal maximum value, but as this often takes the iron beyond the knee of the magnetization curve, it follows that the magnetizing current is increased to a very much greater extent. The extent of the surge depends, (*a*), upon the point with respect to the voltage at which the connection is complete, and (*b*), upon the magnetic state of the transformer core immediately before the circuit is closed.

The critical point of current initiation (and it is critical to the limits of a few electrical degrees or 1/2000th of a second with 50-c/s supplies) is at the power factor angle of the transformer, which is the angle at which the current lags the voltage under normal conditions. This is by far the most important of the two factors mentioned which determine the extent of the initial switching surge. However it must not be forgotten that when the current in a transformer ceases it may leave some residual flux in the core. This flux does not immediately fall to zero but takes a finite time to decay and which may be several seconds. If the direction of the residual flux happens to be in the direction such that it may add to that generated by the new magnetizing current, abnormal surges up to 30 times normal may occur. The current rushes consist of very large positive half-waves followed by very small negative half-waves, each succeeding wave approaching more nearly to the normal, until finally the two half-waves become equal. The time to reach normal may be from several seconds to several minutes, although the very excessive initial current is generally of short duration. Nevertheless, fuses may be blown or the windings subjected to severe stress.

Since the weld heat is proportional to the square of the current, it may be appreciated why synchronous switching, which avoids the danger of these transients, is so necessary. It is only on mild steels that the tolerance of heat, or the duration of weld current flow, is so great that the current surges may be ignored. Mechanical contactors, therefore, are unsuited for the precise control of weld current required when non-ferrous or stainless steels are to be welded. The contacts cannot be made to close in synchronism with the supply voltage with the accuracy required. Local transient currents in the operating coil make the actual closing speed difficult or even impossible to predict, and although this can sometimes be overcome, there is still the insurmountable difficulty of measuring out exact periods of weld time. The prolonged arc drawn out at the contactor tips results in an unpredictable duration of current flow, so that an electronic control becomes essential for all cases of non-ferrous metal working.

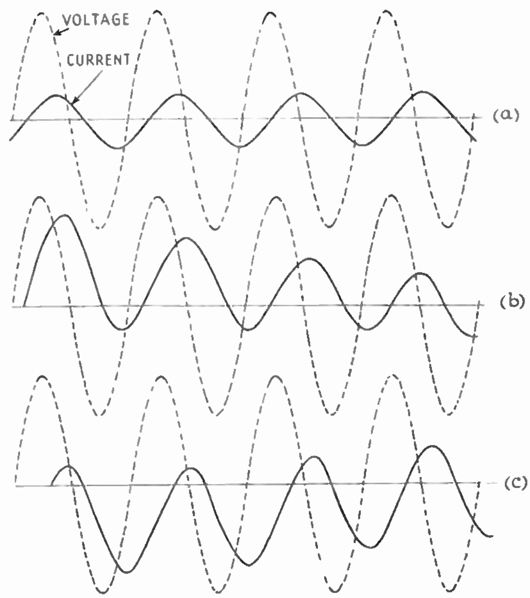

Fig. 10.—Voltage and current relations for a weld transformer.
(*a*) *Where the current flow starts exactly at the p.f. angle.*
(*b*) *Transient currents caused by starting the weld current ahead of the p.f. angle.*
(*c*) *Transients caused by starting the current behind the p.f. angle.*

When considering the effect of transient currents the surges themselves present no serious problem provided they are predictable or of a consistent value. As may be seen from Fig. 10, starting the current flow behind the power factor angle creates a smaller than normal positive current surge but a large negative surge. If current were to be permitted to flow only in half-cycle pulses, then the effect of starting a half-cycle of current behind the power factor angle would only be a smaller than normal pulse. By repeating this for the opposite half-cycle, but again delaying the start of the current behind the power factor angle, a similar smaller than normal pulse would be obtained. This method of controlled smaller than normal transient switching is easy to provide using electronic valves, for the firing of a thyratron or an ignitron may be delayed to any desired point. Variations in the firing point obviously regulate the magnitude of the current pulse. When this occurs exactly at the power factor angle, the two current pulses join up to make a complete sine wave, but by delaying the ignition points of a pair of valves connected in reverse-parallel, the average value of the current may be considerably reduced. This method of shifting the firing angle of a pair of valves is usually known as Heat Control, and since the current is started at a point which must bear some exact relationship in respect to the voltage, the method of switching is known as Synchronous Control.

The danger of any residual flux in the core of transformer adding to that of newly generated flux has already been mentioned. To avoid this it is essential that the polarity of a new current pulse is opposite to that of the current pulse which ended the last weld. In other words, the current must consist of an equal number of positive and negative pulses. This is achieved by means of circuits known as Leader-Follower circuits, in which one valve only, known as the Leader valve, is under control by the initiating device. Another valve, known as the Follower, is so arranged that it cannot pass current until the Leader fires, and thus for every half-cycle that the Leader passes current the Follower duplicates the action.

The basic principle of the fully synchronous electronic welding control may now be given, and is shown in Fig. 11. A pair of ignitrons connected in reverse parallel is used as a main power switch, and may be considered to be the electronic equivalent of the mechanical contactor. In fact the unit is commonly referred to as an Ignitron Contactor. An ignitron is a mercury pool valve with a water-cooled stainless steel jacket. Electron flow to the heavy graphite anode is initiated by means of a pulse of current of about 40 amperes through a pointed ignitor of carborundum, or similar semi-conducting material, permanently immersed in the mercury pool. The heavy current sets up a high potential gradient at the tip of the ignitor, which releases a few electrons from the mercury. Provided that the anode is at a suitable potential an arc is struck up between the cathode and anode. Ignition takes place within a few micro-seconds so that the total ignition-power demand is small. Current flow is extinguished each time the anode potential falls below the arc voltage drop and must be re-started every half-cycle.

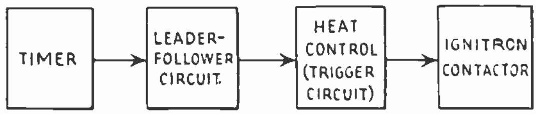

Fig. 11.—Basic principle of a synchronous weld-control.

Power for the ignitors is usually drawn from the anode supply and is controlled by means of a thyratron. Thus each ignitron has a trigger thyratron connected between its anode and ignitor. The heavy current has to pass through the thyratron for a few micro-seconds only, for the moment the ignitron fires the potential across its anode and ignitor is only the few volts of the arc drop in the ignitron, and the ignition current falls to zero.

The pair of trigger thyratrons together with their own phase-shiftable firing circuits are usually mounted on a self-contained panel and the unit is known as a Heat Control Panel.

7.1. *Trigger Circuits*

The trigger thyratrons across the ignitrons are usually fired by means of a pulse of voltage from a peaking transformer. This is a transformer with a secondary winding wound on a small core of mu-metal or similar material. The core is arranged so that it becomes saturated very quickly, and thus a change of flux occurs only at the beginning and the end of an applied sine wave of current. The secondary voltage has a sharply peaked wave form which, by careful design of the transformer, can have a steep front. The current in the peaking transformer lags far behind the voltage, and the secondary peaks, which are in phase with the magnetizing current, usually need correcting by some means to bring them not more than 45 deg. behind the anode voltage of the trigger thyratrons. This may be done by phase-shifting the supply to the peaker or by tuning the peaking transformer.

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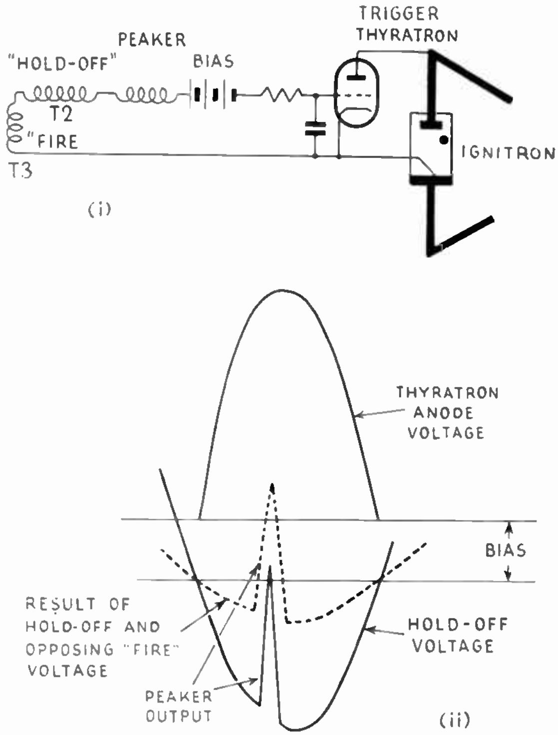
A standard variable R-C phase-shifting circuit is used to vary the peaks with respect to the main supply voltage and so adjust the firing angle of the trigger thyratrons. Since each ignitron, and hence its associated trigger valve, is at a different potential from its fellow, the circuit of each thyratron is entirely separate. Thus, in Fig. 12, the circuit for only one trigger valve is shown, since the other valve has a duplicate circuit. This is a very common arrangement, in which the output from a secondary winding of a peaking transformer is biased by means of an a.c. sine wave greater than the peaks. A " firing " voltage opposing the bias or " hold-off " voltage partly cancels the effect of the hold-off whenever it is desired to fire the thyratron.

A variation of this circuit is shown in Fig. 13a, where the peaker is replaced by an ordinary transformer, T1. A phase-shifting network, not shown, may adjust the angle of lag of the output of T1, which is applied direct to the grid of the trigger thyratron V1. Voltage from another transformer, T2, is also applied to the grid through a diode V2. The T2 voltage is out of phase with T1 and in effect the T2, V2, circuit acts as an a.c. limiter. Thus, the grid voltage of V1 is as shown in the heavy line of Fig. 13b, and V1 does not fire.

A third transformer winding, T3, however, is included in the circuit, and is arranged that when it is energized it opposes T2. Thus, by switching power to T3, the sine wave of T1 is allowed to fire V1 at a point depending upon the angle of lag of the T1 voltage.

7.2. *Leader-Follower Circuits*

As has been shown in Fig. 13, the trigger circuits need to be governed by a voltage from a transformer winding in order to ensure that the trigger-valves fire in the correct order. Since the trigger-valves must pass an equal number of positive and negative half-cycles of power to the ignitron ignitors, the " firing " transformer, T3, of Figs. 12 and 13, must be fed with current in the form of complete cycles. Two basic circuits, shown in Figs. 14 and 15, are in general



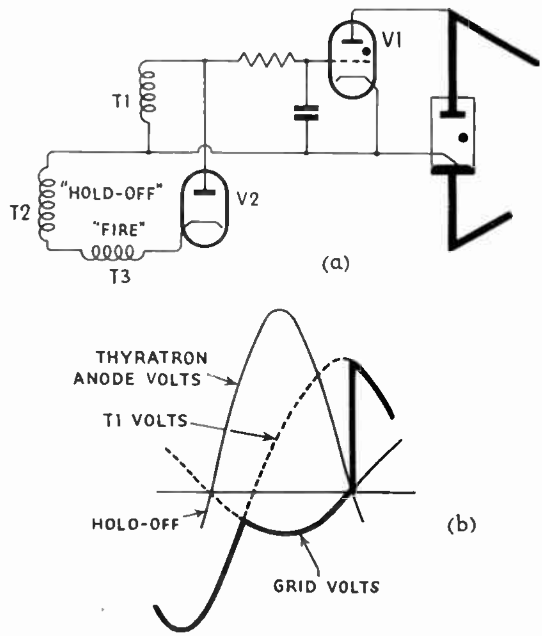


Fig. 12 (top right)—Ignitron trigger circuit using a peaker transformer.

Fig. 13 (bottom right)—Ignitron trigger circuit using an ordinary transformer as the initiating device for the trigger thyratrons.

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use for this purpose, and are known as Leader-Follower circuits. The follower valve V2 is so arranged that it cannot fire until the leader valve has fired, and then can fire only for one half-cycle immediately following a half-cycle of current passed by the leader valve V1.

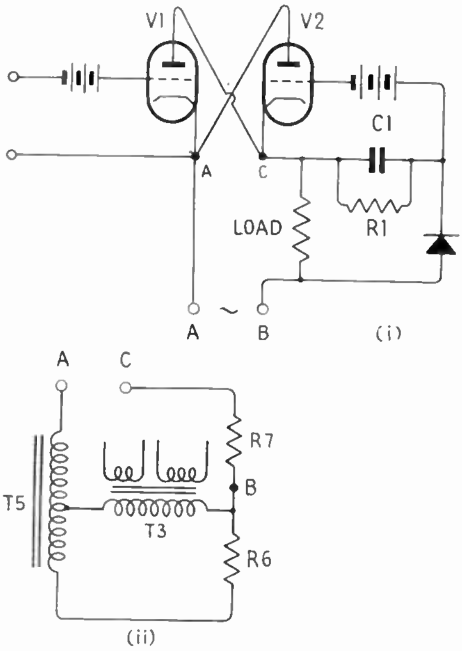

Fig. 14.—Schematic diagram illustrating a leader-follower circuit for resistive loads.

In the circuit of Fig. 14a, V1 and V2 are shown connected in reverse-parallel and power is applied via a load resistance. The valves are prevented from firing by a bias voltage in each of their grid circuits and, therefore, no current flows through the load. If V1 is permitted to fire, by temporarily reducing its grid bias, current will flow through the load from B, through the anode of V1 down to A. Some current will also flow through the rectifier and R1 and C1 will charge up. The polarity of this charge will be such as to oppose the bias voltage in the grid of V2, so that when the alternating current reverses polarity, the positive potential of the V2 grid permits V2 to pass current. C1 and R1 are so proportioned that the charge on the capacitor leaks away within the time of one cycle so that unless C1 is re-charged by a subsequent firing of V1, the bias regains control and V2 passes current for only one half-cycle. Thus for every half cycle that V1 passes current through the load, V2 duplicates the action during the following half-cycle.

This circuit is used in conjunction with that of Fig. 14b. A centre-tapped transformer has the "firing" transformer, T3, connected to it in such a way that current is fed to T3 via resistor R6. A resistor of equal value, R7, is arranged so that when points A and C are connected together, the effect is that of a voltage-divider being placed across the transformer winding of T5. Since the resistors are of equal value, there is no voltage from the centre tapping to the common terminal of the resistances when A and C are shorted together, and the voltage of the T3 winding is reduced. The output of T3 is normally used as the "hold-off" a.c. bias in the trigger circuit of Fig. 12 and reduction of this hold-off voltage permits the trigger valve to fire. If the leader-follower circuit of Fig. 14a is connected to points A, B and C, the transformer T3 can have its voltage output reduced in periods of complete cycles, as is required for governing the trigger-valves in the desired leader-follower sequence.

The circuit just described is suitable only for resistive loads and where it is desired to have a leader-follower arrangement with an inductive load the circuit of Fig. 15 is used. Here, a transformer, T4, is connected across the load-transformer T3, with its secondary winding arranged so as to duplicate in the V2 grid circuit the voltages of the inductive load. When V1 fires this voltage is initially of the same polarity as the grid bias of V2, but it eventually changes its polarity at the end of the half-cycle. With a purely ohmic load, the voltage across it would, on reaching zero, remain there. However, under the influence of the magnetizing current of the transformer T3, which does not change its direction until a lagging phase displacement of about 90 deg. has occurred, the load voltage begins to increase again until the magnetizing current becomes zero. This voltage peak serves to overcome the bias of V2 and enables the valve to pass current. Just as in the circuit of Fig. 14, the follower valve, V2, cannot fire until the half-cycle after V1 fires and even then may do so only for one half-cycle after V1 ceases to fire. Transformer T3, therefore, is fed with only full cycles of current consisting of equal numbers of positive and negative half-cycles.

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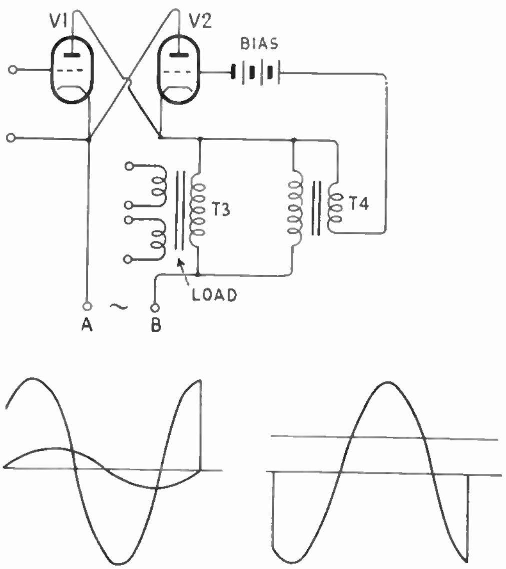

Fig. 15.—Basic principle of a leader-follower circuit for inductive loads.

7.3. *Precision Timers*

It is often necessary to provide weld-times down to one cycle (1/50th of a second in a 50-c/s supply), and any of the standard R-C timing circuits may be used provided that the moment of charge of the capacitor or discharge, as appropriate, is accurately under control and is independent of the actual time of closure of the initiating contacts. This requirement is largely because leader-follower circuits are used after the timing control, for once a leader-follower circuit is started, it must complete its cycle. If a timer measuring out one cycle (i.e. 1/50th of a second) starts its period at the mid-point of a negative half-cycle of voltage, the leader-follower circuit will not measure out its once complete cycle until the beginning of the next cycle, which occurs a quarter of a cycle later. The end of the timing period, therefore, occurs in the mid-point of the next negative half-cycle. Thus, the timing period has to be one quarter of a cycle longer than normal (i.e. a tolerance of + 25 per cent.) before two cycles of weld current are measured out instead of the desired one. If the starting point of the timer is at random, and happens to occur just before the starting point of the leader-follower system, then the over-value tolerance is extremely small, and only a few per cent. over-normal will cause two cycles to be measured out by the leader-follower valves. For this reason the actual starting point, with respect to the sine wave of the supply voltage, is always accurately governed in precision timing circuits. The starting point is usually made to occur in a negative half-cycle so that the beginning of the next positive one triggers off the leader-follower circuit.

A typical precision timer is illustrated in Fig. 16, which gives the complete circuit for a synchronous spot-weld-control (see Section 8).

7.4. *Seam Weld Timers*

In order to provide pulses of voltage to control the leader-follower circuit for seam welding an asymetric multivibrator is generally used. Synchronization with the supply is accomplished by injecting a trigger voltage from a peaking transformer into the grid circuit of the valves, and to provide accurately rectangular output pulses thyratrons are generally used. The coupling capacitors are shunted by variable resistors, usually adjustable in steps so as to provide pulses of " on " time and " off " time in steps of one cycle of mains frequency. A common provision is from 1 to 30 cycles, in one-cycle steps. The basic circuit is completely standard and is familiar to most radio engineers and therefore will not be described here.

8. The Complete Circuit for a Synchronous Spot Weld Control

Figure 16 shows the full circuit for a complete synchronous spot weld control. Before describing the timing circuit, points about other parts of the circuit will be mentioned. The resistances R10 and R11 in the anode circuits of the thyratrons V5 and V6 are provided to limit the current through the thyratrons. Under no circumstances may the thyratrons used (usually type MT57 or MT5544 or equivalent) carry a peak current of more than 40 A, so that if the resistance of the ignitors fall below the normal value of between 10 – 150Ω R10 and R11 keep the current within safe limits. Small capacitors are provided between the grid and the cathode of all thyratrons to shunt any transient voltages that may be picked up in any of the grid circuits and which may cause unwanted operation of a thyratron.

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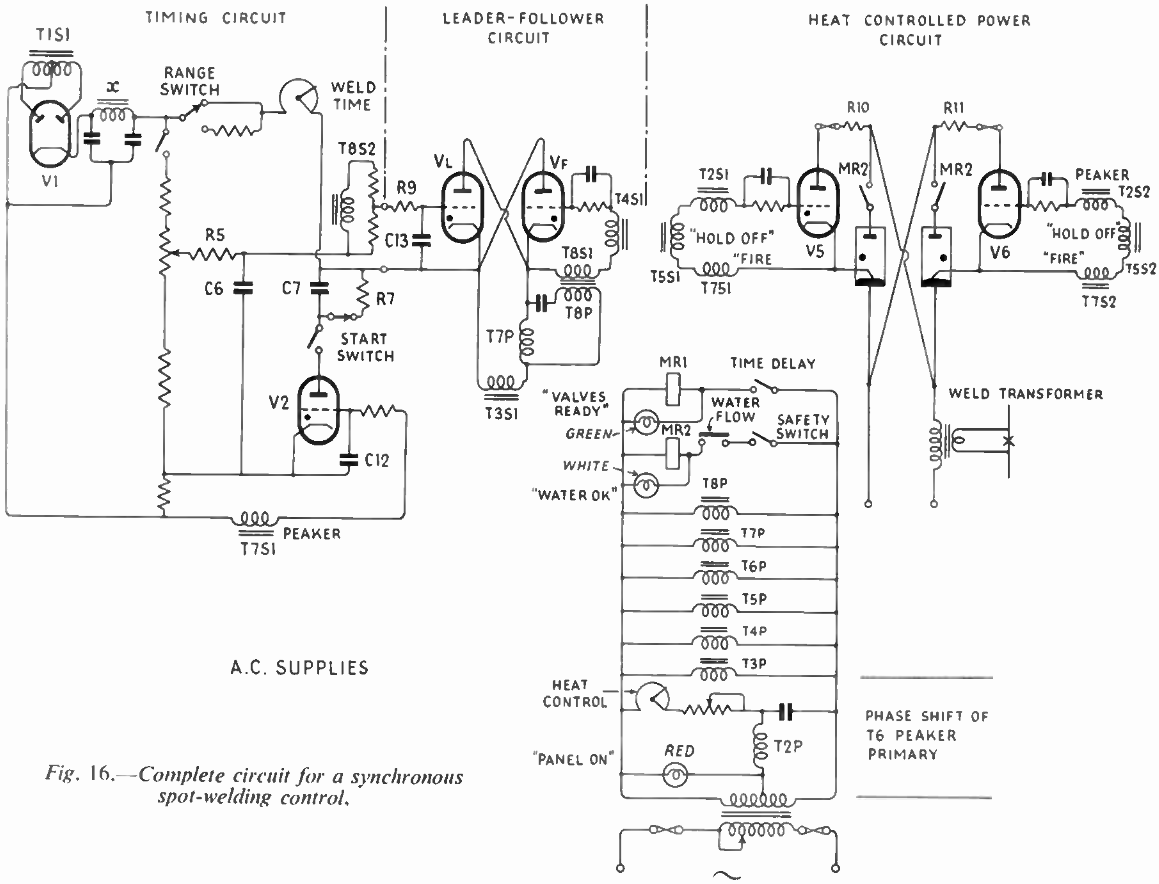

Fig. 16.—Complete circuit for a synchronous spot-welding control.

A.c. biasing arrangements are very often used and are shown in the circuit. This is of the grid leak type which lends itself to use with thyratron valves because of the heavy grid current which normally flows. There is, of course, no objection to using a standard d.c. bias and this method is often resorted to.

The timing circuit is built around a voltage ladder fed with d.c. The grid of the leader valve is connected to a point on this ladder at about 63 per cent. of the ladder voltage. Under stand-by conditions the cathode of the leader valve is connected to the top of the voltage ladder so that the grid is negative with respect to the cathode and the leader valve is held non-conducting. The operating principle of the circuit is to force the cathode negative with respect to the grid and then to raise its potential until it becomes positive to the grid again. When the start-relay contacts close a circuit is completed to the anode of a small thyratron V2 and, at a moment determined by the peaking transformer winding T2S1, the thyratron will fire. Since C7 is initially uncharged the cathode temporarily assumes a potential below that of the grid at a value depending upon the arc drop of V2. C7 will immediately start to charge through the weld-time rheostat and, after a time depending upon their relative values, the cathode potential will rise above that of the grid again. Since the grid is at a potential of approximately 63 per cent. above that to which the cathode may fall, C7 has to rise to this percentage of its charging voltage before the leader-valve ceases firing. The time, therefore, is dependent upon the time-constant, *R.C*, and the curve of voltage rise of the capacitor is linear for all practical purposes. Furthermore, since the voltage to which C7 must rise to pass the potential of the grid is a percentage of the charging voltage, it is obviously independent of the value of that charging voltage. The circuit, therefore, is independent of voltage variations either before or during the weld.

In the grid circuit of the leader valve a transformer winding, T8S2, is provided to inject a small out-of-phase voltage so as to ensure that the leader-valve fires either at the beginning of a half cycle or not at all.

R5 and C6 are provided to smooth out any unwanted sudden voltage dips which might be passed into the circuit from the mains supply. It often happens that where several welding machines are in use the supply voltage may have sudden voltage dips which although lasting for a very short time may affect the performance of electronic equipment.

Safety interlocks are provided to prevent the equipment from operating until the valves are correctly warmed up and ready for use, and a water flow relay ensures that the ignitrons have sufficient cooling water. Very often coloured lights are provided to indicate " Power on," " Valves ready," and " Water flow O.K.," and these have been shown in the circuit of Fig. 16.

Many of the newest designs are arranged so that the various circuits such as the heat control, the leader-follower circuit, and the timing circuit, are mounted on separate panels connected by means of plugs and sockets. Such construction means that a timing circuit for a spot weld machine can quickly be changed for a seam weld timer if desired. Furthermore, the panels may be quickly removed for maintenance or repair as necessary.

9. Slope Control

When undertaking certain welding operations, particularly with aluminium, it is desirable to vary the current in a pre-determined manner. This control of the rate of change or "slope" of the current is obtained by means of an electronic variable resistance in the standard phase-shift circuit of the heat control panel shown in Fig. 16. The effective resistance of a valve is reflected into the phase-shifting circuit through a full wave rectifier and matching transformer. The reflected resistance is changed by varying the grid voltage, and the effect of slope control is obtained by arranging that this varies between adjustable limits at a desired rate. The amount of phase shift is limited by the minimum resistance of the valve and its voltage and current ratings. If the phase shifter has a high impedance load then the maximum shift is of the order of 130 – 150 degrees.

This circuit is also used to provide automatic adjustment of current in response to supply voltage, or weld-current, variations. A signal is applied to the grid of the impedance valve in the heat-control phase shifting circuit, which is proportional to the error or variation of the voltage or current away from a reference.

10. Conclusion

Electronic control of resistance welding processes has now become firmly established as one of the most successful and versatile applications of electronic techniques to industry. A considerable amount of experience has been gained in many parts of the world and the circuits described have proved trustworthy even under the worst industrial conditions. The reluctance to accept valves and complicated electronic circuits has been largely overcome. This is particularly so because in many cases valves have proved to be more reliable than many mechanically operated devices, and so there is now a tendency to eliminate all moving parts. The latest type of controls of spot and seam welding equipment are often all-electronic, although care in design is necessary to keep the initial cost down to an economic level. Nevertheless, the use of electronic welding controls is continually being extended as new techniques and processes are being evolved with their aid.

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See also the following British Patents relating to Resistance Welding: Nos. 431,992; 448,883; 463,561; 478,729; 515,537; 524,925; 530,105; 556,521; 699,315; British Patent Application No. 15380/51.

DISCUSSION

P. Huggins (*Associate Member*): One or two aspects of welding control ought to be mentioned at this juncture, for instance, "voltage compensation" and "constant current." Drawing off a heavy current from the mains can bring about changes in the weld because of regulation difficulties and various devices have been brought out, whereby compensation is effected as voltage changes. As load conditions change (either due to output or input), compensation is applied to bring the work conditions back to what they were originally.

The three-phase system has advantages and disadvantages from the welding point of view. Its principal advantage is the fact that you are drawing 300-400 amperes from the three-phases instead of one. However, the equipment is rather complicated, although various people are working on developments to simplify it.

Resistance welding is not altering with the times in using relays and having timers in the order of a second or longer. These operate inaccurately by charging a capacitor with a 50-cycle ripple, and rely, for instance, on the 97th ripple being sufficient to terminate the weld. I think the dekatron is better when you are doing a job in cycles as you are counting pulses, which is what a welding engineer is interested in, not trying to time something.

Finally, Mr. Bates made a very good point: welding mild steel is nice and easy and I would like to throw out a challenge in the light of this. There are, when welding mild steel, three parameters: pressure, heat and the time for which current is applied. As there is a certain amount of latitude, why provide the operator with a machine with three controls? We ought to be able to offer him a machine which, when you put the material under the welding press, will choose a programme of these three parameters, depending on the thickness of material and assuming that the two pieces to be welded are of the same thickness.

C. R. Bates (*in reply*): Automatic current and voltage controls have been briefly mentioned in the paper, which has, however, restricted its scope to single-phase controls. It is fairly safe to say that three-phase controls have not yet been in use for sufficiently long a time for any of the methods to be considered permanent. Systems which were in use 10 years ago are now obsolete, whereas single-phase controls have varied only in detail over the last 25 years.

There is a modern tendency to consider the use of dekatrons for timing controls, but for welding use they are perhaps superfluous. Their advantage is in the extreme accuracy in counting the cyclic pulses of weld current. But where long times are involved, which is the only case where the capacitor discharge type of timer cannot provide sufficient accuracy, the accuracy is not required.

If it were considered possible to produce a computer to adjust the settings of a welder automatically to suit the work, then I fancy that the problem would have been tackled a long while ago. It does not seem to be a practical proposition, or an economical one, even for mild steel welding. For other metals the problem is even more acute. An engineer of one company bewailed in a recent article that he had 12 adjustment controls on his welders. If you can imagine the problems involved in setting up a machine like that, then it can be appreciated how popular an automatic computer would be.

N. Armitage: At first sight, there is no immediate relationship between my problem—I am interested in magnetizing permanent magnets—and resistance welding. Does Mr. Bates know of any particular control circuit which is suitable for producing pulses for magnetization?

C. R. Bates (*in reply*): The basic welding control circuits are suitable for application to magnetization circuits, and it is in fact standard practice to make use of them.

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MATERIALS USED IN RADIO AND ELECTRONIC ENGINEERING

A Survey by the Technical Committee of the Institution

PREFACE

One of the problems which often confronts the engineer and designer is the correct specification of materials for a particular purpose. The radio and electronic engineer cannot be expected to be conversant with the properties of all materials which are used in the design of equipment. He is thus required to search reference books and other publications for the information regarding properties of these materials.

Rarely is the information collected together in one comprehensive publication, and it is for this purpose that the Technical Committee has, during the course of the last two years, collected together the required information on certain of the materials with which the engineer comes in contact and which are often critical in their specification.

The first two materials covered in the following review are aluminium and its alloys, and piezo-electric crystals. The information given is not exhaustive, and for those engineers who require more detailed information, a selected bibliography is given where appropriate. In the case of aluminium and its alloys, it is attempted to relate the various types of materials to British specifications which are applicable to them.

It is not intended that the series of reviews will cover an infinite range of materials, but will be limited to those materials most commonly related to equipment design. Component applications of the materials where a unique functional property is often of prime consideration will not be considered.

Generally, because of the difference in the types and properties of the materials considered, the individual treatment cannot follow a standard pattern. The form is determined solely by the need to present in a concise manner the primary information needed to form a useful practical guide.

With all reviews of this type, it is necessary to point out that the information is common knowledge to experts in the subject, and such readers will, no doubt, feel that the treatment of a particular subject could be more exhaustive. It is, however, the aim of the Committee to keep these reviews within reasonable bounds since their usefulness would be reduced by a superfluity of information.

1. Aluminium and Aluminium Alloys*

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1. Introduction

The most widely used structural metals in radio and electronic equipment are aluminium and aluminium alloys. It is important that the most suitable choice of material is made for any specific purpose, and for this reason this section of the review has attempted to bring together details and specifications of aluminium and aluminium alloys which are available.

The material has been presented in tabular form showing all the important characteristics for the convenient use of designers and manufacturers. Wherever possible, trade names of proprietary alloys have been given and the manufacturers identified in the final section.

The review is limited to those alloys used for structural purposes. No attempt has been made to indicate their possible use in component manufacture which usually calls for other characteristics.

2. Nomenclature used in B.S.I. Specifications for Aluminium and Aluminium Alloys

PREFIXES

- E Bars, rods and sections.
- S Sheet not greater than 0·252 in. thick and strip not greater than 0·192 in. thick.
- C Clad sheet and strip.
- P Plate.
- PC Clad plate.
- T Tube.
- F Forgings.
- R Wire for rivets.
- W Welding wire.
- G General-purpose wire.
- LM Ingots.
- LMx Castings.
- N Non-heat treatable.
- H Heat-treatable.

SUFFIXES

- 0 Soft annealed.
- ¼H Quarter hard.
- ½H Half hard.
- ¾H Three-quarter hard.
- H Hard.
- M As manufactured.
- T Naturally ageing. Solution heat-treated. No precipitation treatment required.
- W Solution heat-treated. Responds to precipitation treatment.
- P Precipitation treatment only (castings).
- WP Fully heat-treatable.

An example of the use of the above nomenclature is: B.S. 1470.**S.**1A.**½H**, which refers to a sheet produced to B.S. 1470/1A having a temper "half-hard." (The prefix and suffix are printed here in bold face for emphasis.)

3. Aluminium

3.1. *B.S.I. Aluminium Specifications*

The nomenclature used in the B.S.I. Specifications is as given above in Section 2. Tables 1-3 summarize the most useful items.

Table 1—Aluminium not less than 99·8% pure

British Standards Institution Designation	Description of Material	Temper	Mechanical Properties: Ultimate Tensile Strength (tons/in²)	% Elongation on 2″	Bend Test	Usage in Radio Industry
B.S.1470 S.1A	Sheet & Strip	0	4—5	35	flat	Used only for very high corrosion resistance or for components requiring exceptional ductility.
		¼H	6—7·5	8	½Th	
		H	8	5	Th	
B.S.1477 P.1A	Plate 0·253″—1·00″ inc.	M	3·5	30	—	
	Plate 0·253″—0·5″ inc.	½H	6—7·5	8	—	
B.S.1476 E.1A	Bars, Rods, Sections, Extrusions	M	3·5	30	—	
B.S.1471 T.1A	Tubes, General	0	4—5	—	—	
	,, up to 3″ dia.	H	7	—	—	
	,, over 3″ dia.	H	6·5	—	—	

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Table 2—Aluminium not less than 99·5% pure

British Standards Institution Designation	Description of Material	Temper	Mechanical Properties: Ultimate Tensile Strength (tons/in²)	% Elongation on 2″	Bend Test	Usage in Radio Industry
B.S.1470 S.1B	Sheet & Strip	0	4·5—6	30	Flat	Used in applications where good ductility and good electrical conductivity are required. More expensive than Grade 1C (see Table 3).
		½H	6·5—8	8	½ Th	
		H	8·5	5	Th	
B.S.1477 P.1B	Plate 0·253″—1·00″ inc.	M	4	30	—	
	Plate 0·253″—0·5″ inc.	½H	6·5—8	8	—	
B.S.1476 E.1B	Bars, Rods, Sections, Extrusions	M	4	25	—	
B.S.1471 T.1B	Tubes, General	0	4·5—6	—	—	
	,, Up to 3″ dia.	H	7·5	—	—	
	,, Over 3″ dia.	H	7	—	—	

All specifications are available under the proprietary name of Kynal P5.

Table 3—Aluminium not less than 99% pure

British Standards Institution Designation	Description of Material	Temper	Ultimate Tensile Strength (tons/in²)	% Elongation on 2″	Bend Test	Usage in Radio Industry
B.S.1470 S.1C	Sheet & Strip	0	5—6·5	30	Flat	Most generally used specifications for commercially pure aluminium. Can be gas, arc or resistance welded.
		¼H	6—7·5	12	Flat	
		½H	7—8·5	7	½ Th	
		¾H	8—9·5	5	½ Th	
		H	9	3	Th	
B.S.S. 3L.16	Sheet & Strip	½H	7—8·5	—	½ Th	
B.S.S. 3L.17	,, ,,	0	5—6·5	—	Flat	
B.S.1477 P.1C	Plate 0·253″—1·00″ inc.	M	4·5	30	—	
	Plate 0·253″—0·5″ inc.	½H	7—8·5	7—8	—	
B.S.1476 E.1C	Bars, Rods, Sections, Extrusions	M	4	20	—	
B.S.S. 2L.34	Bars, Rods, Sections, Extrusions	M	5 Max	—	—	
B.S.1471 T.1C	Tubes, General	0	5—6·5	—	—	
	,, Up to 3″ dia.	H	7·5—8	—	—	
	,, Over 3″ dia.	H	7	—	—	
B.S.S. L.54	Tubes, Up to 3″ dia.	H	8	—	—	
	,, Over 3″ dia.	H	7	—	—	

All specifications are available under the proprietary name of Kynal P10 and Noral 2S.

3.2. *Other Specifications for Aluminium*

There are no commonly used specifications for aluminium other than the B.S.I. Specifications listed on Tables 1-3.

Aluminium of purity greater than 99·99 per cent. is obtainable commercially, but it is expensive. It is used in the radio industry for special application where exceptionally high ductility and/or corrosion resistance is required. This grade of aluminium is also used for highly polished reflectors.

Aluminium wire has been excluded from this Report owing to its limited application to radio.

4. Aluminium Alloys

4.1. *B.S.I. and M. of S. Specifications*

Aluminium Alloy Specifications issued by the British Standards Institution and the Ministry of Supply are given in Tables 4-12 inclusive.

The nomenclature used in B.S.I. Specifications is as given in Section 2.

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Table 4—Non-Heat-Treatable Alloys I

Authority	Designation of Specification	Description of Material	Temper	Mechanical Properties: 0·1% Proof Stress (tons/in²)	Ultimate Tensile Strength (tons/in²)	% Elongation on 2"	Bend Test	Composition	Proprietary Alloys	Usage in Radio Industry
BSI	B.S.1470 NS3 B.S.S. L.61	Sheet and Strip	0	—	6–7·5	30	Flat	1–1·5% Mn (0·1% Mg in L59, 60 & 61 only)	B.A.60; Kynal P.A.19; Noral 3S; T.I.111.	Ductile, not very strong but better than aluminium. Good resistance to corrosion; can be welded. Can be cold worked according to temper. Used also for hollow ware.
BSI	B.S.1470 NS3 B.S.S. L.60	Sheet and Strip	$\frac{1}{4}$H	—	7·5–9·5	12	Flat			
BSI	B.S.1470 NS3	Sheet and Strip	$\frac{1}{2}$H	—	9–11	7	$\frac{1}{2}$Th			
BSI	B.S.1470 NS3 B.S.S. L.59	Sheet and Strip	$\frac{3}{4}$H	—	10·5–12·5	5	Th			
BSI	B.S.1470 NS3	Sheet and Strip	H	—	11·5	3	2Th			
BSI	†B.S.1470 NS4	Sheet and Strip	0	—	11–14	18	Flat	*1·80–2·7% Mg †1·75–2·75% Mg	B.A.21; Birmabright 2; Kynal M.35/1; M.G.2; Noral M.57S; T.I.222.	Stronger than N.S 3 series but slightly less resistant to corrosion and less ductile. Can be welded. Softer tempers can be cold worked.
MOS	†D.T.D.634	Sheet and Strip	0	4·5	11	18	Flat			
BSI MOS	†B.S.1470 NS4 †D.T.D.606	Sheet and Strip	$\frac{1}{2}$H	12	15	5	Th			
BSI	†B.S.1477 NP4	Plate 0·253–0·5" inc.	M	—	13	15	—			
BSI	†B.S.1477 NP4	Plate 0·5"–1·0" inc.	M	—	12	15	—			
BSI	†B.S.1476 NE4 *B.S.2L44	Bars, Rods, Sections, Extrusions	M	—	11	18	—		B.A.21; Birmabright 2; Hiduminium 22; Kynal M.35/1; M.G.2; Noral M.57.S; T.I.222.	
BSI	†B.S.1471 NT4 *B.S.S.L.56	Tubes	0	—	11	18	—			
BSI	†B.S.1471 NT4 *B.S.S.L.56	Tubes	0	—	14 max 9 min	18	—			
BSI	†B.S.1471 NT4 *B.S.S. L.55	Tubes	$\frac{1}{2}$H	11	15	5	—			

Table 5—Non-Heat-Treatable Alloys II

Authority	Designation of Specification	Description of Material	Temper	Mechanical Properties: 0·1% Proof Stress (tons/in²)	Ultimate Tensile Strength (tons/in²)	% Elongation on 2"	Bend Test	Composition	Proprietary Alloys	Usage in Radio Industry
BSI	B.S.1470 NS5	Sheet and Strip	0	6	14	18	Flat	3·0–4·0% Mg	B.A. 27; Birmabright 3; Kynal M.35/2; M.G. 3; Noral 54S; T.I. 223.	Strong alloy. Reasonably ductile generous radii desirable in bends. Can be welded satisfactorily. Argon-shielded arc process desirable particularly on N6 alloys. Used mainly for structures and chassis carrying heavy components.
MOS	D.T.D.180B	Sheet and Strip	0	8	14	18	Flat			
BSI	B.S.1470 NS5	Sheet and Strip	¼H	11	17	8	Th			
BSI	B.S.1476 NE5	Sections, Bars, Rods, Extrusions up to 2"	M	6	14	18	—		B.A. 27; Birmabright 3; Hiduminium 33; Kynal M.35/2; M.G. 3; Noral 54S; T.I. 223.	
		over 2"	M	5	14	18	—			
BSI	B.S.1471 NT5	Tubes	0	7	14	18	—			
			½H	12	16	5	—			
BSI	B.S.1470 NS6	Sheet and Strip	0	8	17	18	Flat	4·5–5·3% Mg	B.A. 28; Birmabright 5; Kynal M.36; M.G. 5; Noral A.56S; T.I. 225.	
			¼H	14	19	8	2Th			
BSI	B.S.1476 NE6	Bars, Rods, Sections, Extrusions up to 2"	M	8	16	18	—		B.A. 28; Birmabright 5; Hiduminium 05; Kynal M.36; M.G. 5; Noral A.56S; T.I. 225.	
		over 2"	M	7	16	18	—			
BSI	B.S.1471 NT6	Tubes	0	8	17	18	—			
			½H	14	18	5	—			
BSI	B.S.1477 NP5/6	Plate up to 1"	M	8	17	12	—	3·0–5·5% Mg	B.A. 27; Birmabright 3 and 5; Kynal M.35/2 and M.36; M.G. 3 and 5; Noral B.54S; T.I. 224.	

Table 6—Non-Heat-Treatable Alloys III

Authority	Designation and Specification	Description of Material	Temper	Mechanical Properties 0·1% Proof Stress (tons/in²)	Ultimate Tensile Strength (tons/in²)	% Elongation on 2"	Bend Test	Composition	Proprietary Alloys	Usage in Radio Industry
BSI	B.S.1470 NS7	Sheet and Strip	0	9	20–23	18	Th	6·5–7·5% Mg	Birmabright 7; Kynal M.37; M.G. 7.	Essentially structural alloy. Very strong. Not ductile, care required when bending to use large radii. When welding, Argon - shielded aıc process to be used.
MOS	D.T.D.182A	Sheet and Strip	0	10	20–23	20	Th	6·5–10% Mg		
BSI	B.S.1476 NE7	Bars, Rods, Sections and Extrusions	M* M†	9 8	20 20	18 18	— —	6·5–7·5% Mg	Birmabright 7; Hiduminium 07. Kynal M.37; M.G.7, Noral 58S; T.I.227.	
MOS	D.T.D.297	Bars, Rods, Sections and Extrusions	0	8	20	15	—	6·5–10% Mg	Birmabright 7; Kynal M.37; M.G.7; Noral 58S; T.I.227.	
BSI	B.S.1472 NF7	Bars for forging	0 M	8	20	18	—	6·5–7·5% Mg	Birmabright 7; Hiduminium 07. Kynal M.37; M.G.7; Noral 58S; T.I.227.	
BSI	B.S.1472 NF7	Forgings only	0	8	20	18	—		Hiduminium 07; M.G.7.	
BSI	B.S.1471 NT7	Tubes	0 ½H	9 16	20 25	18 5	— —		Birmabright 7; Hiduminium 07. Kynal M.37; M.G.7; Noral 58S; T.I. 227;	
MOS	D.T.D. 186A	Tubes 12 SWG and less Tubes 12 SWG over	H H	18 17	26 25	— —	— —	6·5–10% Mg		

* Up to 2". † Over 2".

Table 7—Heat-Treatable Alloys I

Authority	Designation of Specification	Description of Material	Temper	Mechanical Properties: 0·1% Proof Stress (tons/in²)	Ultimate Tensile Strength (tons/in²)	% Elongation on 2″	Bend Test	Composition	Proprietary Alloys	Usage in Radio Industry
BSI	B.S.1476 HE9	Bars, Rods, Sections, and Extrusions (Up to 6″ dia. or thickness)	M	—	7	15	—	0·4–0·9% Mg 0·3–0·6% Si	B.A. 24; Birmabright 055; Kynal M.39/1; Noral 50S; Signal; T.1.440.	This alloy is similar in nature to H10 but is not so strong and cannot be obtained so freely. Used in Electrical Trade for cables.
			W	5	9	18	—			
			WP	10	12	12	—			
MOS	D.T.D.372	Bars, Rods, Sections, and Extrusions	W	—	9	18	—	0·4–0·8% Mg 0·3–0·6% Si		
BSI	B.S.1470 HS10	Sheet and Strip	W	7	13	15	2Th	0·4–1·5% Mg 0·75–1·3% Si	B.A. 25; Birmabright 019; Duralumin H; Kynal M.39/2; T.1.444.	Widely used general-purpose alloy. Medium strength good corrosion resistance for this class of alloy. Can be formed and welded.
MOS	D.T.D.346	Sheet and Strip	WP	15	19	8	3Th			
BSI	B.S.1477 HP10	Plate: Under ½″	0	—	11 max	20	Flat	0·5–1·5% Mg, 0·75–1·25% Si		
		½″–1″	W	7	13	15	—	0·4–1·5% Mg 0·75–1·3% Si		
		Under ½″	W	7	13	12	—			
		½″–1″	WP	14	18	8	—			
BSI	B.S.1476 HE10	Bars, Rods, Sections, and Extrusions (Up to 6″ dia. or thickness)	WP	14	18	6	—	0·4–1·5% Mg 0·75–1·3% Si	B.A. 25; Birmabright 019; Duralumin H; Hiduminium 44; Kynal M.39/2; Noral 51S; T.1.444.	
			W	7	12	18	—			
BSI	B.S.1472 HF10*	Bars for Forging	WP	15	18	10	—			
BSI	B.S.1472 HF10*	Forgings	WP	15	18	10	—			
			W	7	12	18	—			
BSI	B.S.1471 HT10	Tubes: 16 SWG and under	W	7	14	12	—			
		20 SWG–16 SWG	W	7	14	14	—			
		12 SWG and over	W	7	14	16	—			
		16 SWG and under	WP	15	19	7	—			
		Over 16 SWG	WP	15	19	9	—			

* B.S.1472 HF10 does not include Kynal M.39/2 for Forging Bars, nor Kynal M.39/2, T.1.444, Birmabright 019, B.A. 25 for Forgings.

Table 8—Heat-Treatable Alloys II

Authority	Designation of Specification	Description of Material		Temper	Mechanical Properties: 0·1% Proof Stress (tons/in²)	Mechanical Properties: Ultimate Tensile Strength (tons/in²)	Mechanical Properties: % Elongation on 2″	Mechanical Properties: Bend Test	Composition	Proprietary Alloys	Usage in Radio Industry
BSI	B.S.1476 HE11	Bars, Rods, Sections, and Extrusions	up to ⅜″	WP	19	24	8	—	1·0–2·0% Cu; 0·5–1·25% Mg; 0·75–1·25% Si	Duralumin E; Hiduminium 03; Kynal C69; Noral 62S; T.I.663.	Very strong alloys, used mostly for machined parts. Needs to be protected against corrosion.
			⅜″–6″	WP	20	25	8	—			
			6″–8″	WP	17	23	6	—			
			—	W	10	17	15	—			
MOS	D.T.D. 443	Bars, Rods, Sections, and Extrusions		W	10	17	15	—			
MOS	D.T.D. 423B	Extrusions	up to ⅜″	WP	19	24	10	—			
			over ⅜″	WP	20	25	10	—			
		Bars and Rods for machining	up to 6″	WP	20	25	10	—			
			over 6″	WP	17	23	6	—			
BSI	B.S.1472 HF12	Bars for forging 2″ and less		WP	19	25	8	—	1·8–2·8% Cu	Duralumin T; Hiduminium RR56; Kynal Y88.	High strength, very good hot working properties, used widely for forgings and stampings. Needs to be protected against corrosion. May be used for high-temperature work.
		Forgings 2″ and less		W	10	20	15	—	0·6–1·2% Mg; 0·5–1·3% Si	Duralumin T; Hiduminium 55.	
				WP	19	25	10	—			
MOS	D.T.D.130A	Bars for forging 3″ and less		WP	21	27	10	—	1·8–2·5% Cu; 0·65–1·2% Mg	Duralumin T; Hiduminium RR56; Kynal Y89; T.I.886.	
	D.T.D.410	Bars for forging over 3″									
	D.T.D.130A	Forgings 3″ and less							0·55–1·25% Si	Duralumin T; Hiduminium RR56.	
	D.T.D.410	Forgings over 3″									

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Table 9—Heat-Treatable Alloys III

Authority	Designation of Specification	Description of Material	Temper	Mechanical Properties: 0·1% Proof Stress (tons/in²)	Ultimate Tensile Strength (tons/in²)	% Elongation on 2"	Bend Test	Composition	Proprietary Alloys	Usage in Radio Industry
BSI	B.S.1470 HS14 B.S.1477 HP14	Sheet Strip and plate	See end column.					High copper content	—	Not normally used as such. Highly prone to corrosion. Some of these alloys are used when clad with corrosion-resisting material. See Table 10, etc.
	B.S.1476 HE14 B.S.1476 HE15	Bars, Rods, Sections and Extrusions								
	B.S.1471 HT14 B.S.1471 HT15	Tubes								
	B.S.1472 HF14 B.S.1472 HF15	Forgings								
MOS	D.T.D.150A	Forgings	T	13·5	24·0	15	—	3·5–4·5% Cu 0·4–0·9% Mg 0·7% Si	Duralumin B; Hiduminium 01. Noral 17 A;	Used mainly on Government contracts for air-borne equipment.
	D.T.D.603B	Sheet and Strip	W	16*	26	15	3Th	3·5–4·8% Cu 0·6% Mg 1·5% Si	B.A.313; B.M.B.551; Duralumin S; Kynal C66; Noral 26S; T.1.666.	

* Material over 25 SWG.

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Table 10—Heat-Treatable Alloys IV
(Clad Sheet and Strip)

Authority	Designation of Specification	Description of Material	Temper	Mechanical Properties				Composition	Proprietary Alloys	Usage in Radio Industry
				0·1% Proof Stress (tons/in²)	Ultimate Tensile Strength (tons/in²)	% Elongation on 2"	Bend Test			
BS1	B.S.1470 HC14	Clad Sheet and Strip	Th	14	24	15	3Th	Coating: 99·7% Al Core: 3·5–5·0% Cu 0·4–1·2% Mg 0·7% Si	Aldural B; B.A. 352; B.M.B.473; Kynalcore C65A; T.I. 554.	Used where very strong light structures are required. Good corrosion resistance except at cut edges.
MOS	D.T.D.610.B.	Clad Sheet and Strip	W	15*	25	15	3Th	Coating: 99·7% Al Core: 3·5–4·8% Cu, 0·6% Mg, 1·5% Si	Alclad; Aldural S; B.A. 353; B.M.B. 551; Kynalcore C66 A; Noral 26S; T.I. 666.	Age hardens. Reaches its maximum strength after standing for a period of days subsequent to solution heat treatment and quenching.

* Material over 25 SWG.

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Table 11—Non-Heat-Treatable Casting Alloys

Authority	Specification Designation	Type of Casting*	Temper or Condition	Mechanical Properties: Ult. Tens. Str. tons/in² SAND	Ult. Tens. Str. tons/in² CHILL	% Elongation on 2" SAND	% Elongation on 2" CHILL	Composition Main Alloying Constituents	Proprietary Alloys	Usage in Radio Industry
BSI	LM1	G	M	8·0	10·0	—	—	6·0–8·0% Cu, 2·0–4·0 Si, 2·0–4·0 Zn	Z3	Most generally used casting alloys. All secondary alloys (not necessarily made from virgin metal). Normally used as cast but may be improved by heat treatment particularly LM4.
BSI	LM2	P	M	8·0	9·0	—	—	0·7–2·5% Cu, 9·0–11·5 Si	—	
BSI	LM3	S	M	9·0	—	—	—	2·5–4·5% Cu, 9·0–13·0 Zn	—	
BSI	LM4	S, G or P	M	9·0	11·0	2	2	2·0–4·0% Cu, 4·0–6·0% Si	Birmal; D7 and D8; Hiduminium 20 Noral 117.	
MOS	D.T.D.424A	S, G or P		9·0	10·0	2	2	0·3–0·7% Mn		
BSI MOS	LM5 D.T.D.165A	S or G	M	9·0	11·0	3	5	3·0–6·0% Mg, 0·3–0·7% Mn	Birmabright	Good corrosion resistance. Suitable for marine conditions. LM6 is easy to cast and is used for thin sections. LM5 anodizes well and takes a high polish. Good shock resistance.
BSI	LM6 BS3L33	S, G or P	M	10·5	12·0	5	7	0·10% Mg, 0·5% Mn 10·0–13·0% Si	Alpax; Hiduminium 10; Noral 160; Wilmil.	

*G—gravity, P—pressure, S—sand.

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Table 12—Heat-Treatable Casting Alloys

Authority	Specification Designation	Type of Casting*	Temper or Condition	Mechanical Properties: Ult. Tens. Str. tons/in² SAND	CHILL	% Elongation on 2" SAND	CHILL	Composition Main Alloying Constituents	Proprietary Alloys	Usage in Radio Industry
BSI	LM7	S or G	P	10·0	12·5	2	3	1·0–2·5% Cu, 0·05–0·20% Mg 1·5–3·5% Si, 0·5–1·7% Ni,	Ceralumin B; Hiduminium RR50	Requires only precipitation treatment. Used generally for stressed castings.
			M	9·0	10·0	2	2			
BSI	L51	S or G	P	10·0	12·5	2	3	0·8–2·0 Cu, 0·5–0·2 Mg, 1·5–2·8 Si, 0·8–1·7 Ni, 0·8–1·5		
BSI	LM8	S or G	WP	15·0	17·0	—	2·5	0·2–0·6% Mg, 4·5–6·0% Si, 0·3–0·7% Mn	Birmidal; Hiduminium 40; Noral B116	Suitable for complicated castings, particularly where pressure tightness is required.
			P	11·0	15·0	2·5	4·0			
MOS	D.T.D.727	S or G	W	10·5	13·5	3	8	0·3–0·8% Mg, 3·5–5·5% Si, 0·5% Mn		
BSI	LM9	S or G	P	11·0	15·0	1·5	2·0	0·2–0·6% Mg, 10·0–13·0% Si, 0·3–0·7% Mn	Alpax Beta; Alpax Gamma; Wilmil M	Similar to LM6 but responds better to heat treatment.
BSI MOS	LM9 D.T.D.245A	S or G	WP	15·5	19·0	—	—			
BSI	LM10 L53	S or G	W	18·0	20·0	8	12	9·5–11·0% Mg	Hiduminium 90; Noral 350	Used for special applications only. Difficult to cast. LM10 has excellent corrosion resistance.
BSI MOS	LM11	S or G	W	14·0	17·0	7	13	4·0–5·0% Cu	Hiduminium 80; Noral 226	
BSI MOS	LM11 D.T.D.304A	S or G	WP	18·0	20·0	4	9			
MOS BSI	D.T.D.272A LM16	S or G	W	11·0	13·0	2	—	1·0–1·5% Cu, 0·4–0·6% Mg, 4·5–5·5 Si, 0·6% Fe, 0·5% Mn, 0·1% Zn	Noral 125	Used for very strong and intricate castings.
MOS BSI	D.T.D.276A LM16	S or G	WP							
BSI	LM18	S, G or P	M	7·5	9·0	3	4	4·5–6·0% Si	—	Useful all-purpose alloy.
BSI	LM19	S or G	W	14·0	17·0	3	5	2·0–4·5% Cu, 0·2–1·5% Mg, 0·5–2·5% Cd	Aeral A	Free cutting for repetition work.
BSI	LM20	G or P	M	10·5	12·0	3·5	5	10–13% Si	—	Purely a diecasting material.

*G—gravity, P—pressure, S—sand.

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4.2. *Alloys other than those in Tables* 4-12

B.S. 1473 HR13 is a rivet material and its use in the radio industry is confined to bought-out rivets.

There are a group of high-strength alloys whose composition includes zinc and magnesium. They are expensive and their use is generally restricted to very special applications which do not occur frequently in the radio industry.

The group of alloys which include nickel are intended for high-temperature use (e.g. pistons) and are seldom encountered in the radio industry.

6. Availability of Specifications

Specifications issued by the B.S.I. may be obtained from: British Standards Institution, Sales Branch, 2 Park Street, London, W.1.

Copies of most Specifications issued by the Ministry of Supply may be obtained from H.M. Stationery Office.

7. Acknowledgment

Acknowledgment is made to the member-firms of the Aluminium Development Association who supplied certain information included in this report.

5. Index of Proprietary Alloys with their Suppliers

Name	*Supplier*	*Address*
Aeral ..	.. William Mills Ltd.	Wednesbury, Staffs.
Alclad	.. Northern Aluminium Co. Ltd.	Bush House, Aldwych, London, W.C.2.
Aldural	.. James Booth & Co. Ltd.	Nechells, Birmingham.
Alpax	.. Light Alloys Ltd.	St. Leonards Road, London, N.W.10.
B.A. ..	.. The British Aluminium Co. Ltd...	Norfolk House, St. James's Square, London, S.W.1.
B.M.B. ..	Birmetals Ltd.	Woodgate Works, Quinton, Birmingham, 32.
Birmabright ..	Birmetals Ltd.	Woodgate Works, Quinton, Birmingham, 32.
Birmal ..	Birmingham Aluminium Casting (1903) Co. Ltd.	Smethwick, Birmingham, 40.
Birmasil ..	Birmingham Aluminium Casting (1903) Co. Ltd.	Smethwick, Birmingham, 40.
Birmidal ..	Birmingham Aluminium Casting (1903) Co. Ltd.	Smethwick, Birmingham, 40.
Ceralumin	.. J. Stone & Co. Ltd.	Deptford, London, S.E.14.
Duralumin	.. James Booth & Co. Ltd.	Nechells, Birmingham.
Hiduminum	.. High-Duty Alloys Ltd.	Buckingham Avenue, Trading Estate, Slough, Bucks.
Kynal	I.C.I. Ltd., Metals Division	Witton, Birmingham, 6.
Kynalcore ..	I.C.I. Ltd., Metals Division	Witton, Birmingham, 6.
M.G. ..	.. James Booth & Co. Ltd.	Nechells, Birmingham.
Noral ..	.. Northern Aluminium Co. Ltd.	Bush House, Aldwych, London, W.C.2.
Sigmal	.. James Booth & Co. Ltd.	Nechells, Birmingham.
T.I. ..	.. T.I. Aluminium Ltd.	Redfern Road, Tyseley, Birmingham, 11.
Wilmil	.. William Mills, Ltd.	Wednesbury, Staffs.
Z3 ..	.. Birmingham Aluminium Casting (1903) C. Ltd.	Smethwick, Birmingham, 40.

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2. Piezo-electric Crystals*

1. Introduction

The present art of piezo-electric practice has its origin in the classical experiments of Jacques and Pierre Curie in 1880.[1] This original discovery was confined to the "direct" effect, i.e. the production of a measurable electric charge resulting from mechanical stress. Lippmann then suggested the converse effect[2] which the Curies were able to confirm.

The earliest practical application of the phenomena was by Professor Langevin in 1918.[3] Langevin's invention was the forerunner of the modern ultrasonic generator.[4] The first record of piezo-electric elements being used in other devices was about the years 1917-1918 when A. M. Nicolson developed a form of piezo-electric element for use in gramophone pick-ups, microphones and loudspeakers.[5] Nicolson also controlled the frequency of an oscillator piezo-electrically.[6] This was followed by Cady (1921) who further developed the crystal oscillator.[7] He showed that the frequency stability of the crystal oscillator was superior to any other type of oscillator existing at that time.

2. Principal Piezo-electric Materials

The materials exhibiting piezo-electric properties are very numerous. They are essentially substances having non-conducting electrical properties.

Those crystalline compounds which have at least one direction of non-symmetry in their molecular structure will exhibit piezo-electric phenomena. Rochelle salt produces the greatest effect but its deliquescence renders it unsuited to many applications.

Table 1 gives a few of the more useful substances in use at the present time, and Table 2 gives their more important properties.

3. Availability

With the notable exceptions of quartz and tourmaline, all materials listed in Table 1 are synthetic.

It is well known that silicon dioxide is one of the most common materials on the surface of the earth. The quality and size of quartz required in the radio industry for the manufacture of piezo-electric devices is such that only a very minute percentage is suitable however.

Tourmaline is much more rare and practically falls into the class of semi-precious stone. This usually precludes its use on economic grounds.

The other materials listed may be grown artificially with reasonable success. This applies particularly to Rochelle salt and ethylene diamine tartrate.

During the last decade the successful growth of synthetic quartz of a useful size and quality has become a reality. Chief supplies are still imported from Brazil, however, with possible but less profitable sources of supply in Madagascar, Japan and India.

Tourmaline is found in similar zones, notably Brazil.

4. Manufacturing Hazards

Each of the piezo-electric materials has some peculiarity which provides a processing hazard in manufacture.

Natural quartz is prone to a growth disturbance known as "twinning." This defect may affect a minute proportion of the mass of the crystal or be so widespread as to render it useless. Many other piezo-electric materials are so affected, more particularly those found in nature.

Fractures, needles (microscopic tubular holes) and bubbles, containing air or fluid, must be avoided. The synthetic crystals, carefully produced, can provide a means of overcoming these hazards.

A further hazard which is common to both natural or synthetic material, is that of fracturing due to differences in linear expansion with temperature changes. Ethylene diamine tartrate is seriously affected in this way.

Moisture is the enemy of most of the synthetic crystals, and particularly is this so in the case of Rochelle salt which requires hermetically sealing at the earliest opportunity. Quartz and tourmaline are not hygroscopic.

5. Applications of Piezo-electric Materials

These are set out in detail in Table 3.

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U.D.C. No. 537.228.1.002.3:621.37/9.

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Table 1
Raw Materials for Piezo-electric Applications

Material	Source	Crystal Class	Chemical Formulae	Water Affinity	Remarks
Rochelle salt	Synthetic	Orthorhombic bisphenoidal	$NaKC_4H_4O_6.4H_2O$	Deliquescent	Easily grown in laboratory
Quartz	Brazil, Japan, Madagascar, etc.	Trigonal trapezohedral	SiO_2	Non-hygroscopic	Best quality only is used in piezo-electric applications
Quartz	Synthetic	Trigonal trapezohedral	SiO_2	Non-hygroscopic	May be grown in autoclave
Ethylene diamine tartrate (EDT)	Synthetic	Monoclinic sphenoidal	$C_6H_{14}N_2O_6$	Hygroscopic	Grown in controlled conditions
Ammonium dihydrogen phosphate (ADP)	Synthetic	Tetragonal scalenohedral	$NH_4H_2PO_4$	Hygroscopic	
Dipotassium tartrate (DKT)	Synthetic	Monoclinic sphenoidal	$K_2C_4H_4O_6.\frac{1}{2}H_2O$	Hygroscopic	Grown in controlled conditions
Tourmaline	Brazil, etc.	Ditrigonal pyramidal	Various*	Non-hygroscopic	In class of semi-precious gems
Potassium dihydrogen phosphate (KDP)	Synthetic	Tetragonal scalenohedral	KH_2PO_4	Hygroscopic	
Barium titanate	Synthetic	Tetragonal (Ceramic)	$BaTiO_3$	Non-hygroscopic	Moulded readily to any form. Requires polarization

* e.g., lithium trisodium chromate hexahydrate, lithium trisodium molybdate hexahydrate, etc.

6. Modern Tendencies

Probably the greatest present-day demand is for crystal elements for the control of radio frequency oscillators and typical types and their properties for this purpose are given in Table 4.

Frequency stabilities of the order of a few parts in 10^8 are required for laboratory and broadcast station frequency control. Overall stabilities, including the effects of varying temperatures between perhaps $-55°C$ and $+90°C$, are required to be of the order of 30 to 50 cycles per megacycle for general equipment applications.

The output of the oscillator types of piezo-electric element greatly outnumbers that of other types.

There is a possibility of a breakdown in supplies of suitable quartz during a major war, and even in peace-time the supply is limited. The concurrent development of synthetic materials should help to meet requirements.

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Table 2

Properties of some Piezo-electric Materials

(at 20°C)

Material	**Dielectric Constant** ϵ	**Piezo-Electric Constant** d_{mn} (i)	**Elastic Constant** s_{mn} (ii)	**Electro-Mechanical Coupling Constant** k (iii)	**Density** gm/cm^3	**Frequency Constant (Average)** kc/s-mm (iv)
Rochelle salt	11·1	$30–95 \times 10^{-8}$	$3{\cdot}0–30{\cdot}0 \times 10^{-12}$	0·245–0·760	1·77	1500
Quartz	4·6	$2{\cdot}5–6{\cdot}7 \times 10^{-8}$	$0{\cdot}11–2{\cdot}86 \times 10^{-12}$	0·095–0·142	2·65	2700
EDT	8·2	$20–50 \times 10^{-8}$	$3{\cdot}8–10 \times 10^{-12}$	0·126–0·215	1·54	1900
ADP	15·0	$5–10 \times 10^{-8}$	$0{\cdot}75–4{\cdot}3 \times 10^{-12}$	0·290	1·80	1600
DKT	6·4	$2–66 \times 10^{-8}$	$1–10 \times 10^{-12}$	0·20–0·27	1·99	1500
Tourmaline	7·0	$1–54 \times 10^{-8}$	$0{\cdot}4 \times 10^{-12}$	0·10–0·13	3·10	3600
KDP	4·6	14×10^{-8}	$0{\cdot}4–2{\cdot}0 \times 10^{-12}$	0·120	2·30	1200
Barium titanate ceramics	1400 700–1450*	about 10^{-10} — 10^{-8}†	$0{\cdot}9 \times 10^{-12}$	0·170–0·500	5·60	2500

* Dependent upon polarizing voltage and temperature. In the region of 1400 at normal temperature and zero polarizing voltage.

† Dependent on degree of polarization used in preparation and the remanent polarization therefrom.

Notes.—(i) *Piezo-electric Constant* (d_{mn}), is defined as the magnitude of the surface charge developed in c.g.s. electrostatic units (statcoulombs) per unit of stress in dynes per cm^2.

(ii) *Elastic Constant* (s_{mn}), is defined as the elastic compliance of the material in a given direction, stated as a deformation in cm^2 per dyne of applied pressure.

(iii) *Electro-mechanical Coupling Constant* (k), conveniently summarizes the general conversion efficiency from electrical to mechanical energy. The defining equation is given as

$$k = d_{mn}\sqrt{\frac{4\pi}{\epsilon S_{mn}}}$$

(iv) *Frequency Constant* (kc/s-mm) is given as the product of the resonant frequency, in kilocycles per second, and the lineal dimension in a direction parallel to the direction of wave propagation, in millimetres. The constant is given in kilocycle-millimetres.

5. A. M. Nicolson. *Trans. Amer.I.E.E.*, **38**, pp. 1467-1485, 1919.

6. A. M. Nicolson. American Patent 2,212,845. Filed April, 1918.

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Table 3
Applications of Piezo-electric Materials

Type of Product	Material Used	Usual Form of Element	Mode of Useful Vibrations	Remarks
Microphones	Rochelle salt	Double wafers or bars	Bending; torsional	Damaged by extreme high or low humidity, also temperatures in excess of 45°C
Pick-ups	Rochelle salt	Double wafers or bars	Bending; torsional	Damaged by extreme high or low humidity, also temperatures in excess of 45°C
Ultrasonic transducers	Quartz, barium titanate, ADP	Rectangular or circular slabs, often in mosaic	Thickness vibration	Barium titanate has advantage in that it may be moulded to specific shape
Oscillators:				
(*a*) Radio frequency	Quartz, tourmaline	Thin wafers	Thickness-shear	Mechanical harmonics may be used
(*b*) Low frequency	Quartz, EDT, DKT	Thin bars or rectangular plates	Longitudinal or face shear	Mechanical harmonics may be used
Filter crystals	Quartz, EDT, DKT	Thin bars or rectangular plates	Longitudinal or face shear	Mechanical harmonics may be used

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Table 4
Crystals for Frequency Control
(Typical Examples in Common Use)

Frequency Range	Material	Cut	Vibration Mode Utilized	Remarks
Oscillator Elements:				
1–40 kc/s	Quartz	NT; X-cut bars	Flexure	Zero temperature coefficient Controlled by design within limits
40–500 kc/s	Quartz	+5° X-cut bars CT; DT; ET; FT;	Extensional Face shear Face shear*	Zero temperature coefficient between 0° and 45°C depending on design
		GT	Extensional	High-precision stability without temperature control necessity
500–10000 kc/s	Quartz	AT	Thickness shear	Temperature coefficient substantially linear; approaches zero over wide range
500–10000 kc/s	Ethylene diamine tartrate	a—b crystal-lographic plane	Thickness shear	Zero temperature coefficient Presents fabrication problems
3000–25000 kc/s	Quartz	BT	Thickness shear	Temperature coefficient parabolic Turnover point controllable
20000–75000 kc/s	Quartz	AT	Mechanical harmonics	Temperature coefficient substantially linear; approaches zero over wide range
Filter Elements:				
40–500 kc/s	Quartz	+5° X-cut bars	Extensional	Low temperature coefficient Secondary couplings present difficulties
		−18·5° X-cut bars	Extensional	High temperature coefficient Secondary couplings predictable
500–10000 kc/s	Quartz	AT; BT	Thickness shear	Low temperature coefficient Little degree of control over equivalent circuit parameters
40–500 kc/s	Ethylene diamine tartrate	A; B; Y-cut bars	Extensional	Low temperature coefficient Equivalent inductance values smaller than those of quartz filters of similar proportions

* Mechanical harmonics.

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