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INDUSTRIAL APPRENTICESHIPS

Opening the Bristol Aeroplane Company's Apprentices School on March 12th, the Minister of Education stated that the object of an apprenticeship scheme was "to combine earning and learning." In modern industry that statement is true, whether it applies to a craft, student, or graduate apprenticeship.

Apprenticeship schemes tended to lose favour because of the fear that the trainee would only be fitted for one particular type of production. However, as Sir David Eccles stated, modern schemes are designed to enlarge the powers of the apprentice "and give him greater freedom to find the job which suits him best."

In Great Britain to-day everyone has a job, and there is little slack to meet the growing demands of industry. Apprenticeship schemes which are designed to assist in meeting the ever-increasing demand for engineers in radio and electronics are, therefore, of tremendous importance to the future of the industry.

There has recently been a spate of contributions to technical journals on the most desirable methods of improving the training of the radio engineer. Indeed, the subject almost vies in popularity with that of improving technique in sound reproduction! Interchange of opinion can do good and sometimes stimulates the acceptance of new ideas. For example, in the post-war years there has been an increase in the number of training courses which are available to the student of radio and electronics and there are more industrial training schemes. These are of three types: "*sandwich courses*," where the student spends alternative periods at college and in industry; *student apprenticeships* of three or five years' duration, where the student is prepared for professional examinations and is released from industry one day per week for attendance at a technical college; *craft apprenticeships* of three or five years' duration with, or without, part-time release, for the training of technicians.

The number of "sandwich courses" at present in operation is very small. The obvious advantage of this type of course is that, in addition to practical training, the time available for study at a technical college is almost double that which is possible through part-time release. Smaller companies can run a scheme of this type, with only two or three students in any one stage; where opportunities for practical experience are limited, two or more companies in the same area could exchange trainees. This is already done in large companies with several different establishments, the students spending some time at each of the establishments.

Some form of co-operative training could make a very useful contribution to the problem and bring in many of the smaller companies who, by reason of size, are not contributing to industry training schemes, although benefiting from the policy of the larger manufacturers.

Such training must be under the jurisdiction of a properly qualified training officer, rather than being delegated to an already overburdened engineer. In this way, co-operation can be fostered between technical colleges and industry. For example, where technical college training in the right subjects and of the required standard is not immediately available, colleges are usually prepared to institute new courses, provided that the demand is likely to be continuous.

The present shortage of engineers will not be eased by wholly relying on the output of the few large companies, and the individual efforts of junior engineers to improve their position by attendance at evening classes. The extension of industry-sponsored training schemes appears to be one of the most fruitful methods of solving a very pressing problem.

NOTICES

Institution Dinner

The customary dinner of the Institution with the Immediate Past President as the Guest of Honour will take place at the Savoy Hotel, London, on Thursday, May 26th, 1955. Tickets may be obtained on application to the General Secretary.

List of Members

The latest edition of the List of Members (1954) has now been published and copies have been sent to all members except Students. Registered Students of the Institution may obtain copies on application to 9 Bedford Square, London, W.C.1, price 2s. 6d. post free. The charge to non-members is 7s. 6d. post free.

Apart from listing all members of the Institution, above the grade of Student, and giving their geographical distribution, the publication contains the Memorandum and Articles of Association in full, the constitution and composition of the Standing and Local Committees, and details of Institution Premiums and Prizes.

Additional London Section Meeting

As has already been announced, the B.B.C. is to start, on May 2nd, the system of v.h.f. broadcasting, using frequency modulation, by the opening of the first station, at Wrotham, Kent. Accordingly, the Programme and Papers Committee have decided that a very useful purpose would be served by arranging a forum, at which the new service and its possible problems can be discussed.

An extra discussion meeting has therefore been arranged for Wednesday, April 13th (to be held at 6.30 p.m. in the London School of Hygiene and Tropical Medicine, Keppel Street, Gower Street, W.C.1), which will be opened by Dr. K. R. Sturley, head of the B.B.C.'s Engineering Training Department. He will be followed by Mr. F. T. Lett, who serves on the Institution's General Council and Papers Committee, and who will present the industry's viewpoint.

Digests of the contributions of the opening speakers will be prepared, but will only be available to members attending the meeting. Those who wish to take part in the discussion should inform the Publications Officer before April 13th, so that they can be called upon from the chair. It is hoped to publish a full account of the proceedings of the discussion meeting in an early issue of the *Journal*.

The plans of the B.B.C. to set up this system of v.h.f. stations has caused considerable interest among engineers all over the world and the Karachi Section were fortunate enough to be able to hear at their first meeting of the 1954-55 Session, last December, a paper by Mr. F. C. McLean, Deputy Chief Engineer of the B.B.C., entitled "Development of V.H.F. Sound Broadcasting."

Mr. McLean, who was visiting Pakistan to advise the authorities on matters concerning the development of broadcasting, gave an account of the present unsatisfactory conditions of medium-wave broadcasting in Great Britain and other Western European countries and discussed the Corporation's tests of v.h.f. systems. He then surveyed the plans for setting up, during 1955-56, a network of ten stations to serve the most densely-populated parts of Great Britain; Mr. McLean also gave details of the proposed automatically-controlled v.h.f. transmitters and of the special aerial systems which would be used.

Colonel G. W. Raby

It has recently been announced that Colonel G. W. Raby (Member) has been appointed Deputy Director (Engineering) to the research group of the United Kingdom Atomic Energy Authority at Harwell. He takes up his duties in April.

Colonel Raby has had a most distinguished career, and his most important recent appointments have been Chief Superintendent of the Signals Research and Development Establishment at Christchurch, Woolwich and, since 1951, Chairman and Managing Director of the Sudan-Gezirah Board.

Colonel Raby was elected a member of the Institution in 1947.

Radio Industry Council Premiums

Two members of the Institution are among the recipients of R.I.C. premiums for 1954, the awards for which have just been announced. They are Mr. A. E. Maine (Associate), for two papers on Magnetic Amplifiers, published in *Electronic Engineering*, and Mr. W. R. Cass (Graduate), whose joint paper with Mr. R. M. Hadfield on Dip-Soldered Chassis Production was published in the *Wireless World*.

THE SCOPE OF GAMMA-RADIOGRAPHY*

by

L. Mullins, Ph.D.†

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

SUMMARY

The relative merits of gamma-rays and x-rays are discussed with special reference to the practice and scope of radiography. It is shown that the methods are to a large extent complementary and that radiography by gamma-rays has special features which have assisted the rapid expansion of the radiographic inspection of castings and welds.

1. Introduction

The main purpose of this present paper is to review the relative merits of gamma-ray and x-ray sources, and in so doing to indicate their respective scope in industrial radiography.

With the increasing availability of convenient sources of gamma-rays arising as a result of atomic energy research, there has been a marked tendency to extend industrial radiography by using these sources not only for work for which they are well suited but also for work for which they are less suited. The wide disparity between the capital cost of an x-ray unit of any type and that of a gamma-ray source with its container has done much to encourage the unsuitable use of gamma-ray sources. Add to this, that gamma-ray sources can penetrate even greater thicknesses of steel than radiation from x-ray units regularly available, and it is abundantly clear why gamma-ray equipment is competitive with industrial x-ray apparatus.

The present situation of x-rays versus gamma-rays in industry is therefore distorted by factors which are largely economic rather than scientific. There seems to be no doubt that when ultimately the position clarifies, it will be found that the two methods are complementary to one another and each will find its use for the appropriate work for which it is suited.

2. Gamma-ray Sources

Whatever element is used as the source of gamma-rays, the fundamental phenomenon underlying their generation is a change within the atomic nucleus. The radiation is, of course, electromagnetic and is emitted as a line spectrum which differs markedly from the continuous spectrum of x-rays, as shown in Fig. 1a and b respectively.[1] The wavelengths and relative intensities of the lines in each gamma-ray spectrum depend on the element from which they arise.

Historically the first use of gamma-rays for industrial radiography was in 1925, when the naturally occurring element radium was used.[2] By 1934 radon, the radio-active gas from radium, was being recommended.[3] The prime merit of this source, which was not achieved fully until the war years, is the high gamma-ray energy which can be concentrated in what is essentially a point source,[4] e.g., 0·5 mm cube. Sources of such small dimensions may be used either to give improved definition for the same source-film distance as that used for radium; or to permit a reduction of source-film distance without deterioration of definition but with consequent reduction in exposure relative to that for the same strength of radium source.

Although the quality of gamma-rays emitted by radium and by radon are identical, because radon is the gamma-ray emitting product of radium, these elements differ in one feature which is characteristic of gamma-ray sources, namely their half-life period. This is the time taken for the initial intensity of the source to be halved, it being impossible to quote the whole life, owing to the exponential nature of the disintegration of the source. The half-lives for radium and radon are 1,600 years and 3·825 days respectively. It will be obvious that a radon source will deteriorate rapidly but, provided that a source of relatively high energy, e.g., 1,200 mC, is purchased, it may be radiographically useful for up to a fortnight, this period depending, of

*Manuscript received June 28th, 1954. (Paper No. 304.)
†Technical Advisory Department, Kodak Ltd., Harrow, Middlesex.
U.D.C. No. 620.179 : 621.386 : 778.33.

course, on the initial gamma-ray strength of the source.

It is only within recent years that these naturally occurring sources have been supplemented, and largely replaced, by the so-called "artificial radio-isotopes" obtained in the atomic energy projects. Of these, five are commercially available as gamma-ray sources for industrial radiography, namely:

Cobalt 60; Tantalum 182;
Iridium 192; Thulium 170;
Caesium 137.

The properties of these, relative to radium and radon, are summarized in Table 1.[5] It is worthwhile recording, however, that cobalt 60 and tantalum 182 emit radiation comparable, radiographically, with that from radium and radon and from x-ray sets operating in the voltage range 1,000 to 2,000 kV: the exact voltage equivalent cannot be obtained because of the differences in the nature of the wavelength spectrum. Iridium 192 and caesium 137 give softer radiation said to be comparable radiographically with that of x-rays generated at about 500 kV and 700 kV respectively. Thulium 170 gamma-rays are comparable in penetration to x-rays generated at about 120 kV.

Apart from the fundamental differences in the spectra, uncertainty in fixing the equivalents in x-ray generating voltage also arises from the differences in wave-form of the outputs of the various x-ray units. Most of the x-ray units in industrial radiography[6] are based on self-rectified half-wave rectified, Villard or Greinacher circuits operating at peak kilovoltages up to a maximum of 400 kV. A few 1,000-kV units and even fewer 2,000-kV units are in use in this country for industrial x-ray inspection. These use the resonance transformer or the Van der Graaf generator. In addition some investigatory, but not routine, work is being done with synchrotrons, betatrons, and linear accelerators[7] working in the megavolt range.

In calculating the exposure required for a source, due allowance must be made for the time which has elapsed since the source was measured. As an example, consider a radon source where the deterioration is relatively rapid. Assuming, as a first approximation, a half-life period of four days, the strength of a radon source over a period of 12 days would fall as indicated in Table 2. This table illustrates the point made earlier, namely that a radon or other source may well be useful over a period longer than the half-life period, because even a 200-mC source is a practical proposition for many purposes.

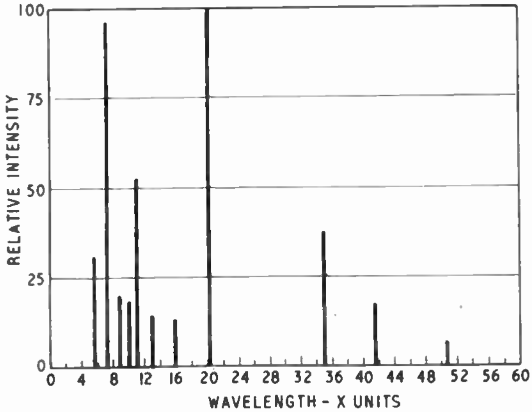
Table 1

Gamma-ray Source	Main Lines in Spectrum (MeV)	Half-life	Minimum and maximum metal thicknesses for which they are appropriate*
Radium†	0·6, 1·12, 1·76	1,600 years	2″ to 6″ steel
Radon†		3·825 days	2″ to 10″ steel
Cobalt 60‡	1·17, 1·33	5·3 years	2″ to 6″ steel
Tantalum 182‡	0·15, 0·22, 1·13, 1·22 (complex)	112 days	2″ to 6″ steel
Iridium 192‡	0·13, 0·29, 0·58, 0·60, 0·61	74 days	½″ to 2½″ steel
Caesium 137†	0·667	33 years	1″ to 4″ steel
Thulium 170‡	0·084	127 days	$\frac{1}{16}$″ to ½″ aluminium

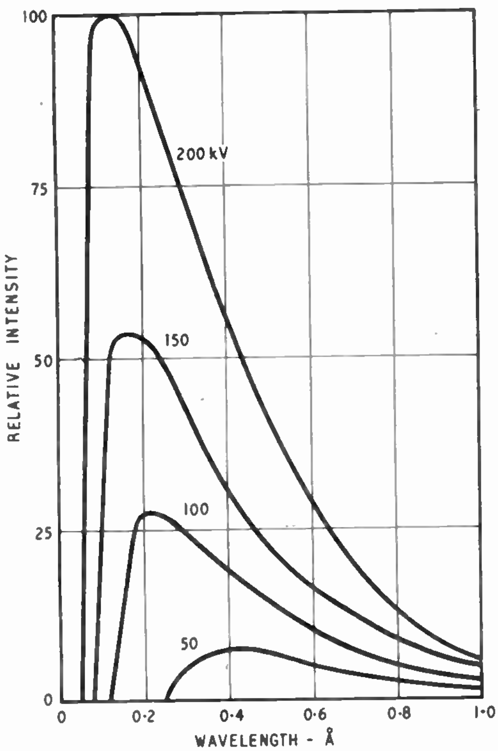
* This range is based not only on the penetration available but also on the average strengths of sources generally obtainable.

† Available from the Radiochemical Centre, Amersham.

‡ Available from the Atomic Energy Research Establishment, Harwell.



(a)



(b)

Fig. 1.—*(a) Spectrum of typical gamma-radiations.*
(b) Spectrum of various energy levels of x-rays.

NOTE.—1 X-unit = 10^{-11} cm.
1 angstrom unit = 10^{-8} cm.

Table 2

Time from initial measurement (days)	Strength—milli-curies
0	960
4	480
8	240
12	120

Whereas, a decade or so ago, 250-milligram sources of radium were the strongest gamma-ray sources available for industrial radiography, it is now common to have sources of artificial radio-active elements with initial intensities many times stronger. Nevertheless, the exposure time required with these sources to give a radiograph of an equivalent density or blackness for a given specimen thickness may run into hours owing to the relatively low-energy output, relative to minutes for an exposure with x-rays of similar penetration.

The chief merits of gamma-ray sources are firstly, their small bulk which permits them to be used in sites relatively inaccessible to an x-ray set; secondly, the absence of any need for electric or water supplies; thirdly, their extremely low cost in comparison with x-ray units emitting radiation of similar penetration, and fourthly, the high penetration of their radiation relative to that arising from x-ray units in common use industrially. A fifth merit, relative to readily available x-ray units sometimes arises, namely the lower image contrast which permits a large range of metal thicknesses to be recorded at one exposure on one film; in some instances, however, as in radiographing specimens of relatively uniform thickness such as welds, this low contrast may be objectionable because it operates against the optimum conditions for fault detection.

Artificial radio-active sources are commercially available as right cylinders of 2 mm, 4 mm and 6 mm diameter. As mentioned earlier, radon sources of high strength may be as small as 0·5 mm cube. Radium sources, which are now rarely used for radiography, vary in their geometric size according to the weight (and thus the strength) of the sources. A 250-milligram radium source, comparable in intensity with a 250-mC radon source, occupies a cylinder of about 6·5 mm diameter.

The geometric size of gamma-ray sources is therefore generally comparable with, and sometimes less than, the focal-spot size of many x-ray tubes so that image definition, due to geometric factors, need not be worse than that given by x-rays provided that the distance from the source of radiation to the film (source-film distance) is similar. Frequently, however, the source-film distance is made shorter for gamma-ray exposures, in order to reduce the exposure by virtue of the inverse square law relationship, and there is inevitably a loss in image definition.

3. Safety Precautions

Owing to the highly penetrating nature and harmful effects of gamma-rays, their use, which is subject to the Radio-active Substances Act, 1949, is fraught with danger unless the proper precautions are taken.[8] Whereas x-ray sources may be switched on and off at will, gamma-ray sources emit radiation all the time. The only way to reduce this to a safe level, when the source is not in use, is to surround it with a sufficient thickness of lead or other radiation-absorbent material.

During use, operators and other personnel must be protected by a barrier capable of reducing the radiation to a safe level, or by maintaining a sufficiently large distance between the source and the operator. Further safety is provided by arranging for the remote control of the source container.

The amount of protection, and the safe working distance, depend on factors such as:

(*a*) the nature of the source,

(*b*) the strength of the source,

(*c*) how the source is being used (panorama or beam-technique, see below),

(*d*) the time for which the person is exposed.

This last point justifies expansion. Experience has shown that the amount of radiation received per week over the body should not exceed 0·3 roentgen,[9,10,11] where the roentgen is defined as that "quantity of x- or gamma-radiation such that the associated corpuscular emission per 0·001293 gram of air, produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign." It does not appear to matter whether the maximum permissible dose is received on one occasion or whether it is the cumulative dose over the week. Although therefore, the safe working-dose rate for a continuous 40-hour week is 0·12 mr per minute, it is possible to work for short periods under higher intensities, provided that the maximum weekly dose is not exceeded.

If the radiation is received only on the hands and forearms, the feet and ankles, or the head and neck, a total dose rate of up to 1·5r per week is permissible, according to the latest international authoritative statement.[11] In the case of the head, however, the eyes must be protected so as to restrict the dose rate they receive to 0·3r per week.

Various techniques are available for checking the intensity, namely:

(1) the capacitor dose-meter, in which a conducting wire held in insulators along the axis of a conducting cylinder is charged to a fixed value relative to the cylinder. Incident radiation discharges the capacitor, so that the residual charge provides a measure of the dose received by the meter,

(2) the Geiger-Müller counter,

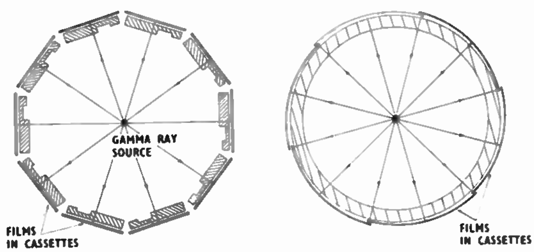
(3) photographic films: as these do not provide an immediate reading, their use is limited to providing a check of the total radiation incident on the film (or on the person wearing the film) during the period of exposure.[12]

Devices for measuring radiation intensity, based on the first two methods are available commercially, and the National Physical Laboratory provides a service for checking personnel protection, based on the film method.

4. Gamma-source Containers

Gamma-ray sources are used in one or two ways for radiography. As they emit radiation in all directions simultaneously, an unshielded source may be used, as shown diagrammatically in Fig. 2a, for the simultaneous radiography of a large number of castings arranged around the source, or of the whole of a circumferential weld in a pressure vessel, as indicated in Fig. 2b.

This method of use is very similar to that of the extended anode type of x-ray tube, except that the beam in the latter case, although covering 360 deg, is limited to a small angle relative to the major plane of the radiation. Two applications of this unshielded source technique demonstrate advantages over x-ray tubes. In the first a gamma-ray source container, capable of housing three separate sources, is provided with tubes extending from the container and provision is made for moving a source along the tube so that it may be placed anywhere along the tube within the job being inspected. At the completion of the exposure the source may be retracted into the container. The second example refers to the inspection of butt welds in pipes, with the source within the pipe. A small hole is drilled a few inches away from the weld and the source is inserted on a bent rod, fitted with a limit stop to ensure that the source is placed centrally in the pipe and in the same plane as the weld. By placing films in suitable containers around the weld, the whole of it may be radiographed at one exposure. The hole is subsequently plugged and welded over. This technique has found most application in the inspection of pipe welds in the oil fields.[13]



(*a*) (*b*)

Fig. 2.—(a) Arrangement for using an unshielded gamma-ray source for the simultaneous radiography of a circumferential weld in a pressure vessel.

(b) Radiographic examination of a large number of castings arranged around an unshielded gamma-ray source.

Where only a beam of gamma-rays is required this can be readily achieved by housing the source in a lead- or tungsten-alloy container of sufficient thickness to provide the necessary protection, with a conical outlet of about 60 deg. Many devices of this kind are available commercially: they vary in design and in the technique of opening the aperture. In some, the source is set eccentrically in a rotating centre within the outer shield, so that the source is brought before the aperture by turning the centre through 180 deg. In another type, the aperture is sealed by a conical plug of heavy metal and this is removed as required for the exposure by an offset handle, so arranged that the hand need never be in the main beam.

The size of the container depends on the protective metal used and on the strength and gamma-ray emission of the source. A lead-alloy container for a 250–500 mC cobalt 60 source is a sphere of about 5 in. diameter: if tungsten alloy is used the container is about 3 in. in diameter. A thulium 170 source of similar strength may be housed in a much smaller container. The size is also dependent on the protection required, the usual arrangement providing a safe dosage for continuous exposure at a distance of about a metre from the closed container. Occasional exposure, e.g., of the hands, nearer the container is not objectionable provided the maximum permissible dose over the week is not exceeded.

Usually these containers also provide facilities for using the source unshielded. In the simplest, the source is withdrawn on a long rod, which is readily attached to the source, by a screw thread or bayonet catch. In these conditions the operator need not approach closer to the source than the length of the rod. In another type the source may be pushed out of the container on a short stem about 6 in long, so that the radiation is emitted in a solid angle generally greater than a hemisphere, the limiting factor being the source container. This movement can be achieved at a distance of up to 15 ft from the source by remote control, using a Bowden cable, so that distance provides ample protection for the operator. One manufacturer has provided a motor-operated device which withdraws the source at the commencement of the exposure, and replaces it in its container at the end of a predetermined time corresponding to the exposure time: this entirely eliminates any danger to the operator. In some containers, protection against unauthorized use of the source is provided by a Yale or similar lock.

5. Films for Gamma-radiography

Despite the differences in quality of radiation from x-ray tubes and gamma-ray sources, the same types of films and intensifying screens are applicable. The films used are described by long usage as "x-ray films" and fall into two main groups, namely:

(1) The so-called "screen-type" films which are intended primarily for use with salt (calcium tungstate) intensifying screens but which are rarely used in this way in gamma-radiography.

(2) The so-called "direct-type" or "non-screen" films, which may be exposed either without screens, or between lead intensifying screens. The latter serve to increase the effect of the radiation on the film by electron emission, and are used for almost all gamma-ray exposures.

Direct-type films are available in three speeds, namely fast, medium and slow, the grain being finest for the slow film. The fine-grain film is therefore recommended for all work requiring the detection of fine details. The fast film has the merit of high speed, being six times or more faster than the fine-grain type, but the grain may interfere with interpretation when fine details are involved.

Owing, however, to the relatively low contrast available with the higher energy gamma-ray sources, the tendency is to use the fine-grain high-contrast films with lead intensifying screens, which latter not only intensify but also serve to minimize the effects on the image of scattered and therefore non-image forming radiation. There is no doubt that this film-screen combination provides the best conditions for fault detection. Where the exposure time must be reduced to a minimum, and providing the resulting fault detection is adequate, the fastest non-screen type film may be used. Unfortunately, there is a tendency to rate exposure speed as the most important factor, without realizing the loss in fault detection which results.

The processing of the films follows the accustomed practice of developing, rinsing, fixing, washing and drying. In order to obtain maximum speed out of the films, extended development is sometimes used but if carried too far this may well lead to a reduction in fault detection due to the consequent worsening in image grain size and the increase in fog.

Much evidence is now available to show that fault detection is greatly enhanced by exposing the films to give very high photographic densities up to as much as 3·0, according to the type of film, in order to make full use of the resulting higher image contrast. Obviously this increases the exposure time. This may be offset by using stronger sources but this should not be achieved by using a greater geometric-size source, otherwise image definition is impaired. For the same reason, the increased film density should not be achieved by reducing the source-film distance. It will be evident, therefore, that the choice of films, screens, and exposure factors is a matter calling for great experience in balancing the effects of the many factors involved.

Exposure charts[14] and slide rules[15, 16] are available to assist in choosing the exposure, but due allowance must be made for the inherent deterioration of the source, which is a most important factor when using sources of short half life, e.g., iridium 192.

6. The Scope of Gamma-radiography

There can be no doubt that gamma-ray sources, and particularly the cheaper ones which have become available during the past few years, have greatly extended the scope of industrial radiography. It is true that given sufficiently penetrating sources of x-rays, as exemplified by the megavolt units, in the form of 1,000 and 2,000-kV resonance units, 2,000-kV Van der Graaf units, linear accelerators, synchrotrons, betatrons, and the like, much of the work at present justifiably left to high-energy gamma-ray sources could equally well, and more rapidly, be undertaken with x-rays, because of the considerably higher radiation output of such generators. The operative factor here is undoubtedly the high capital cost involved. Except in special circumstances, where their cost can be justified and where the specimens can be brought to the equipment, there seems to be little chance of x-ray units supplanting gamma-ray sources in the near future. Certainly many of the smaller firms now using gamma-ray sources would be unable to justify the high cost of the appropriate x-ray equipment.

Moreover, there will inevitably be conditions where their small bulk, high mobility, and freedom from any need for water and electricity supplies, will make gamma-ray sources the first choice, despite the long exposures.

With these factors in mind, it will be readily understood that the scope of gamma-radiography cannot be clearly defined, but the usual applications are to the heavy metals and fall into the following groups:

(1) the inspection of heavy metal castings, particularly where these are outside the range of the available x-ray equipment.

(2) the inspection of steel welds, where these are too thick for any x-ray equipment available, or are more conveniently inspected by gamma-rays, e.g., pipe welds on site, ship welds.

In addition, there are many applications where the examination of castings or welds is undertaken by gamma-rays because the quantity of work involved does not justify the purchase of an x-ray unit of appropriate kilovoltage, or where the firm concerned cannot afford its cost.

7. The Inspection of Castings

The chief merits of gamma-ray sources for casting inspection are firstly, the relatively low contrast permitting the simultaneous recording of a large range of metal thicknesses; and secondly, the possibility of examining a large number of castings at the same time by the panoramic technique, so effectively increasing the number which may be examined in a given time.

The need for radiographic inspection is obvious, bearing in mind not only the potential dangers in service of hidden defects such as slag pockets, shrinkage cavities, cracks and so on; but also the wisdom of eliminating faulty castings before time and money are needlessly spent in machining them, only to discover defects at that late stage.

The advantages of radiography as a non-destructive means of detecting casting defects are now well established, as is shown by the number of official engineering bodies which have written radiographic inspection into their acceptance codes for castings intended for specific purposes. In Great Britain, perhaps the more important of these authorities are the Admiralty, and the Aeronautical Inspection Directorate of the Ministry of Supply. In America, the lead has been taken by the American Society of Mechanical Engineers and the American Society for Testing Materials. Unfortunately, with the exception of the acceptance-standard code laid down by the American Society for Testing Materials,[17] little guidance is given regarding the acceptability or otherwise of the defects which are revealed, and even this code has been severely criticized. More will be said on this aspect later.

The defects in the castings are revealed, in the radiograph, by images which are usually darker than the surrounding image, although of course there is the possibility of lighter images occurring, as for instance when segregation of a heavier component is present. The clues to the cause of the images are given by their shape, contrast, size and position, but accurate interpretation calls both for long experience, and for a sound knowledge of the job being examined and of its potential defects. Great caution is necessary in differentiating between these images and those due to:

(1) marks, e.g., chipping-tool marks, on the surface of the job, and
(2) fortuitous images which sometimes arise owing to the faulty handling, exposing or processing of the films.

Guidance on the interpretation of radiographs of castings is given in the American acceptance code mentioned above and a British Standard on this subject is now well advanced. In the absence of these, some assistance may be had from the various text-books on industrial radiography and from technical papers. The subject is, however, far too complicated and extensive to discuss adequately in the present paper.

Very large castings in heavy metals involving large metal thicknesses, e.g., ships' stern frames and turbine casings, are obviously ideally suited for gamma-radiography, particularly because apart from the great thicknesses involved, they also contain a wide range of thicknesses. By virtue of the lower image contrast of gamma-ray sources relative to that of x-ray sources normally available, the gamma-radiograph covers a greater range of metal thicknesses, and will often give adequate information on one film where several x-ray radiographs, each covering a smaller thickness range, may have been necessary. This feature sometimes proves advantageous in inspecting smaller castings. For example, a grey-iron casting intended for a film perforator had metal thicknesses ranging from $\frac{1}{2}$ in. to $3\frac{1}{2}$ in. and five radiographs were necessary to provide an overall inspection with a 200-kV x-ray unit. Even then, the thickest section could not be examined owing to the penetration limitation of the x-ray source. A single radiograph with a 250-500 mC cobalt 60 source now provides all the information required. Since many of these castings can be radiographed simultaneously, as described earlier, and because the exposures may be made overnight, the much longer exposure time with the gamma-ray source causes no hardship.

This particular casting also illustrates the saving which can result from the use of radiography. The machining costs on this casting before completion are in the region of £200, which may be completely wasted if the casting were found to be defective during or on completion of machining. By a comparatively small expenditure on radiography it is now possible to eliminate, before machining, all castings likely to be found defective. This not only saves money but also delays in production.

Radiography has also been applied extensively in foundry control where it provides a simple means of revealing defects in pilot castings,[18] so that the foundry technique can be modified where necessary to yield satisfactory castings before going into full production. A striking example of radiography as a means of improving the quality of castings occurred in the production of a cast-gear blank. In view of a rejection rate of 14 per cent. on the first 50,000 blanks, a change in foundry procedure was considered. By using radiography for the inspection of pilot castings made by alternative methods, a new production technique was evolved giving a rejection rate of only 1·2 per cent. in the next 75,000.

The alternative to radiography is the sectioning of castings which, apart from being wasteful, may miss defects. The possibility of missing defects is, of course, also true of radiography, especially when the contrast is as low as is usual in gamma-radiographs, and this limitation must be kept in mind. It does not follow that the absence of images of internal defects is indicative of a sound casting. Very fine defects, e.g., hair-line cracks, or fine inter-crystalline shrinkage may not be detected. Grosser cracks, too, may be missed if their plane is not reasonably well in line with the direction of the radiation; fortunately, however, they usually occur in positions suitable for their detection.

8. The Inspection of Welds

The greatly extended use of welding in the construction of such important structures as ships, bridges, pressure vessels, and oil-refinery equipment has brought with it the usual attendant worries regarding perfection, which result from a major change from an older well-established technique such as riveting.

Fortunately radiography has provided a ready non-destructive check on the weld quality. As this check was first used on welds within a few months of the discovery of x-rays in 1895[19] and has been used consistently in industry for well over 20 years for the inspection of Class I pressure vessels, there is no uncertainty about the scope of weld radiography. The major change has, of course, been in the increasing availability of gamma-ray sources, which has in fact increased the scope of weld inspection by providing more mobile sources for the increasing number of sites and jobs inconveniently placed for ready accessibility of an x-ray unit.

Perhaps this is best illustrated by reference to shipyard radiography. Although a welded ship was examined by radiography in the early 'thirties, it was not until about 14 years ago that this application really started to become well established. X-rays were then used and considerable hazards were found in their use under shipyard conditions. As the units had to be used in all weathers, the consequent need for weather-proofing soon became very obvious. There was the additional danger of a high-tension cable being cut on the sharp edges of plates, or by some heavy object accidentally dropped on it, and there was always the possibility of damage to the whole unit by some slip during lifting. Nevertheless extensive and valuable experience was gained under the ægis of the Admiralty (D.N.C.).[20]

Such difficulties prompted the design of x-ray units specially intended for such work. One of the earliest made to meet some of these demands provided complete weather-proofing, and the facility to separate it into small components to increase mobility. The external high-tension cables remained, however, and when these were extended up to 20 ft or so, to facilitate the inspection, the hazards to them were correspondingly greater.

Later x-ray equipment has avoided the external high-voltage cables by building the high-tension transformer into the tube head. In spite of this, the size of the tube head has been kept well within the limits set by the manholes through which they may have to be introduced into the ship's structure. The weight, too, is within the lifting capacity of two men, so that cranage facilities need not be used, thus freeing the shipyard cranes for constructional work. These tubes do not, generally, utilize cooling, so that only low continuous currents (about 4 to 8 mA) are possible, but where provision for cooling is made the permissible loading may be increased. The maximum kilovoltage available runs from 150 kV to 220 kV. As the steel-plate thicknesses do not, in general, exceed about $1\frac{1}{2}$ in such voltages are quite ample.

Despite the availability of such x-ray equipment gamma-ray sources are tending to supplant x-rays for the inspection of welds on ships. In fact, the only disadvantages of gamma-radiography for this work are:

(1) the long exposure times,

(2) the lower image contrast, relative to x-rays of the correct voltage for the job.

The first is not particularly serious provided that the work is done outside normal working hours, or that the welds being radiographed are well away from workmen on the ship. The latter factor of lower contrast is likely to prove more serious, particularly where very fine defects are being sought. Nevertheless, where iridium 192 sources are used in conjunction with fine-grain direct-type films and lead-intensifying screens, very useful results are being obtained, but there is little to be said in favour of more penetrating sources, such as cobalt 60, for the normal range of thicknesses in ship plates.

Another application of weld inspection which offers great scope for gamma-rays is the checking of weld quality in the butt joints in oil lines. As these are generally very distant from power supplies, their inspection by x-rays would necessitate taking a motor-generator, in addition to the x-ray unit, to the site. Inspection by a gamma-ray source placed centrally in the pipe, as described earlier, provides a radiograph of the whole joint at one exposure; alternatively the source may be used outside the pipe. The time factor is not so important provided several sources are available, so that some exposures are being made whilst other sources are being set up elsewhere.

Whatever technique is used for weld inspection, whether gamma-rays or x-rays, the aim is to detect any internal defects present, for example, cracks, inclusions, gas defects, lack of fusion. The form of the image corresponding to such defects has been described in a British Standard[21] and other publications.[22, 23, 24] Porosity, for instance, is revealed in the radiograph as dark circular spots, occurring in groups. Line inclusions, generally of slag, are also characterized by dark images but these take the form of linear bands, with irregular edges, running along the length of the weld. Shrinkage cracks appear in the radiograph as fine, dark, tortuous or wavy lines.

The value of radiography for weld inspection is well established and it now forms a part of weld-inspection procedures laid down by many inspecting bodies, e.g., Lloyd's Register of Shipping, the Admiralty, the American Society of Mechanical Engineers, the Associated Offices Technical Committee, the American Petroleum Institute. The Ministry of Supply, too, used radiography in checking welds in atomic-energy plant.[25] Most of these inspection codes relate to x-ray inspection, but gamma-rays are also applicable in many instances.

9. The Significance of Radiographic Evidence

The assessment of the importance in service of defects revealed radiographically calls for an extensive knowledge of the principles of the technique, for experience in interpretation, and for a knowledge of the products being inspected and their service conditions.

The simplest case arises in the inspection of an assembly, in which the number and position of the components are known. Here it is usually a matter of deciding whether a component is missing or out of place, when the assembly is usually rejected. Greater difficulty arises when castings or welds are being examined. Ideally, no defects should be present in the perfect specimen. In practice, some may be present, and their type, extent and position, can rarely be forecast with any certainty. Extremely critical examination of the image is therefore necessary to determine all the information it contains. Great care must be taken to ensure that images arising from surface marks on the specimen, or from adventitious images rising from faulty radiographic technique, are not confused with images due to defects within the specimen. It may, in some instances, be impossible to dogmatize with certainty on the defect producing the image, and further radiographs, possibly taken with a different beam direction, may be necessary to assist in its identification.

Assuming that the causes of all the images have been correctly interpreted, it then becomes necessary to determine whether the job is acceptable or not for service. Unfortunately, only scanty generalizations exist concerning the effect of internal defects on the strength of the weld or casting in service. Accordingly, the reliability of the decision for acceptance or rejection will depend on the opinion and experience of the inspector or surveyor, who must take into account the type, extent, and position of the defect, and the service conditions.

Even for welds, which would appear to be the simplest case, information relating to the effect of defects on strength is far from complete. It is known, however, that planar defects, for example, cracks and lack of fusion, can be dangerous, particularly under cyclic loading. It is clear too that certain defects, for example, slag pockets, may act as stress raisers in service and must therefore be considered as potential sources of failure. These criteria provided the justification for the A.S.M.E.—A.P.I. acceptance standards for Class I fusion-welded pressure vessels and for the Admiralty code for Class A welds. Detailed though these standards are, they contain certain anomalies, and no service-acceptance standards exist for welds other than those designed to Class I (or Class A) specifications.

So far as castings are concerned, the American Society for Testing Materials is the only body which has so far published any standards of acceptance based on radiographic evidence. The major objection to these standards is that too little detail is given concerning the radiographic technique, which has such important effects on the detection of defects.

Whilst there are many who regret this position, there are many who favour it, since the absence of an all-embracing acceptance standard enables each case to be considered on its merits. A vital fact does emerge, however, namely that castings or welds must not necessarily be condemned because of the presence of an internal defect. The question that must be decided is whether the defect will be of any importance in service. The absence of definite standards of acceptance emphasizes the need for skill and experience in evaluation and radiographic evidence, but the present wide and successful use of radiography in this up-to-date inspection procedure demonstrates that acceptance standards are not necessarily important.

10. Conclusions

The increasing availability of gamma-ray sources has greatly extended the scope of industrial radiography, by virtue of the greater thickness penetrations possible. For both economic and practical reasons gamma-ray sources are being used in some circumstances where x-rays might be better employed. The radiographs so obtained are generally less capable of revealing the very fine defects shown by x-rays.

It seems most unlikely that gamma-ray sources will ever completely replace x-ray equipment, and certainly at present x-rays offer many advantages in speed of exposure and in choice of penetration, which are particularly valuable features in the inspection of light-alloy castings.

The best competition against this extension of gamma-radiography would be provided by making x-ray units simpler, smaller and cheaper than those existing to-day.

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DISCUSSION

Mr. C. W. Miller (*Associate Member*): Dr. Mullins has in his paper on gamma-radiography given a comprehensive survey of the scope of this important technique of inspection and has rightly pointed out the very real advantages of low cost and absence of power supplies. Elsewhere (Ref. 8) I have discussed industrial radiography in general and showed that in dealing with thick specimens high-energy radiation and powerful sources are required. A particular type of x-ray generator was shown to fulfil this requirement. Dr. Mullins states that gamma-radiography and x-radiography are complementary. This is of course correct, but nevertheless, they are to a certain extent also competitive.

It has been stressed that gamma sources are of small physical size but it must be remembered that such sources are also of small activity entailing very long exposures. When one turns to sources of large activity one finds that they are of considerable size. For instance, a 1,000-curie source of cobalt 60 is about 2·5 cm in diameter. With x-ray equipment discussed in my paper the source size is of the order of 5 mm diameter and the output equivalent to about $\frac{1}{2}$ cwt of radium, say 25,000 curies.

I would challenge Dr. Mullins's statement about gamma-radiography being useful for those cases outside the range of x-ray methods. The range of x-ray methods is indeed far wider than that of gamma-radiography.

The success or otherwise of a radiographic technique is often assessed by a quantitative statement of flaw detection sensitivity. It is perhaps disappointing that Dr. Mullins has not given such figures and I would, therefore, provide some figures and ask for his comments. The best figure I have been able to find for cobalt 60 is an optimum of 0·5 per cent. flaw detection sensitivity and this occurs for about 5 in of steel. Corresponding figures for a 4-MeV linear accelerator are 0·4 per cent. at 5 in improving to 0·3 per cent. at 13 in.

Dr. L. Mullins (*in reply*): I welcome Mr. Miller's challenge regarding the relative merits of x-rays and gamma-rays, because I think I covered this point by my statement that "much of the work at present justifiably left to high-energy gamma-ray sources could be equally well, and more rapidly, undertaken with x-rays."

So far as sensitivity of fault detection is concerned, I deliberately avoided quoting figures because of the many complexities in defining what is being measured. The principle of assessing sensitivity is to increase artificially the specimen thickness by attaching a thin step wedge (penetrameter) of the same material to the source side of the specimen. The sensitivity is then expressed as the percentage corresponding to the ratio of the thinnest step visible in the radiography to the specimen thickness at that point. Thus the larger the figure, the worse the sensitivity. The actual figure measured depends on the type of penetrameter used, on how the results are evaluated, on the films and screens used, and in fact on the conditions of viewing.

APPLICANTS FOR MEMBERSHIP

New proposals were considered by the Membership Committee at a meeting held on February 24th, 1955, as follows: 64 proposals for direct election to Graduateship or higher grade of membership and 53 proposals for transfer to Graduateship or higher grade of membership. In addition, 51 applications for Studentship registration were considered. This list also contains the names of two 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 the 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.

Direct Election to Member

HEGDE, Professor Kojakully Shivaram, M.A., B.E. *Badanidiyur, Madras.*

Direct Election to Associate Member

CURRY, William Reginald. *London, N.11.*
MORRISON, James. *London, N.21.*
NICOL, William Paul. *Colnbrook.*
RANGACHARI, Thirumalai Seshachari, M.A., M.Sc. *Royapettah, Madras.*

Transfer from Associate to Associate Member

LEPPARD, Sqdn. Ldr. Ronald William, R.A.F. *North Cheam.*

Transfer from Graduate to Associate Member

DENNY, Ronald Maurice. *London, S.W.10.*
LANE, Dennis Edward. *Woking.*
McGREGOR, Peter. *Acharn, Perthshire.*
READ, Peter George. *Surbiton.*
REYNOLDS, Peter Harold. *London, S.E.9.*
SODHI, Flt. Lt. Jasjit Singh, B.A., Indian Air Force. *Cranfield.*

Transfer from Student to Associate Member

COPESTICK, Leslie Bennett. *New Malden.*
PRADHAN, Keshav Balkrishna, B.Sc. *Bombay.*

Direct Election to Associate

ANSON, Stanley Edmund. *Seria, Brunei.*
JEFFERSON, Alan Gordon. *Gosport.*
WIGAN, Michael Paul. *Orpington.*

Transfer from Student to Associate

AHMAD, Capt. Saiyed Amin Uddin, Pakistan Army. *Rawalpindi.*
BURRILL, Kenneth Arthur. *Yenishir, Turkey.*
CUTHBERT, James Anderson. *Edinburgh.*
DIXON, Geoffrey Harewood. *Hull.*
DONNISON, John William. *London, S.E.27.*
FREEMAN, Philip Stanley. *Luxembourg.*
GIBSON, Leslie. *Cambridge.*
GLASSBROOK, George James. *London, S.W.19.*
JAMES, David Benjamin Garfield, B.Sc.(Hons.). *Swansea.*
MILLER, William Aikman. *Edinburgh.*
PATRICK, George Benjamin. *Birmingham.*
SINCLAIR, David. *Moreton, Cheshire.*
STONE, Frederick John. *Slough.*

Direct Election to Graduate

THOMPSON, John Edward Harold. *London, W.7.*
VENKATARAMANI, B., B.Sc. *Madras.*

Transfer from Student to Graduate

BEEFTINK, Johan. *Welwyn Garden City.*
BLACK, William Stewart. *Glasgow.*
BOWN, Geoffrey Charles Stanley. *Penarth.*
CHOPRA, Krishan Singh, B.A. *Coventry.*
COFFEE, Ronald Alan. *London, S.W.16.*
GILBERT, Alan Percy. *Stanmore.*
JARVIS, John Walter. *Stevenage.*
JHA, Chandra Shekhar, B.Sc.(Hons.). *Edinburgh.*
KLIMEK, Andre Mathieu. *London, S.W.9.*
LONGLAND, David Arthur, B.Sc. *Feltham, Middlesex.*
MELINN, Michael Gerard. *Balbriggan, Co. Dublin.*
MILES, Ronald Boyce. *Harrow.*
MORDEKHAI, Ephraim Hay. *Ramat Gan, Israel.*
NIGHTINGALE, Daniel Edgar. *London, S.W.12.*
SINHA, Sudhansu. *Carshalton.*
STANBROOK, Donald. *Stevenage, Herts.*
WOLFE, Brian Sinclair. *London, N.20.*

STUDENTSHIP REGISTRATIONS

ABU EL HAJ, Akram. *Ramallah, Jordan.*
ACHYUTHA RAO, Krishnamurthy, B.E. *Bangalore.*
BARRETT, Brendan. *Coventry.*
BELL, John Stanley. *Sutton.*
BROMBERGER, Eric R. *Lilongwe, Nyasaland.*
BRUSH, Alberto Valera. *London, N.W.2.*
BUCHBINDER, Martin J. *Tel-Aviv.*
CAREY, Henry George. *London, N.W.10.*
CARLTON, John William. *Waterbeach.*
CARTER, Colin Raymond. *St. Albans.*
COLLINS, Vernon J. W. *Richmond, Surrey.*
EL-JADIRY, Fakhri Abdul Karim. *London.*
FLECK, William. *Lisburn, Co. Down.*
GEORGE, Panthradil Samuel. *Kozhencherry.*
GRAHAME, Jackson. *Lusaka, Northern Rhodesia.*
GROVES, Flg. Off. Peter, B.Sc., R.A.F. *Calne.*
HAMILTON, James Henry. *Mlanje, Nyasaland.*
HISCOCK, David John. *Droitwich.*
ISMAIL, Sulman. *Southampton.*
IYER, Capt. Ramkrishna Narayana, B.Sc., Indian Army. *Deolali, Bombay.*
JINADU, Saula Aremu. *Ibadan, Nigeria.*
JOHNSON, Oliver Norman. *Pembroke Dock.*
KLIMEK, Georges Eugene. *London, S.W.9.*
KOUREAS, Varnavas Demetri. *London.*
LI YUAN-LU. *Chelmsford.*
LLOYD, Frederick Keith. *Andover.*
McCARTHY, Kenneth John. *London, W.2.*
MANVENDRA SINGH CHAUHAN, M.Sc. *Agra.*
MITRA, Somendra Nath. *Bangalore.*
MURCH, Leslie John. *Southend-on-Sea.*
PRESTON, Ronald Stephen. *Durban.*
QUINE, Robin Brian. *Wolverhampton.*
RAJINDAR NATH VYAS, B.A. *Jorhat, Assam.*
RANGANNA, B., B.Sc. *Bangalore.*
RUTHERFORD, John. *Sohano, New Guinea*
SAHIB, Pushkar Nath. *New Delhi.*
SARIN, Satish Kumar. *Hoshiarpur.*
SEKHRI, Guatam Dev. *Bangalore.*
SENGUPTA, Jyoti Bhusan. *Jabalpur.*
SHYAM MURARI. *Dehra Dun.*
SINHA, Major Udaya Prakash. *New Delhi.*
SOHI-ZADE, Isaac. *London, N.16.*
TAWDE, Shishir Nanasaheb. *Bombay.*
THOMPSON, Alan Coulthurst. *Bury, Lancs.*
TOWNSEND, Brian Joseph. *Peterborough.*
WATKINS, Richelieu S. *London, N.W.3.*
WHARAM, Robert Geoffrey. *St. Albans.*
WHITEMAN, John. *Nottingham.*
YOUNG, Alexander Robertson. *Falkirk.*
YOUNG, William Thomas. *Whitehouse, Co. Antrim.*
ZOHOOR ud din SIDDIQI, B.Sc. *Quetta.*

A DIRECT-INDICATING PHASE METER*

by

A. van Weel, Dr.Techn.Sc.†

SUMMARY

A phase-measuring method is described in which the phase angle to be measured is introduced in an oscillating circuit, thus influencing the oscillator frequency. The phase angle can be determined by measuring the frequency shift of the oscillator. The most important parts of a phase meter based on this principle are discussed in detail and a description of a complete apparatus is given.

1. Introduction

Many different methods are known for measuring phase angles, but new methods are still regularly published, indicating that existing phase meters are not satisfactory for all purposes. This is not surprising, considering what demands could be made on a truly versatile phase meter:

1. *Range*—the maximum range is limited to 0-2π radians, phase angles outside this range being ambiguous. For certain applications the ranges are much smaller.
2. *Sensitivity*—phase angles as small as 10^{-4} radian have to be measured for certain applications, e.g. group-delay measurements,[1,2] loss-angle measurements, etc.
3. *Accuracy*—the demands in this respect are usually not excessive, an accuracy of 1-2 per cent. being sufficient in most cases.
4. *Amplitude variations* of the voltages between which the phase relation is to be determined should not influence the measurement.
5. *Measurements at various frequencies* are sometimes necessary (e.g., tracking of a Nyquist diagram).
6. *Direct indication* of the unknown phase angle is important as it simplifies measurement. Many phase-measuring methods do not comply with this point as they are based on a zero-setting of some reference voltage.

As far as the author knows, no phase-measuring method exists combining all these features. Nor does the phase meter to be described in this paper answer all these demands. However, the principle to be described allows the realization of five of the six points mentioned; only the possibility of measuring at different frequencies is limited to a restricted frequency band.

2. Basic Principle

The measurement of a physical quantity should be based on the observation of an effect which depends directly, and preferably exclusively, on the quantity to be measured. For phase angles, this effect can be found in the frequency of a stable sinusoidal oscillating circuit.

As is well known, stable oscillation is possible if two conditions are met. According to one condition the total amplification, measured after one complete passage through the closed loop which constitutes the oscillating circuit, should be equal to unity. The second condition prescribes that the total phase variation after one passage through the loop should be zero or $2\pi n$. This phase variation depends on the magnitude of the resistances and reactances in the circuit. Provided the circuit elements are constant, the only variable parameter is the frequency, the magnitude of which thus follows directly from the second condition for stable oscillation.

Let us suppose that a certain phase variation occurs in an already oscillating loop circuit. The phase condition will no longer be fulfilled at the original oscillating frequency, but at another frequency the phase condition will again be met, enabling stable oscillation on this new frequency. One might say that the oscillating frequency shifts itself to an extent such that the phase variation caused by this frequency variation exactly cancels the original phase variation. Evidently a certain relation exists between the original phase variation and

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the resulting frequency variation, this relation being determined by the properties of the circuit. The phase variation may therefore be determined from a frequency measurement, an advantageous situation, as frequencies can be measured with great accuracy.

The problems to be solved in realizing a phase meter according to this principle are:

1. The introduction of the unknown angle in an oscillating circuit.
2. The realization of a linear relation between phase angle and frequency variation, so as to simplify the calibration of the apparatus.
3. The stabilization of the oscillator frequency for all other influences, including amplitude and frequency variation of the voltages between which the phase relation is to be determined.
4. The direct indication of the measured phase angle on a calibrated scale.

The first problem is most easily solved when the phase angle to be measured is of the transfer impedance of a quadripole, of which input and output terminals are directly accessible. This case will be considered in Section 3, and some conditions for a linear phase-frequency characteristic are also discussed in the same section.

For the general case, where a phase angle between two given voltages must be measured, a special oscillator circuit is necessary, permitting the introduction of the unknown phase angle into the oscillating loop. This circuit is described in Section 4 where a measure to be taken against frequency variation of the given voltage is also discussed. The suppression of amplitude variations in limiter circuits without accompanying phase variation is the subject of Section 5.

A general description of a realized phase meter is given in Section 6, while Sections 7 and 8 discuss in some detail the most interesting parts of this phase meter. Section 9 gives some quantitative information about the properties of the instrument.

3. Phase Measurement on a Quadripole

A quadripole, of which input and output terminals are accessible, can be directly inserted in the closed loop of an oscillator, thus introducing the unknown phase angle into this loop. This is shown in Fig. 1 where Q is the quadripole, while A contains the circuits and amplifiers of the oscillator proper. The influence of amplitude variations will be discussed separately in Section 5, so we will only consider phase properties here.

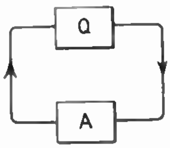


Fig. 1.—Inserting a quadripole Q into the loop of an oscillator circuit (A) enables the measurement of the phase of its transfer impedance from the frequency shift of the oscillator.

Let us first assume the phase angle $\Delta\phi$, introduced by the quadripole Q, to be small. The angular frequency variation $\Delta\omega$ which gives an opposite phase variation in the whole circuit can be calculated from

$$\Delta\phi + \left(\frac{\partial\phi}{\partial\omega}\right) . \Delta\omega = 0 \quad \ldots\ldots\ldots\ldots (1)$$

where ϕ is the phase variation of a signal at the oscillating frequency after one complete passage through A and Q. The magnitude of $\Delta\omega$ is clearly influenced by the phase properties of both A and Q. To realize a constant and linear relation between $\Delta\omega$ and $\Delta\phi$, two conditions should be fulfilled:

1. The value of $\partial\phi/\partial\omega$ of the oscillating circuit proper (A) should be large compared with $\partial\phi/\partial\omega$ of the quadripole Q.
2. The phase-frequency characteristic of A should be linear over the maximum range of phase angles to be measured.

The first condition restricts the method to those applications where the order of the magnitude of $\partial\phi/\partial\omega$ of the quadripole is known which enables the choice of a suitable value of $\partial\phi/\partial\omega$ for the part A of the oscillator circuit.[1] The second condition can be met by using phase linear networks; these networks can be realized for almost any range of phase angles.

Equation (1) holds not only for the phase variation to be measured, but for any phase variation occurring in the circuit. For accurate measurements, parasitic phase variations, caused by temperature variations of the other circuit elements, should be small compared with the phase variations to be measured. This indicates the need for a very stable oscillator circuit, a stability which must be basically a phase stability and not only a frequency stability, as could be realized by using very selective circuit elements (quartz crystals, for instance). Due to the high value of $\partial\phi/\partial\omega$ of these elements, frequency variations caused by phase variations can be made very small, but this holds for "wanted" phase variations as well as for parasitic variations!

4. Phase Measurement on Given Voltages

The necessity of accessibility of both input and output terminals of the quadripole which determines the unknown phase angle, severely restricts the possibility of application of the principle discussed in the preceding section. We will now proceed to the description of an oscillating circuit, permitting the introduction of a phase angle between the given voltages, which circuit enables more general phase measurements to be made.

The circuit, as shown in the block diagram of Fig. 2, contains two converter stages M1 and M2, to one of the input grids of each, the voltages between which the phase angle is to be measured are applied. The frequency of these voltages is $f_p = p/2\pi$, the angular frequency being denoted by p. The converter valves are at the same time

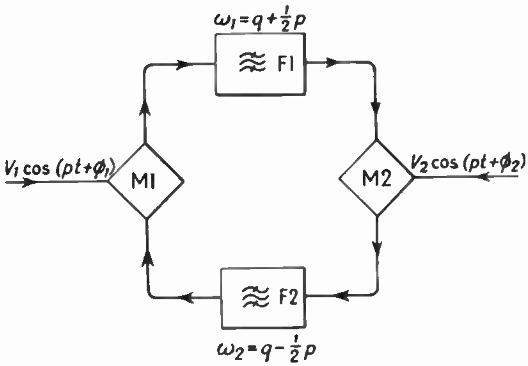


Fig. 2.—A circuit, oscillating in a pair of frequencies, ω_1 and ω_2, where the phase angle $(\phi_1 - \phi_2)$ between two external voltages can be introduced in the oscillating loop proper.

a part of the oscillator circuit indicated above, which is formed by the filters F1 and F2 in series with M1 and M2. As we will see, this oscillator circuit does not generate one frequency, but a pair of frequencies ($f_1 = \omega_1/2\pi$ and $f_2 = \omega_2/2\pi$ respectively), to which the filters F1 and F2 are tuned. The magnitude of the frequencies f_1 and f_2 are arbitrary except for the condition that either their sum or their difference should equal the frequency f_p. For this reason we can write for these frequencies $f_1 = f_q + \frac{1}{2}f_p$ and $f_2 = f_q - \frac{1}{2}f_p$, in which the frequency f_q might be chosen arbitrarily.

Each converter stage has two input voltages: one of the external voltages of frequency f_p and one of the output voltages of the filter F1 or F2 of frequencies f_1 or f_2. In Fig. 2 it can be seen that a loop circuit M1–F1–M2–F2–M1 is formed in this way, and, provided amplitude and phase conditions are met, stable oscillation at the pair of frequencies f_1 and f_2 is possible.

The phase variation, which is impressed on a signal during one complete passage through the entire loop depends on the phase properties of filters F1 and F2, but also on the phase difference $\phi_1 - \phi_2$ of the given voltages V_1 and V_2. This can be proved as follows: Let the output voltage of filter F2 be $v_2 \cos(q - \frac{1}{2}p)t$.

The output current of converter M1 contains a component $i_1 \cos\{(q + \frac{1}{2}p)t + \phi_1\}$, which causes at the output terminals of filter F1 a voltage $v_1 \cos\{(q + \frac{1}{2}p)t + \phi_1 + \psi_1\}$, the angle ψ_1 being introduced by filter F1.

The output current of converter M2 can now be written $i_2 \cos\{(q - \frac{1}{2}p)t + \phi_1 - \phi_2 + \psi_1\}$ and the output voltage of filter F2 due to this component as

$$v_2' \cos\{(q - \tfrac{1}{2}p)t + \phi_1 - \phi_2 + \psi_1 + \psi_2\}.$$

Stable oscillation is possible if

$$v_2' = v_2 \text{ and } \phi_1 - \phi_2 + \psi_1 + \psi_2 = 0.$$

Evidently the phase angle $(\phi_1 - \phi_2)$ will influence the oscillator frequencies in exactly the same way as the phase properties of the filters F1 and F2. The phase difference $\phi_1 - \phi_2$ can therefore be determined from each of the oscillating frequencies, provided the phase characteristics of the filters F1 and F2 are linear.

However, the oscillating frequencies f_1 and f_2 in this case not only depend on the phase properties of the circuit, but also on the frequency f_p of the given voltages. This disturbing influence can be eliminated by adding both oscillator frequencies f_1 and f_2 in a third converter stage, the sum frequency $f_q + \frac{1}{2}f_p + f_q - \frac{1}{2}f_p = 2f_q$ being no longer dependent on the frequency f_p. One should be aware, however, that the symmetrical way of writing the frequencies f_1 and f_2 as $f_q \pm \frac{1}{2} f_p$ is quite arbitrary, and does in itself not guarantee that a variation of Δf_p of f_p will divide itself equally over both frequencies f_1 and f_2. This will only be the case if the phase characteristics of the filters F1 and F2 have an equal slope $(\partial\psi/\partial\omega)$; but in a situation where the magnitude of for instance $\partial\psi_1/\partial\omega$, would be large compared with $\partial\psi_2/\partial\omega$, the frequency variation Δf_p would be transferred mainly to f_2. The sum frequency would in this case be equal to $2f_2 - \Delta f_p$, evidently being still dependent on the frequency of the external voltage.

Elimination of the frequency sensitivity is therefore possible by measuring the sum (or the difference) of the frequencies f_1 and f_2, provided the slope of the phase-frequency characteristic is the same for both filters. Even so, the tolerable frequency variations are still limited, because a certain frequency deviation Δf_p from the normal value f_p causes a deviation of the oscillator frequencies of $\frac{1}{2}\Delta f_p$. The phase characteristics of the filters F1 and F2 are linear only over a restricted frequency range, and this frequency range has to be increased to the extent of the frequency variations to be admitted. This condition means a practical limit to the tolerable frequency deviations.

No separate third converter stage for adding the frequencies f_1 and f_2 is necessary, in practice, as in most cases a current of the frequency $2f_q$ may be taken from one of the converter stages M1 or M2. Third power non-linearity of the characteristic of converter M1 for instance will cause an output current of the frequency $2(f_q - \frac{1}{2} f_p) + f_p = 2f_q$.

5. Phase-stable Limiter Stages

The amplitude condition for stable oscillation prescribes a total amplification equal to unity in the oscillator loop. In practical oscillators the amplification is always made larger than this value, which causes an increasing oscillator amplitude. However, a limiter stage reduces the amplification with increasing amplitude until the value unity has been reached, after which stable oscillation will be maintained.

Clearly, the limiter should only influence the magnitude of the amplification without introducing phase variations. However, this ideal situation can only be approximated as all limiter stages do always influence the phase to a certain extent, due to the following effects:

1. input impedance variation,
2. output impedance variation,
3. variation of the phase angle of the slope,
4. variation of the degree of non-linearity,
5. influence of external coupling between input and output terminals.

We will restrict our considerations to a detailed survey of these problems as they are present in limiter stages based on the variation of the slope of a valve. Here the *input impedance* variation is mainly a variation of the input capacitance, which can amount to one or two picofarads. The influence on the phase can be reduced in two ways. One method is to use a low external impedance between grid and cathode; this reduces the amplification to the same extent as the phase variation. Phase variation can also be reduced and even fully eliminated by using a purely reactive grid-cathode impedance. However, it is not always possible to insert such reactive stages in an oscillator loop.

Input capacitance variation can be reduced by an unbridged cathode resistor. This measure should be used with caution in limiter stages because it may at the same time introduce phase variations of the effective slope.[4]

The *output impedance variation* is mainly a change in the internal resistance of the valve. Provided the total anode impedance is purely ohmic, no phase variation would occur. To reduce phase variations due to this effect, it is necessary to reduce the susceptance of the anode circuit; a tuned anode circuit should therefore be *exactly* tuned.

The *phase angle variation of the slope* with varying grid bias is a frequency-dependent effect. To give an idea of the magnitude: experiments as well as calculations indicate that at a frequency of 1 Mc/s, a phase variation of about 5×10^{-4} radian is to be expected when the slope is varied over a range of 1 : 10.

The *influence of non-linearity of the limiter* on the phase in the oscillator loop can be explained as follows: Consider the output current of a non-linear limiter, which will contain a component of the oscillator frequency as well as a component of twice that frequency. Both current components will, via the loop circuit, cause a certain voltage at the grid of the limiter valve. Due to the non-linearity of this valve these two components will beat together, giving an extra anode current component of the basic frequency. As the phase angle of the harmonic voltage component on this grid will differ very much from the phase angle of the fundamental frequency component, the phase angle of the extra anode circuit component of the basic frequency will differ substantially from the normal component, thus introducing an extra phase angle. This extra phase angle depends on the proportion of normal and extra components and therefore on the amount of non-linearity of the limiter. With different limiter settings, this

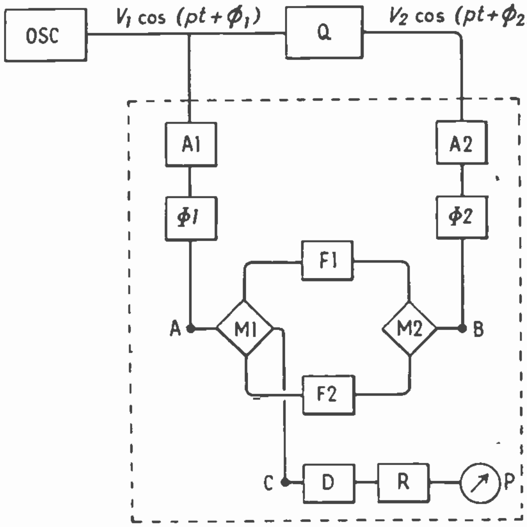


Fig. 3.—Block diagram of the complete phase meter. A1, A2 amplifiers; Φ1, Φ2 phase shifters; M1 – F1 – M2 – F2 oscillating circuit: D frequency discriminator circuit; R range switch; P meter indicating the phase angle.

amount will vary, causing a phase variation and consequently a frequency variation.

Linear limiters reduce this phase instability; increasing the selectivity of the loop circuit will have the same effect, as it reduces the relative amplification of the harmonics of the oscillator frequency.

Parasitic coupling of input and output circuits of the limiter does introduce the possibility of phase variation as this coupling is in parallel to the coupling by way of the mutual conductance. Variation of the latter will change the phase of the total coupling if the parasitic coupling is reactive.

Analogous to this effect is *the influence of feedback* on the input or output impedances, which may also cause a variable phase angle.

All these potential phase-disturbing possibilities should be taken into account when designing a limiter for a stable oscillator. Only one type of limiter was considered above; other limiting methods introduce other difficulties. For instance, limiters based on amplitude-dependent resistances can only be used in purely resistive circuits, as a susceptance component would cause phase variation. The amount of power, essential for the working of these limiters, necessitates either a coupling transformer (with the inherent non-ohmic elements) or the use of unpractically large valves. After consideration of all effects involved the author prefers grid biased limiters.

6. General Description of the Phase Meter

The phase meter which will be discussed in the following paragraphs was developed with the aim of demonstrating the versatile properties of this phase-measuring method. The apparatus has for this reason become a multi-range instrument, the phase angle ranges being:—

0–12°; 0–36°; 0–60°; 0–108°; 0–180°; 0–540°.

The same apparatus can thus be used for measuring large phase angles as well as very small angles; a demand which is generally not to be expected for a phase meter.

The frequency of the voltages between which the phase angle is to be measured, was chosen for opportune reasons to be 300 kc/s. At this frequency both a calibrated phase shifter and a frequency-changing unit, which converts an arbitrary frequency between 1 and 100 Mc/s to 300 kc/s, was available.[5]

Figure 3 gives a block diagram of the complete set-up for phase measurements. A signal source Osc feeds a signal of the angular frequency p to the input terminals of the quadripole Q, of which the phase angle is to be measured. The input voltage $V_1 \cos(pt + \phi_1)$ and the output voltage $V_2 \cos(pt + \phi_2)$ are passed on to the phase meter proper, which is indicated by the broken line. These voltages are amplified in A1 and A2 and subsequently pass the phase shifters Φ1 and Φ2, which are necessary for measuring small *variations* of a large phase angle. The oscillator bridge M1–F1–M2–F2 is clearly indicated, the frequencies of the filters F1 and F2 being $\frac{1}{2}f_p + f_q = 170$ kc/s and $\frac{1}{2}f_p - f_q = 130$ kc/s respectively. A component of the frequency $2f_q = 40$ kc/s is taken from the output of converter M1 and fed to a frequency discriminator circuit D, the d.c. output of which is measured via the range switch R, by a meter P. The scale of meter P is directly calibrated in degrees.

The amplifiers A1 and A2 are conventional stable amplifiers; the phase shifter Φ1 introduces phase variations in steps of $\pi/2$ radians, whereas phase shifter Φ2 varies the phase continuously over $\pi/2$ radians. The phase shifters are each constituted of two RC-combinations in tandem, dimensioned so as to give a phase shift of $\pi/2$ radians. The continuous phase shift is introduced by detuning a tuned LC circuit contained in one of the amplifiers A1 and A2.

7. Description of the Oscillator Bridge

The first problem to be met in the design of the oscillator bridge is the choice of the frequencies f_1 and f_2. The main point to be taken into consideration with respect to this choice is the fact that the output current of each converter stage contains not only a component of the wanted frequency, but a number of other frequencies as well. The filters F1 and F2 (Fig. 3) should substantially attenuate these other frequencies, as they may disturb the phase measurement. Suppose for instance that the p-frequency component in the output current of converter M1 would pass filter F1 and give a voltage (with arbitrary phase) on the input terminals of converter M2. This voltage acts more or less in parallel with the voltage $V_2 \cos(pt + \phi_2)$, so its arbitrary phase angle will disturb the phase properties of the bridge circuit as discussed in Section 4. Analogous considerations hold for converter output components of other frequencies, and it is therefore advantageous to use a converter stage with good quadratic characteristic, thus attenuating higher conversion products.

Unwanted output components can also be attenuated by using balanced converter stages. Although both input voltages to such a converter stage can be balanced, we only considered the combination of one balanced input voltage and one in-phase input voltage. The two input circuits can be designed almost completely independently in this case, which considerably

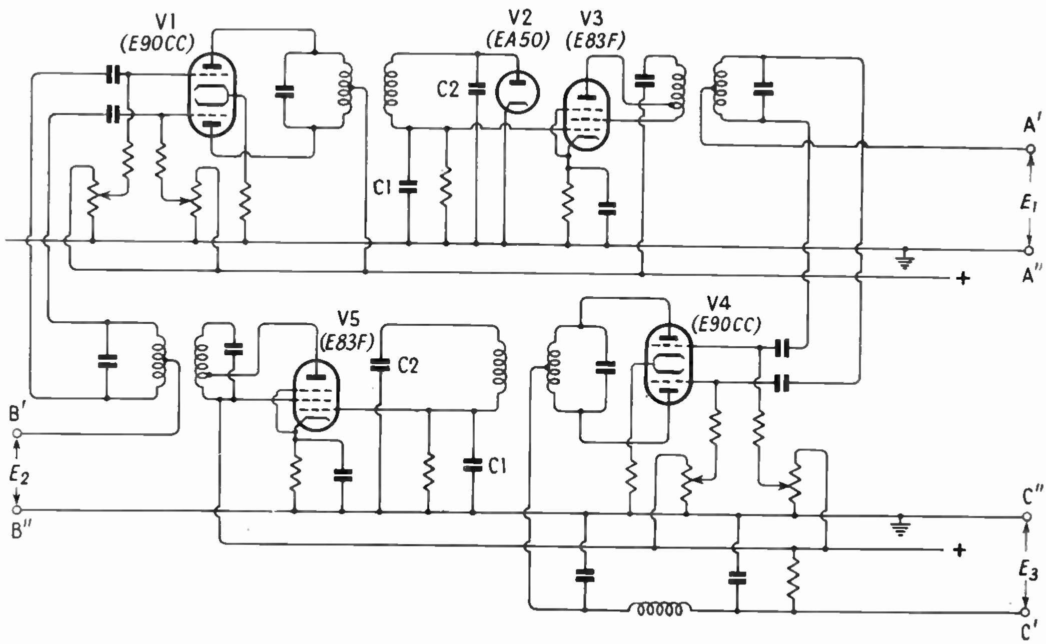


Fig. 4.—Circuit diagram of the two-frequency oscillator. The double triodes act as converters, the upper pentode is the limiter, the lower pentode an amplifier valve. E_1 and E_2 are the voltages between which the phase angle is to be measured. E_3 is the output voltage of the frequency $2f_q$ to be measured in the discriminator.

simplifies the circuits. In our phase meter the external voltage was balanced for the following reasons. At least one of the two input voltages of each converter should have a rather high level, so as to give a reasonable conversion mutual conductance. When the phase meter is set to work, the oscillation starts initially with a low voltage, so the corresponding converter input level is low. Therefore the other input voltage (the f_p voltage) has to be rather high, giving large output currents of this frequency. To attenuate these output components the modulators are balanced for the input voltages.

Even with a reasonable amount of balancing, further substantial attenuation of the p-frequency component in the filters F1 and F2 remains necessary; so a large frequency separation between the frequencies f_1 and f_q on one side, and f_p on the other side is advisable. This can be realized by choosing for f_1 either a large or a small value. A small value was used in this phase meter, because the frequency discriminator circuit must work on the frequency $2f_q$ and a sensitive discriminator is most easily made at a low frequency. This led to the choice of $f_q = 20$ kc/s, $f_1 = 130$ kc/s and $f_2 = 170$ kc/s.

The design of the filters F1 and F2 is not only determined by the necessary selectivity properties, as the most important property of this filter is the linearity of its phase–frequency characteristic over the range of phase angles to be measured. For this phase meter, a maximum range of 3π radians (540°) was aimed at. The number of necessary tuned circuits can be coarsely calculated by assuming that every tuned circuit has a linear phase characteristic over about $\pi/2$ radians, which indicates a total of about six tuned circuits. The next point to be considered is the necessity of a limiter stage, which might be combined with one of the converter stages, but which we preferred to insert separately in one of the filters F1 or F2. For symmetry an analogous non-limiting amplifier stage was inserted in the other filter.

From these considerations it followed that both filters had to be split up, which led to the ultimate design of each filter consisting of two pairs of tuned coupled circuits, separated by either a limiter or an amplifier stage. The coupling coefficient of these bandpass filters was dimensioned for a linear phase characteristic rather than a linear amplitude characteristic. The phase characteristic of one such bandpass filter can be made linear over a range of well over $\pi/2$ radians, so the complete oscillator circuit is phase linear over the phase range of more than 2π radians. The phase-frequency characteristic of such a linear-phase bandpass filter with coupling coefficient $KQ = 0{\cdot}71$ is shown in Fig. 5.

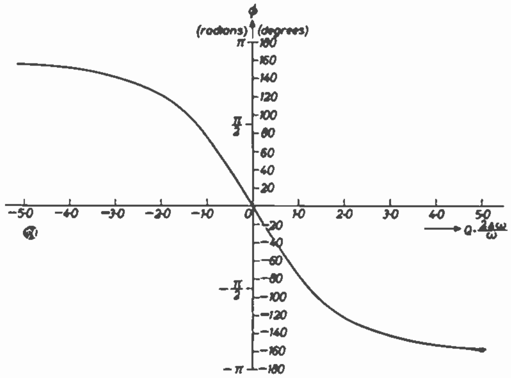


Fig. 5.—Phase angle as a function of frequency for a bandpass filter circuit with coupling coefficient KQ=0·71. The phase characteristic is linear over more than two radians.

The selectivity of these bandpass filters determines both the attenuation of the unwanted converter output components and the sensitivity of the circuit in terms of frequency shift per radian phase angle. By using inductances with an r/L value equal to 20,000 sec^{-1} (corresponding to Q-values of filters F1 and F2 of $Q_1 = 41$ and $Q_2 = 53$ respectively), the necessary selectivity could be realized, when the phase sensitivity became 14 c/s per degree. (A certain amount of valve damping has to be taken into consideration.)

The circuit diagram of the oscillator bridge is depicted in Fig. 4, in which the letters A, B and C refer to the analogous points in the block circuit of Fig. 3. The two balanced converter stages M1 and M2 consist of double triodes V1 and V4. The oscillator voltages are fed in push-pull to the grids of these valves, whereas the p-frequency voltages E_1 and E_2 taken from the output terminals A and B of the phase shifters Φ1 and Φ2 (Fig. 3) are in phase on the grids of each converter valve. The output voltage of the bandpass filter in the anode circuit of valve V1 is detected in diode V2, the detected voltage being used to bias the grid of limiter valve V3. The a.c. voltage on this grid is only one-ninth of the output voltage of the preceding bandpass filter as C_1 is equal approximately to $8C_2$. The non-linearity of the limiter stage is substantially reduced in this way.

The low impedance between grid and cathode resulting from this tapping of the voltage is important in reducing the influence of input capacitance variation on the phase of the oscillator signal. For the same reason the anode of this valve has been tapped (1 : 8) on the primary circuit of the second bandpass filter, the output-voltage of which is fed to the second converter.

The lower half of the oscillator circuit is quite analogous to the upper half, with the exception that the valve V5 acts as an amplifier valve.

The d.c. settings of each grid of the converter valves can be varied separately to ensure good balancing of these valves. To reduce unwanted harmonics, the a.c. voltages on these valves are kept at a level of about 0·5 V maximum. The influence of the unwanted conversion products can be kept sufficiently low in this way, although the third-order conversion products are still sufficiently present to select from the anode current the 40-kc/s component ($2f_q$) necessary for the frequency measurement. This component is in phase for both parts of each converter stage and is therefore selected by passing the sum anode current of valves V4 through a low pass filter which suppresses the oscillator frequency components. The output voltage E_3 between the terminals C of this filter is passed to the frequency measuring circuit.

8. Description of Frequency Measuring Circuits

The frequency $2f_q$ (= 40 kc/s) is measured in a conventional discriminator circuit (Fig. 6). The output voltage of the low pass filter, mentioned in the preceding paragraph, is first amplified in a single-valve amplifier, the output of which is kept constant by a delayed a.g.c. circuit acting on the same valve. This constant voltage is passed to the grids of two output valves (EL83) in parallel, the total anode current of which enters the frequency discriminator circuit proper. The reason for the use of two large valves in parallel is the need for a high sensitivity of the frequency discriminator circuit, also the anode current of the valves should not contain appreciable harmonic components as these influence the output of the discriminator in an uncontrollable manner.

The great difference between the largest and the smallest range (0–540° and 0–12°) did not allow the use of one discriminator circuit, as a discriminator sufficiently sensitive for the smallest range could not be given sufficient bandwidth to be linear over the largest range. Therefore two separate discriminator circuits with different selectivity are used, which are chosen by the "sensitivity" switch (S in Fig. 6).

The diode part of. the discriminator circuit has been slightly modified to give a d.c. current

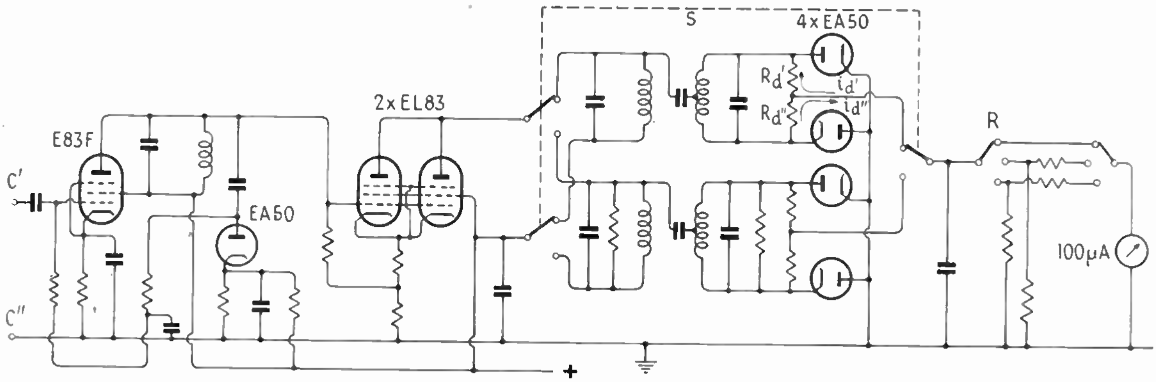


Fig. 6.—Frequency discriminator circuit. Two complete discriminators for high and low sensitivity (to be chosen by switch S). Diodes connected so that a d.c. current output is available. Range switch R controls the sensitivity of microammeter.

output rather than a d.c. voltage output. This eliminates the necessity of a valve voltmeter for measuring the output voltage.

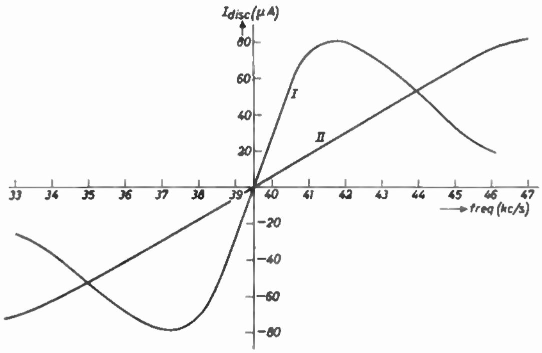


Fig. 7.—Discriminator output current versus frequency for both discriminator circuits.

The operation of the circuit can be understood by considering the d.c. currents of both diodes in the connection between the centre point of the two resistances and earth (i_d' and i_d'' in Fig. 6). At the zero frequency of the discriminator, both h.f. voltages over the diodes are equal in magnitude, and the same holds for the d.c. voltages over the load resistances R_d' and R_d''. Provided $R_d' = R_d''$, both d.c. currents will be equal in magnitude and opposite in direction, consequently the total d.c. current in the connection will be zero. With deviations of the frequency of the applied signal, the d.c. current will change in the same way as does the d.c. voltage in the conventional discriminator circuits with voltage output. Fig. 7 shows the current–frequency diagrams of both discriminator circuits.

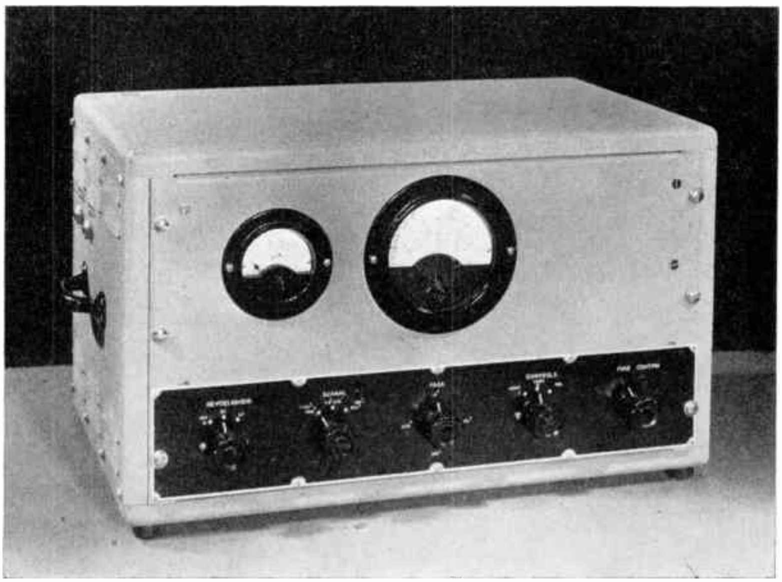
9. Complete Phase Meter

The phase meter in its final form can be seen in the photograph (Fig. 8). The two voltages between which the phase angle is to be measured enter the apparatus at the terminals at the left side. The large meter on the front panel indicates the phase angle. The ranges are chosen by the two knobs on the left side of the front panel; the outside knob chooses one of the two discriminator circuits (the third position switches the whole apparatus "off") and the inner knob varies the sensitivity of the meter of the discriminator output current.

The phase shifters ($\Phi 1$ and $\Phi 2$ in Fig. 3) are controlled by the centre knob (steps of $\pi/2$ radians) and the outer right knob (continuous). The inner right knob serves in combination with

Fig. 8.—Photograph of the phase meter.

Controls are (from left to right): sensitivity; range; phase variations in steps of 90°; monitoring switch; continuous phase variation.



the small meter for monitoring purposes, enabling the measurement of the output voltages of each of the *p*-frequency amplifiers as well as the magnitude of the oscillation voltage.

The electrical properties of this phase meter can be summed up as follows:—

Frequency: 300 kc/s ± 2 kc/s.

Ranges: Maximum sensitivity 0–12°; 0–36°; 0–108°.

Minimum sensitivity 0–60°; 0–180°; 0–540°.

The zero position of the meter is in the centre of the scale; the calculations printed on the scale are −90° to +450°; 90° to 270° and 150° to 210°. In the maximum sensitivity position, these values have to be divided by five.

Accuracy

The −90° to +450° scale has been printed in black between 0° and 360° and in red from −90° to 0° and from 360° to 450°, thus indicating that outside the 0° to 360° range the accuracy deteriorates. Inside the 0° to 360° range the accuracy is ±2°. A continuous change of the phase angle of more than 360° causes the meter needle to move along the scale correspondingly until somewhere in the "red" region the needle suddenly jumps back to the beginning of the "black" scale. This sudden change in oscillator frequency can also be provoked by manipulating the 90°-phase switch.

The relative accuracy is about ½ per cent., which holds for the other ranges as well.

Influence of frequency variations

This influence could not be measured with sufficient accuracy as the calibrated phase shifter used for calibrating this phase meter was not completely insensitive to frequency variations itself but introduced phase variations of about 1·5° per kc/s frequency shift. We can only state that the error of the phase meter for frequency variations of ±2 kc/s was well below the error of the phase shifter.

Influence of amplitude variations

The amplitude tests (on the phase meter itself) were performed over a rather restricted range of amplitudes. However, it can be stated that, by carefully taking into consideration all points mentioned in Section 5, limiters have been developed at a frequency of 300 kc/s which showed phase variations smaller than 3×10^{-4} radians with amplitude variations of 1 : 10.

10. Possible Applications

The restricted bandwidth within which a phase meter, based on the principle discussed above, can be used, limits the application more or less. There are situations, however, where this restriction is not important, for instance with radio navigation systems, where phase angles are often measured at a fixed frequency. The possibility of measuring large phase angles as well as very small phase variations is very useful in this aspect.

When measuring group delay characteristics of a complete link, the high sensitivity is important as it enables a very good precision in the measurement.[1, 2]

The combination with a frequency converter unit[5] eliminates the limitation; measurements of phase characteristics, for instance, of amplifiers with negative feedback, or of transistors, are quickly performed in this way.

11. Acknowledgment

Active assistance in the realization of the phase meter described in this article was given by Mr. C. J. Heuvelman.

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TELEVISION DEVELOPMENTS IN GREAT BRITAIN

Progress is now being made on the B.B.C.'s new medium-power television station for North-East Scotland, situated some twenty miles north-west of the city of Aberdeen, at Meldrum. A temporary station for use while the permanent station is being completed, consisting of low-power vision and sound transmitters in a mobile building, and a temporary mast and aerial, has already been erected at the existing sound broadcasting station at Redmoss, near Aberdeen.

The full programme service from the temporary station started on December 14th. A service is provided for the city of Aberdeen and its immediate surroundings; the power is adjusted to give an average signal-strength in Aberdeen comparable with that expected from the permanent station at Meldrum. This will replace the temporary station towards the end of 1955 and will extend the service to include the whole of Kincardine and those parts of Moray, Banffshire, Aberdeenshire, and Angus, north-east of a line running roughly from Burghead to Brechin and Montrose.

The frequencies of both the temporary and the permanent stations are in Channel 4 (vision 61·75 Mc/s and sound 58·25 Mc/s) and the transmissions are horizontally polarized.

* * *

The television service from the temporary low-power station at North Hessary Tor (South Devon), about one mile north-west of Princetown, was inaugurated on December 17th. The station comprises low-power vision and sound transmitting equipment installed in mobile buildings and a temporary 150-ft. mast to carry the aerials. The permanent medium-power station will be completed on the same site in about a year's time.

The temporary station serves Plymouth and most places within 20 miles of that city. It receives the programme by direct pickup from Wenvoe. When the permanent station comes into operation the service will be extended to include all those parts of Devon that are not served by the high-power station at Wenvoe, and practically the whole of Cornwall.

The temporary station is using the same frequencies as those later to be used by the permanent station, as follows:—

Frequency ..	Vision 51·75 Mc/s Sound 48·25 Mc/s	Channel 2
Polarization ..	Vertical	
Transmission ..	Asymmetric sideband system	

The frequencies of the vision and sound carriers are slightly offset from those of the high-power transmitters using the same channel (Holme Moss) so as to reduce the effects of mutual interference in the fringe areas.

* * *

In a recent announcement the Independent Television Authority has given details of the estimated service area of the temporary transmitter at Croydon which is to radiate independent television programmes in Band III. Operations will commence in September, and the primary service area is calculated to extend to Welwyn in the north and Horley in the south, while the eastern and western limits will be approximately Tilbury and Henley. There is a population of 9·4 millions in this area and an additional 1·05 millions live within the area of secondary service. The minimum signal strengths on which these figures are based are 2 to 2·5 mV, and about 0·5 mV respectively.

* * *

The B.B.C. has just introduced the prototype of a new extending-mast vehicle. This vehicle, which has been produced for use with television outside broadcasts, provides means whereby the radio link transmitting or receiving aerials, and associated electronic equipment, can be elevated to a height of just over 60 ft., in order to clear obstructions that might otherwise impede the transmission or reception of signals. The aerial, consisting of a 4-ft. diameter paraboloid which is mounted on top of this mast, has to be set to within approximately $\pm 1°$ and a system of remote control has been devised whereby this can be readily achieved. The aerial can be rotated continuously through 360° in the horizontal plane. The remote control system employed enables a pre-set bearing to be determined and set up to within $\pm \frac{1}{2}°$.

The mast is erected from the horizontal position on the vehicle to the vertical position on the ground by a system of hydraulic rams. A similar system is then used to extend it to its full height of approximately 60 ft. In this position the mast is self-supporting.

THE EDUCATION AND TRAINING OF RADIO ENGINEERS

A Discussion Meeting held in London on December 29th, 1954

In the Chair: Professor E. E. Zepler, Ph.D. (A Vice-President of the Institution)*

Introduction by the Chairman

For nearly 30 years, the Institution has set standards for the entrant to the radio and electronics profession. The importance of electronics in every branch of science and technology is now growing very rapidly, and there can hardly be an industry which does not use either communications or industrial electronics. In recognition of the growing importance of industrial electronics, the Institution has now decided to extend its examination syllabus to include Applied Electronics in the new examination scheme.

Two main centres of training are open to the young man, universities and technical colleges. Undergraduates may train as physicists or as engineers, either with or without special radio training. The problems of technical colleges providing courses for external degrees are the same as those of the universities. Whereas universities can shape their own courses, however, the technical colleges must conform with the external regulations and syllabus laid down. Technical colleges also offer courses for the Higher National Diploma or Certificate in Radio, the City and Guilds of London Institute Final and Full Technological Certificates in Radio and Telecommunications, and the examinations of the professional institutions.

The problem has arisen, should universities and technical colleges cater specially for radio training? It is likely that there are many places which would wish to do so, but cannot afford the time. A university might provide only about 10 or 12 lectures on radio engineering in the Honours Physics course, mainly because the knowledge of pure physics required is so wide that an additional specialist subject such as radio engineering, limits the time spent on basic physics. On the other hand, some universities provide training in electronics as a specialization in the third and final year of the Honours Physics course.

The same problem faces the Honours *Engineering* student. Some courses devote considerable time to electronics and telecommunications; others virtually none, despite their description as "light current" engineering degrees. The possible solution is the arranging of a post-graduate diploma in electronics for the physicist and engineer. With this vastly expanding subject it is quite possible the conclusion will be reached that four years is the required time for training.

A problem which concerns us all deeply is that of recruitment. The experience of the City and Guilds of London Institute and of the Institution (as shown in the last Brit.I.R.E. annual report) reveals the inadequacy of students both in quality and quantity. One might argue that too much is asked of them, but the examination standard has been constructed on what is considered necessary for the man who wishes to be justified in calling himself a professional radio engineer. The fault might ultimately be found to lie with the selection and early training of the students themselves.

Professor Emrys Williams, B.Eng., Ph.D. (Member)†

It is a matter of principle that, whatever a man's ultimate vocation, he should have a broad liberal education. This principle is sometimes brushed aside, and often described as old-fashioned and outmoded. However, it must be followed if a man is to get the most out of life at the same time as the nation, or the human race, gets the most out of him. This principle is far from being implemented at present, partly

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because of lack of imagination, but much more because of lack of funds.

In the meantime, education is a compromise. It is very important to realize this fact, for otherwise many progressive measures can be obstructed and even prevented by repeating loudly and often the half-truth that these measures do not constitute a broad liberal education. It may be true that they themselves do not do so; but at the same time it may also be true that they furnish a much better compromise than that which they are intended to replace.

There is another general principle, often expressed, and to which many people think the universities should subscribe, namely, that it does not matter what you teach a man as long as he learns to think. This has been used to justify all sorts of educational policies. Nowadays, it *does* matter what you teach, to train a man to think. If there are several subjects of study which will serve to provide training in straight thinking, then clearly it pays to choose the course of study most closely related to the intended vocation of the student. This may be obvious, but an important point springs from it.

From the educational point of view, particularly for an intending radio and electronics engineer, the most important basic subjects are those which teach him to think. A highly specialized course of study can well satisfy this criterion. What branch of study is more specialized, for instance, than pure mathematics, which is "pure" in the sense that it avoids contact with the maximum number of other subjects? Yet no one denies the cultural value of pure mathematics. Specialization at this stage is in no way objectionable from the educational point of view. The argument that to specialize in radio and electronic engineering does not constitute a broad general education may sound plausible, but it is really a completely irrelevant observation.

The question of how to specialize, and the danger of over-specialization, arises primarily from professional and vocational considerations. To the extent that the profession is itself a changing one, the nature of the specialization may be expected to change. Since the subject of electronics is now invoking so many different physical principles, and invading so many different industrial activities, the education demanded for a radio and electronics engineer must include a broad and thorough grounding of general physics. For this reason, the Institution is always trying to improve the standard of general physics and mathematics.

Only a certain number of years can be spent on education and training. They must include a thorough grounding of general physics, but there must also be room for a great deal of radio and electronic engineering. Here again, it is a matter for compromise. That does not mean that it is not important what particular compromise is made: it is of very great importance. Moreover, it is appropriate that a professional institution and a university should make this compromise rather differently. The universities are the only institutions in Britain which can provide a training suitable for the higher flight of engineer-scientists. It is therefore important that, whatever other levels a university may cater for, it must regard the training of the first-class engineer-scientist as its priority task.

The educational schemes planned and recommended by a professional institution, on the other hand, are not, and *must not*, be subject to this restriction. Any professional institution whose education and examination syllabi aspire to copy those of a university is liable to find that it is admitting only university graduates to its membership—and by exemption, rather than by examination. The particular compromise to be recommended by our own institution should emphasize the broad syllabus of general physics. However, where *techniques* and *technology* are concerned, the maximum degree of specialization should be permitted, consistent with sound pedagogic considerations.

Radio engineering has for many years been able to stand on its own feet as a subject of study. Indeed, so fast are the applications of electronics proceeding, that there is a need for optional sub-specializations in the later years of study. The development of education and training in radio and electronic engineering will be very seriously retarded unless the policy of regarding electrical engineering as a convenient indivisible unit of subject matter is abandoned. The process need not necessarily be a painful one.

Hugh A. Warren, M.Sc.(Eng.)*

From the Technical College point of view, the training of the radio engineer is not one problem, but many. There is no "British Standard Radio Engineer," and to every single problem there are many solutions; and so the training must be as complex, as varied and as vital as the industry itself. This point is fully accepted by the technical colleges, who strive to be compatible with a progressive industry, and a progressive Institution.

There is no attempt to lay down one course, on a take-it-or-leave-it basis: there are many courses. In the South-East London Technical College there are five, and that does not speak for the other 250 Technical Colleges in this country, about half of which conduct senior courses relative to the training of radio engineers.

Their diversity is shown by the fact that the courses can be either by full-time, sandwich, part-time, day release or evening attendance. The degree facilities that many of the more senior technical colleges enjoy have already been described by Professor Emrys Williams, and the following remarks will therefore deal with National Certificates, City and Guilds of London Institute examinations, and those of the professional institutions.

Technical colleges as a whole prepare students for a bewildering variety of qualifications, including the degree, the National Diploma, the Ordinary and Higher National Certificates, a number of different City and Guilds Certificates relating to particular branches of industry, and the examinations of the professional institutions. Men and women are enrolled irrespective of class, creed, nationality and colour, purely on the basis of ability to profit by the courses.

To assess in their proper perspective the great number of courses that are available, it is necessary to have in mind the ramifications of this industry. It covers wireless communications, with the several divisions, transmission, industrial communications and radar; line communications with their research, development, manufacture and operation; broadcast reception, with research and development in this field; the manufacture of radio and television receivers and their maintenance, and—closely associated with them—reproduction, recording and amplifying equipment, the use of which is expanding so rapidly; valve technology, research, development and manufacture; and last but not least, the increasing range of applications of electronics to industry and armaments.

The radio engineer thus has many and diverse fields of operation, and is not restricted to those in which he originally worked. If technical education is going to do its job, and serve in all those fields, it must be both live and complex, so to adapt itself to any development of industry for which it can be proved that a new form of training, and possibly new qualifications, are required.

There are several fairly well-defined levels of qualifications, which relate to corresponding levels of employment. In this country they blend into one another like the colours of the spectrum, whilst in some other countries there are hard and fast divisions between them. It is difficult to delimit the exact boundaries between the professional engineer, the technician, and the technologist, but for the sake of this discussion four levels are considered: in the highest flights, the research and development engineer; the technologist; the technician; and the semi-skilled worker.

At the first level, there are the engineering and physics degrees and the professional examinations, also the Higher National Diploma. These qualifications can be studied either full-time, or by means of sandwich courses, where the student is either employed in the industry and released for alternate periods of weeks, terms, or six months; or is attached to the college and goes into industry for similar periods. Some degrees can also be studied part-time.

For the technologist, there is the Higher National Certificate, and the City and Guilds of London Institute's examinations for the full Technological Certificate in Radio and Telecommunications, both of which may be taken from part-time, day or evening classes. In the matter of the new technological degree, there is the question of whether it should be taken in the technical college or the university. That is an important problem which has yet finally to be solved, but which will influence the future of technological training.

* Principal, South-East London Technical College, Lewisham Way, London, S.E.4.
(Representing the Association of Principals of Technical Institutions.)

The technician is catered for by the City and Guilds instrument-making classes, and the Radio and Television Servicing Certificate examination which is conducted jointly by the City and Guilds of London Institute and the Radio Trades Examination Board. It is suggested that there is a case for a new certificate for radio technicians, comparable to that already existing for mechanical engineers, for those who are not destined to be designers, but would make high-grade technicians.

Finally, there is the very large unskilled or semi-skilled labour force which, with T.W.I. (training within industry) schemes, cannot be omitted from a complete review. In all their work, the technical colleges expect, and get, the closest co-operation from industry, a fact which is much appreciated by the Principals of the colleges.

Apprenticeship training for industry may conform to two officially sponsored schemes. These are related to the National Certificate scheme, and the City and Guilds of London Institute Examination. The National Certificate scheme warrants further explanation. Briefly, the student attends either three evenings per week, or, preferably, one day per week with an occasional supplementary evening, at the local technical college. The rest of his apprenticeship training is carried out within the industry. This combined academic and practical training forms the basis of apprenticeship training over a period of three years for the Ordinary National Certificate, and five for the Higher National Certificate.

This contrasts with the French system of apprenticeship training, which is conducted mainly in "centres d'apprentissage" run by the State under the Technical Education Service; conditions at these centres closely resemble industry in that they carry out productive work. The larger firm is permitted to run its own works training scheme under the patronage of, and with a grant from, the State. Thus the practical and academic training, which in this country are separate components, are merged in one centre.

Perhaps here there should be greater powers of selection at the beginning of training, instead of all students being considered to have the Field-Marshal's baton in their knapsacks. "Failed National Certificate" is not a good qualification: there are, in the present system, so many who fall by the wayside, and may fall too late to pick themselves up again.

There is a final point of increasing concern to those engaged in technical education. It is the tendency to teach power without purpose, to develop talent without responsibility and to be so engrossed in training men for industry as to forget that, ultimately, industry serves the needs of men. Is technical education to be so utilitarian that it teaches men to serve machines and not how best to avail themselves of the power of those machines? Many are of opinion that such consideration of the social, economic and philosophical problems of our age is the very characteristic and meaning of the word "Profession."

R. E. Burnett, M.A.*

It is agreed by all manufacturers of radio equipment that there is still a great shortage of both professional engineers and technicians. Even though it may be only enlightened self-interest there is no doubt that training is regarded as a matter of great importance, even by the most hard-headed industrialists.

The lion's share of this education and training is, of course, being taken by the universities, technical colleges and similar institutions, but a very important complementary part is now being played by the radio industry. The bulk of this training within the industry is being done by the large firms and groups of companies for obvious reasons, but training is, of course, just as important a problem to the small firms. The more progressive of these smaller firms are, in fact, now making a proportional contribution to the total effort.

In the large firms training normally consists of three grades of apprenticeship, although some important training is done outside these formal courses. The three main grades of apprenticeship are entitled, Craft, Student and Graduate.

Taking the most junior first, the craft apprentice begins his training, at the age of 16, with instruction of six months to a year's duration in an Apprentice Training Centre—a centre which

* Principal, Marconi College, Arbour Lane, Chelmsford.

most large firms have set up, fully equipped with first-class machines and tools and with a group of experienced instructors. Here he is introduced to hand tools, machine tools, workshop practice, instrument making, small assembly and so on. After this formal training the apprentice then enters the works, where he gains experience in various departments, such as the machine shop, assembly bays, model shops and so on, until he is 21 years old, when he is graded as a craftsman.

It is generally accepted that it is desirable for a 16-year-old boy at the beginning of his apprenticeship to have formal training, if possible in an apprentice training centre, so that when he goes into the shops he can make a real contribution. This is much more satisfactory for the boy himself, and in the long run for the Company, than sending him straight into the works, and it eliminates the traditional unproductive "tea-making" which used to be such a feature of the experience of the young apprentice. During the whole of these five years the craft apprentice is normally given day release to attend technical college and study for City and Guilds Examinations. This day release will continue as long as the boy is able to profit by it, even beyond the completion of his apprenticeship, although if it becomes clear that the boy is unable to cope with academic studies, he may cease to attend at the college.

The second type of apprenticeship is for the boy who enters industry at 17 or 18 years of age. He is usually called a student apprentice, and his training lasts four years or possibly five if it is thought that he will benefit from more advanced tuition. He also begins in the training centre, where he may spend slightly less time than the craft apprentice before he goes on to gain experience in the works. Like the craft apprentice, he has one day per week at a technical college, and may also attend on one or two evenings a week. His goal is probably the Higher National Certificate in Telecommunications or the City and Guilds Full Technological Certificate, or perhaps a professional examination such as that held by the British Institution of Radio Engineers. Unlike the craft apprentice, the student moves eventually from the production side to the drawing offices and then to the laboratories. In this way he gains experience in circuitry and design techniques, both electrical and mechanical. His progress through the different departments should be in step to some extent with his technical college courses.

In the student grade particularly, there crops up the problem of those who fail to reach full professional status. There should be some slightly lower qualification which a man can acquire other than—as Principal Warren said—"Failed Higher National Certificate." For the craft apprentice, too, it would help a great deal if City and Guilds courses, H.N.C. and the professional institute examinations were brought into line with each other so that it is possible for him to progress along a smoother avenue of promotion to full professional status.

The third type of apprentice is generally known as the Graduate Apprentice. The graduate apprentice will have completed a degree, usually in electrical engineering or physics. This graduate apprenticeship introduces a point of controversy —is it to be or not to be? Most firms who run an organized graduate apprenticeship take a view similar to that of my organization, namely that a man may choose whether or not he will do an apprenticeship. Some graduates are, therefore, accepted from the universities for direct employment in research and development laboratories, with no further formal training.

Graduate apprenticeship training normally begins as with the other apprenticeships, in the apprentice training centre, but the graduate passes through the centre much more rapidly, taking only two or three months to complete the course. From there, for the next nine months or so, a graduate apprentice in the Company with which I am concerned usually does one of three things: either he enters the works with a view to gaining an insight into production methods; or he is put in charge of the progressing of a small project right through the works; or he is attached to a team in either the Time and Motion Study Department or the Operational Research Department. In all of these activities his duties bring him into contact with the multifarious sections in a modern works. The third stage of graduate training in our organization is attendance at a formal course on electronics of five or six months' duration. These courses are of an advanced nature and to some extent they carry on where the university or technical college leaves off. Their aim is to bring home to the student the difference between practice and theory, and the lectures and laboratory work are centred on design techniques and on systems operation and planning.

The graduate by this time is usually able to decide in which direction he wishes to make his career. His last six months, therefore, are devoted to functional training in the department of his choice, so that when he completes his training 18 months or two years after coming to the Company he is appointed to the staff and is immediately able to play an effective part. This part of his training is planned between the Education Department, the young man himself and the head of his future department.

The direct-entry graduate, at the end of a similar two-year period, will have advanced in knowledge and experience, possibly in a somewhat narrow field, but he will by then be regarded as a valuable member of his team. There is, however, no doubt that compared with the man who did a graduate apprenticeship, he will have missed a very valuable training which may be of service later in life. Nevertheless, many graduates develop just as well, perhaps even better, by taking an appointment immediately on leaving the university, and whether the full two years' graduate apprenticeship required by some of the professional institutions is justifiable, must remain the subject of debate.

In addition to formal apprenticeships, there are other important forms of industrial training. The Radio Industry Council has a scheme similar in many ways to student apprenticeship, for the training of technicians. This lays down guidance for works training and day release, and attendance at a technical college is a *sine qua non*.

It is also necessary in these days to provide *ad hoc* courses and training schemes for young men who join the company rather late in life, perhaps after acquiring a liking for electronics after two years' National Service. Such men enter industry at the age of 20 or 21, and they are a valuable source of recruitment.

The greatest need to-day is for experienced engineers: since the demand at present exceeds the supply it is up to industry to increase the supply by increasing its own training capacity and by encouraging the taking of sandwich courses. Even the small firm must contribute to the training of future radio engineers; experience and advice are readily available at the institutions. The safest assets of the industry lie in its young engineers and apprentices—the industry would do well to develop them.

A number of members and visitors took part in the informal discussion which followed the contributions of the three main speakers.

Mr. W. M. Dalton (Associate Member) referred to the very large number of students who attended evening classes but did not complete the courses or examinations for which they originally aimed. Very few, in fact, passed professional or similar examinations. Evening classes involved tremendous effort on the part of the student, particularly where courses were long and arduous. Mr. Dalton commented that, in his opinion, colleges experienced difficulty in obtaining a sufficient number of evening class lecturers.

It would assist if the syllabi of courses for radio engineers could be so arranged to exclude a large amount of subject matter which had a very indirect bearing on the main aim of the course.

Mr. R. Benjamin appealed for the wider teaching of philosophy and the humanities to engineers and scientists, and expressed an opinion for the need of vocational guidance and selection.

Mr. E. M. Wareham stressed the large and serious gap between the standard of training of the university graduate, and the qualifications required for employment in a design and development laboratory. In his experience, the graduate was unlikely to become a successful electronics designer for at least two years, and probably five years after graduation. The greatest difficulty was the shortage of skilled designers, particularly in the microwave and industrial electronics field.

Mr. Wareham suggested that to meet the present standards in design ability, the process of developing the university graduate into a skilled designer must be accelerated. More time should be given to post-graduate training; facilities in Great Britain were inadequate, as manufacturers did not provide sufficient opportunities.* Sandwich courses were not sufficiently realistic and the technical colleges, with few exceptions, had the greatest difficulty in obtaining lecturers with adequate qualifications and industrial experience.

Skilled designers could, in his opinion, be obtained from the universities *and* the technical colleges. To do this, the technical colleges must provide courses of a somewhat higher standard with more intensive specialization in the last two years of the Higher National Certificate and similar examinations.

Mr. C. W. Robson referred to the training scheme outlined by Mr. Burnett, which in his opinion was ideal. The Radio Industry Council would do well to spread such a scheme amongst other companies. He stated that in the South London area there was only one firm that had any scheme similar to that outlined by Mr. Burnett, although there were large radio firms in the area. These firms have many different schemes, and one of the difficulties of the technical colleges was the large variety of courses that have to be provided. One of the National Certificate schemes at the South East London Technical College devoted approximately 50 per cent of its time to radio and electronic engineering. For the industrial electronics engineer, there was the National Certificate in Applied Physics, but of the five years covering 500 teaching hours, only about 30 per cent is devoted to electronic subjects. Mr. Robson concluded by defining the technician and engineer in a very simple form as asked by an earlier speaker: "The technician is one who knows how a machine works, the engineer is one who knows why it works."

*Attention is drawn to the Editorial on page 129 of this issue.

Mr. J. Dickson (Associate Member) asked for greater publicity in the schools for the opportunities available in radio and electronic engineering. He felt that it was a relatively new science which should attract many recruits, but more propaganda was necessary. He drew attention to the recent booklet, "Careers in Radio and Electronics," published by the Radio Industry Council and the Ministry of Labour and National Service, which made a very good start in this field. Mr. Dickson also asked that greater attention should be given to the period of national service, where he considered that, if properly planned, it could and must be used and integrated into the engineer's career.

Mr. J. Sykes (Member) referred to the limited usefulness of the correspondence school, in providing a service to those persons who had no other means of guided study. An example was sea-going radio officers, many of whom had the ability and the desire to join the radio industry.

Wg. Cdr. W. E. Dunn (Member) made a plea for a National Certificate in radio engineering. At the present time, he pointed out the Ordinary National Certificate contained virtually no radio engineering, and the student was bogged down in a welter of traditional electrical engineering material. He stressed that the development of the radio industry was vital to the defence and other Services of this country, and was sufficiently important to warrant its own scheme of training.

The Education and Examinations Committee, which was responsible for the arrangements of the meeting, feels that many members outside the London area who were unable to take part, may like to have the opportunity of adding points of view on this important subject. Accordingly, short contributions will be welcomed for consideration for publication.

NEW BRITISH STANDARDS

The British Standards Institution has recently issued the following new and revised Standards, copies of which may be obtained from the British Standards Institution, Sales branch, 2 Park Street, London, W.1.

B.S. 441 : 1954. **Rosin-cored Solder Wire "Activated" and "Non-activated" (non-corrosive).** Price 3s.

Since 1932 methods of activating the rosin-core of the solder have been developed, and this new edition specifies solder wire with a core or cores, incorporating the advantages of these methods. The scope of the standard has been widened by the inclusion of five grades of solder, for each of which information is given on melting characteristics and typical uses, and on tests for the hardening of the flux residues, and their freedom from corrosive action.

B.S. 1981 : 1953. **Unified Machine Screws and Machine Screw Nuts.** Price 6s.

The publication of the above standard marks a further step in the Unification of Screw Threads. It is complementary to the standards for hexagon bolts and nuts which were issued two years ago and provides, as they did, for screws having unified threads and heads selected from a range already standardized in the United States. The standard covers slotted and recessed head screws of the following types: 80 deg countersunk and raised countersunk, pan, cheese and hexagon heads; dimensions of nuts and washers are also specified.

B.S. 2026 : 1953. **Tolerances for Mouldings in Thermosetting Materials.** Price 3s.

A widely used practice has been to specify tolerances such as $\pm 0{\cdot}005$ in for decimal dimensions and $\pm\frac{1}{64}$ in for fractional dimensions for plastics mouldings of thermosetting materials. These figures are arbitrary and bear no relation to conditions peculiar to plastics moulding technique. A system has therefore been drawn up of standard tolerances for thermosetting mouldings, having a technical instead of an arbitrary basis. It should, however, be noted that the measurement of moulded pieces can never attain great accuracy because minor dimensional changes take place during ageing, the rate of which is affected by ambient conditions. Tolerances to nearer than 0·001 in are thus likely to be unrealistic because of these changes.

B.S. 2031 : 1953. **Metal Rectifiers for Intrinsically Safe Signalling and Control Circuits.** Price 2s. 6d.

Rectifiers of the type covered by this standard are used as a component of certain intrinsically safe circuits to serve various purposes, such as to provide unidirectional current from an a.c. source, or to suppress sparking when the circuit is broken. The electrical characteristics and reliability of the rectifier are, therefore, essential features of the design that affect the performance and safety of the apparatus with which it is associated.

This type of rectifier unit is used in association with circuits and apparatus that are required to be "intrinsically safe" as that term is defined in B.S. 1259, "Intrinsically Safe Electrical Apparatus and Circuits," where the circuit voltage does not exceed 15 V a.c. r.m.s. or 25 V d.c., and where the circuit current does not exceed 1·6 A a.c. r.m.s. or 2·6 A d.c.

B.S. 2039 : 1953. **Enamelled Round Copper Wire (Enamel with Vinyl Acetal Base) Metric Units.** Price 4s.

B.S. 2084 : 1954. **Cotton Covered Round Copper Wires (Metric Units).** Price 2s. 6d.

The British Standards Institution has now published metric editions of B.S. 1844 and B.S. 1791. These have been prepared primarily from the point of view of exports and differ only in that all qualities are expressed in metric units. The ranges of diameters covered are 0·050–4·00 mm and 0·150–5·00 mm respectively. For normal purposes in the United Kingdom the appropriate original standards should still be used.

B.S. 2061 : 1953. **Phosphor Bronze Spring Washers for General Engineering Purposes.** Price 2s. 6d.

This standard for spring washers manufactured from phosphor bronze supplements that for steel spring washers, B.S. 1802. Although these washers have a more restricted field than the steel type, they have a definite advantage where resistance to corrosion, non-magnetic or similar distinctive properties are required.

The range of nominal sizes for the three types in the tables, i.e. single coil, square and rectangular sections and double coil, varies from 10BA to $\frac{3}{4}$ in for the first and 6BA to $\frac{3}{4}$ in for the other two. A number of manufacturing and testing requirements are given and the highly important feature of the material is provided for by a complete analysis of the phosphor bronze.

B.S. 2517 : 1954. **Definitions for Use in Mechanical Engineering.** Price 6s.

The aim of this standard is to provide a logical code of definitions which are both clear and consistent; general use of the various terms in the sense in which they are here defined should go far to obviate misunderstandings. The definitions given relate to terms of general application in engineering, and more particularly the mechanical engineering industry. The eight sections of the standard relate to construction, drawings and schedules, geometry of parts, size and tolerances, limits and fits, screw threads, surface texture and gauges, respectively; numerous illustrations are included. Students will find it of great assistance in their appreciation of the theoretical conceptions on which all practical engineering is based.

B.S. R1 : 1954. **Sizes and Forms of Civil Aircraft Radio Equipment.** Price 7s. 6d.

This standard is the first of a series of specifications dealing with radio equipment for civil aircraft. It prescribes standard dimensions for radio units (and subsidiary units) and associated racking. Standard forms of construction are prescribed in conjunction with standard methods of connection using plugs and sockets. The specification, which does not deal with performance requirements, is divided into five sections dealing with: rack-mounted units, rack mountings, subsidiary units, marking on units, and finishes.

GRADUATESHIP EXAMINATION—NOVEMBER 1954

SECOND PASS LIST

This list contains the results of all oversea candidates which were available on February 4th, 1955.

The following candidates have now completed the requirements of the Graduateship Examination, and are eligible for transfer or election to graduateship or higher grade of membership.

ANANTHANAMIAH, A. V. (S) *Bangalore.*
BAPAT, Yeshivant Narayan. (S) *Bombay.*
BHATTI, Dharam Singh. (S) *Nagpur.*
GILL, Santokh Singh. (S) *Secunderabad.*
JAYAKARAN, Israel. (S) *Mhow.*
PARAMESWARAN, Sivaramakrishnan Nurani. *Madras.*
RAMACHANDRA RAO, Venkata Arkalgud. (S) *Bombay.*
SIDHU, Niranjan Singh. (S) *Ferozepore.*
VENKATARAMANI, B. *Madras.*

The following candidates passed the parts indicated against their names

AHMAD, Akhwand Fayyaz. (S) *Karachi.* (IIIa.)
AHUJA, Bhagwan Singh. (S) *Kanpur.* (I, IIIa.)
AHUJA, Puran Lal. *Kanpur.* (I.)

BHAGAT, Shiv Raj Huria. (S) *Agra.* (II.)
BUTA SINGH. (S) *Delhi.* (IIIa.)

CHANDRA DUTT, Govindan. (S) *Trivandrum.* (II, IV.)
CHARANJIT SINGH. (S) *Agra.* (IIIa.)
CHAUHAN, Narayan Velshi. (S) *Ahmedabad.* (I.)
CHHABRA, Charanjit Singh. (S) *Delhi.* (I.)
CHUGH, Jyoti Prakash. (S) *Lucknow.* (IIIa.)

DASGUPTA, Debabrata. (S) *New Delhi.* (IIIa.)
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DHIR, Shiv Dass. (S) *Jullundur.* (I, II.)
DUGGAL, Jagmohan Sarup. (S) *Bombay.* (II.)

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GARAI, Profulla Kumar. (S) *Calcutta.* (II.)
GOGATE, Bhalchandra Damodar. (S) *Miraj.* (I, II.)

HATTANGADI, Bansidhar Srinivas. (S) *Gwalior.* (I, II.)
HERLEKAR, Balvant Vishnu. (S) *Bombay.* (I.)

JAIN, Naim Chand. (S) *New Delhi.* (I.)
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JONES, Kandathil Philip. (S) *Amla.* (II.)

KAR, Saroj Kumar. (S) *Bombay.* (IIIa.)
KASINATHAN, T. S. (S) *Bangalore.* (IIIa.)
KRISHNAMOORTHY, T. Sundaresan. (S) *Madras.* (II, IIIa, IIIb.)
KRISHNASWAMY, T. L. (S) *Bangalore.* (I, II.)
KUMAR, Om. (S) *Kanpur.* (IIIa.)
KUNDU, Sushyamal. (S) *Bangalore.* (I, IIIa.)

LAKDAWALA, Homi Feroze. (S) *Bombay.* (I, II.)

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MASAND, Bhagwan Menghraj. (S) *New Delhi.* (II.)
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MITRA, Somendra Nath. (S) *Bangalore.* (I.)
MONTIERO, Alfred Peter. (S) *Bombay.* (II, IIIa.)
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MUKHERJEE, Sitapati. (S) *Calcutta.* I.)
MUTHANNA, Meruvanda Panappa. (S) *Mysore.* (II.)

NAIR, Patinchararaevetil S. (S) *Bangalore.* (IIIa.)
NARASIMHAMURTHY, Wudali. (S) *Madras.* (II.)
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PINTO, Cyprian. *Kanpur.* (IIIb.)
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QAZI, Moh'd Akram. (S) *Multan.* (II.)

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RAJENDRA NATH. (S) *Bangalore.* (I, II.)
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SANKARANARAYANAN, S. (S) *Bangalore.* (II.)
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The results of the remaining oversea candidates will be given in a final pass list to be published in the April issue of the *Journal.*

ELECTRONICS IN AUTOMATIC DIRECT READING SPECTROMETERS FOR THE ANALYSIS OF METALS*

by

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

SUMMARY

After first discussing the fundamentals of photoelectric spectrometry, the basic essentials of automatic direct reading instruments are reviewed, reference being made to a 3-metre direct reading spectrometer with 30 channels which has been developed as a rapid routine production control unit in the making of non-ferrous alloys. The circuit employs features not previously used in this type of equipment, including a "dekatron" counter circuit and a printing recorder to register the counts corresponding to the intensity ratios of the selected spectral lines of the constituent elements being measured. The concentrations are then determined from working curves established experimentally for each measuring channel to give the concentration as a function of the count for the corresponding element.

PART I — INTRODUCTION

1. Purpose of the Instruments

Direct reading spectrometers with electronic measuring and control systems are an outstanding feature of post-war developments in instruments for spectrochemical analysis of metals. These instruments are particularly suited to the rapid routine analysis of complex metallic alloys and in their latest automatic forms are capable of determining the composition of an alloy in a few minutes. For instance, a typical run with the spectrometer described in some detail in the paper, will give measurements for 15 elements selected at will in 2 min. 40 sec., and with all 30 measuring channels in operation, will complete a run for 30 elements in less than five minutes. The instrument is entirely automatic; all that the operator has to do is to insert a specimen of the metal to be analysed into the spark stand and press a button. Figures for the analysis which can be up to 30 elements for one setting of the instrument are displayed on a four decade "dekatron" counter and are printed automatically on a strip of paper.

The advantages which such instruments give to the user compared with previous spectrographic (photographic) instruments or direct chemical analysis arise through the accuracy and rapidity of analyses. The importance of this to the metallurgical industries will be realized for the time of analysis is sufficiently short for alloys to be held in the molten state whilst their exact chemical constitution is checked and, if necessary, additions made to bring the melt to specification before pouring.

Such instruments are necessarily complex and correspondingly high priced, but it has been claimed by their makers that the economies and increased efficiencies resulting from their use more than justify the initial outlay within the space of a year or two. From this it will be appreciated that the utmost attention must be paid to making the equipments suitable for continuous reliable operation.

2. Principles of Spectroscopic Measurement

The technique and practice of spectrochemical analysis by measurement of the relative intensities of selected spectral lines of the arc or spark emission spectra of metals by conventional spectrographic methods are of long standing and of widespread use in industry throughout the world.

In these instruments a high voltage spark or an arc discharge between electrodes of the specimen is used to excite its characteristic emission spectra. The light from the discharge passes through the entrance slit of an optical prism or grating spectrograph where the resulting dispersed spectrum is photographed by

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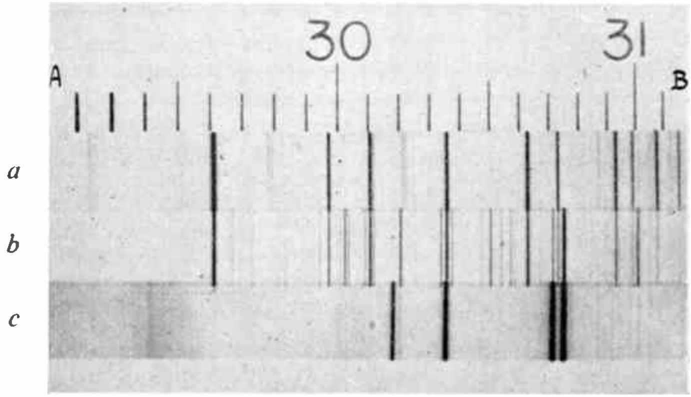
a film or plate at the focal curve of the spectrograph. A typical spectrogram is shown in Fig. 1 to illustrate the problem. Measurement of the relative densities of the recorded spectral lines by means of a microphotometer then gives a measure of the concentration of the constituent elements from established working curves for the analysis.

3. Fundamentals of Photo-electric Direct Reading Analysis

The development of photo-electron multipliers of high sensitivity, stability, low dark current, and suitable spectral response, and their successful application to the direct measurement of the relative intensities of spectral lines was a milestone in the approach to the problem of speeding up analysis. By such direct photo-electric measurements the delays involved in photographic processing and the microphotometry of the resultant spectrogram are eliminated. Much is owed to the early work of Hasler and Dietert,[1] Dieke and Crosswhite,[2] Saunderson, Caldecourte and Peterson,[3] and Engstrom,[4] which formed the basis of the first instruments to be developed.



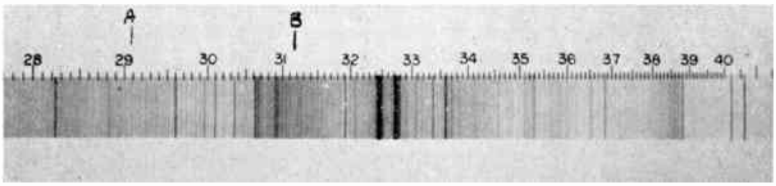


Fig. 1.—Typical spectrogram of metallic spectra in the ultra-violet region ; (a) copper, (b) brass, (c) zinc. Lower illustration shows spectra of copper arc for 2800A to 4000A.

The principle of measurement with direct reading instruments remains basically the same as for the conventional spectrograph, namely the measurement of the intensity ratios of selected constituent spectral lines used in conjunction with working curves giving the concentration of the constituents in terms of intensity ratios. Much of the success of the method depends on the choice of the particular spectral lines to be compared and they must, if possible, conform to the following criteria :

1. The reference line is to belong to the major constituent (the base metal) and the analysis spectral lines to be those of minor constituents.
2. The relative intensities should be independent of the excitation conditions. Such spectral lines are said to be " homologous."

PART II — GENERAL APPROACH TO THE DESIGN OF A COMPLETE INSTRUMENT

Existing direct reading spectrometers consist of four basic components. These are :—

1. The Source Unit for exciting the spark or arc discharge.
2. The Spark or Arc Stand — holding the specimen electrodes.
3. The Optical Spectrometer with exit slit and photo-multiplier system.
4. The Measuring and Automatic Control Unit.

The principal features of these units are now described to give an overall picture of the signals which the system has to measure.

4. Source Units

Considering these first as they determine the time-intensity waveforms and fluctuations of the spectral lines to be measured, it is found that there are four main types of circuits used. These may be classified as follows and three main circuit elements are shown schematically in Fig. 2.

4.1. *High Voltage Condensed Spark*

Figure 2a shows the basic circuit of a Spark Set, in which T is a leaky transformer with secondary taps at 7·5, 10, 12, 15 kV r.m.s. on open circuit with a secondary short circuit current of about 17 milliamperes. C is a 0·005 μF 22 kV peak working mica capacitor and L is an inductor (Hemsalech coil) with taps at 0·03, 0·06, 0·13, 0·25, 0·5 millihenries.

The discharge across the analysis gap takes place periodically with single or several trains of oscillatory sparks each half cycle of the mains input voltage. The inductor L varies the discharge waveform, and the purpose of the capacitor C is to increase the energy of discharge.

4.2. *A.C. Arc*

Figure 2b outlines the basic circuit of an Intermittent Arc Unit. This utilizes the transformer T and capacitor C of the spark set which are discharged each half cycle of the mains voltage through an auxiliary spark gap in series with the primary winding of the Tesla coil (Tc). The high frequency oscillatory discharge from the secondary of the Tesla coil ionizes the analysis gap sufficiently to initiate the main power discharge from the power circuit, which includes capacitor C1 (48 μF) to increase the peak energy of the discharge. Capacitor C2 offers a low impedance to the high frequency discharge and also acts as an interference suppressor in conjunction with coils L1 and L2.

4.3. *Controlled Sources*

Various circuits of this type exist with the common aim of providing uniform high energy discharges to increase the reproducibility of measurements. The circuit originated by Walsh in 1946 at the British Non-Ferrous Metals Research Association is taken by way of example as typical of the general approach to the problem. The Hilger BNF Controlled Source Units FS120 and FS130 embody this circuit which is shown schematically in Fig. 2c.

The capacitor C, variable from 10 μF to 250 μF in steps of 10 μF, is charged from the a.c. mains via a rectifier during one half cycle of the mains voltage. During the following half cycle the capacitor is discharged through the analysis gap which is ionized by a transitory high voltage low energy trigger spark, recurring at mains frequency and phased to give a regular discharge sequence. By suitable choice of the value of the capacitor C, damping resistor R and series inductor L, the discharge can be given either arc-like or spark-like characteristics, or set between these two extremes.

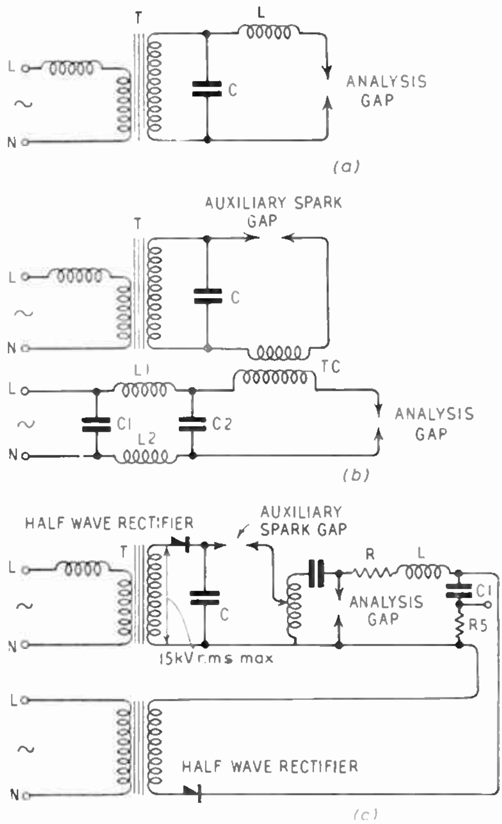


Fig. 2.—(*a*) *High voltage condensed spark.*
(*b*) *A.c. arc.*
(*c*) *Controlled source — Hilger-BNF. R5 is a calibrating resistor to enable charging and discharging currents of C1 to be viewed on an oscilloscope.*

Typical current waveforms of the discharge are illustrated in Fig. 3.

Many papers have been written on source units and a selection is given in the References 5—10.

4.4. *The D.C. Arc*

In addition to the foregoing, d.c. arc arrangements are sometimes used to give high sensitivity. Generally speaking these do not give the reproducibility of result obtained by the a.c. arc or controlled sources described.

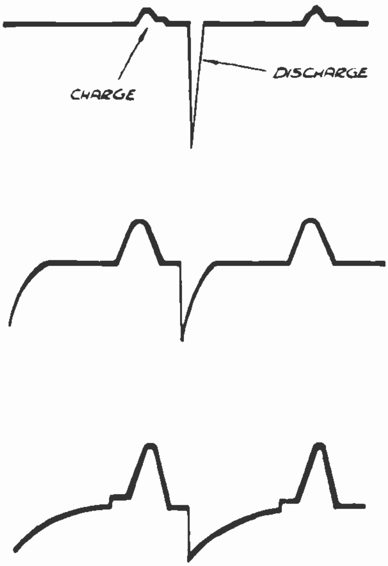


Fig. 3.—Current waveforms for the Hilger-BNF Source.

5. The Spark or Arc Stand

This consists of a specimen electrode holder with means for setting the electrode gap width. It is important to arrange effective electrical screening of both source and stand, and their interconnecting cables, in order to avoid interference with the electronic system of the Direct Reader.

6. Optical Spectrometer and Photo-multiplier Unit

The purpose of the spectrometer is to disperse the light passing through its entrance slit into its spectrum, which is imaged at the focal curve of the instrument. Exit slits are positioned on the focal curve to select the spectral lines of interest whilst blanking off the unwanted radiation. The light passing through the exit slits is directed on to the photo-multiplier cathodes. This is the basis of all of the large multi-channel Automatic Direct Readers which have been made, and these have all used long focal length diffraction gratings as the dispersing means.

6.1. *Choice of Slit System*

If we now consider the problem of measuring the intensity of individual spectral lines imaged along the focal curve of the spectrograph, it will be seen that we may use a fixed system of masks with fine slits placed along the focal curve to allow lines of interest to pass simultaneously from the spectrograph to the photo-multipliers. The response currents of the photo-multipliers can then all be integrated at the same time.

Alternatively we may use a scanning arrangement in which the slit and its associated photo-multiplier, or several slits and photo-multiplier assemblies, are mounted on a movable carriage which traverses the slit, or slits, along the focal curve. This method was first described by Dieke and Crosswhite.[2] The system can be arranged so that spectral lines of interest are scanned by one or other of the slits.

Both schemes have been employed in direct reading instruments.

6.2. *Relative merits of the Simultaneous Integration and Scanning Methods*

One of the difficulties to be met in attempting to take precise measurements of spark or arc spectral line intensities is that due to the continuous marked variations in the intensities due to the inherent fluctuations in the discharge, quite apart from the actual nature of the light signal itself. The fixed slit integrating method in which the collector current of each photo-multiplier is made to charge a low leakage capacitor over a period of time tends to minimize the effects of the source instabilities on the actual results.

The scanning method on the other hand does not allow prolonged integration of the photo-multiplier response if a reasonable overall speed is to be maintained, and this is an inherent limitation coupled with the fact that measurements are not taken simultaneously for an appreciable number of elements with any known unit. This means that any changes in the spectrum during the discharge period might introduce errors.

On balance it would seem that the fixed slit system is the more acceptable for routine control instruments.

6.3. *Photo-multiplier Unit*

The foremost aspect of the unit is the choice of types of photo-multiplier for the low level measurements involved. The essential features required are :—

1. High sensitivity.
2. Low dark current.
3. Stability of response.

Whichever type of photo-multiplier is chosen there is always some need to select them according to the actual performance required of them in the instrument.

For the visible and near ultra-violet wavelength region the choice may fall between :—

RCA	1P21 or RCA 931A (selected)	9-stage
Mazda	27M1	9-stage
EMI	6094	11-stage

For the ultra-violet region they may be selected from :—

RCA	1P28	9-stage
Mazda	27M3	9-stage
EMI	6256	13-stage

The response currents of the photo-multipliers consist of the following components :—

(*a*) A photo-electric current proportional to the intensity of the spectral line being measured and having a waveform depending on the type of discharge.

(*b*) A photo-electric current proportional to the unwanted background radiation.

(*c*) A dark current component due to thermionic emission from the cathode and to leakage currents.

The charge, and hence the potential difference across each integrator capacitor, is proportional to the sum of these components integrated over the exposure period, and it is necessary to take account of the unwanted components (*b*) and (*c*) in evaluating the relative intensities of the spectral lines.

Some instruments rely on the straightforward approach of selecting photo-multipliers of low dark current and high sensitivity, so that (*c*) becomes relatively unimportant, and of making allowances where necessary for the spectral background.

The instrument designed by Saunderson[3] differs in this respect as it includes a dark current balancing circuit and means for reversing the connections to the capacitor once per second in synchronism with the movement of a shutter. The shutter allows the spectral lines, plus background, to pass to the photo-multiplier during one period and allows only the adjacent background radiation to pass to the photo-multiplier during the reversal period. In this way the effects of background and dark current are largely eliminated.

It should, however, be mentioned that the background and dark current are but two of the significant causes of error, and that variations in the sensitivity of the photo-multipliers with time and with fluctuations in their supply voltages must be guarded against. It is well known that for some photo-multipliers fatigue effects cause a reduction of sensitivity with time, especially if the level of illumination results in a collector current exceeding a few micro-amperes. Thus it is necessary to ensure that the working conditions should preclude any chance of such an effect taking place, and in general it has been found best to arrange that the photo-multipliers be constantly illuminated at a low level between measurements to condition them for measurement. Such a process is known as fatiguing.

7. The Measuring and Automatic Control Unit for Multi-channel Pre-set Slit Systems

The method of charging low leakage capacitors by the collector (anode) currents of the photo-multipliers is common to the large direct readers referred to in this paper. The capacitors collect charge in proportion to the integrated light intensity of the spectral lines being measured, and it is required to measure the charge on each capacitor by measuring the potential difference developed across each capacitor. The integration provides a convenient method of coping with the peculiar waveforms of the signal currents and tends to minimize the effects of instabilities in the discharge.

Results are displayed either as a direct indication of the percentage composition of the test specimen or as a reading which is referred to a previous calibration. The automatic control system controls the sequence of events and is a notable aid in speeding up the action of those instruments.

8. Measuring Circuits

Three basic types of circuits for measuring the potential difference across the capacitors in each measuring channel are to be found in existing instruments. These are all circuits of high input resistance and low input capacitance so as not to reduce the charge on the integrator capacitors by momentary connection.

8.1. *D.C. Bridge Amplifier with Pen Recorder (Fig. 4).*

As with all d.c. amplifiers this system suffers the inherent drawback of drifts which demand zero correction. The circuit employed in many A.R.L. equipments uses a matched pair of 959 acorn valves in a simple bridge amplifier with the recorder connected in the anode circuit. Zero correction is derived between measuring periods from contacts on the recorder which always tend to bias the system towards zero when the balance point drifts away from zero.

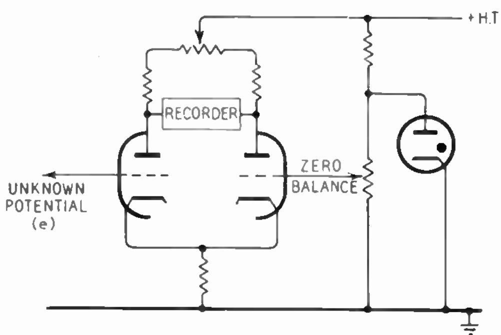


Fig. 4.—D.C. bridge amplifier.

The scales of the pen recorder are calibrated to read in terms of percentage concentration set by adjustable backing off and sensitivity controls in each measuring channel.

8.2. *D.C. Amplifier and Comparison Trigger Circuit with Indicating Clocks*

The Baird instrument uses an elegant method, due to Saunderson,[3] of comparing the charges in the constituent capacitors with that in the reference (base metal), capacitor. Fig. 5 shows the scheme in which, at the beginning of measurement, all the capacitors to be measured are connected with their potentials in opposition to that of the internal standard reference capacitor.

The trigger circuits, each consisting of a stable d.c. amplifier operating a relay A1 when the differential input potential passes through zero, are arranged so that the clocks are energized when the input is negative and switched off when the input passes through zero.

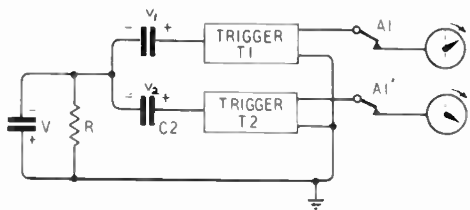


Fig. 5.—Saunderson-Baird measuring circuit.

By way of example suppose now that the potential differences developed across the constituent capacitors C1 and C2 are v_1 and v_2 respectively, where v_1 is greater than v_2, and that the corresponding potential difference across the reference capacitor C is V_0, where V_0 is greater than either v_1 or v_2.

At the moment of simultaneous connection of the capacitors to their respective trigger circuits T1 and T2 the discharge resistor R is connected across C, which then begins to discharge exponentially, the potential difference across C at any instant being defined by

$$V = V_0 \exp(-t/RC)$$

where t is the elapsed time in seconds since the commencement of discharge.

At the instant of starting the discharge the trigger circuits T1 and T2 are both biased negatively by virtue of V_0 being greater than v_1 or v_2, and hence both clocks will begin to run at constant speed until the potential V across C has fallen to v_1, at which instant contact A1 opens and the clock associated with C1 will stop. A little later V will have fallen further to v_2, and contact A1′ opens and the C2 clock will then stop. Let these elapsed times be t_1 and t_2 respectively

We have $v_1 = V_0 \exp(-t_1/RC)$

and $v_2 = V_0 \exp(-t_2/RC)$

From these

$$t_1 = RC \log \frac{V_0}{v_1} = RC \log V_0 - RC \log v_1$$

$$t_2 = RC \log \frac{V_0}{v_2} = RC \log V_0 - RC \log v_2$$

Hence the deflections of the clocks may be calibrated in terms of the logarithms of the potential differences appearing across the constituent capacitors or, as in practice, calibrated in terms of the concentrations on a logarithmic scale.

The logarithmic response tends to give a constant relative accuracy of reading of the percentage concentration over the whole scale which is useful as, for example, the absolute error in determining an element at 5 per cent. concentration is in general about ten times as great as the absolute error at 0·5 per cent. concentration.

8.3. *Description of the Trigger Circuits*

Each trigger in the arrangement described by Saunderson[3] consisted of a two-stage d.c. amplifier with degenerative feedback to stabilize the zero balance position between measurements. The basic scheme is shown in Fig. 6.

V1 and V2 comprise a two-stage d.c. amplifier, the input valve being a 6J7 used as an electrometer valve with a low heater current giving a low grid current of the order of 10^{-11} amperes.

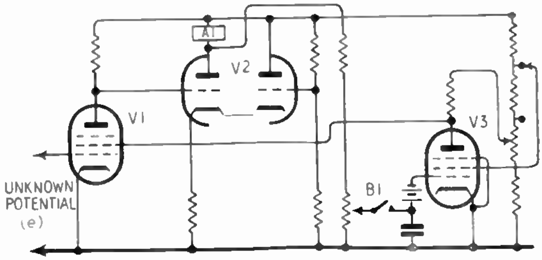


Fig. 6.—Trigger amplifier.

The negative feedback is via V3 and a relay contact B1, which disconnects the feedback loop during an actual measurement. With feedback the sensitivity is about 200 millivolts per milliampere flowing in the clock relay A1, and the drift of zero is small under these conditions. During measurement the contact B1 is opened to remove the feedback and the sensitivity then becomes about 5 mV per mA. The capacitor in the grid circuit of V3 tends to hold the balance potential across the input of V3 constant during the short measuring period. In this way it is claimed that the drift in the amplifier from the balance (zero) position can be limited to about 1 millivolt in say 30 seconds, and that the unit is capable of measuring the ratios of potential of the order of 1 volt to better than ½ per cent.

8.4. *Voltage Comparator and Dekatron Counter and Printer*

The scheme adopted in the instrument described in Part III consists of a discriminator and modulator circuit which generates a train of impulses whose total count is a measure of the potential on each capacitor measured. The results are displayed on a four-decade dekatron counter with a read-out circuit to give a printed record of the count. An automatic servo-controlled zero control is incorporated, which maintains the zero to within a single count.

9. Stabilized Power Supply Units

The overall current amplification of the photo-multipliers is equal to the average amplification per dynode stage raised to power n, where n is the number of dynode stages. For small changes in the dynode potential the stage amplification varies almost directly as the potential difference per stage, and hence the overall amplification varies almost as the nth power of the average voltage applied to each dynode stage. This entails a high degree of stability in the e.h.t. supply to the tubes.

All of these instruments use well-established supply circuits, both for the photo-multipliers and the measuring circuits. These are mainly conventional in form and it is not proposed to describe them in detail here.

10. Automatic Control Circuits

These serve to give completely automatic operation.

10.1. *The Sequence of Events*

This is basically as follows :—

1. Insert the specimen electrodes and press the " Start " button.
2. The spark or arc is then excited for a short period — the pre-spark period, before the measurements are taken. During this period the measuring circuits are " zeroed " and the integrating capacitors discharged in readiness for the exposure period.
3. Exposure Period : The capacitors are switched to their respective photo-multiplier and collect charge proportional to the integrated light intensity. At the end of the exposure period the capacitors are open circuited and the source unit switched off.
4. The capacitors are connected in turn to the potential measuring circuit as in the A.R.L. and Hilger instruments, or connected simultaneously as in the Baird Unit.

10.2. *The Exposure Period*

The exposure period may either be determined by a timing circuit which disconnects the integrating capacitors from their charging circuits at the end of a given period, e.g. 30 seconds, or alternatively by a reference circuit which stops the integration when the integrated signal, due to an internal standard spectral line, reaches a predetermined level. The instruments would normally be arranged so that either scheme may be used.

The internal standard method is the one normally chosen in the Hilger instrument as the intensity results for the minor constituents are then automatically displayed as ratios to the internal standard line.

Various schemes for terminating the exposure from the internal standard are in use. For instance, with a d.c. bridge amplifier and recorder, the recorder can be set to measure the rise of potential of the internal standard integrating capacitor and to terminate the exposure when full scale deflection is reached. In the Hilger system the exposure ends when the potential across the internal standard capacitor reaches a predetermined level set by a reference potential applied to the comparator.

PART III — DESCRIPTION OF THE HILGER 3-METRE GRATING POLYCHROMATOR (DIRECT READING SPECTROMETER)

11. Design Aim

The aim in designing this equipment was to produce an instrument capable of determining the composition of an alloy in a few minutes for as many as 30 elements. It is primarily a routine control instrument, and the first instrument has already been installed for the analysis of non-ferrous metals. This instrument has been in operation for several thousand hours altogether, and has shown almost complete reliability in the electronic system. No valve failures have occurred, other than a particular thermal delay switch which has undergone abnormal use during extensive trials.

12. General Description

The complete instrument is shown in Fig. 7. The main body of the instrument comprises the 3-metre Grating Spectrograph with the Spark and Arc Stand shown at the extreme left mounted on a support bar. The hinged door at right-hand end of the instrument opens to expose the slits, and the mirrors and photomultipliers associated with each slit.

The console on the right contains the measuring unit and control equipment. The console is 6 ft. high, giving an indication of the overall size of the equipment.

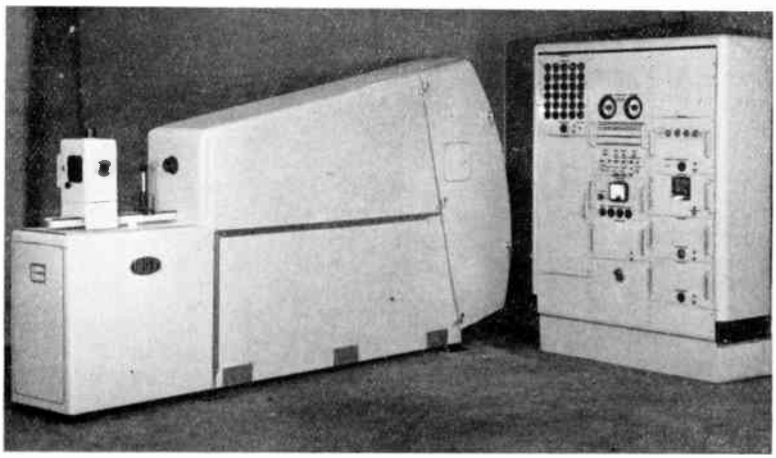


Fig. 7.—Illustration of the Hilger 3-metre grating direct reading spectrometer. The polychromator, and arc and spark stand are on the left and the measuring console is on the right.

12.1. *Optical System*

The optical section of the instrument consists of a 3-metre radius concave grating spectrograph with a series of exit slits arranged in the focal surface to isolate the selected spectral lines.

Light from the analysis gap enters the spectrometer via the entrance slit (S, Fig. 8) and is reflected by plane mirror M on to the grating, which forms a dispersed image of the spectrum along the focal surface. The light passing through each of the exit slits (S_1 – S_n) is directed on to the cathode of a photo-multiplier via a mirror arrangement (M1).

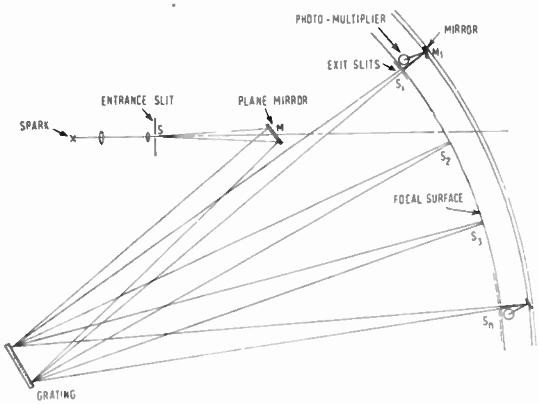


Fig. 8.—Schematic diagram of optical system.

The unit has been designed to employ up to 30 exit slits, each with its own photo-multiplier and separate integrating channel. Actually there are 50 locations for the photo-multipliers to allow some latitude in placing them.

12.2. *Photo-multipliers*

The photo-multipliers used in the equipment are E.M.I. end window types 6094 and 6256 (see Fig. 9) which have been found to have excellent performance characteristics for this instrument.

The type 6094 is an 11-stage photo-multiplier with a glass window suitable for use in the visible and near ultra-violet over a wavelength range from 3200 to 6000 angstroms.

The type 6256 is an ultra-violet sensitive 13-stage photo-multiplier with a quartz window which has a spectral response extending from approximately 1950 angstroms in the ultra-violet to 6000 angstroms in the visible.

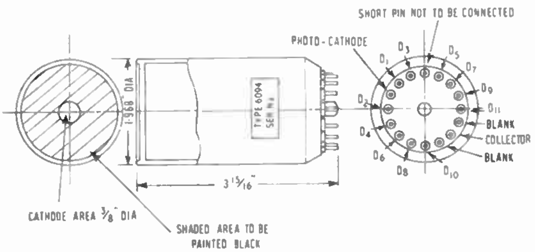


Fig. 9.—Illustration of EMI photo-multiplier.

Choice of tube depends on the particular spectral lines required to be measured. Generally there will be the need for both types, bearing in mind the higher price of the quartz window tubes.

The wiring is shown in Fig. 10, which also shows the connection panel for the cables interlinking the spectrometer with the console.

Steps are taken to condition the photo-multipliers by means of a fatiguing lamp, which is switched automatically between measurements.

12.3. *Electronic Console*

The console comprises the following units :—

1. E.H.T. Photo-multiplier Supply Unit.
2. Integrator.
3. The Comparator.
4. Counter.
5. Printer.
6. Oscillator Unit.
7. Stabilized H.T. Unit.
8. Rectifier Unit for Relay Circuits.
9. Channel Selector.

Breeze type inter-connecting cables are used to prevent wrong connection and in addition the co-axial signal leads are all coded for ease of connection. The connections to the spectrometer are run in a steel conduit rigidly attached at each end. For ease of servicing the individual chassis are mounted on extendable slides so that they can be drawn forward out of the rack and are pivoted so that they can be tilted upwards to enable access to be gained to the underneath part of the chassis, as shown in Fig. 11.

It is an essential feature of this kind of industrial control equipment that it should give unbroken service, and it will normally be left switched on continuously. Hence ready servicing arrangements are vital.

13. Basic Scheme of Measurement

13.1. *Counting and Printing Method*

The factors underlying the choice of a fixed exit slit system with integration have been referred to in Part II. The basic scheme of measurement is shown in Fig. 12, in which for simplicity, only one integrating circuit is shown, the others being identical and connected in turn via relays to the common voltage measuring unit, which is termed the Comparator. The comparator generates a train of pulses, which in number are proportional to the input voltage to the comparator, and the resultant count is presented as a number on the four decade counter, and also printed on a paper strip simultaneously with the printing of the channel identification number.

The keyboard on the channel selector allows the operator to select the integrating channels which he wishes to be measured, those not selected being passed over quickly in the automatic stepping cycle.

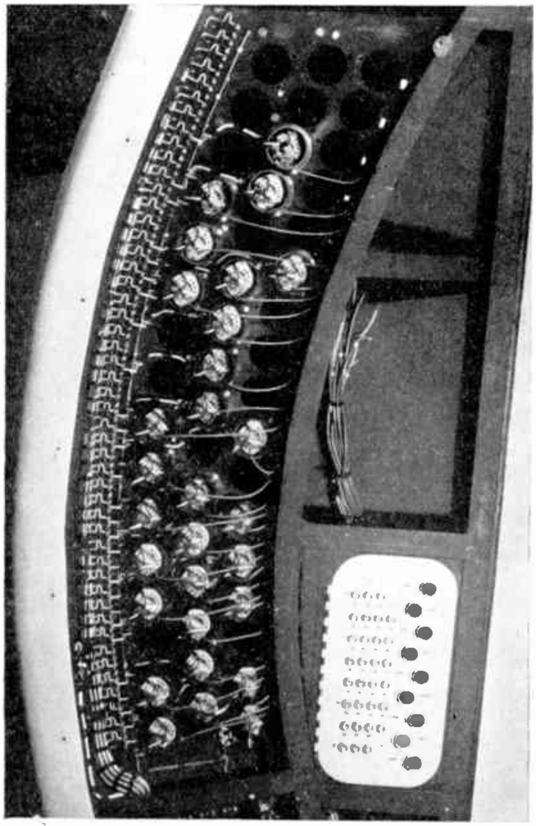


Fig. 10.—View of wiring of photo-multiplier holders.

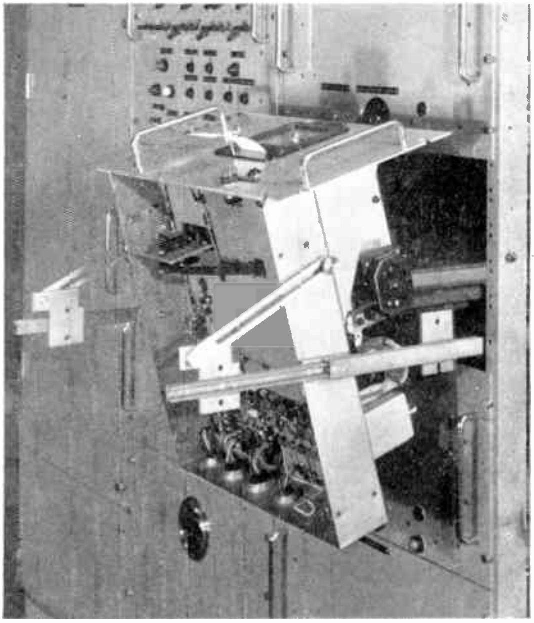


Fig. 11.—View of printer withdrawn for servicing.

13.2. *Alternative Direct Meter Indication of Photo-multiplier Collector Current for Setting-up Purposes*

It is desirable to be able to obtain a continuous measurement of the photo-multiplier collector currents when making slit adjustments, or setting the channel sensitivity switches. The foregoing method is not convenient for this purpose, being a step by step method, and an alternative circuit is provided to give a measure of the collector currents directly on a meter. For this the collector current is arranged to flow through a load resistor in the input circuit to the first valve of the comparator, which serves as a direct coupled differential amplifier with a meter between cathodes K1 and K2 (Fig. 12).

14. Description of Units

14.1. *E.H.T. Photo-multiplier Supply Unit*

The circuit of this unit is a conventional type series-parallel stabilizing circuit giving an output up to 1300 V. at 15 mA d.c. with a stability of better than 0.05 per cent. Separate coarse and fine adjustments on the front panel enable the sensitivity of each photo-multiplier to be

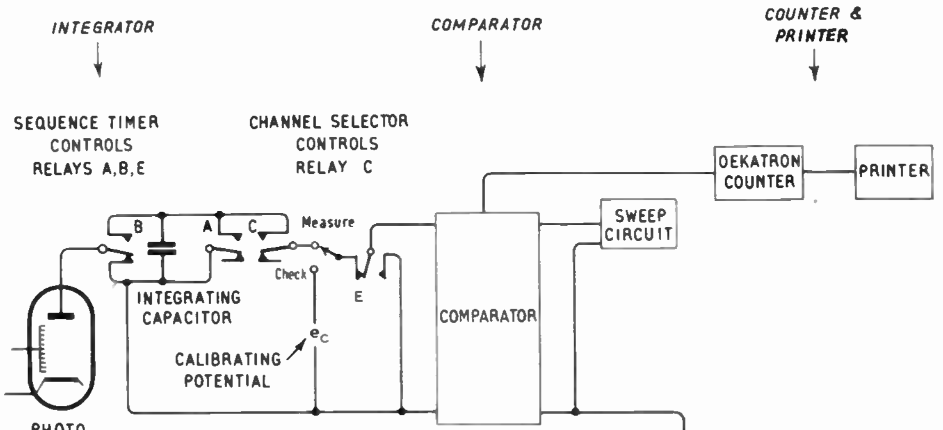


Fig. 12.—*Basic scheme of Hilger measuring circuit.*

varied independently over a range of approximately 2000 to 1.

14.2. *Integrator Unit*

This unit contains the integrating capacitors and associated relays for the automatic switching cycle for the full 30-channel arrangement of the basic circuit shown in Fig. 12. It is a completely enclosed unit with a desiccator to help to maintain high insulation, and has a Perspex window so that the functioning of the relays can be observed by merely opening the front door at the left hand side of the console.

The capacitors (0.1 μF) are plastic film types to ensure low leakage during the storing period, and are of low dielectric absorption. The relays have Mycalex insulated contact assemblies and have a suitably high insulation resistance.

The relays are energized from the sequence controller as follows :—

(*a*) Relays A to earth the capacitors at the beginning of a run.

(*b*) Relays B to connect the capacitors to their respective photo-multipliers during the exposure period.

(*c*) Relays C to connect the capacitors to the measuring circuit in turn.

During the interval between any of the conditions *a*, *b* or *c*, the capacitors are open circuited.

* The comparator described here is the subject of a British Patent Application No. 24397. (K. P. Rippon and Hilger & Watts, Ltd.)

14.3. *The Comparator — for measuring electrical potentials**

In considering the design of the circuit for measuring the potentials across the integrating capacitors there were four main objectives in view :—

(*a*) The input resistance of the circuit was to be sufficiently high and the capacitance small enough to allow repeated connections to any capacitor without appreciably discharging it.

(*b*) Speed of measurement and recording was to be rapid — not more than, say, 6 seconds per channel in view of the large number of channels in the equipment.

(*c*) The potentials were to be measured to a high degree of accuracy and precision over an extended range so as not to limit the overall analytical accuracy.

(*d*) The results of measurement were to be presented in an easily read form — preferably numerically by means of a printer, which would also indicate the particular measuring channel.

In the instrument being described it is believed that these aims have been met in full by the use of an analogue-to-digital comparator unit in conjunction with a dekatron counter and printer.

In this system a discriminator valve is used to compare the potential to be measured with that derived from a linear sweep generator. The resulting difference potential is then used to operate a modulator which generates a train of pulses from the commencement of run down to the instant when the sweep potential becomes equal to the unknown. The pulse train is derived from a constant frequency oscillator, and the total number of pulses gives a measure of the unknown potential.

14.4. "*Dekatron*" *Counter*

The four decade electronic counter used in the instrument was designed and constructed in the Company's Research Division. When this project was started a suitable counter, capable of a count rate of 10,000 counts per second with read-out facilities, was not available, but since that time the development of a high speed cold cathode tube (Ericsson GC10D) has made the problem very much simpler, and there is no difficulty in constructing a suitable unit.

At one stage in the development of the equipment it was found necessary to halve the impulse frequency, introducing a "divide by two" circuit between the 10,000 c/s modulator and the counter, as counting rates higher than 5,000 counts per second could not be obtained with the GC10B tubes available. With this count rate the rate of rundown of the Miller integrator was halved in order to double the actual time of rundown, so that the total count remained the same for any given input voltage.

The final form of counter employs a GC10D tube in the first (units) position and GC10B in the remaining three stages, with double triode 12AT7 coupling tubes. Resetting to zero is automatically carried out during the measuring cycle.

The general form of the circuit is conventional and will not be described in detail, but it has the special feature of a "read-out" circuit which enables the printer to be operated from the information stored in the counter at the completion of each potential measurement.

14.5. *The Printer*

The printer is arranged to print the channel number, or designation, besides each result as shown in Table 1. The actual time required for each printing operation is about 3 seconds.

Between each printing action the recording paper is advanced by about $\frac{3}{8}$in. and the typewriter ribbon is moved about the same distance. The system incorporated a reversing mechanism in the typewriter ribbon drive which automatically reverses the direction of motion of the ribbon when the supply spool is empty.

14.6. *Oscillator*

The 10-kc/s carrier signals for the comparator modulator and the phase sensitive rectifier for the servo-operated zero control are provided by a two-stage (12AU7 and 6AM6) quartz crystal oscillator stabilized in amplitude by rectified feedback (a.g.c.) from the anode of the output valve. The quartz crystal is an S.T.C. type 4023, and the frequency stability of the circuit is at least an order better than is required for the system of measurement.

14.7. *Stabilized H.T. Unit*

All the h.t. and valve heater supplies in the comparator unit are stabilized, and these are supplied by a separate stabilizer unit. The main 250 V h.t. circuit consists of a series-parallel valve regulator which also supplies the heaters of all of the valves, these being wired in series. Additional outputs at + 170 V and —85 V are derived from voltage regulator tubes.

14.8. *Rectifier Unit for Relay Circuits*

The relays throughout the equipment are operated from an unsmoothed full wave selenium rectifier unit giving 48 volts at 3 amps d.c. This unit is mounted on a separate chassis, which also contains a 6 volt 50 watt constant voltage transformer supplying the calibrating and fatigue lamp in the spectrometer.

14.9. *Channel Selector and Automatic Control Unit*

This unit is the main control unit selecting the channels to be measured and, from the moment of pressing the "start" button, governing the automatic and manual operation of the whole equipment in accordance with the sequence of events outlined in Section 10.

Table 1
Printed Result of Measurement of the two check voltages.

Channel	*Count*	*Channel*	*Count*	*Channel*	*Count*
30	8177	29	8175	30	4087
28	8175	27	8177	28	4088
26	8177	25	8175	26	4088
24	8177	23	8177	24	4089
22	8175	21	8177	22	4089
20	8177	19	8177	20	4088
18	8176	17	8177	18	4089
16	8177	15	8175	16	4088
14	8176	13	8175	14	4088
12	8177	11	8175	12	4088
10	8177	09	8177	10	4087
08	8176	07	8175	08	4088
06	8176	05	8176		
04	8176	03	8176		
02	8178	01	8174		

14.9.1. Channel selector

During an analysis run all integrating capacitors connected to photo-multipliers are charged in varying degree according to the photo-multiplier collector currents, and the purpose of the channel selector is to enable the operator to select the particular capacitors to be routed to the comparator measuring circuit during the potential measuring cycle by depressing the appropriate key switches on the front panel of the unit. Each switch is associated with one of the 30 integrating circuits and serves to determine the stepping of a G.P.O. type uniselector switch, which in turn operates the measuring relays C in the integrator unit.

The way in which this selector circuit operates is illustrated by Fig. 13, which shows the basic scheme for up to 25 channels using a 3-bank 25-way uniselector. By way of explanation it is sufficient to show 3 key switches S1, S2 and S3, with 2 change-over springsets A and B each.

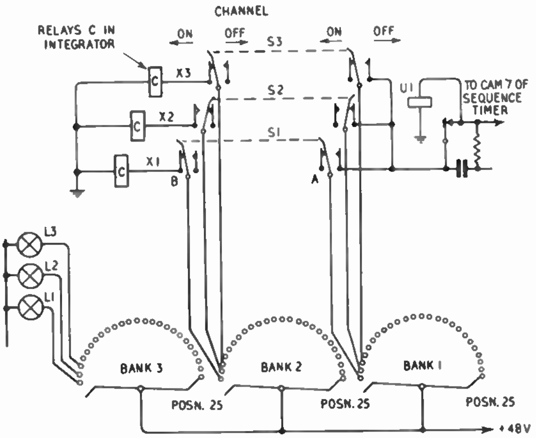


Fig. 13.—*Schematic diagram for channel selector.*

Suppose now that it is desired to measure the channels X1 and X3 associated with key switches S1 and S3 but to pass over the second channel X2 associated with S2. Then the keys for S1 and S3 are depressed, leaving S2 in the off position as illustrated. At their initial rest position the wipers of the uniselector bank are in the position 25 as shown, and on completion of the exposure period are stepped forward one step to position 1 by a single impulse applied to the operating coil from the sequence controller, which is arranged to provide such an impulse every 6 seconds.

(*a*) When the wiper of Bank 1 steps on to position 1 there is no through connection of the 48 V d.c. supply to the stepping coil via S1A, and the wiper dwells for 6 seconds on position 1 until the system receives another stepping impulse from the sequence controller. During this period the wiper on Bank 2 applies 48 V to the measuring relay C for channel X1 in the integrator unit, and causes the system to count, and print, a record corresponding to the potential of channel X1. Simultaneously the indicator lamp L1 for channel X1 is energized by the wiper in position 1 on bank 3.

(*b*) After the measuring period of 6 seconds, determined by the sequence controller, the uniselector stepping coil receives another impulse and steps on to position 2, which causes 48 V to be applied to the stepping coil via the uniselector break contact U1 and immediately the wiper is stepped on to position 3. The relay C corresponding to channel X2 is not operated and no measurement takes place. At the same time the indicator lamp L2 for this channel merely receives a short impulse via bank 3 and does not light up.

(*c*) When the wipers have stepped to position 3 they dwell in that position for 6 seconds until the sequence controller steps the wipers on. During the dwell period relay C for channel X3 is operated to switch the capacitor to the comparator and lamp L3 is energized.

Thus it will be seen that during the measuring cycle only those channels will be measured for which the selector key has been depressed to the "on" position and the remainder will be passed over.

In the unit itself two uniselectors are used to provide the switching for 30 channels.

14.9.2. Sequence controller

The automatic control is centred in the sequence timer and relay circuit which determines the sequence of events.

The sequence timer consists of a bank of contacts actuated by eight cams on a common shaft driven by a synchronous motor via a solenoid operated clutch. The motor is geared down to drive the cams through 1 complete revolution in 6 seconds, which is the time required to measure each capacitor and to print the result. The cam contacts each have their own function in switching on the operational relays.

15. Description of Operation

The operation of the unit follows the sequence of events described in Section 10 and is completely automatic from the instant of pressing the "Start" button to the printing of the record.

The measuring cycle may be repeated by operating a "re-cycle" push switch which enables the potentials on the capacitors to be re-measured.

Manual control of the measurement cycle is provided by merely depressing a key switch and then operating a push button to cause the system to step from one channel to the next selected channel. Indicator lamps on the front panel indicate whether the fatigue lamp has been switched off during the integrating period and show when the complete cycle has finished.

16. Performance

The analytical accuracy of a direct reader of this type is very largely determined by spectroscopic considerations. The objective under these conditions is to make the electronic system such that the errors introduced by it are negligibly small compared with those arising from the spectroscopic technique adopted.

The aim in designing the electronic system of the instrument was to obtain an accuracy of 0·1 per cent. in the measurement of the potential differences developed across the integrating capacitors, and to ensure a standard deviation of less than 0·05 per cent. in the precision of measuring the ratio of two voltages. This has been achieved with the system described.

The variation in the photo-multiplier sensitivities, and the slight non-linearity in the integration due to the fall in the photo-multiplier collector potential during the charging period, have all been kept within limits which allow intensity ratios of spectral line derived from a stabilized mercury discharge lamp to be measured with a precision such that the standard deviation is not more than 0·3 per cent. It should, perhaps, be mentioned that much of the variation in this measurement is due to the variation in the spectral line intensities themselves. The calibration curves for percentage composition versus count then take into account any non-linearity which may be present in any small degree.

17. Acknowledgments

The author wishes to thank Dr. A. C. Menzies, Director of Research, Hilger & Watts, Ltd., for permission to publish this paper and acknowledge very gratefully the help of his colleagues, Mr. K. P. Rippon, Mr. D. S. Larner, Mr. P. V. Jermy and Mr. S. C. Collins, who have played such a large part in all aspects of the designing and construction of the electronic system of the Polychromator. An equipment of this nature, involving spectroscopic, optical and electronic techniques, required the closest team work in all aspects and the acknowledgment would be incomplete without mention of the co-operation of Mr. J. S. Skinner and Mr. D. J. Webb on the optical and spectroscopic side. Special mention, too, should be made of the help at all times of Mr. M. Milbourne of Imperial Chemical Industries, Ltd.

Fuller papers on special aspects of the equipment by the staffs of Hilger & Watts, Ltd., and of I.C.I., Ltd., will be published elsewhere.

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