Dielectric Measurement of Liquids at Microwave Frequencies

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pletely exchanged. This is in line with the results for other paraffins, and proves that methane is formed via methyl radicals. The "unreacted" neo-pentane is not appreciably exchanged, and hence recombination of radicals to reform neo-pentane does not occur.

The other products, and particularly the C_2 fraction, are only slightly exchanged. Ethane cannot, therefore, have arisen via CH_3, or C_2H_5, i.e., by the reactions

$$2CH_3 \rightarrow C_2H_6,$$

or

$$C_2H_5 + H \rightarrow C_2H_6.$$

The only reasonable alternative appears to be that it arises in one step from a reaction of neo-pentane or neo-pentyl. The most likely reaction of this type appears to be

$$H + C_5H_{11} \rightarrow C_5H_{12}^*,$$
$$C_5H_{12}^* \rightarrow C_2H_6 + \text{other products}.$$

Offhand this appears to violate the ideas of Rice and Teller.[11] However, it seems to us that there is a very distinct difference between the postulation of reactions of the type

$$H + C_5H_{12} \rightarrow C_2H_6 + \text{etc.},$$

which are definitely contrary to the Principle of Least Motion, and of

$$H + C_5H_{11} \rightarrow C_5H_{12}^* \rightarrow C_2H_6 + \text{etc.}$$

In the latter case an excited molecule is formed which may be expected to have a relatively long life. It is therefore similar to an ordinary neo-pentane molecule which has been activated thermally and can undergo decomposition by a molecular rearrangement in the ordinary way.

The authors wish to express their indebtedness to Dr. B. deB. Darwent for many suggestions and discussions.

[11] F. O. Rice and E. Teller, J. Chem. Phys. 6, 489 (1938).

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Dielectric Measurement of Liquids at Microwave Frequencies*

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A method of measuring the dielectric properties of medium and high loss liquids at microwave frequencies is described. In this method the liquid sample is placed in an open circuit-terminated section of wave-guide and standing wave-ratios are measured at intervals as the length of the dielectric liquid column in the wave guide is changed. The method of measuring the wave-length of the radiation in the liquid-filled wave guide is indicated. A simple procedure for calculating the dielectric properties from these measurements is presented. Some dielectric properties of liquids measured with this method at 3-cm wave-length are given.

I. INTRODUCTION

DIELECTRIC measurements have been made for more than half a century by investigators who were either interested in studying molecular structure or appraising materials to be used in electric installations. No single method of measuring the dielectric constant and power factor of a substance has been found that could be applied at all frequencies, so it is necessary to employ different methods if one wishes to investigate the dielectric properties of a material over all available frequency ranges. Moreover, at a single frequency it is sometimes necessary to employ different methods, determined by the power factor of the material being investigated, so that the methods that have been and are being employed for dielectric measurements, are numerous indeed. At certain frequencies there are

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materials which can be measured very easily while at other frequencies the measurements become more difficult. Since, in this sense, there are limitations to all methods, any method must be considered in regard to the region over which it is particularly applicable. The experimental work described here has been limited to an investigation of medium loss liquids, although the theory is applicable to any liquid dielectric.

Drude[1] was one of the pioneers in systematic dielectric measurements. He proposed two methods: (1) the measurement of the wavelength of radiation directly in the dielectric medium surrounding a resonant section of a pair of lecher wires and (2) the measurement of the capacitance of a condenser attached to the lecher wires and containing the material as a dielectric. Investigators have employed Drude's first method[2] as well as his second method[3] up until the present day. The method described here is, in some respects, analagous to Drude's first method.

As techniques to operate at higher frequencies have become available, dielectric measurements on solids and liquids have followed, so that in recent years coaxial transmission lines and wave guides have been used.[4] Resonant cavity methods[5] at microwave frequencies probably have been used more extensively elsewhere than in this country. Certain investigators[6] have been concerned with absorption measurements alone. Optical methods[7] have also been employed at microwave frequencies.

More specific to wave-guide measurements on liquids, a method has been described employing a fixed length of liquid followed by an air-filled wave guide terminated by a movable plunger.[8] A coaxial line method has been employed by Adabie[9] in which the length of a liquid column is varied. Measurements, using a wave-guide method in which the length of a liquid column is varied, have been made by a group at Princeton University. This method was described in ONR reports under Contract N6ori-105, Task Order IV.

The references chosen are representative methods of dielectric measurements and are by no means complete. Additional methods and techniques have been described in the literature.

II. THEORY

We are here concerned with the application of transmission line theory and electromagnetic theory in order to determine the dielectric properties of a liquid. Appropriate application of transmission line equations to wave guides enables one to determine the propagation constant of radiation in a dielectric, and from this an application of Maxwell's equations enables one to calculate ϵ', the real part, and ϵ'', the imaginary part of the dielectric constant.

A. Calculating ϵ'' for Medium Loss Liquids

When radiation passes down a uniform wave guide and strikes a dielectric specimen, reflections will occur which produce a standing-wave pattern in the wave guide. One can analyze this standing-wave pattern either on the basis of

[1] Paul Drude, Ann. Physik und Chemie **55**, 633 (1895); *ibid.* **61**, 466 (1897); Zeits. f. physik. Chemie **23**, 267 (1897).

[2] J. Malsch, Ann. d. Physik **12**, 865 (1932); *ibid.* **19**, 707 (1934); *ibid.* **20**, 33 (1934); R. King, Rev. Sci. Inst. **8**, 201 (1937).

[3] J. W. Miller and B. Salzberg, R.C.A. Review **3**, 486 (1938); W. Hemple, E. N. T. **14**, 33 (1937); C. Klazer, Physik. Zeits. **43**, 151 (1942).

[4] H. R. L. Lamont, Phil. Mag. **7–29**, 521 (1940); *ibid.* **7–30**, 1 (1940). A. von Hippel, D. G. Jelatis, and W. B. Westphal, "The measurement of dielectric constand and loss with standing waves in coaxial wave guides," Laboratory of Insulation Research, Massachusetts Institute of Technology, Cambridge, Massachusetts, National Defense Research Committee Contract OEMsr-191, PB-4656 (1943). W. P. Conner and C. P. Smyth, J. Am. Chem. Soc. **65**, 383 (1943); C. R. England, Bell Sys. Tech. J. **23**, 114 (1944); W. B. Westphal, "Techniques and calculations used in dielectric measurements on shorted lines," Laboratory of Insulation Research, Massachusetts Institute of Technology, NDRC Contract OEMsr-191, Report IX (August 1945). W. B. Westphal and M. G. Haugen, "The design of equipment for measurement of dielectric constant and loss with standing waves in wave guides," Laboratory of Insulation Research, Massachusetts Institute of Technology, NDRC Contract OEMsr-191, Report XII (October 1945). S. Roberts and A. von Hippel, J. App. Phys. **17**, 610 (1946); T. W. Dakin and C. N. Works, J. App. Phys. **18**, 789 (1947); W. Jackson, Trans. Faraday Soc. **42A**, 91–101 (1906).

[5] D. L. Hollaway, J. Inst. Eng. Aust. **21**, 79 (1940); C. N. Works, T. W. Dakin, and F. W. Boggs, Trans. A.I.E.E. **63**, 1092 (1944); W. R. MacLean, J. App. Phys. **17**, 558 (1946); W. Jackson and J. G. Powles, Trans. Faraday Soc. **42A**, 101–108 (1946); C. H. Collie, D. M. Ritson, and J. B. Hasted, Trans. Faraday Soc. **42A**, 129–136 (1946).

[6] D. H. Whiffen and H. W. Thompson, Trans. Faraday Soc. **42A**, 114–129 (1946).

[7] M. Velasco and G. L. Hutchinson, Proc. Phys. Soc. London **51**, 689 (1939).

[8] H. A. Hall, I. G. Halliday, W. A. Johnson, and S. Walker, Trans. Faraday Soc. **42A**, 136–143 (1946).

[9] P. Adabie, Trans. Faraday Soc. **42A**, 143–149 (1946).

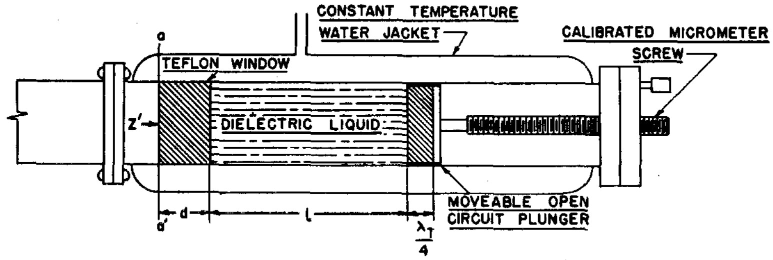

FIG. 1. Liquid cell.

the multiple reflections which occur at the dielectric interfaces or (as has been shown by many authors[10]) on the basis of an incident, a reflected and a transmitted wave. If the cross section of the wave guide changes, radiation is attenuated in a non-uniform manner along the guide. In such a case the transmission line concept is no longer applicable for it is only in the case of a uniform wave guide that the boundary conditions are satisfied with an incident, reflected, and transmitted wave. We shall here consider only the $TE_{0,1}$ mode of propagation.

That part of the wave guide containing the dielectric is shown in Fig. 1.

The impedance Z' at aa' (Fig. 1) due to a length (d) of solid dielectric and a length (l) of liquid dielectric terminated by an open circuit plunger is given by the following expression:

$$Z'=Z_T\left[\frac{Z_T \sinh\gamma_T d+Z_l \cosh\gamma_T d}{Z_T \cosh\gamma_T d+Z_l \sinh\gamma_T d}\right] \tag{1}$$

where γ_T is the propagation constant of the polytetrafluorethylene-filled wave guide, Z_T is the intrinsic impedance of the wave guide filled with the teflon, and

$$Z_l=Z\left[\frac{Z \sinh\gamma l+Z_R \cosh\gamma l}{Z \cosh\gamma l+Z_R \sinh\gamma l}\right], \tag{2}$$

where γ is the propagation constant of the liquid dielectric-filled wave guide, Z is the intrinsic impedance of the liquid-filled wave guide, and l is the length of the liquid column in cm. Z_R is the impedance at the face of the movable plunger.

The voltage reflection coefficient Γ is related to the impedances in the following manner:

$$\Gamma=\frac{Z'-Z_0}{Z'+Z_0}. \tag{3}$$

Z_0 is the intrinsic impedance of the air-filled wave guide. Also

$$\rho=\frac{1+|\Gamma|}{1-|\Gamma|}, \tag{4}$$

where ρ is the voltage standing-wave ratio actually observed in the air-filled wave guide.

Unless certain conditions are imposed upon γ_T, d, and Z_R the solution of (2) for γ in terms of the measured quantities is too difficult to be practical. It is, therefore, necessary to make certain assumptions regarding γ_T, d, and Z_R and design the liquid cell to validate these assumptions. We shall proceed by assuming we have completely fulfilled these assumptions, in discussing the measurement of ϵ' and ϵ''. This is justified since measured losses in the teflon window, the wave guide, and the terminating plunger are negligible compared to those in medium loss liquid. The terminating plunger is so constructed that Z_R is very large. (A detailed discussion of this construction will be given later.)

If we choose d = one-half a wave-length in the teflon-filled wave guide and assume $\alpha_T\rightarrow 0$ it is seen $\sinh\gamma_T d\rightarrow 0$. α_T is the attenuation constant in nepers per cm in a teflon-filled wave guide. Actually, if we let (d) become very small, $\sinh\gamma_T d$ would approach zero. However, for mechanical reasons of obtaining a liquid tight joint, (d) equal to half a wave-length in the dielectric-filled guide is preferable. The requirement that $\alpha_T\rightarrow 0$ as well as the requirement that the window should be made of a chemically inert material prompted the choice of teflon. This material has a very

[10] J. C. Slater, *Microwave Transmission* (McGraw-Hill Book Company, Inc., New York, 1942). S. Ramo and J. R. Whinnery, *Fields and Waves in Modern Radio* (John Wiley and Sons, Inc., New York, 1946).

small loss factor and is chemically and mechanically satisfactory for our purpose.

Equation (1) thus reduces to:

$$Z'=Z_l=Z\left[\frac{Z\sinh\gamma l+Z_R\cosh\gamma l}{Z\cosh\gamma l+Z_R\sinh\gamma l}\right]. \quad (5)$$

If, as we have assumed, $Z_R\rightarrow\infty$:

$$Z_l=Z\left[\frac{1+e^{-2\gamma l}}{1-e^{-2\gamma l}}\right].$$

To examine the way the above equation varies with (l) we may rewrite it in the form

$$Z_l=Z\left[\frac{1+e^{-2\alpha l}(\cos 2\beta l-j\sin 2\beta l)}{1-e^{-2\alpha l}(\cos 2\beta l-j\sin 2\beta l)}\right], \quad (6)$$

where α is the attenuation constant in nepers per cm in the liquid-filled wave guide, β is the phase constant in radians per cm in the liquid-filled wave guide.

If now we assume $l=\lambda_d/4$, $l=3\lambda_d/4$, $l=5\lambda_d/4$, (where λ_d is the wave-length of the radiation in the dielectric-filled wave guide) we can plot $|Z_l/Z|$ as ordinate *versus* $\alpha\lambda_d$ for various values of (l). In this manner the curves in Fig. 2 are obtained.

Referring to Eq. (4) it is seen that

$$\rho=\frac{1+\left|\dfrac{Z_l-Z_0}{Z_l+Z_0}\right|}{1-\left|\dfrac{Z_l-Z_0}{Z_l+Z_0}\right|}=\left|\frac{Z_l}{Z_0}\right|(1+\text{correction factor}). \quad (7)$$

Alternatively, if $|Z_l|<|Z_0|$, the standing-wave ratio is given by $|Z_0/Z_l|(1+\text{corr. f.})$. The latter is the correct expression in this case because we shall consider quarter wave-length sections of the open circuit, liquid-filled wave guide. The same equations also apply if one considers half wave-length sections of short-circuited wave guide, for in this case $|Z_l|<|Z_0|$.

Even though it is possible to examine the variation in the standing-wave ratios with length, for columns of liquid which are multiples of a half wave-length when the open circuit plunger is used, the relation which one obtains between the standing-wave ratios, will in some cases be rather complicated. For liquids with certain loss factors this ratio may even exhibit a minimum.[11]

Referring to Eq. (7) the correction factor is due to the fact that there is an angle in the complex plane between 1 and the quantity $(Z_l-Z_0)/(Z_l+Z_0)$. That is to say, the intrinsic

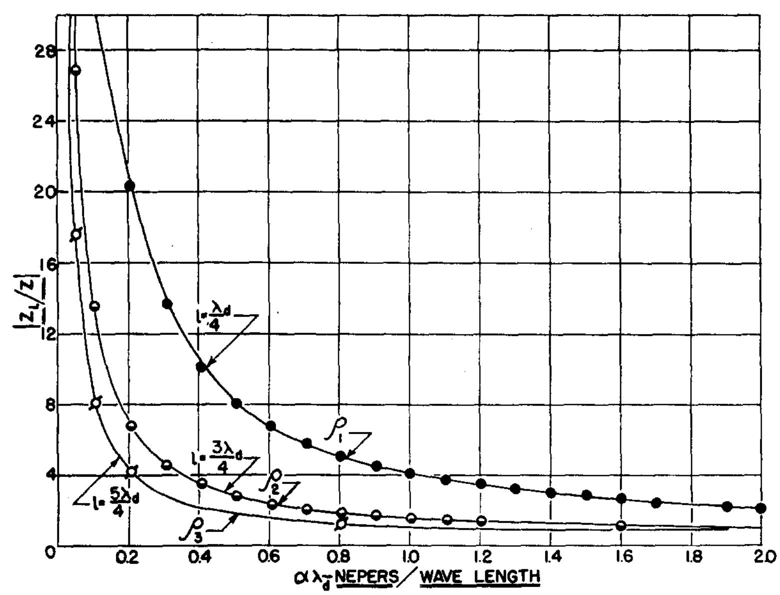

FIG. 2. Per unit impedance of a dielectric-filled wave guide *versus* dielectric attenuation in nepers per wave-length.

[11] W. H. Surber, Jr., "Methods of measurement of dielectric constant and loss factor for liquids at microwave frequencies," Office of Naval Research Contract N6ori-105, Task Order IV, Technical Report No. 1, (March, 1947). To be published in J. App. Phys. 19, (June, 1948).

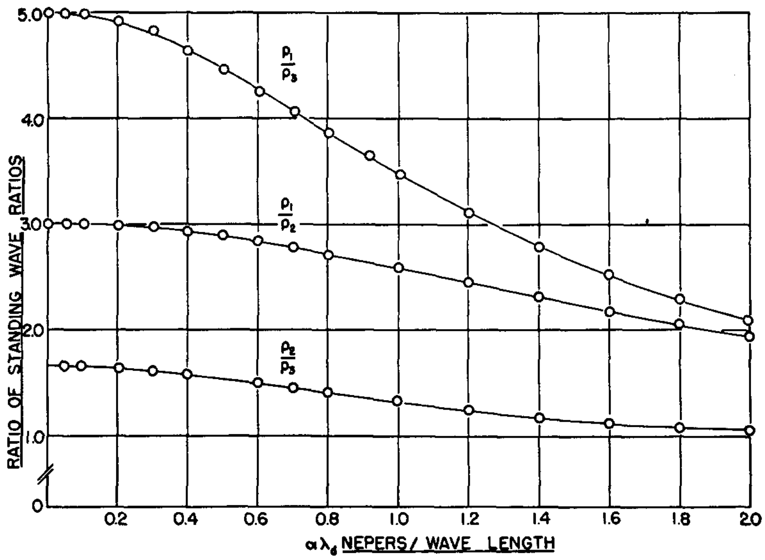

FIG. 3. Ratio of wave-guide standing wave-ratios *versus* dielectric attenuation.

impedance of the dielectric-filled guide is complex. However, the factor may be neglected in the calculations, as will be demonstrated.

$$1+\left|\frac{Z_l-Z_0}{Z_l+Z_0}\right|=1+\left|\frac{CZ_d-1}{CZ_d+1}\right|.$$

This is true because for the particular values of l with which we are here concerned $Z_l=CZ_d$ where C is a constant. $Z_d=Z/Z_0$ is defined as the per unit intrinsic impedance of the dielectric-filled wave guide. The error introduced in the standing-wave ratio as given by Eq. (7) is larger than the actual error introduced in the calculations since the errors tend to cancel when the ratios of the standing-wave ratios are taken.

From Eq. (7)

$$\rho_1=Z_0/Zl_1(1+C_1),$$

where C_1 is the required correction factor.

$$\rho_2=Z_0/Zl_2(1+C_2),$$

where C_2 is the required correction factor.

Here the subscript (1) refers to $l=\lambda_d/4$, (2) refers to $l=3\lambda_d/4$. But $Zl_1=Z\coth\gamma\lambda_d/4$, etc.

$$\therefore\quad \rho_1=\left|\frac{Z_0}{Z\coth\gamma\lambda_d/4}\right|(1+C_1) \tag{8}$$

also

$$\coth\gamma\frac{\lambda_d}{4}=\tanh\alpha\frac{\lambda_d}{4},$$

since

$$\frac{\gamma\lambda_d}{4}=\frac{\alpha\lambda_d}{4}+\frac{j\beta\lambda_d}{4}.$$

$$\therefore\quad \frac{\rho_1}{\rho_2}=\left|\frac{\coth\alpha\lambda_d/4}{\coth 3\alpha\lambda_d/4}\right|(1+C_3) \tag{9}$$

where

$$C_3=\frac{-2|Z_d|^2(\tanh^2 3\alpha\lambda_d/4-\tanh^2\alpha\lambda_d/4)}{(1-|Z_1|^2)(1-|Z_2|^2)}\cdot F^{12} \tag{10}$$

$$F=1-\left[\tfrac{1}{2}\left(1+\frac{1}{(1+D^2)^{\frac{1}{2}}}\right)\right]^{\frac{1}{2}},$$

$$D=\frac{\epsilon''}{\epsilon'-(\lambda_0/\lambda_C)^2}.$$

λ_0 is the free space radiation wave-length; λ_C is the cut off radiation wave-length.

$$|Z_1|=|Z_d|\tanh\alpha\lambda_d/4;\quad |Z_2|=|Z_d|\tanh 3\alpha\lambda_d/4.$$

The correction factor C_3 (Eq. 10) increases as ϵ'' increases or as ϵ' decreases. In most cases it amounts to only a fraction of a percent and may be considered negligible. Similarly, an expression for ρ_1/ρ_3, ρ_2/ρ_3, etc. may be written.

In Fig. 3 ρ_1/ρ_2, ρ_2/ρ_3, ρ_1/ρ_3 are plotted for various values of $\alpha\lambda_d$. The curves may be in-

[12] W. H. Surber, Jr., "Universal curves for wave guides containing a lossy dielectric medium and applications to dielectric measurements," ONR Contract N6ori-105 Task Order IV, Technical Report No. 2, (August, 1947).

terpreted, neglecting the correction factor, as the ratios of ordinates for a given value of attenuation shown in Fig. 2. Correspondingly, ρ_1/ρ_∞, ρ_2/ρ_∞ and ρ_3/ρ_∞ may be interpreted as the $(l=\lambda_d/4)(l=3\lambda_d/4)(l=5\lambda_d/4)$ curve in Fig. 2. ρ_∞ is the standing-wave ratio observed in the wave guide when $l\rightarrow\infty$. That is to say the length of the liquid column is sufficiently long so that motion of the plunger has no effect on the standing-wave ratio. $\alpha\lambda_d$ is determined from the curves of ρ_1/ρ_3 or ρ_1/ρ_∞, etc. λ_d is obtained from measurements of successive minima in the liquid-filled wave guide. Hence, ϵ'' is calculated from the equation

$$\epsilon''=(1/\pi)(\lambda_0/\lambda_d)^2\alpha\lambda_d.^{**} \tag{11}$$

B. Calculating ϵ' for Medium Loss Liquids

The procedure for calculating ϵ' is to measure λ_d, introduce correct values of ϵ'' as determined previously, and solve Eq. (12) for ϵ'.

$$\epsilon''^2\pi^2\lambda_d^2/\lambda_0^4=(2\pi/\lambda_d)^2+(2\pi/\lambda_c)^2-\epsilon'(2\pi/\lambda_0)^2.^{**} \tag{12}$$

III. MEASURING λ_d

Since the dielectric-filled section of wave guide is in most cases somewhat lossy and in some cases quite lossy, λ_d cannot be measured by means of the slotted wave guide unless corrections are introduced. If the probe is situated at a voltage maximum for $l=\lambda_d/4$ and the plunger is moved until the probe is again situated at a voltage maximum, the distance the plunger has moved will not be equal to $\lambda_d/2$ unless the liquid cell is filled with a lossless dielectric. Because the phase angle of the reflection coefficient varies with the length of the dielectric column, in general, it is necessary to introduce a correction to the quantity which is measured to be $\lambda_d/2$, as will be seen in the next section. However, alternatively it is possible to introduce a directional coupler and observe directly the distance $\lambda_d/2$ the plunger is moved between successive maxima as indicated in the usual way by means of a directional coupler. This is possible because the distance the plunger is moved in order for the absolute magnitude of the reflection coefficient to go through successive maxima is very nearly $\lambda_d/2$ even for medium loss dielectrics.

The voltage reflection coefficient (Γ) at the position aa' for $l=\lambda_d/4$ in Fig. 1 is given by the following expression:

$$\Gamma_1=(1+Pe^{-\alpha\lambda_d/4})/(P+e^{-\alpha\lambda_d/4}), \tag{13}$$

where

$$P=(Z_d+1)/(Z_d-1).$$

Z_d is the per unit impedance of the section of dielectric-filled wave guide. For $l=3\lambda_d/4$ at aa'

$$\Gamma_2=(1+Pe^{-3\alpha\lambda_d/4})/(P+e^{-3\alpha\lambda_d/4}). \tag{14}$$

From expressions (13) and (14) it is seen that for a lossless dielectric the reflection coefficients Γ_1 and Γ_2 have the same phase angle. However, if there are any losses it is seen that this is no longer true. This is to say that if a probe is situated at a voltage maximum for $l=\lambda_d/4$ and the length of the dielectric liquid column is adjusted until the probe is again situated at a voltage maximum, the length by which the dielectric column has been increased will not be $\lambda_d/2$. The actual voltage maximum corresponding to $l=3\lambda_d/4$ has been shifted relative to that corresponding to $l=\lambda_d/4$, half the number of degrees that the reflection coefficient has changed. This shift may be of the order of magnitude of 15 or 20 degrees. For instance, assuming an ϵ' of 4.0 and an $\epsilon''=3.0$ the shift amounts to approximately 14 degrees in this particular set-up.

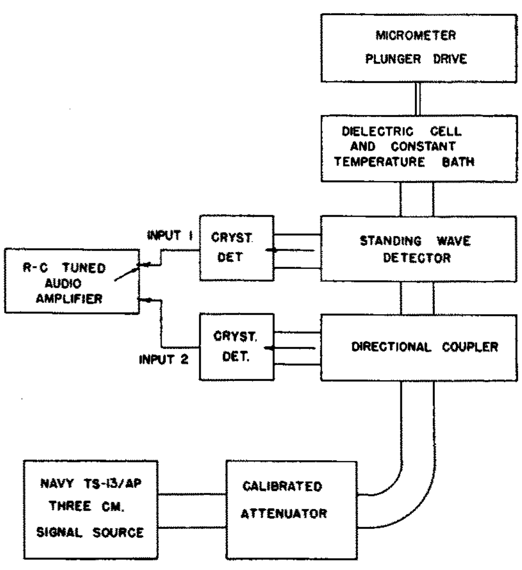

FIG. 4. Experimental apparatus.

** Equations (11) and (12) are familiar equations obtained from the propagation constant of a dielectric-filled wave guide.

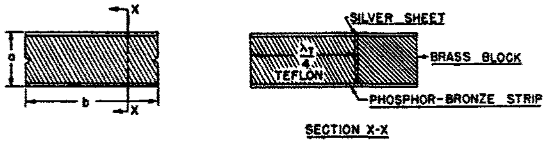

FIG. 5. The terminating plunger.

(It is possible to use an approximate value of ϵ' and ϵ'', assuming no shift in the voltage maximum, and then calculate the change in the reflection coefficient. From the phase difference in the reflection coefficient a corrected value of $\lambda_d/2$ may be obtained. However, the algebra involved is such that it is simpler to measure $\lambda_d/2$ directly by means of a directional coupler.)

The region of applicability of the standing-wave detector for measuring λ_d is for low loss dielectrics in which $\tan\delta$ is approximately 0.05 or smaller while the directional coupler is useful in the region for which $\tan\delta$ varies from approximately 0.05 to approximately 0.50. For extremely high loss liquids it becomes more difficult to measure λ_d, even using a directional coupler, because the maxima and minima become less well defined. Finally, in the case of liquids which are electrolytes, it becomes exceedingly difficult to determine ϵ' because it is so masked by an extremely large ϵ''. Such is the case of metals.

In any case, whether one uses a directional coupler or a standing-wave detector, ϵ'' is calculated from the ratio of the standing-wave ratios as previously discussed. In the case of low loss liquids, corrections for wave-guide, plunger, and junction losses must be introduced.

IV. EXPERIMENTAL APPARATUS

The physical arrangement of the apparatus is shown in Fig. 4.

The apparatus consists of standard components with the exception of the liquid cell and the terminating plunger. As shown in Fig. 1, the liquid cell is constructed from a 3-cm wave guide which is terminated at one end by a teflon window and at the other end by a movable open circuit plunger.

The requirements for the teflon window are (1) that it should be a half wave-length long and fit the wave guide so as to obtain a liquid-tight contact, and (2) that it should be a very low loss material so that the impedance looking in at the window is very nearly the same as that looking in at the liquid surface.

The essential requirement for the plunger is that it present an open circuit termination for the liquid dielectric and should therefore introduce as little loss as possible.

Diagrammatic cross sections of the terminating plunger are shown in Fig. 5. A brass block of any length that is convenient, for it only serves as a physical support around which to build the plunger, is attached to a silver sheet. A teflon block is placed next to the sheet of silver so that the very low impedance at the surface of the silver will appear as a very high impedance at the face of the plunger; which is a quarter wave-length away as measured in the teflon dielectric. Phosphor-bronzes trips are placed, as shown, so that a good electrical contact between the plunger and the wave-guide walls may be maintained at the face of the plunger. Here the impedance is a maximum, and hence the losses resulting from the contact of the strips and the wave guide are a minimum. Phosphor-bronze strips are only necessary on the sides of the plunger perpendicular to the electric field as there are no currents flowing between the plunger and the narrow wave-guide walls. A bottom view of the plunger is also shown. The small notches in the sides are to allow the liquid to flow by as the plunger is moved.

V. PROCEDURE

The liquid cell shown in Fig. 4 is removed and a shorting plate is placed at the end of the standing-wave detector. The probe is located on a voltage minimum. The cell containing the liquid to be measured is then replaced. The plunger is moved until contact is made with the teflon window. As the plunger is withdrawn from the window the length of the liquid column increases. For a certain length of liquid column a minimum will appear as observed by the directional coupler. The position of the plunger is recorded and the standing-wave ratio is determined. Again the length of the liquid column is increased until another minimum is observed. The position of the plunger and the standing-wave ratio are again recorded. The plunger is moved repeatedly until perhaps three or four minima have been observed.

The difference between the positions of the plunger for successive minima represents half a wave-length of the radiation in the liquid. Having thus determined the wave-length of the radiation in the liquid, it is immediately possible to determine ϵ' if the liquid is very low loss. However, for medium loss liquids it is first necessary to determine ϵ'' before proceeding with the determination of ϵ'.

In order to determine ϵ'' it is necessary to consider ρ_1, ρ_2, ρ_3, ρ_∞, etc. From Fig. 2 or Fig. 3 it is possible to determine $\alpha\lambda_d$ corresponding to ρ_1/ρ_∞, ρ_1/ρ_3, etc., for if readings of the standing-wave ratios are correctly taken, then the ratios of the standing-wave ratios will lie on a vertical line which will intersect the abscissae at the value of $\alpha\lambda_d$ characteristic of the liquid being tested. It is possible to algebraically determine $\alpha\lambda_d$ but the curves shown in Fig. 2 and Fig. 3 considerably facilitate the calculations. In passing it might be pointed out that it is not possible for a given value of $\alpha\lambda_d$ to uniquely determine ρ_1, ρ_2, ρ_3; however, for given values of ρ_1, ρ_2, ρ_3 it is possible to determine uniquely $\alpha\lambda_d$.

The essential difference between measurements of low loss liquids and medium or high loss liquids is in the method of measuring λ_d. In the case of low loss liquids in which the difference in the phase angle of the reflection coefficients for $l=\lambda_d/4$, $l=3\lambda_d/4$, etc. is very small, λ_d may be measured with sufficient accuracy by moving the terminating plunger and observing successive minima by the standing-wave detector. In the case of medium loss liquids, however, the distance the plunger is moved is recorded when successive minima are observed by means of the directional coupler. (Care must be taken to place the probe on a minimum, when determining λ_d with the direction coupler, so that reflections from the probe do not give false minima.) The standing-wave ratios are determined in the usual way by means of the calibrated attenuator. The calculations follow identically as given, that is, it is necessary to first calculate ϵ'' and introduce ϵ'' in Eq. (12) before calculating ϵ'.

VI. SUMMARY

The procedure is as follows:

1. Calculate ϵ'' from measurements of standing-wave ratios alone.
2. Calculate ϵ' from measurements of λ_d and the previously determined value of ϵ''.

Using standard radar test equipment, it is not difficult to measure the dielectric properties of medium loss liquids quite satisfactorily at 3 cm. The data in Table I are given as typical results obtained by the method of measuring dielectric liquids described here. The compounds measured were obtained through the usual commercial channels and were not especially purified. Measurements were made at a temperature of 25°C.

TABLE I.

Liquid	ϵ'	$\tan\delta$
Chlorobenzene	4.83	0.34
n-butyl bromide	5.55	0.36
n-butyl alcohol	3.04	0.21
Bromobenzene	4.90	0.44
Ethyl bromide	8.32	0.14

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