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Technical Report ARAED-TR-92023

MICROWAVE ABSORPTION MEASUREMENTS AND INTERFERENCE EFFECTS FOR A LIQUID FUEL BETWEEN 2.5 and 18 GHz

D. A. Wiegand
ARDEC

F. Murray
General Dynamics, Pomona Division
Pomona, CA

February 1993

U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Armament Engineering Directorate

Picatinny Arsenal, New Jersey

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operation and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Feb 1993	

4. TITLE AND SUBTITLE

MICROWAVE ABSORPTION MEASUREMENTS AND INTERFERENCE EFFECTS FOR A LIQUID FUEL BETWEEN 2.5 AND 18 GHz

5. FUNDING NUMB

6. AUTHOR(S)

Donald A. Wiegand and Frank Murray

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSES(S)

ARDEC, AED
Energetics and Warheads Div
(SMCAR-AEE-WW)
Picatinny Arsenal, NJ 07806-5000

General Dynamics
Pomona Division
P.O. Box 2507
Pomona, CA 91769-2507

8. PERFORMING ORGANIZATION REPORT NUMBER

Technical Report
ARAED-TR-92023

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(S)

ARDEC, IMD
STINFO Branch (SMCAR-IMI-I)
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The incident, reflected and transmitted powers were measured and the reflection and transmission coefficients calculated for a liquid fuel. Two sizes of double-ridge waveguide were used to cover the frequency ranges 2.5 to 7.5 and 7.5 to 18 GHz and corrections were made for waveguide losses. Strong interference effects were observed and the real part of the dielectric constant was obtained primarily from the separation of interference maxima and minima. The loss tangent was obtained by curve fitting to the normalized power loss, and the absorption coefficient was calculated as a function of frequency from the dielectric data.

14. SUBJECT TERMS

Microwave, Reflection coefficient, Transmission coefficient, Absorption coefficient, Dielectric constant, dielectric loss, Loss tangent, Real part of dielectric constant, Imaginary part of dielectric constant, Complex dielectric constant.

15. NUMBER OF PAGES 19

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

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BACKGROUND

The objective of this work was to survey a number of liquid fuels and hazardous materials (explosives, propellants, and pyrotechnics) to determine if there is significant absorption over a reasonably wide region of the microwave spectrum. The emphasis was placed on obtaining a measure of the absorption coefficients as a function of frequency and not on high accuracy or precision. The results for one liquid fuel are presented here. The procedure was to determine the in-waveguide reflection and transmission coefficients as a function of frequency from the measured incident, reflected, and transmitted powers after correction for waveguide and other losses. The complex dielectric constant was obtained from these coefficients and the absorption coefficient calculated.

Measurements were made over the frequency range 2.5 to 18 GHz by the use of two sizes of double-ridge waveguide to cover the ranges 2.5 to 7.5 and 7.5 to 18 GHz. Step scanning at 0.1 and 0.25 GHz intervals was used for the low frequency range and the high frequency range respectively, and the incident, reflected, and transmitted powers were recorded at each frequency. A complete description of the apparatus is given elsewhere (refs 1 and 2). The sample cell consisted of a verticle waveguide section 30.45 cm (12 in.) in length bounded on the bottom by a thin (0.0076 cm) mylar support window for the liquid fuel. The top of the cell was connected to the microwave source by means of a bidirectional coupler for measurements of the incident and reflected powers, P_i and P_r, while the bottom of the cell was connected to an identical coupler for measurement of the transmitted power, P_t. This coupler was terminated in its characteristic impedance. The thin mylar support window was placed across the waveguide normal to the propagation direction and sandwiched between the waveguide section used for the sample holder and the bidirectional coupler used to measure the transmitted intensity. Therefore, the mylar support window interrupted the continuity of the waveguide. All powers were corrected for waveguide and other losses and calibration differences (refs 1 and 2). By conservation of energy

$$P_i = P_r + P_t + P_{ab} \tag{1}$$

where P_{ab} is the power absorbed at the sample and cell. By division of equation (1) by P_i

$$1 = R + T + A \tag{2}$$

where $R = P_r/P_i$ and $T = P_t/P_i$ are the power reflection and transmission coefficients and

$$A = P_{ab}/P_i = 1 - (R + T) \tag{3}$$

is the normalized absorbed power.

Expressions for the power refelction and transmission coefficents, R and T, for normal incidence on a plane parallel slab of dielectric in air in a waveguide were derived using the techniques given by Ramo and Whitnnery (ref 3). These are

$$R = r_{12}^2[e^{2\alpha d}+e^{-2\alpha d}-2\mathrm{Cos}(2\beta d)] / [e^{2\alpha d}+r_{12}^4 e^{-2\alpha d}-2r_{12}^2\mathrm{Cos}(2\phi_{12}-2\beta d)] \tag{4}$$

and

$$T = t_{12}^2 t_{21}^2 / [e^{2\alpha d}+r_{12}^4 e^{-2\alpha d}-2r_{12}^2\mathrm{Cos}(2\phi_{12}-2\beta d)] \tag{5}$$

where d is the dielectric slab thickness in the direction of propagation and

$$\rho_{12} = r_{12}e^{j\phi_{12}} = (Z_2-Z_1) / (Z_2+Z_1) \tag{6}$$

$$\tau_{12} = t_{12}e^{j\varphi_{12}} = 2Z_2 / (Z_2+Z_1) \tag{7}$$

$$\tau_{21} = t_{21}e^{j\varphi_{12}} = 2Z_1 / (Z_2+Z_1) \tag{8}$$

$$\alpha = 2\pi f(\mu_o\varepsilon_o\varepsilon'/2)^{1/2}\{1-(f_c/f)^2/\varepsilon'\}^{1/2}\{1+[(\varepsilon''/\varepsilon')^2/[1-(f_c/f)^2/\varepsilon']^2]^{1/2}-1\}^{1/2} \tag{9}$$

and

$$\beta = 2\pi/\lambda = 2\pi f(\mu_o\varepsilon_o\varepsilon'/2)^{1/2}\{1-(f_c/f)^2/\varepsilon'\}^{1/2}\{1+[(\varepsilon''/\varepsilon')^2/[1-(f_c/f)^2]^2/\varepsilon']^{1/2}+1\}^{1/2} \tag{10}$$

ε' and ε'' are the real and imaginary parts of the complex dielectric constant; μ_o and ε_o are the permeability and permittivity of vacuum (air); f_c is the waveguide cutoff frequency in air; and λ is the wavelength in the waveguide in the dielectric (ref 3). Equations 4 and 5 are valid when the waveguide section after the sample (bidirectional coupler) is terminated in its characteristic impedance so that there is no reflected wave in this section. Z_1 amd Z_2 are the in-waveguide impedances of vacuum (air) and the dielectric, respectively, and are given by

$$Z_1 = (\mu_o/\varepsilon_o\,[1-(f_c/f)^2])^{1/2} \tag{11}$$

$$Z_2 = (\mu_o/\varepsilon_o\varepsilon'[1-j\varepsilon''/\varepsilon']\,[1-(f_c/f)^2/\varepsilon'])^{1/2} \tag{12}$$

ρ_{12} and τ_{12} are the field reflection and transmission coefficients for normal incidence on the dielectric slab when conditions are such that there is no reflected wave in the dielectric. τ_{21} is the similar transmission coefficient for a wave in the dielectric incident on air. α and β are the real and imaginary parts of the complex field propagation constant in the dielectric defined by

$$E = E_0 e^{-(\alpha - j\beta)z} \tag{13}$$

where z is the distance in the direction of propagation. α is therefore the field attenuation or absorption coefficient, and β is 2π times the reciprocal wave length (eq 10), both in the dielectric slab. Born and Wolf give relationships similar to equations 4 and 5 for out-of-waveguide conditions (ref 4).

Significant simplifications of the above equations are possible for low-loss materials, i.e., when $\varepsilon''/\varepsilon' \ll 1$. This is the case for the liquid fuel under considerations and the appropriate approximations were made in the calculations of R and T.

RESULTS AND DISCUSSION

Measurements have been made on two liquid fuels, liquid water, eight hazardous materials, and two polymeric materials, but because of space limitations, only the results for one liquid fuel (Diesel 2) are presented here. The results for liquid water and the other materials will be published elsewhere (ref 1).

Measurements were made of P_i, P_r, and P_t for the empty cell and the reflection and transmission coefficients calculated. Typical reflection coefficient results are given in figure 1a for the low frequency range. Similar results were obtained for the high frequency range. The peaks in the reflection coefficient spectra are due to the discontinuity in the waveguide caused by the thin mylar support window. This was verified by measurements for the empty waveguide, i.e., without the mylar and by measurements for plastic samples which were machined to fit snugly into the waveguide and so used without the mylar. Calculations were also made of the reflection coefficients for the mylar alone. These calculations indicate that the reflection coefficient for the thickness of mylar used is negligible over the whole frequency range used for these studies. Peaks of this type were also found in the reflection and transmission spectra for liquid samples in the cell (fig. 1b). No attempt is made here to correct the results for these peaks due to the discontinuity in the waveguide. However, in fitting the calculated reflection and transmission coefficients to the experimental coefficients allowance was made for the effects of the discontinuity.

The experimentally determined reflection coefficient for the fuel Diesel 2 is given as a function of frequency in figure 1b for the low frequency range. Somewhat similar results were obtained for the high frequency range (not shown). The maxima and minima are due to interference effects and the change in wavelength with frequency. The effect of the mylar window and so the discontinuity in the waveguide on the reflection coefficient of the sample can be clearly seen by a comparison of figures 1a and 1b. Large peaks in the reflection coefficient of the sample in the cell occur at approximately the same frequencies as the peaks in the reflection coefficient of the empty cell.

Also shown in figure 1b is the calculated reflection coefficient with ε' and $\varepsilon''/\varepsilon'$ chosen as a function of frequency so that the differences between the calculated and experimental reflection and transmission coefficients are minimized. The mylar window and the discontinuity are not considered in the calculations. However, calculations which were made for the sample and the mylar but without the discontinuity indicate that the mylar alone has neglibible effect on the total reflection coefficient. Measurements were made every 0.1 GHz, and the calculated reflection coefficient of figure 1b is also given for comparison purposes only at every 0.1 GHz at the same frequencies as those used in the measurements.

An examination of figure 1b indicates excellent agreement between the frequencies of the maxima and minima of the experimental and calculated reflection coefficients. In addition, the amplitudes of the experimental and theoretical coefficients are in rather good agreement except at frequencies corresponding to the frequencies of the peaks of the empty cell as given in figure 1a. The initial value of ε' was estimated from the separation of the maxima and minima and was then adjusted as a function of frequency to obtain the best match between the positions of the maxima and minima of the experimental and theoretical reflection coefficients (ref 1)

The transmission coefficient data and calculations are not presented. $\varepsilon''/\varepsilon'$ was determined by using the normalized absorbed power, A, of equation 3. The calculated values of A were adjusted to the experimental values for the sample at selected frequencies by the choice of $\varepsilon''/\varepsilon$ at each frequency. A polynomial was then fitted to the values of $\varepsilon''/\varepsilon'$ versus frequency and used to calculate A as a function of frequency. The final values of ε' and $\varepsilon''/\varepsilon'$ at each frequency were selected to minimize the differences between the experimental and theoretical values of R and A.

ε' was found to decrease with increasing frequency between 2.5 and approximately 8.5 GHz and then to remain constant between 8.5 and 18 GHz within experimental error. $\varepsilon''/\varepsilon'$ was found to decrease with increasing frequency over most of

the frequency range but to plateau at about 15 GHz with indications of an increase with further increases in frequency. These results indicate that there is a relaxation process giving a maximum of absorption at a frequency below the frequency range of measurement and further that there is another relaxation process with an absorption maximum above the frequency range of measurement. The dielectric constant results will be discussed in detail elsewhere (ref 1).

The out-of-waveguide absorption coefficient for Diesel 2 was calculated using equation 9 with $f_c = 0$ and the experimentally determined values of ε' and $\varepsilon''/\varepsilon'$ and is given in figure 2. This coefficient increases with frequency throughout the range of measurement and is small.

SUMMARY

Measurements were made of the in-waveguide incident, reflected and transmitted powers of liquid fuel between 2.5 and 18 GHz, corrections were made for waveguide and other system losses, and reflection and transmission coefficients calculated. The reflection and transmission coefficients indicate strong interference effects. Expressions were obtained for the in-waveguide theoretical reflection and transmission coefficients in terms of the complex dielectric constant, the waveguide cutoff frequency, and the sample thickness. The real part of the dielectric constant was then chosen as a function of frequency so that the maxima and minima of the calculated reflection spectrum matched those of the experimental spectrum and further minimized the differences between the two reflection spectra. The loss tangent was chosen as a function of frequency so as to match the calculated normalized power loss to the experimental values. The out-of-waveguide absorption coefficient was then obtained as a function of frequency from these results. The absorption coefficient is small and increases with frequency.

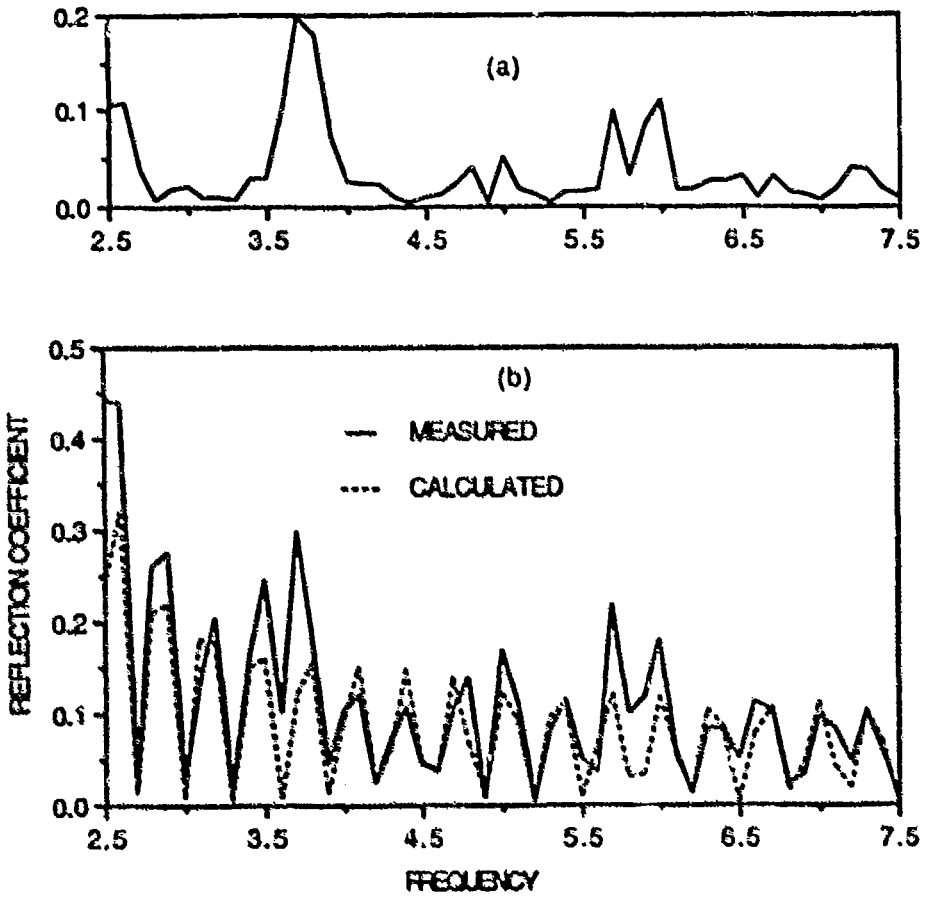

Figure 1. (a) Measured reflection coefficient of the empty sample cell. (b) Measured reflection coefficient of the sample (Diesel 2 fuel) and cell and the calculated reflection coefficient of the sample.

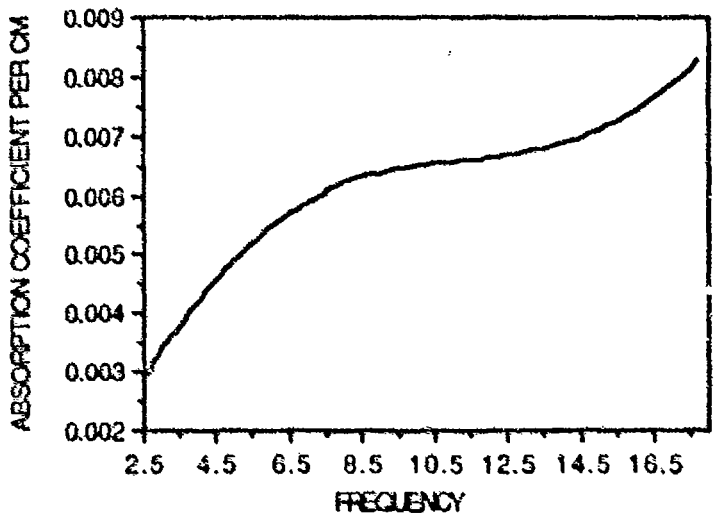

Figure 2. Absorption coefficient versus frequency for Diesel 2 fuel

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