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Measurements of Complex Dielectric Constants of Paints and Primers for DSN Antennas: Part I

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In past years, it was known that paint on reflector surfaces causes degradation of antenna gain and noise temperatures, but it was not known how much degradation occurs as a function of paint and primer thickness or frequency. This article presents an approach used to study the properties of paint by first measuring the complex dielectric constants of paint and primers at frequencies of interest. After the complex dielectric constants become known, theoretical calculations then can be made of degradation of antenna gain and noise temperatures due to paint/primer thicknesses as functions of incident-wave polarization and incidence angles in free space. Tables are presented for measured complex dielectric constants over a frequency range from 24 through 34 GHz for (1) the paint and primer currently being used on DSN antenna main and subreflector surfaces and (2) paint and primer that are candidate replacements.

I. Introduction

In the past, noise temperature degradation due to antenna surface paints was measured radiometrically on thin paint layers[2] [1] or determined through use of a resonant cavity method [2]. It is difficult to extrapolate limited amounts of these types of test data to predict degradation caused by larger paint thicknesses or to predict degradation at other frequencies.

A waveguide technique to determine the dielectric constant of a very thin (0.25-mm) film of paint sample is described in [3]. The real part of the complex relative dielectric constant of the paint sample in WR42 waveguide was measured to be 4.5 at 19.9 GHz. However, the measurement technique did not yield information on the loss tangent needed for determination of noise temperatures.

Another waveguide approach, presented in this article, is to fabricate paint test samples that are several wavelengths thick and measure their S-parameters. Complex dielectric constants of the test samples then can be derived from the measured S-parameters. Once the complex dielectric constants are known, the noise temperatures of paint layers of any thickness can be calculated. In the past, there has been an absence of technical literature on how to fabricate paint test samples that fill a waveguide test section.

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[1] Communications Ground Systems Section.

[2] A. Tanner, "AWVR Paint Test Results," JPL Interoffice Memorandum 3863-98-019 (internal document), Jet Propulsion Laboratory, Pasadena, California, September 25, 1998.

There also has been scarcity of data on the dielectric constants and loss tangents of paints in the microwave region.

The purpose of this article is to fill this need for more information on paints. The following sections of this article describe the paint-sample fabrication methods and the waveguide measurement and data-processing techniques that were employed. Tables are presented for measured complex dielectric constants of (1) the paint and primer currently being used on DSN antenna main and subreflector surfaces and (2) the paint and primer that are candidate replacements.

II. Test-Sample Fabrication Methods

Since paint degradation becomes worse at higher frequencies, a decision was made to perform an experimental paint study in the region of 32 GHz, which is one of the DSN Ka-band frequencies. The appropriate waveguide size for this frequency region is WR28, which has a cross-sectional dimension of 0.71×0.36 cm (0.28×0.14 in.).

Initial attempts at making paint samples for waveguides encountered problems with paint shrinkage and voids inside the paint volume after drying. The following describes fabrication methods for fabricating paint test samples without voids or shrinkage.

Figure 1 shows a photograph of the Teflon WR28 jig used to fabricate paint test samples. The top wall of a Teflon WR28 waveguide is purposely machined off. Teflon end blocks can be slid to accommodate different desired test-sample lengths. The paint test-sample-preparation methodology was to paint a thin layer of paint into the WR28 trough about every 8 to 12 hours. This process of painting was repeated every day until the paint sample was built up to the full desired height of 0.36 cm (0.14 in.). The full-height test sample then was slid out of the Teflon jig and cleaned with acetone. After cleaning, the test sample was coated on all sides with fresh paint and slid into an empty WR28 waveguide test section. After a final drying period, the test-sample ends were lapped to be flush with the waveguide flange faces. This method of test-sample preparation took about 3 weeks.

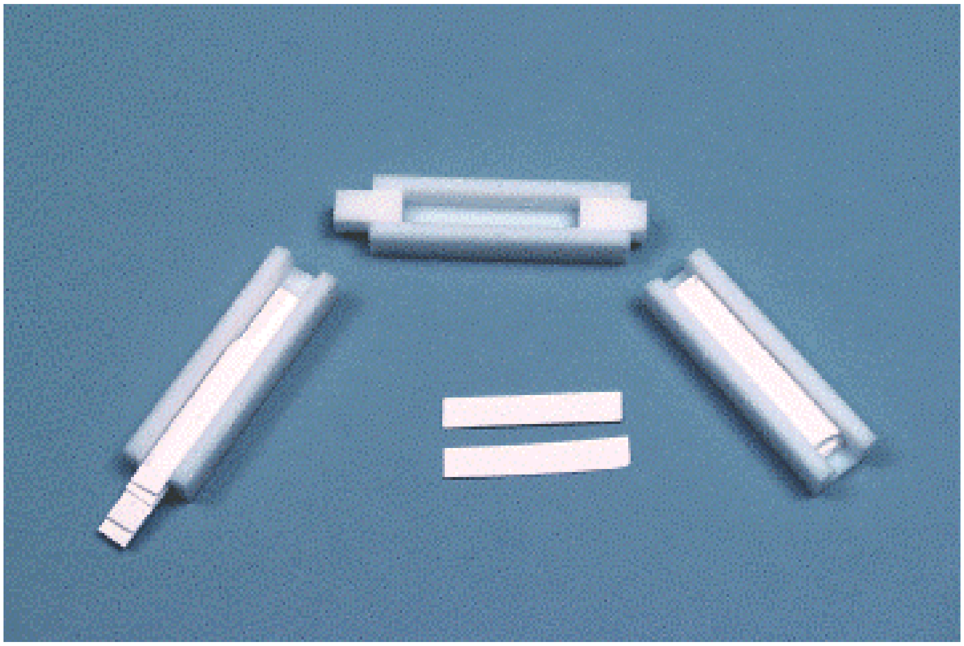

Fig. 1. Jigs for fabrication of WR28 paint samples with and without laminated paint strips.

A new method developed later is to apply a thin layer of paint or primer onto the surface of a 30.5 × 30.5 cm (12 × 12 in.) flat Teflon plate (see Fig. 2). Then, after drying, the paint layer is peeled off the Teflon plate and cut into thin strips close to but narrower than the width of the WR28 dimension of 0.71 cm (0.28 in.). The strips are wiped clean with acetone, painted with a thin coat of fresh paint, and stacked together. The wet paint acts like a glue that bonds the individual strips together. The glued layers are painted on the sides and then placed into the Teflon WR28 jig (Fig. 1). After drying, the final overall test sample is removed from the jig and cleaned again with acetone and coated on all sides with paint. Then, while still wet, the sample is slid into an empty waveguide test section (see Fig. 3). After another drying period, the ends are trimmed with an Exacto blade. Then the ends again are painted, and, after drying, they are lapped to be flush with the waveguide flange faces. This new process speeds up the test-sample-fabrication process, and a test sample can be made in about 1 week as compared with 3 weeks with the earlier process, described above.

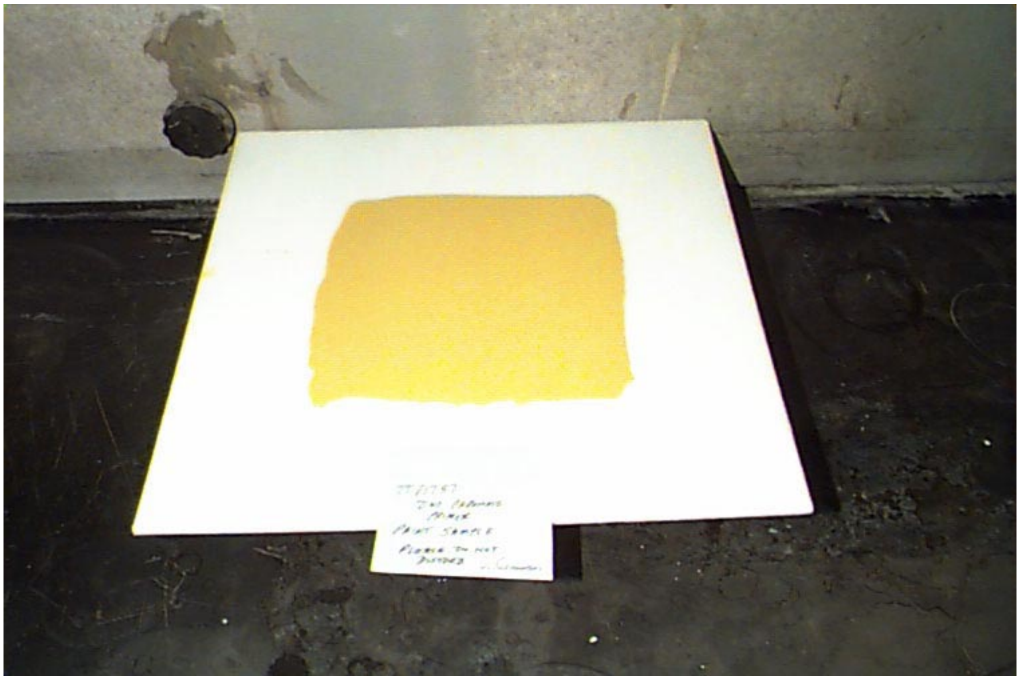

Fig. 2. Thin layer of zinc chromate primer on a 30.5-cm x 30.5-cm x 0.63-cm flat Teflon plate.

III. Waveguide Measurement and Data-Processing Techniques

The measurement procedure is simply to measure the S-parameters of the waveguide test sample over the desired frequency ranges using an automatic network analyzer such as the Hewlett Packard 8510C (HP 8510C). If all four S-parameters are measured, then two data sets result. The first is the (S11,S21) data set, and the second is the (S22,S12) data set.

The basic theory and equations for obtaining complex dielectric constants from measured S-parameter data can be found in [4,5]. Due to the unknown electrical length (with multiples of 360 deg of phase that need to be included), these equations will give a multiplicity of possible solutions for the relative dielectric constant that fits the measured S-parameter data and the given physical test-sample length. Two methods were derived to find the correct unique solution from the multiplicity of solutions. The first was to use the Beatty–Otoshi group-delay equations [6] to calculate theoretical group delays of a waveguide filled with the dielectric having the possible complex dielectric-constant values. These theoretical values then were compared with measured group delays. Measured group-delay values were calculated from measured S21

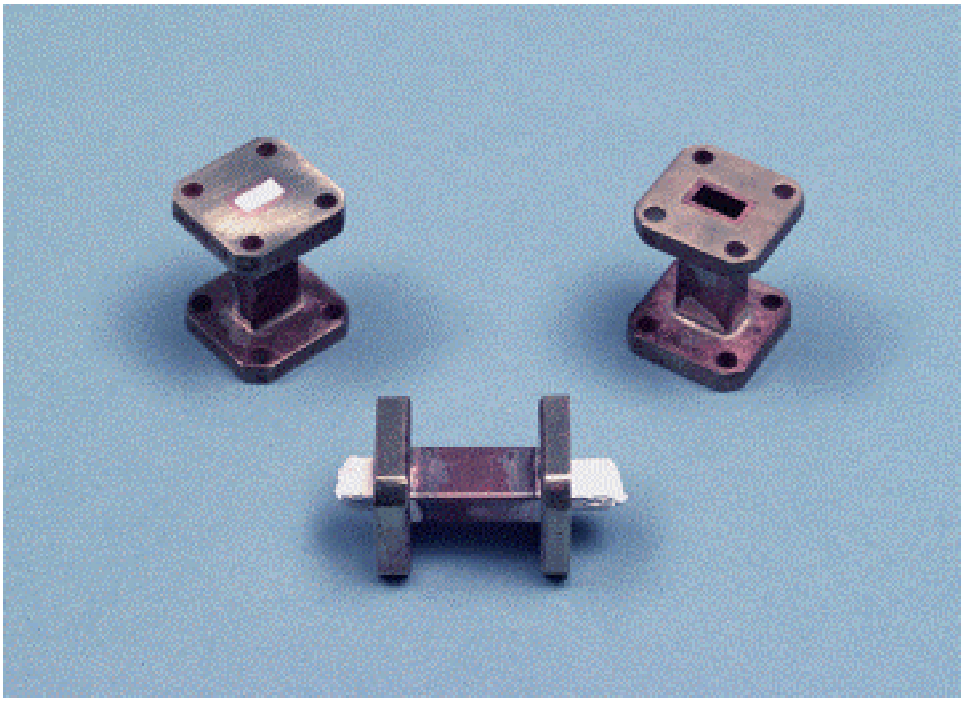

Fig. 3. Clockwise starting from the top right, an empty WR28 test section 2.54 cm in length, a paint sample inserted into a WR28 test section, and a completed WR28 paint test sample.

phase versus frequency in small frequency steps [7]. The correct unique solution gives the best comparison between measured and calculated group-delay values. The second method (of verifying that the correct solution was found) was to make sure that the computed complex relative permeabilities had values close to $(1.0 - j\ 0.0)$. These search methods were written into the computer program that processed the data. With this processing-data method, it no longer was required that an approximate dielectric constant of the sample under test be known a priori. The test sample may be several wavelengths long if desired.

After determining the test-sample electrical phase with the appropriate integer multiples of 360 deg included, an approximate complex dielectric-constant value is found. This process is referred to in [5] as finding the correct root of the general solution. Two methods then were employed to enhance the accuracy of the complex dielectric-constant value being determined. The first accuracy-improvement method was to use the same root that was found for the approximate value, then to rerun the computer program using an option to make the complex permeability be $(1.0 - j\ 0.0)$, and to solve only for the complex dielectric constants. This option assumes that the material being tested is non-ferrous. The second improvement method was to calculate a theoretical conductivity loss based on the length of the test-sample-holder waveguide (when filled with the test-sample material) and then to correct the attenuation constant so that it would not include the test-sample-holder waveguide loss. These accuracy-improvement techniques were not mentioned in earlier published material [4,5] on this waveguide technique for measuring the complex dielectric constants of materials. As will be shown in the following test results, loss tangents as low as 0.0003 were measured using these two accuracy-improvement methods.

After determining the complex relative dielectric constants of the paint samples, the final step is to use another computer program that calculates S-parameters of single dielectric sheets having the desired thicknesses and the complex dielectric-constant values that were measured. S-parameter equations for a single sheet, as functions of incidence angles and polarizations, can be found in numerous publications, including [8]. Then S-parameter cascading equations [9] are used to determine the overall two-port S-parameters of the multilayered stack of dielectric sheets. Finally, the input reflection coefficient of the multilayer dielectric stack is computed for the case when the dielectric stack is terminated with a metallic reflector surface of known conductivity, such as 6061 aluminum. An alternative to using S-parameter cascading equations is to use equations that were derived specifically for studying properties of multilayer dielectric sheets on a reflector surface [10].

Once the input reflection coefficient is known for a particular paint/primer thickness, incidence angle, and polarization, the overall noise temperature of a painted reflector can be calculated from

$$T_n = \left(1 - |\Gamma_{\text{in}}|^{2N}\right) T_p \tag{1}$$

where

$\Gamma_{\text{in}} =$ the input voltage reflection coefficient as seen looking at the painted reflector.

$N =$ the number of times that the incident wave reflects off similarly painted reflectors in cascade before arriving at cold sky. The notation $2N$ denotes that a 2 times N operation takes place.

$T_p =$ the physical temperature of the reflector surface, K.

If one is interested in only the excess noise temperature contribution due to paint or primer, or both, the following equation applies:

$$\Delta T_n = \left(|\Gamma_1|^{2N} - |\Gamma_2|^{2N}\right) T_p \tag{2}$$

where Γ_1 and Γ_2 are the input voltage reflection coefficients as seen looking at the unpainted (bare metal) and painted reflector surfaces, respectively.

IV. Test Results

Table 1 shows complex dielectric constants for selected frequency points across the frequency band from 23 through 35 GHz. The tabulated values are based on averaging the (S11,S21) and (S22,S12) data sets. Paint/primer measurement data processed to date are (1) Triangle no. 6 white flat paint, (2) zinc chromate primer, (3) 18FHR6 white water-based paint, and (4) 283 water-based Aquapoxy primer. Test samples (3) and (4) are candidate replacements for (1) and (2), which are, respectively, the paint and primer currently being used on main reflector and subreflector surfaces of DSN antennas. All of the above paints were manufactured by Triangle Coatings, Inc., located in San Leandro, California.

A WR28 Teflon test sample, made from stock material Teflon, was measured for test-integrity verification purposes. It is known that Teflon has a dielectric constant close to 2.0 and a loss tangent of less than 0.0005 in the microwave region. The last section of Table 1 shows that the measured results for Teflon agree well with the expected results.

Tables 2 through 6 show the test results divided into 2-GHz-wide regions with values averaged for 401 frequency points. All test samples (except the Triangle no. 6 paint) were measured over a frequency range from 24 through 34 GHz. Previous tests made on a shorter, 1.92-cm (0.754-in.) Triangle no. 6 paint sample showed that the measured complex dielectric-constant values were inconsistent over the frequency range. The inconsistency may have been due to the paint not being completely dry at the time of testing. A new Triangle no. 6 paint sample that was 2.555-cm (1.006-in.) long was made and tested over a larger frequency range, from 23 through 35 GHz. The new results may be seen in the first section of Table 1 and in Table 2.

Table 1. Average test-sample data at selected frequencies over the measured frequency range; averages are based on (S11,S21) and (S22,S12) data sets.[a]

Frequency, GHz	ε_r'	ε_r''	Loss tangent
Triangle no. 6 paint			
23	5.85	0.10	0.017
($N = 2$)	0.03 SD	0.01 SD	0.002 SD
27	5.87	0.115	0.020
($N = 4$)	0.02 SD	0.004 SD	0.001 SD
31	5.913	0.133	0.022
($N = 4$)	0.004 SD	0.001 SD	0.001 SD
32	5.89	0.13	0.022
($N = 2$)	0.02 SD	0.02 SD	0.003 SD
35	5.94	0.183	0.031
($N = 2$)	0.04 SD	0.007 SD	0.001 SD
Zinc chromate primer			
24	4.372	0.098	0.0224
($N = 2$)	0.002 SD	0.001 SD	0.0003 SD
28	4.365	0.0953	0.0218
($N = 4$)	0.003 SD	0.0004 SD	0.0001 SD
32	4.362	0.0949	0.0218
($N = 2$)	0.001 SD	0.0002 SD	0.00004 SD
34	4.359	0.0947	0.0217
($N = 2$)	0.0003 SD	0.0002 SD	0.00004 SD
18FHR6 water-based paint			
24	5.346	0.21	0.039
($N = 2$)	0.005 SD	0.01 SD	0.002 SD
28	5.388	0.218	0.041
($N = 2$)	0.0004 SD	0.006 SD	0.001 SD
32	5.366	0.200	0.0374
($N = 2$)	0.005 SD	0.002 SD	0.0005 SD
34	5.377	0.204	0.0380
($N = 2$)	0.002 SD	0.002 SD	0.0003 SD
283 water-based Aquapoxy primer			
24	3.3761	0.1539	0.0456
($N = 2$)	0.0004 SD	0.0005 SD	0.0002 SD
28	3.3736	0.148	0.0440
($N = 2$)	0.0003 SD	0.002 SD	0.0007 SD

[a] SD = the standard deviation of the average based on N data points.

Complex relative dielectric constant = $(\varepsilon_r' - j\ \varepsilon_r'')$.

Loss tangent = $\varepsilon_r''/\varepsilon_r'$.

Table 1 (contd).[a]

Frequency, GHz	ε_r'	ε_r''	Loss tangent
283 water-based Aquapoxy primer (contd)			
32 ($N = 2$)	3.3681 0.0008 SD	0.1404 0.0004 SD	0.0417 0.0001 SD
34 ($N = 2$)	3.3647 0.0003 SD	0.1379 0.0008 SD	0.0410 0.0002 SD
Teflon			
24 ($N = 2$)	1.9718 0.0009 SD	0.0004 0.0001 SD	0.0002 0.0001 SD
28 ($N = 2$)	1.9759 0.0006 SD	0.0007 0.0005 SD	0.0003 0.0003 SD
32 ($N = 4$)	1.9802 0.0008 SD	0.0005 0.0002 SD	0.0003 0.0001 SD
34 ($N = 2$)	1.990 0.002 SD	0.0006 0.0003 SD	0.0003 0.0001 SD

[a] SD = the standard deviation of the average based on N data points.

Complex relative dielectric constant = $(\varepsilon_r' - j\ \varepsilon_r'')$.

Loss tangent = $\varepsilon_r''/\varepsilon_r'$.

The results in these tables are shown to four or five decimal places only to be consistent with some of the very small standard deviations that were rounded off to four or five decimal places (e.g., data in Tables 3, 5, and 6). The results show that, over 2-GHz frequency-range intervals, the average complex dielectric-constant values do not change significantly. However, there are small but noticeable differences between the results based on the (S11,S21) and the (S22,S12) data sets. The best measured value for the complex dielectric constant can be obtained by taking the average of the two data sets and rounding off to the appropriate number of decimal places, depending on the standard deviation resulting from the averaging.

V. Concluding Remarks and Future Work

In the past, radiometric and cavity measurements were made on thin, 0.025- or 0.050-mm (1- or 2-mil) paint layers on top of aluminum surfaces. It is difficult to extract the complex dielectric constants of thin paint samples from these types of measurement techniques. By comparison, for the results presented in this article, measurements typically were made on thick (2.54-cm) individual paint samples for determining their complex dielectric constants at Ka-band frequencies. It was shown that, when using thicker test samples, two decimal accuracies typically were obtained for the real and imaginary parts of the complex dielectric constants of the paint samples being tested.

A test sample for a new type of paint, Triangle 500FHR6 white paint, has been prepared and tested, but at the time of the writing of this article, the data had not yet been processed. This particular type of paint, made with a urethane base, is now being used on National Radio Astronomy Observatory antennas.

Table 2. Summary of Triangle no. 6 flat white paint test results (average values over specified frequency ranges).[a]

Frequency, GHz	Number of points	Data file	ε_r'	ε_r''	Loss tangent
23-25	401	(S11,S21)	5.8512 0.0144 SD	0.1052 0.0114 SD	0.0180 0.0019 SD
23–25	401	(S22,S12)	5.8597 0.0043 SD	0.1116 0.0048 SD	0.0191 0.0008 SD
25–27	401	(S11,S21)	5.8627 0.0065 SD	0.1210 0.0074 SD	0.0206 0.0013 SD
25–27	401	(S22,S12)	5.8789 0.0043 SD	0.1212 0.0054 SD	0.0206 0.0009 SD
27–29	401	(S11,S21)	5.8703 0.0087 SD	0.1250 0.0083 SD	0.0213 0.0014 SD
27–29	401	(S22,S12)	5.8606 0.0121 SD	0.1374 0.0123 SD	0.0235 0.0021 SD
29–31	401	(S11,S21)	5.8901 0.0091 SD	0.1324 0.0091 SD	0.0225 0.0016 SD
29–31	401	(S22,S12)	5.8919 0.0213 SD	0.1255 0.0159 SD	0.0214 0.0027 SD
31–33	401	(S11,S21)	5.9112 0.0103 SD	0.1565 0.0106 SD	0.0265 0.0018 SD
31–33	401	(S22,S12)	5.9041 0.0287 SD	0.1390 0.0207 SD	0.0235 0.0035 SD
33–35	401	(S11,S21)	5.9100 0.0154 SD	0.1650 0.0161 SD	0.0279 0.0027 SD
33–35	401	(S22,S12)	5.9109 0.0281 SD	0.1536 0.0263 SD	0.0260 0.0045 SD

[a] SD = the standard deviation of the average based on the number of frequency points.

Complex relative dielectric constant = $(\varepsilon_r' - j\ \varepsilon_r'')$.

Loss tangent = $\varepsilon_r''/\varepsilon_r'$.

Frequency range = 23–35 GHz.

WR28 test-sample length = 2.555 cm (1.006 in.).

Complex relative permeability = $(1.0 - j\ 0.0)$.

This type of paint has been reported to be less lossy than the Triangle no. 6 paint at 32 GHz.[3] Another paint sample that has been prepared and tested is a Triangle no. 710 glossy white paint that is being used on Cassegrain cone surfaces, microwave test packages, and exterior antenna support structures. Although the authors are confident that the correct solutions were found by the methods described in this article, a few additional paint samples having different lengths will be fabricated and tested to ensure that the correct solutions were found.

When measurements of all complex dielectric constants of the new paint samples are completed, the noise temperatures of primer and paint layers of interest will be computed as functions of thickness, frequency, polarization, and incidence angle. The results will be presented in a future article.

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[3] Ibid.

Table 3. Summary of zinc chromate primer test results (average values over specified frequency ranges).[a]

Frequency, GHz	Number of points	Data file	ε_r'	ε_r''	Loss tangent
24–26	401	(S11,S21)	4.3725 0.0013 SD	0.0963 0.0004 SD	0.0220 0.0001 SD
24–26	401	(S22,S12)	4.3702 0.0015 SD	0.0971 0.0005 SD	0.0222 0.0001 SD
26–28	401	(S11,S21)	4.3687 0.0012 SD	0.0957 0.0003 SD	0.0219 0.0001 SD
26–28	401	(S22,S12)	4.3666 0.0010 SD	0.0959 0.0003 SD	0.0220 0.0001 SD
28–30	401	(S11,S21)	4.3591 0.0008 SD	0.0941 0.0010 SD	0.0216 0.0002 SD
28–30	401	(S22,S12)	4.3663 0.0024 SD	0.0969 0.0015 SD	0.0222 0.0003 SD
30–32	401	(S11,S21)	4.3554 0.0005 SD	0.0938 0.0006 SD	0.0215 0.0001 SD
30–32	401	(S22,S12)	4.3626 0.0021 SD	0.0968 0.0018 SD	0.0222 0.0004 SD
30–32 Repeat	401	(S11,S21)	4.3635 0.0009 SD	0.0949 0.0002 SD	0.0217 0.0001 SD
30–32 Repeat	401	(S22,S12)	4.3648 0.0013 SD	0.0952 0.0003 SD	0.0218 0.0001 SD
32–34	401	(S11,S21)	4.3602 0.0008 SD	0.0947 0.0002 SD	0.0217 0.00004 SD
32–34	401	(S22,S12)	4.3612 0.0012 SD	0.0950 0.0003 SD	0.0218 0.0001 SD

[a] SD = the standard deviation of the average based on the number of frequency points.

Frequency range = 24–34 GHz.

WR28 test-sample length = 3.099 cm (1.220 in.).

Complex relative permeability = $(1.0 - j\ 0.0)$.

Acknowledgments

The authors thank Jerry Person for fabricating the WR28 test sections and machining WR28 Teflon test jigs for the paint samples. The authors also thank Triangle Coatings, Inc. for furnishing the variety of paints and primers that were mentioned in this article.

Table 4. Summary of 18FHR6 paint-test results (average values over specified frequency ranges).[a]

Frequency, GHz	Number of points	Data file	ε_r'	ε_r''	Loss tangent
24–26	401	(S11,S21)	5.3256 0.0125 SD	0.1755 0.0077 SD	0.0330 0.0014 SD
24–26	401	(S22,S12)	5.3030 0.0035 SD	0.1928 0.0057 SD	0.0364 0.0011 SD
26–28	401	(S11,S21)	5.3392 0.0060 SD	0.1953 0.0040 SD	0.0366 0.0008 SD
26–28	401	(S22,S12)	5.3243 0.0072 SD	0.1851 0.0037 SD	0.0348 0.0007 SD
28–30	401	(S11,S21)	5.3409 0.0032 SD	0.2025 0.0031 SD	0.0379 0.0006 SD
28–30	401	(S22,S12)	5.3383 0.0061 SD	0.1869 0.0035 SD	0.0350 0.0007 SD
30–32	401	(S11,S21)	5.3459 0.0073 SD	0.1993 0.0065 SD	0.0373 0.0012 SD
30–32	401	(S22,S12)	5.3563 0.0070 SD	0.1968 0.0069 SD	0.0367 0.0013 SD
32–33	401	(S11,S21)	5.3622 0.0013 SD	0.2004 0.0374 SD	0.0374 0.0003 SD
32–33	401	(S22,S12)	5.3705 0.0009 SD	0.2019 0.0018 SD	0.0376 0.0003 SD
33–34	401	(S11,S21)	5.3731 0.0041 SD	0.1989 0.0022 SD	0.0370 0.0004 SD
33–34	401	(S22,S12)	5.3739 0.0013 SD	0.2043 0.0009 SD	0.0380 0.0002 SD

[a] SD = the standard deviation of the average based on the number of frequency points.

Frequency range = 24–34 GHz.

WR28 test-sample length = 2.553 cm (1.005 in.).

Complex relative permeability = $(1.0 - j\ 0.0)$.

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Table 5. Summary of 283 Aquapoxy primer results (average values over specified frequency ranges).[a]

Frequency, GHz	Number of points	Data file	ε_r'	ε_r''	Loss tangent
24–26	401	(S11,S21)	3.3757 0.0004 SD	0.1519 0.0008 SD	0.0450 0.0002 SD
24–26	401	(S22,S12)	3.3758 0.0003 SD	0.1530 0.0010 SD	0.0453 0.0003 SD
26–28	401	(S11,S21)	3.3739 0.0004 SD	0.1486 0.0012 SD	0.0440 0.0003 SD
26–28	401	(S22,S12)	3.3749 0.0006 SD	0.1507 0.0004 SD	0.0447 0.0001 SD
28–30	401	(S11,S21)	3.3672 0.0008 SD	0.1433 0.0004 SD	0.0426 0.0001 SD
28–30	401	(S22,S12)	3.3669 0.0007 SD	0.1453 0.0010 SD	0.0413 0.0003 SD
30–32	401	(S11,S21)	3.3649 0.0007 SD	0.1413 0.0006 SD	0.0420 0.0002 SD
30–32	401	(S22,S12)	3.3648 0.0009 SD	0.1427 0.0006 SD	0.0424 0.0002 SD
32–33	401	(S11,S21)	3.3672 0.0008 SD	0.1394 0.0003 SD	0.0414 0.0001 SD
32–33	401	(S22,S12)	3.3667 0.0005 SD	0.1399 0.0005 SD	0.0415 0.0001 SD
33–34	401	(S11,S21)	3.3653 0.0004 SD	0.1381 0.0004 SD	0.0410 0.0001 SD
33–34	401	(S22,S12)	3.3653 0.0004 SD	0.1388 0.0002 SD	0.0413 0.0001 SD

[a] SD = the standard deviation of the average based on the number of frequency points.

Frequency range = 24–34 GHz.

WR28 test-sample length = 2.551 cm (1.0045 in.).

Complex relative permeability = $(1.0 - j\ 0.0)$.

Table 6. Summary of Teflon test results (average values over specified frequency ranges).[a]

Frequency, GHz	Number of points	Data file	ε_r'	ε_r''	Loss tangent
24–25.995	400	(S11,S21)	1.9724 0.0005 SD	0.0007 0.0004 SD	0.0003 0.0002 SD
24–25.325	241[b]	(S22,S12)	1.9724 0.0001 SD	0.0004 0.0002 SD	0.0002 0.0001 SD
26–28	401	(S11,S21)	1.9730 0.0004 SD	0.0008 0.0003 SD	0.0004 0.0002 SD
26–28		(S22,S12)		(not available)	
28–30	401	(S11,S21)	1.9762 0.0003 SD	0.0010 0.0005 SD	0.0005 0.0002 SD
28–29.99	238[b]	(S22,S12)	1.9761 0.0002 SD	0.0006 0.0003 SD	0.0003 0.0002 SD
30–32	401	(S11,S21)	1.9805 0.0002 SD	0.0005 0.0003 SD	0.0003 0.0001 SD
30–32	401	(S22,S12)	1.9787 0.0004 SD	0.0005 0.0002 SD	0.0002 0.0001 SD
32–34	388[b]	(S11,S21)	1.9810 0.0006 SD	0.0004 0.0005 SD	0.0002 0.0002 SD
32–34	401	(S22,S12)	1.9794 0.0005 SD	0.0010 0.0004 SD	0.0005 0.0002 SD

[a] SD = the standard deviation of the average based on the number of frequency points.

Frequency range = 24–34 GHz.

WR28 test-sample length = 2.581 cm (1.016 in.).

Complex relative permeability = $(1.0 - j\ 0.0)$.

[b] Some frequency point data were edited out because the ε_r'' values, although very close to 0.000, had negative values and, therefore, were not valid.