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Antenna Performance Degradation Resulting From Aviation Fuel Exposure

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Special Thanks To:

Raytheon Company, EW (Goleta, CA) for permission to show the enclosed technical presentation

Abstract

Often, antennas operate within a hostile environment that potentially alters the antenna's electrical performance. A case study was conducted to evaluate the performance of an antenna in the presence of aviation fuel such as JP-5 using HFSS (high frequency, finite element method, structure simulator.) An extensive research effort was conducted to obtain the JP-5 aviation fuel's electrical performance characteristics at microwave and millimeter frequencies.

Two Archimedean planar cavity-backed spiral antennas and associated microstrip and coaxial tapered baluns were designed for right hand polarization (RHCP). A quartz fiber radome was also designed and included in the model.

Formulation for a dielectric composite mix material scenario was used to model cases where material and fuel mixed in various concentrations. Several mathematical models for the estimation of the effective dielectric constant and loss tangent resulting from composite materials were evaluated. These included but were not limited to the Finite Element, Maxwell Garnett, and Bruggeman methods.

The enclosed presentation is a brief summary presentation extracted from extensive research conducted in 2005.

ACKNOWLEDGMENTS

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- **Dr. Dejan Filipovic** from University of Colorado, Boulder, Colorado and **Brad Brim** from Ansoft Corporation for providing common design examples of dual arm, planar spiral antennas.

From Raytheon Company, Space and Airborne Systems, EW, Goleta, California.

- **Dr. Kevin Buell** (Antenna Engineer) for the millimeter antenna design. **Tom Debski** and **Kim McInturff** (Sr Principal Engineers) for assistance in the development of mathematical formulation and Gaussian data fit programs. **Marc Altman** (System Engineer) for procuring documents necessary for the analysis. **Dr. Dennis Holst** (Antenna Department Supervisor) for providing technical guidance. The author is also grateful to **John Hofmann**, **Robert Llamas**, and **Johnson Woo** from the Information Technology Department for providing and supporting the powerful 64 Bit, 16 microprocessors computer to conduct the analysis.

- Finally, **William W. Wallace** from the Naval Air Systems Command, Patuxent River, Maryland, for providing information documents on JP-5 fuel.

DIELECTRIC COMPOSITE MATHEMATICAL METHODS

An excellent summary on the theories for the dielectric constant can be found in reference number 1. The study reviews dielectric constant mathematical derivations methods by Onsager, Kirkwood and Cole[1]. After reviewing numerous papers available in literature, the effective dielectric material composite formulation used in this report was selected from those mathematical methods described in reference 2 and 3. These formulas are widely accepted in industry and are listed below:

Maxwell-Garnet formula

$$\varepsilon_{av} = \varepsilon_m \left[1 + \frac{3f\left(\frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m}\right)}{1 - f\left(\frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m}\right)} \right] \tag{1}$$

where ε_m = dielectric constant of matrix; ε = dielectric constant of inclusion;
f = volumetric fraction of the inclusion.

The other formulation is the Bruggeman

$$f_1 \frac{\epsilon_1 - \epsilon_{av}}{\epsilon_1 + 2\epsilon_{av}} + (1 - f_1)\frac{\epsilon_2 - \epsilon_{av}}{\epsilon_2 + 2\epsilon_{av}} = 0 \tag{2}$$

Where, $\varepsilon 1$ and ε_2 are the dielectric constant of the composite materials and f_1 is the volume occupied by dielectric material of ε_1. Note that Bruggeman formula is for symmetrical cases and the Maxwell Garnett formula is reported[3] to be less accurate for volumetric fraction greater than 0.3.

The above formulas were reformulated and programmed in Excel. Other approaches to determine the composite materials electrical properties are by the use of finite element (HFSS,) and/or finite difference methods. Several publications on these techniques are available[4,5]. These references also address the effective loss tangent.

Other approaches were also used in this analysis to determine the composite material electrical performance. These are briefly described below:

With the use of finite element method (HFSS) the following geometry was modeled in a small size sample:

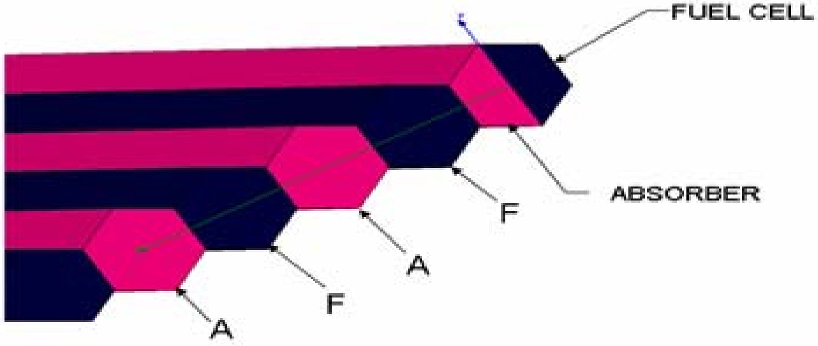
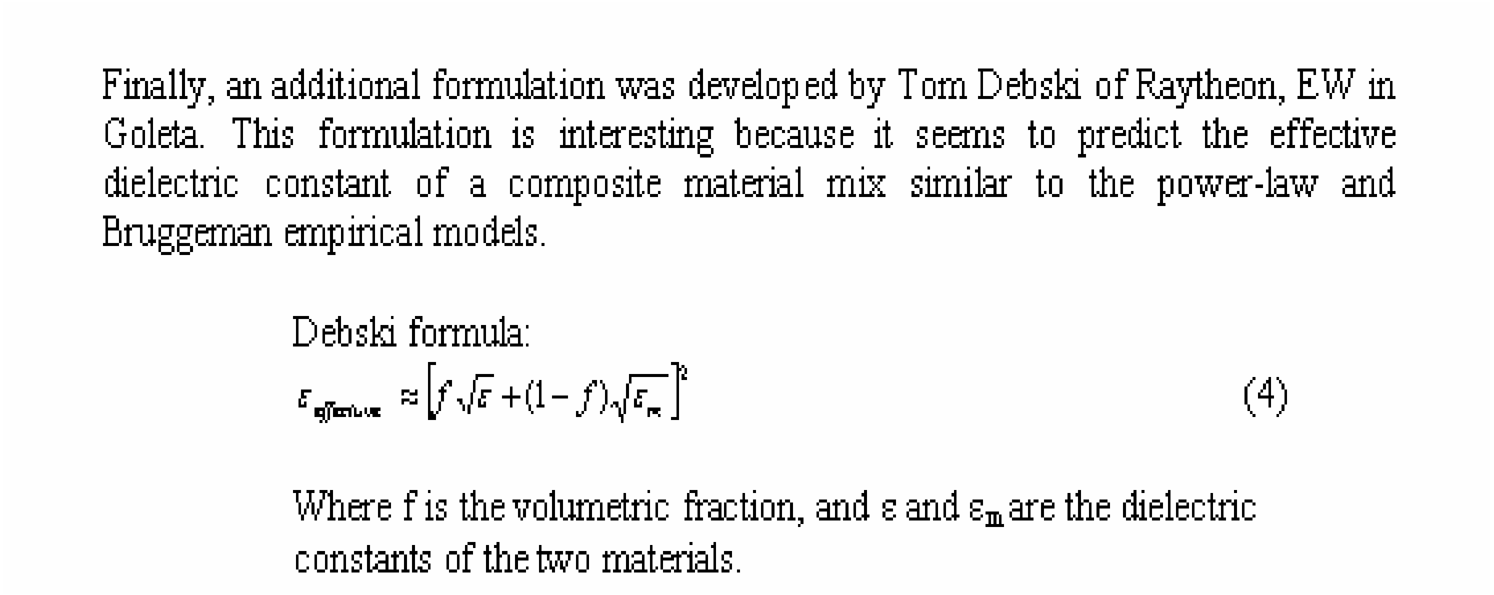


Figure 12

The cell size was chosen to be equal to $2\pi r/\lambda \simeq 0.1$, where r is the longest length of the hexagonal face and λ is the wavelength. Smaller size hexagonal tubing was tried. When compared to available measured data, this approach appears to yield a surface effects rather than a volumetric material mix effect. There is more discussion that merits attention on the dielectric subject such as the Debye relation and the dielectric characteristic of a material[6], but this is beyond the scope of this report. Additional studies about permittivity of material compounds were considered with improved results like the finite element method (FEM) and the Monte Carlo method[7]. For example, the previously cited reference indicated that the effective loss tangent ($\tan\delta$) and the effective permittivity (ε_e) to be logarithmic related as shown below:

$$\tan\delta = A^{*}\log(\varepsilon_e) + B \qquad (3)$$

where A and B are numerical constants used for curve fitting.



Finally, an additional formulation was developed by Tom Debski of Raytheon, EW in Goleta. This formulation is interesting because it seems to predict the effective dielectric constant of a composite material mix similar to the power-law and Bruggeman empirical models.

Debski formula:

$$\varepsilon_{effective} \approx \left[f\sqrt{\varepsilon} + (1-f)\sqrt{\varepsilon_m}\right]^2 \qquad (4)$$

Where f is the volumetric fraction, and ε and ε_m are the dielectric constants of the two materials.

Bruggeman Relationship
Formulation for the Excel program

$$f\times((E_1-E_{av})\div(E_1+2E_{av}))+(1-f)\times((E_2-E_{av})\div(E_2+2E_{av}))=0$$

$$f\times((E_1-E_{av})\times(E_2+2E_{av}))+(1-f)\times((E_2-E_{av})\times(E_1+2E_{av}))=0$$

$$f\times\left[E_1E_2+(-E_2+2E_1)\times E_{av}-2E_{av}^2\right]+(1-f)\left[E_1E_2+(2E_2-E_1)\times E_{av}-2E_{av}^2\right]=0$$

$$-2E_{av}^2+2\left[f\times(E_1-(E_2\div2))+(1-f)\times(E_2-(E_1\div2))\right]\times E_{av}+E_1E_2=0$$

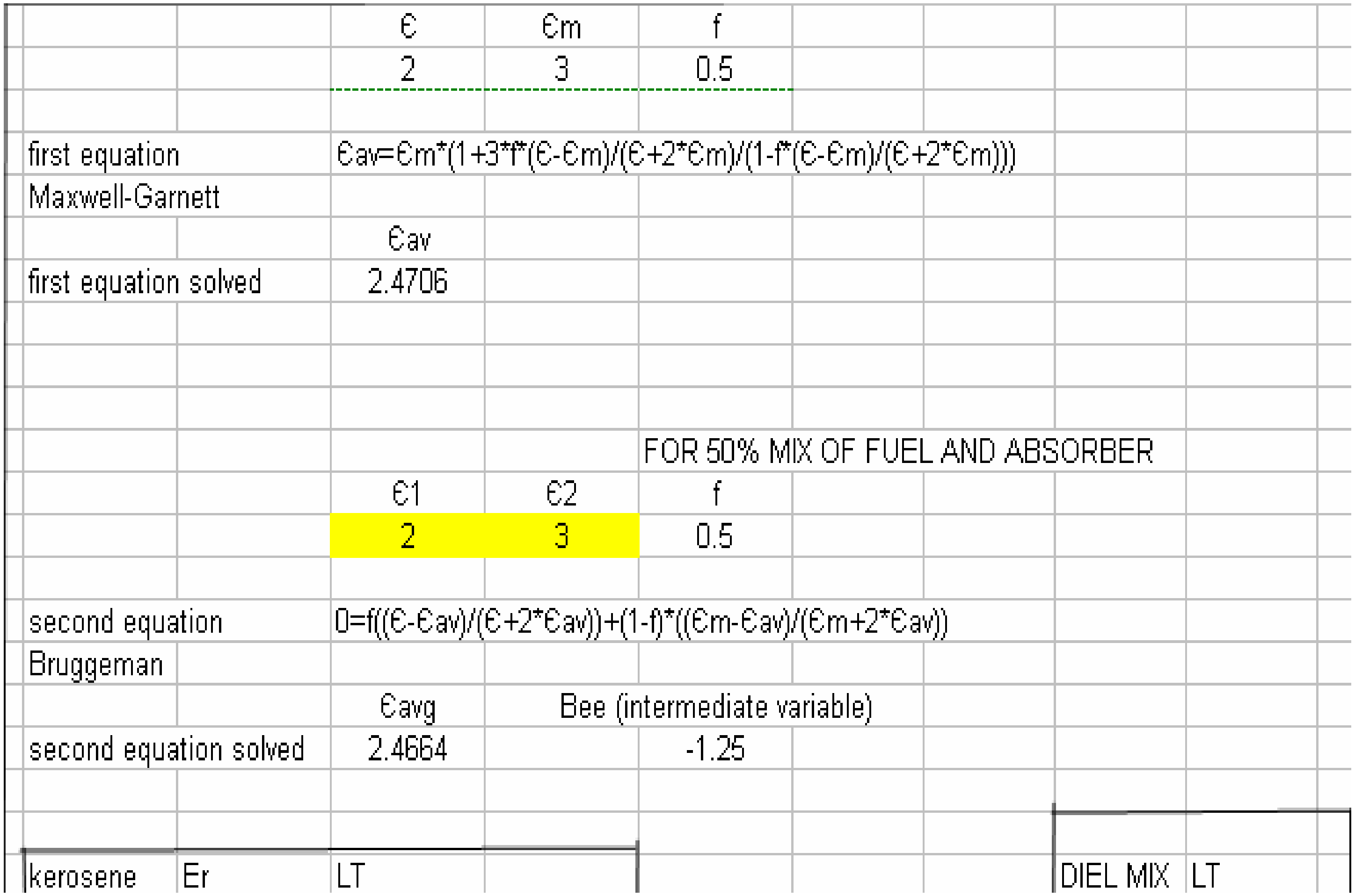
$$E_{av}^2-\left[f\times(E_1-(E_2\div2))+(1-f)\times(E_2-(E_1\div2))\right]\times E_{av}-(E_1E_2\div2)=0$$

$$B=f\times(E_1-(E_2\div2))+(1-f)\times(E_2-(E_1\div2)),C=(E_1E_2)\div2$$

$$Note:x^2-Bx-C=0\rightarrow x=(B\pm\sqrt{B^2+4C})\div2)$$

$$E\underline{_{av}=(B+\sqrt{B^2+2E_1E_2})}\div2\rightarrow beacuse...E_{av}>0$$

Dielectric Mixing Equations



		Є	Єm	f				
		2	3	0.5				
first equation		Єav=Єm*(1+3*f*(Є-Єm)/(Є+2*Єm)/(1-f*(Є-Єm)/(Є+2*Єm)))						
Maxwell-Garnett								
		Єav						
first equation solved		2.4706						
				FOR 50% MIX OF FUEL AND ABSORBER				
		Є1	Є2	f				
		2	3	0.5				
second equation		0=f((Є-Єav)/(Є+2*Єav))+(1-f)*((Єm-Єav)/(Єm+2*Єav))						
Bruggeman								
		Єavg	Bee (intermediate variable)					
second equation solved		2.4664		-1.25				
kerosene	Er	LT					DIEL MIX	LT

Material Research

- Extensive research was conducted to determine the composition and properties of JP-5 fuel.
- First, it was determined that JP-5 fuel is specially refined kerosene and is part of the hydrocarbon liquid family. Although JP-5 contains several additives like antioxidant, corrosion, and icing inhibitors, the author decided not to include the additives in the analysis. This was based on comparison of kerosene data versus JP-5 at some discrete frequencies.
- Second, the conductivity[8] of JP-5 is in the range of 150 to 600 pS/m at room temperature. This is hardly a conductive substance. Nevertheless, the conductivity was included in the analysis.
- Measurements show that the dielectric constant of JP-5 fuel changes in a linearly versus temperature[9,10]. At 400 Hz, the dielectric constant change from -60º to +260º was 2.25 to 2.08, compared to 2.15 at room temperature. This constitutes a percent change of 8%. Since the dielectric constant varies linearly with temperature, the dielectric change as a result of temperature appears to be independent of frequency. Therefore, the dielectric constant versus frequency of the JP-5 fuel for the HFSS model was varied ± 8%. The loss tangent was also changed but not to the same ±8% factor.
- The antennas performance parameters evaluated were the gain, beam squint, and beamwidth at microwave and millimeter frequencies. The electrical properties of JP-5 fuel found in literature[11,12,13,14,15,16] for the final HFSS model were altered to represent to the worst dielectric variation versus frequencies.
- Pressure also impacts the dielectric constant value, but this factor was determined to have minimal influence, and was not considered in the current analysis.

Material Research

- The "Dielectric Materials and Applications" book by Arthur von Hippel is an excellent source for petroleum oils (JP-1, JP-3, Kerosene,) but only at 3 GHz. This source reported Kerosene (≈JP-5) ϵr =2.09 and tanδ =0.0045. Another source "Fuel Properties" NAVAIR report number 06-05-06 provided by Naval Air Systems Command, Patuxent River, Maryland, site reported a JP-5 dielectric ϵr =2.05 at 400 Hz. This source appear to agree with "Study to Determine the Electrical and Physical Properties of Aviation Fuel," by C.C. Petersen, WADC report 52-53, Wright Air Development Center. Another source[17] reported an ϵr =2.086 at 9.538 GHz. An Interesting study on Unpolar liquid kerosene ϵr and tanδ by C. Cotae and Gh. Calugaru[18] (Department of Physics, Polytechnic Institute, Jassy, Romania) was also considered in the determination of Kerosene electrical properties. Additional JP-5 sources were evaluated but not referenced in this report. For high frequency[19] (millimeter band as an example) data on electrical properties of fluids, the study conducted by V.V. Meriakri, "Low-loss Materials for Application in Millimetre and Submillimetre Wave Ranges, was used to gain insight to non-polar liquids electrical performance at mm wave frequencies.

- The loss tangent (tanδ) and dielectric constant (ϵr) values located in publications on JP-5 and Kerosene were altered based on other factors like temperature and in house formulation calculations. For example, the 2, 4, and 6 mil boundary impedance surface layer calculations for kerosene at microwave and millimeter frequency band revealed that the real part of the impedance hardly changed..

Spiral Antenna
Radome Design and Materials Used for the Analysis

- Two Archimedean dual arm spiral antennas for microwave and millimeter frequency bands were designed. The spirals were designed for right hand circular polarization only. The left hand circular polarization was not addressed since the fuel effects should be the same for both polarizations. The designed consisted of a spiral, dual arm gold element, and a balun impedance transformer. These components were supported by honeycomb structure with free space foam under the elements. The design was based on common knowledge available in literature[20,21,22,23,24,25,26]. Both spiral antennas were validated with HFSS (baseline data shown in page 16). Two quartz fiber radomes[27,28] combined into one structure were also designed

- The antennas and associated components are depicted by Figures 1, 2 and 3. The honeycomb material used between the microwave spiral element and housing bottom plate was not carbon loaded. The honeycomb dielectric constant for the vertical wall was 1.042 and 1.06 for the horizontal geometry. The loss tangent was 0.00083 and 0.00036 respectively. The Rohacell HF 71H low loss foam ($\epsilon r \approx 1.05$ at 2 GHz and 1.042 at 30 GHz with loss tangent≈ 0.0002 to 0.016 at 30 GHz) was used between the honeycomb and element substrate. The substrate is an 8 mil thick Roger RT/duroid 5880. High loss absorber within spiral back cavity similar to FDS and GDS were also used within the spiral back cavity. The data for the frequency of interest can be obtained from Rogers Corporation. The radome electrical material properties and other materials were programmed in HFSS with frequency dependent material function. The HFSS models were solved at individual frequencies increments. The convergence parameters were maintained constant from the baseline model versus the fuel layers models.

TYPICAL MICROWAVE SPIRAL ANTENNA

(Cut Plane View)

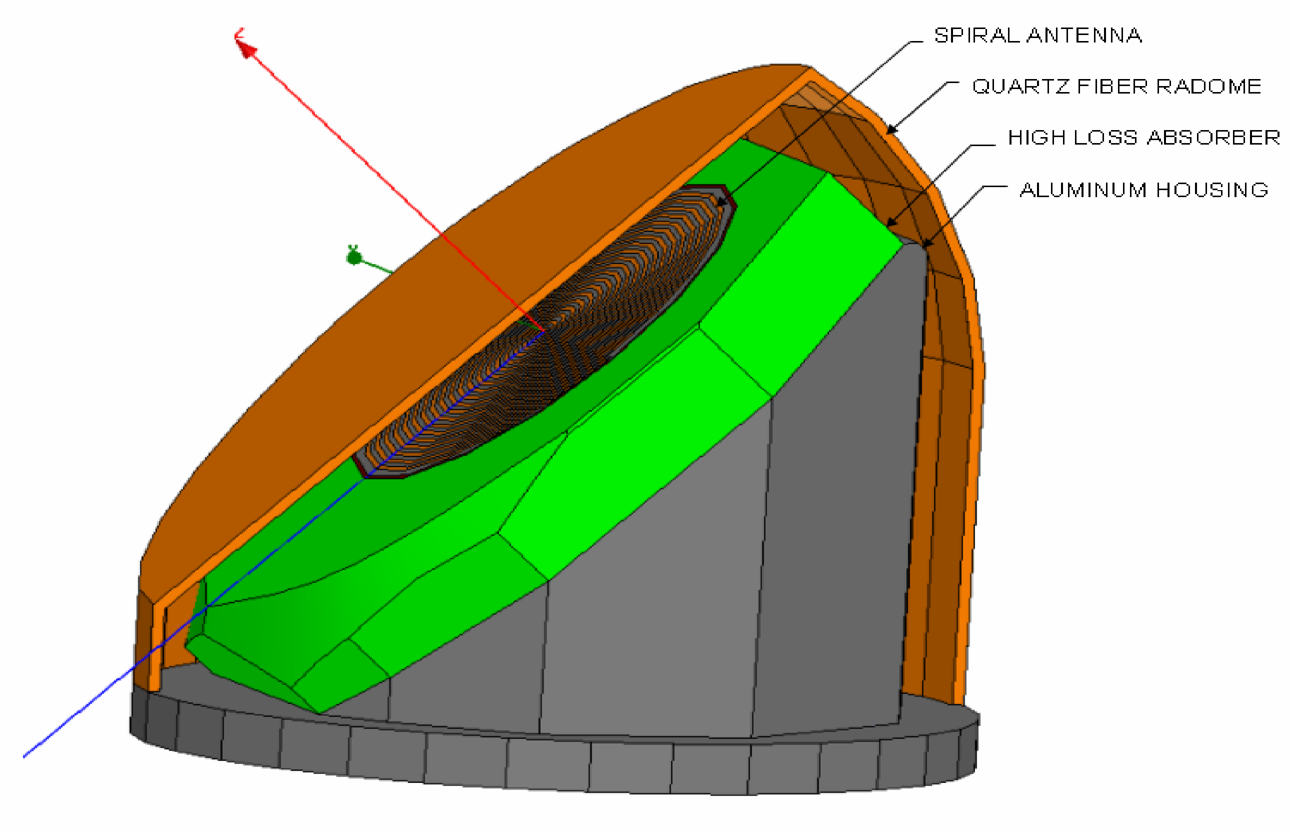


Figure 1

TYPICAL MICROWAVE SPIRAL ANTENNA

(View of internal components)

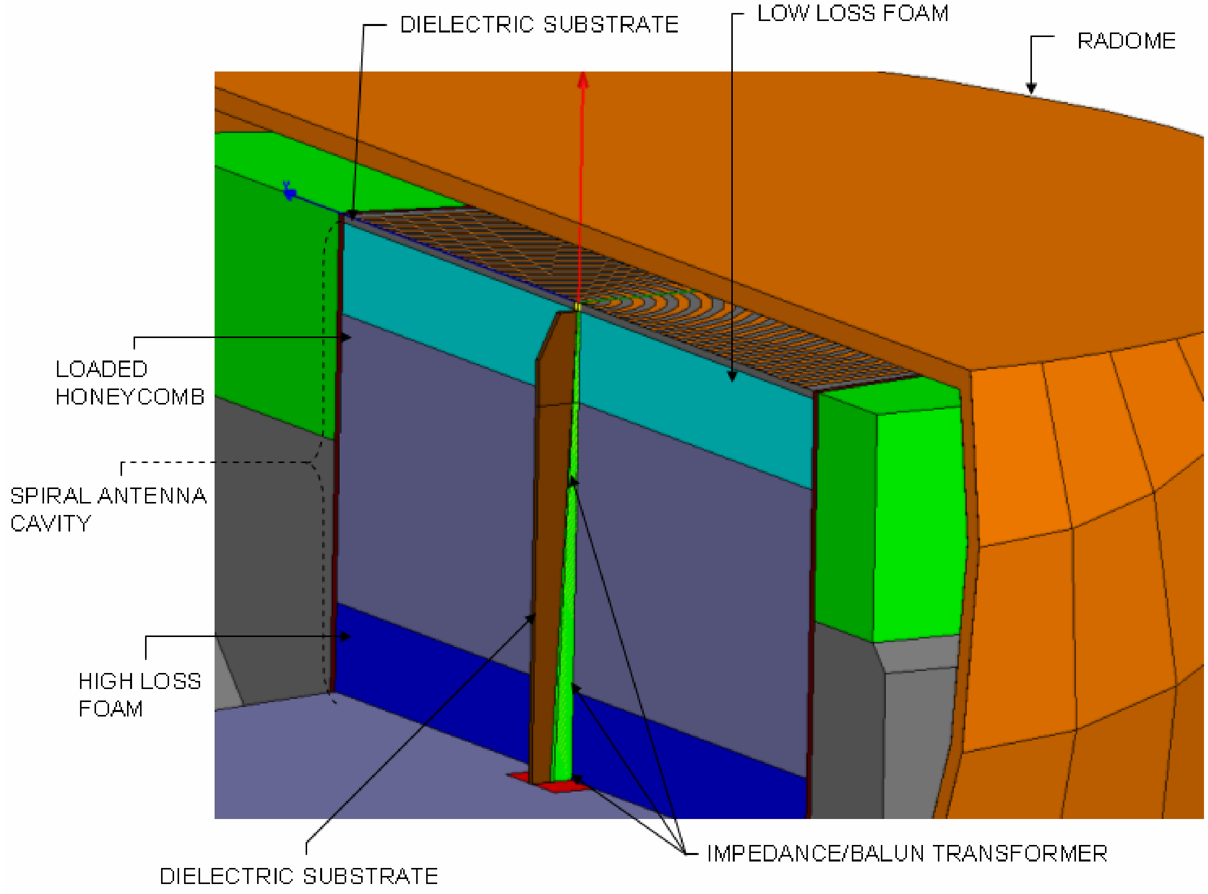
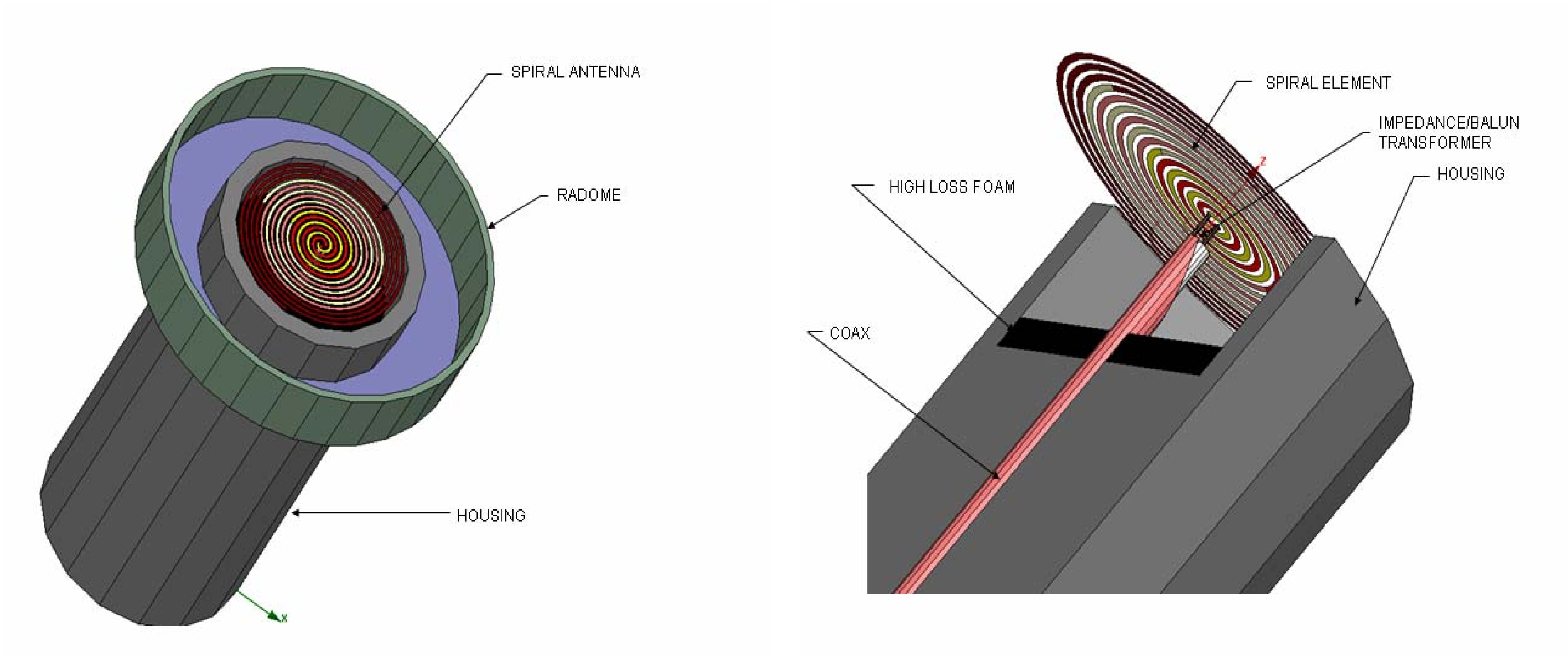


Figure 2

TYPICAL MILLIMETER SPIRAL ANTENNA

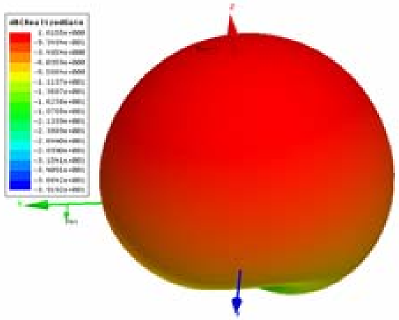


(a)

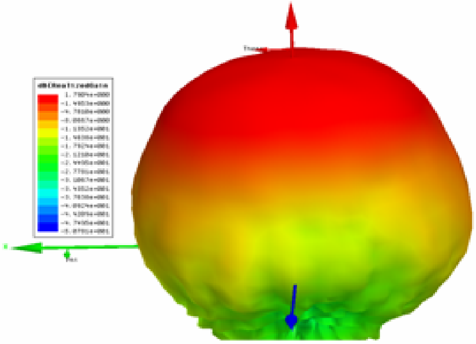
(b)

Figure 3

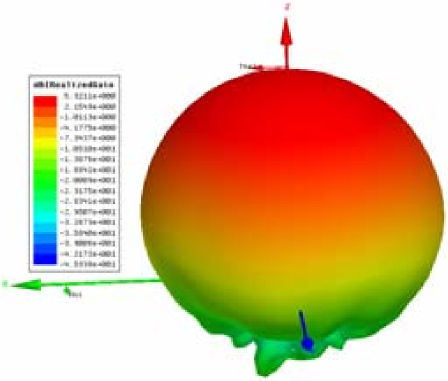
BASELINE 3D RADIATION PATTERNS



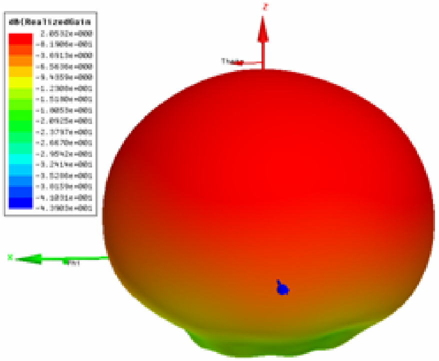
AT 3 GHz



AT 19 GHz



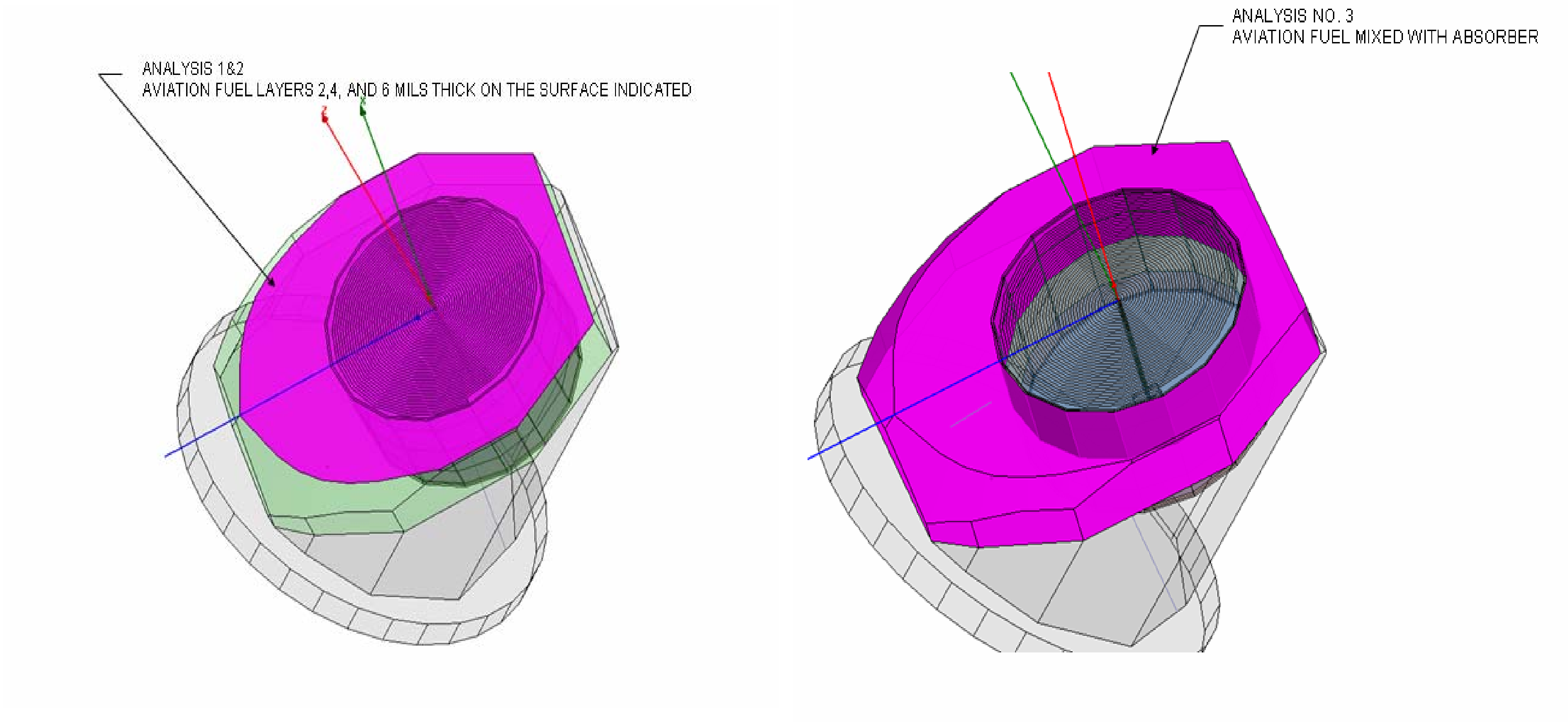
AT 11 GHz



AT 27 GHz

Figure 4

EXAMPLES OF ANALYSIS SCENARIO



(a) (b)

Figure 5

ANALYSIS RESULTS

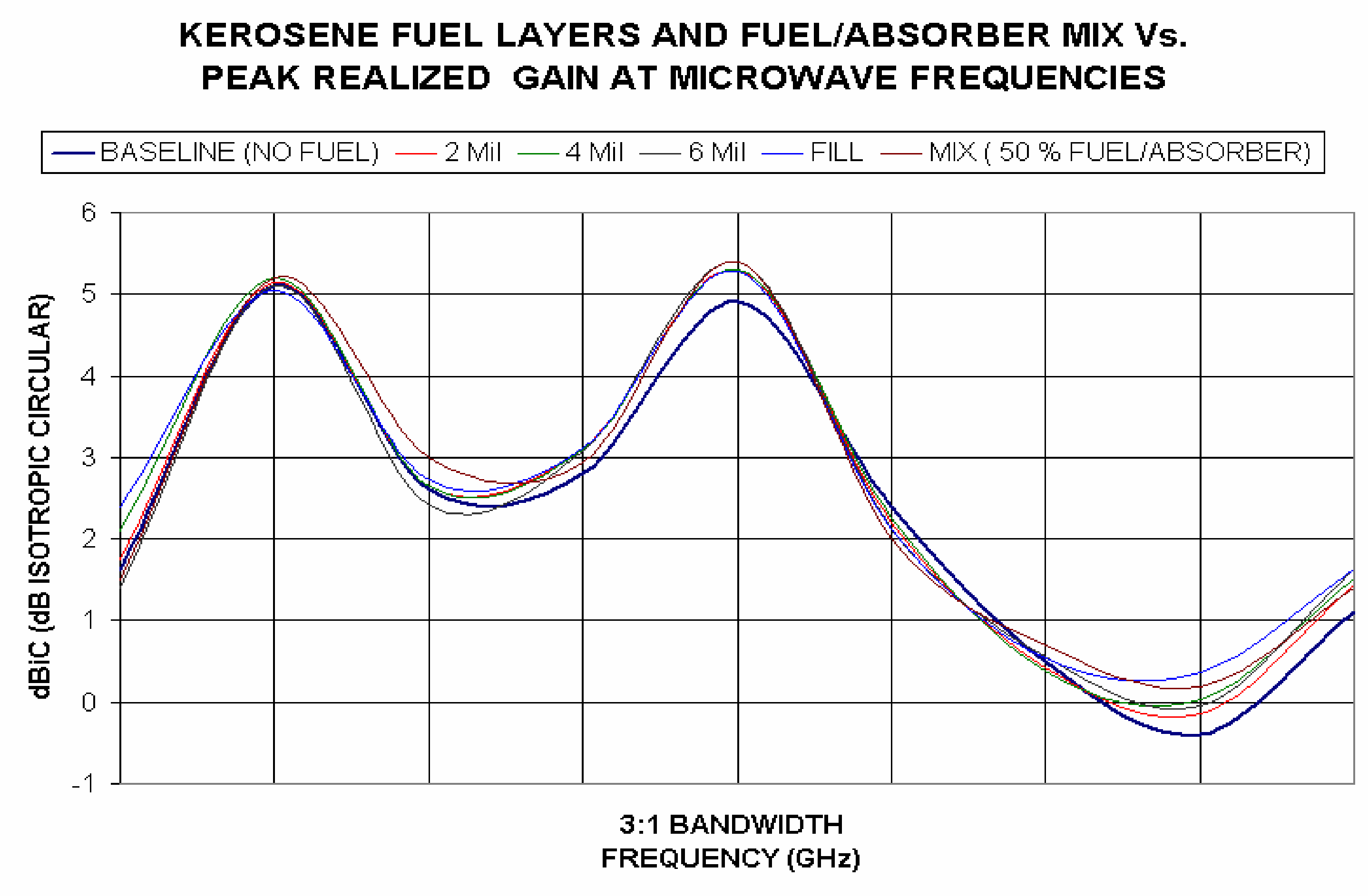
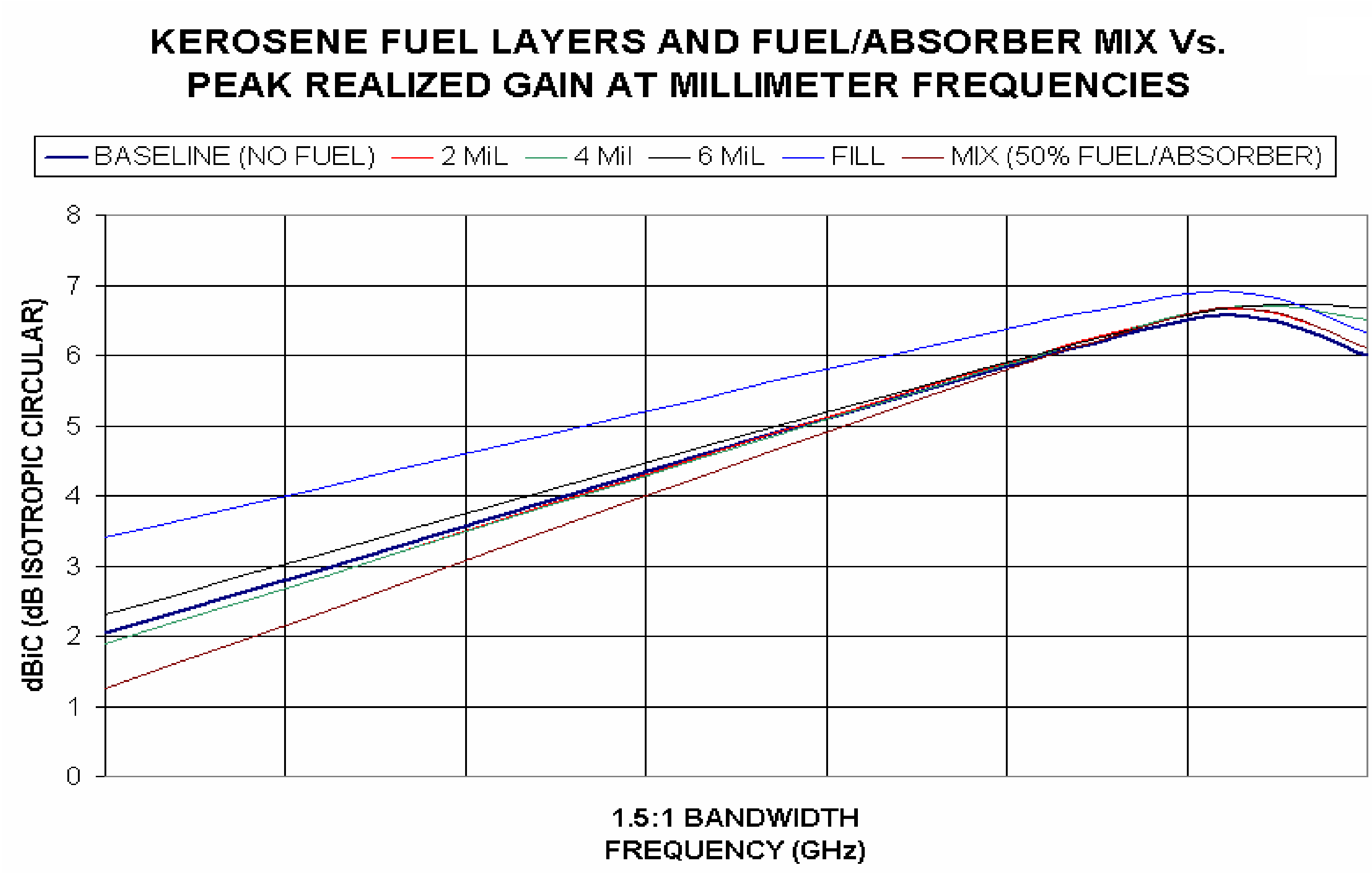


Figure 6

ANALYSIS RESULTS



KEROSENE FUEL LAYERS AND FUEL/ABSORBER MIX Vs.
PEAK REALIZED GAIN AT MILLIMETER FREQUENCIES

Figure 7

ANALYSIS RESULTS

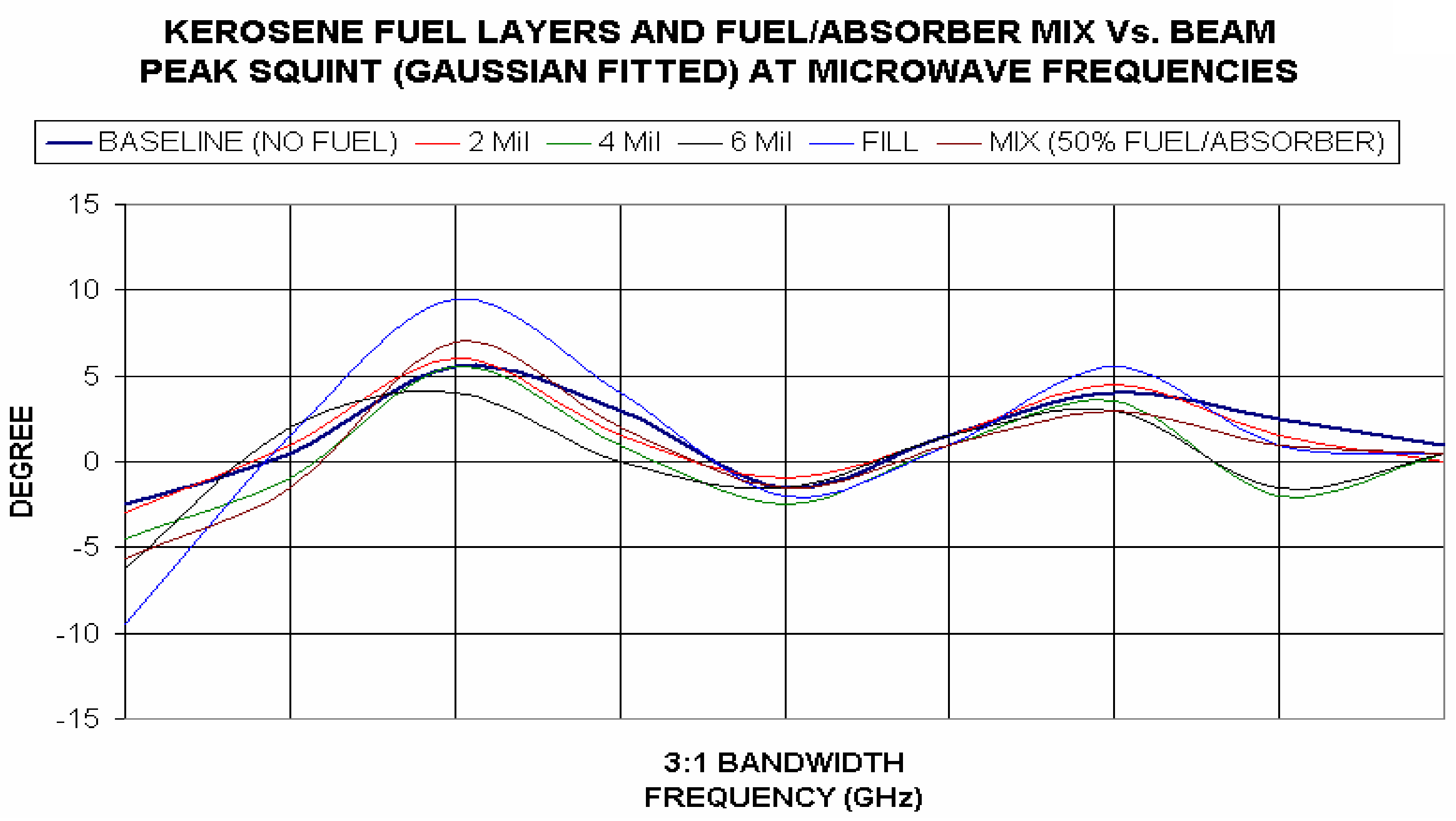


Figure 8

ANALYSIS RESULTS

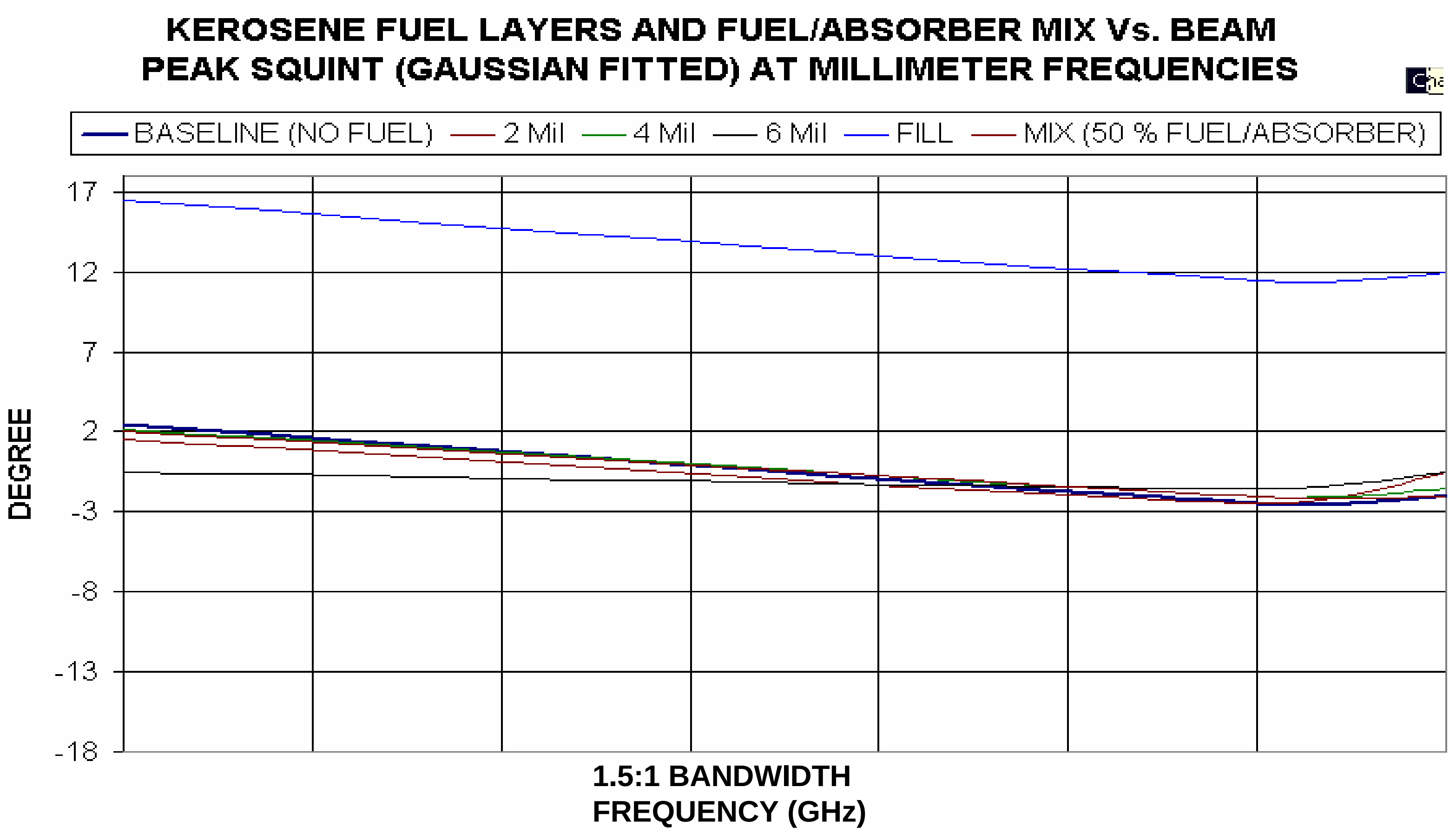

KEROSENE FUEL LAYERS AND FUEL/ABSORBER MIX Vs. BEAM PEAK SQUINT (GAUSSIAN FITTED) AT MILLIMETER FREQUENCIES

Figure 9

ANALYSIS RESULTS

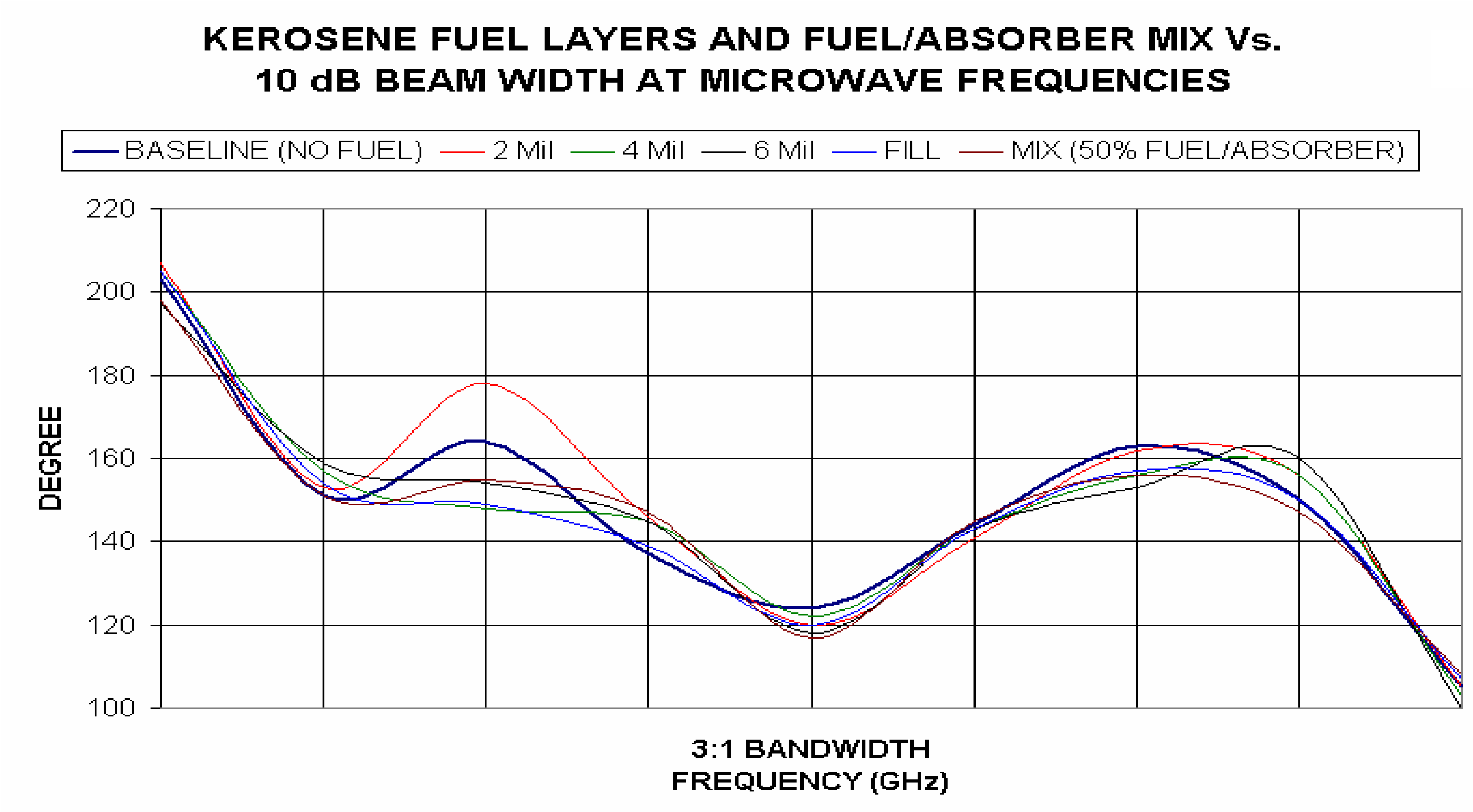

KEROSENE FUEL LAYERS AND FUEL/ABSORBER MIX Vs.
10 dB BEAM WIDTH AT MICROWAVE FREQUENCIES

Figure 10

ANALYSIS RESULTS

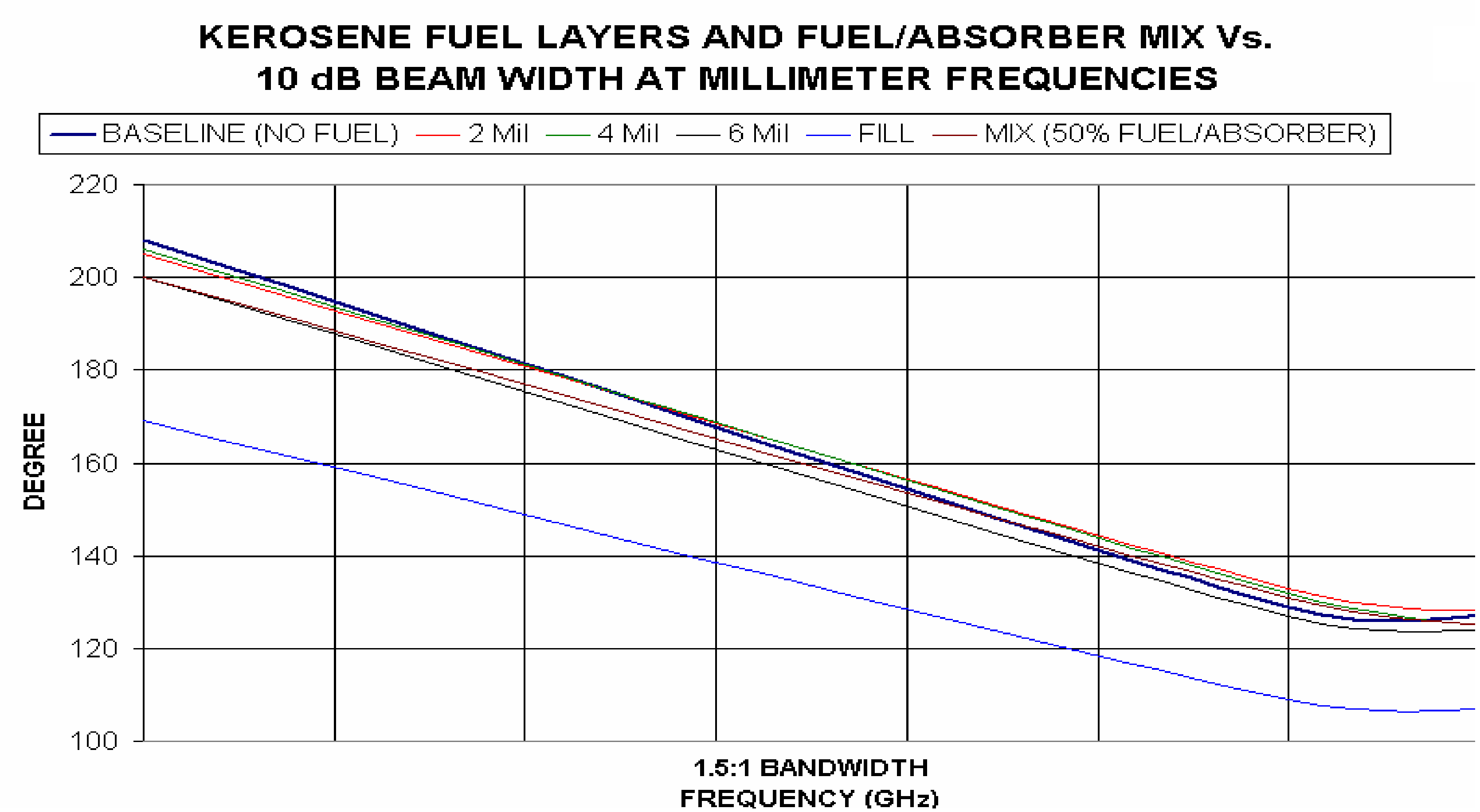


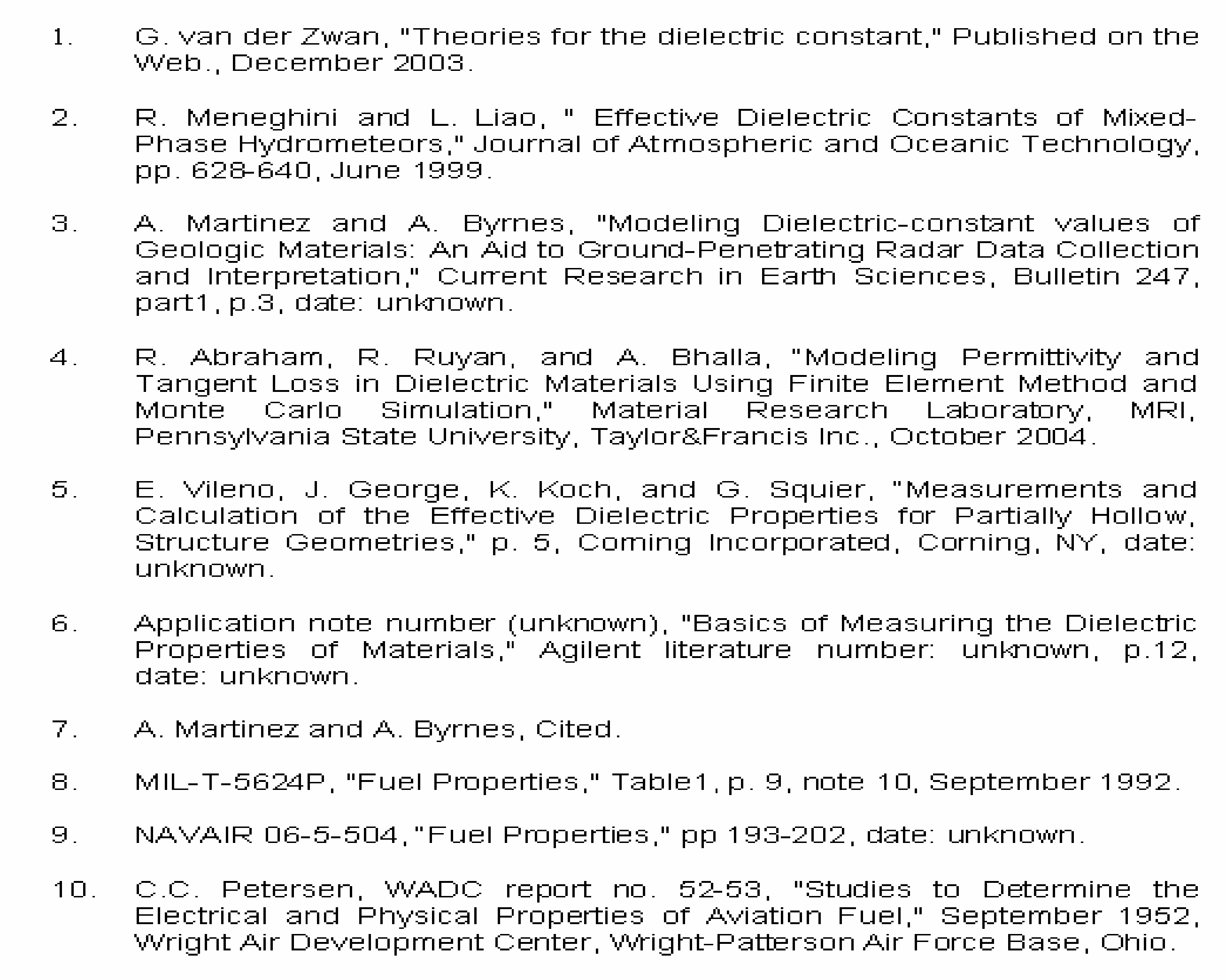
Figure 11

COMMENTS

- The enclosed presentation showed that HFSS and additional formulations can also be used to study environmental factors such as ice, and water that affect antennas performance

Questions

REFERENCES



1. G. van der Zwan, "Theories for the dielectric constant," Published on the Web., December 2003.

2. R. Meneghini and L. Liao, " Effective Dielectric Constants of Mixed-Phase Hydrometeors," Journal of Atmospheric and Oceanic Technology, pp. 628-640, June 1999.

3. A. Martinez and A. Byrnes, "Modeling Dielectric-constant values of Geologic Materials: An Aid to Ground-Penetrating Radar Data Collection and Interpretation," Current Research in Earth Sciences, Bulletin 247, part1, p.3, date: unknown.

4. R. Abraham, R. Ruyan, and A. Bhalla, "Modeling Permittivity and Tangent Loss in Dielectric Materials Using Finite Element Method and Monte Carlo Simulation," Material Research Laboratory, MRI, Pennsylvania State University, Taylor&Francis Inc., October 2004.

5. E. Vileno, J. George, K. Koch, and G. Squier, "Measurements and Calculation of the Effective Dielectric Properties for Partially Hollow, Structure Geometries," p. 5, Coming Incorporated, Corning, NY, date: unknown.

6. Application note number (unknown), "Basics of Measuring the Dielectric Properties of Materials," Agilent literature number: unknown, p.12, date: unknown.

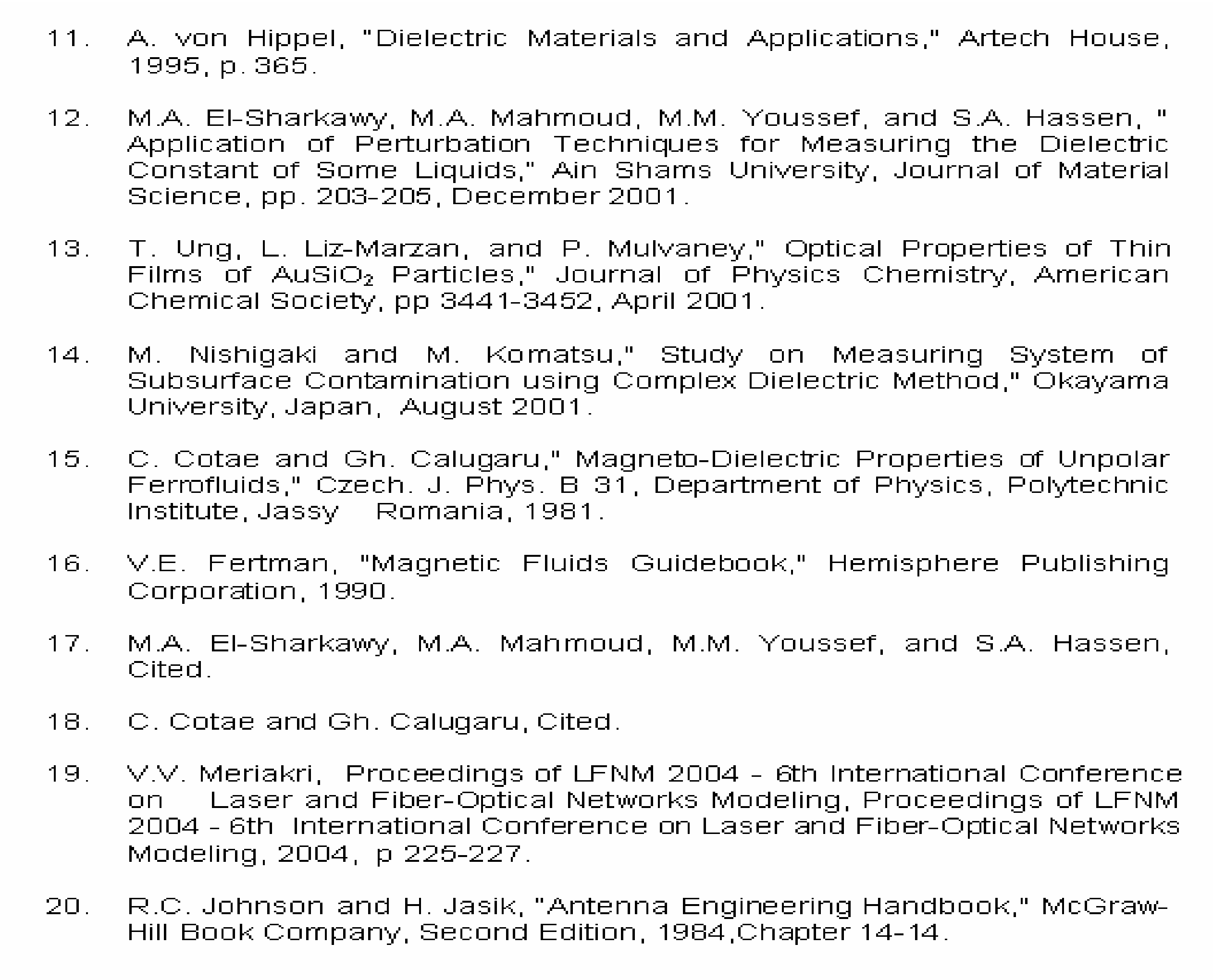
7. A. Martinez and A. Byrnes, Cited.

8. MIL-T-5624P, "Fuel Properties," Table1, p. 9, note 10, September 1992.

9. NAVAIR 06-5-504, "Fuel Properties," pp 193-202, date: unknown.

10. C.C. Petersen, WADC report no. 52-53, "Studies to Determine the Electrical and Physical Properties of Aviation Fuel," September 1952, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.

REFERENCES



11. A. von Hippel, "Dielectric Materials and Applications," Artech House, 1995, p. 365.

12. M.A. El-Sharkawy, M.A. Mahmoud, M.M. Youssef, and S.A. Hassen, " Application of Perturbation Techniques for Measuring the Dielectric Constant of Some Liquids," Ain Shams University, Journal of Material Science, pp. 203-205, December 2001.

13. T. Ung, L. Liz-Marzan, and P. Mulvaney," Optical Properties of Thin Films of $AuSiO_2$ Particles," Journal of Physics Chemistry, American Chemical Society, pp 3441-3452, April 2001.

14. M. Nishigaki and M. Komatsu," Study on Measuring System of Subsurface Contamination using Complex Dielectric Method," Okayama University, Japan, August 2001.

15. C. Cotae and Gh. Calugaru," Magneto-Dielectric Properties of Unpolar Ferrofluids," Czech. J. Phys. B 31, Department of Physics, Polytechnic Institute, Jassy Romania, 1981.

16. V.E. Fertman, "Magnetic Fluids Guidebook," Hemisphere Publishing Corporation, 1990.

17. M.A. El-Sharkawy, M.A. Mahmoud, M.M. Youssef, and S.A. Hassen, Cited.

18. C. Cotae and Gh. Calugaru, Cited.

19. V.V. Meriakri, Proceedings of LFNM 2004 - 6th International Conference on Laser and Fiber-Optical Networks Modeling, Proceedings of LFNM 2004 - 6th International Conference on Laser and Fiber-Optical Networks Modeling, 2004, p 225-227.

20. R.C. Johnson and H. Jasik, "Antenna Engineering Handbook," McGraw-Hill Book Company, Second Edition, 1984,Chapter 14-14.

REFERENCES

21. T. A. Milligan," Modern Antenna Design," McGraw-Hill Book Company, 1985, Chapter 12.

22. V.H. Rumsey, "Frequency Independent Antennas, "1957 IRE National Convention Record, pt. 1, pp 114-118.

23. I. Yildiz, "Design and Construction of Reduced Size Planar Spiral Antenna in the 0.5-18 GHz Frequency Range," Graduate Thesis, Middle East Technical University, October 2004.

24. P. C. Warren," Design, Analysis, and Construction of an Archimedean Spiral Antenna and Feed Structure," IEEE, Session 10D3, Proceedings-1989 Southeastcon.

25. R.W. Kloppenstein," A Transmission Line of Improved Design," Proceedings of the IRE, pp. 31-35, January 1956.

26. J.W. Duncan and V.P. Minerva, "100:1 Bandwidth Balun Transformer," Proceedings of the IRE, pp. 156-164, February 1960.

27. T. Cook and M.C. Cray," Supersonic Radomes in Composite Materials," British Aerospace, Dynamics Group, Stevenage Division, 3rd Technology Conference, Tara Hotel, March 1983.

28. R. L. Cravey," Complex Permittivities of Candidate Radome Materials at W-band," NASA Technical Memorandum 110344, Langley Research Center, Hampton, Virginia 23681

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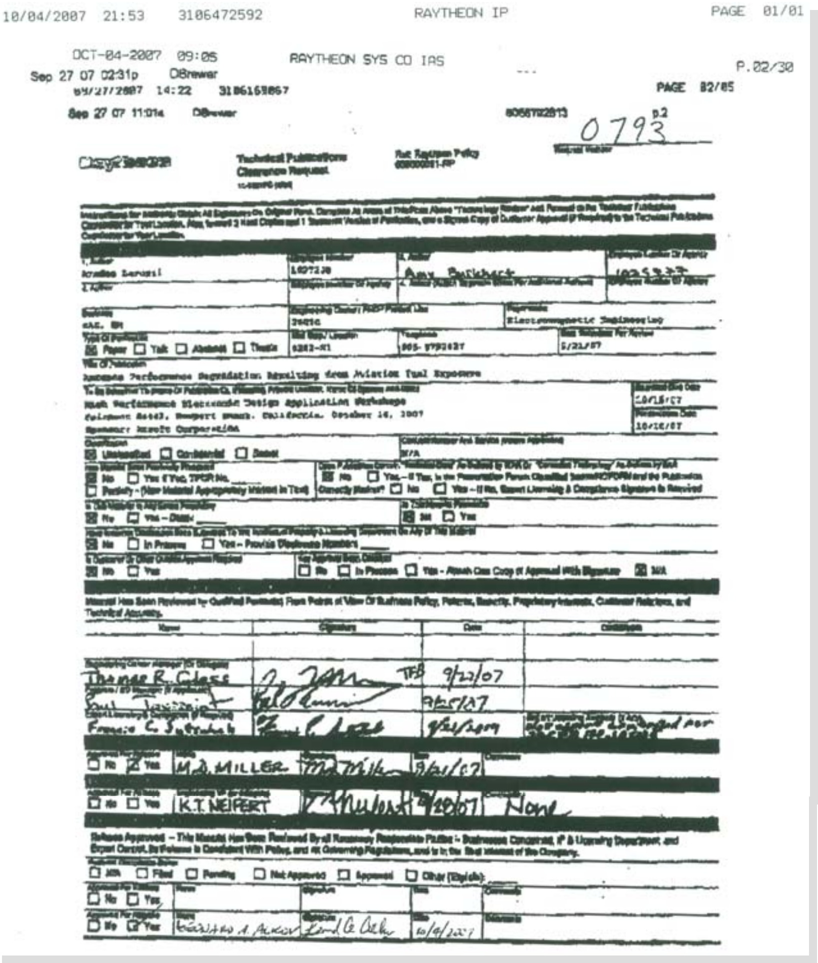
Authorization



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