A Wideband Coaxial Technique for Measuring Permittivity of Materials at Microwave Frequencies

by Robert Tan

19960617 094

REPORT DOCUMENTATION PAGE

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 Operations 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 June 1996	3. REPORT TYPE AND DATES COVERED Final, from 6/14/94 to 3/12/95

4. TITLE AND SUBTITLE A Wideband Coaxial Technique for Measuring Permittivity of Materials at Microwave Frequencies	5. FUNDING NUMBERS PE: 62120
6. AUTHOR(S) Robert Tan	

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory Attn: AMSRL-WT-NF 2800 Powder Mill Road Adelphi, MD 20783-1197	8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-1082
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory 2800 Powder Mill Road Adelphi, MD 20783-1197	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

AMS code: 622120.1400011
ARL PR: 6WM841

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

An analytical solution for the intrinsic impedance of a material is applied to a method of measuring the dielectric and loss tangent with the use of a coaxial test fixture and a vector network analyzer. The use of the equations is best suited for determining the electrical properties of lossy dielectrics over large frequency ranges. The method is unique in that it is not a numerical technique nor does it neglect reflections from any of the material surfaces.

14. SUBJECT TERMS permittivity, microwave			15. NUMBER OF PAGES 13
			16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

1

Contents

Figures

1. Introduction

An analytical solution for the intrinsic impedance of a material has been found, given the transmitted and reflected transverse electromagnetic (TEM) wave, for the classical three-region problem. This problem is illustrated in figure 1, where regions one and three are air, and region two is the material under test.

Equations (1) and (2) are the well-known solutions for the transmitted and reflected TEM waves.

$$S_{21} = \frac{4e^{-idk}\eta_0\eta_2}{(\eta_0 + \eta_2)^2 \dfrac{1 - e^{-2idk}(\eta_0 - \eta_2)^2}{(\eta_0 + \eta_2)^2}} \cdot \tag{1}$$

$$S_{11} = \frac{-\eta_0 + \dfrac{\eta_2\left(1 + \dfrac{e^{-2idk}\left(\eta_0 - \eta_2\right)}{\eta_0 - \eta_2}\right)}{1 - \dfrac{e^{-2idk}\left(\eta_0 - \eta_2\right)}{\eta_0 + \eta_2}}}{\eta_0 + \dfrac{\eta_2\left(1 + \dfrac{e^{-2idk}\left(\eta_0 - \eta_2\right)}{\left(\eta_0 - \eta_2\right)}\right)}{1 - \dfrac{e^{-2idk}\left(\eta_0 - \eta_2\right)}{\eta_0 + \eta_2}}} , \tag{2}$$

where d = region length and k = wave number. Mathematica™ was used to solve these equations in terms of the intrinsic impedance of the material η_2; regions one and three have the same intrinsic impedance η_0. This solution is unique [1,2] in that it is not a numerical solution nor does it neglect reflections from the interface of region 2 with region 3. The solution can be used along with coaxial vector network analyzer measurements to provide a simple way of determining the intrinsic impedance and permittivity of nonmagnetic materials. The technique described in this paper is complementary to cavity methods: it is best suited for lossy materials over large

Figure 1. Classical three-region problem: regions one and three are air, and region two is the material under test.

Region 1 $\eta_0 = 377$ Region 2 η_2 Region 3 $\eta_0 = 377$

Planewave incident

S_{21}

S_{11}
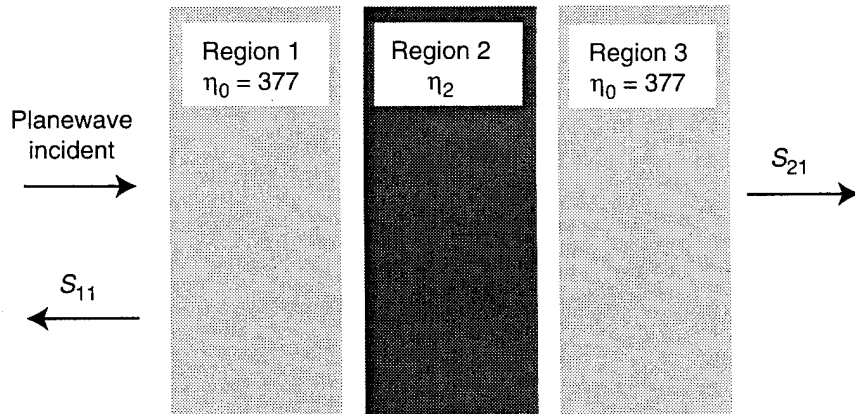
frequency ranges, whereas cavity techniques are better suited for measuring low-loss materials at single frequencies.

2. Calculations

Solving equation (2) for k results in

$$k = -\frac{i}{d}\ln\frac{-\sqrt{-\eta_2^2 + S_{11}\,\eta_2^2 - 2S_{11}\,\eta_2\eta_0 + \eta_0^2 + S_{11}\,\eta_0^2}}{\sqrt{-\eta_2^2 + S_{11}\,\eta_2^2 + 2S_{11}\,\eta_2\eta_0 + \eta_0^2 + S_{11}\,\eta_0^2}} \,. \tag{3}$$

Substituting k from equation (3) into equation (1) gives S_{21} (eq (4)) as a function of S_{11}, η_0, and η_2:

$$S_{21} = \frac{-4\,\eta_0\eta_2\sqrt{-\eta_2^2 + S_{11}\,\eta_2^2 + 2S_{11}\,\eta_2\eta_0 + \eta_0^2 + S_{11}\,\eta_0^2}}{\left(\eta_0 + \eta_2\right)^2\sqrt{-\eta_2^2 + S_{11}\,\eta_2^2 - 2S_{11}\,\eta_2\eta_0 + \eta_0^2 + S_{11}\,\eta_0^2}\left(1 - \dfrac{\left(\eta_0 - \eta_2^2\right)\left(-\eta_2^2 + S_{11}\,\eta_2^2 + 2S_{11}\,\eta_2\eta_0 + \eta_0^2 + S_{11}\,\eta_0^2\right)}{\left(\eta_0 + \eta_2^2\right)\left(-\eta_2^2 + S_{11}\,\eta_2^2 - 2S_{11}\,\eta_2\eta_0 + \eta_0^2 + S_{11}\,\eta_0^2\right)}\right)} \,. \tag{4}$$

Now, solving equation (4) for η_2 and letting $\eta_0 = 376.789\ \Omega$ for air results in equation (5), which expresses the intrinsic impedance of the material in terms of the scattering parameters S_{11} and S_{21}:

$$\eta_2 = \frac{376.789\sqrt{-1 - 2S_{11} - S_{11}^2 + S_{21}^2}}{\sqrt{-1 + 2S_{11} - S_{11}^2 + S_{21}^2}} \,. \tag{5}$$

S_{11} and S_{21} in equation (5) are in terms of voltage and are complex numbers. The dielectric constant and loss tangent can then be calculated from the intrinsic impedance, if the material is nonmagnetic. The intrinsic impedance η equals $(z/y)^{1/2}$, where $y = \omega\varepsilon'' + j\omega\varepsilon'$, and $z = \omega\mu'' + j\omega\mu'$ [3]. If we let $\mu'' = 0$ for no magnetic losses and solve for the complex permittivity ε, in terms of permeability (μ') and η, we get

$$\varepsilon' - j\varepsilon'' = \mu'/\eta, \tag{6}$$

where the relative dielectric constant, ε_r, is $\varepsilon'/\varepsilon_0$, and the loss tangent, $\tan\delta$, is $\varepsilon''/\varepsilon'$ [3]. A program was written using PV-wave™ that solves for ε' and ε'' as a function of frequency, using equation (5) to determine the intrinsic impedance and equation (6), with $\mu' = 4\pi \times 10^{-7}$ H/m (free space μ_0), to determine permittivity, given measured S-parameters as a function of frequency.

3. Limitations

When $\tan\delta$ is at or below about 0.1, there are errors at frequencies where the material sample is an integer multiple of a half wavelength because the magnitude of S_{11} is such a small number. But these errors are easily recognized as stray points at integer multiples of a half wavelength. When $\tan\delta$

is at or below about 0.01, the imaginary part of permittivity ε_r'' tends to have large error simply because the numbers are so small. Also, the phase of S_{11} cannot be accurately measured for small magnitudes of S_{11}; therefore, if accurate results are desired for the imaginary part of the permittivity, the use of the equations will be limited to lossy dielectric materials ($\tan \delta > 0.1$).

4. Experimental Results

The National Institute of Standards and Technology (NIST) supplied S-parameter measurements for two dielectric material samples, cross-linked polystyrene and nylon. A 7-mm-diameter, 10-cm-long air line coaxial fixture was used to make the measurements. The cross-linked polystyrene and nylon were 55 and 15 mm long, respectively. The samples were placed in the air line such that the sample was flush with the port 1 side of the coaxial air line, and S-parameter measurements were made on a vector network analyzer from 10 MHz to 1 GHz. The relative permittivities—ε_r' and ε_r'', of cross-linked polystyrene and nylon, respectively—were calculated with the use of the program described above, but with corrections for the phase of S_{21} because the material samples were shorter than the air line. Corrections were also used to account for the small air gaps between the center conductor and the material and the outer conductor and the material [4]. The results compare with results given by NIST, which used its EPSMU software [4], with relatively good agreement, despite the low $\tan \delta$ (<0.1) of both nylon and cross-linked polystyrene (see fig. 2 and 3). The curve in the data near 10 MHz is attributed to the accuracy of the S-parameter measurements at these low frequencies. *

Figure 2. Comparison of ARL's calculations and NIST's EPSMU software: (a) ε_r' plotted as a function of frequency for nylon.
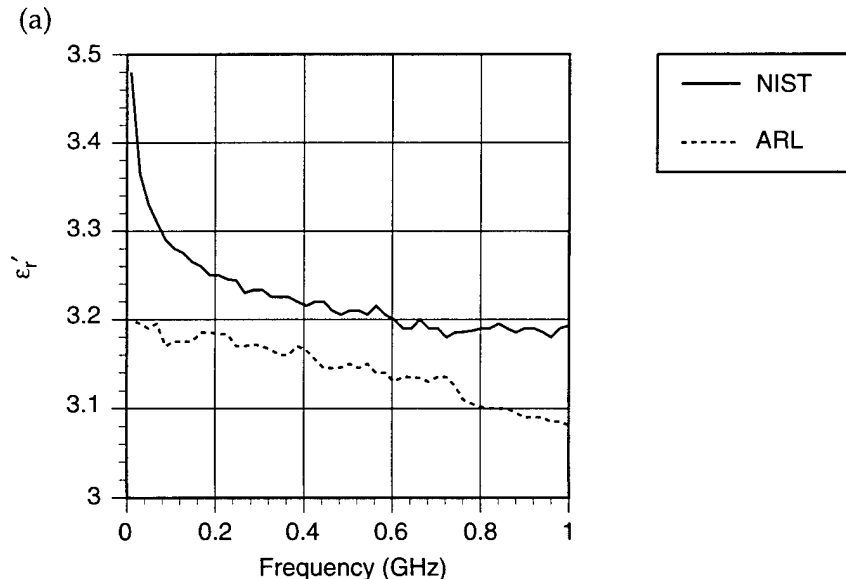
Discussion with M. Janezic of National Institute of Standards and Technology, April 1995.

Figure 2 (cont'd). Comparison of ARL's calculations and NIST's EPSMU software: (b) ε_r'' plotted as a function of frequency for nylon.
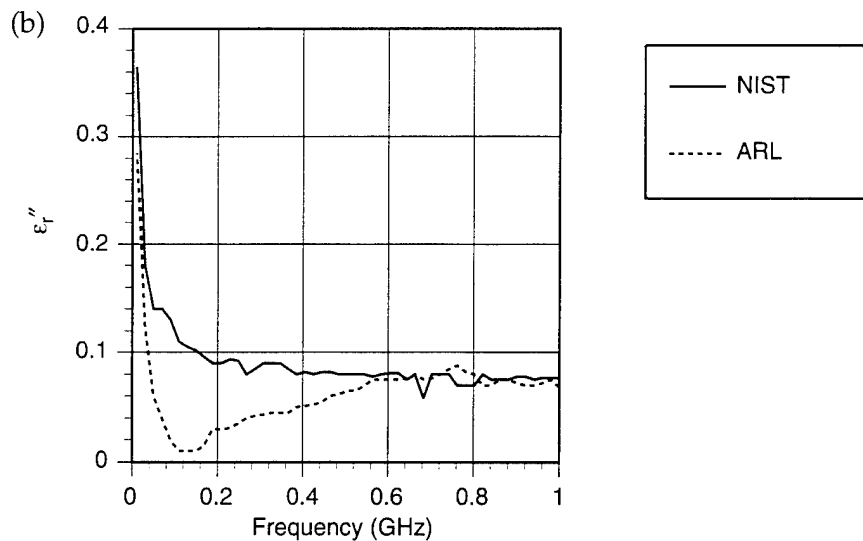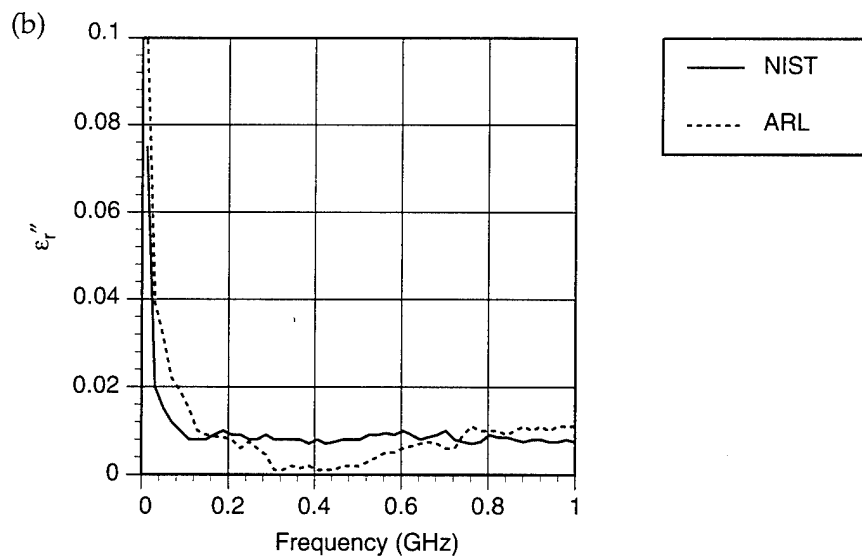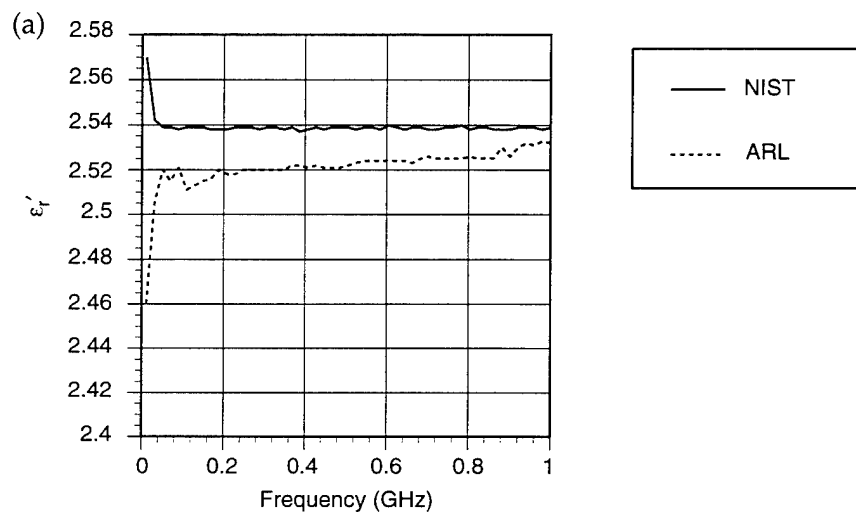
Figure 3. Comparison of ARL's calculations and NIST's EPSMU software: (a) ε_r' and (b) ε_r'' plotted as a function of frequency for crosslinked polystyrene.

5. Discussion and Conclusions

Using equation (5), the intrinsic impedance of a material (including magnetic materials) can be calculated from S-parameter measurements of a simple coaxial test fixture containing the material. The complex permittivity can be calculated from the intrinsic impedance using equation (6) if the material is nonmagnetic. The technique is intended to provide a simple way to determine the intrinsic impedance and/or the permittivity of nonmagnetic materials. The equations can be solved on a scientific calculator or, preferably, by a simple program. If accurate results are desired for the loss-tangent, then the measurement technique is limited to lossy dielectrics. One should keep in mind that the measurement is related to the physics of the S-parameter measurements. At frequencies where the material sample is an integer multiple of a half wavelength, there are larger errors, especially if it is a low-loss material. These errors result because, at these frequencies, the magnitude S_{11} tends to be a very small number; also, phase error in the network analyzer measurement increases as the magnitude of the signal decreases. The materials measurement is only as good as the S-parameter measurements.

References

1. A. Nicolson, "Measurement of the Intrinsic Properties of Materials by Time-Domain Techniques," *IEEE Trans. Inst. Meas.* **19**, No. 4, November 1970, pp 377–382.

2. Ching-Lieh Li and Kun-Mu Chen, "Determination of Electromagnetic Properties of Materials Using Flanged Open-Ended Coaxial Probe-Full-Wave Analysis," *IEEE Trans. Inst. Meas.* **44**, No. 1, February 1995, pp 19–27.

3. R. Herrington, *Time-Harmonic Electromagnetic Fields*, McGraw-Hill, 1961.

4. J. Baker-Jarvis, M. Janezic, J. Grosvenor, Jr., and R. Geyer, *Transmission/ Reflection and Short-Circuit Line Methods for Measuring Permeability*, National Institute of Standards and Technology (NIST) Technical Note 1355-R, December 1993.

Distribution

Admnstr
Defns Techl Info Ctr
Attn DTIC-OCP
8725 John J Kingman Rd Ste 0944
FT Belvoir VA 22060-6218

Advncd Rsrch Proj Agcy
Attn DSO B Hui
3701 N Fairfax Dr
Arlington VA 22203

HQ
Dfns Nuc Agcy
Attn RAEE G Baker
Attn RAEE LTC M Lynch
6801 Telegraph Rd
Alexandria VA 22310-3398

Ofc of the Secy of Defs
Attn ODDRE/R & AT-ET S Gontarek
The Pentagon
Washington DC 20301

Army Matl Comnd
Attn AMCRD-AR J Aveta
5001 Eisenhower Ave
Alexandria VA 22333-0001

HQ, Dept of the Army
Dep Chf of Staf Oprs & Plns
Attn DAMO-FDI LTC R Morton
Room 2C536 The Pentagon
Washington DC 20310-0460

Ofc of the Assist Scy of the Army for Rsrch
  Dev & Acqstn
Attn SARD-TT Dr F Milton
Attn SARD-TT C Nash
Rm 3E479 The Pentagon
Washington DC 20310-0103

US Army CECOM
Attn AMSEL-RD-NV-ADS-SP R Irwin
Attn AMSEL-RD-NV-ADS-SP R Torisio
FT Monmouth NJ 07703-5206

US Army BRDEC
Attn STRBE-NA R Weaver
FT Belvoir VA 22060-5606

US Army CECOM Intllgnc/Elect Warfare
  Drctrt
Attn AMSEL-RD-IEW-SPO D Helm
Vint Hill Farm Sta
Warrenton VA 22186-5100

Comdt
US Army Infantry Schl
Attn ATSH-CD-E K Sines
FT Benning GA 31905-5400

Cmdr
US Army Matl Cmnd
Attn AMCAQ-AP J Kreck
5001 Eisenhower Ave
Alexandria VA 22333-0001

US Army Mis Cmnd
Attn AMSMI-RD-WS-UB R D Barber
Attn AMSMI-RD-WS-UB D Holder
Redstone Arsenal AL 35898-5000

US Army Night Vision & Electronic Sensor
Attn AMSEL-RD-NV-ADS-SP M Kovach
FT Monmouth NJ 07703-5206

US Army Prgm Mgr—Firefinder
Attn SFAE-IEW-FF A Dirienzo
FT Monmouth NJ 07703-5305

Cmdr
US Army Sp & Strtgc Defns Comnd
Attn CSSD-AT-C I Merritt
Attn CSSD-EC-E R Berg
PO Box 1500
Huntsville Al 35807-3801

US Army TRADOC
Attn ATCD-G J Gray
FT Monroe VA 23651

Distribution

Nvl Rsrch Lab
Attn Code 4650 T Andreadis
Attn Code 4650 T Wieting
4555 Overlook Avenue SW
Washington DC 20375-5000

Sp & Nav Warfare Systs Comnd
Attn SPAWAR 332 J Albertine
2451 Crystal Park
Arlington VA 22245-5200

US Air Force
Rome Lab
Attn ERPT T Pesta
Griffiss AFB NY 13441-5700

Depart of the Air Force
US Air Force Phillips Lab
Attn PL/WS W L Baker Bldg 413
Attn PL/WSH H Dogliani
Attn PL/WSH M Harrison
Attn PL/WSH S Mason
Attn PL/WSH W Snyder
Attn PL/WSM P Vail Bldg 909
3550 Aberdeen Ave SE
Kirtland AFB NM 87117-5776

Cmdr
Wright Rsrch Dev Ctr
Attn WRDC/ELM T Kemerley
Bldg 620 Area B
Wright Patterson AFB OH 45433-7408

Lawrence Livermore Natl Lab
Attn L-86 H S Cabayan
PO Box 808
Livermore CA 94550

IITRI
Electromagnetic Compatability Anlys Ctr
Attn J Weidner
185 Admiral Cochrane Dr
Annapolis MD 21402

Jaycor
Attn W Crevier
3700 State Stret Ste 300
Santa Barbara CA 93105

Mssn Rsrch Corp
Attn J McAdoo
Attn M Bollen
8560 Cinderbed Rd
Newington VA 22122

Sci Applications Intrntl Corp
Attn MS 2-3-1 G Bergeron
1710 Goodridge Dr
McLean VA 22102

SRI Intrntl
Attn G August
333 Ravenswood Ave
Menlo Park CA 94025

Teledyne Brown Engrg
Attn R E Lewis
Cummings Research Park
Huntsville AL 35807-7007

US Army Rsrch Lab
Attn AMSRL-WT I May
Attn AMSRL-SL J Wade
Attn AMSRL-WT J Rocchio
Attn AMSRL-WT G Klem
Attn AMSRL-SL-I D Bassett
Bldg 433
Aberdeen Proving Ground MD 21005-5001

US Army Research
Attn AMSRL-SL-EA G Mares
Attn AMSRL-SL-EA J Palomo
White Sands Missile Range NM 88002-5513

US Army Rsrch Lab
Attn AMSRL-EP-IA E Baidy
Attn AMSRL-EP-M V Gelnovatch

Distribution

US Army Rsrch Lab (cont'd)
Attn AMSRL-EP-RA E Hakim
Attn AMSRL-SL-EI J Nowak
FT Monmouth NJ 07703

US Army Rsrch Lab
Attn AMSRL-IS-TA C Glenn
Attn AMSRL-OP-SD-TA Mail & Records
  Mgmt
Attn AMSRL-OP-SD-TL Tech Library
  (3 copies)
Attn AMSRL-OP-SD-TP Tech Pub (5 copies)

US Army Rsrch Lab (cont'd)
Attn AMSRL-SE-RU J McCorkle
Attn AMSRL-WT-N E Scannell
Attn AMSRL-WT-NA R A Kehs
Attn AMSRL-WT-NF L Jasper
Attn AMSRL-WT-NF R Kaul
Attn AMSRL-WT-NF R Tan (10 copies)
Attn AMSRL-WT-NF T Bock
Attn AMSRL-WT-NH G Huttlin
Attn AMSRL-WT-NH J Corrigan
Adelphi MD 20783-1197