TOPIC: NDE ACTIVITY AT JPL.

Our speaker will review the NDE technology under development at the Jet Propulsion Lab (JPL). Emphasis will be given to Ultrasonics and application of sensors to space technology. Further, the efforts of JPL in technology transfer to the industry in the area of NDE will be covered.

ABOUT OUR SPEAKER: Dr. Yoseph Bar-Cohen is the NDE Principal Investigator at Jet Propulsion Laboratory (JPL). Dr. Bar-Cohen has about 22 years experience working on research and development of NDE methods for defects detection and characterization and materials properties determination. He received his Ph. D. in Physics from the Hebrew University of Jerusalem in 1979. He has numerous papers, patents, and presentations al national and international conferences and he co-pioneered the development of the leaky Lamb waves and polar backscattering methods for NDE of composites. Dr. Bar-Cohen is also an Adjunct Professor at the University of California, at Los Angeles (UCLA).

NEED FOR NDE OF COMPOSITES

* COMPOSITE STRUCTURES CAN BE TAILORED SUPERIOR TO METALS

* DAMAGE TOLERANCE IS CHALLENGED BY DEFECTS . COMPLEX FAILURE MECHANISM AND LACK OF COMPREHENSIVE THEORY

* QUANTITATIVE NDE EMPLOYING IMBEDDED/ATTACHED/REMOTE SENSORS ARE KEY TO THE USE OF MATERIAL FULL POTENTIAL

* ACTUATORS-SENSORS CAN MAKE SMART MATERIALS AND STRUCTURES

JPL'S NDE MAJOR TOPICS

* METHODS OF DEFECTS DETECTION AND CHARACTERIZATION
* MATERIAL PROPERTIES DETERMINATION
* SENSORS FOR IN-PROCESS. IN-SERVICE. AND IN-FLIGHT MONITORING
* ESTABLISH PROCESS SPECIFICATIONS

EFFECT OF DEFECTS

POROSITY

- DEGRADES MATRIX-DOMINATED PROPERTIES
- 1% POROSITY REDUCES STRENGTH BY 5% AND FATIGUE LIFE BY 50%
- INCREASES EQUILIBRIUM MOISTURE LEVELS
- AGGRAVATES THERMAL-SPIKE PHENOMENA

PLY GAP

- DEPENDS ON STACKING ORDER AND LOCATION,
  FOR $[0°, +45°, 90°, -45°]_{2S}$ LAMINATE;
  8,7% STRENGTH REDUCTION DUE TO GAP(S) IN 0° PLIES
  16.9% REDUCTION DUE TO GAP(S) IN 90° PLIES

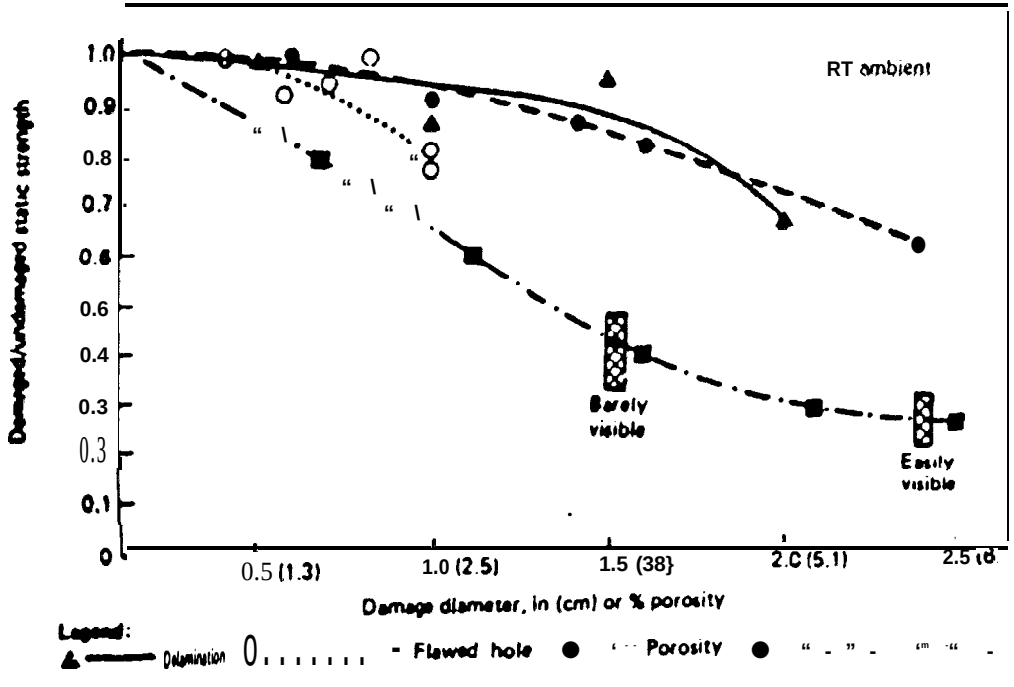
PLY WAVINESS

- STRENGTH LOSS CAN BE PREDICTED BY ASSUMING LOSS OF LOAD-CARRYING CAPACITY DUE TO THE WAVINESS
- FOR 0° WAVINESS IN $[0°,45°,90°,-45°]_{2S}$ LAMINATE, STATIC STRENGTH REDUCTION IS:
  - 10% FOR SLIGHT WAVINESS
  - 25% FOR EXTREME WAVINESS
- FATIGUE LIFE IS REDUCED AT LEAST BY A FACTOR OF 10

SURFACE NOTCHES

- STATIC-STRENGTH REDUCTION UP TO 50%
- LOCAL DELAMINATION AT NOTCH
- STRENGTH REDUCTION IS SMALL FOR SIZES EXPECTED IN SERVICE

REFERENCE: BOEING STUDY BETWEEN 1982 TO 1987, "DAMAGE TOLERANCE OF COMPOSITES", AFWAL-TR-87-3030 VOL. I or AD-B144-937 "DEVELOPMENT OF REQUIREMENTS AND COMPLIANCE DEMONSTRATION", page 24.



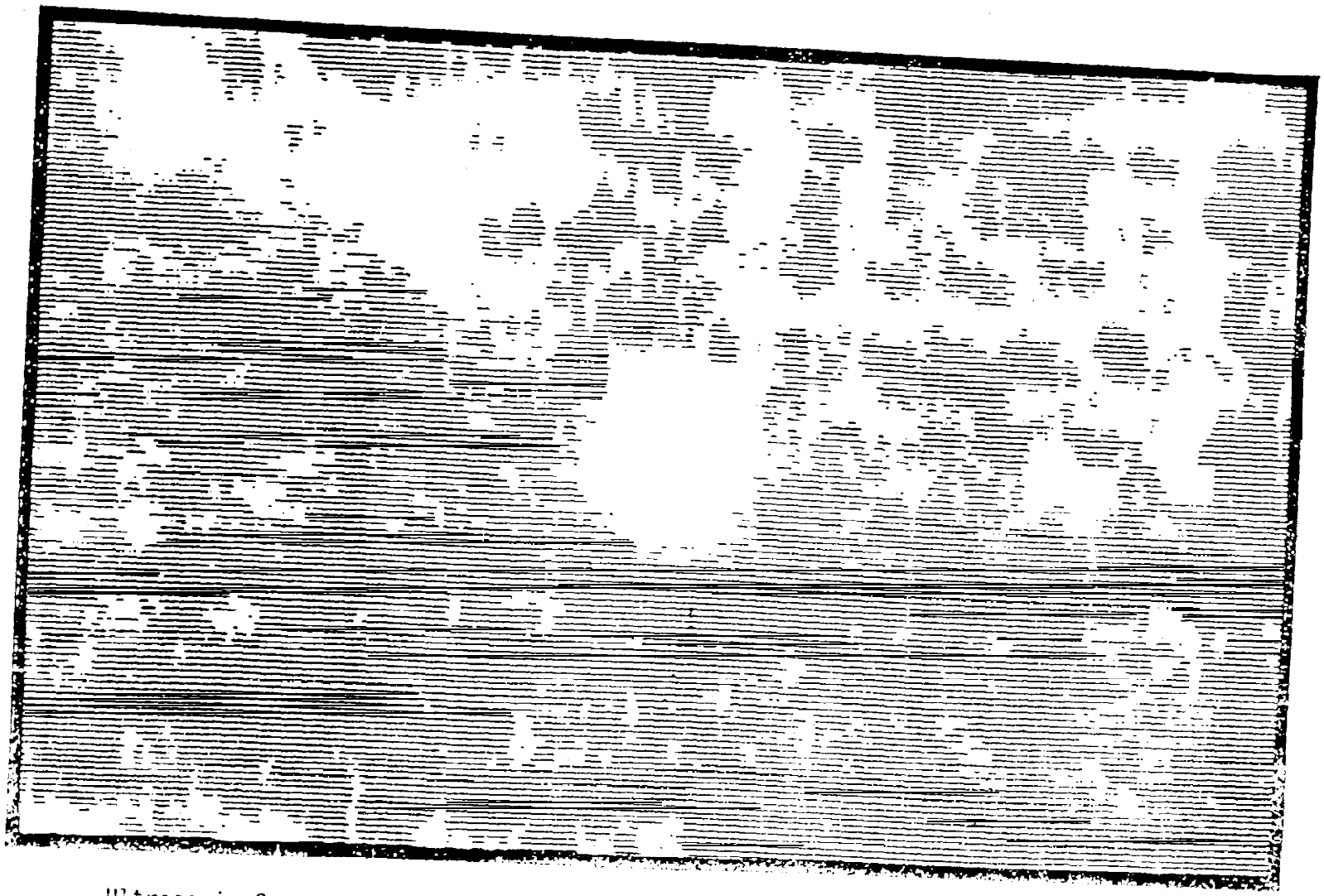
DEFECT/DAMAGE SEVERITY COMPARISON - STATIC STRENGTH (COMPRESSION) .

NDE METHODS FOR FRP COMPOSITES

1. ULTRASONICS
2. RADIOGRAPHY
3. HOLOGRAPHY/SHEAROGRAPHY
4. ACOUSTICS
5. THERMOGRAPHY
6. NMR
7. EDDY CURRENT
8. MICROWAVES
9. ACOUSTIC EMISSION
10. VISUAL INSPECTION
11. LIQUID PENETRANT
12. TAP TESTING

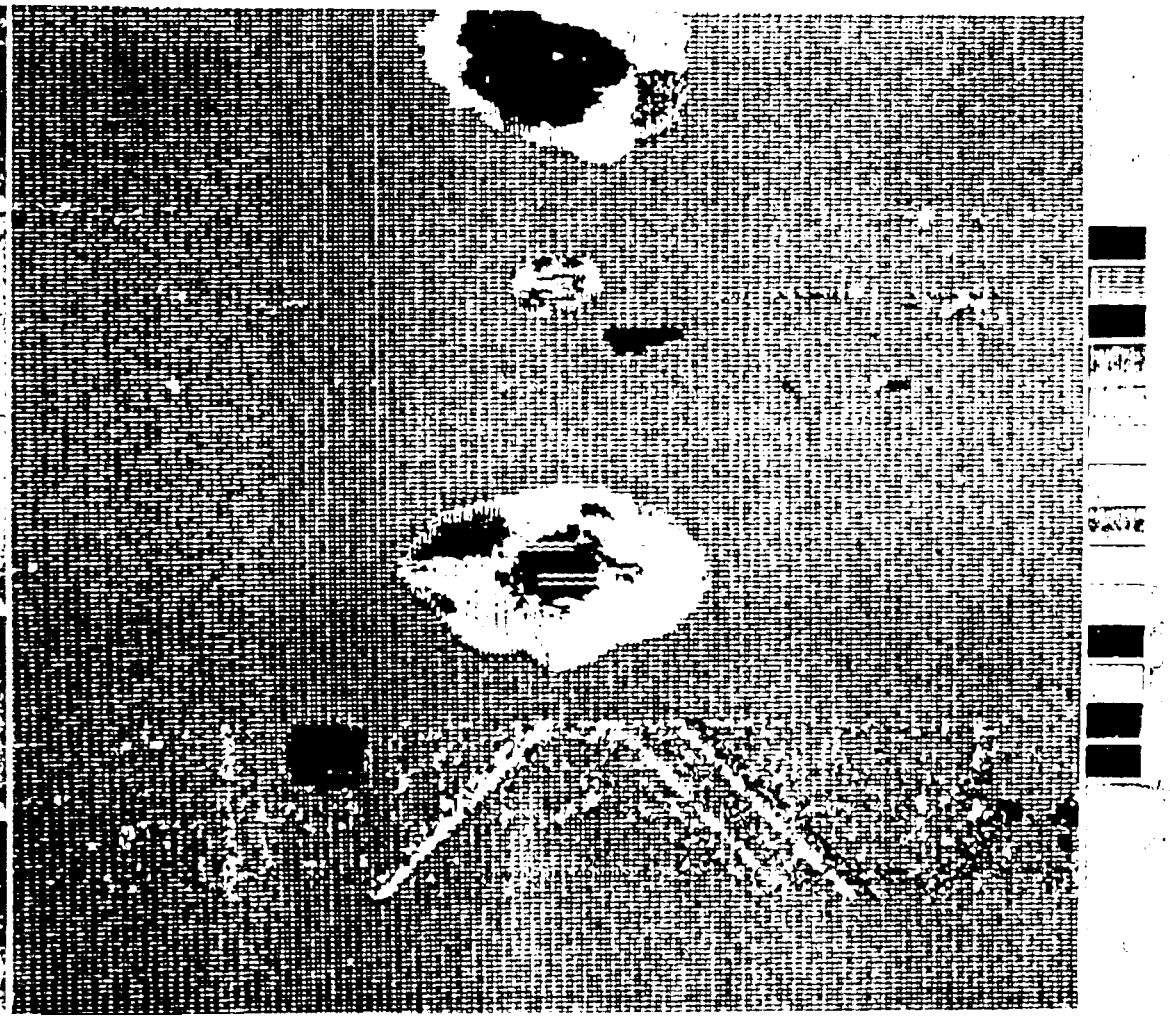
NDE METHODS FOR MMC

1. ULTRASONICS
2. RADIOGRAPHY
3. EDDY CURRENT
4. ACOUSTIC EMISSION
5. VISUAL INSPECTION
6. ACOUSTICS
7. THERMOGRAPHY
8. LIQUID PENETRANT
9. TAP TESTING

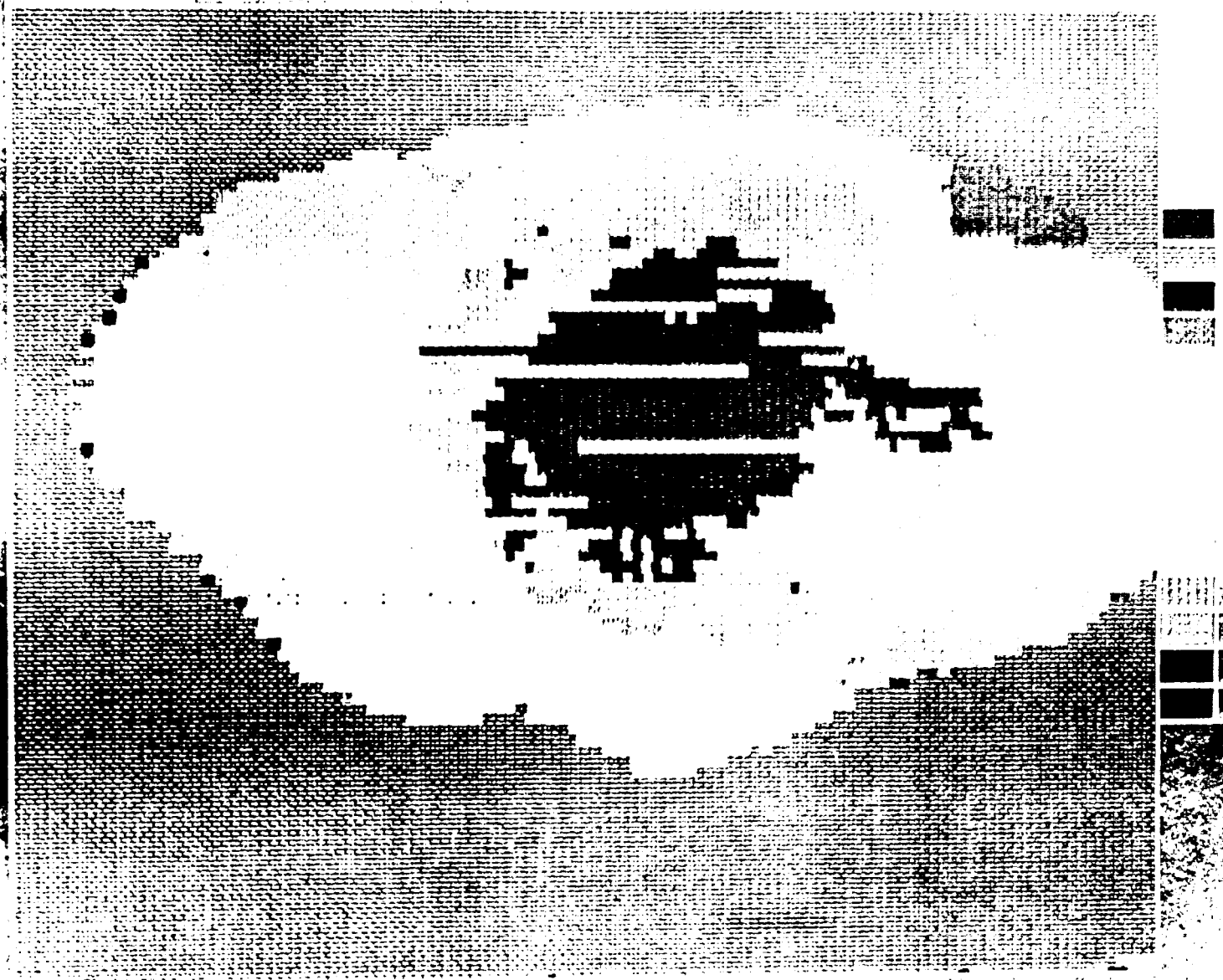


Ultrasonic C-scan of a graphite/Epoxy laminate with delaminations and porosity.

TOF C-SCAN OF IMPACT
DAMAGED
SUPPORTED HORI



DAMAGED
SUPPORTED HORIZONTALLY
ZOOM ON



COMPUTERIZED C-SCAN IMAGING OF IMPACT DAMAGE IN Gr/Ep LAMINATE

DATA HAS BEEN ROTATED IN A MANNER THAT ALLOWS A SIDE VIEW

84-GEN-21211

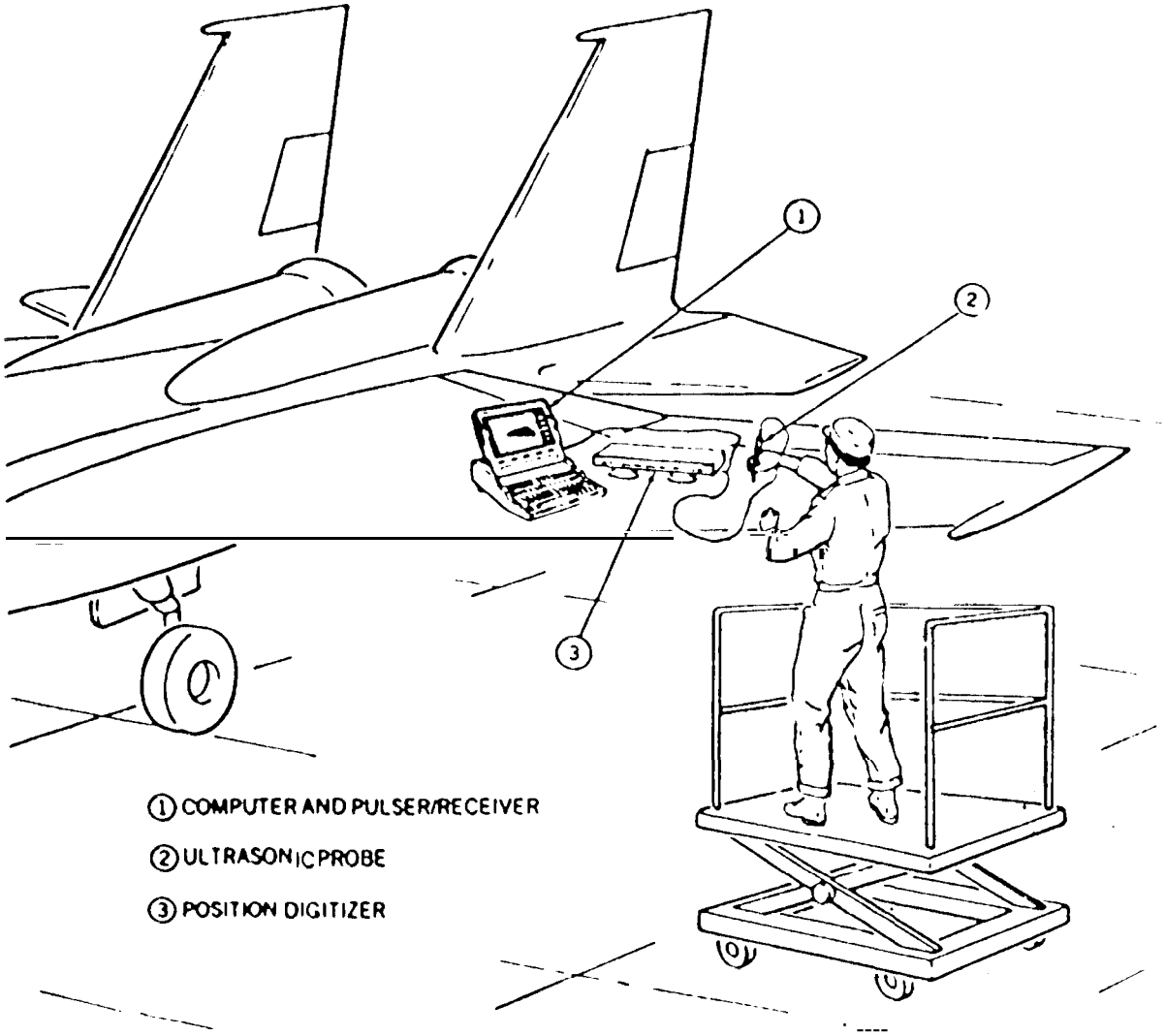


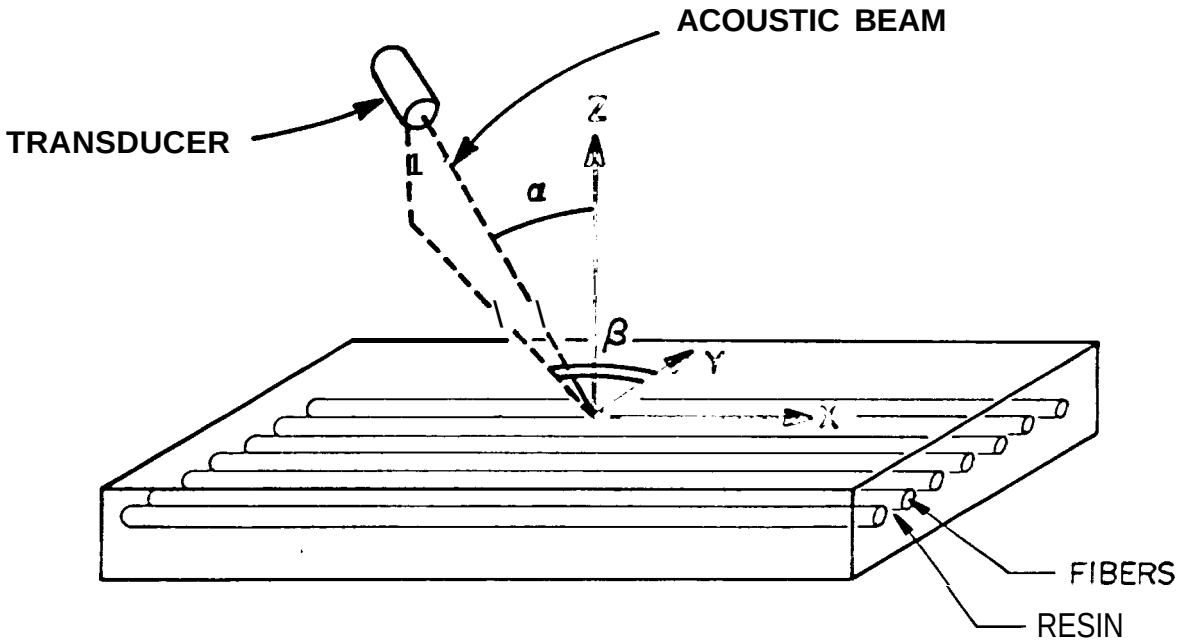
FIGURE 1-1. PORTABLE ULTRASONIC COMPUTERIZED SCANNER (PUCS)

POLAR BACKSCATTERING PBS) PHENOMENON

- IT HAS BEEN STUDIED FOR COMPOSITES SINC≤ 980
- PHENOMENON IS SENSITIVE TO DISCONTINUITIES AT BOTH MACRO AND MICRO- LEVELS
- MOST EFFORTS WERE DIRECTED TO NDE OF POROSITY AND IMPACT DAMAGE.
- APPLICATION TO MMC IS AFFECTED BY THE LARGE FIBER DIAMETER
- THEORETICAL MODELING SO-FAR HAD LIMITED SUCCESS (ACHENBACH, MILLER, ETC.)
- VARIOUS CHARACTERISTICS OF TH≤ PHENOMENON ARE STILL UNEXPLAINED

• BAR-COHEN AND CRANE, 1980.

SCHEMATIC REPRESENTATION OF EXPERIMENTAL SET-UP USED TO MEASURE BACKSCATTERING FROM COMPOSITE SAMPLES



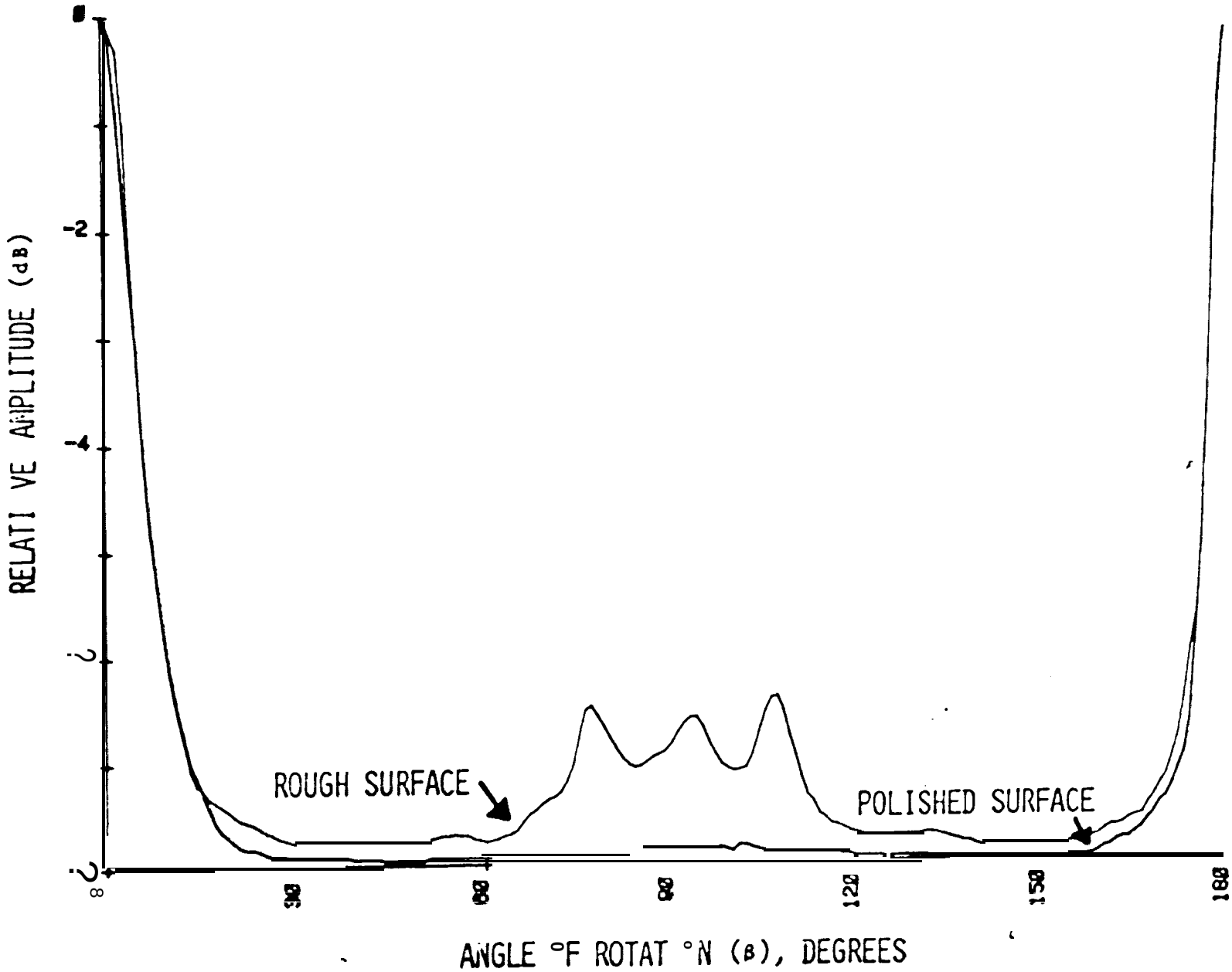
WHERE :

a - ANGLE OF INCIDENCE

~ - ANGLE BETWEEN Y-AXIS AND THE TRANSMITTER BEAM TRAJECTORY ON THE LA' ? PLANE

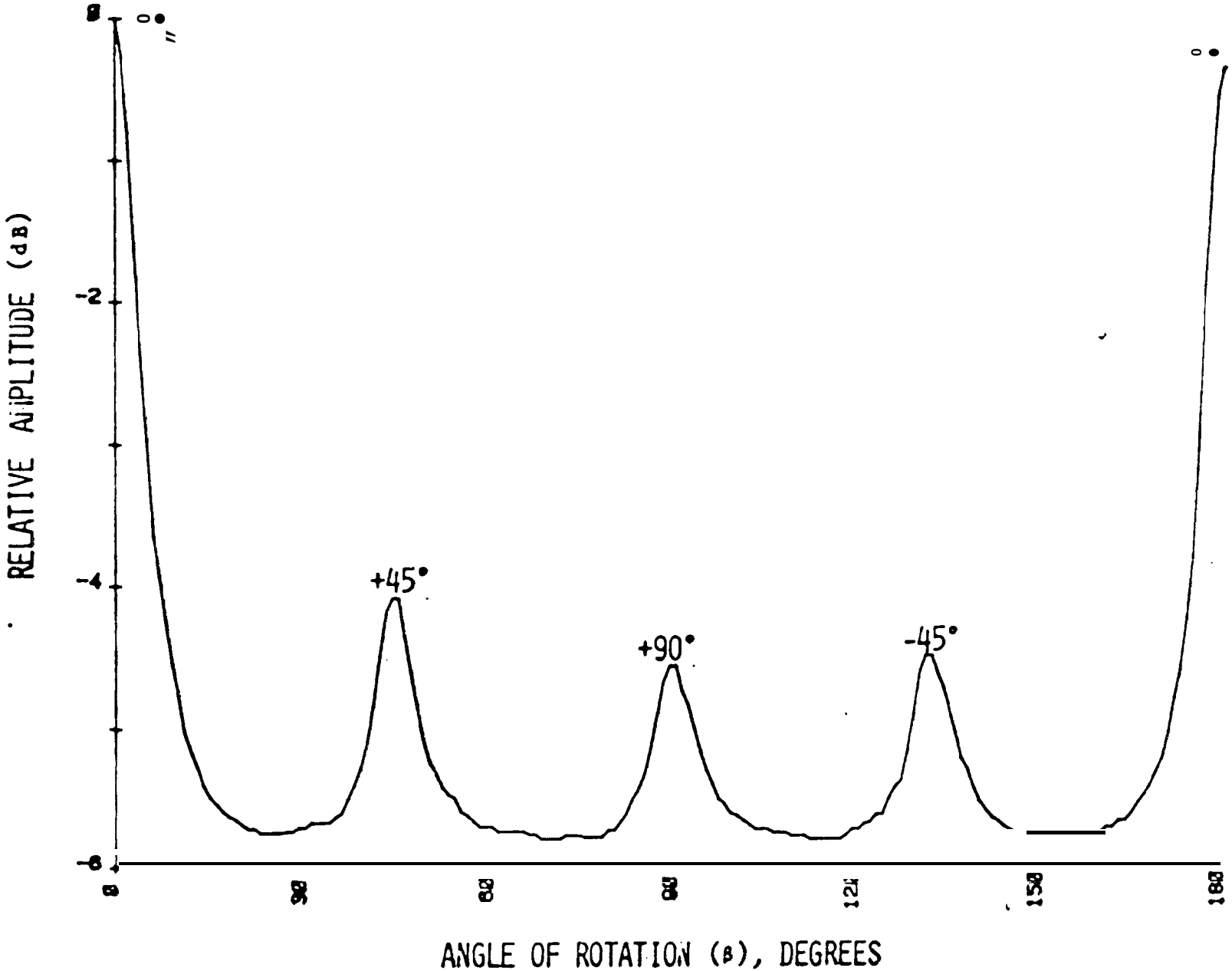
[illegible] [illegible] [illegible] [illegible]

[illegible] OF SURFACE ROUGHNESS [illegible] THE ANGLE OF [illegible] [illegible] [illegible]°.

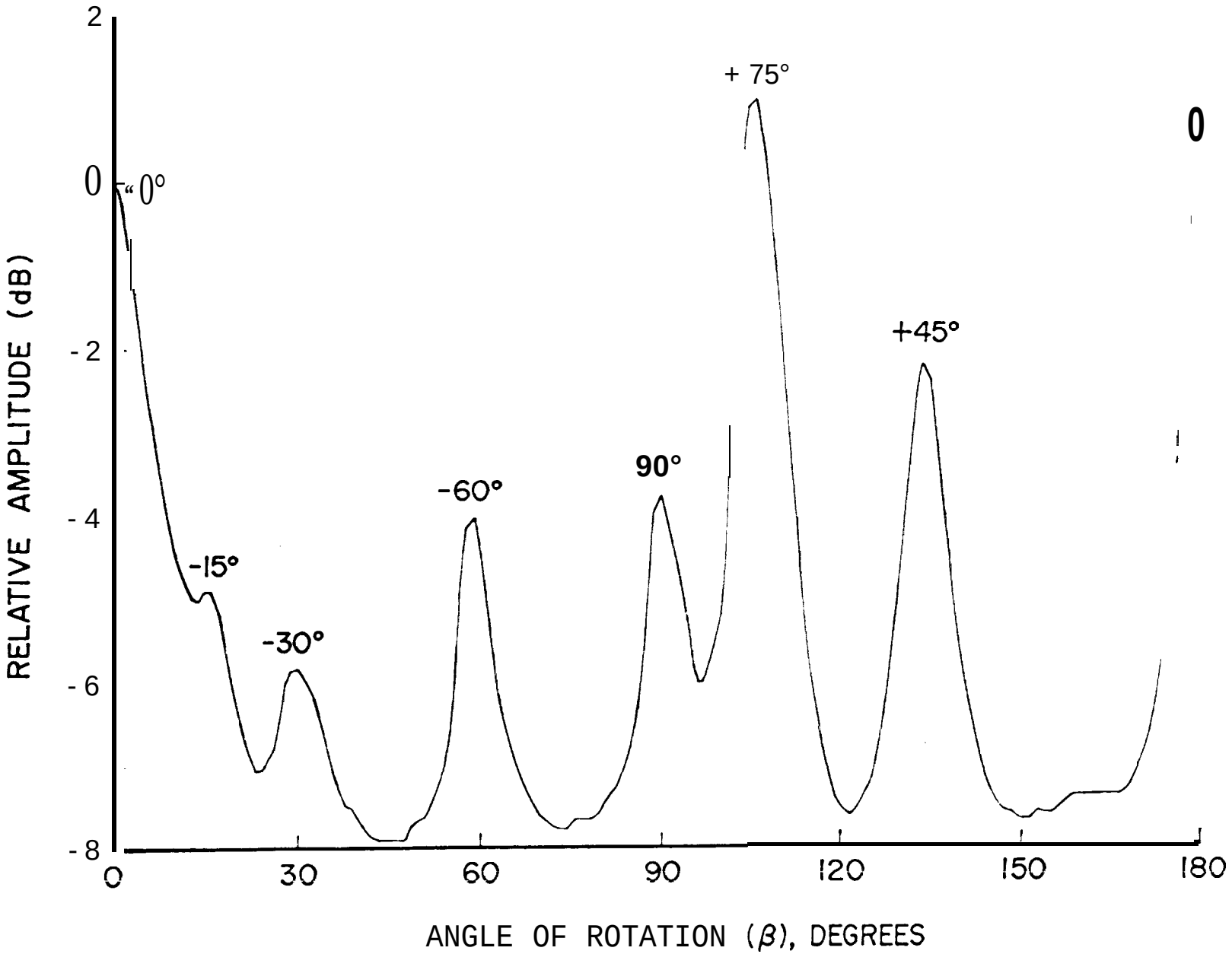


BACKSCATTERING FROM A QUASI-ISOTROPIC (0°, 45°, 90°)$_S$ COMPOSITE

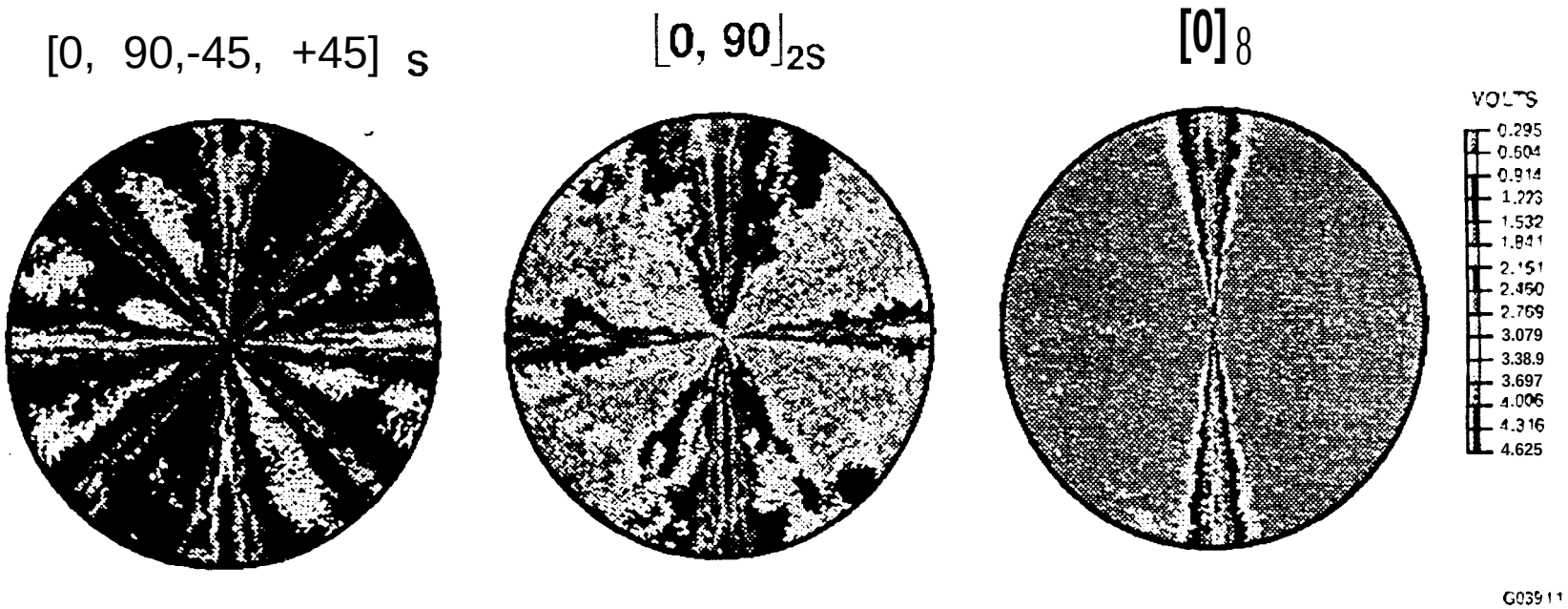
SCATTERING FROM EACH PLY IS APPARENT. THE ANGLE OF INCIDENCE WAS 30°



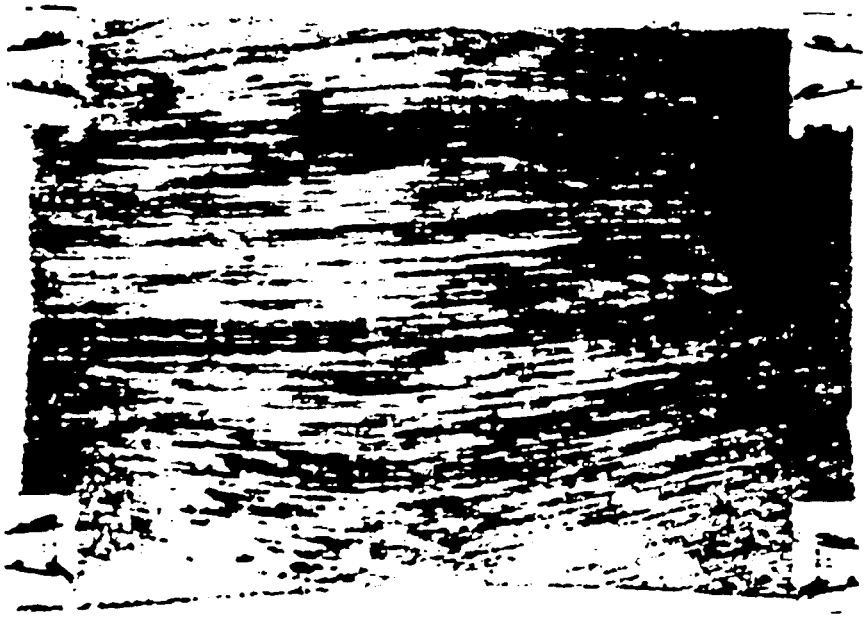
BACKSCATTERING FROM GRAPHITE /EPOXY COMPOSITE [0°, -15°, -30°, +45", -60°, +75°, 90°]$_S$. ANGLE OF INCIDENCE WAS 40°.



POLAR BACKSCATTERING IMAGES OF FIBER ORIENTATION IN GRAPHITE/EPOXY LAMINATES TESTED AT 5 MHz AND α = 30 DEGREES

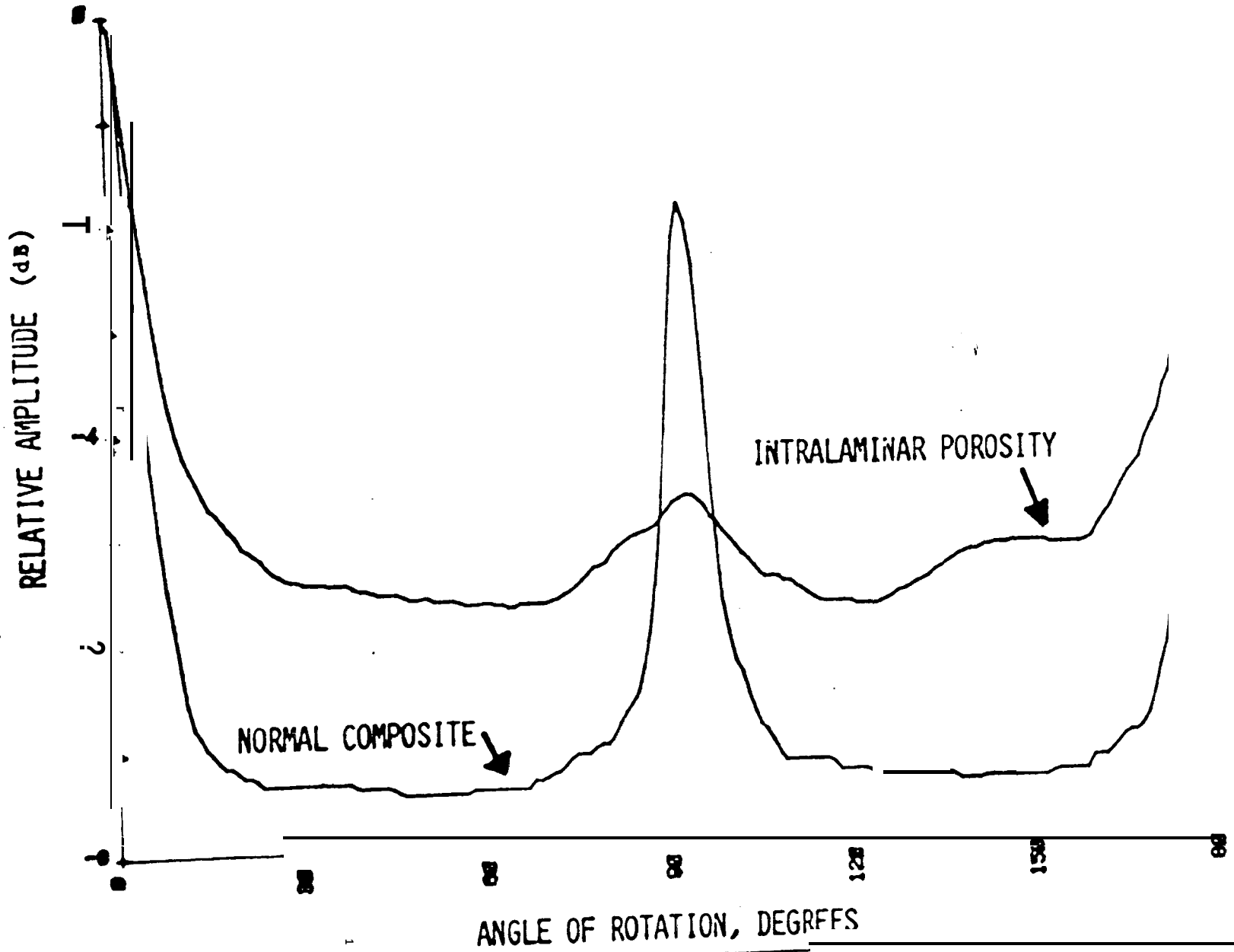


FIBER MISALIGNMENT IN GRAPHITE/PHENOLIC MOLD **USING** BACKSCATTERING IMAGING. (THE CORNER INDICATIONS **ARE** SAMPLE HOLDERS.)



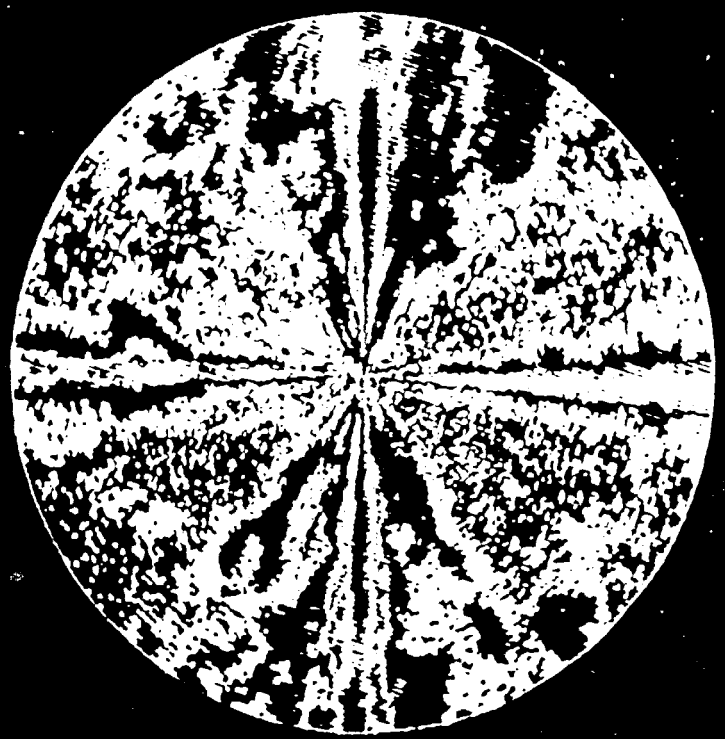
84 GEN 23008

BACKSCATTERING FROM [0,90]$_s$ GLASS/EPOXY COMPOSITE BOTH WITH AND WITHOUT ADDED POROSITY. EPOXY MICRO-BALLOONS WERE USED TO INCREASE POROSITY

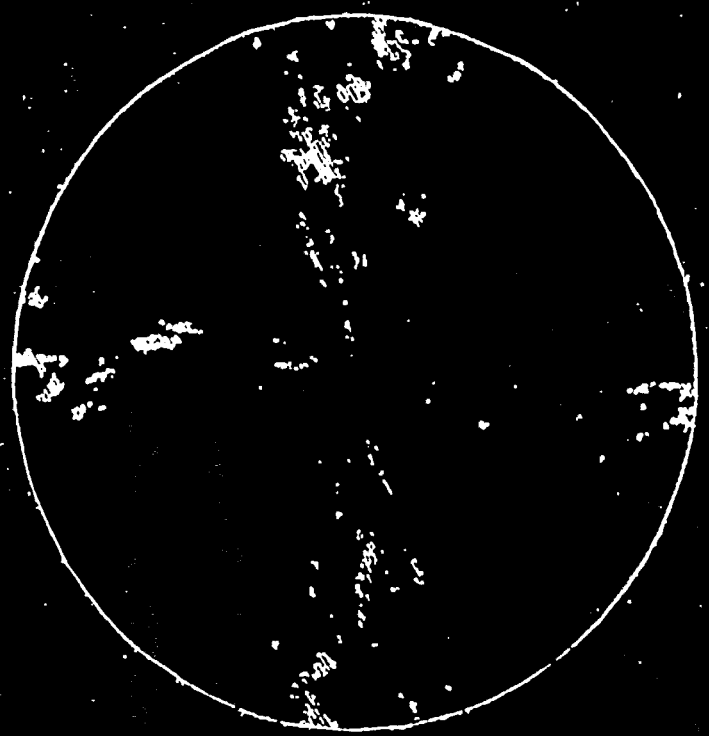


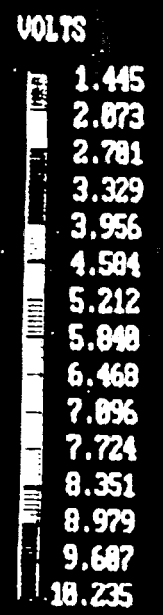
POLAR-BACKSCATTERING FROM Gr/Ep LAMINATES USING 5 MHz 1/4-INCH TRANSDUCER

0.7% POROSITY

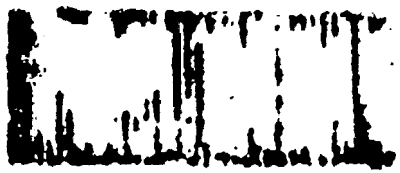


5.71% POROSITY





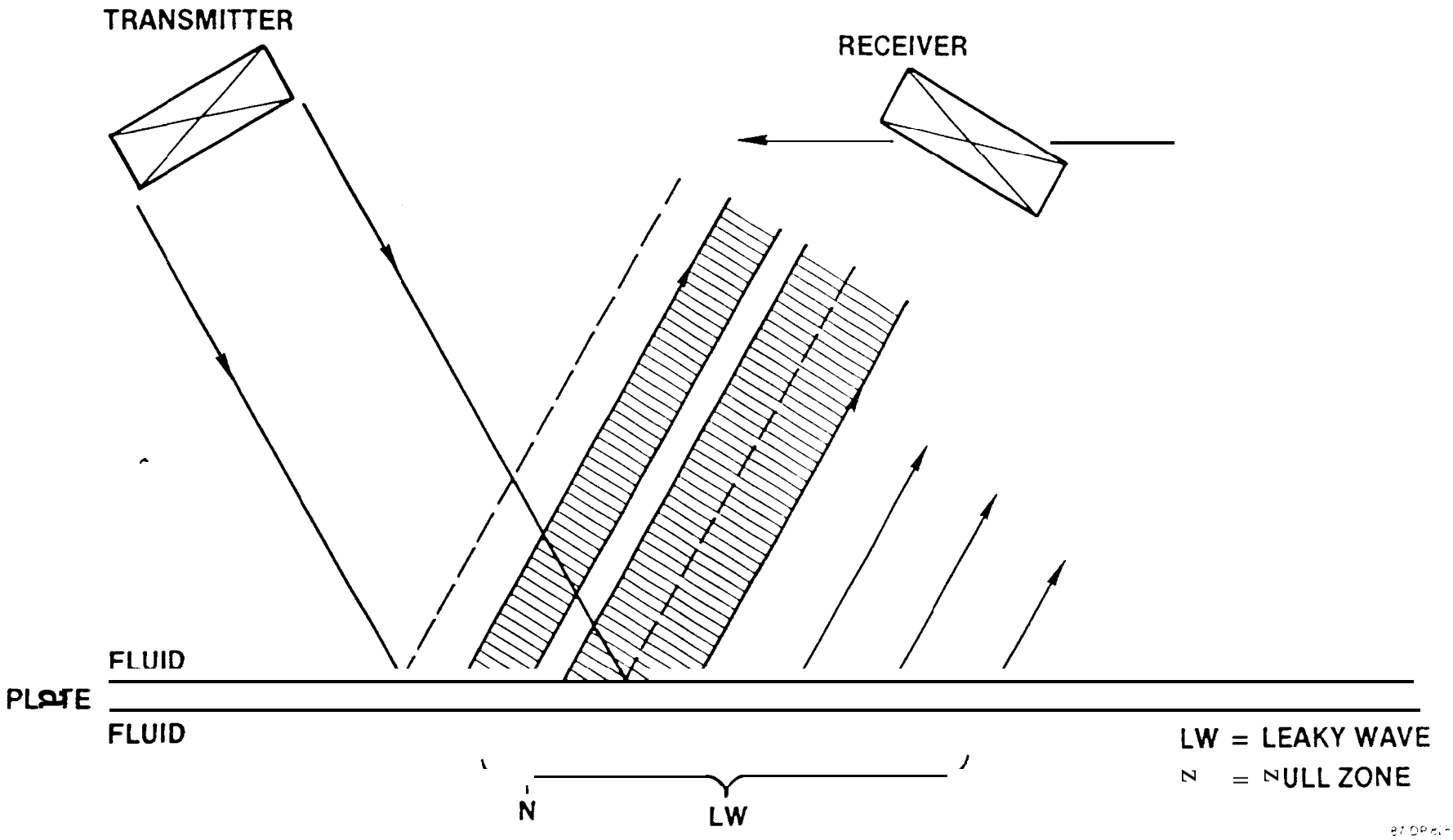
85-MFG-0007



(a)

(b)

BACKSCATTERI S AN OF QUASI-ISOTROPIC
GRAPH TE/EPOXY SPECIMEN FATI U LOADED TO
5% OF ULTIMATE STRENGTH AND 5000 CYCLES

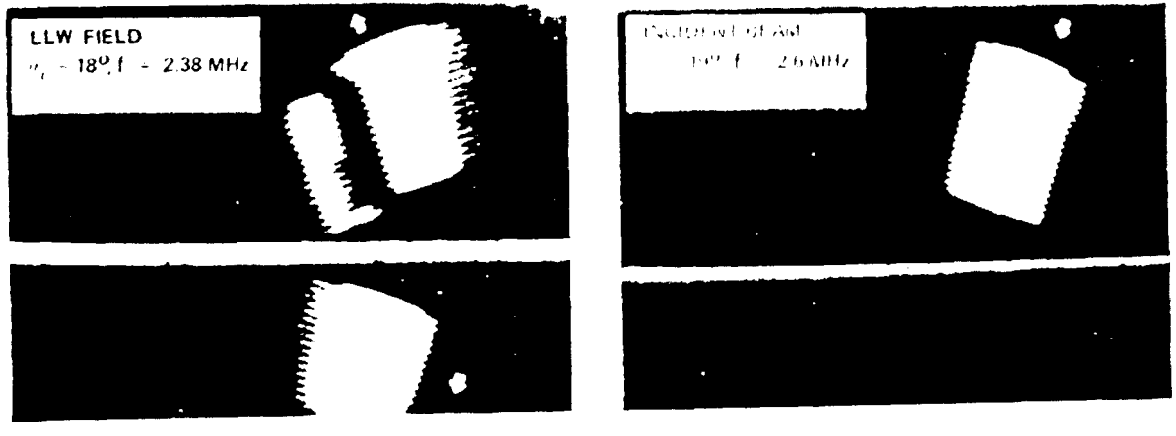

TRANSMITTER
RECEIVER
FLUID
PLATE
FLUID
N
LW
LW = LEAKY WAVE
N = NULL ZONE

LEAKY LAMB WAVE (LLW) PHENOMENA

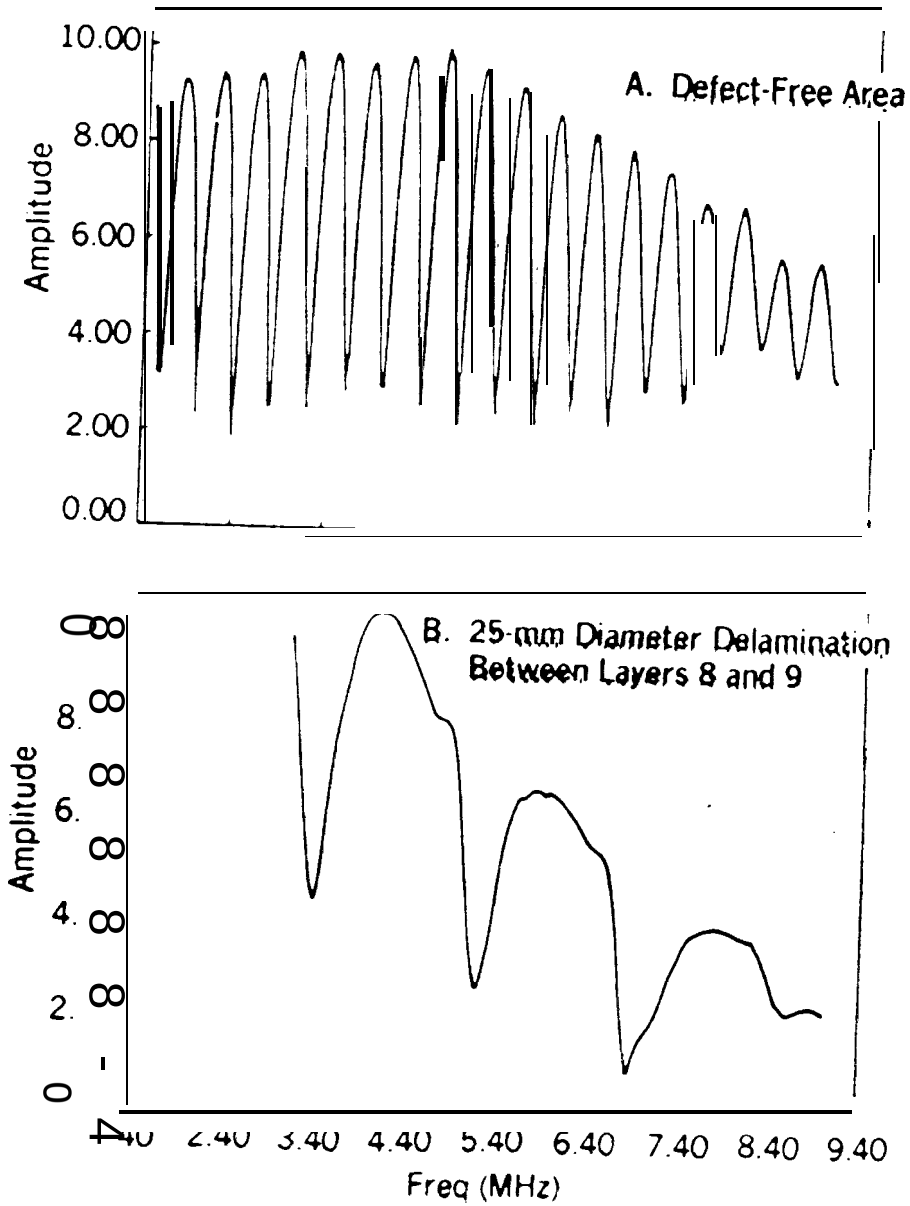
- HAS BEEN STUDIED FOR COMPOSITES SINCE 1983*
- PHENOMENA SENSITIVE TO BOUNDARY CONDITIONS AND ELASTIC PROPERTIES
- THEORETICAL MODELING OF THE PHENOMENA HIGHLY SUCCESSFUL
- APPLIED TO INVERT COMPOSITES PROPERTIES AND CHARACTERIZE BONDING

* BAR-COHEN AND CHIMENTI 1985.

PULSED SCHLIEREN MAGE OF LLW PHENOMENON



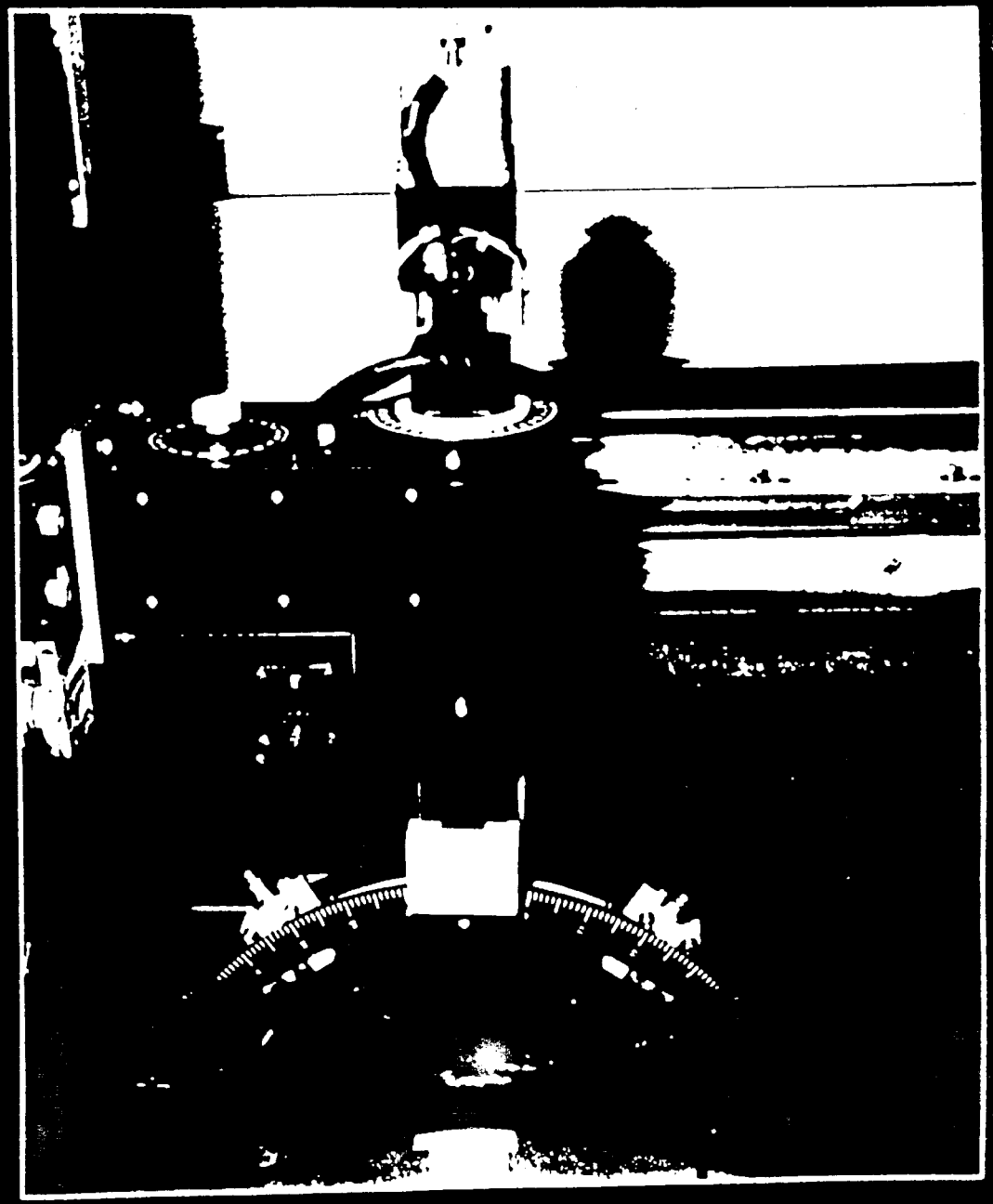
89 GEN 20135



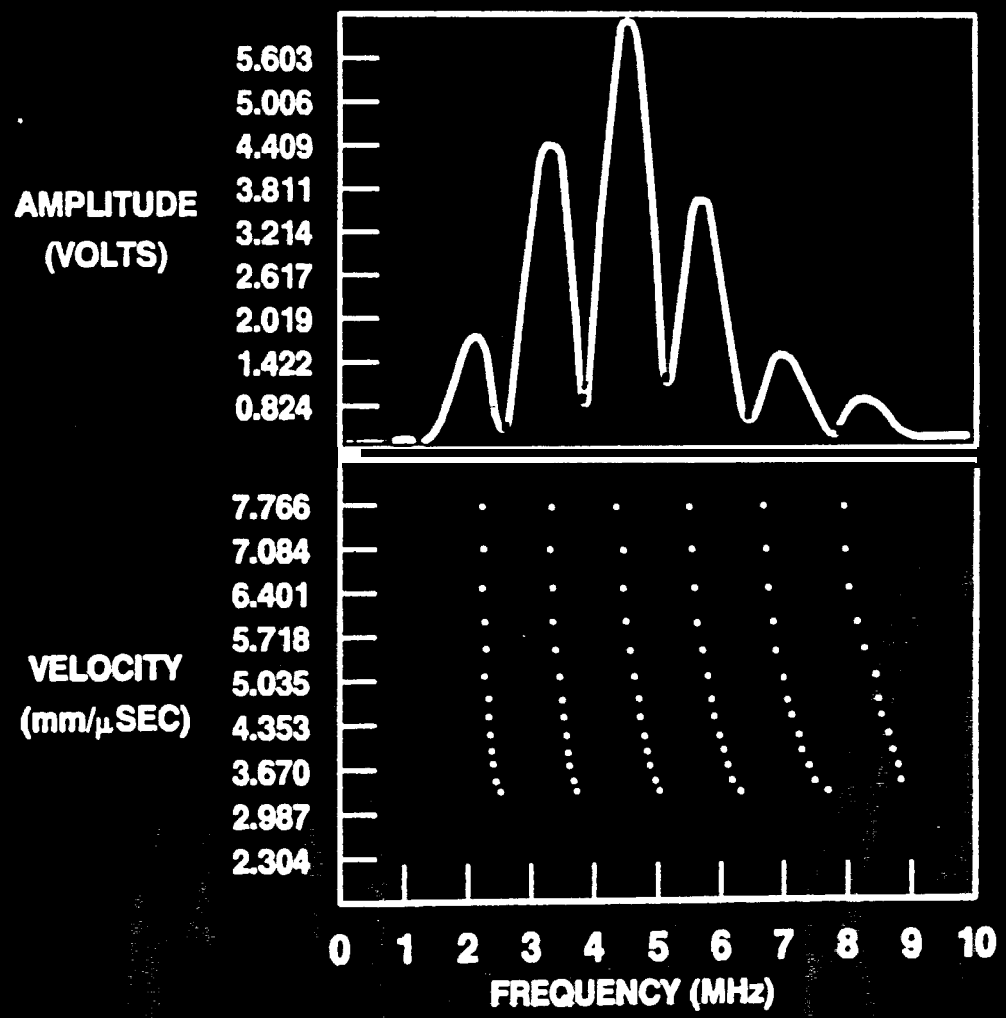
REFLECTION SPECTRA
FOR LEAKY LAMB
WAVE IN GRAPHITE/EPOXY
AS4/3501-6 [0]32 TESTED AT
22 DEGREES ALONG THE FIBERS

86 GE N 22760

MATERIALS CHARACTERIZATION DEVICE EMPLOYING THE LLW AND PBS METHODS

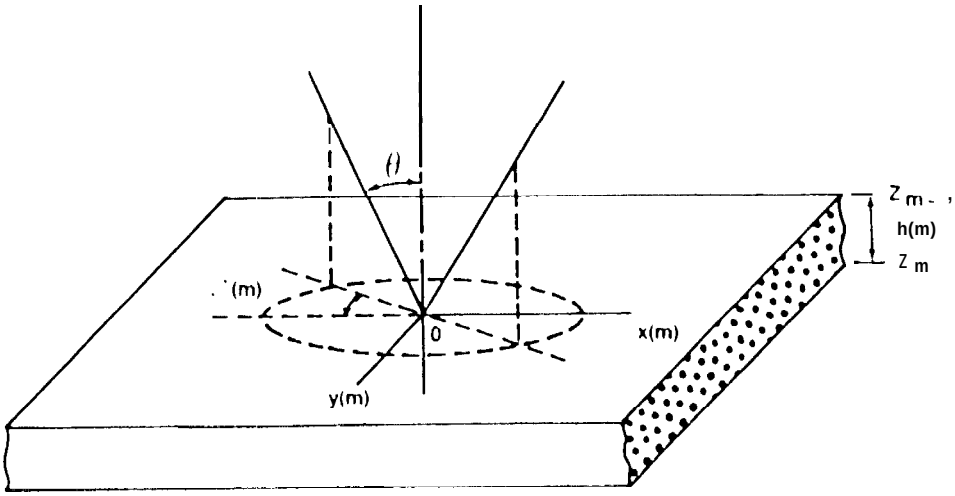


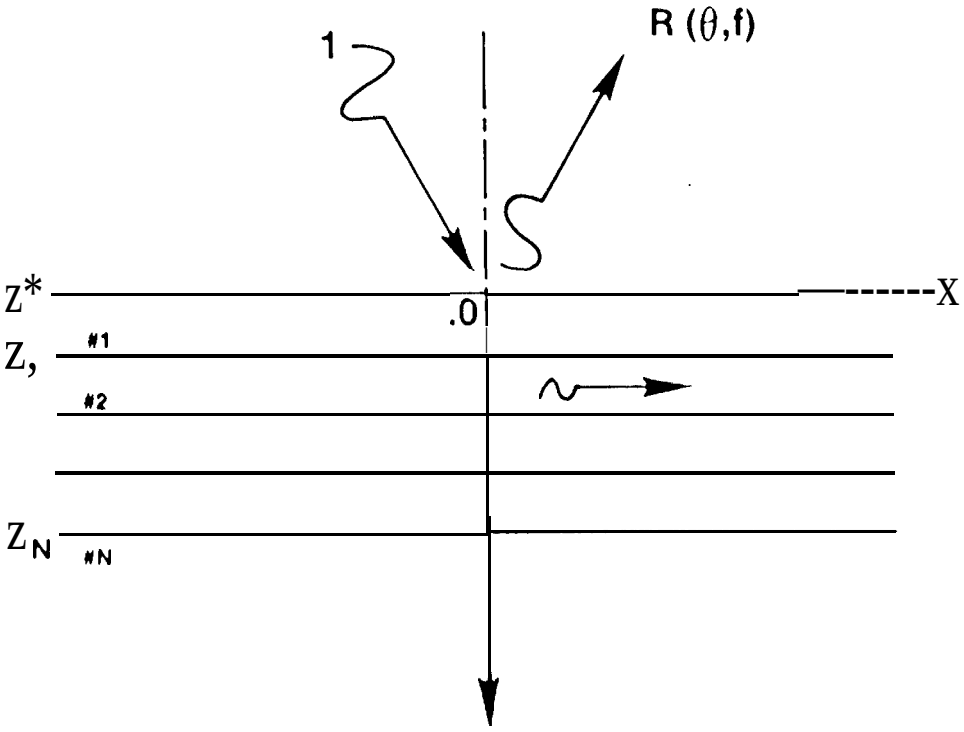
LLW SPECTRA AND DISPERSION CURVE FOR UNIDIRECTIONAL GRAPHITE/EPOXY 0.152 IN. THICK



CD2676.03

GEOMETRY OF THE MULTILAYERED LAMINATE PROBLEM (BOTTOM) AND ORIENTATION OF THE Mth LAMINATE RELATIVE TO THE INCIDENT AND REFLECTED RAYS

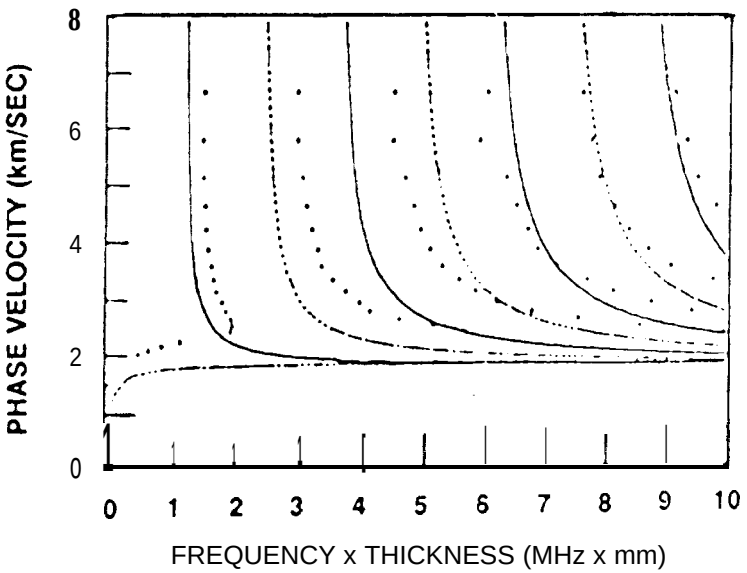




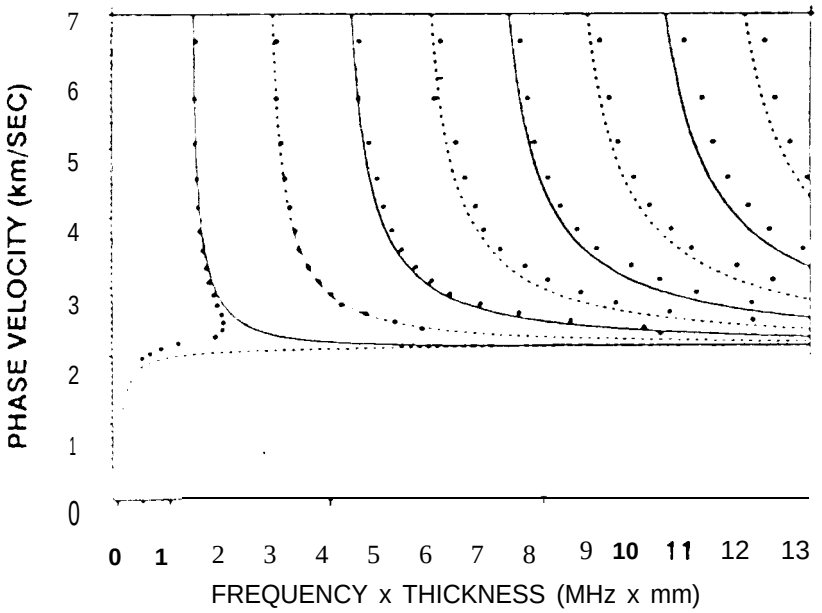
89 GEN 20172

THEORETICAL AND EXPERIMENTAL **DISPERSION CURVES** FOR GRAPHITE/EPOXY **UNIDIRECTIONAL LAMINATE TESTED** ALONG THE FIBERS

a. ASSUMED ELASTIC PROPERTIES



b. INVERTED ELASTIC PROPERTIES



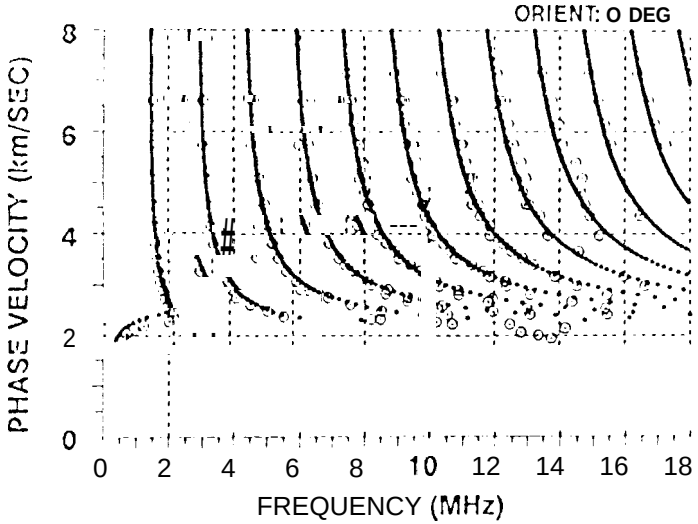
IRAD 896429 3
LVC003 2

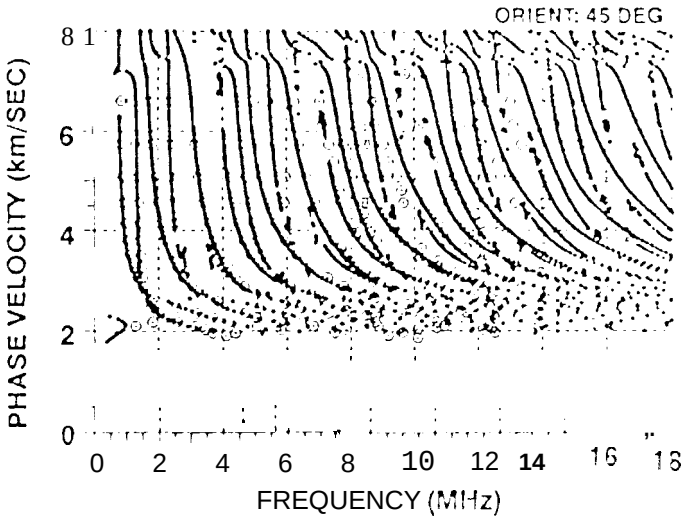
TABLE 1: MATERIAL PROPERTIES

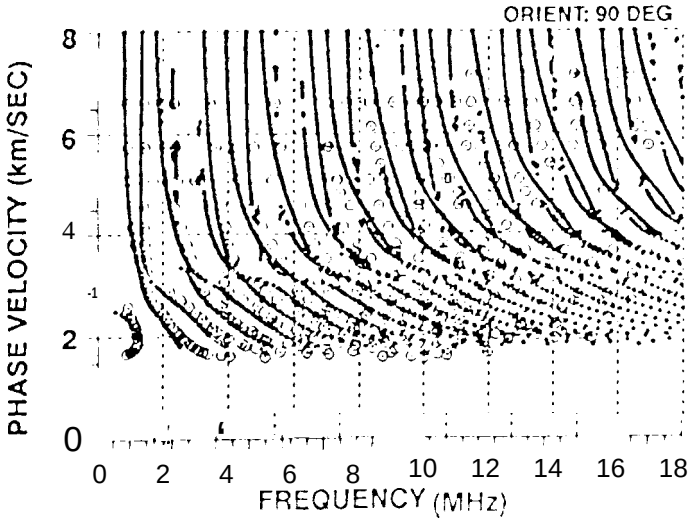
	INITIAL GUESS	SYSTEMATIC INVERSION
E_{11} (GPa)	156.75	157.77
E_{22} (GPa)	10.41	10.82
G_{12} (GPa)	7.07	7.982
G_{23} (GPa)	3.50	3.6367
ν_{12}	0.31	0.3374
ρ (gin/cc)	1.58	1.578
C_{11} (GPa)	160.73	162.729
C_{22} (GPa)	13.92	14.527
C_{12} (GPa)	6.44	7.359
C_{23} (GPa)	6.92	7.25
C_{55} (GPa)	7.07	7.982

CD'60307

DISPERSION CURVES FOR GRAPHITE/EPOXY AS4/3501-6 $[0]_8$



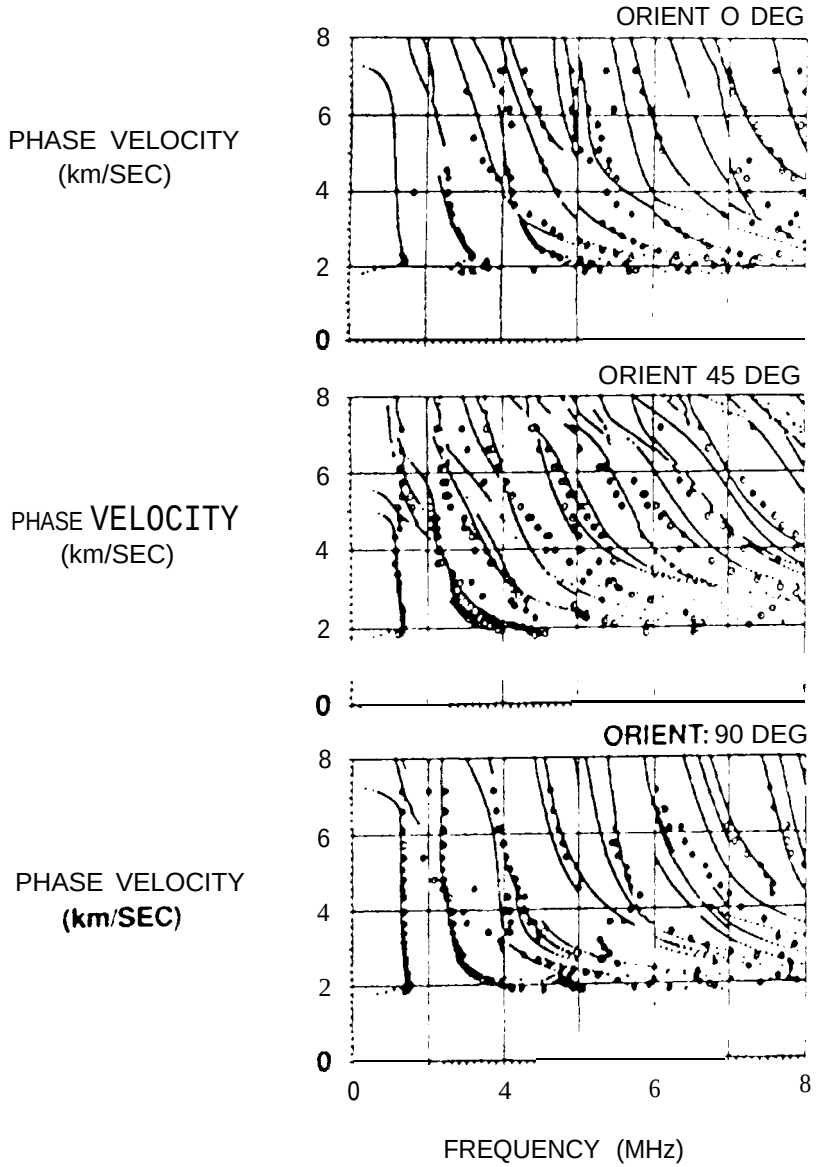




LAMINATE PROPERTIES

E_{11} (GPa)	157.7700
E_{22} (GPa)	10.8200
G_{12} (GPa)	7.9820
G_{23} (GPa)	3.6367
ν_{12}	0.3374
p (gin/cc)	1.5780
C_{11} (GPa)	162.7290
C_{22} (GPa)	14.5270
C_{12} (GPa)	7.3590
C_{23} (GPa)	7.2500
C_{55} (GPa)	7.9820

DISPERSION CURVES FOR GRAPHITE/EPOXY $[0, 90]_{2S}$



PLY PROPERTIES

C_{11} = 162.73 GPa
C_{22} = 15.73 GPa
C_{12} = 7.36 GPa
C_{23} = 7.25 GPa
C_{55} = 7.98 GPa
ρ = 1.578 g/cm^3
E_{11} = 157.8 GPa
E_{22} = 10.82GPa
G_{12} = 7.98 GPa
ν_{12} = 0.3375
ν_{23} = 0.4876

OVERALL LAMINATE PROPERTIES

$\langle C_{11} \rangle$ = 88.62 GPa
$\langle C_{22} \rangle$ = 88.62 GPa
$\langle C_{33} \rangle$ = 15.73 GPa
$\langle C_{12} \rangle$ = 7.35 GPa
$\langle C_{13} \rangle$ = 7.30 GPa
$\langle C_{44} \rangle$ = 5.00 GPa
$\langle C_{55} \rangle$ = 5.00 GPa
$\langle C_{66} \rangle$ = 7.98 GPa

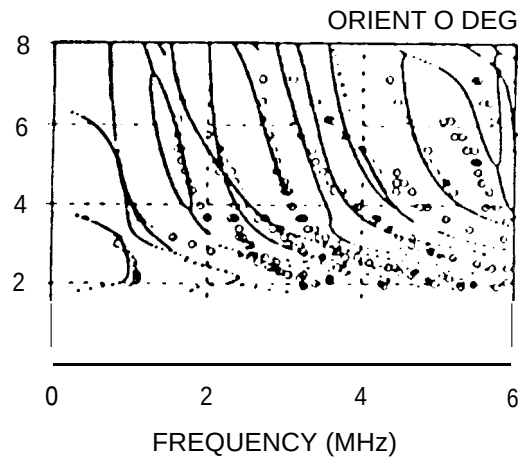
INTERFACE PROPERTIES

h = 7 μm
ρ = 1.2 g/cm^3
u. = 2.1 km/sec
β .0.95 km/see

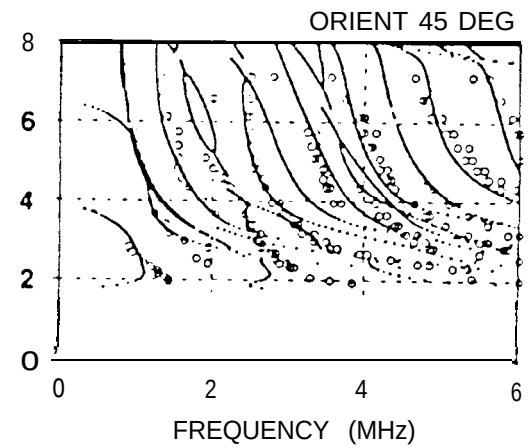
⊙ ⊙ EXPERIMENTAL DATA
— THEORETICAL DATA

DISPERSION CURVES FOR GRAPHITE/EPOXY $[0, \pm 45, 90]_S$

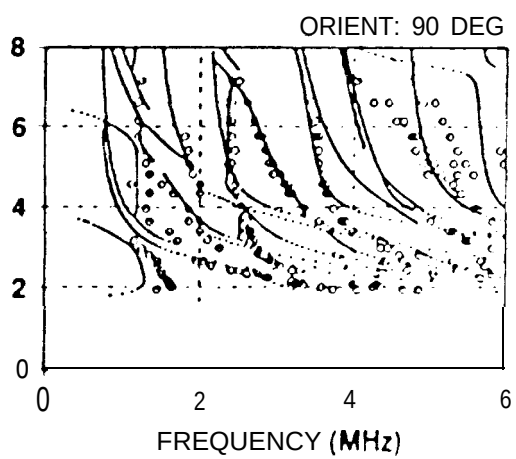
PHASE VELOCITY (km/SEC)



PHASE VELOCITY (km/SEC)



PHASE VELOCITY (kmISEC)



PLY Properties

C_{11} = 160.7 GPa
C_{22} = 20.83 GPa
C_{12} = 7.45 GPa
C_{23} = 7.63 GPa
C_{55} = 8.02 GPa
P = 1.578 g/cm^3
E_{11} = 156.8 GPa
E_{22} = 17.90 GPa
G_{12} = 8.02 GPa
υ_{12} = 0.262
υ_{23} = 0.356

OVERALL IN-PLANE PROPERTIES OF LAMINATE

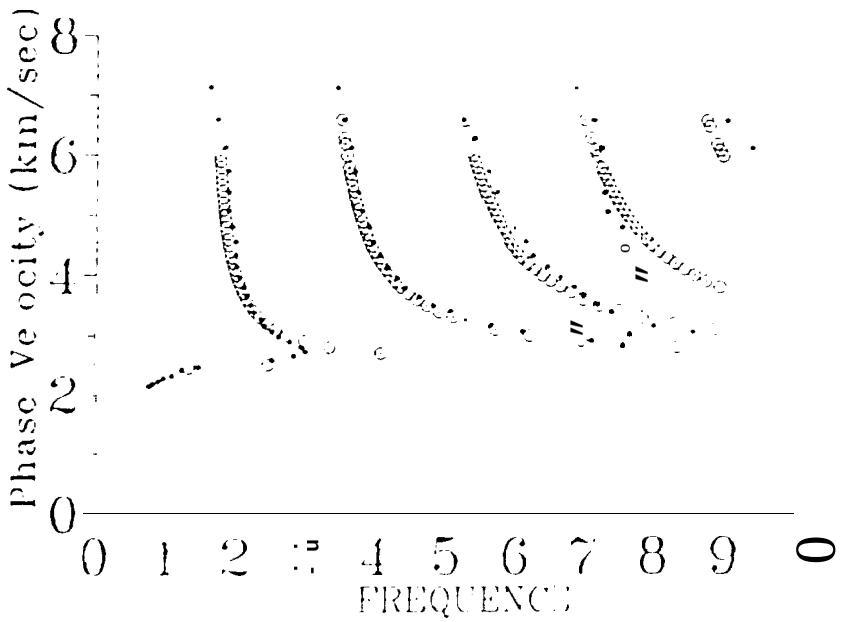
<E> = 61.97 GPa
<υ> = 0.247

INTERFACE PROPERTIES

h = 15 μm
p = 1.2 gm/cc
a = 2.1 km/sec
β = 0.95 km/see

⊙ ⊙ EXPERIMENTAL DATA
—— THEORETICAL DATA

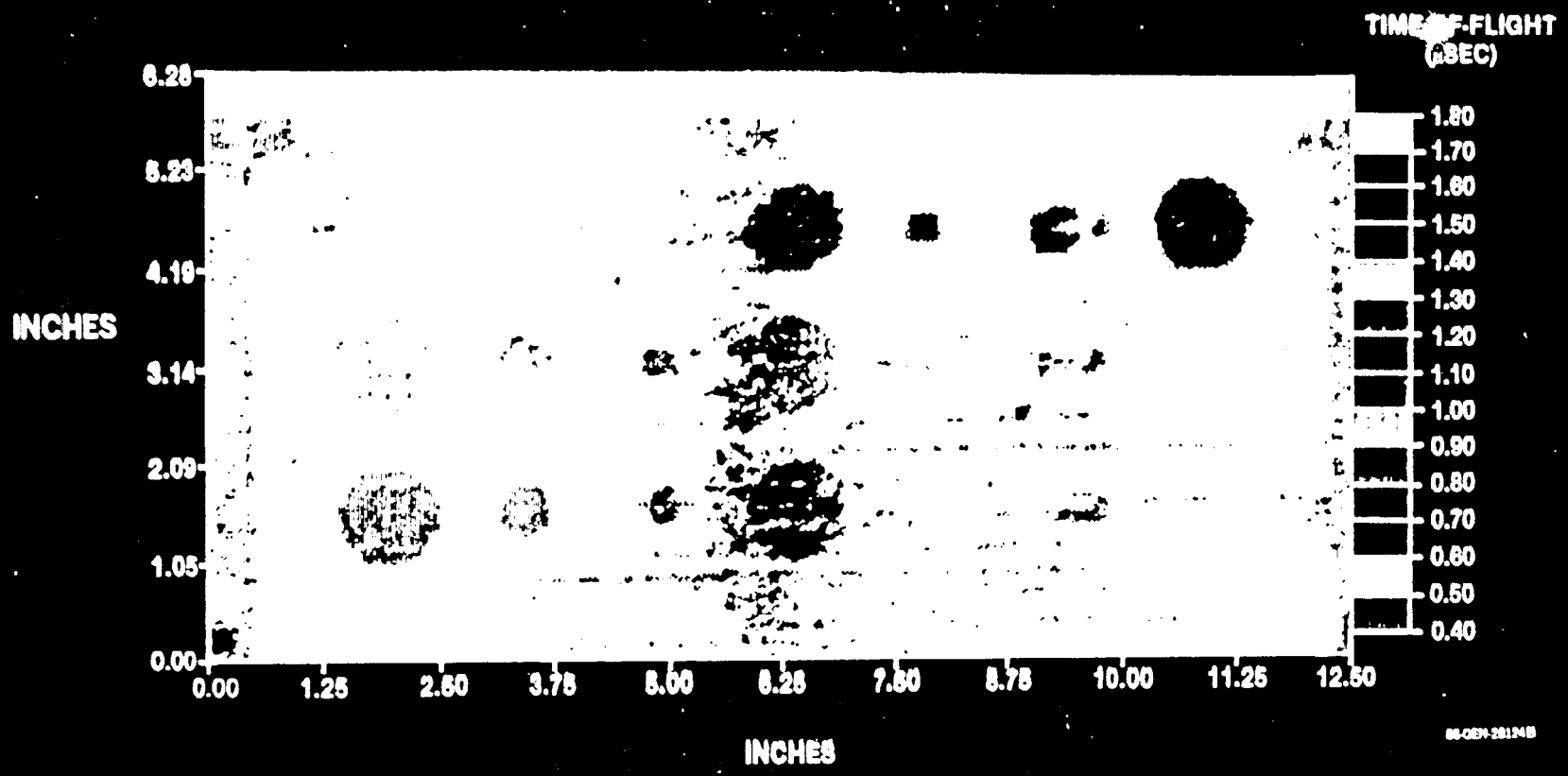
GRAPHITE/ALUMINUM .048 INCH THICK UNIDIRECTIONAL LAMINATE
TESTED ALONG THE FIBERS USING LLW.



INVERTED ELASTIC PROPERTIES

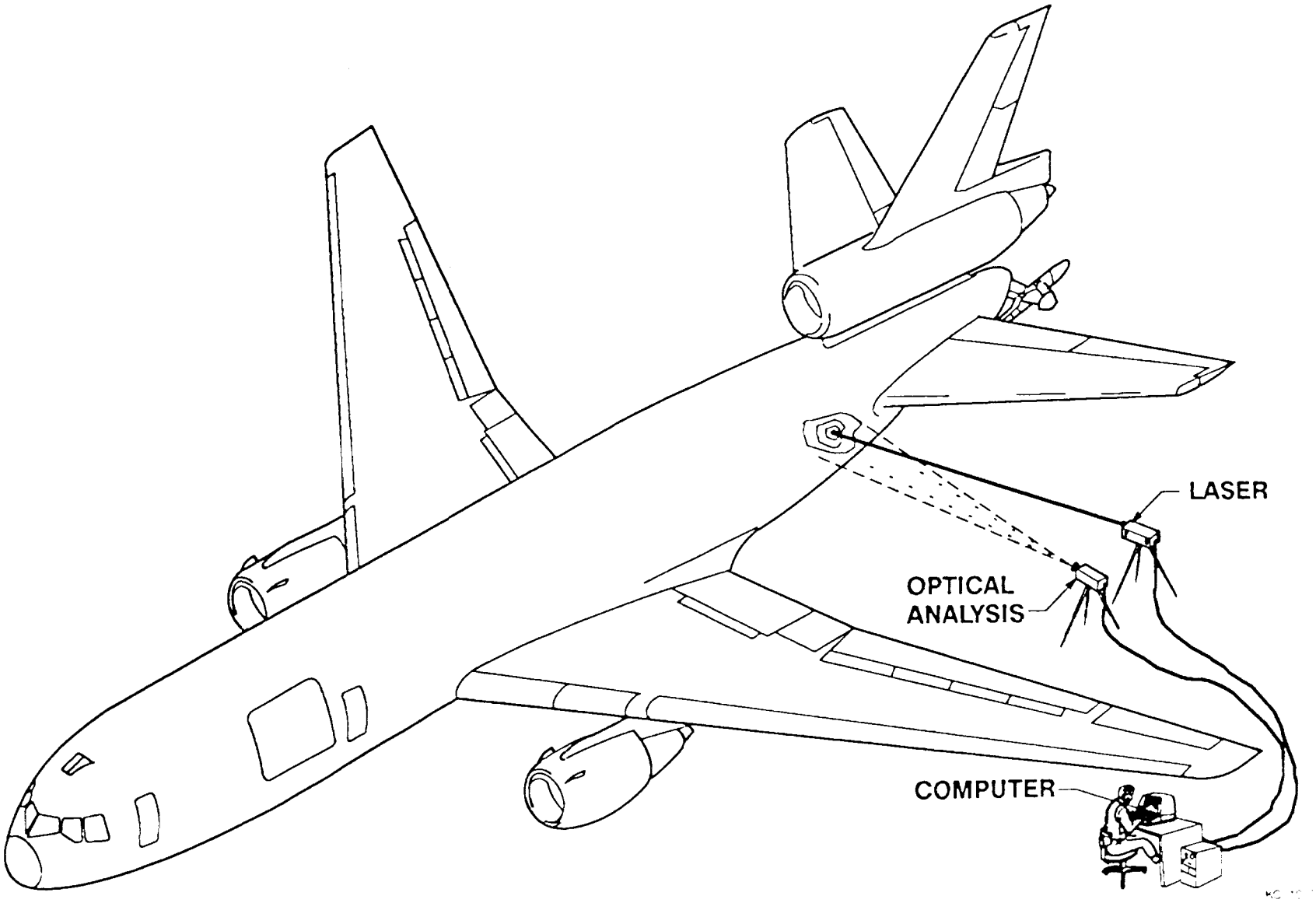
C_{11}	C_{12}	C_{22}	C_{23}	C_{55}
180.0	16.2	34.9	17.7	16.0

LLW C-SCAN IMAGE OF DEFECTS IN GR/EP $[0]_{24}$ LAMINATE, WHERE COLOR WAS ASSIGNED TO THE DIFFERENT DEPTHS*

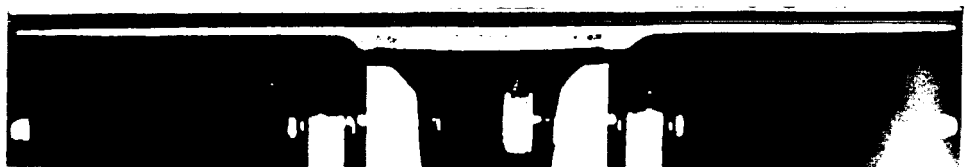


*BAR-COHEN AND MAL, 1988

NDE OF AGING AIRCRAFT USING LASER INDUCED GUIDED WAVES



SENSORS TECHNOLOGY



GENERAL REQUIREMENTS

* DIMENSION, STRAIN, AND GEOMETRICAL VARIATION AND RATE OF CHANGE
* RESIDUAL STRESSES
* DETECTION OF DISCONTINUITIES (IMPACT, DELAMINATION, CRACKS, ETC.)
* MATERIAL PROPERTIES DETERMINATION
* REAL-TIME CHARACTERIZATION DURING CURE, AND SERVICE

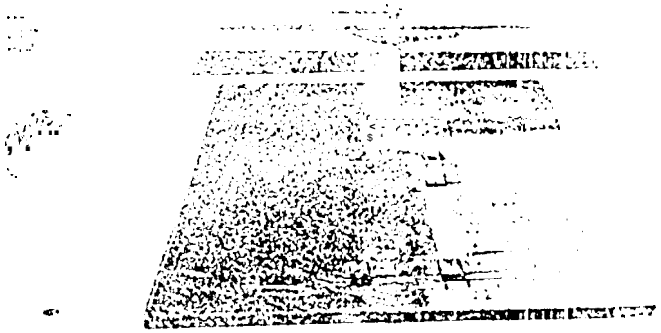


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Figure 6. Eddy Current Probe and Holding Fixture.

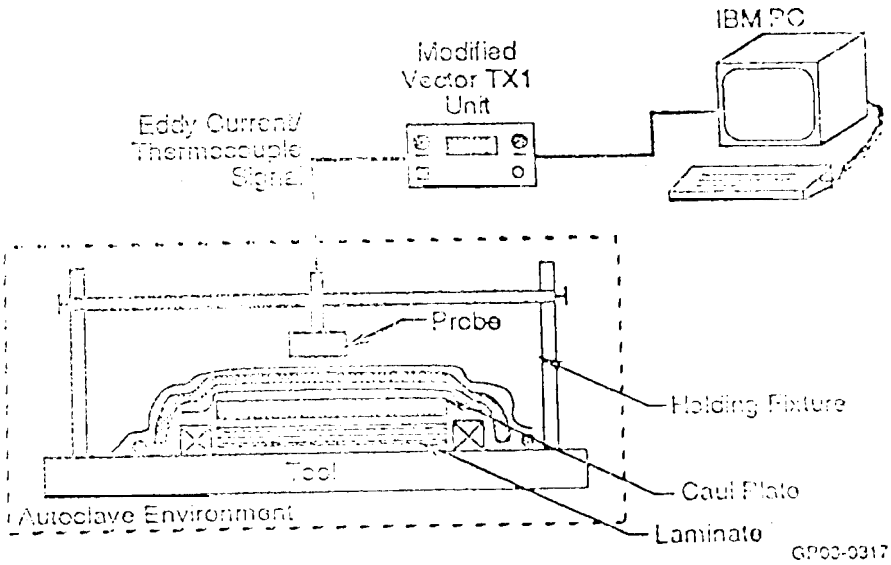

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Figure 7. Eddy Current Thickness Sensor Setup

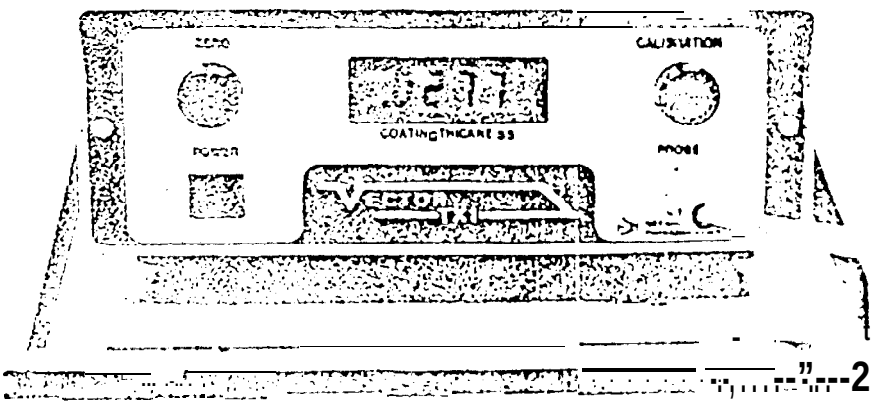

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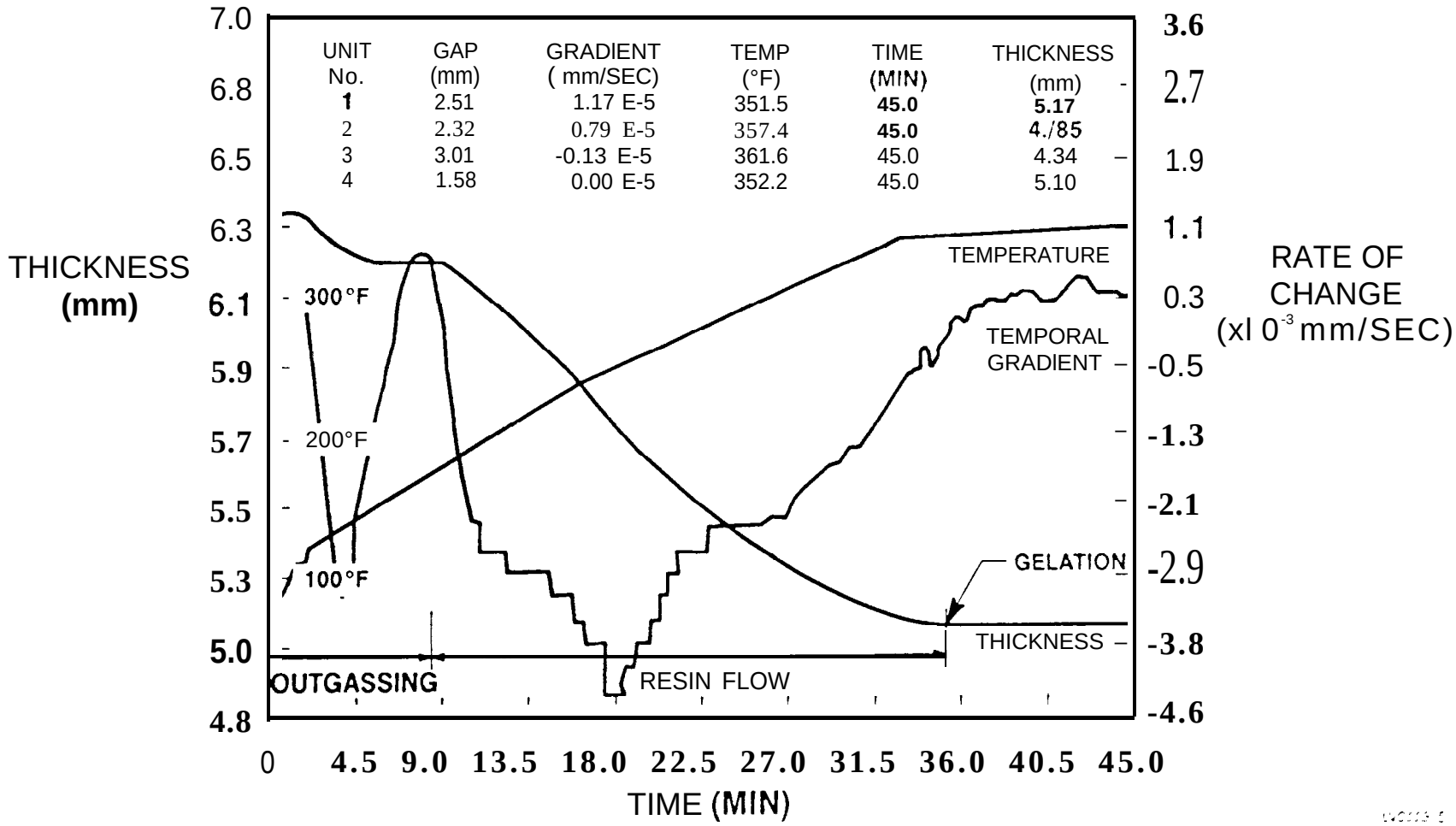
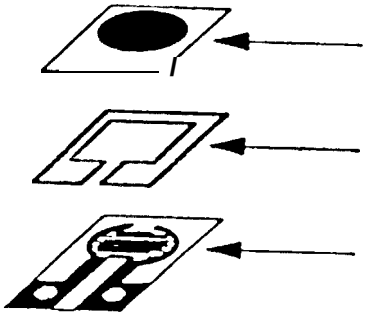
Figure 8. Modified Model Vector TX1 Unit.

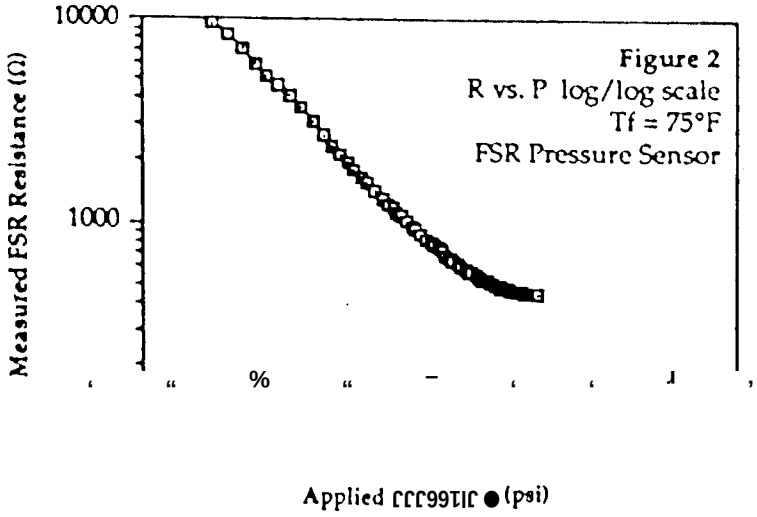
TYPICAL RESPONSE OF CURE MONITORED UNIDIRECTIONAL GRAPHITE/EPOXY LAMINATE



PRESSURE SENSOR

Figure 1
FSR Pressure
Sensor
(Actual Size)





TECHNOLOGY TREND

* MATERIALS ARE INCREASINGLY COMPLEX (ANISOTROPIC, HYBRID, ETC.)

* COMBINING INPUTS FROM SEVERAL NDE METHODS PROVIDE DETAILED AND RELIABLE ANSWERS

* DEFECTS CHARACTERIZATION AND PROPERTIES DETERMINATION USING QUANTITATIVE NDE AND AI

* IMBEDDED/ATTACHED SENSORS ARE MAKING A SIGNIFICANT IMPACT ON IN-PROCESS AND IN-SERVICE MONITORING