NONDESTRUCTIVE CHARACTERIZATION OF COMPOSITE MATERIALS

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ABSTRACT

Increasingly, composite materials are applied to fracture-critical structures of aircraft and spacecraft. While the materials has an effective combination of toughness, specific strength and damage tolerance, they are sensitive to the manufacturing processes, service conditions and aging. Ultrasonics offer the most capable inspection technology and recently developed techniques appear to improve this technology significantly. NDE methods allow the detection and characterization of defects as well as determination of the material elastic properties accessing the material from a single side. Recent progress in ultrasonic NDE of composites will be reviewed.

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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

1?0NNI%

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

W

- 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

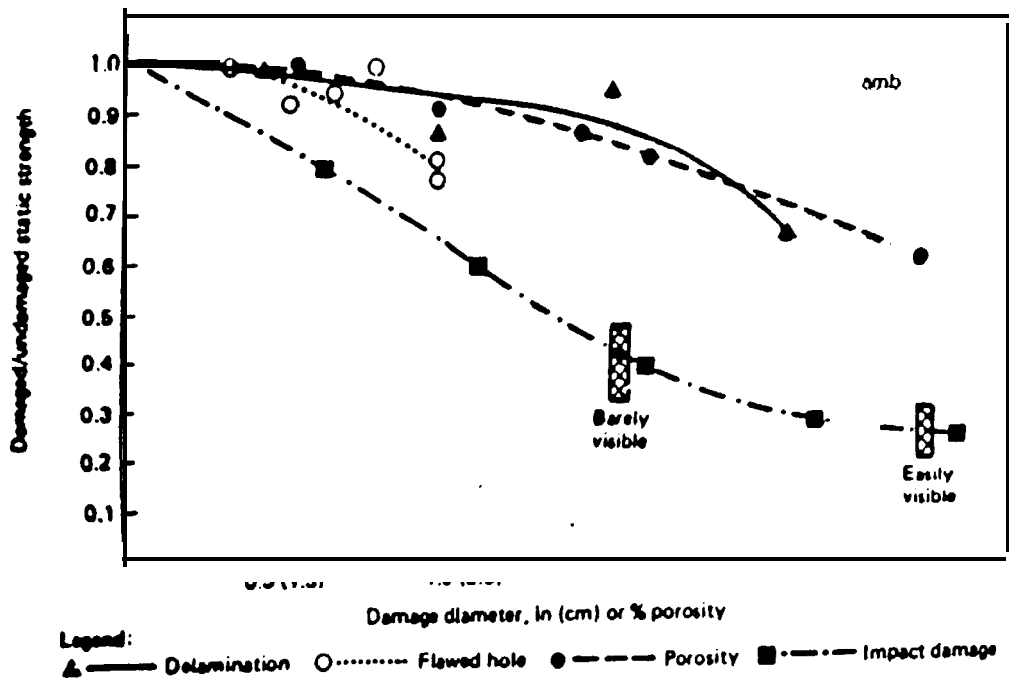
PI Y WAVINESS

- 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 2-4.



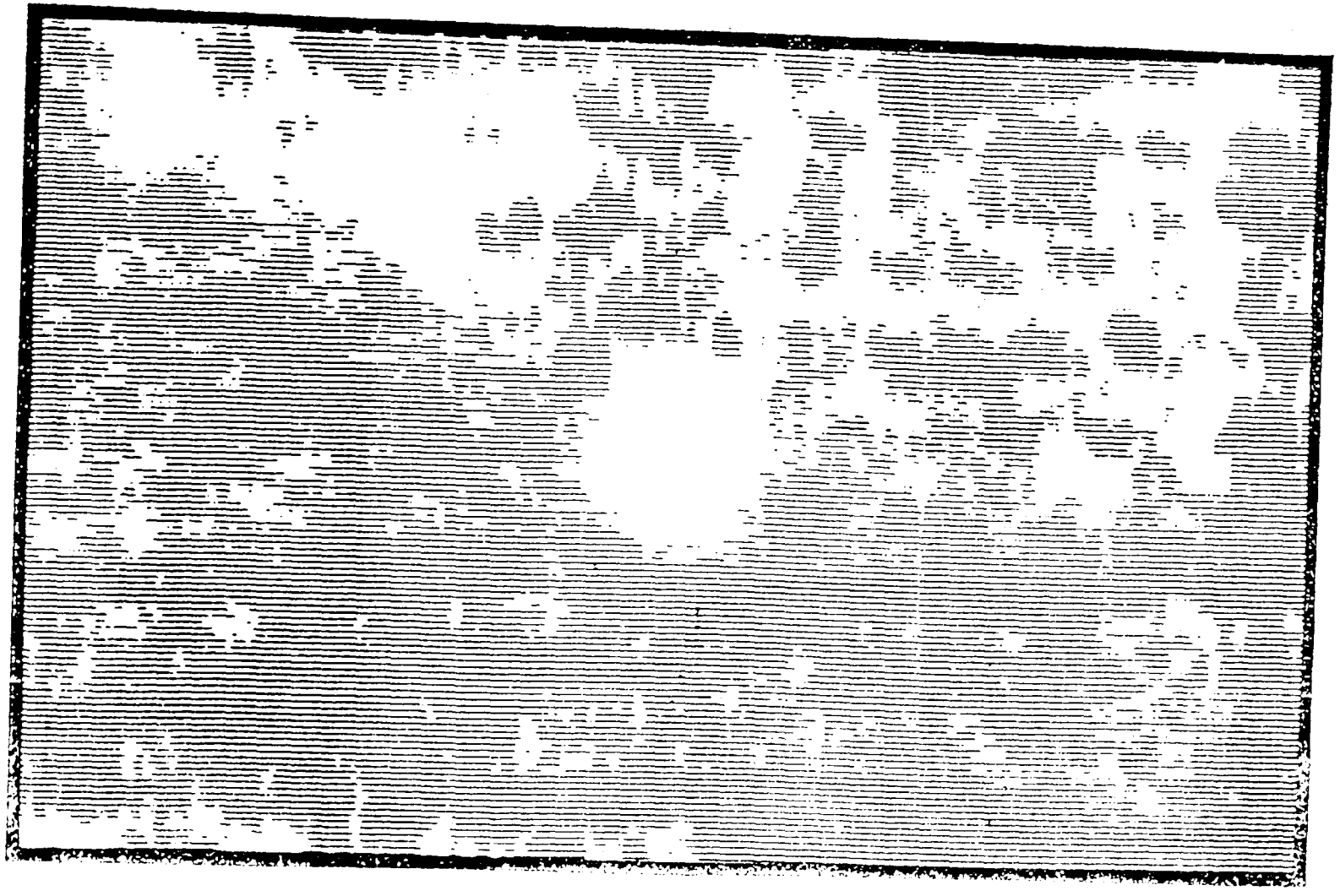
DEFECT/DAMAGE SEVERITY COMPARISON — STATIC STRENGTH (COMPRESSION).

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

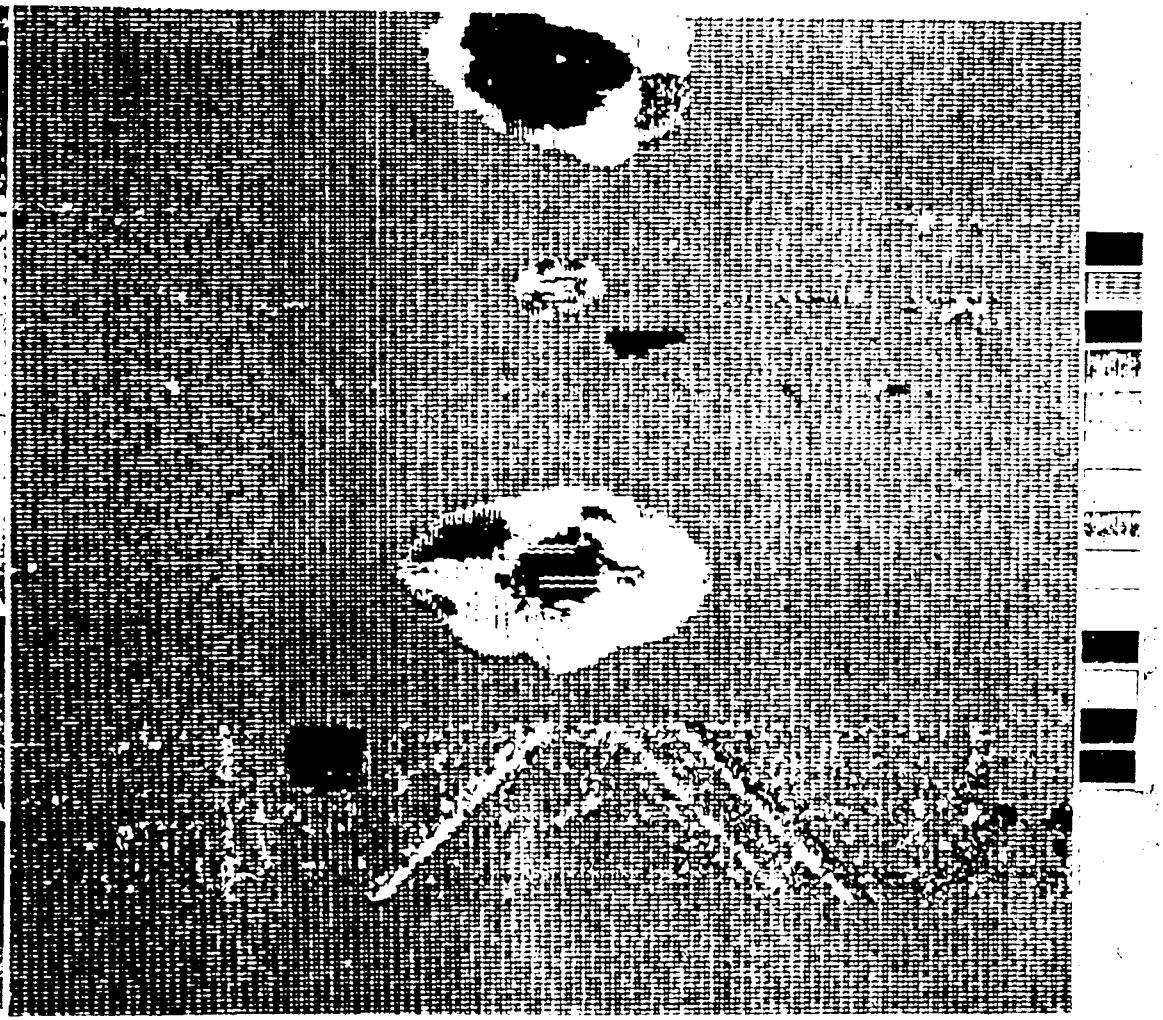
NDE METHODS FOR MMC

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

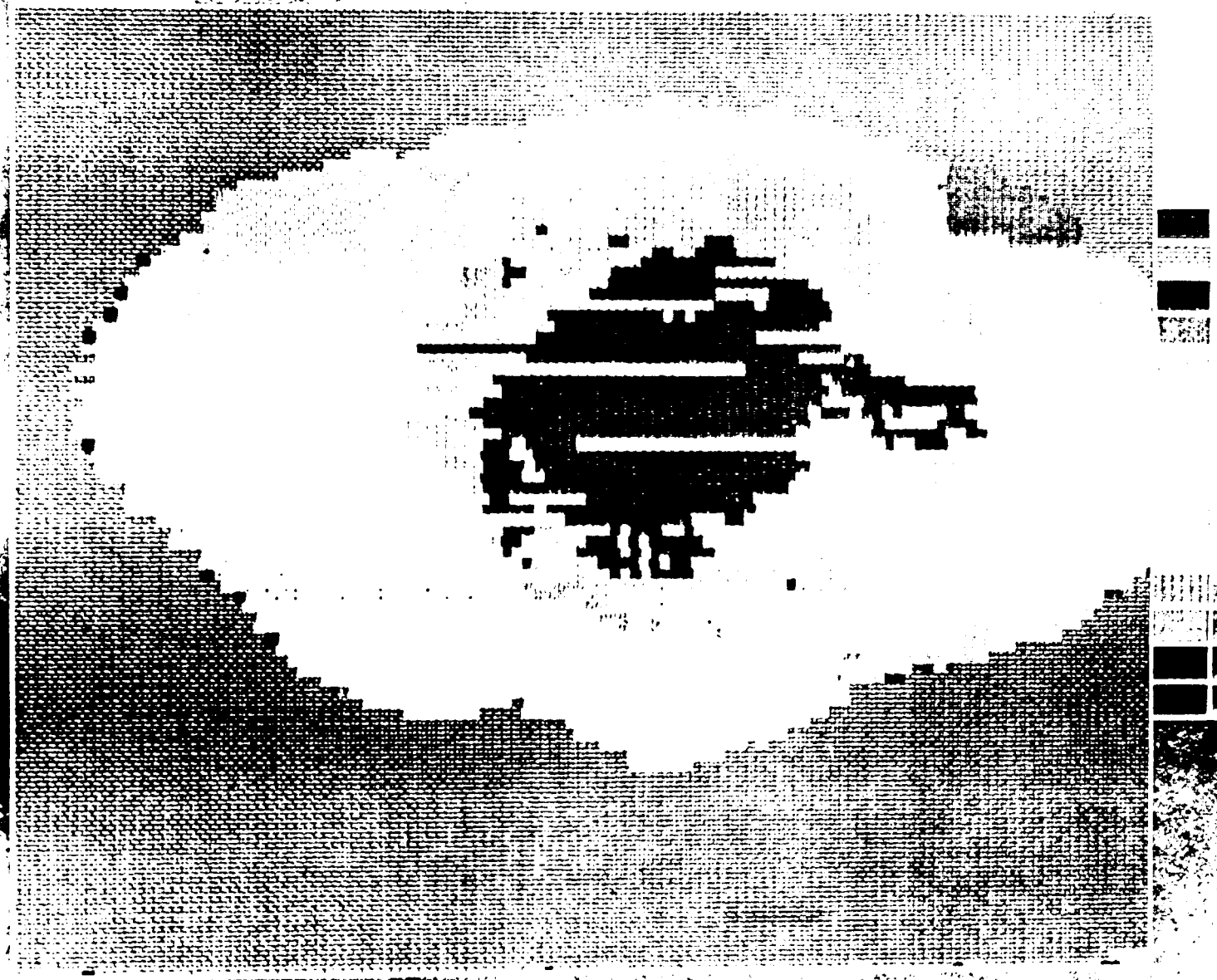


Ultrasonic C-scan. of a graphite/Epoxy laminate with delaminations and porosity.

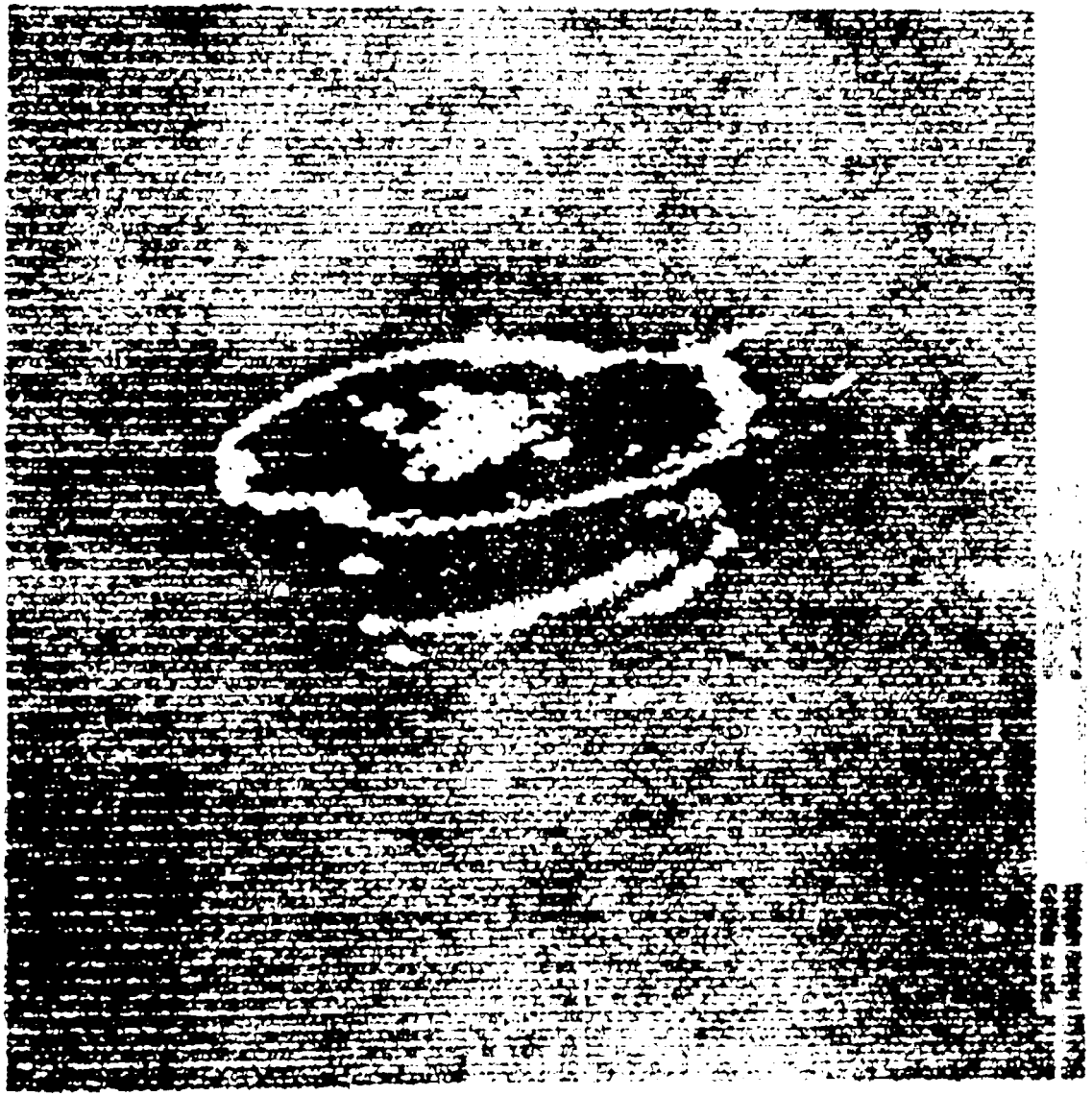
TOF C-SCAN OF IMPACT
DAMAGED
SUPPORTED HORIZ



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

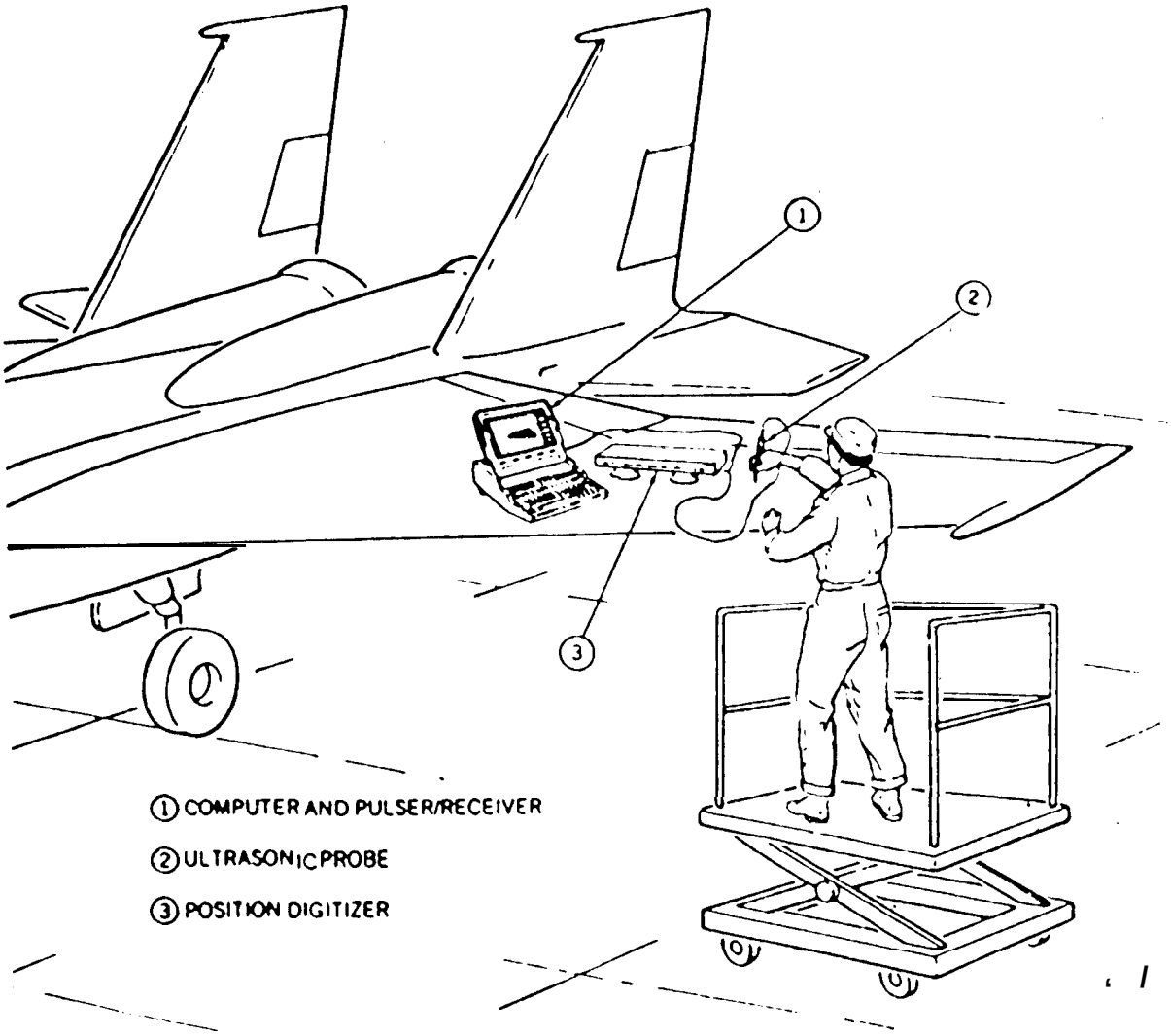


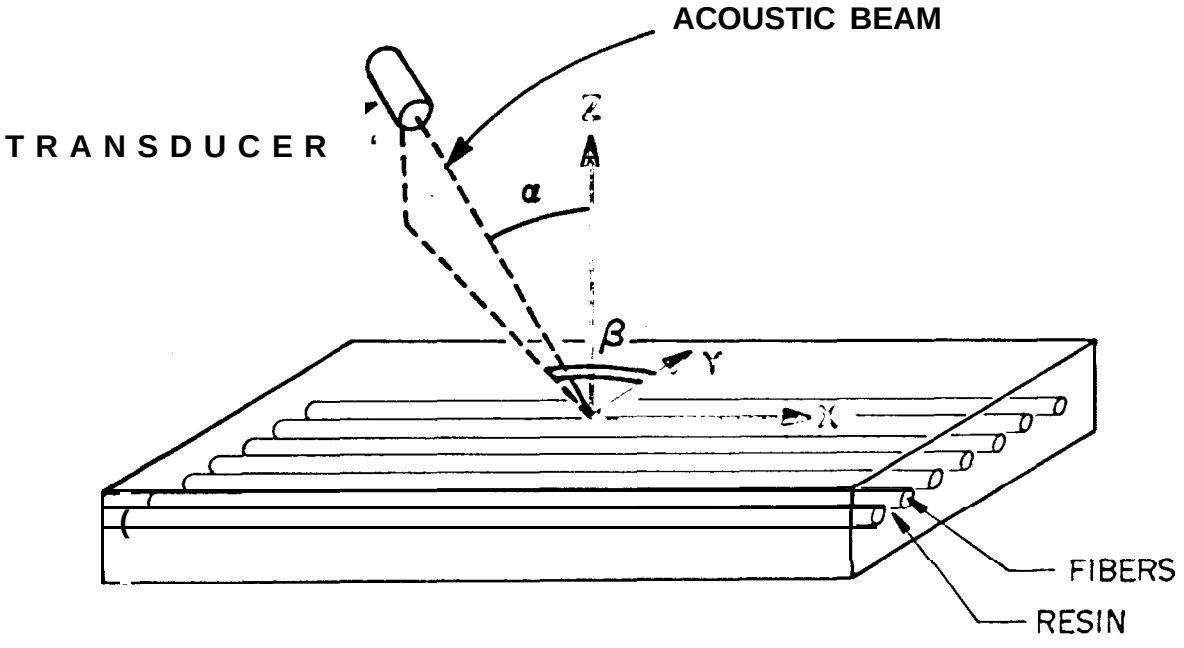
FIGURE 1-1. PORTABLE ULTRASONIC COMPUTERIZED SCANNER (PUCS)

POLAR BACKSCATTERING (PBS) PHENOMENON

- IT HAS BEEN STUDIED FOR COMPOSITES SINCE 1980”
- 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 THE PHENOMENON ARE STILL UNEXPLAINED.

• BAR-COHEN AND CRANE, 1980 .

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



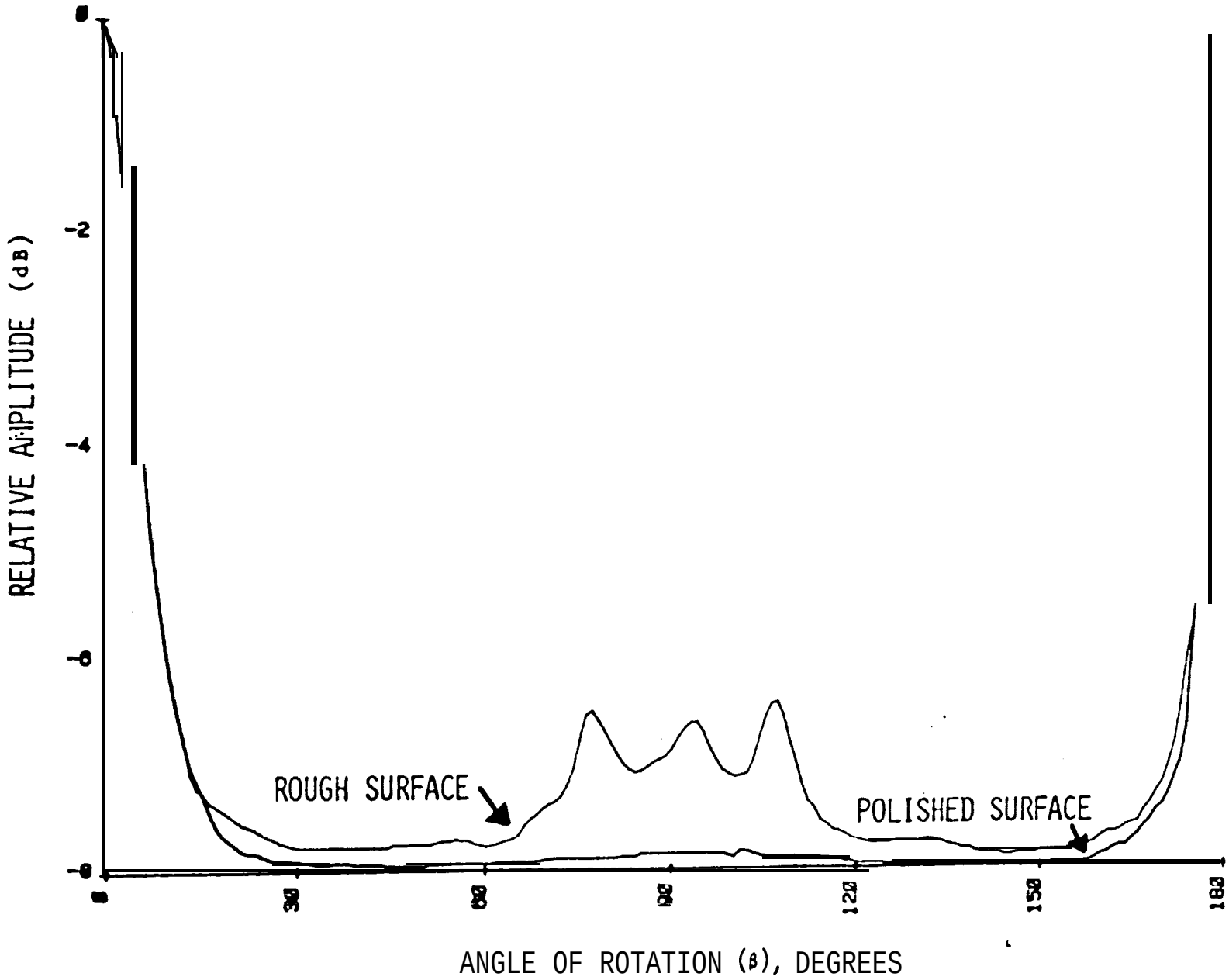
WHERE:

α – ANGLE OF INCIDENCE

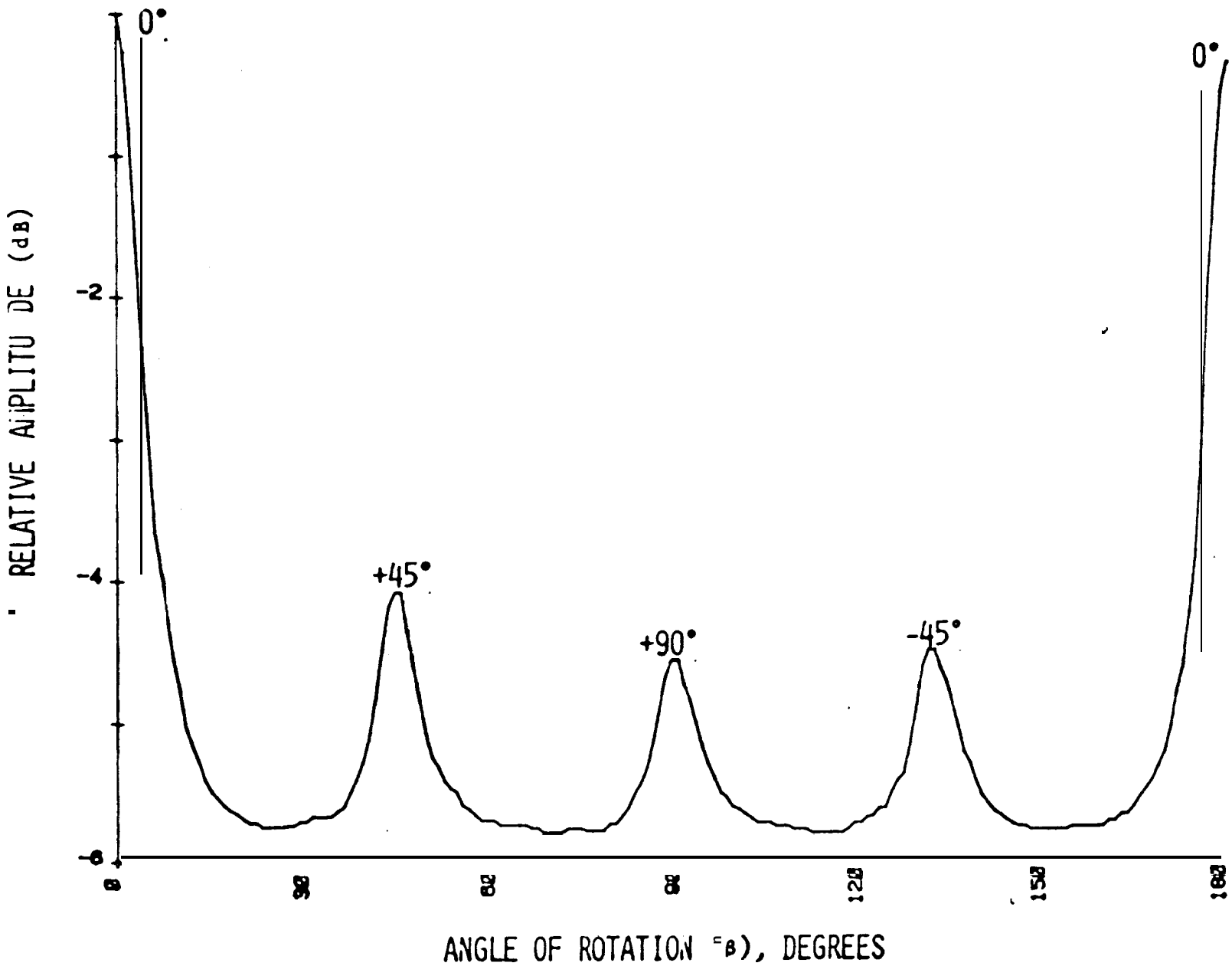
β - ANGLE BETWEEN Y-AXIS AND THE TRANSMITTER BEAM TRAJECTORY ON THE LAYER PLANE

[illegible] GLASS/EPOXY [illegible]

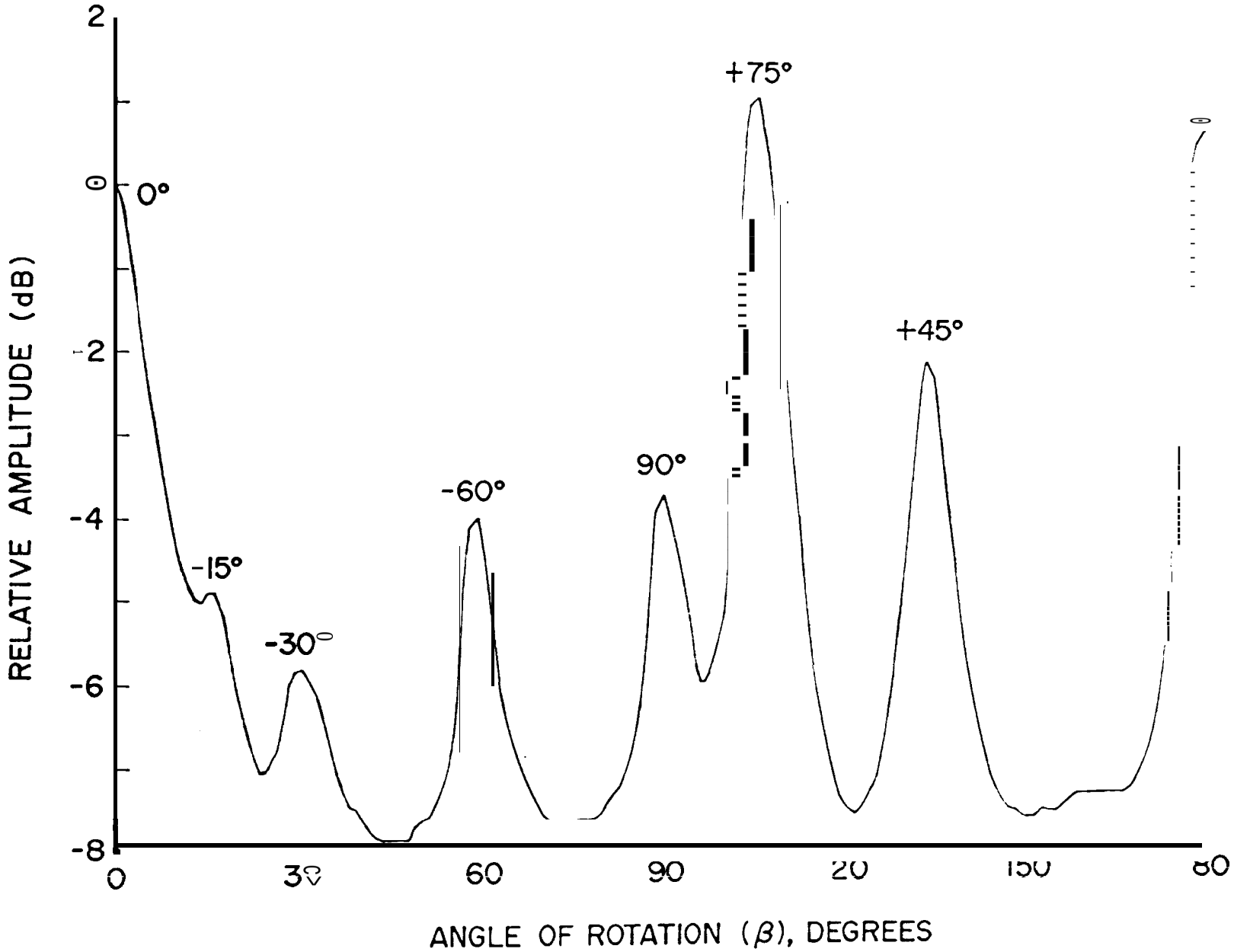
[illegible] SURFACE ROUGHNESS [illegible] THE ANGLE OF [illegible] 40°.



BACKSCATTERING FROM A QUASI-ISOTROPIC (0°, ±45°, 90°)$_S$ COMPOSITE
SCATTERING FROM EACH PLY IS APPARENT. THE ANGLE OF INCIDENCE WAS 30°

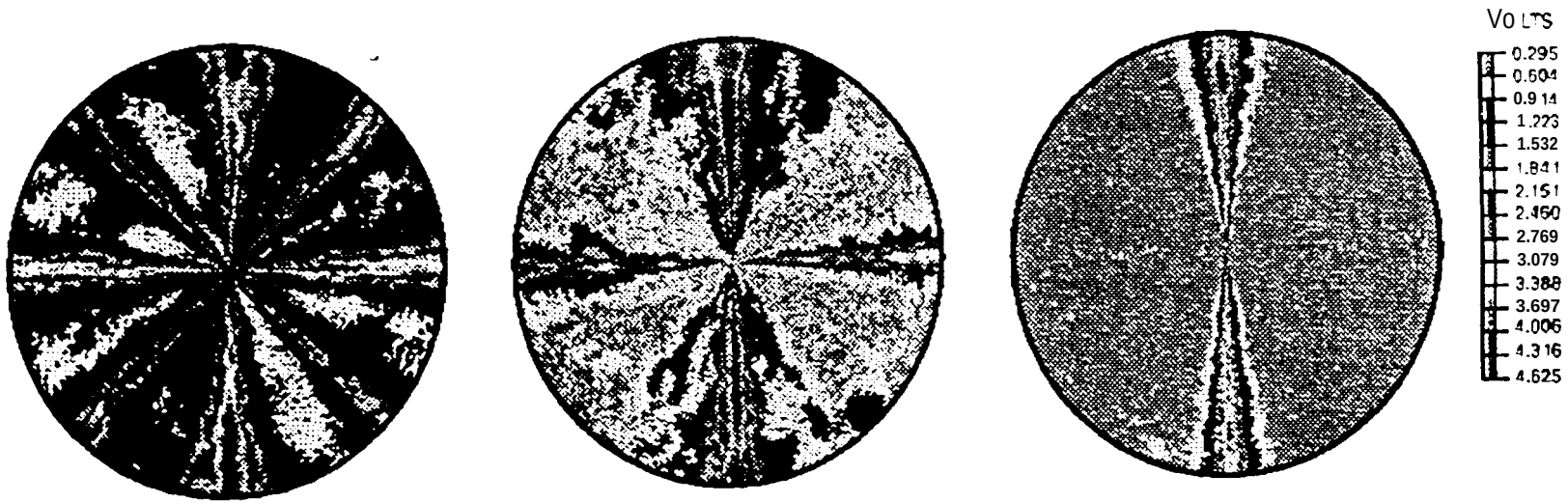


BACKSCATTERING FROM GRAPHITE/EPOXY COMPOS TE [0°, -15°, -30°, +45°, -60°, +75°, 90°]$_S$. ANGLE OF NCIDENCE WAS 40°.



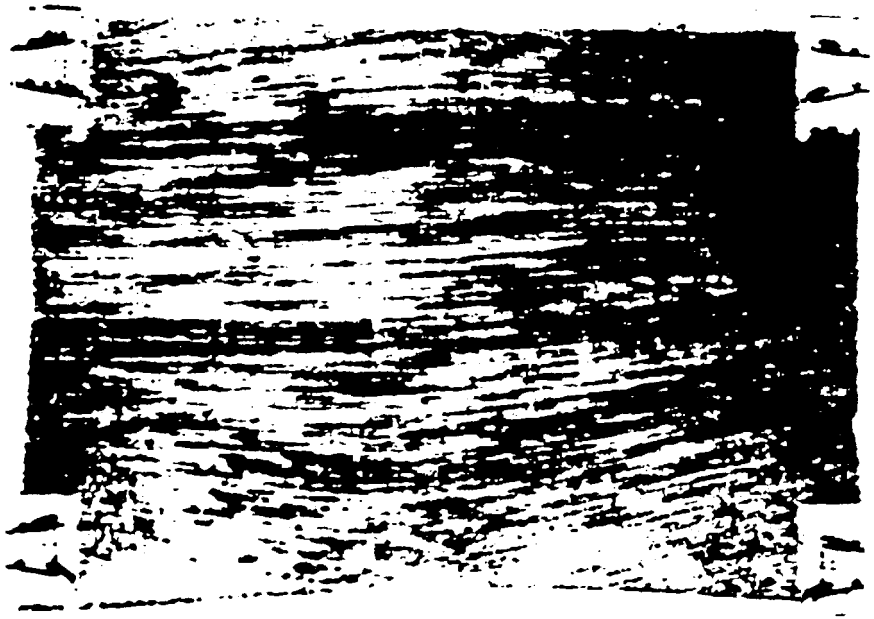
POLAR BACKSCATTERING IMAGES OF FIBER ORIENTATION IN GRAPHITE/EPOXY LAMINATES TESTED AT 5 MHz AND α = 30 DEGREES

$[0, 90, -45, +45]_S$ $[0, 90]_{2S}$ $[0]_8$



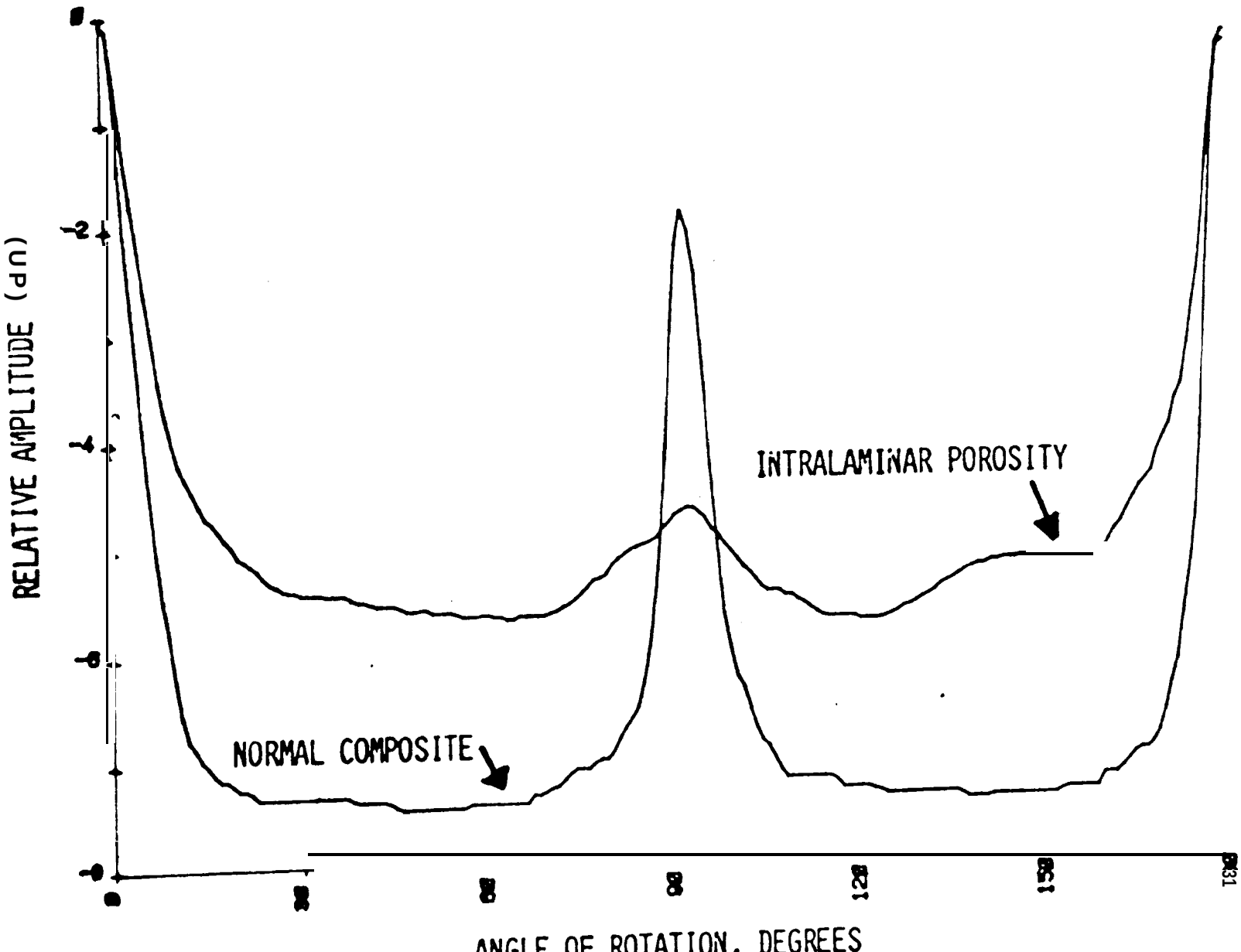
G039 11

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



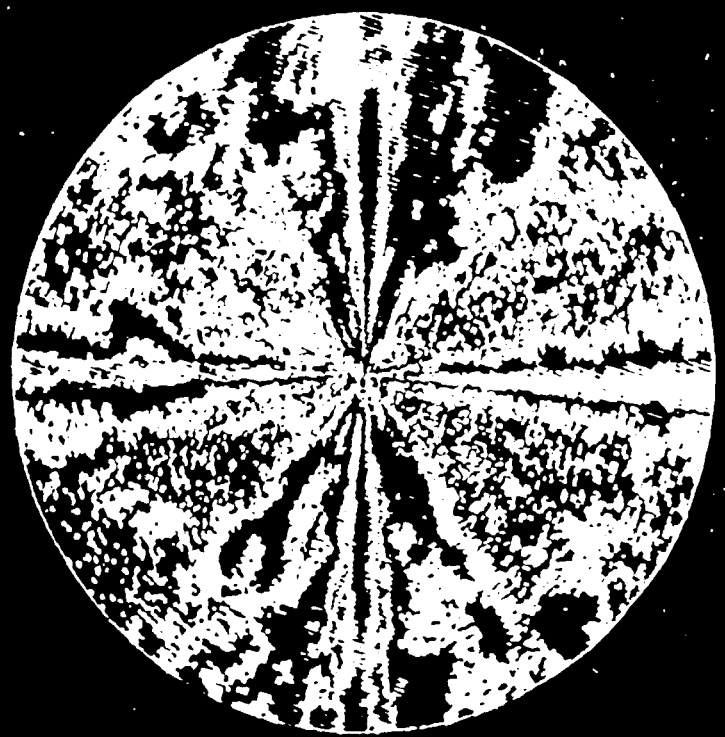
84 GEN 23008

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

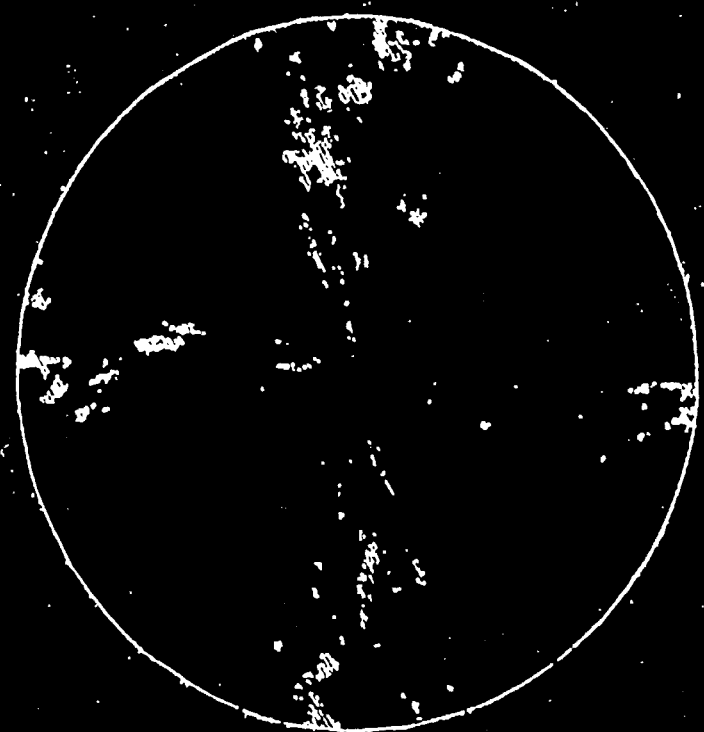


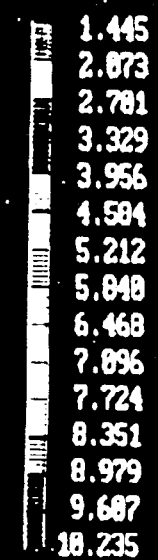
POLAR-BACKSCATTERING FROM Gr/Ep LAMINATES USING 5 MHz 1/4-INCH TRANSDUCER

0.7% POROSITY

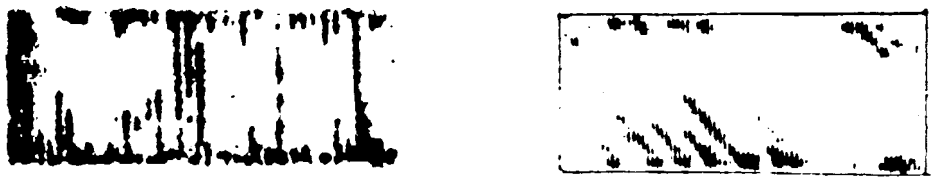


5.71% POROSITY



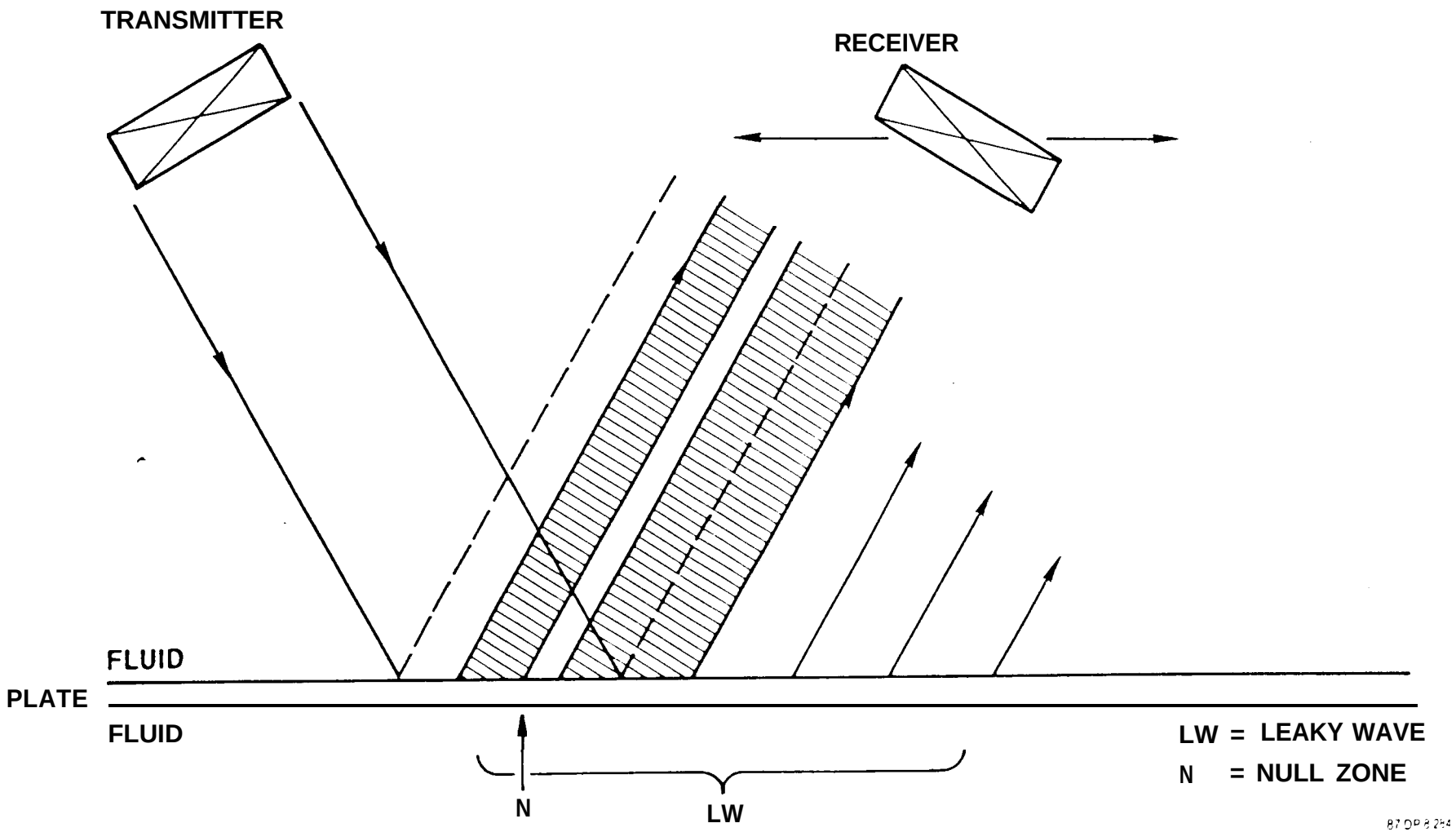


89-MFG-0007



(a) (b)

BACKSCATTERING SCAN OF QUASI-ISOTROPIC
GRAPHITE/EPOXY SPECIMEN FATIGUE LOADED TO
75% OF ULTIMATE STRENGTH AND 5 MILLION CYCLES

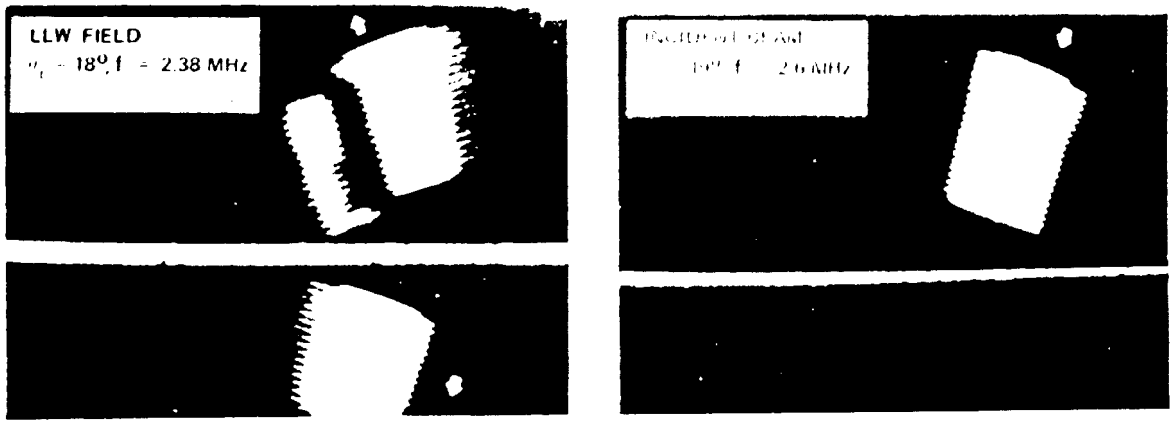

TRANSMITTER
RECEIVER
FLUID
PLATE
FLUID
N
LW
LW = LEAKY WAVE
N = NULL ZONE
87 OP 8 254

LEAKY LAMB WAVE (LLW) PHENOMENA

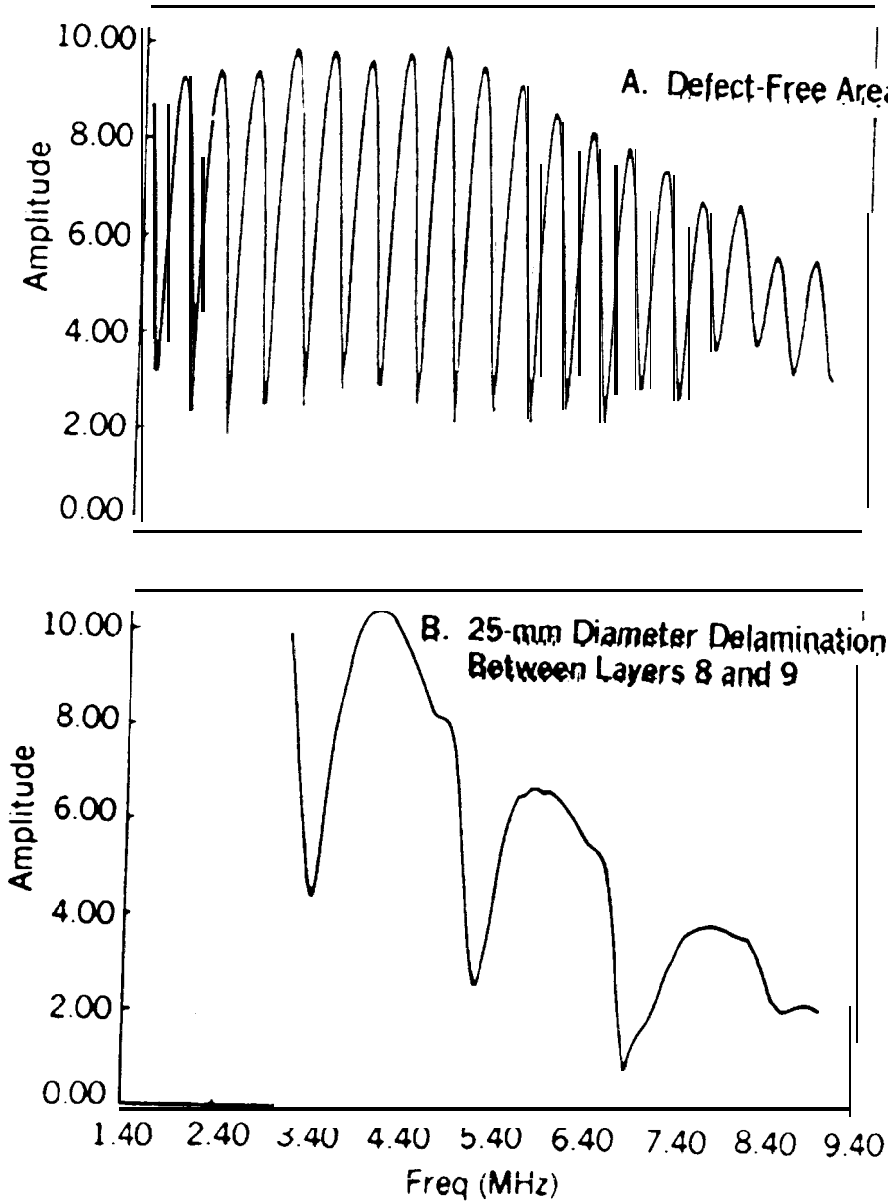
- HAS BEEN STUDIED FOR COMPOSITES SINCE 1983*
- PHENOMENA SENSITIVE TO BOUNDARY CONDITIONS AND ELASTIC ● ROPERTIES
- THEORETICAL MODELING OF THE ● HENOMENA HIGHLY SUCCESSFUL
- APPLIED TO INVERT COMPOSITES PROPERTIES AND CHARACTERIZE ● ONDINQ

* BAR-COHEN AND [illegible] 1985.

PULSED SCHLIEREN IMAGE OF LLW PHENOMENON



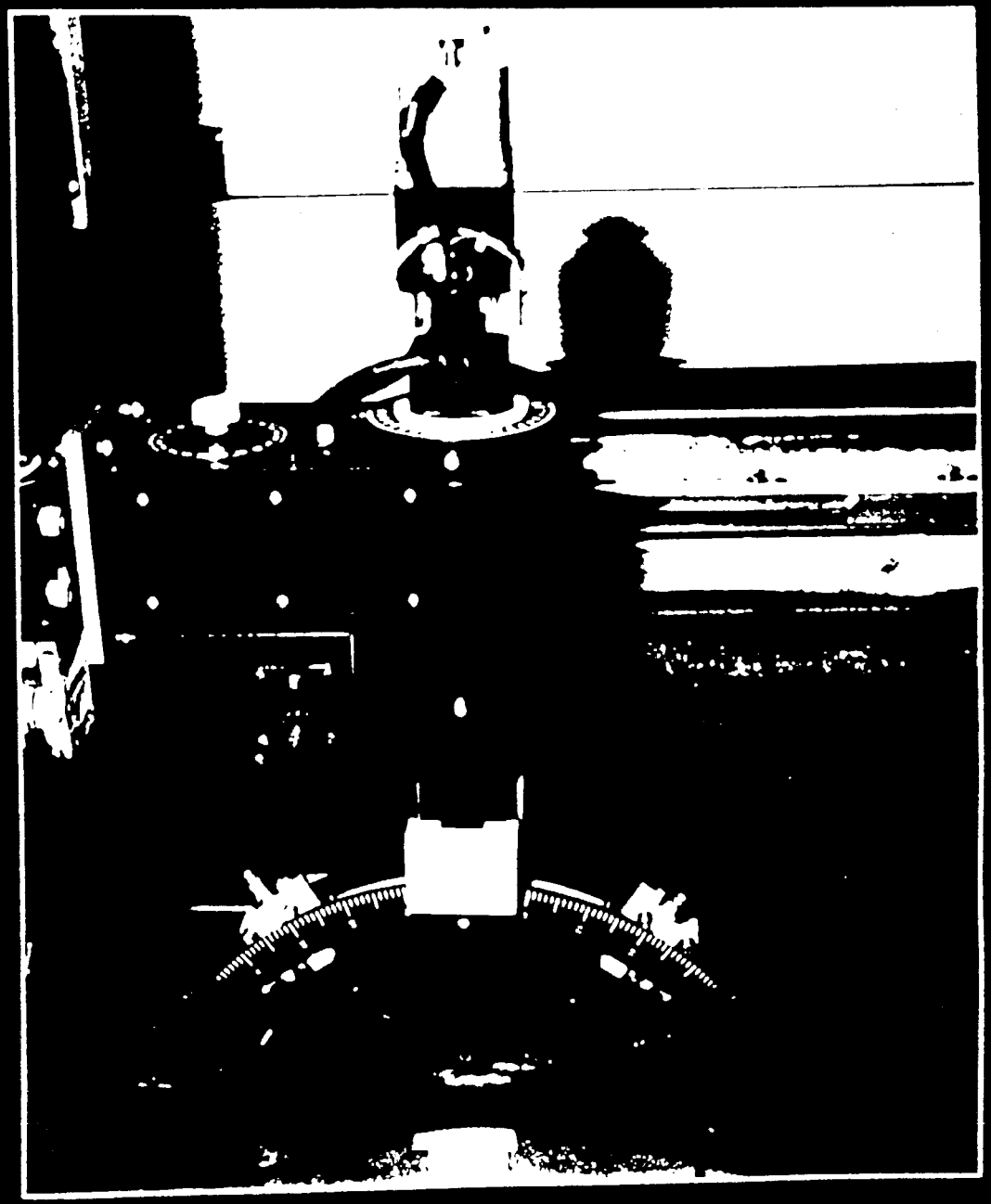
89 GEN 20135



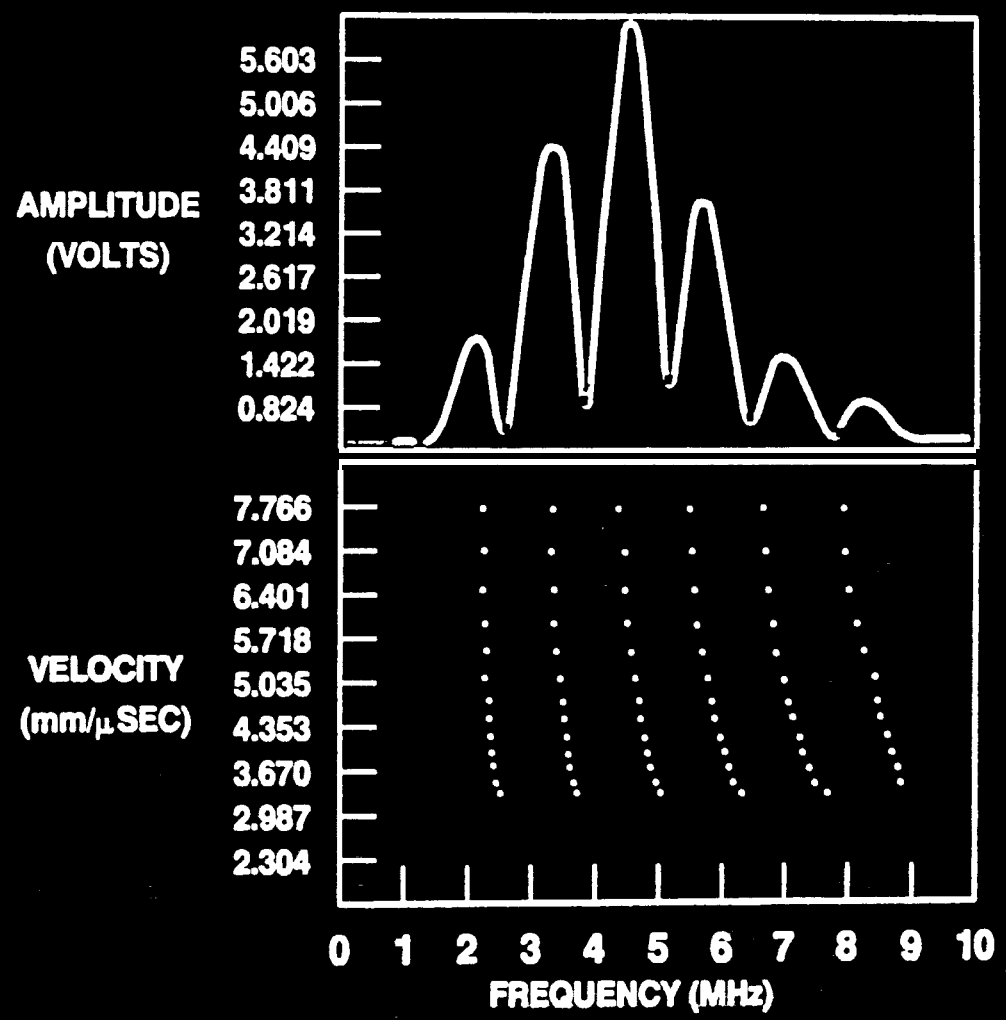
REFLECTION SPECTRA FOR LEAKY LAMB WAVE IN GRAPHITE/EPOXY AS4/3501-6 [0]32 TESTED AT 22 DEGREES ALONG THE FIBERS

86 GEN 22760

ATERIALS
ACTERIZATION
DEVICE
LOYING THE
W AND PBS
IETHODS

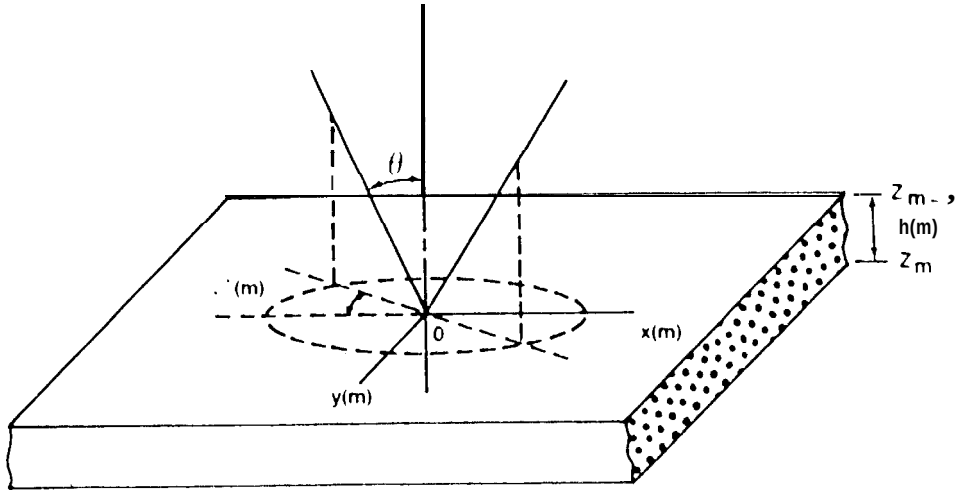


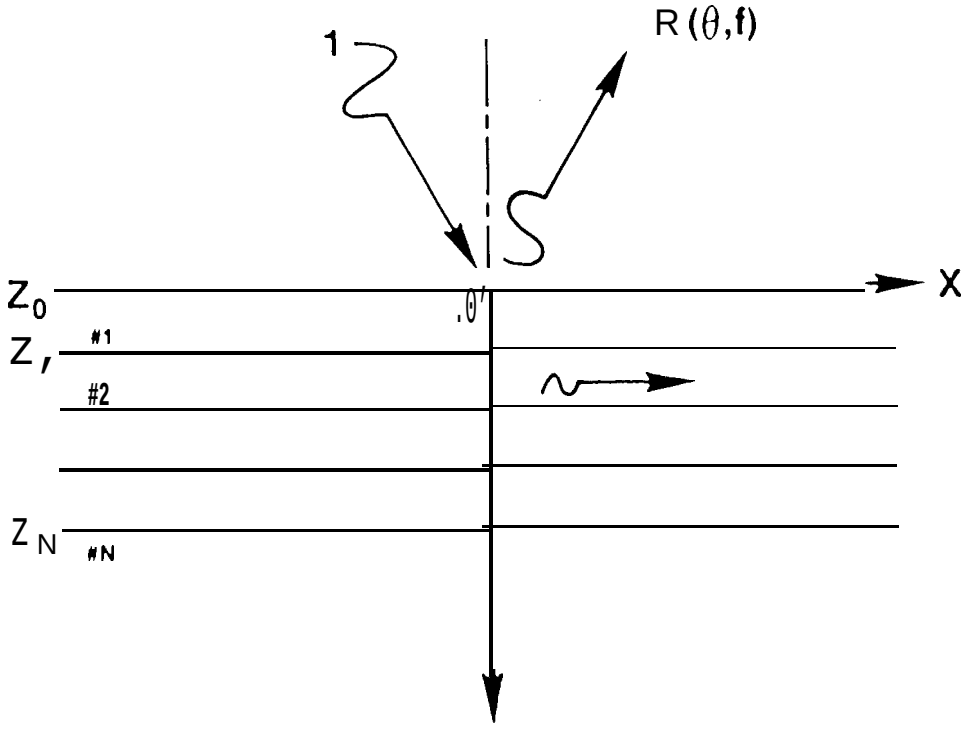
LLW SPECTRA AND DISPERSION CURVE FOR UNIDIRECTIONAL GRAPHITE/EPOXY 0.152 IN. THICK



CD2676.03

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

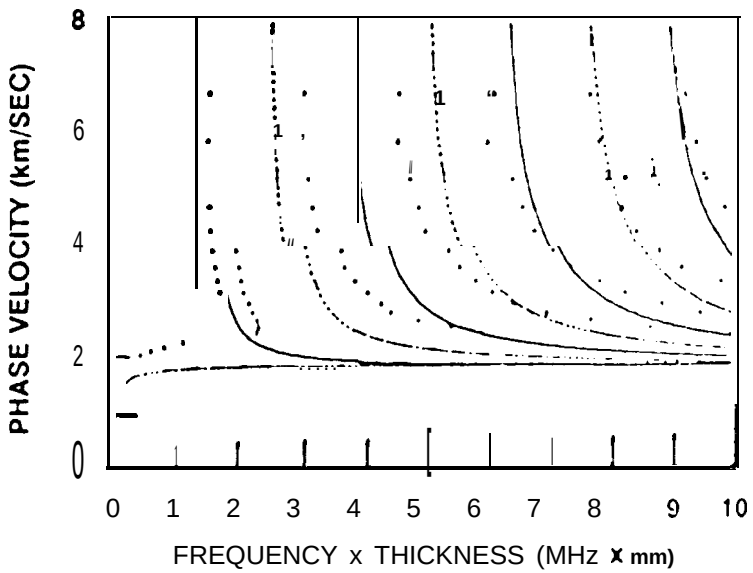




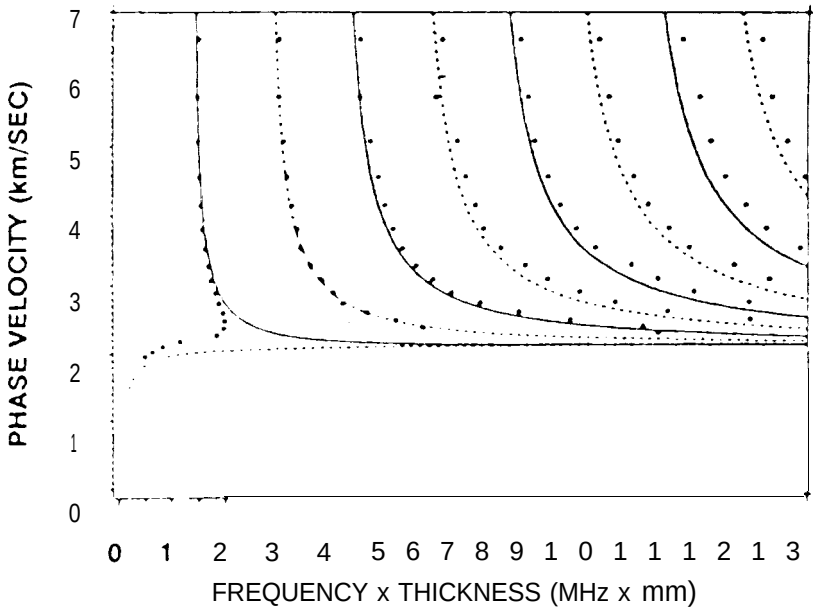
89 GEN 20172

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

a. ASSUMED ELASTIC PROPERTIES



b. INVERTED ELASTIC PROPERTIES



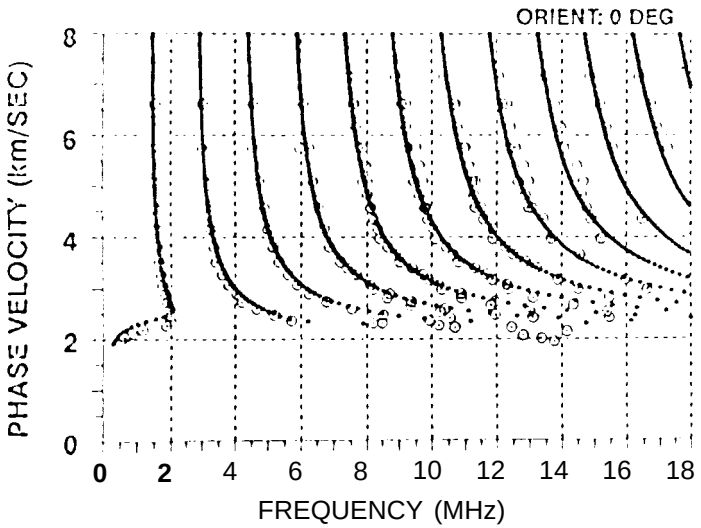
IPAD 896-429 3
LVC003 2

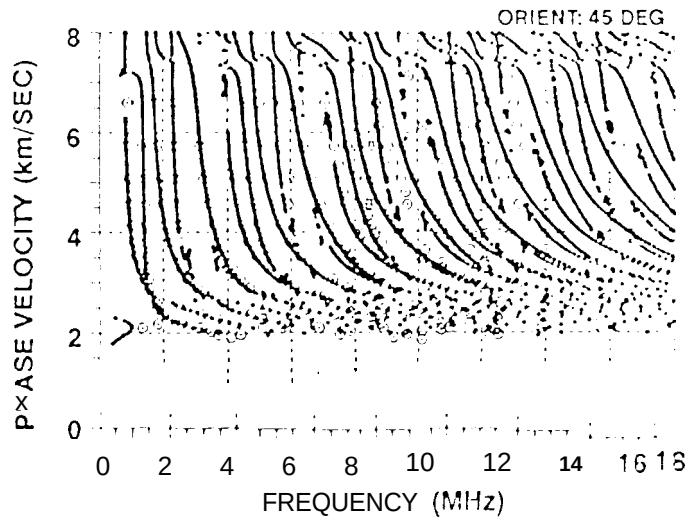
TABLE 1: MATERIAL PROPERTIES

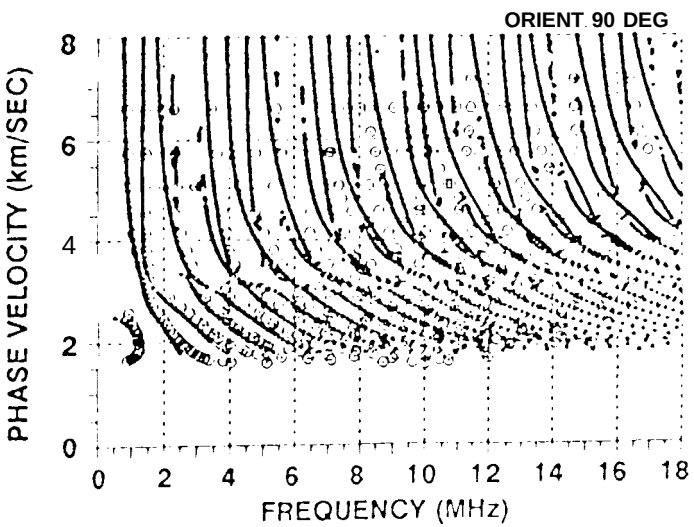
	INITIAL GUESS	SYSTEMATIC INVERSION
E_{11} (GPa)	156.75	157.77
E_{22} (GPa)	10.41	10.82
G_{12} (GPa)	7.07	7.982
G_{23} (GPa)	3.50	3.6367
υ_{12}	0.31	0.3374
ρ (gin/cc)	1.58	1.578
C_{11} (GPa)	160.73	162.729
C_{22} (GPa)	13.92	14.527
C_{12} (GPa)	6.44	7.359
C_{23} (GPa)	6.92	7.25
C_{55} (GPa)	7.07	7.982

CD1603 07

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



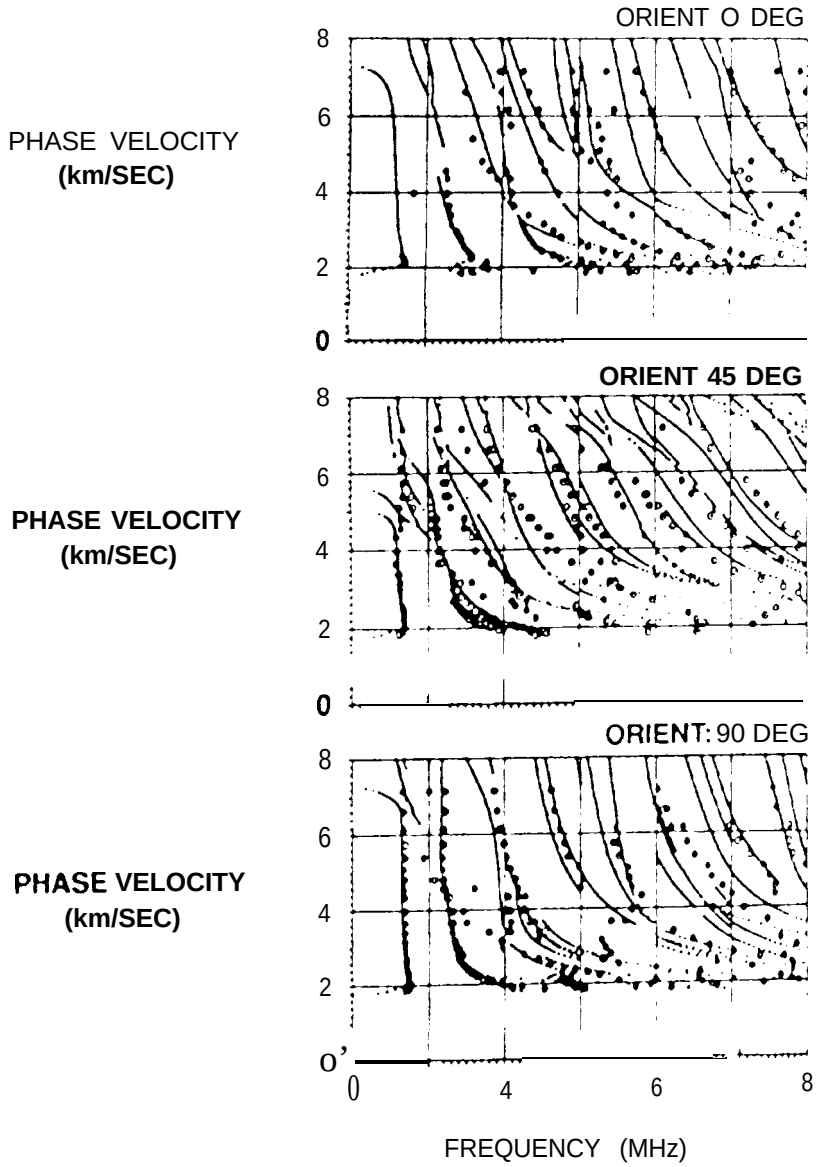




LAMINATE PROPERTIES

E_{11} (GPa)	157.7700
E_{22} (GPa)	10.8200
G_{12} (GPa)	7.9820
G_{23} (GPa)	3.6367
ν_{12}	0.3374
ρ (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/cm³
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

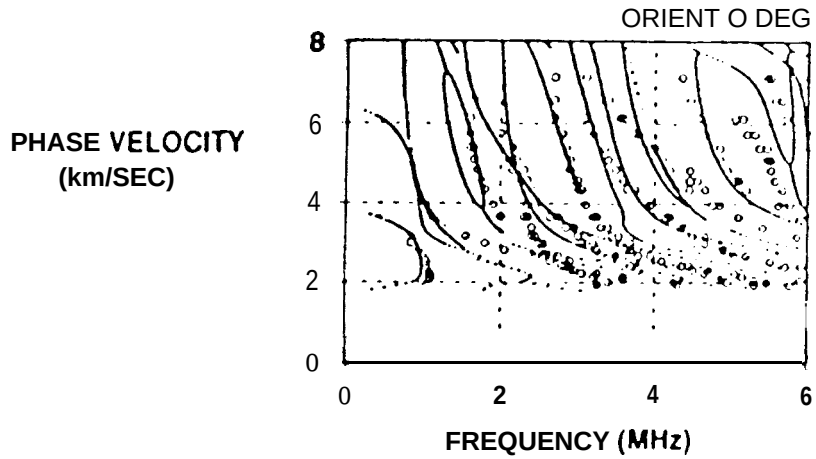
$\langle C_{11} \rangle$ = 88.62 GPa
$\langle C_{22} \rangle$ = 88.62 GPa
$\langle C_{33} \rangle$ = 15.73 GPa
$\langle C_{12} \rangle$ = 7.35 GPa
$\langle C_{13} \rangle$ = 7.30 GPa
$\langle C_{44} \rangle$ = 5.00 GPa
$\langle C_{55} \rangle$ = **5.00 GPa**
$\langle C_{66} \rangle$ = **7.98** GPa

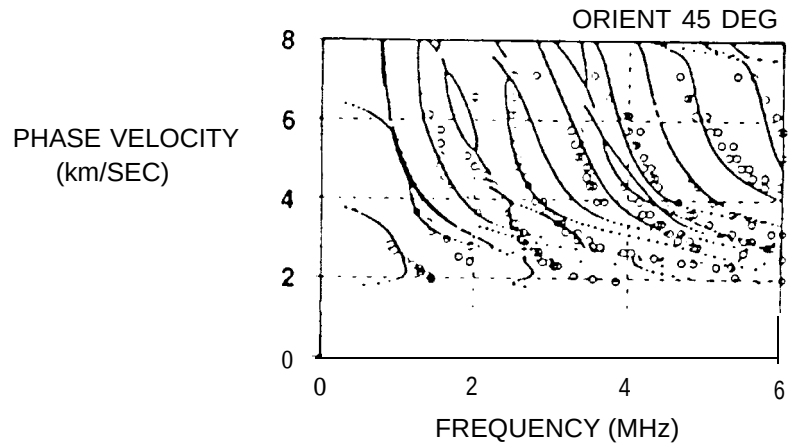
INTERFACE PROPERTIES

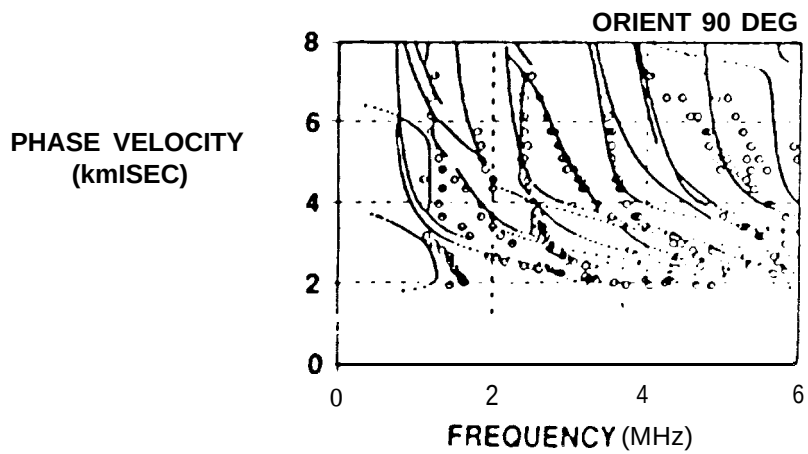
h = 7 μm
ρ = 1.2 g/cm³
α .2.1 km/see
β = 0.95 km/sec

⊙⊙ EXPERIMENTAL DATA
— THEORETICAL DATA

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







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
El, = 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

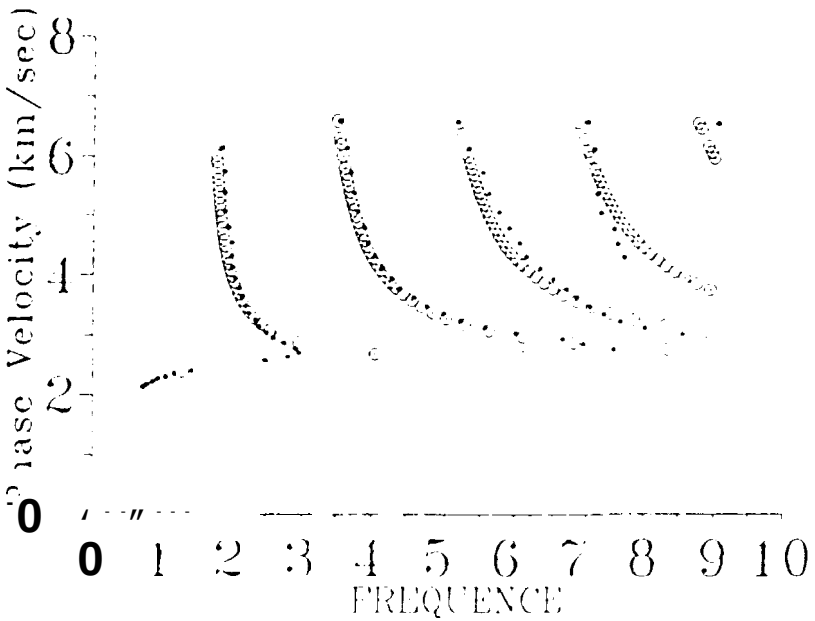
h = 15 μm
p = 1.2 gin/cc
a = 2.1 km/sec
β = 0.95 km/sec

⊙ ⊙ EXPERIMENTAL DATA

—— THEORETICAL DATA

90 DP 8286

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

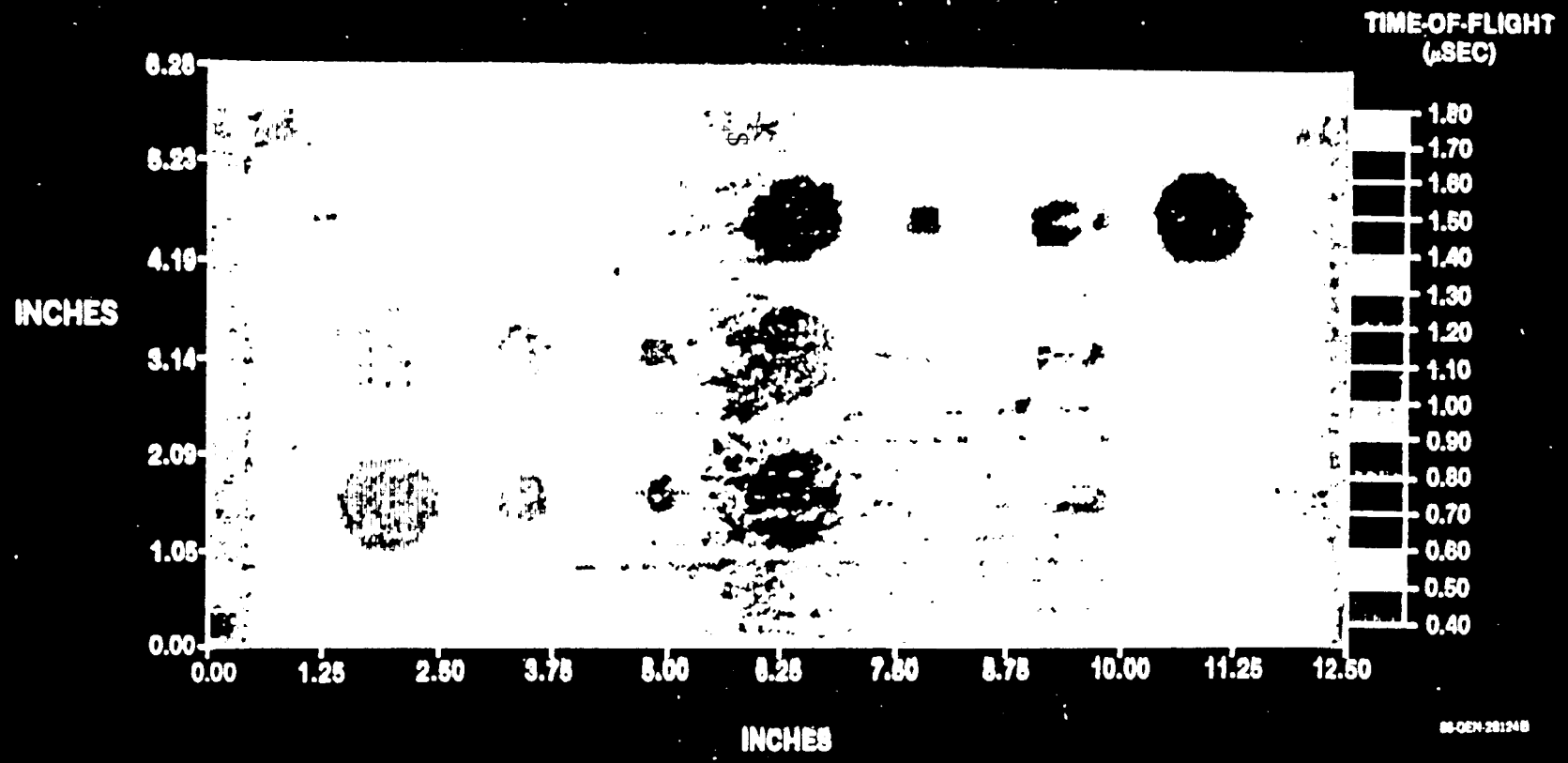


INVERTED ELASTIC PROPERTIES

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

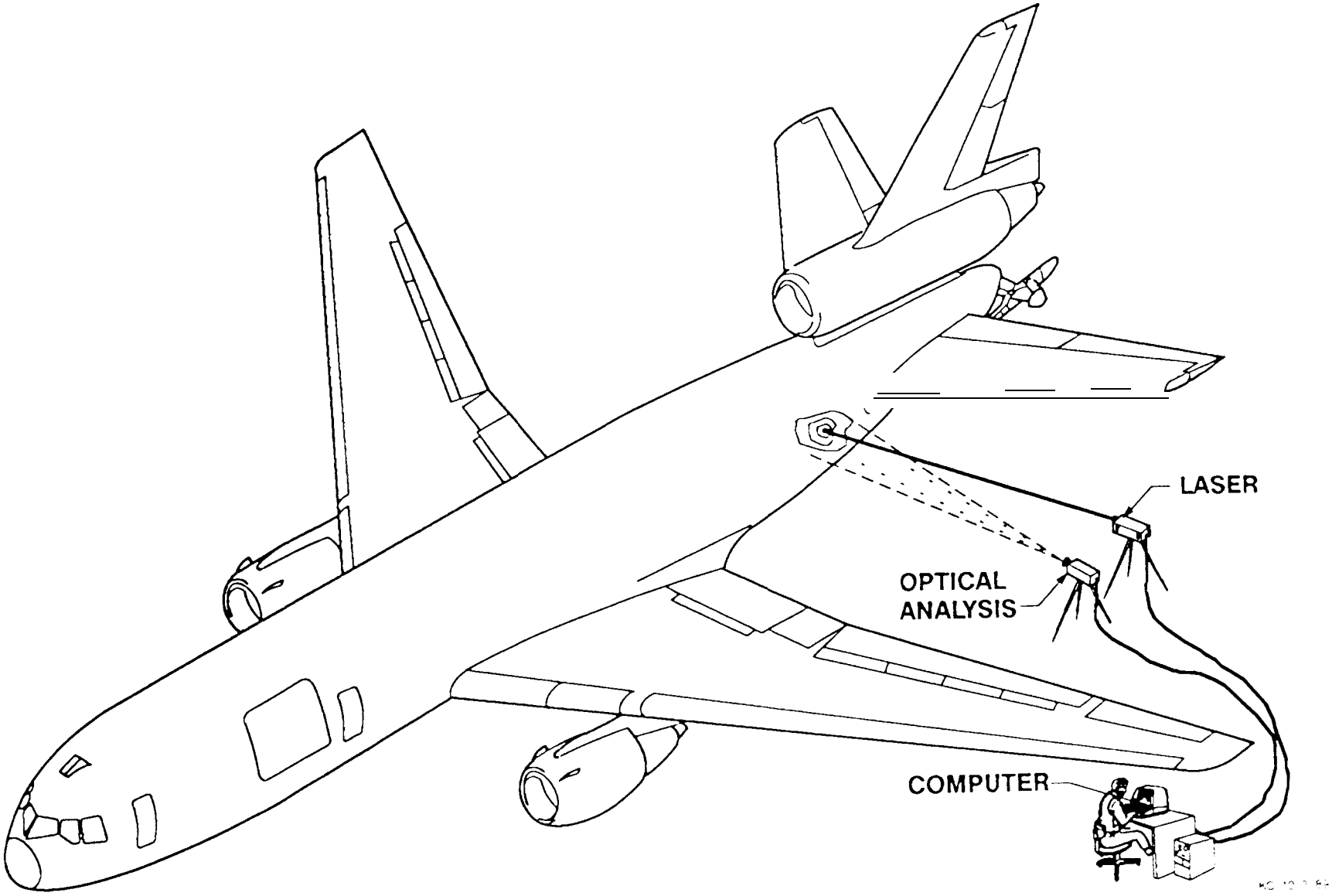
MCDONNELL DOUGLAS

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 AGEING 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, DELAMINATIONS, CRACKS, ETC.)
* MATERIAL PROPERTIES DETERMINATION
* REAL-TIME CHARACTERIZATION DURING CURE, AND SERVICE

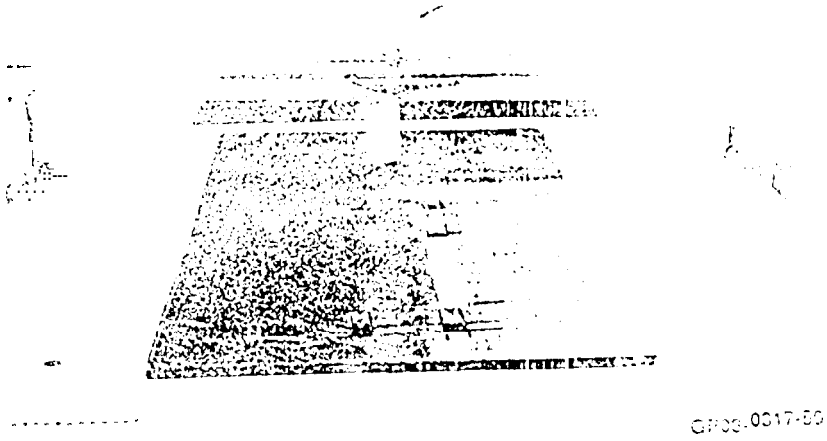


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Figure 6. Eddy Current Probe and Holding Fixture.

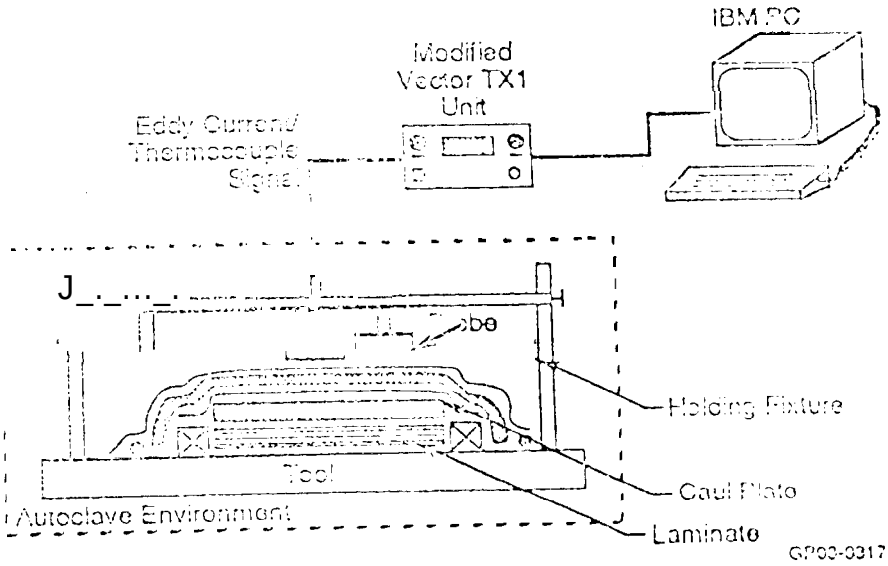

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Figure 7. Eddy Current Thickness Sensor Setup

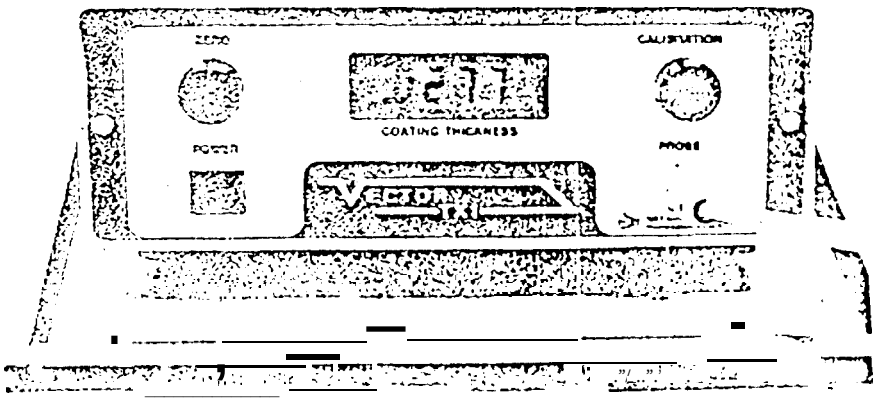

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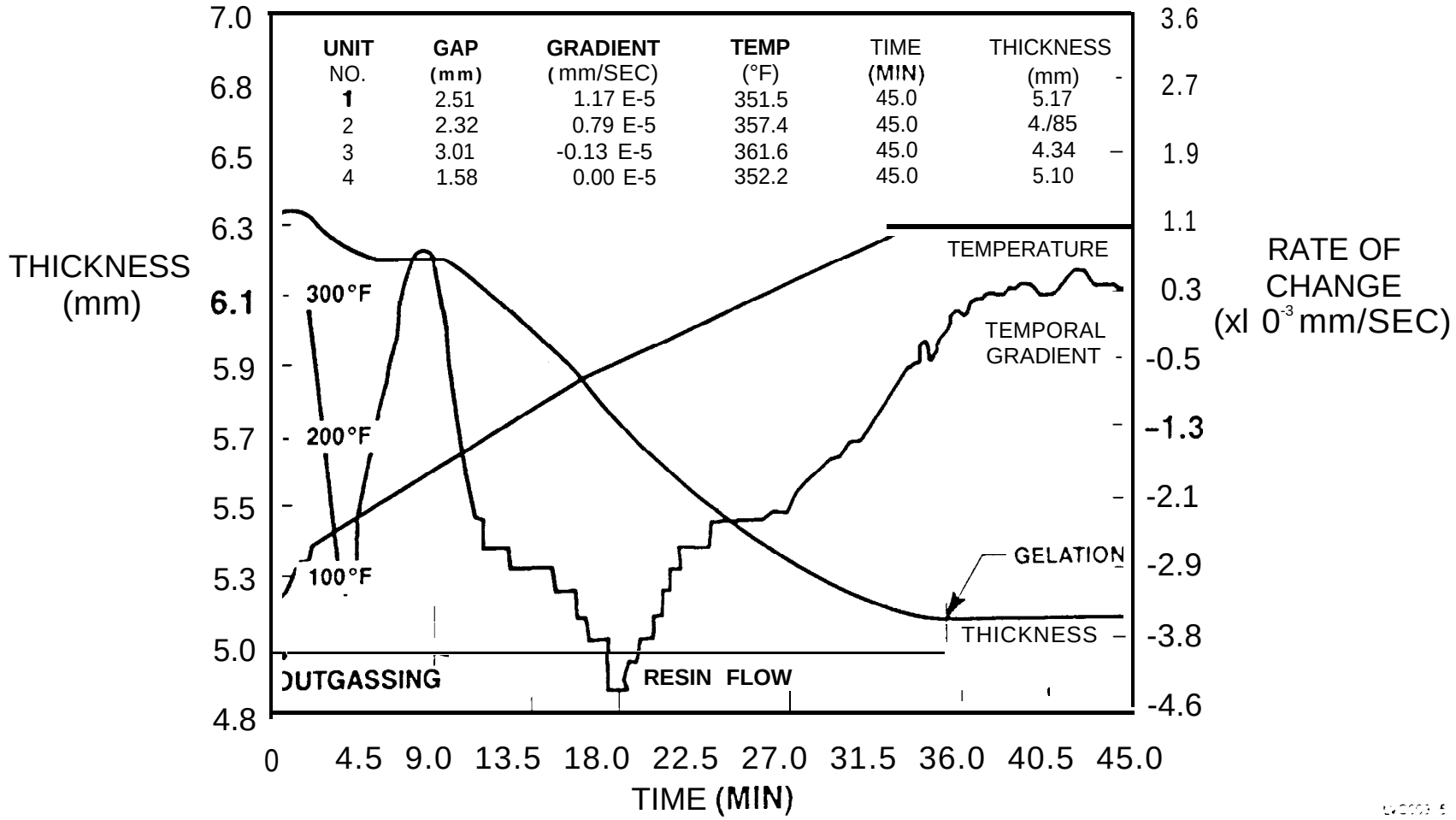
Figure 8. Modified Model Vector TXI Unit.

TYPICAL RESPONSE OF CURE MONITORED
UNIDIRECTIONAL GRAPHITE/EPOXY LAMINATE



PRESSURE SENSOR

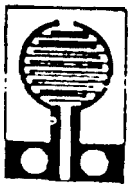
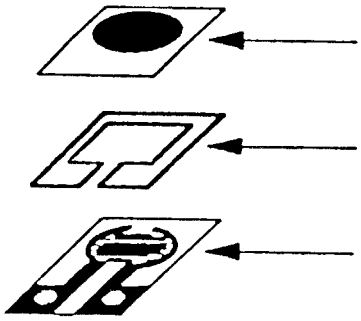
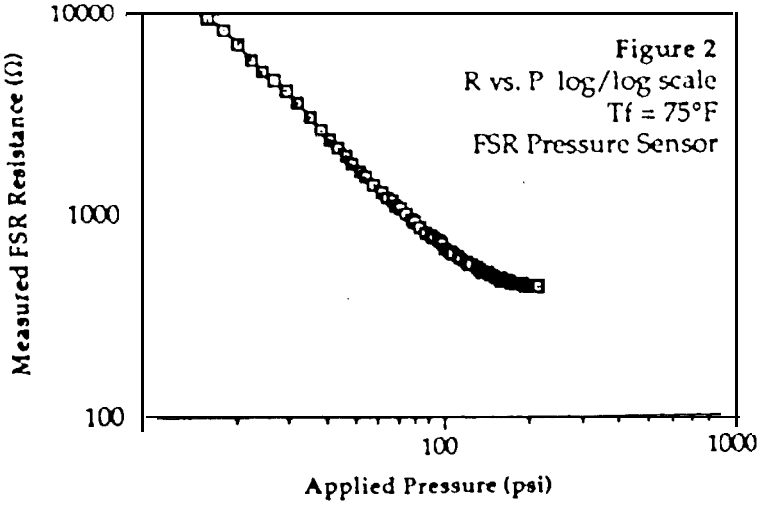


Figure 1
FSR Pressure
Sensor
(Actual Size)





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