

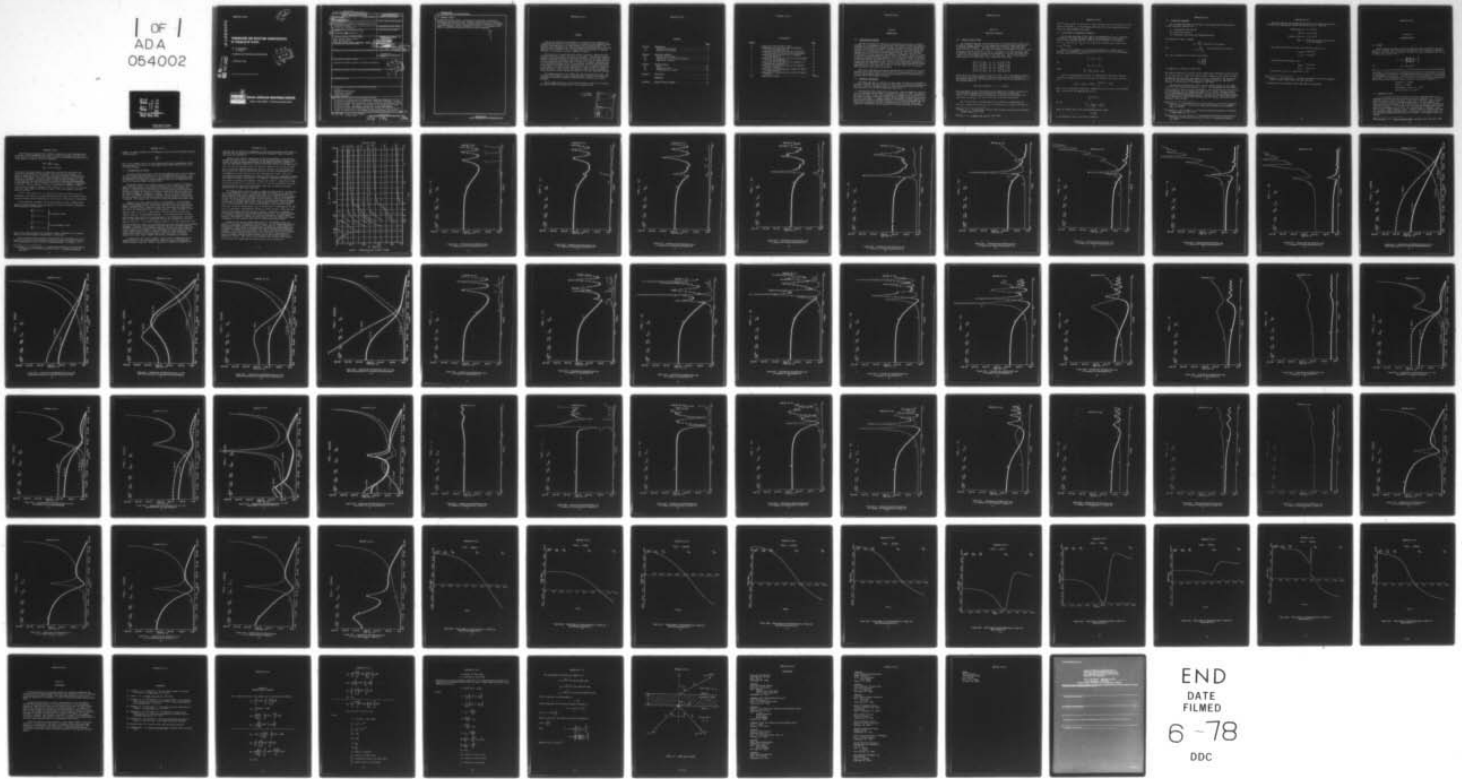
AD-A054 002

NAVAL SURFACE WEAPONS CENTER WHITE OAK LAB SILVER SP--ETC F/G 17/1
TRANSMISSION AND REFLECTION CHARACTERISTICS OF VISCOELASTIC PLA--ETC(U)
FEB 78 W MADIGOSKY, R FIORITO
NSWC/WOL/TR/78-4

UNCLASSIFIED

NL

1 OF 1
ADA
054002



END
DATE
FILMED
6 -78
DDC

NSWC/WOL TR 78-4

12
B.S.

AD A 054002

TRANSMISSION AND REFLECTION CHARACTERISTICS OF VISCOELASTIC PLATES

BY W. MADIGOSKY
R. FIORITO

RESEARCH AND TECHNOLOGY DEPARTMENT

1 FEBRUARY 1978

DDC
MAY 12 1978
F

AD No. []
DDC FILE COPY

Approved for public release, distribution unlimited.



NAVAL SURFACE WEAPONS CENTER

Dahlgren, Virginia 22448 • Silver Spring, Maryland 20910

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NSWC/WOL/TR/78-4	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
6. TITLE (and Subtitle) Transmission and Reflection Characteristics of Viscoelastic Plates		5. TYPE OF REPORT & PERIOD COVERED
7. AUTHOR(s) W./Madigosky R./Fiorito		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Surface Weapons Center White Oak Laboratory White Oak, Silver Spring, Maryland 20910		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61152N; ZR00001 ZR01108
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE 1 Feb 78
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release, distribution unlimited		13. NUMBER OF PAGES 81
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		15. SECURITY CLASS. (of this report) Unclassified
18. SUPPLEMENTARY NOTES		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Acoustic Transmission Coefficient Reflection Coefficient Viscoelastic Plates Acoustic Windows		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) An acoustic transmission matrix program for computing transmission (S) and reflection (R) coefficients for sound waves of arbitrary frequency, incident at arbitrary angles upon viscoelastic plates bounded by semi-infinite fluids, has been developed. The method, an extension of the formulation of Young for elastic plates, (J. Young, J. Acoust. Soc. Am 59, 1500 (1976)), utilizes the elastic and viscoelastic material properties of plates and the program is applied here to the problem of choosing materials for acoustic		

DDC
MAY 12 1978
LIBRARY

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

391 596

over
Jm

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. ABSTRACT (CONT.)

windows and acoustic lenses. The materials considered are Absonic-A, polyethylene and syntactic foam. Computed results are given in the form of transmission and reflection loss and presented as functions of incidence angle and frequency, and are interpreted in terms of the propagation and material constants and modal and half wave plate resonances.



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

SUMMARY

This report describes the development of a method for the computation of transmission and reflection coefficients of viscoelastic plates bounded by semi-infinite fluid media and of the phase change of the transmitted wave. The method has been implemented by a computer program which can provide the acoustic engineer with the necessary data for determining the application of specific materials to the design of acoustic windows and lenses.

The results of investigating three specific materials - Absonic-A, polyethylene and syntactic foam - are given in the report. Although the Absonic-A exhibits a greater transmission loss than polyethylene over the whole spectrum because of its higher absorption, they both have good low loss characteristics at lower frequencies and either might be chosen by a designer, based upon specific transmission windows which can be determined using the described method. A fluctuation in the phase of the transmitted wave for the Absonic-A material as the angle of incidence changes would make it a less satisfactory choice for some applications. The syntactic foam generally exhibits lower transmission losses and better defined transmission windows of the three materials analyzed.

The observed extrema in the transmission and reflection loss curves, representing such phenomena as shear absorption peaks, provide the designer with information concerning transmission characteristics heretofore not readily available.

These extrema obtained by the described method are shown to be consistent with results expected by application of the coincidence rule.

J. R. DIXON
By direction

ACCESSION for	
NTIS	WFO Section <input checked="" type="checkbox"/>
DDC	BIT Section <input type="checkbox"/>
UNANNOUNCED	<input type="checkbox"/>
JUSTIFICATION	
BY	
DISTRIBUTION/AVAILABILITY CODES	
Dist.	Dist.
A	

CONTENTS

		<u>Page</u>
SECTION 1	INTRODUCTION	5
1-1	Background and Purpose	5
1-2	Materials Investigated	5
SECTION 2	ANALYTICAL APPROACH	7
2-1	Transfer Matrix Method	7
2-2	Application to Viscoelastic Materials	8
2-3	Computation Procedure	9
SECTION 3	COMPUTED RESULTS	11
3-1	Format	11
3-2	Theoretical Basis	11
3-3	Interpretation of Results	13
SECTION 4	CONCLUSIONS	69
	REFERENCES	70
APPENDIX A	TRANSFER MATRIX ELEMENTS	A-1

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Dispersion Curves for ABS in Water	15
2	Transmission and Reflection Loss vs Frequency for Water/Polyethylene/FC-75	16
3	Transmission and Reflection Loss vs θ for Water/ Polyethylene/FC-75 and Water/Polyethylene/Water . . .	25
4	Transmission and Reflection Loss vs Frequency for Water/ABS/FC-75	30
5	Transmission and Reflection Loss vs θ for Water/ABS/ FC-75 and Water/ABS/Water	39
6	Transmission and Reflection Loss vs Frequency for Water/Syntactic Foam/FC-75	44
7	Transmission and Reflection Loss vs θ for Water/ Syntactic Foam/FC-75	53
8	Phase Angle of Transmitted Wave vs Theta for Water/ Polyethylene/FC-75	58
9	Phase Angle of Transmitted Wave vs Theta for Water/ ABS/FC-75	63
A-1	Single Layer Problem	A-5/A-6

Section 1

INTRODUCTION

1-1. BACKGROUND AND PURPOSE

The use of materials in underwater sound applications requires a detailed knowledge of the transmission and reflection coefficients for arbitrary angles of incidence and frequencies of propagation when the material forms a liquid/solid interface with various fluid media. Although some data, both experimental and theoretical, are available in the literature, generally they do not provide an adequate basis for the acoustic design engineer who must deal with different thicknesses, different frequencies and different fluid media. Often, as a result of variations in manufacturing processes, "off the shelf" materials may exhibit properties different from those described in the literature. Also, in some cases the relevant acoustic properties may have been inadequately characterized, and in many cases not determined at all. Finally, since experimental measurements of transmission and reflection coefficients are typically made using finite acoustic beams and plates, these experimental results are often difficult to interpret, particularly for large angles of incidence.

This report describes an analytical approach which can provide the acoustic engineer with all the necessary acoustic data (reflection/transmission coefficients and phase angle), given a set of known characteristics of the materials of interest and the interfacing fluid media.

1-2. MATERIALS INVESTIGATED

The method used here is valid for multiple layers of elastic or viscoelastic materials. However, the data presented in this report were generated assuming only one layer of material bounded on the input side by water and on the output side either by water or by the fluorocarbon lens fluid FC-75.

Three materials were analyzed for this report. They are Absonic-A, (an Acrylonitrile-Butadiene-Styrene plastic hereinafter referred to as ABS), polyethylene and syntactic foam. In each case the material was assumed to be in the form of a flat plate one-eighth inch thick (0.003175 meter) bounded by semi-infinite initial and final fluid media. A computer program was developed to perform computations based upon the analytical approach described in the following paragraphs with the output being produced in the form of transmission and reflection losses (dB) relative to the incident beam as functions of frequency and angle of incidence.

Section 2

ANALYTICAL APPROACH

2-1. TRANSFER MATRIX METHOD

The analytical approach used was based upon the "transfer-matrix" method first proposed by Thomson (Reference 1) and subsequently adapted by Young (Reference 2) to computer implementation. The method makes use of the fact that normal and shear stresses, T_{zz} and T_{xz} , and normal and tangential displacements, S_z and S_x , are continuous across a solid-solid interface. Furthermore, for each individual layer of material, the conserved stresses and displacements on one side are linear functions of the corresponding quantities on the other side. Thus a transfer-matrix representation of a solid layer can be constructed in the form:

$$\begin{bmatrix} S_x(1) \\ T_{zz}(1) \\ S_z(1) \\ T_{xz}(1) \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix} \cdot \begin{bmatrix} S_x(2) \\ T_{zz}(2) \\ S_z(2) \\ T_{xz}(2) \end{bmatrix}$$

where (1) and (2) refer to opposite sides of a layer. For a multilayered structure of n layers, the transfer matrix for the entire structure can be constructed by multiplying together the individual matrices for each layer in the appropriate order. The resulting matrix is

$$[M] = [m(1)] [m(2)] \cdots \cdots [m(n)].$$

Using the matrix in this form and applying the appropriate boundary conditions for the fluid-solid interfaces, the reflection and transmission coefficients, R and S , can be computed, given the densities, ρ_I and ρ_F , and the acoustic wave velocities, C_I and C_F , of the initial and final fluid media respectively.

The n^{th} solid layer is characterized by its density ρ_n , longitudinal and shear wave velocities, C_{Ln} and C_{Sn} , and its thickness d_n . The matrix elements for

^{1/} Thomson, W. T., "Transmission of Elastic Waves Through a Stratified Solid Medium," J. Appl. Phy. 21, 89 (1950)

^{2/} Young, J. W., J. Acoust. Soc. Am. 59, 1500 (1976)

the n^{th} layer, $m_{ij}(n)$, are functions of these parameters and of the frequency, ω , and angle of incidence, θ_I , of an incoming plane wave and are thus computable provided values for these parameters are known.

2-2. APPLICATION TO VISCOELASTIC MATERIALS

For the work described in this report, the formulation of Young as described in Reference 2 has been extended to make the method applicable to viscoelastic materials by considering the wave velocities in the material to be complex; i.e., $C_{Ln} = \overset{*}{C}_{Ln}$ and $C_{Sn} = \overset{*}{C}_{Sn}$ for the longitudinal and shear waves respectively in the n^{th} layer.

Figure A-1 of Appendix A illustrates this approach for a single layer of material. In the material, the wave propagation factor for both the longitudinal and shear waves must be complex, i.e.:

$$\overset{*}{k}_L = \vec{k}'_L + i \vec{k}''_L$$

and

$$\overset{*}{k}_S = \vec{k}'_S + i \vec{k}''_S$$

where

$$\overset{*}{k}_L = \omega / \overset{*}{C}_L \quad \text{and} \quad \overset{*}{k}_S = \omega / \overset{*}{C}_S$$

Also, in the viscoelastic material, the amplitude of either wave will have the form of a damped plane wave traveling in the direction of \vec{r} with a velocity c , i.e.,

$$e^{i\vec{k} \cdot \vec{r}} = e^{i(\vec{k}' \cdot \vec{r} + i\vec{k}'' \cdot \vec{r})} = e^{\frac{i\omega}{c} \hat{l}_k \cdot \vec{r}} e^{-\alpha \hat{l}_k \cdot \vec{r}}$$

where α is the appropriate absorption coefficient and \hat{l}_k is a unit vector along $\overset{*}{k}$. Thus, from the real and imaginary parts of $\overset{*}{k}$,

$$\frac{\omega}{\overset{*}{C}} = \frac{\omega}{C} + i\alpha,$$

so that

$$\overset{*}{C} = \frac{C}{1 + \frac{i\alpha C}{\omega}} = \frac{C}{1 + i\tilde{r}}$$

gives the complex form of the corresponding velocity, where

$$\tilde{r} = \frac{\alpha C}{\omega}$$

is the absorption loss for the wave in question.

2-3. COMPUTATION PROCEDURE

For the method described in this report, the assumed known characteristics of the viscoelastic material are:

C_L = longitudinal wave velocity

C_S = shear wave velocity

α_L = absorption coefficient for longitudinal waves.

The procedure is then to compute:

$$\tilde{r}_L = \frac{\alpha_L C_L}{\omega}, \text{ absorption loss (nepers)}$$

and

$$\delta_L = \frac{2\tilde{r}_L}{1 - \tilde{r}_L^2}, \text{ the longitudinal loss factor,}$$

then use the tangential loss factor relationship,

$$2 \frac{\delta_S}{\delta_L} = \left[\frac{C_L}{C_S} \right]^2$$

to compute δ_S , \tilde{r}_S and α_S for shear waves.

The complex velocities, $\overset{*}{C}_L$ and $\overset{*}{C}_S$, and the complex wave propagation factors, $\overset{*}{k}_L$ and $\overset{*}{k}_S$, are then used to compute the transfer-matrix elements m_{ij} and obtain the final transmission and reflection coefficients, S and R, respectively. The expressions for S, R and the matrix elements used in the computer program are described in Reference 2 and are given in the appendix to this report

The procedure described here relies upon the assumed validity of the tangential loss factor relationship between δ_L and δ_S . This assumption has been extensively tested for various plastics and rubbers. The relationship has been verified for polypropylene over the temperature range -50°C to $+100^\circ\text{C}$. Waterman, (Reference 3) and Hartmann and Jarzynski (Reference 4) have provided corroborating data on polyethylene and polymethylmethacrylate. Work done at the Naval Surface Weapons Center (Reference 5) has provided verifying data for rubbers, specifically polybutadiene, butyl and GRS.

3/ Waterman, H. A., "Determination of the Complex Moduli of Viscoelastic Materials With the Ultrasonic Pulse Method," Part 1 and 2 Kolloid - Z.a.Z. Polymere 192, 1-16 (1963).

4/ Hartmann, B., and Jarzynski, J., "Ultrasonic Hysteresis Absorption in Polymers," J. Appl. Phys. 43, 4304 (1972)

5/ Madigosky, W. M., and Fiorito, R., "Transmission and Reflection Characteristics of Single and Multilayered Viscoelastic Plates," J. Acoust. Soc. Am. 62, S83 (1977)

The values used for the absorption coefficient for longitudinal waves were also based upon experimental testing (References 6 and 7). They are:

$$\begin{aligned}\text{Polyethylene, } \alpha_L &= 2.1 \times 10^{-4} f \\ \text{ABS, } \alpha_L &= 2.92 \times 10^{-4} f \\ \text{Syntactic Foam, } \alpha_L &= 1.33 \times 10^{-4} f\end{aligned}$$

where f = frequency in Hertz and the units of α_L are dB/meter.

The respective densities of water and FC-75 were assumed to be,

$$\begin{aligned}\rho_{\text{Water}} &= 1000 \text{ kg/m}^3 \\ \rho_{\text{FC-75}} &= 1762 \text{ kg/m}^3\end{aligned}$$

The velocities were assumed to be,

$$\begin{aligned}C_{\text{Water}} &= 1471 \text{ m/sec} \\ C_{\text{FC-75}} &= 645 \text{ m/sec}\end{aligned}$$

All data were taken at a temperature of 5°C.

6/ Hartmann, B., and Jarzynski, J., "Polymer Sound Speeds and Elastic Constants," NOL TR 72-269, (1972), NSWC, White Oak, Maryland

7/ Measured Data on 3M Syntactic Foam, NSWC, White Oak, Maryland

Section 3

COMPUTED RESULTS

3-1. FORMAT

Typical computer printouts from the transmission matrix program for the three materials considered, ABS, polyethylene and syntactic foam, are shown in Figures 2 through 9. The data shown in Figures 2 through 7 give the transmission loss, TL and the reflection loss RL in dB:

$$TL = 10 \log \left[\left(\frac{\rho_F}{\rho_I} \right) \left(\frac{C_I}{C_F} \right) |S|^2 \right]$$

and

$$RL = 10 \log |R|^2$$

where ρ_I , ρ_F , C_I , C_F are the densities and wave velocities for the initial and final fluid media. S and R represent transmission and reflection coefficients in terms of the displacement potentials of the transmitted and reflected waves and are described in the Appendix to this report. Figures 8 and 9 show the variation in the resulting phase angle of the transmitted wave. In addition to the plotted data, each printout provides the relevant physical characteristics of the material analyzed, i.e.,

thickness, L - meters

density, ρ - kg/m³

longitudinal velocity, C_L - m/sec

shear velocity, C_S - m/sec

3-2. THEORETICAL BASIS

It is of interest to note the extent to which the computed results are in agreement with those predicted qualitatively by theory (Reference 8). It is well known that plates of finite thickness, under proper conditions, support various modes of vibration known as Rayleigh and Lamb waves. In their simplest form these waves may be visualized as the in-phase sums of the multiple reflections of internal plate waves. It can be shown that the equation describing these internal waves can be separated into two parts: one corresponding to "symmetric" waves, and the other to "anti-symmetric" waves. Symmetric waves are compressional since they represent symmetric displacement of the two halves of the plate relative to the mean plane dividing the plate along its thickness. Anti-symmetric waves are flexural.

^{8/} Brekhovskikh, L. M., Waves in Layered Media, (Academic Press, New York, 1960)

The principle of interest here is known in the theory as the coincidence rule. It states: total transmission will occur at an angle of incidence such that the phase velocity of the incident wave along the plate coincides with the phase velocity of the waves in the plate. That is, in general,

$$\text{when } \frac{C}{\sin\theta} = C_{\text{Plate}}$$

$$\text{then } TL \longrightarrow 0 \text{ dB}$$

If the phase velocities parallel to the plate are plotted as functions of the variable fd , the product of the frequency in Hz and the plate thickness, d , a family of dispersion curves is obtained. Each curve represents a particular symmetric or anti-symmetric wave with a definite amplitude distribution across the thickness of the plate. A typical family of curves is shown in Figure 1. The curves shown here were generated from data obtained by experimental measurements on ABS (Reference 5). For the smallest values of fd , only two modes, (Lamb modes) are present. They are shown as s_0 and a_0 , corresponding to symmetric (compressional) and anti-symmetric (flexural) plate vibrations. As the product fd increases, successive higher modes become possible, again constituting symmetric and anti-symmetric families.

As $fd \rightarrow \infty$ the curves s_0 and a_0 asymptotically approach straight lines corresponding to the velocity v_R of Rayleigh surface waves, while the remaining curves approach straight lines corresponding to the velocity of shear waves in the material.

As the frequency is lowered, all the curves except s_0 and a_0 asymptotically approach vertical straight lines corresponding to certain "limiting" frequencies. These frequencies are defined by:

$$\left. \begin{array}{l} \frac{2fd}{C_L} = 1, 3, 5, \dots \\ \frac{fd}{C_S} = 1, 2, 3, \dots \end{array} \right\} \text{For symmetric waves}$$

$$\left. \begin{array}{l} \frac{fd}{C_L} = 1, 2, 3, \dots \\ \frac{2fd}{C_S} = 1, 3, 5, \dots \end{array} \right\} \text{For anti-symmetric waves}$$

Thus all the limiting frequencies correspond to plate thicknesses of an integral number of half wave lengths of longitudinal or shear waves.

Using dispersion curves obtained as described and the coincidence rule, it is possible to find for a given frequency and plate thickness the velocity at which total transmission occurs and then the corresponding angle of incidence. For

^{5/} Madigosky, W. M., and Fiorito, R., "Transmission and Reflection Characteristics of Single and Multilayered Viscoelastic Plates," J. Acoust. Soc. Am. 62, S83 (1977).

example, at normal incidence total transmission occurs at plate thicknesses satisfying the condition

$$\frac{2fd}{c_L} = n$$

when n is an integer, that is, at the limiting frequencies corresponding to thickness resonances of the plate for longitudinal waves. Shear modes will not exist at normal incidence.

3-3. INTERPRETATION OF RESULTS

The theory briefly described in the previous paragraph can be used to interpret the various maxima and minima which occur in the computed TL and RL curves. The TL minima (and RL maxima) should occur at the predicted total transmission points corresponding to the symmetric and anti-symmetric modes for the longitudinal and shear (for other than normal incidence) waves.

An apparent exception to the theory occurs in cases of angles of incidence where shear modes appear. The computed transmission loss curves seem to show TL maxima at frequencies where minima would be predicted by the coincidence rule. However, a detailed analysis has shown that the coincidence rule does still hold. The apparent anomaly is caused by a resonance interaction between two modes such that both a maximum and a minimum are present. This can be seen on some of the RL curves; for example, see Figure 4. However, because the factor of absorption has been included, it overrides the minimum and only the maximum in the TL curve is observed. The minima in the TL curve for longitudinal modes still remain true.

Figures 2 and 3 show computed results for polyethylene. Data for Figure 2 were obtained assuming water as the initial fluid and FC-75 as the final fluid. Figure 3 assumes water for the initial fluid and shows results for both water and FC-75 as the final fluid. Figure 2(a) shows very clearly the first three half-wave points for longitudinal waves at normal incidence. These correspond to the symmetric waves s_1^L and s_2^L at approximately 300 kHz and 900 kHz and the anti-symmetric wave a_1^L , at approximately 600 kHz. At off angles the effect of shear waves becomes more visible with increasing angle of the incident wave. The first mode for shear waves occurs at approximately 85 kHz and corresponds to the anti-symmetric wave a_1^S . It is clearly visible at angles of 10 degrees and greater. This point illustrates the anomaly in the transmission loss curve described in the previous paragraph. Generally, the transmission loss increases with increasing angle of incidence of the input wave as would be expected. However, the loss is less than 5 dB for angles up to 45 degrees. This characteristic is more clearly shown on Figure 3 which provides loss as a function of angle for fixed frequencies. The presentation of data in this format tends to be of more use to the acoustic engineer who is more often concerned with specific frequencies of interest.

A comparison of the curves in Figure 3 shows that the transmission loss is somewhat greater for the water/plate/FC-75 condition than for the comparable water/plate/water condition. However, the degree of similarity between the two

indicates that for purposes of convenience in testing, measurements could be made in water and then corrected for the FC-75 condition by applying a simple correction loss factor for water/FC-75.

Figures 4 and 5 present computed data for ABS corresponding to that for polyethylene in Figures 2 and 3. As expected the ABS generally exhibits a higher transmission loss than the polyethylene because of its larger absorption coefficient. Since the longitudinal velocities in ABS and polyethylene differ by only about 10 percent, the half wave resonance points are nearly the same for the s_1^L and a_1^L waves, as can be seen by comparing Figures 2(a) and 4(a). However, the shear velocity in ABS is nearly twice that of polyethylene and the first point corresponding to the anti-symmetric wave a_1^S does not occur until approximately 150 kHz. Also, the transmission loss peaks exhibited by the ABS for shear waves are considerably stronger than comparable peaks in polyethylene. For example, a comparison of the two at an input angle of incidence of 50 degrees - Figures 2(f) and 4(f) - shows the a_1^S peak for ABS at 150 kHz to be 25 dB greater than the a_1^S peak for polyethylene at 85 kHz. This difference is caused by the much greater shear loss for ABS and the better impedance match for shear mode conversion.

The computed data for syntactic foam are shown in Figures 6 and 7. All data are for a water/foam/FC-75 system. It might be assumed that syntactic foam would be a nearly ideal substance for an acoustic window since it is advertised to be a "pc" material having a near perfect impedance match with water. However, this phenomenon is true only for an infinite half plane of water/syntactic foam, and at normal incidence. As the computed results show, there is considerable interaction at angles of incidence of the input wave between 10 degrees and 60 degrees. These resulting peaks in the transmission loss curves are due primarily to the effects of shear waves, and the points corresponding to a_n^S at odd multiples of approximately 185 kHz, and S_n^S at multiples of approximately 370 kHz are clearly visible. There are, however, specific windows and since syntactic foam has a relatively low absorption coefficient the peaks are sharp with good nulls between them. By a judicious choice of the frequency thickness product, the syntactic foam may be a superior window material. For example, at 300 kHz the plates analyzed for this report show a lower transmission loss for syntactic foam than for either polyethylene or ABS.

Figures 8 and 9 show the computed phase angle of the transmitted wave as a function of the angle of incidence of the input wave. The two figures show data for plates of polyethylene and ABS respectively, in both cases in a water/plate/FC-75 configuration. Phase change in the polyethylene is smooth and slowly varying with the angle of incidence at all frequencies, the range of variation increasing with frequency. For the ABS the phase change is more complex and exhibits rapid changes in direction when a particular mode is excited in the plate. This shows up at angles of incidence between 50 and 60 degrees, and is particularly strong at a frequency of 150 kHz. This effect can be correlated with the data shown on Figures 4(f) and 5(d) illustrating the strong effect of the a_1^S shear wave.

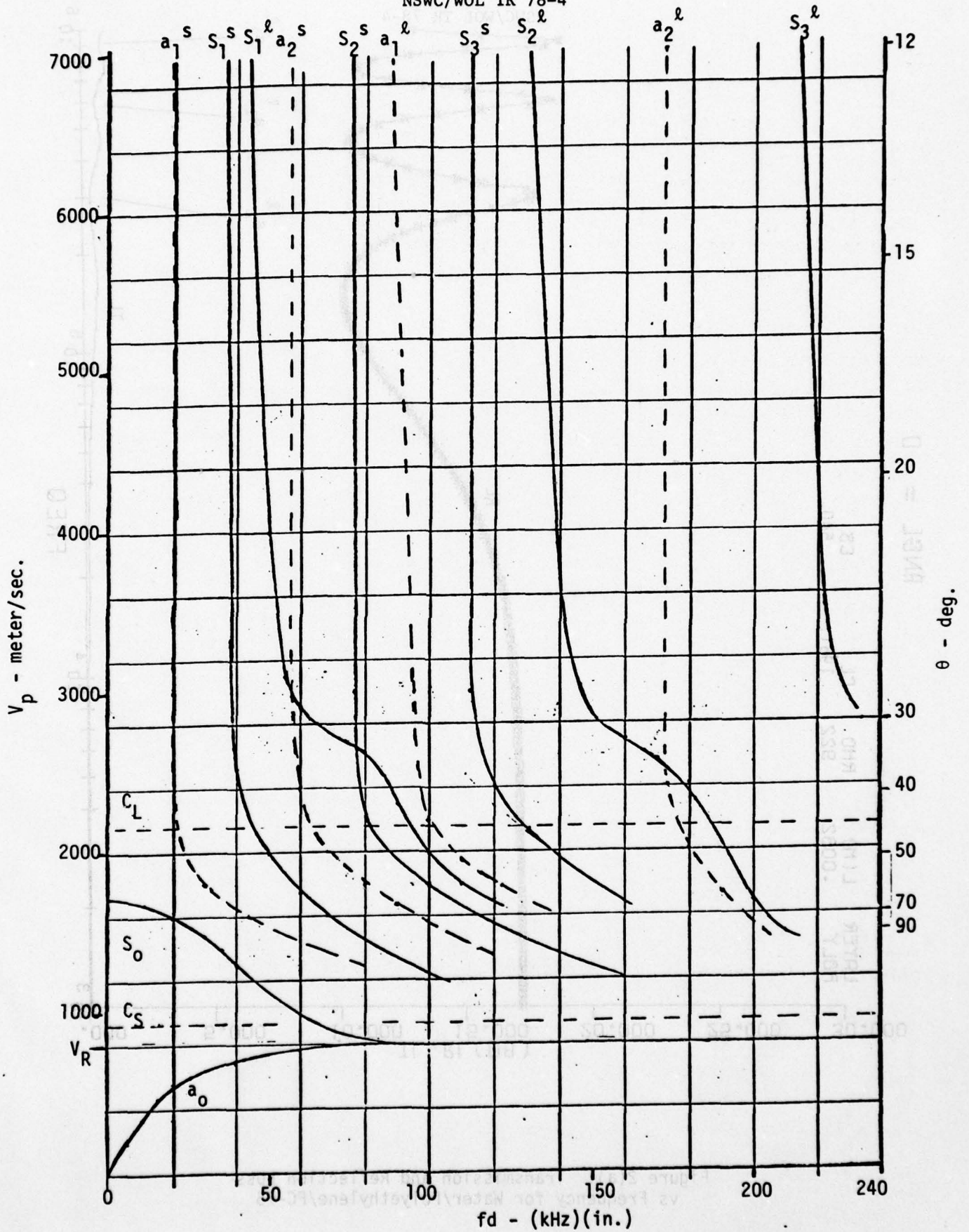


Figure 1. Dispersion Curves for ABS in Water

ANGL = 0

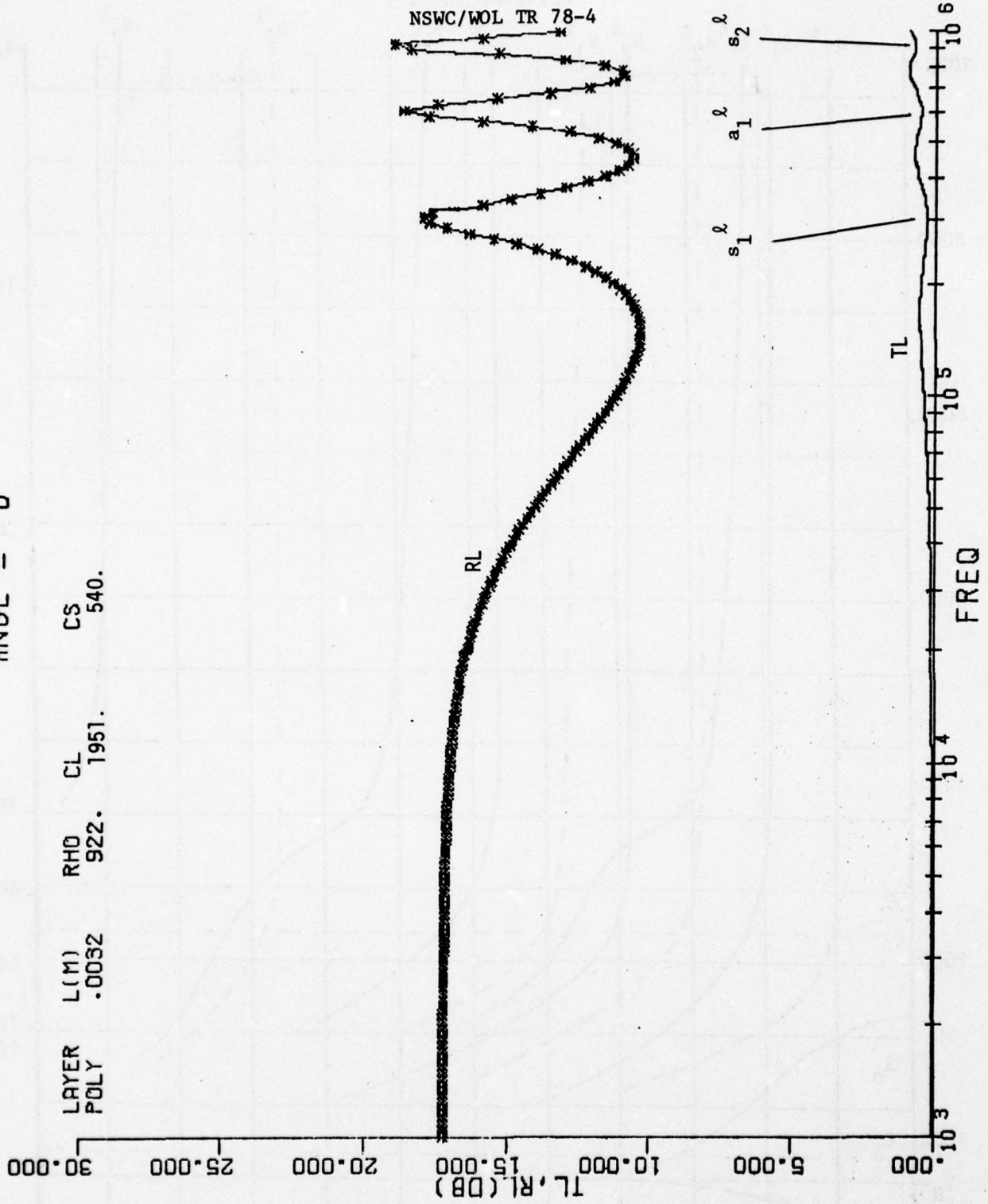


Figure 2(a). Transmission and Reflection Loss vs Frequency for Water/Polyethylene/FC-75

ANGL = 10

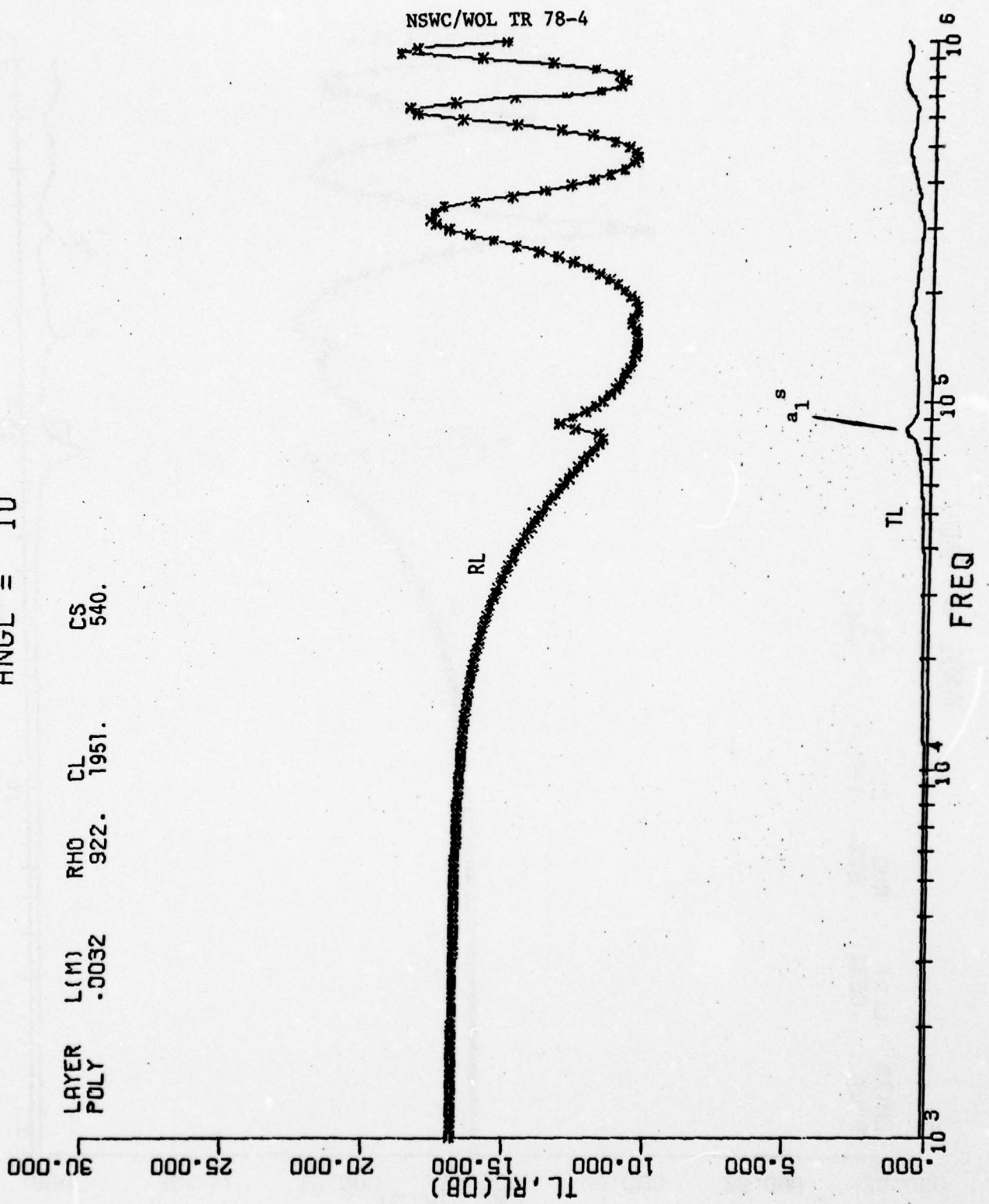


Figure 2(b). Transmission and Reflection Loss vs Frequency for Water/Polyethylene/FC-75

ANGL = 20

LAYER L(M) RHO CL CS
POLY .0032 922. 1951. 540.

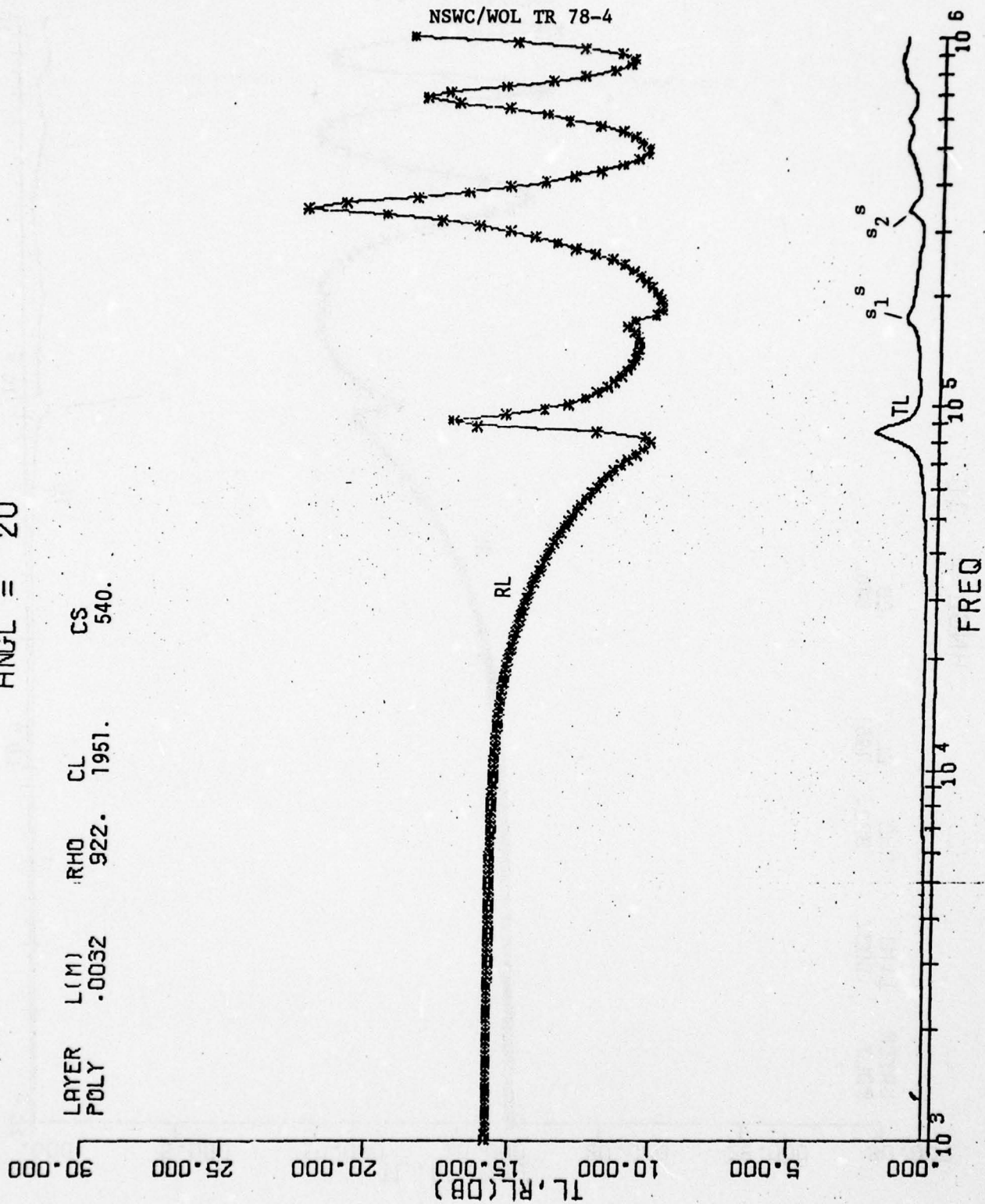


Figure 2(c). Transmission and Reflection Loss vs Frequency for Water/Polyethylene/FC-75

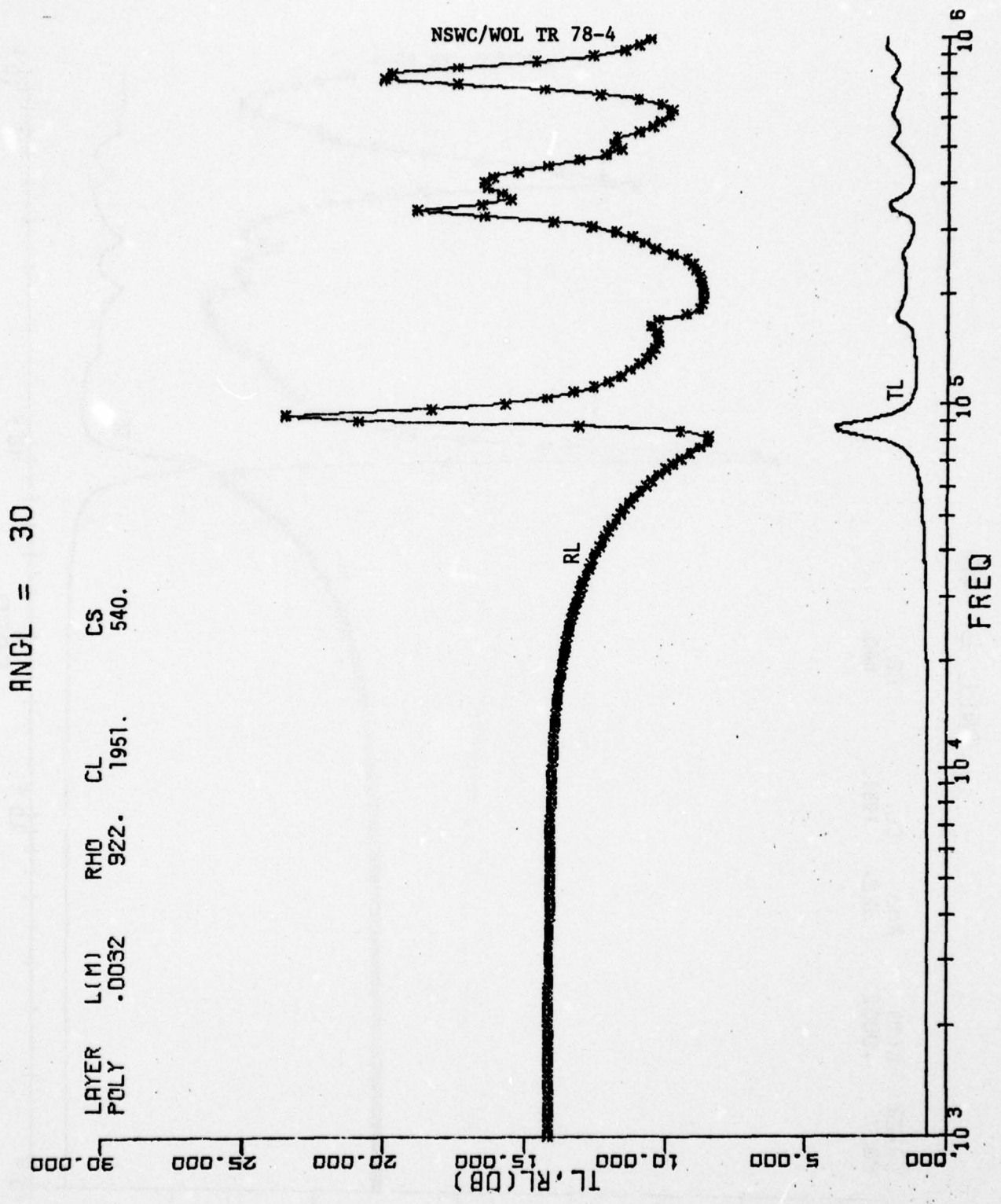


Figure 2(d). Transmission and Reflection Loss vs Frequency for Water/Polyethylene/FC-75

ANGL = 40

LAYER POLY L(M) .0032 RHO 922. CL 1951. CS 540.

NSWC/WOL TR 78-4

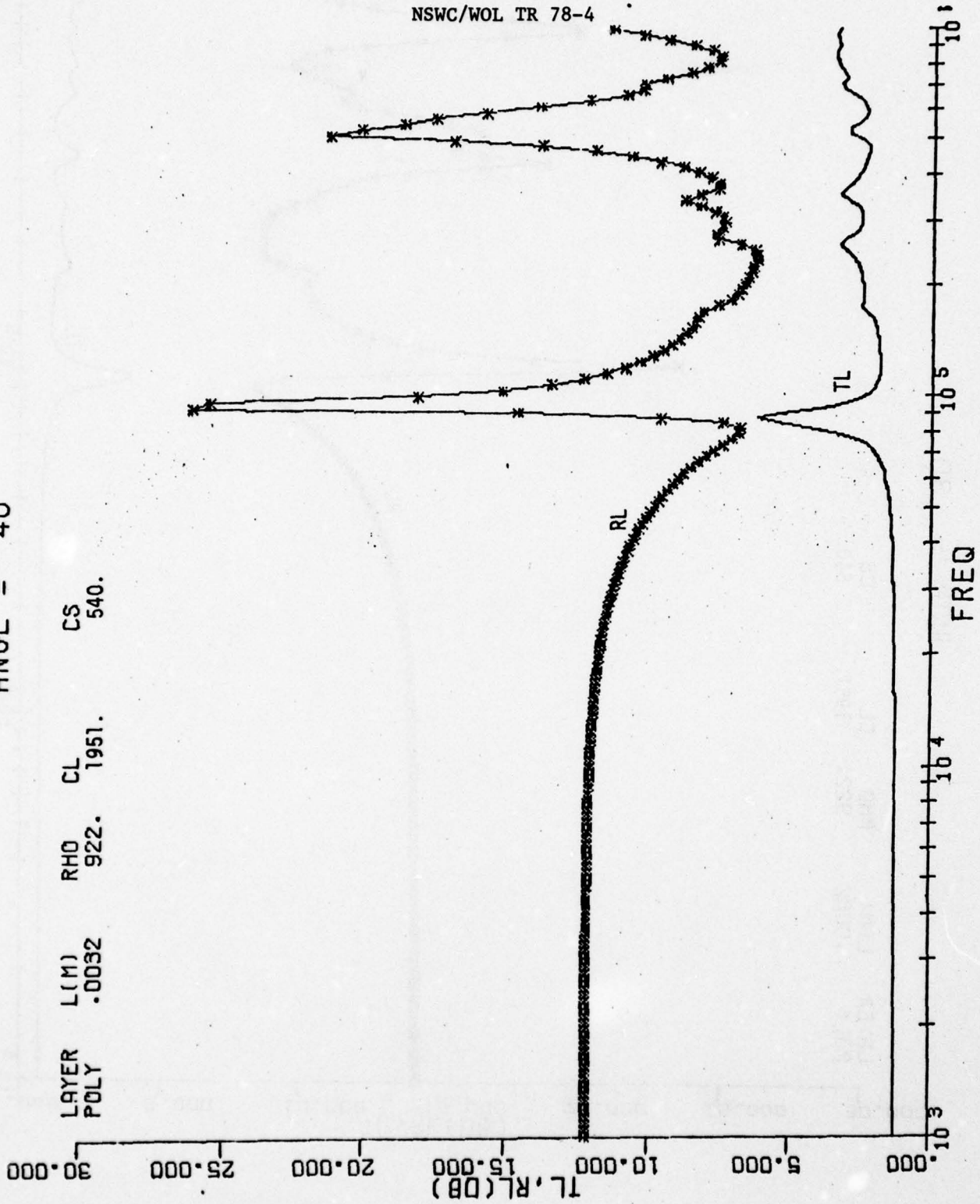


Figure 2(e). Transmission and Reflection Loss vs Frequency for Water/Polyethylene/FC-75

ANGL = 50

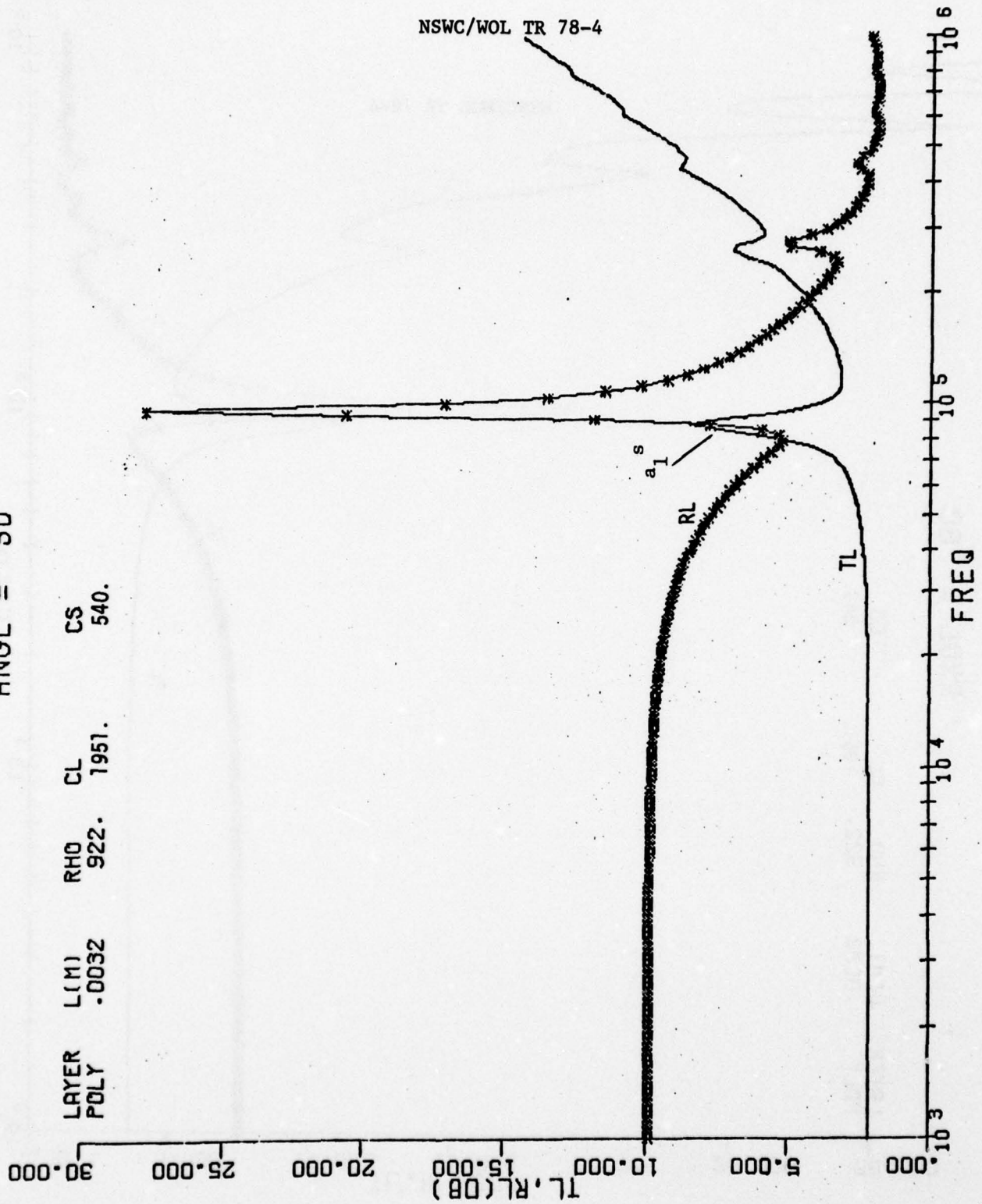


Figure 2(f). Transmission and Reflection Loss vs Frequency for Water/Polyethylene/FC-75

ANGL = 60

LAYER POLY
L(M) .0032
RHO 922.
CL 1951.
CS 540.

NSWC/WOL TR 78-4

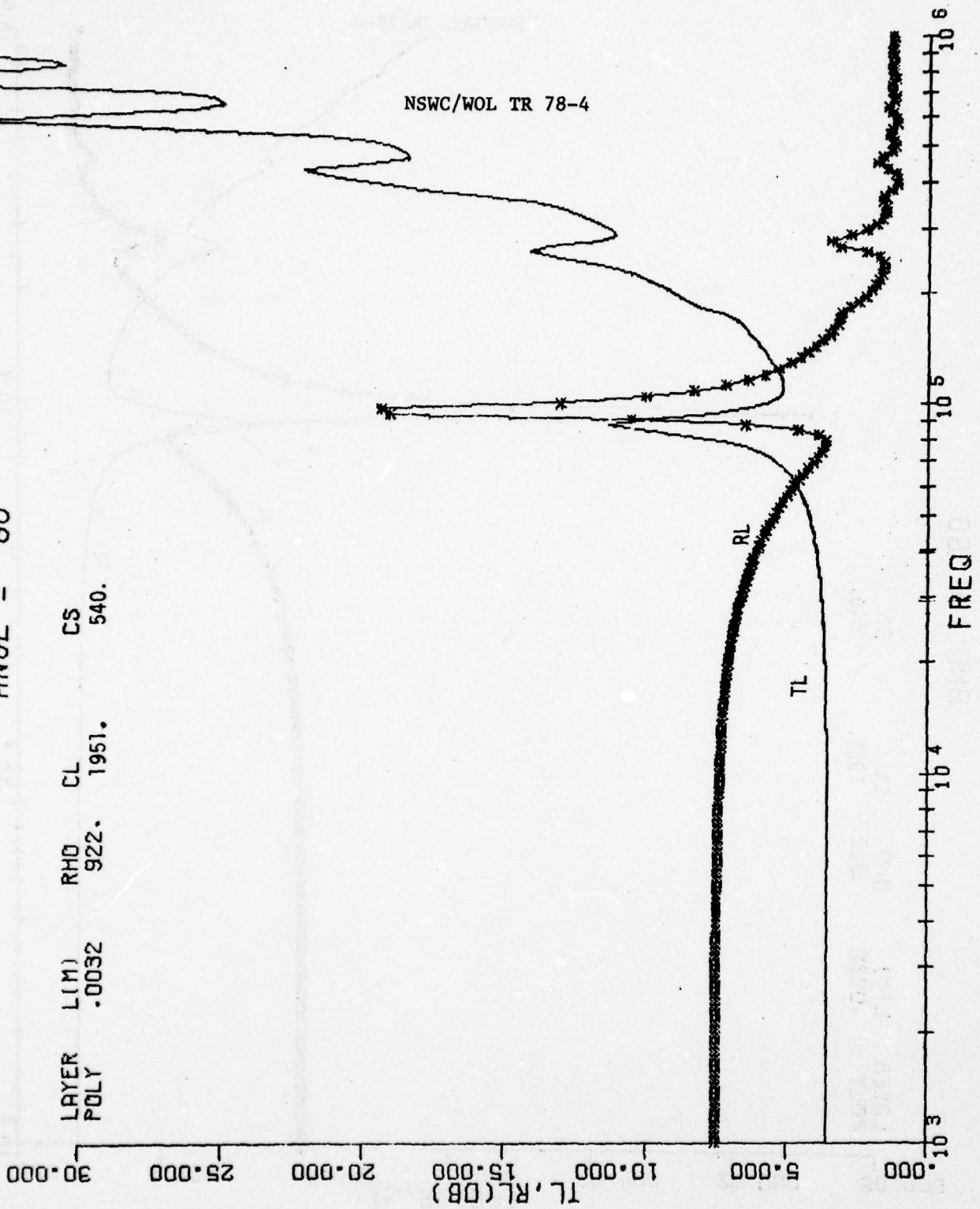


Figure 2(g). Transmission and Reflection Loss vs Frequency for Water/Polyethylene/FC-75

ANGL = 70

LAYER L(M) RHO CL CS
POLY .0032 922. 1951. 540.

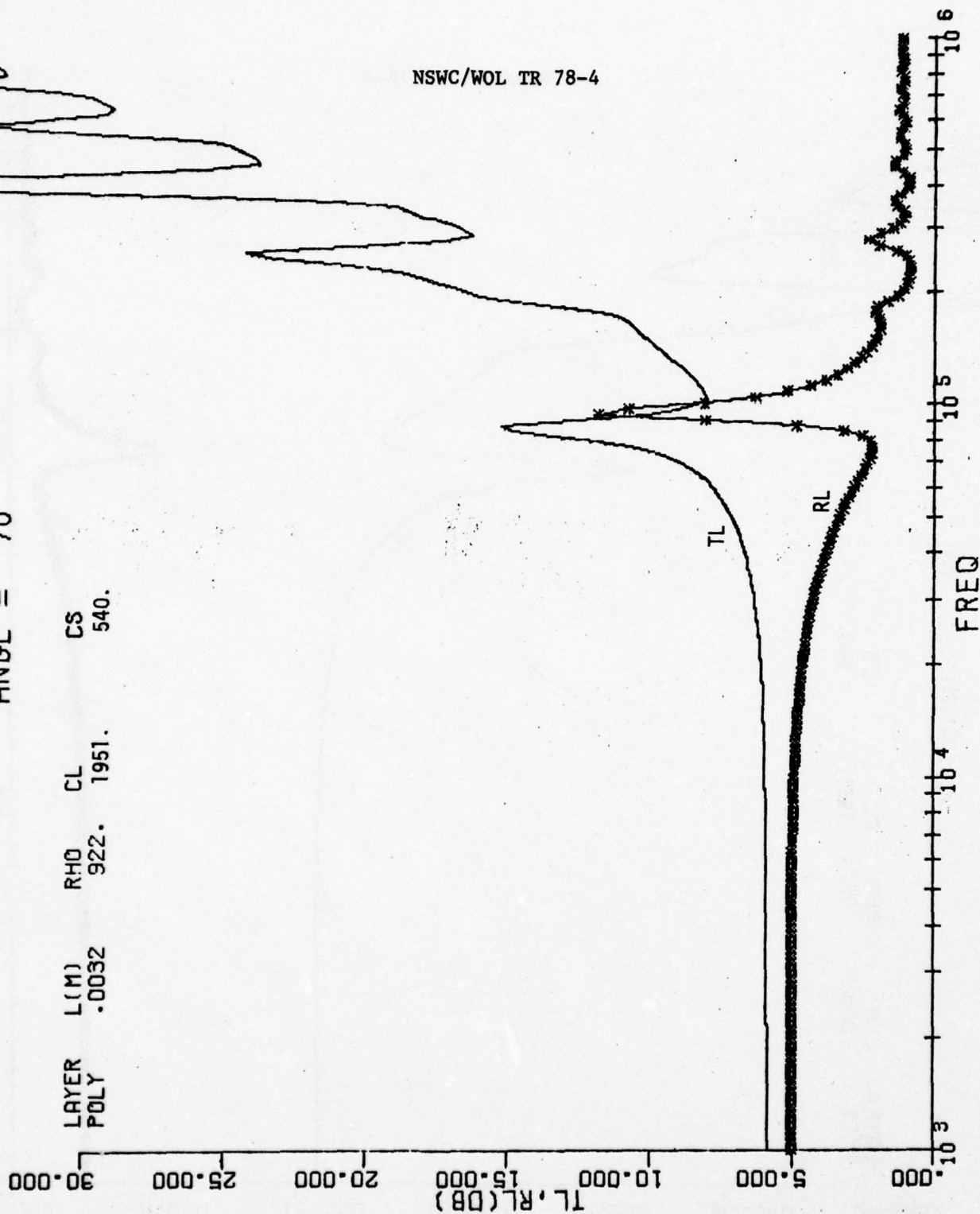


Figure 2(h). Transmission and Reflection Loss vs Frequency for Water/Polyethylene/FC-75

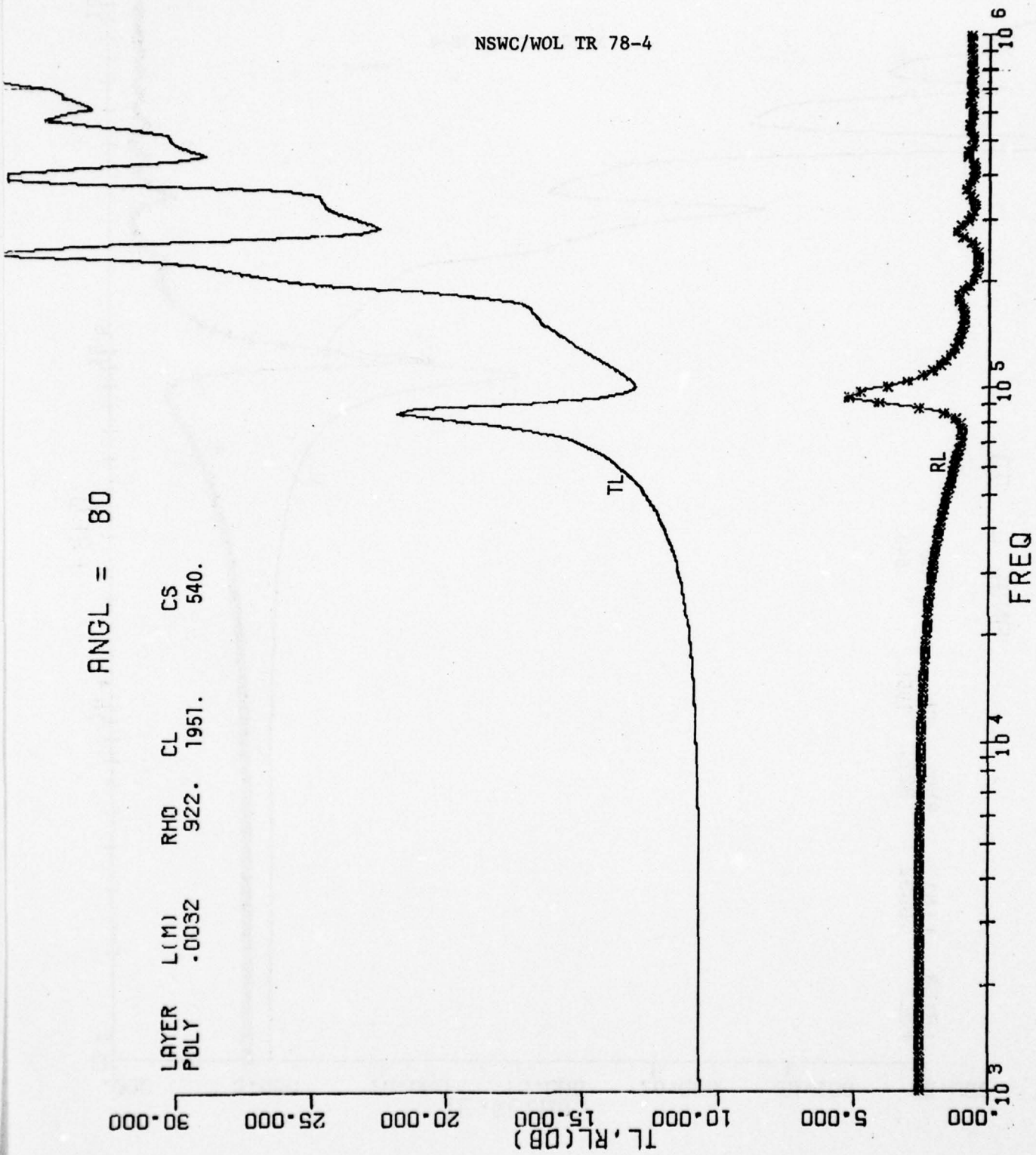


Figure 2(i). Transmission and Reflection Loss vs Frequency for Water/Polyethylene/FC-75

FREQ = 50000

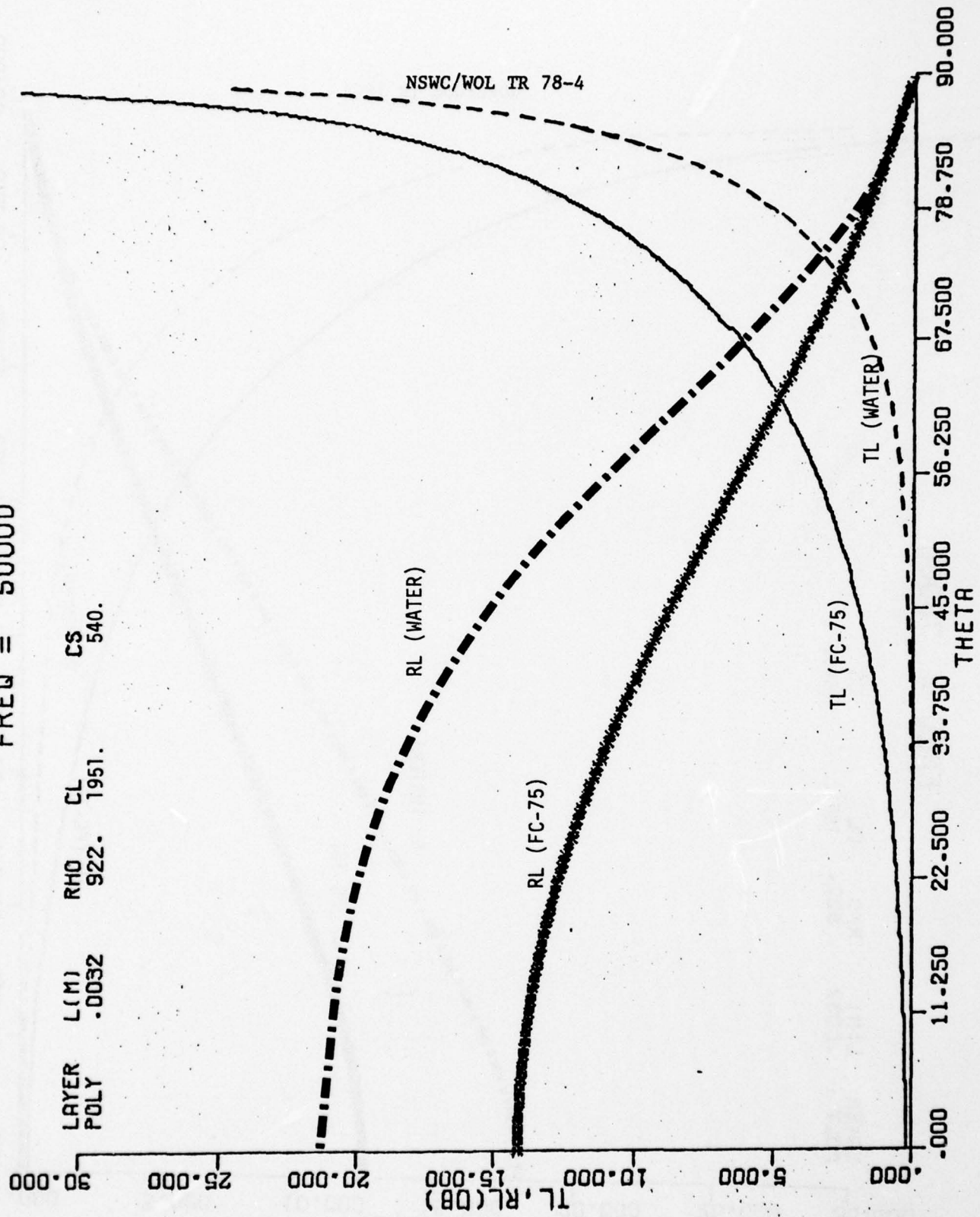


Figure 3(a). Transmission and Reflection Loss vs θ for Water/Polyethylene/FC-75 and Water/Polyethylene/Water

FREQ = 75000

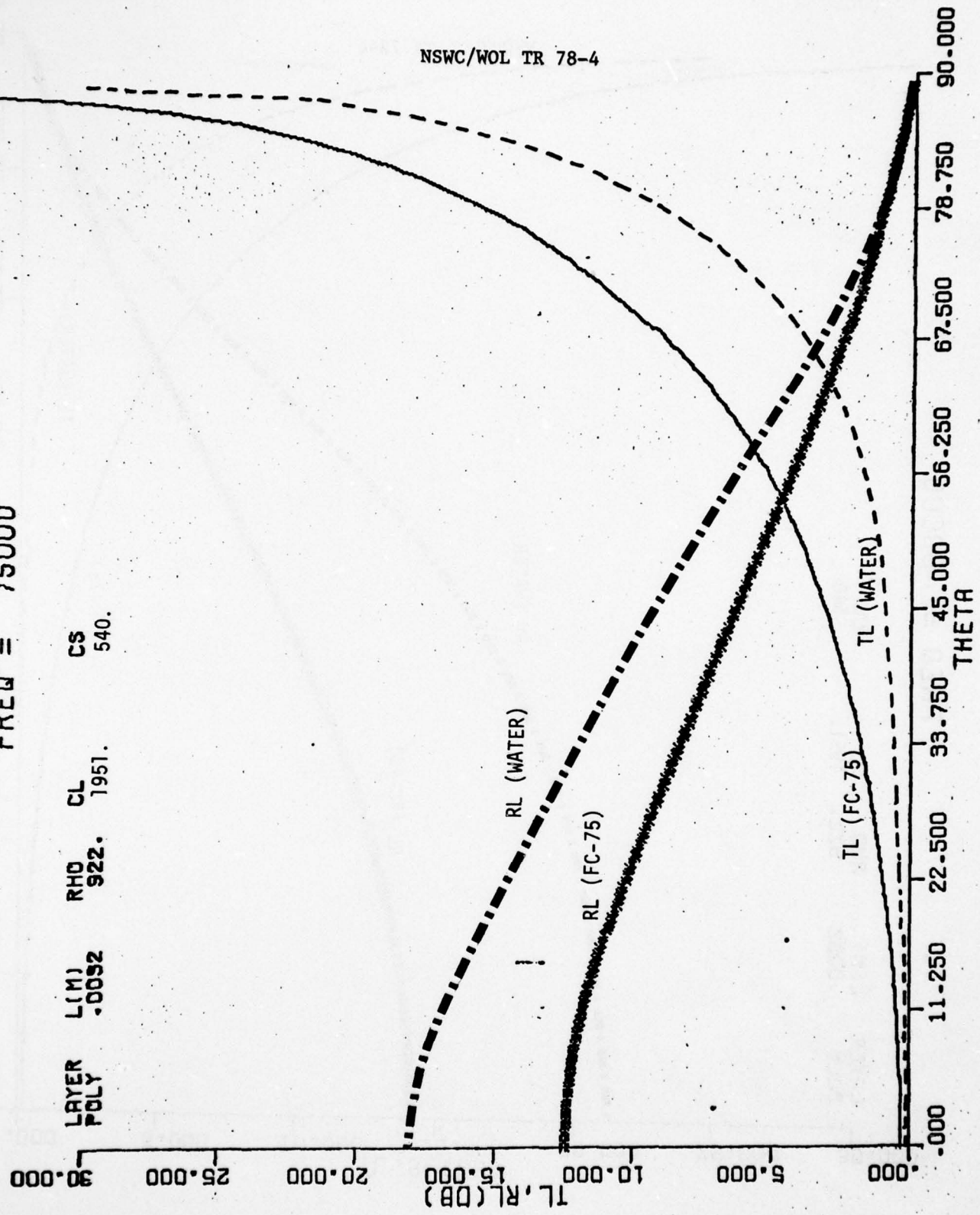


Figure 3(b). Transmission and Reflection Loss vs θ for Water/Polyethylene/FC-75 and Water/Polyethylene/Water

FREQ = 100000

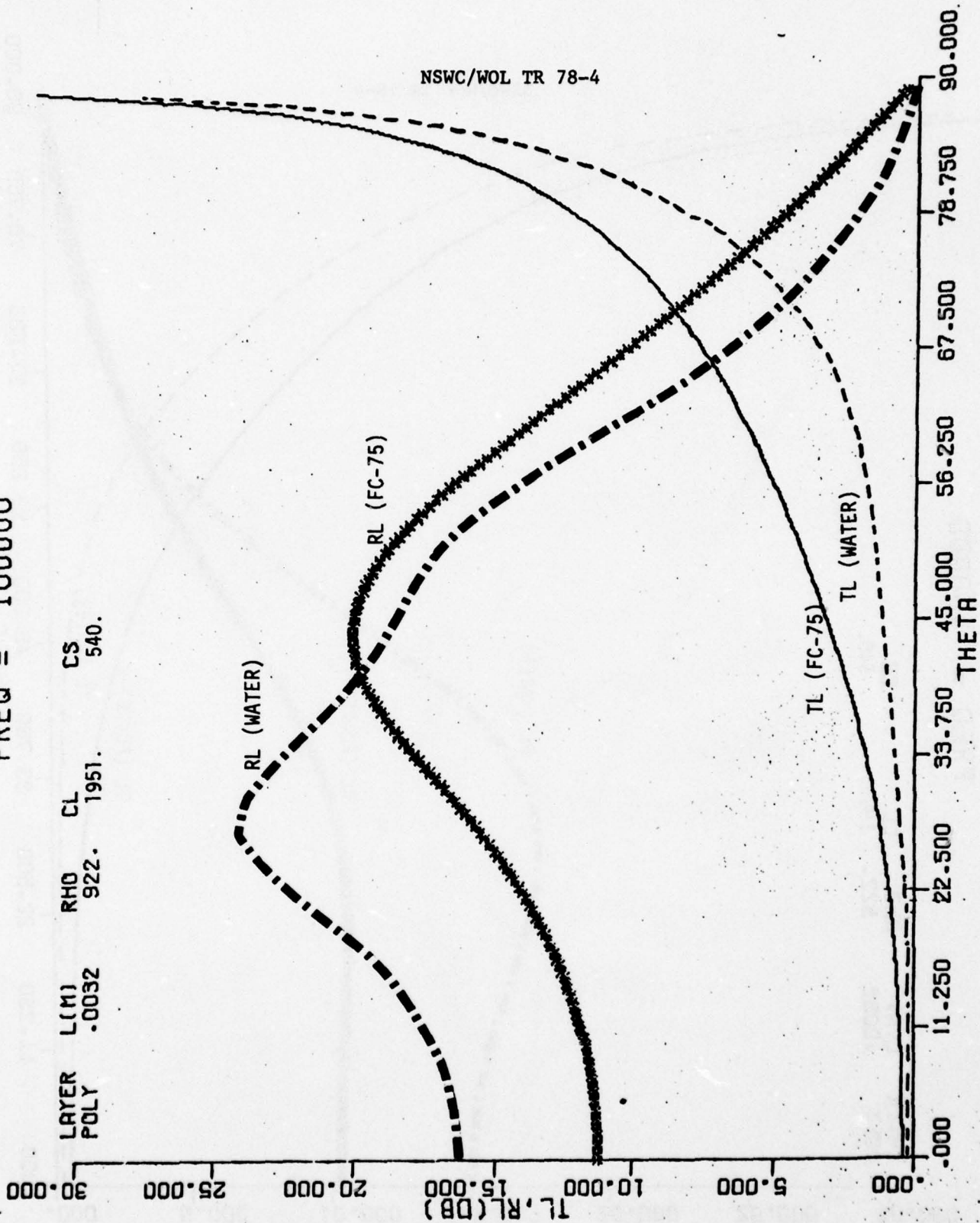


Figure 3(c). Transmission and Reflection Loss vs θ for Water/Polyethylene/FC-75 and Water/Polyethylene/Water

FREQ = 150000

LAYER POLY L(M) .0032 RHO 922. CL 1951. CS 540.

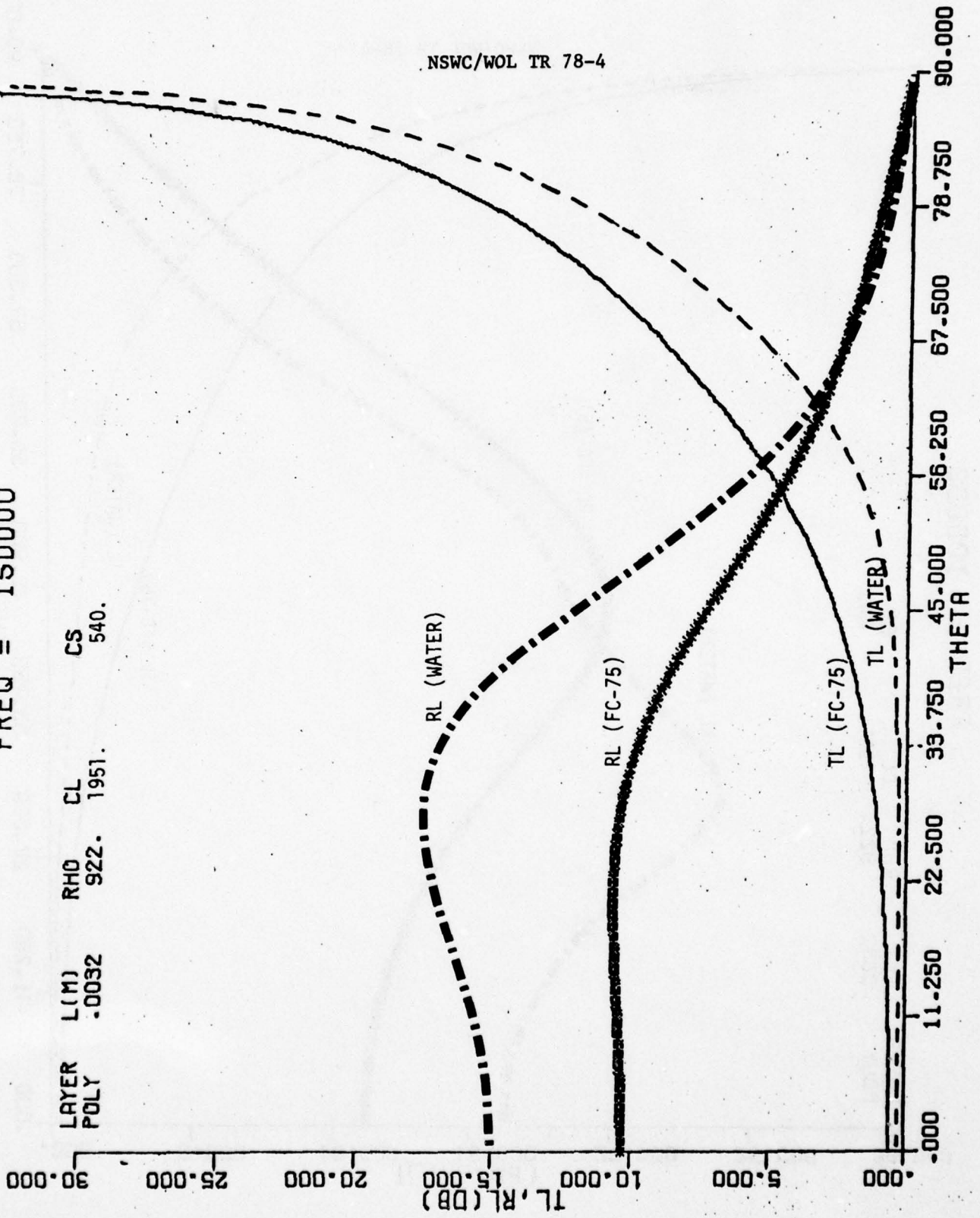


Figure 3(d). Transmission and Reflection Loss vs θ for Water/Polyethylene/FC-75 and Water/Polyethylene/Water

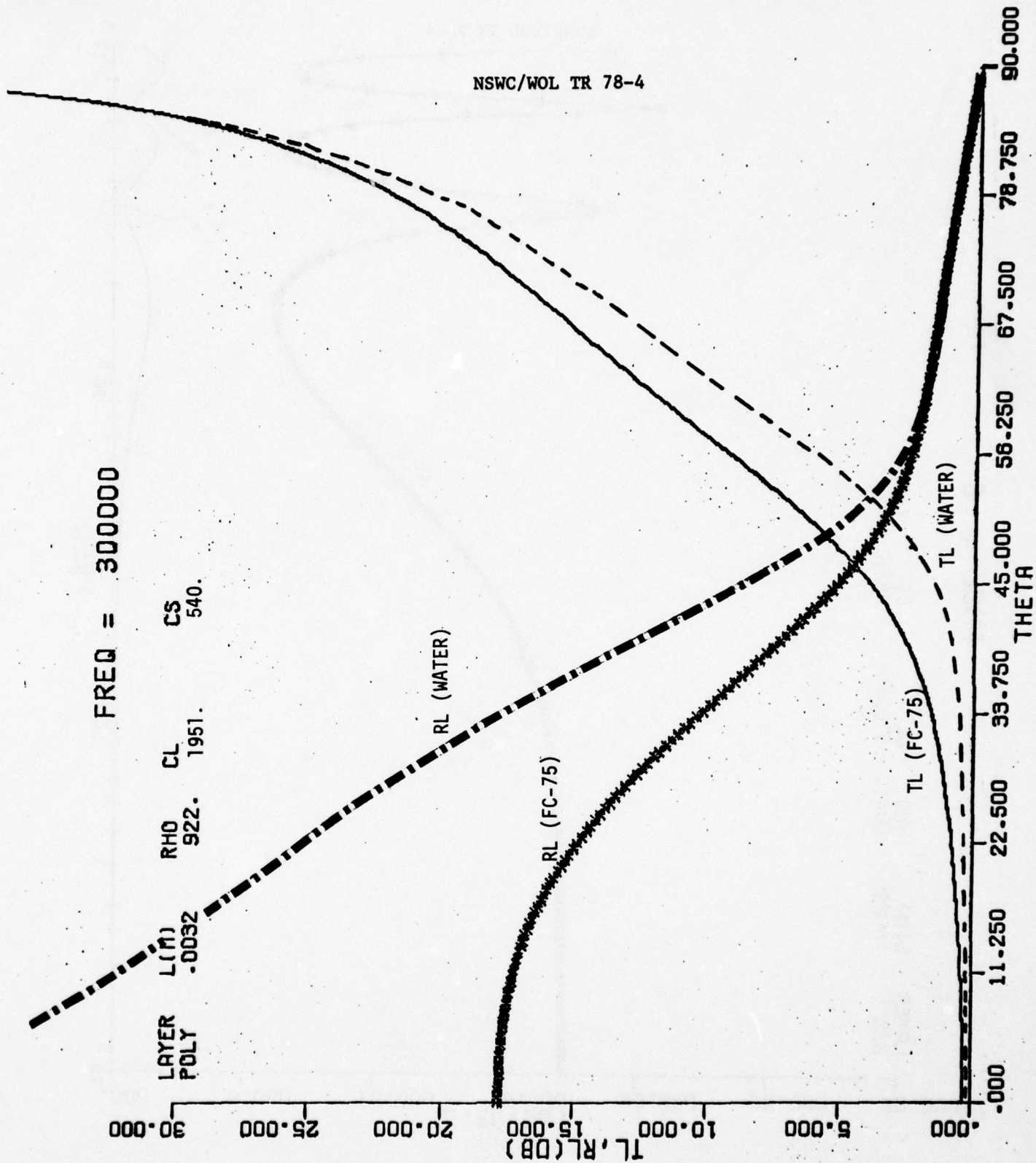


Figure 3(e). Transmission and Reflection Loss vs θ for Water/Polyethylene/FC-75 and Water/Polyethylene/Water

ANGL = 0

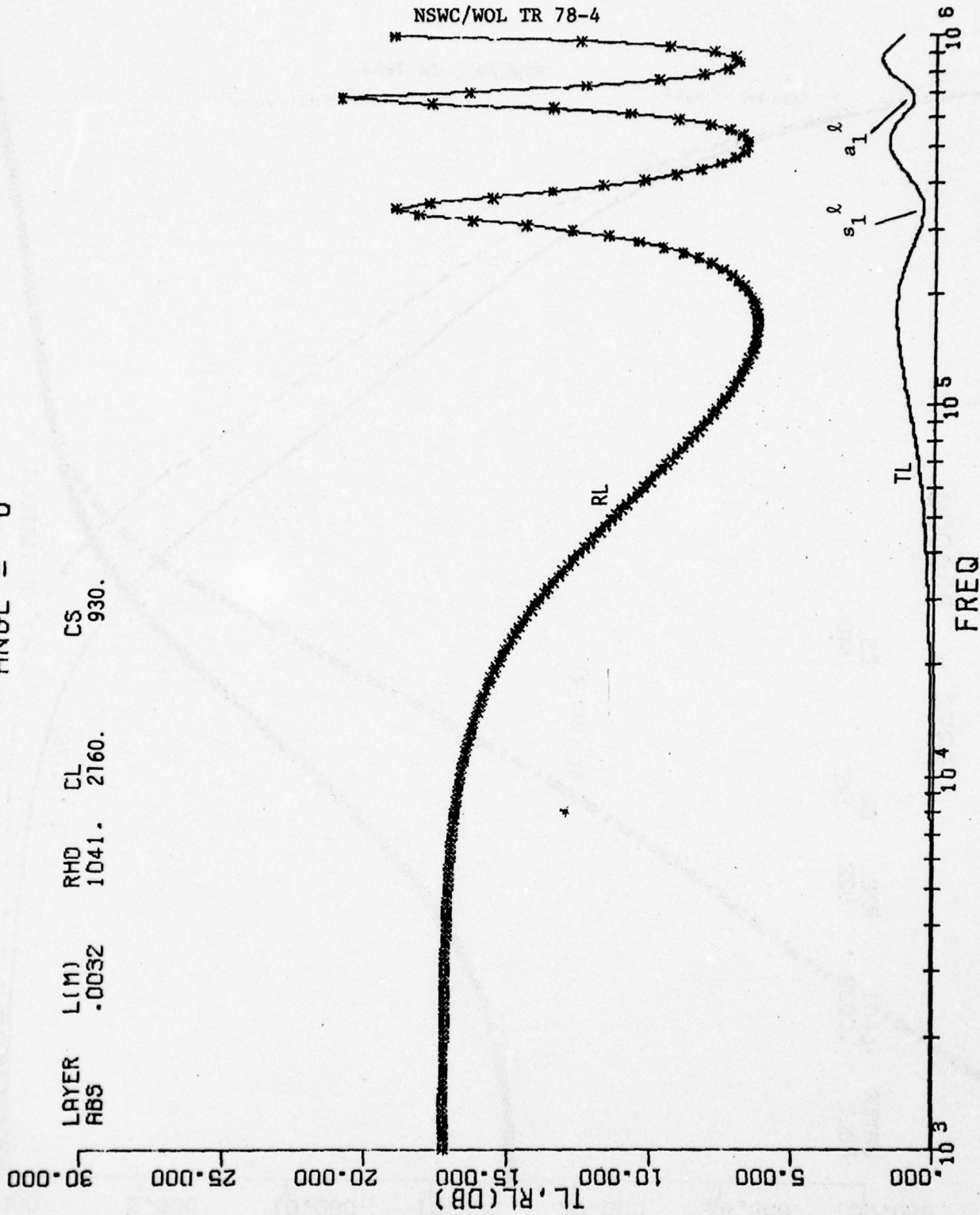


Figure 4(a). Transmission and Reflection Loss vs Frequency for Water/ABS/FC-75

ANGL = 10

LAYER L(M) RHO CL CS
ABS .0032 1041. 2160. 930.

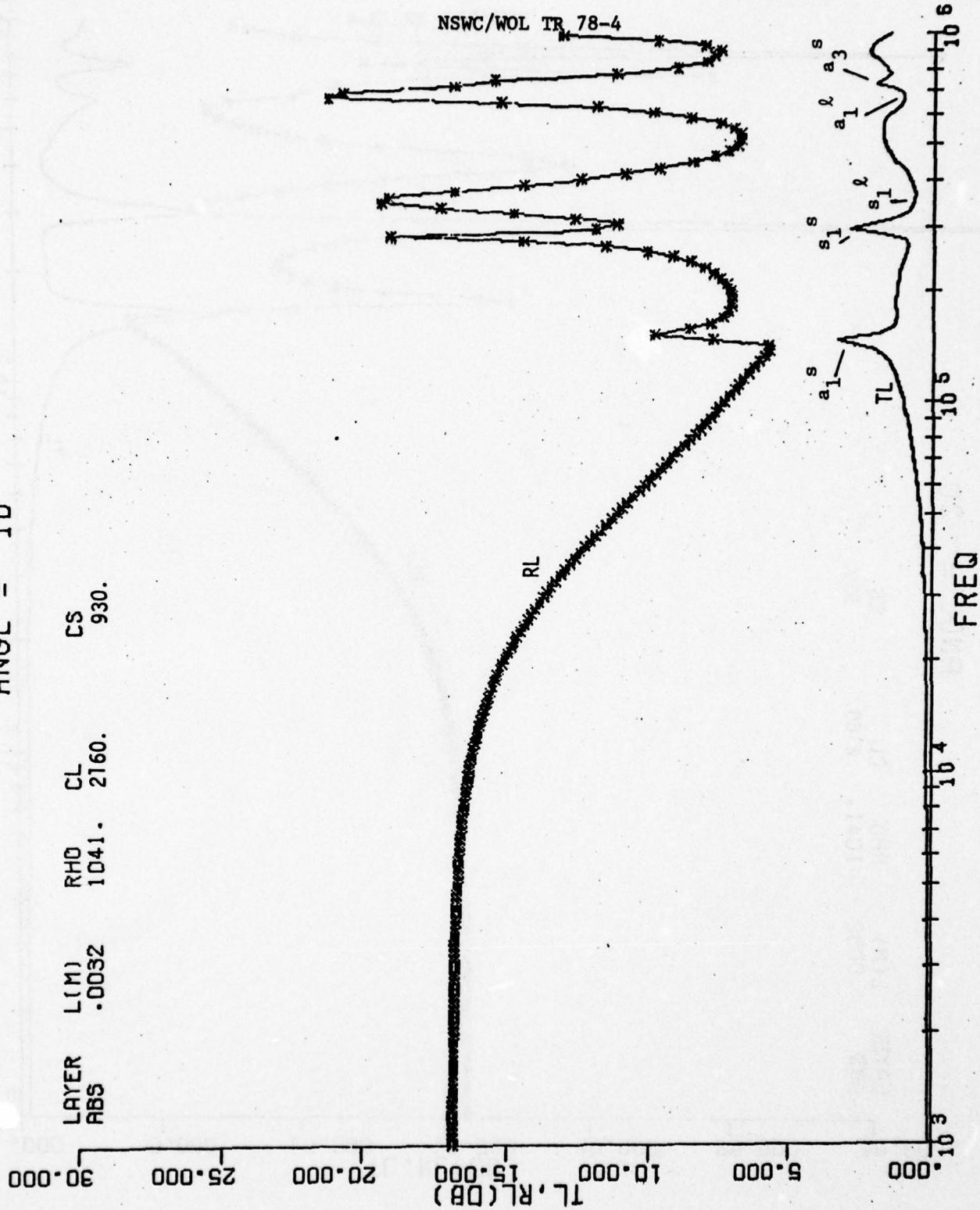


Figure 4(b). Transmission and Reflection Loss vs Frequency for Water/ABS/FC-75

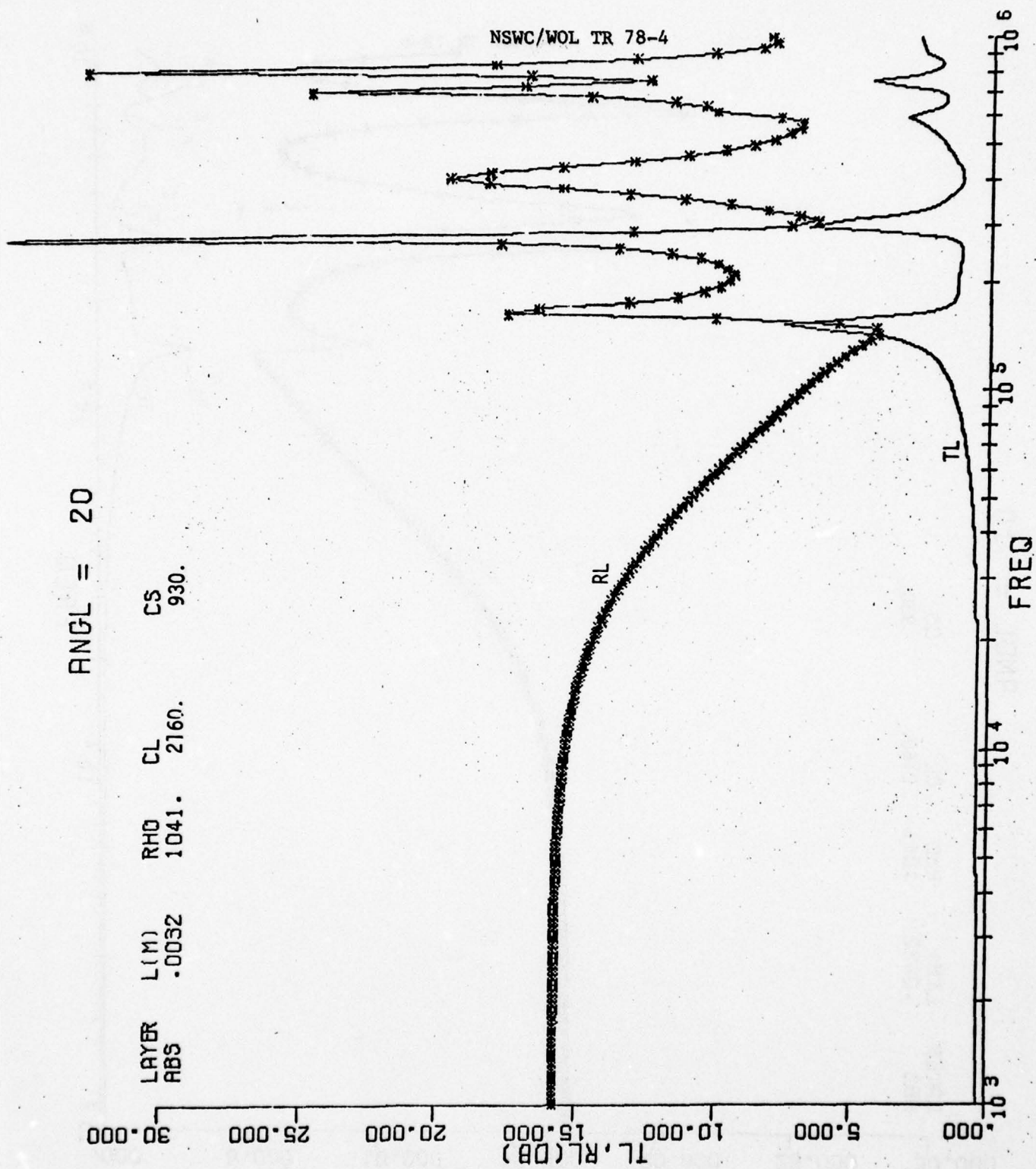


Figure 4(c). Transmission and Reflection Loss vs Frequency for Water/ABS/FC-75

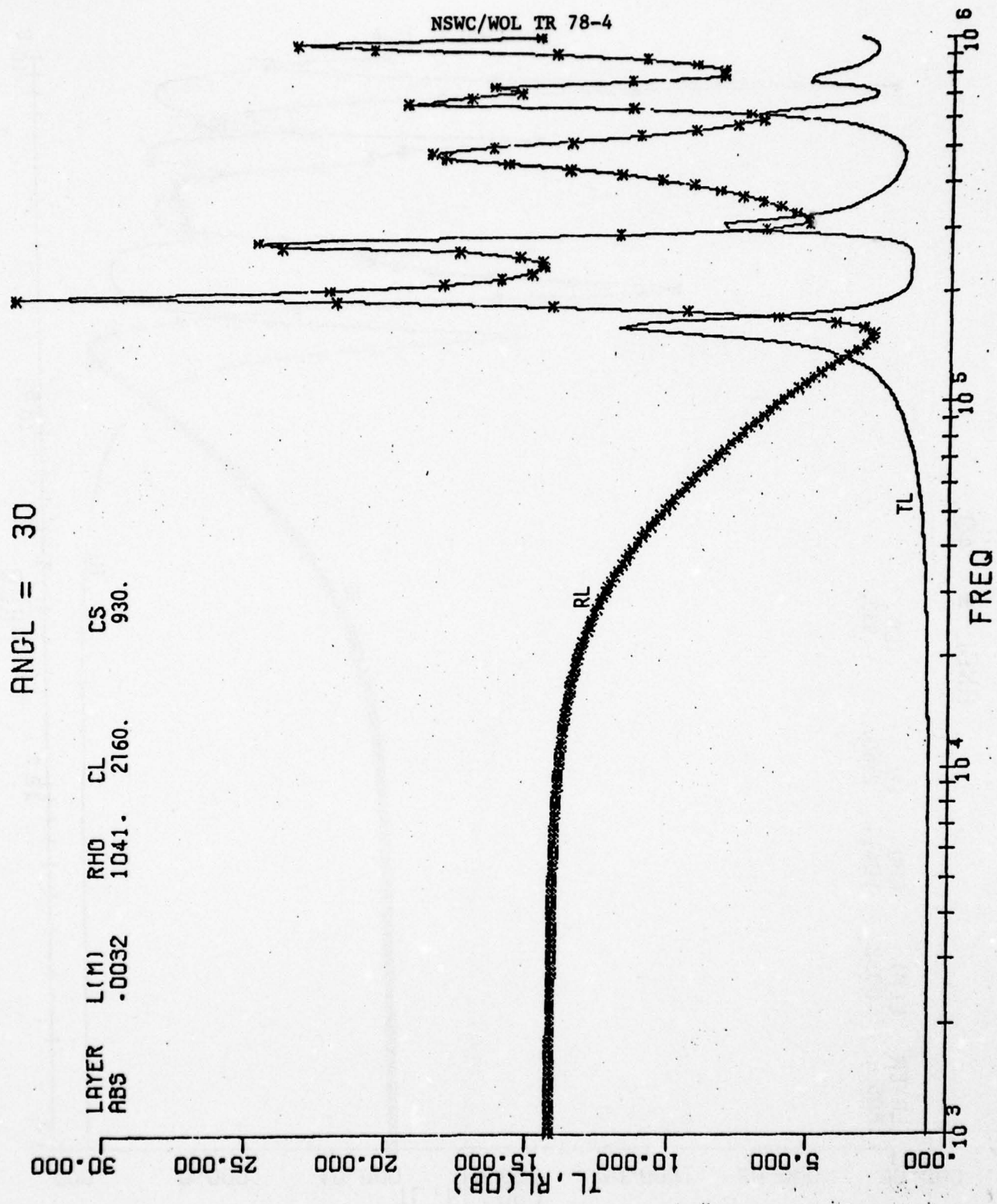


Figure 4(d). Transmission and Reflection Loss vs Frequency for Water/ABS/FC-75

ANGL = 40

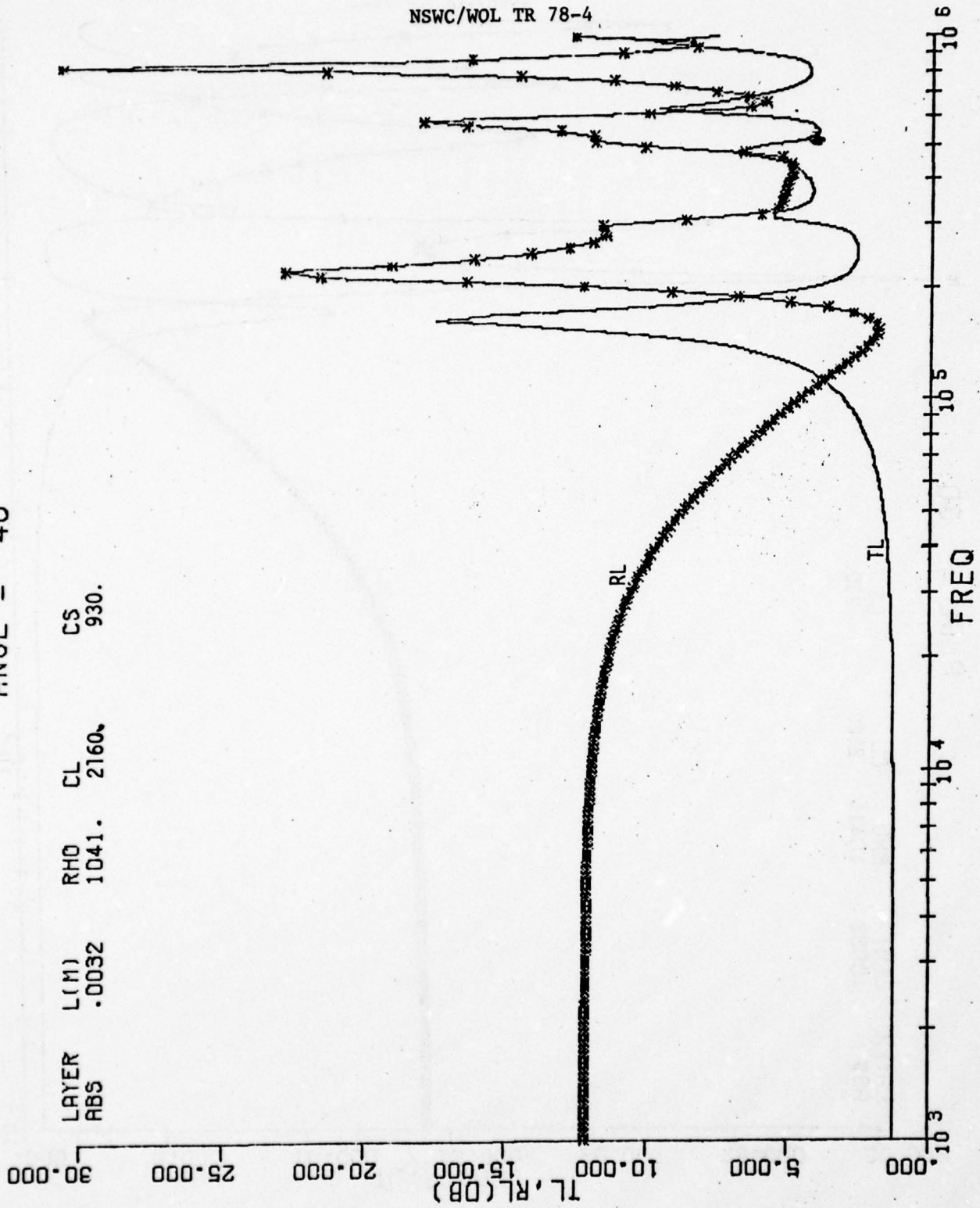


Figure 4(e). Transmission and Reflection Loss vs Frequency for Water/ABS/FC-75

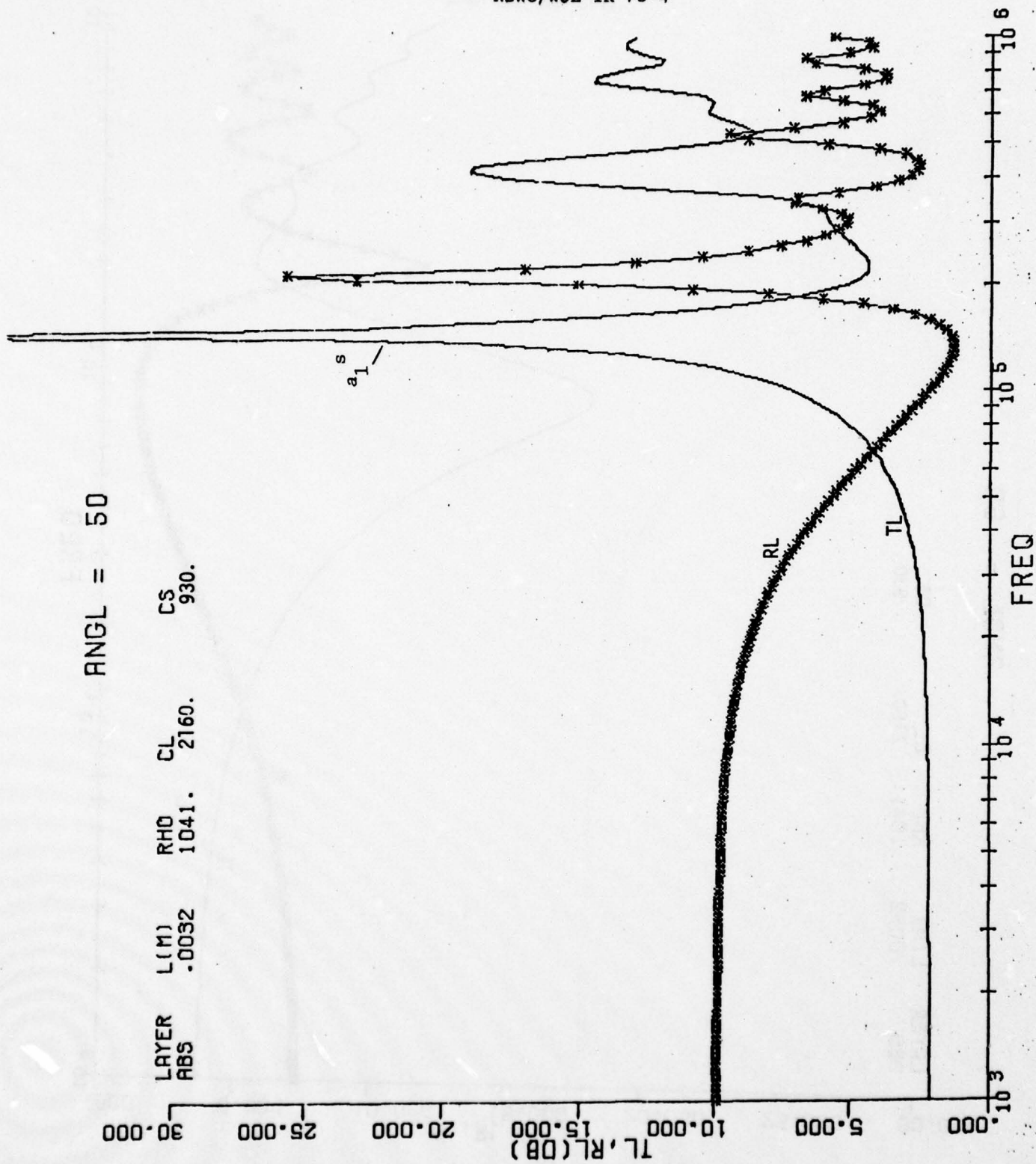


Figure 4(f). Transmission and Reflection Loss vs Frequency for Water/ABS/FC-75

ANGL = 60

LAYER L(M) RHO CL CS
 ABS .0032 1041. 2160. 930.

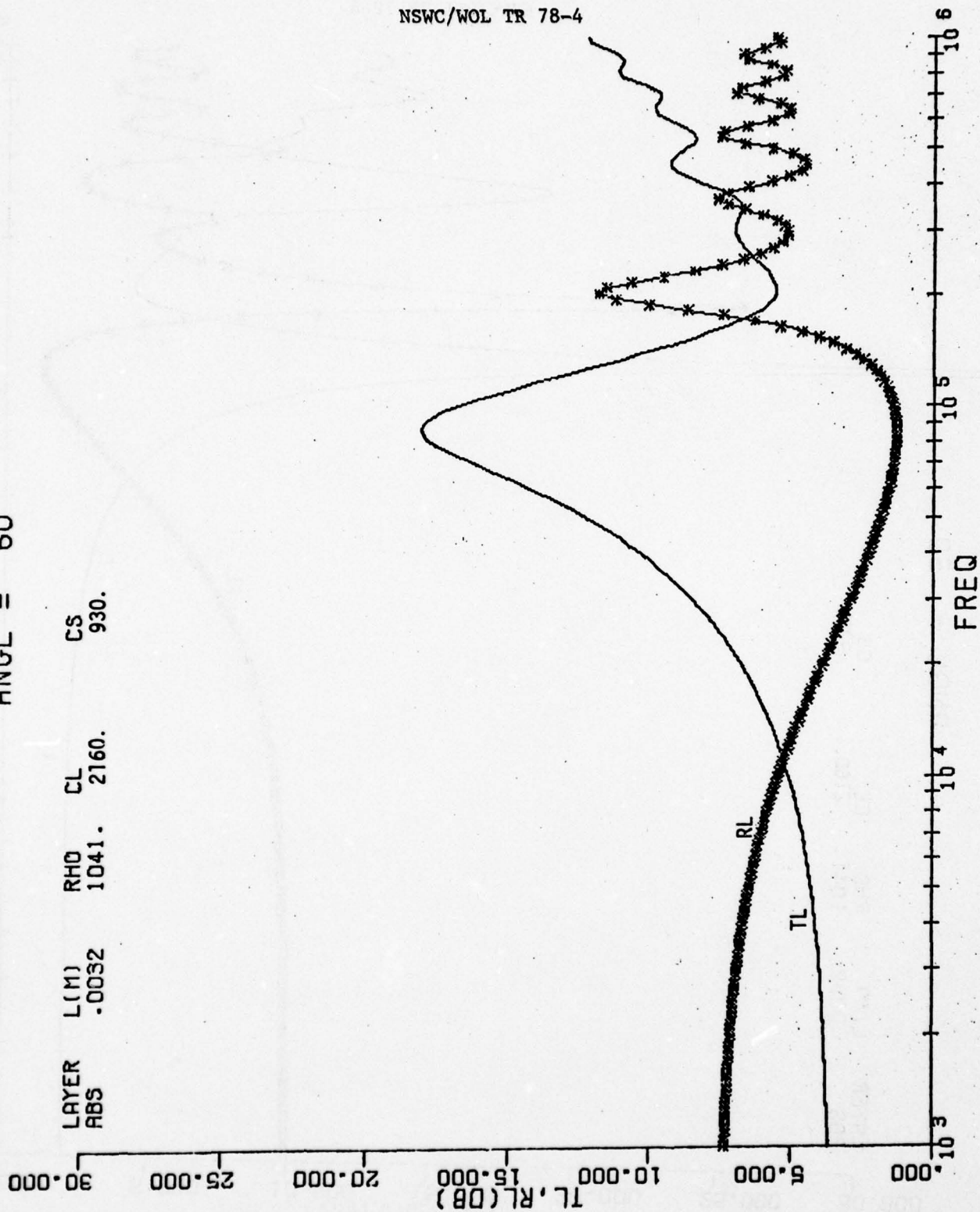


Figure 4(g). Transmission and Reflection Loss vs Frequency for Water/ABS/FC-75

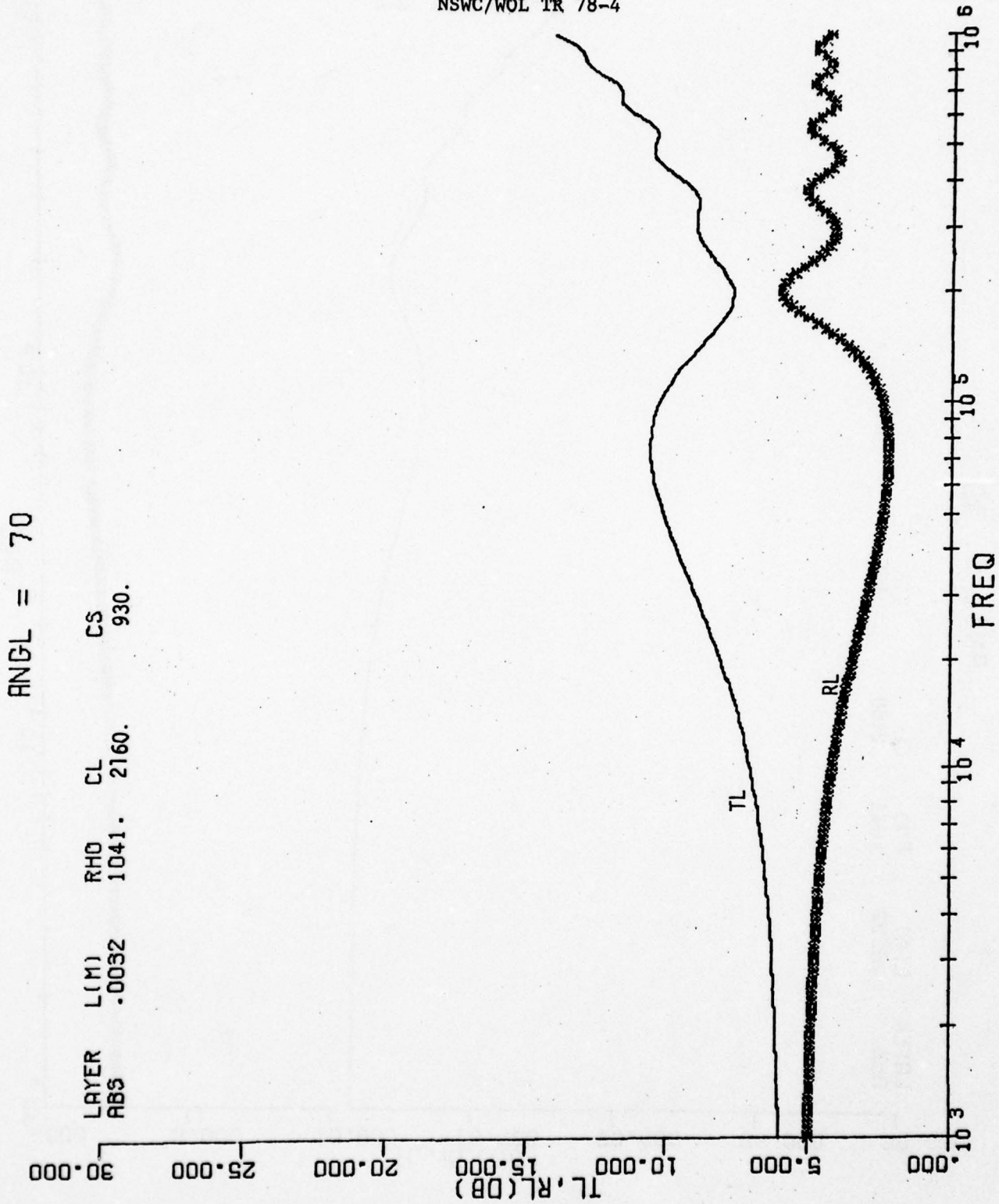


Figure 4(h). Transmission and Reflection Loss vs Frequency for Water/ABS/FC-75

ANGL = 80

LAYER L(M) RHO CL CS
ABS .0032 1041. 2160. 930.

NSWC/WOL TR 78-4

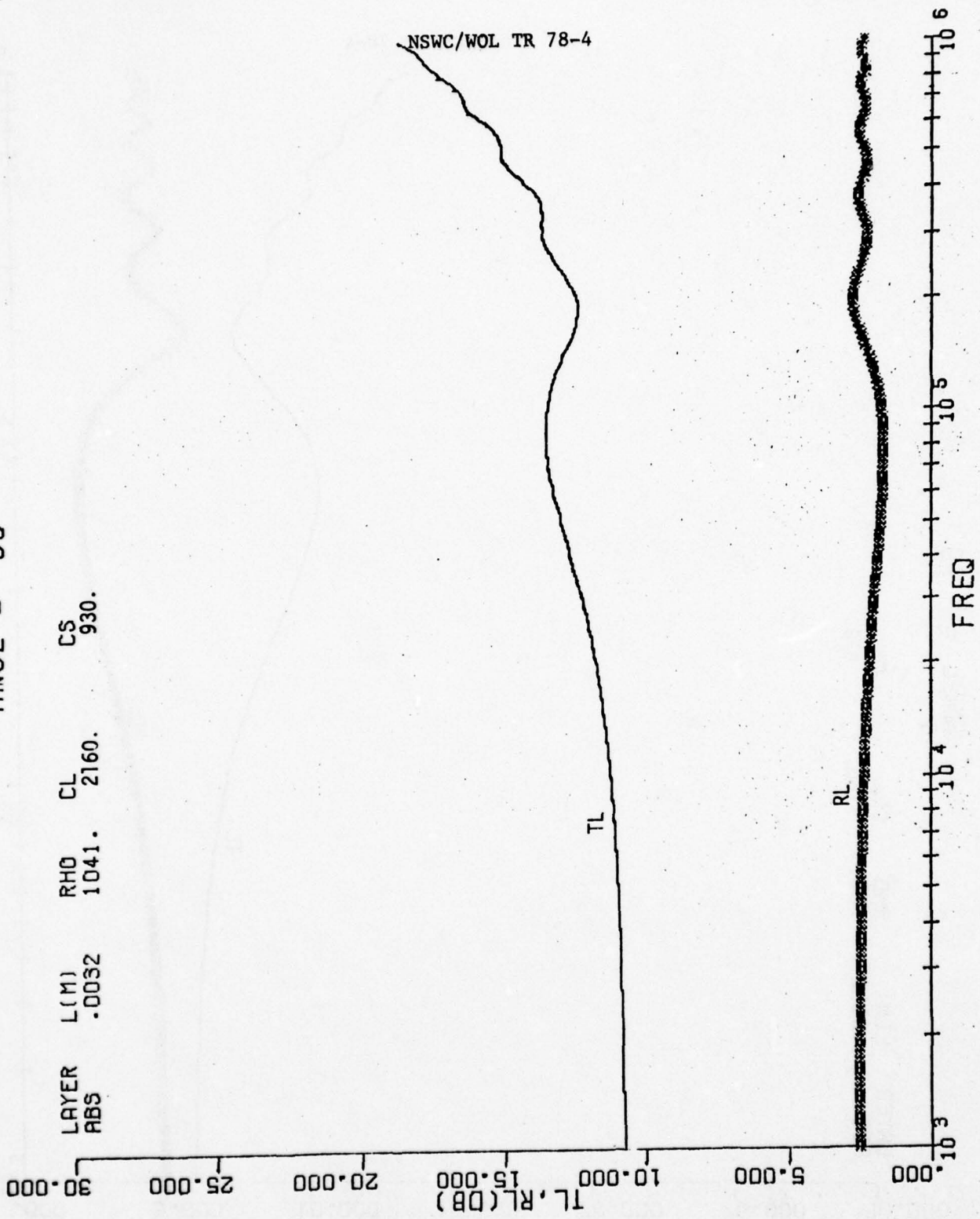


Figure 4(i). Transmission and Reflection Loss vs Frequency for Water/ABS/FC-75

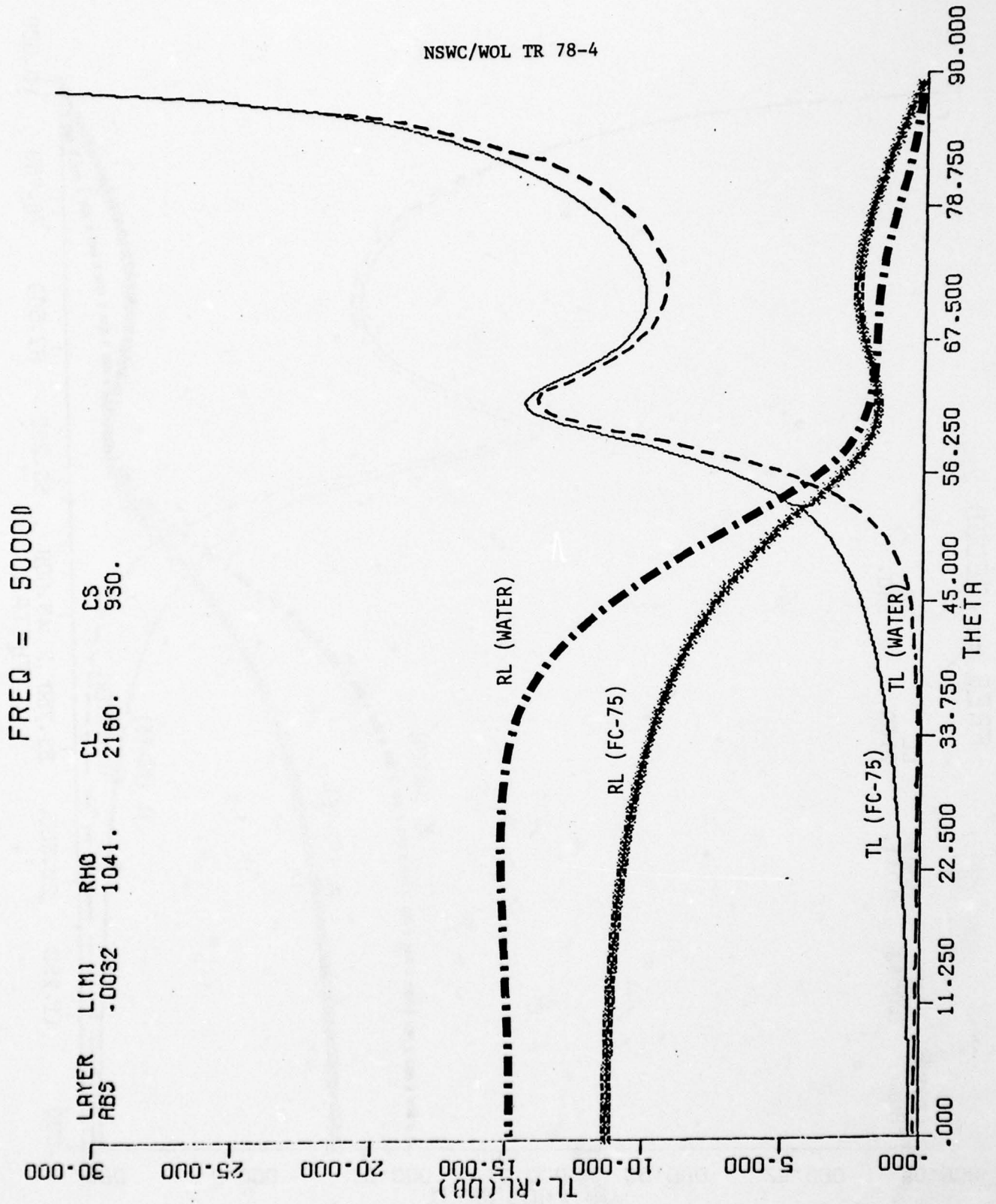


Figure 5(a). Transmission and Reflection Loss vs θ for Water/ABS/FC-75 and Water/ABS/Water

FREQ = 75000

LAYER L(M) RHO CL CS
 ABS .0032 1041. 2160. 930.

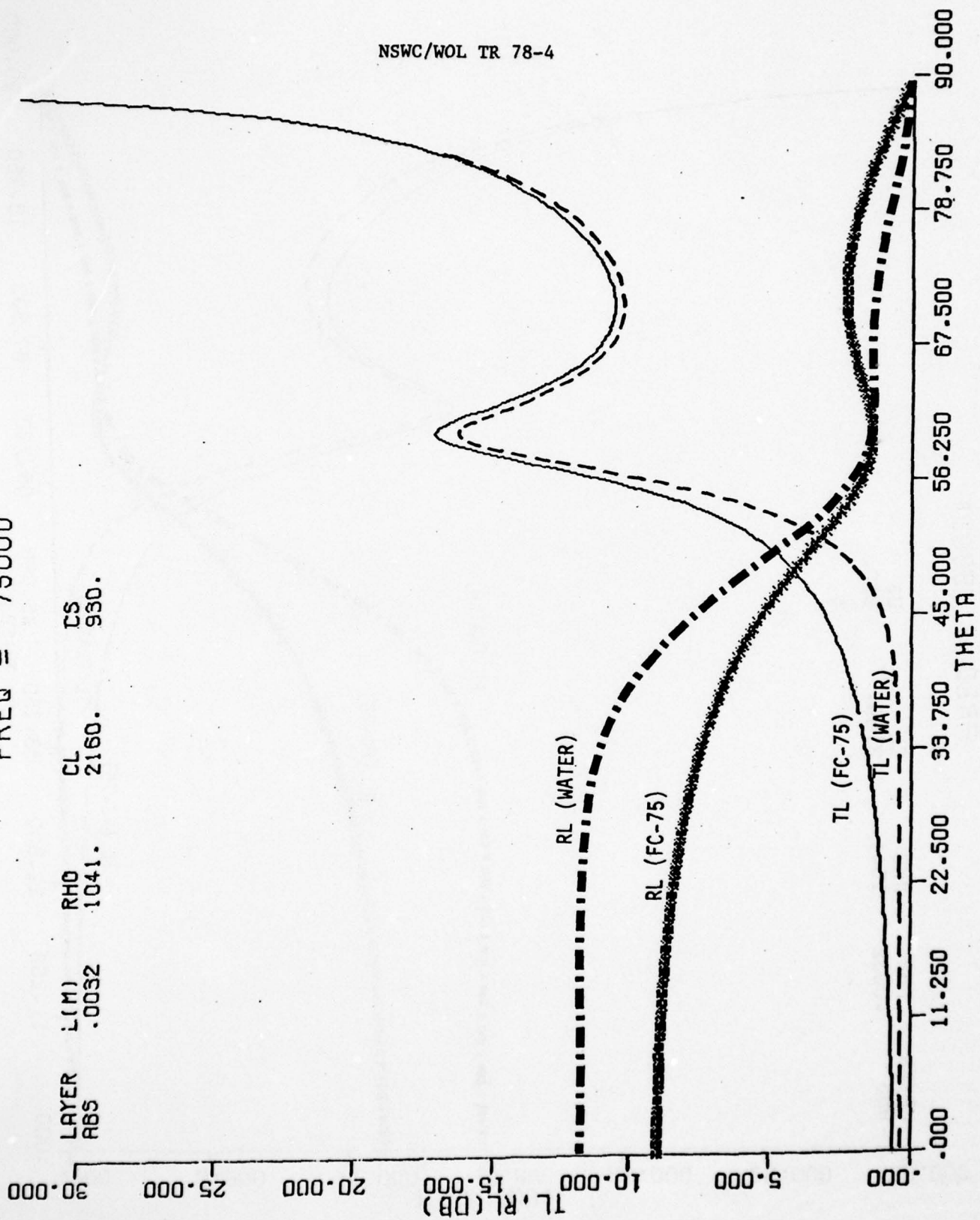


Figure 5(b). Transmission and Reflection Loss vs θ for Water/ABS/FC-75 and Water/ABS/Water

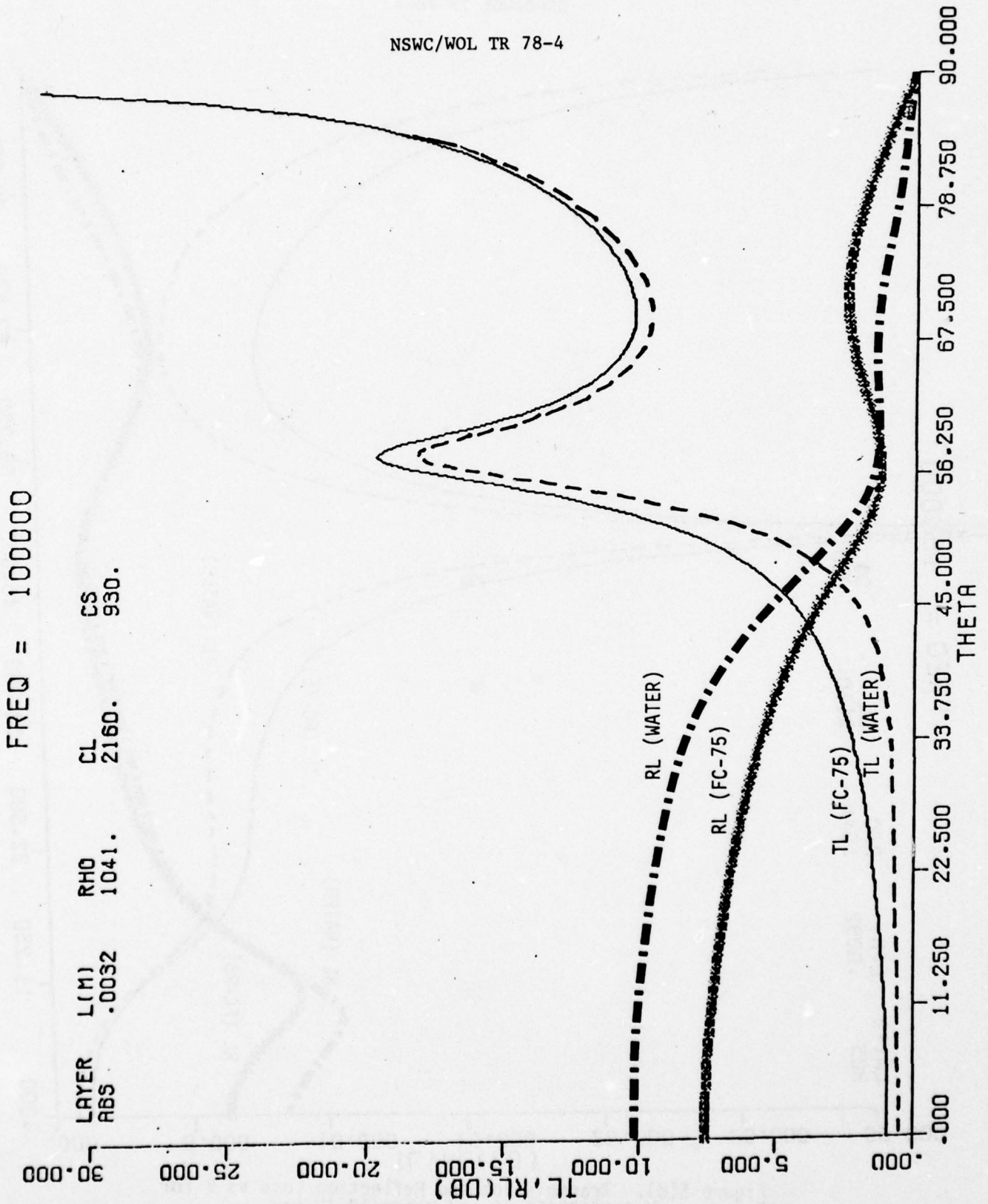


Figure 5(c). Transmission and Reflection Loss vs θ for Water/ABS/FC-75 and Water/ABS/Water

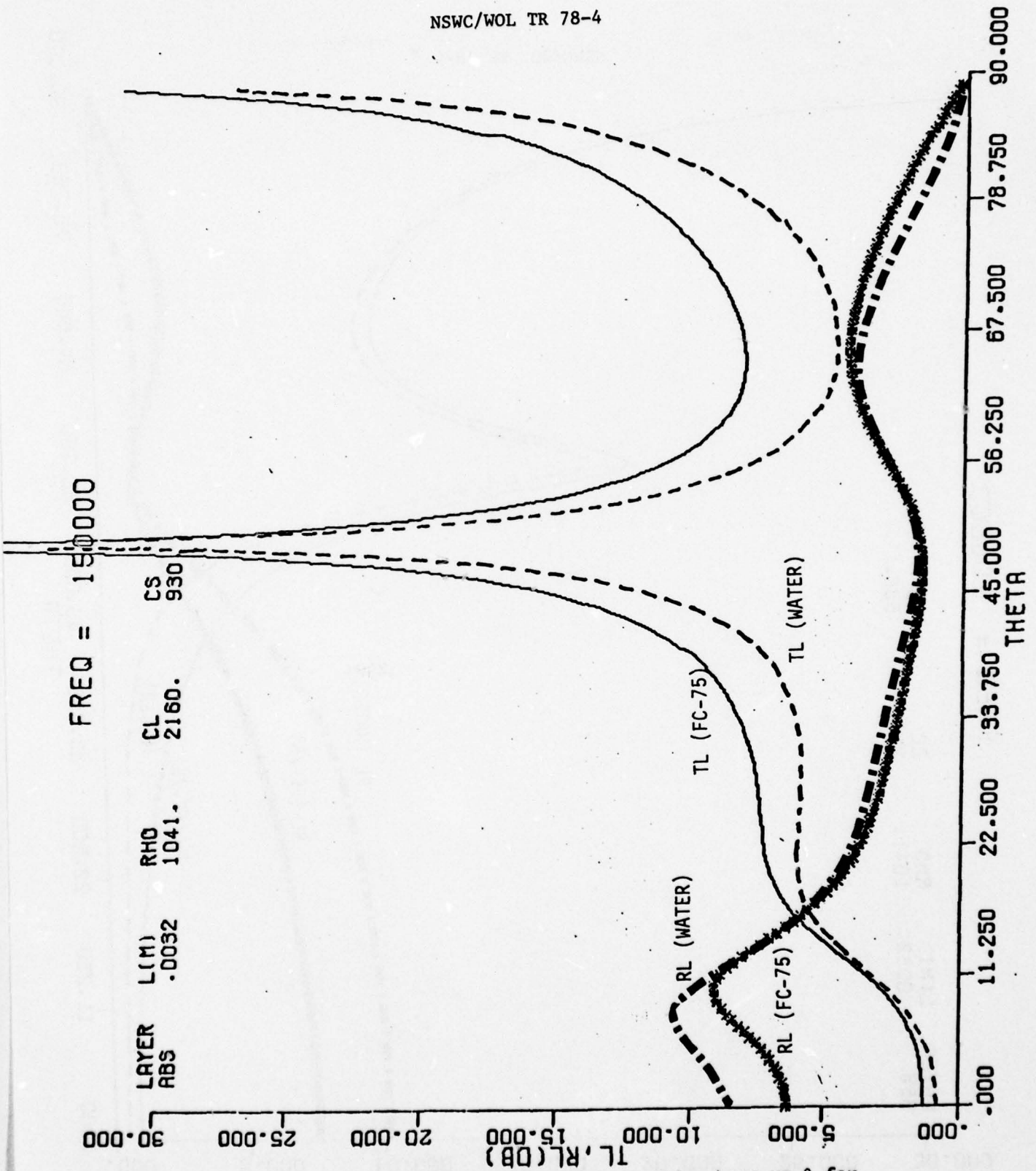


Figure 5(d). Transmission and Reflection Loss vs θ for Water/ABS/FC-75 and Water/ABS/Water

FREQ = 300000

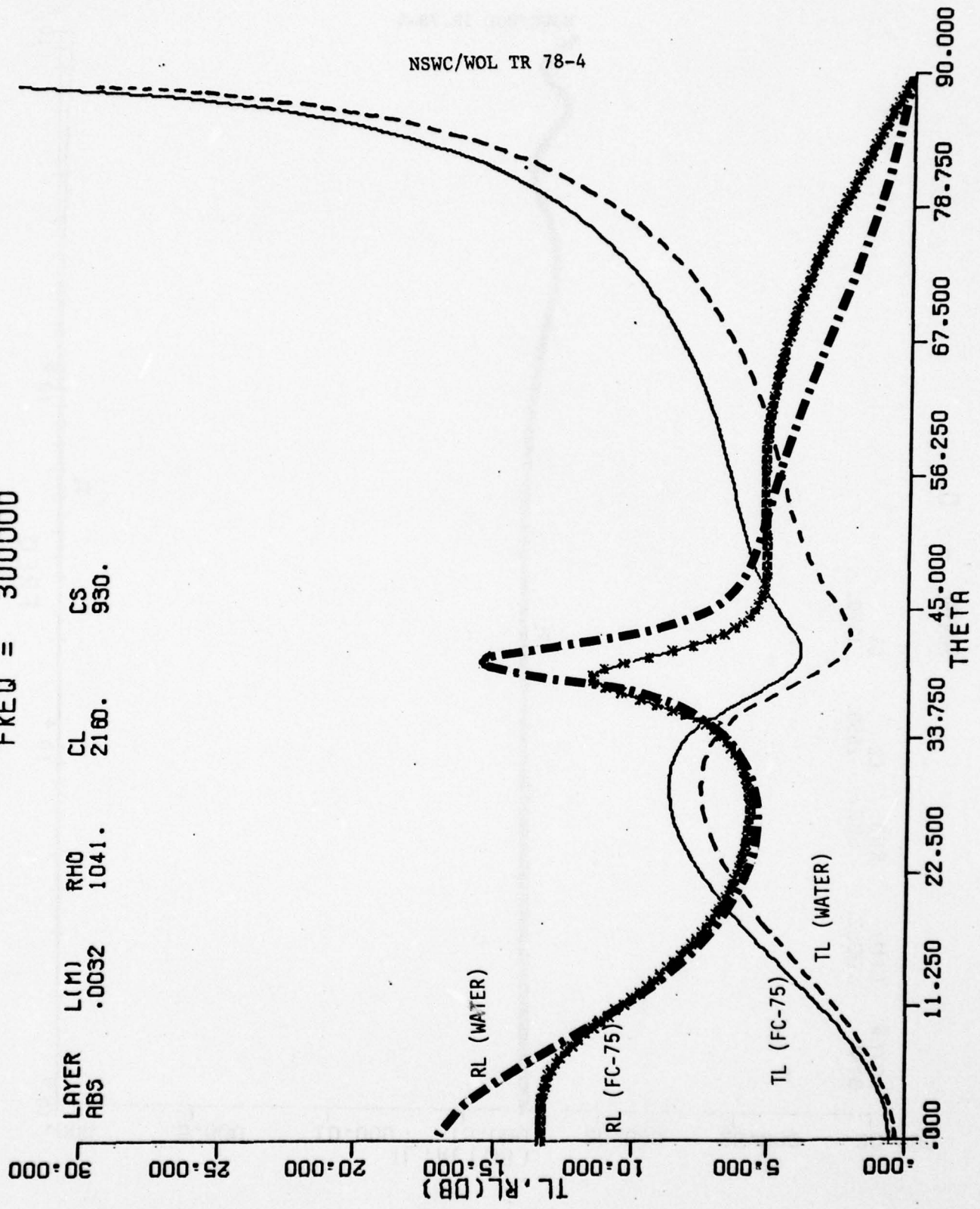


Figure 5(e). Transmission and Reflection Loss vs θ for Water/ABS/FC-75 and Water/ABS/Water

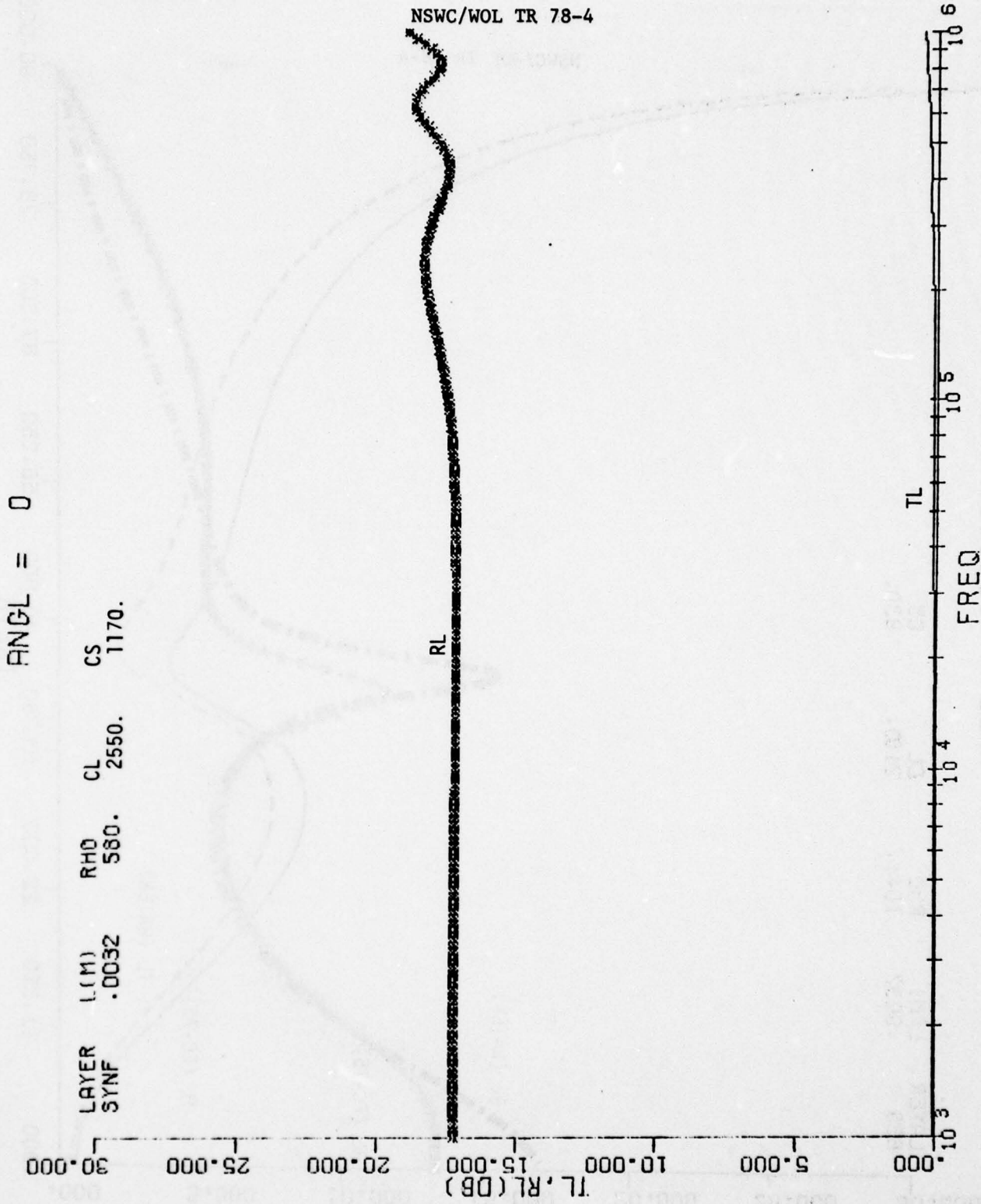


Figure 6(a). Transmission and Reflection Loss vs Frequency for Water/Syntactic Foam/FC-75

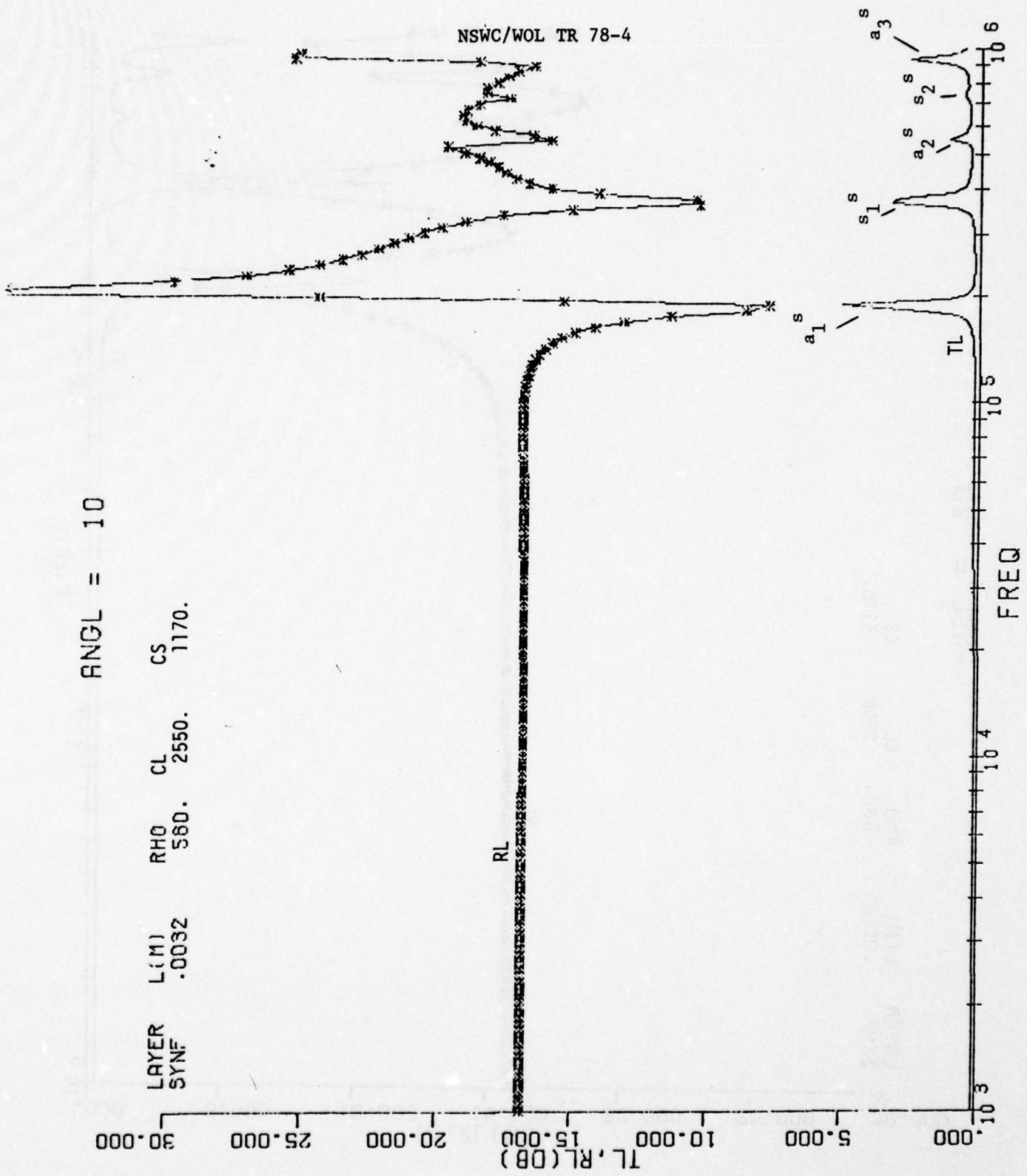


Figure 6(b). Transmission and Reflection Loss vs Frequency for Water/Syntactic Foam/FC-75

ANGL = 20

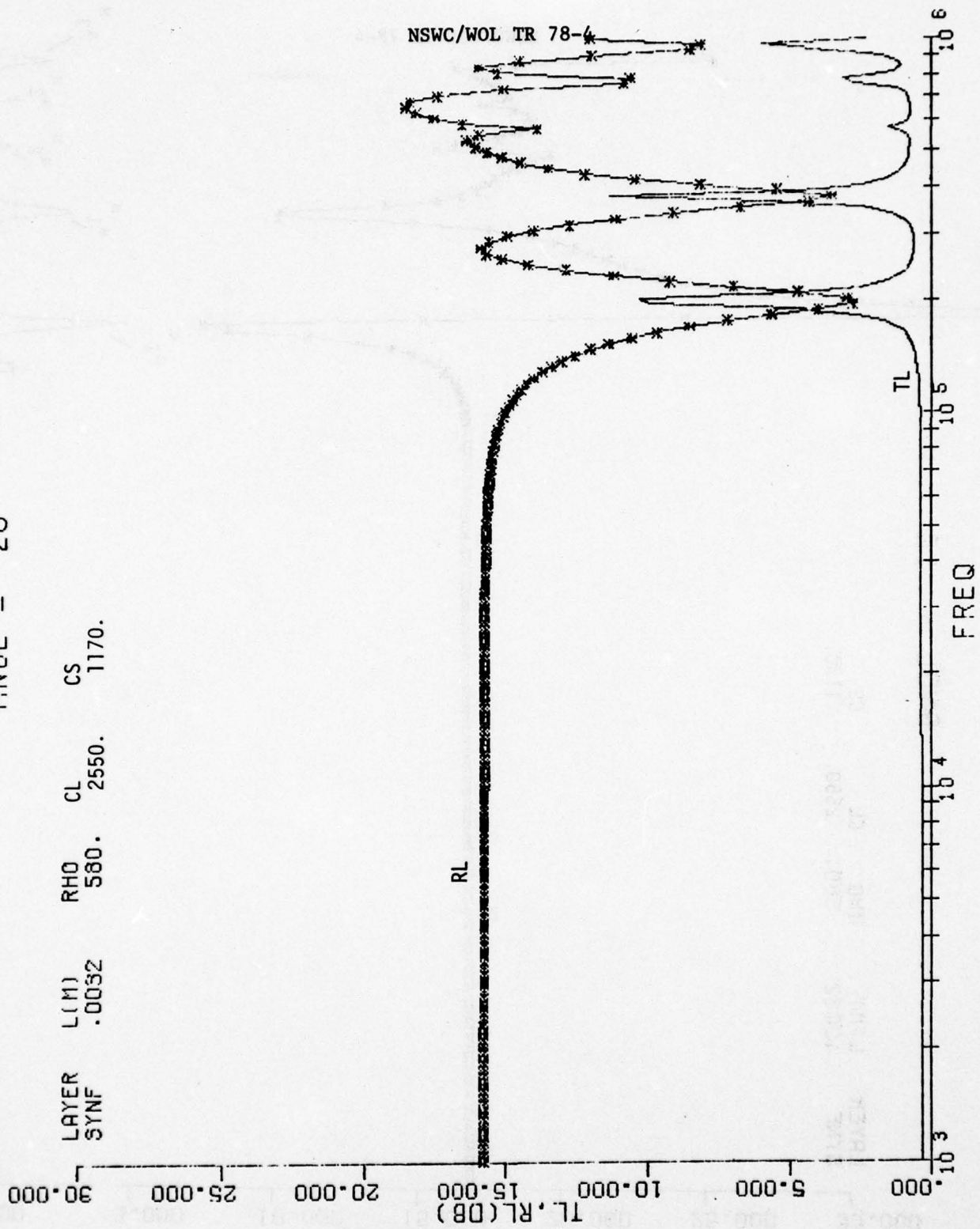


Figure 6(c). Transmission and Reflection Loss vs Frequency for Water/Syntactic Foam/FC-75

ANGL = 30

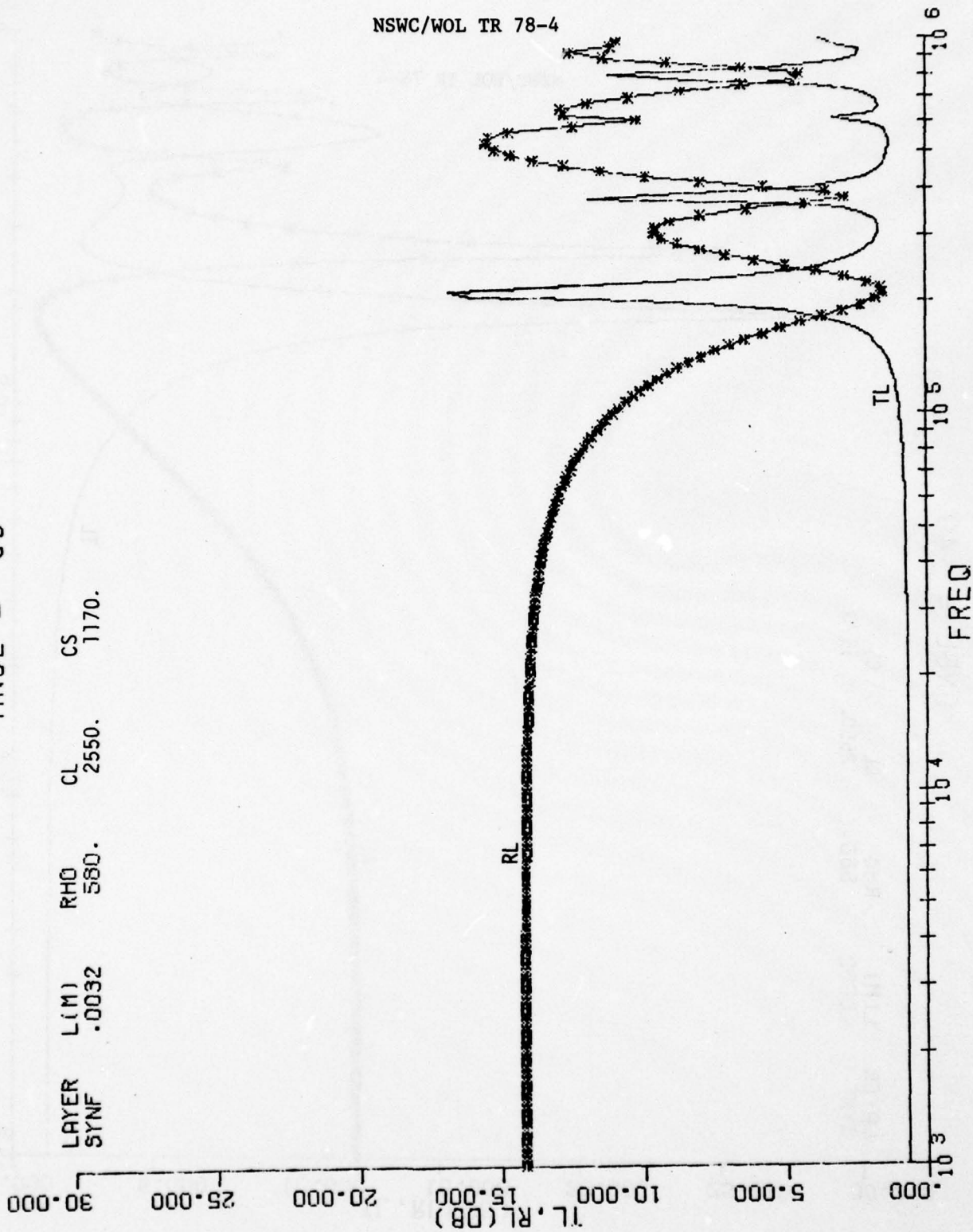


Figure 6(d). Transmission and Reflection Loss vs Frequency for Water/Syntactic Foam/FC-75

ANGL = 40

LAYER L(M) RHO CS
SYNF .0032 1.30 1170.

NSWC/WOL TR 78-4

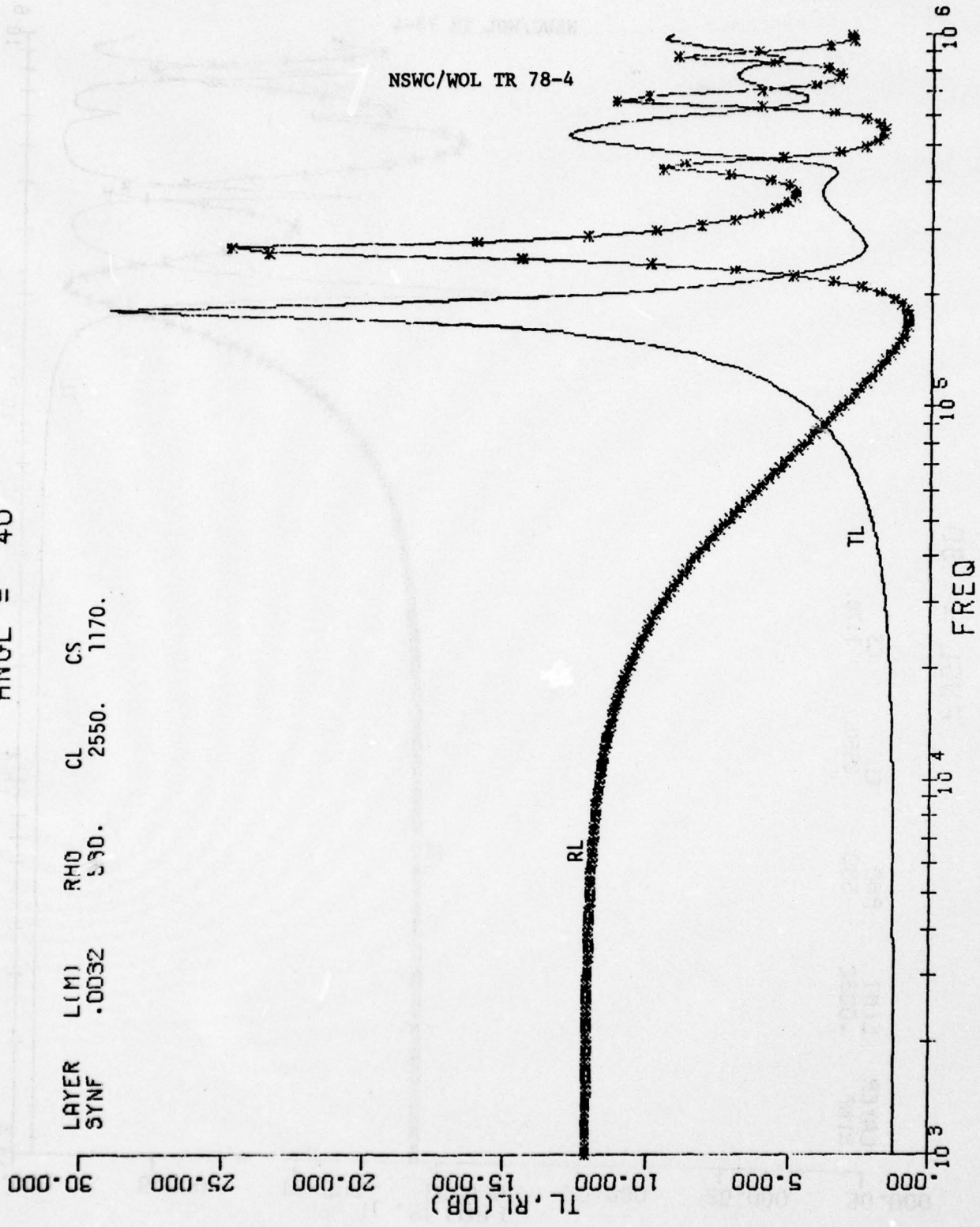


Figure 6(e). Transmission and Reflection Loss vs Frequency for Water/Syntactic Foam/FC-75

ANGL = 50

LAYER L(M) RHO CL CS
SYNF .0032 580. 2550. 1170.

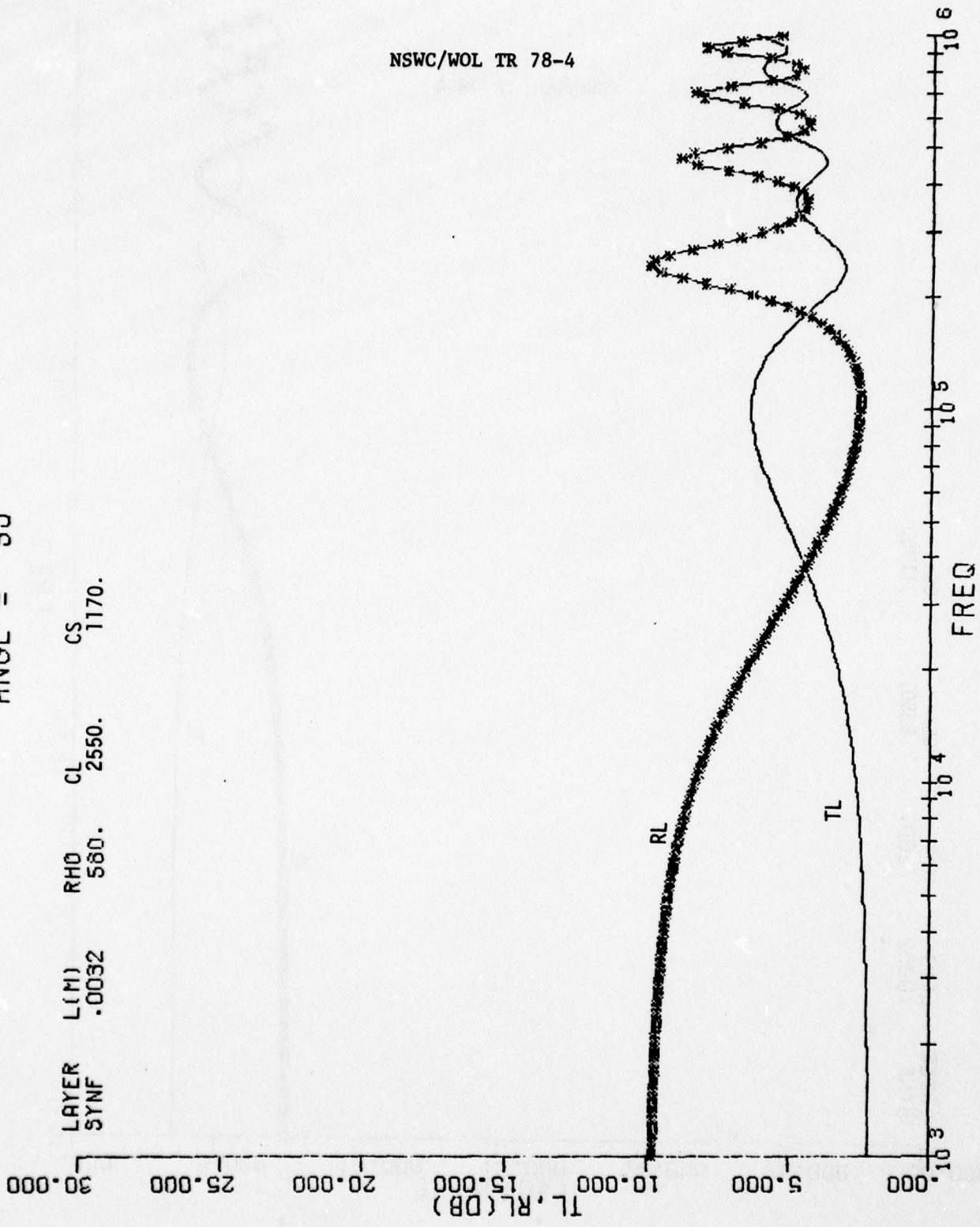


Figure 6(f). Transmission and Reflection Loss vs Frequency for Water/Syntactic Foam/FC-75

NSWC/WOL TR 78-4

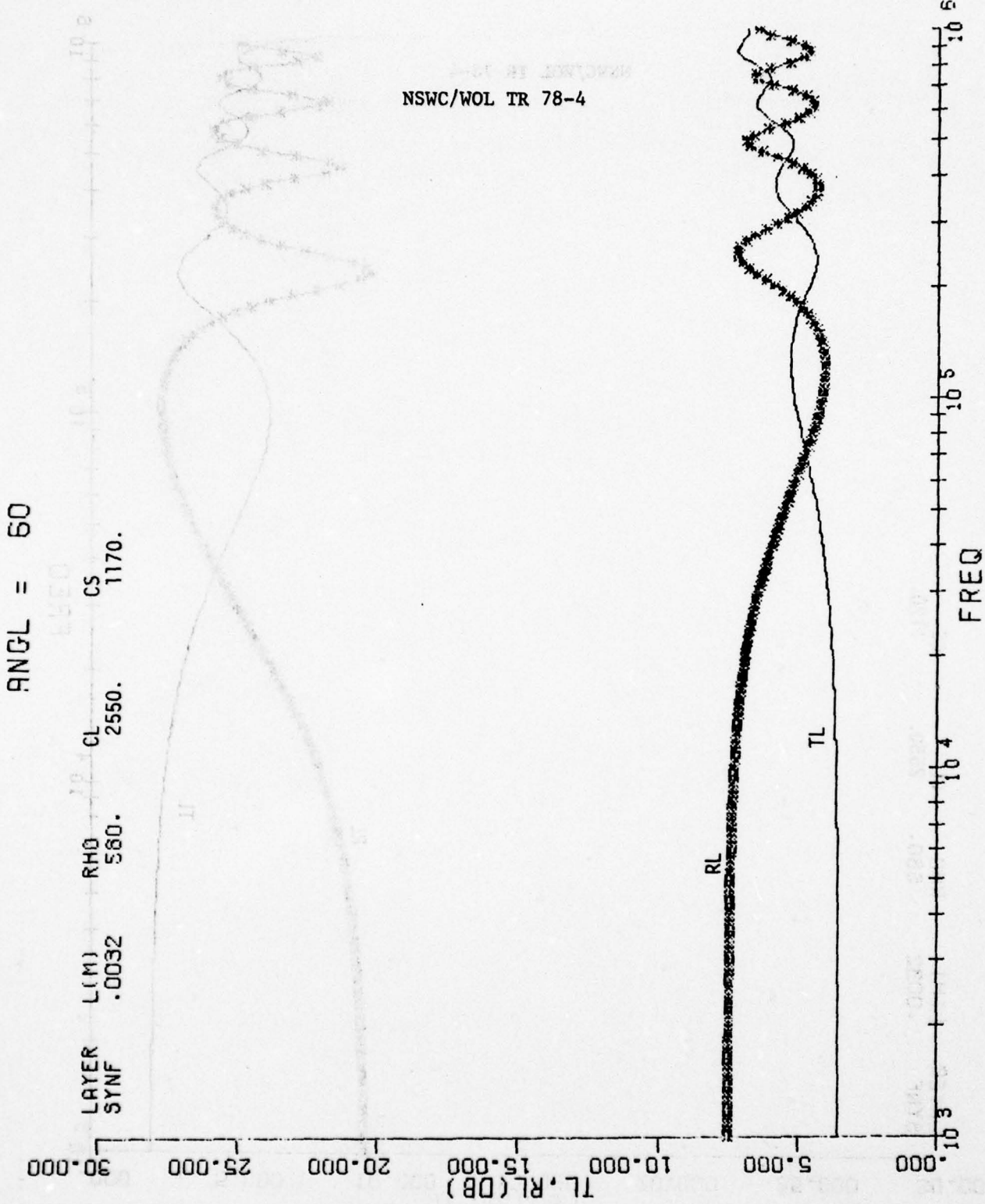


Figure 6(g). Transmission and Reflection Loss vs Frequency for Water/Syntactic Foam/FC-75

ANGL = 70

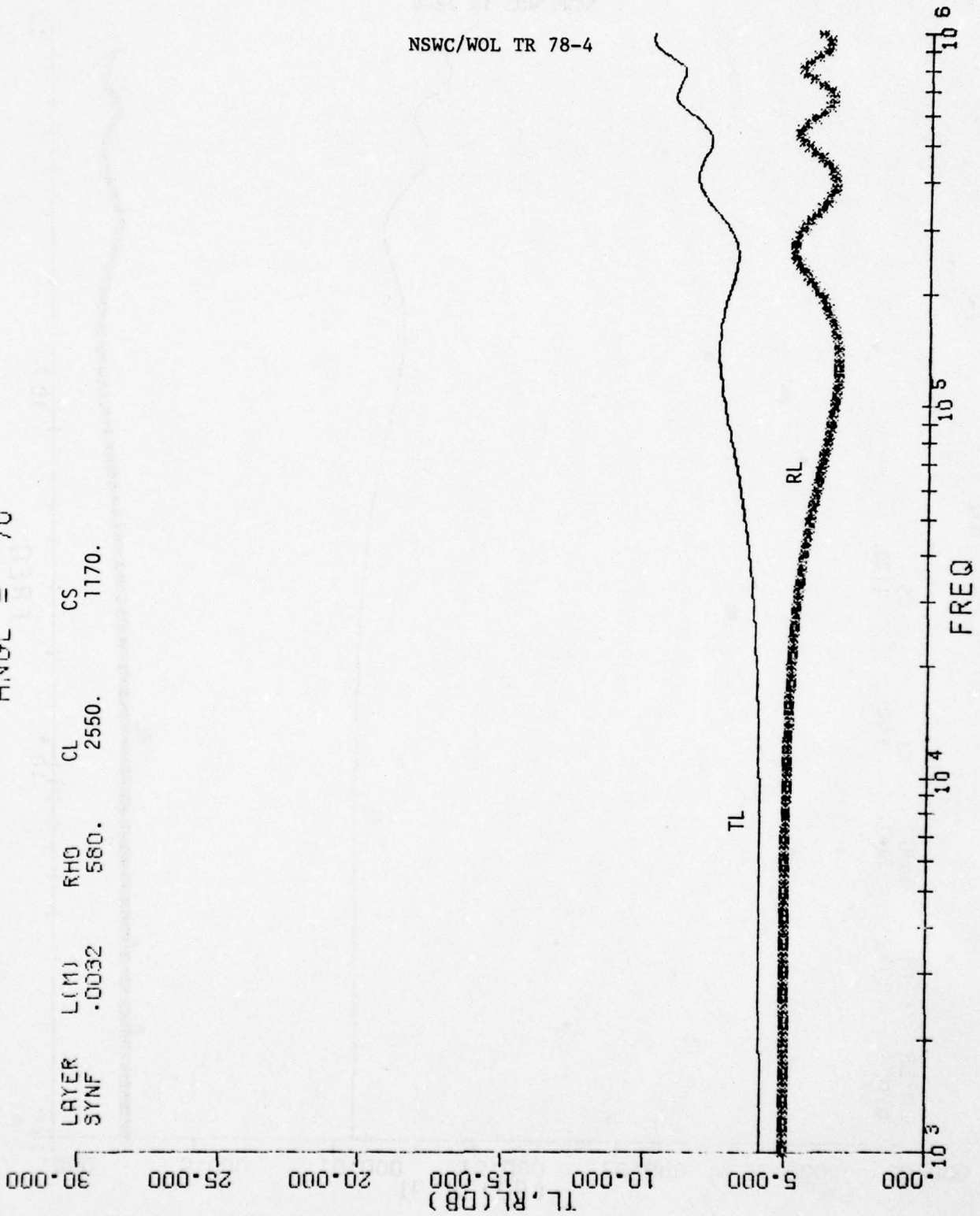


Figure 6(h). Transmission and Reflection Loss vs Frequency for Water/Syntactic Foam/FC-75

ANGL = 80

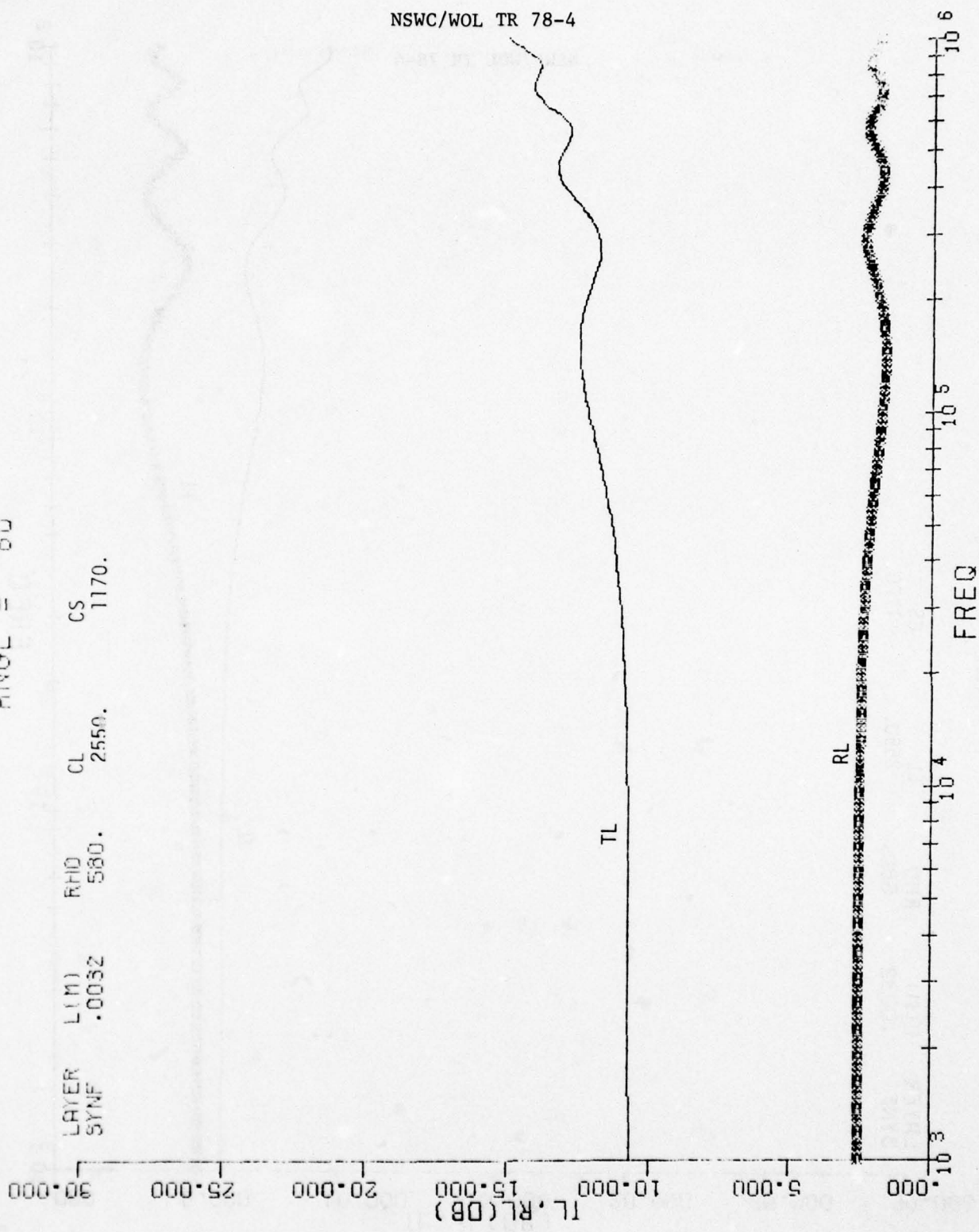


Figure 6(i). Transmission and Reflection Loss vs Frequency for Water/Syntactic Foam/FC-75

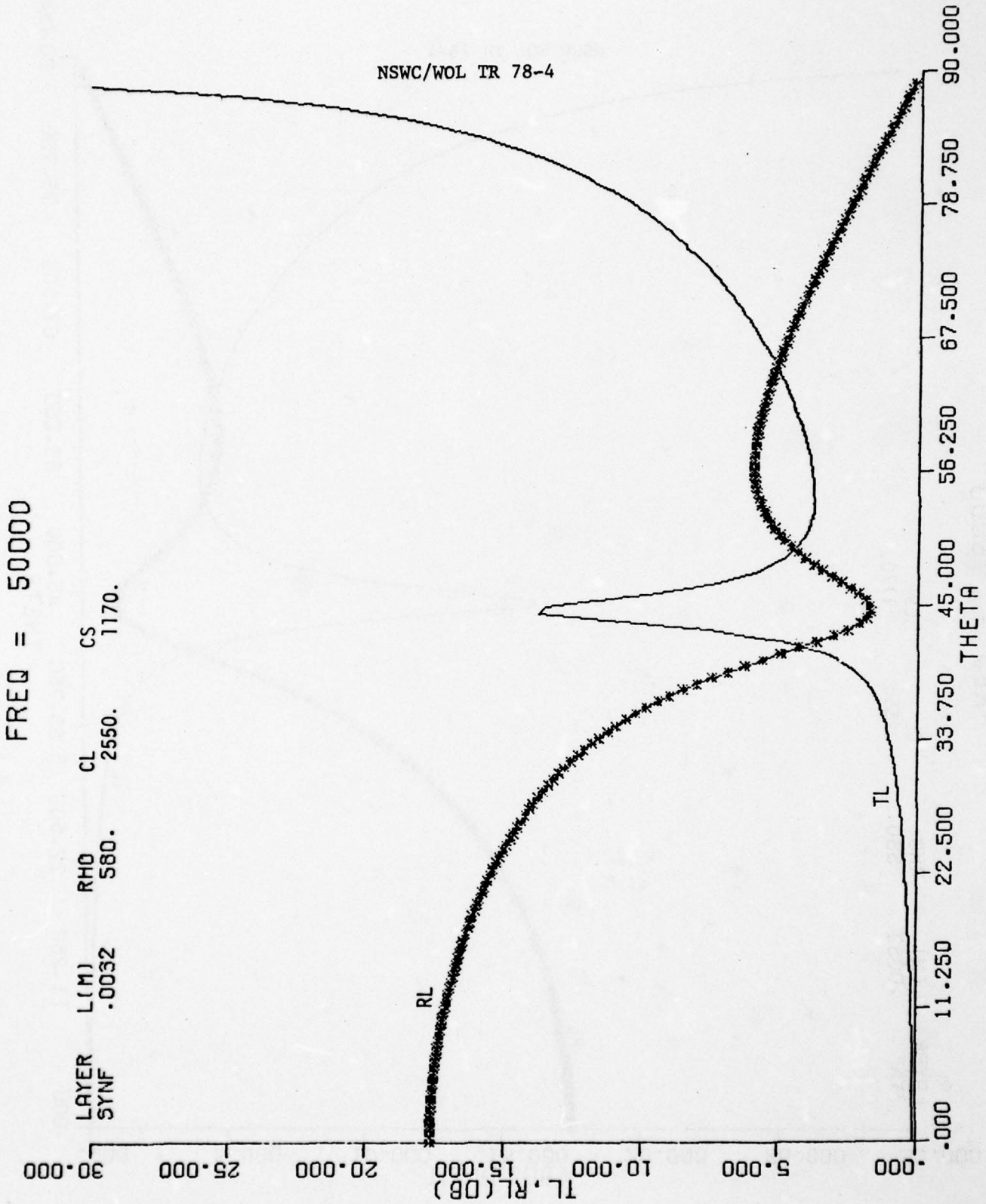


Figure 7(a). Transmission and Reflection Loss vs θ for Water/Syntactic Foam/FC-75

FREQ = 75000

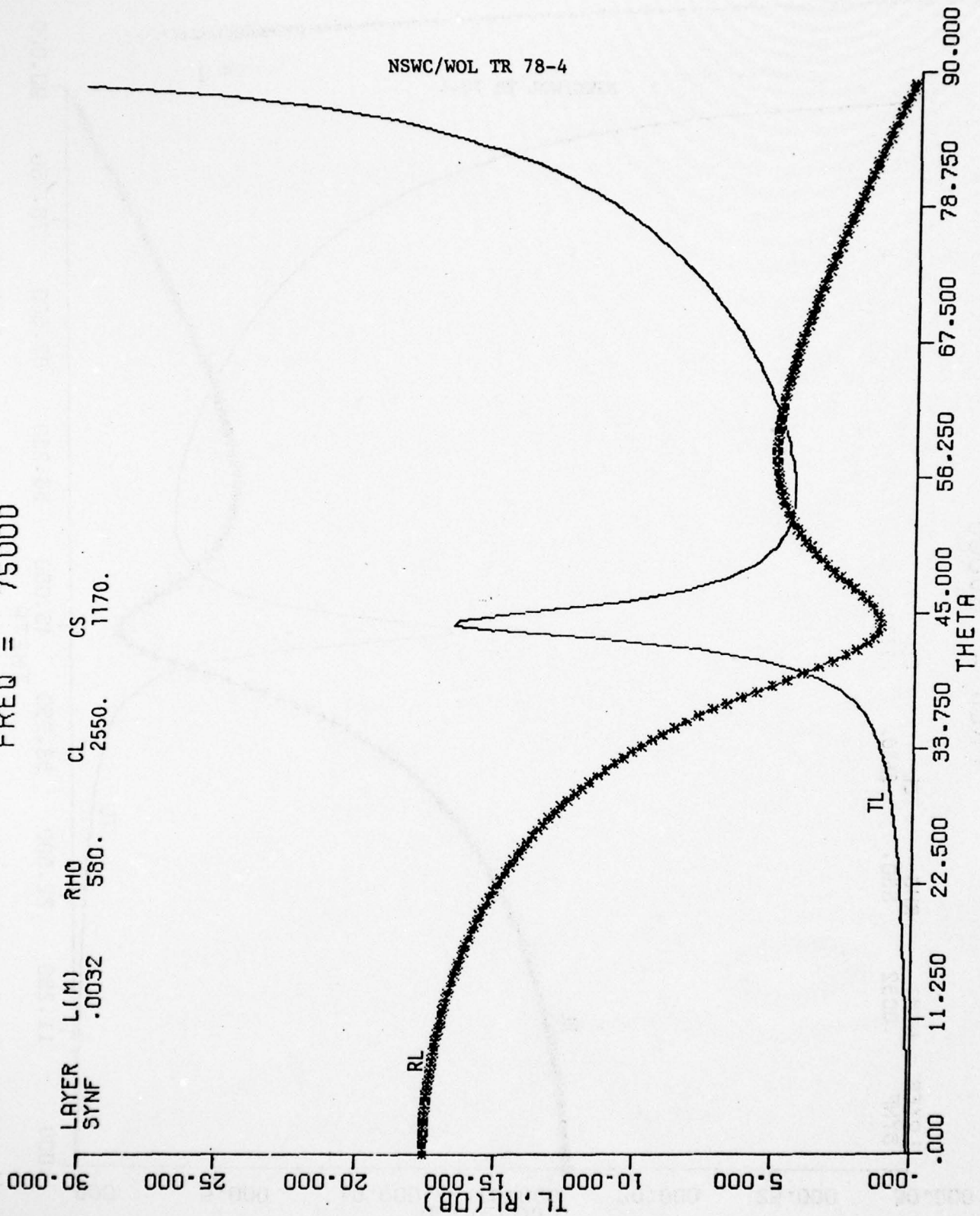


Figure 7(b). Transmission and Reflection Loss vs θ for Water/Syntactic Foam/FC-75

FREQ = 100000

LAYER L(M) RHO CS
SYNF .0032 580. 1170.

NSWC/WOL TR 78-4

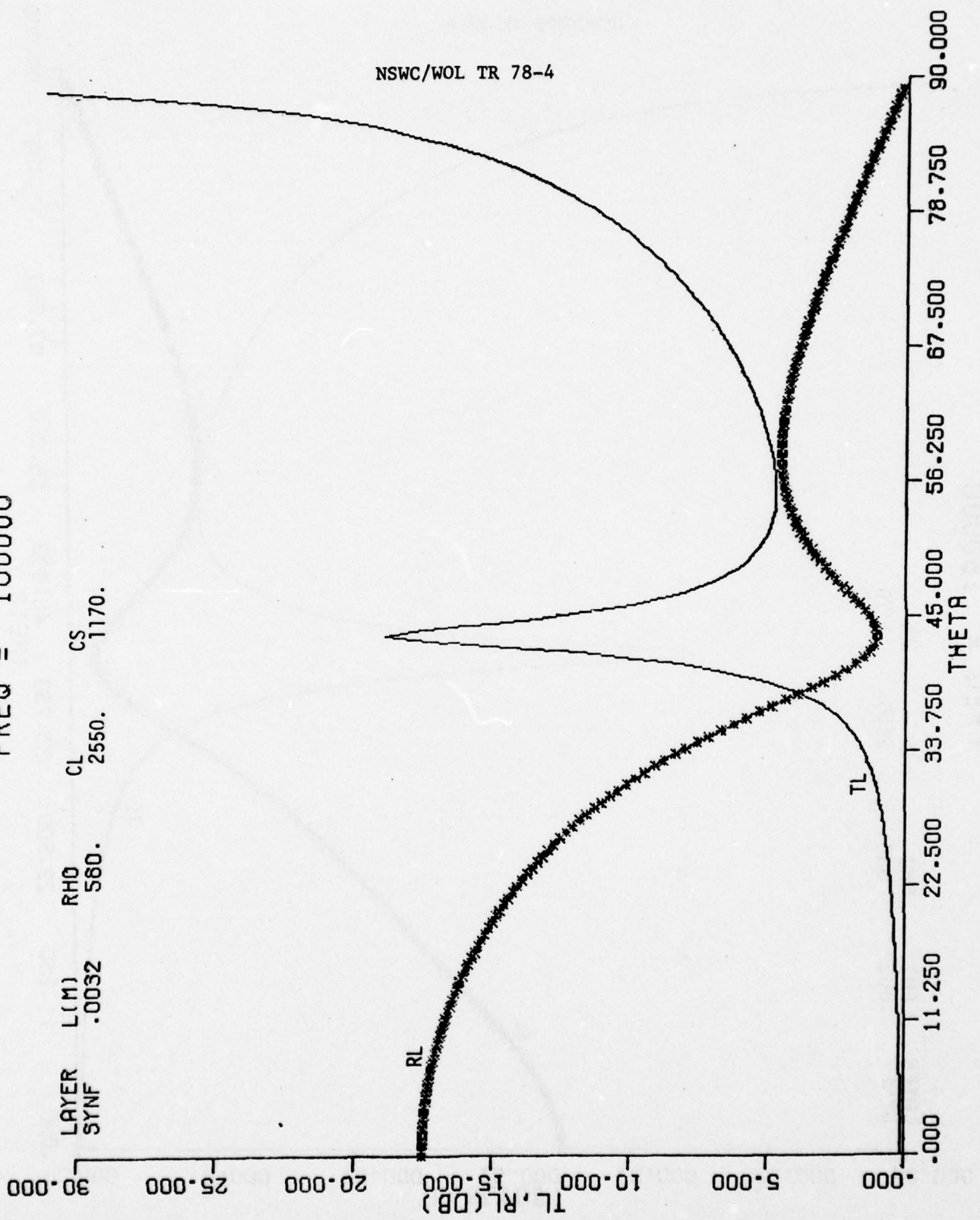


Figure 7(c). Transmission and Reflection Loss vs θ for Water/Syntactic Foam/FC-75

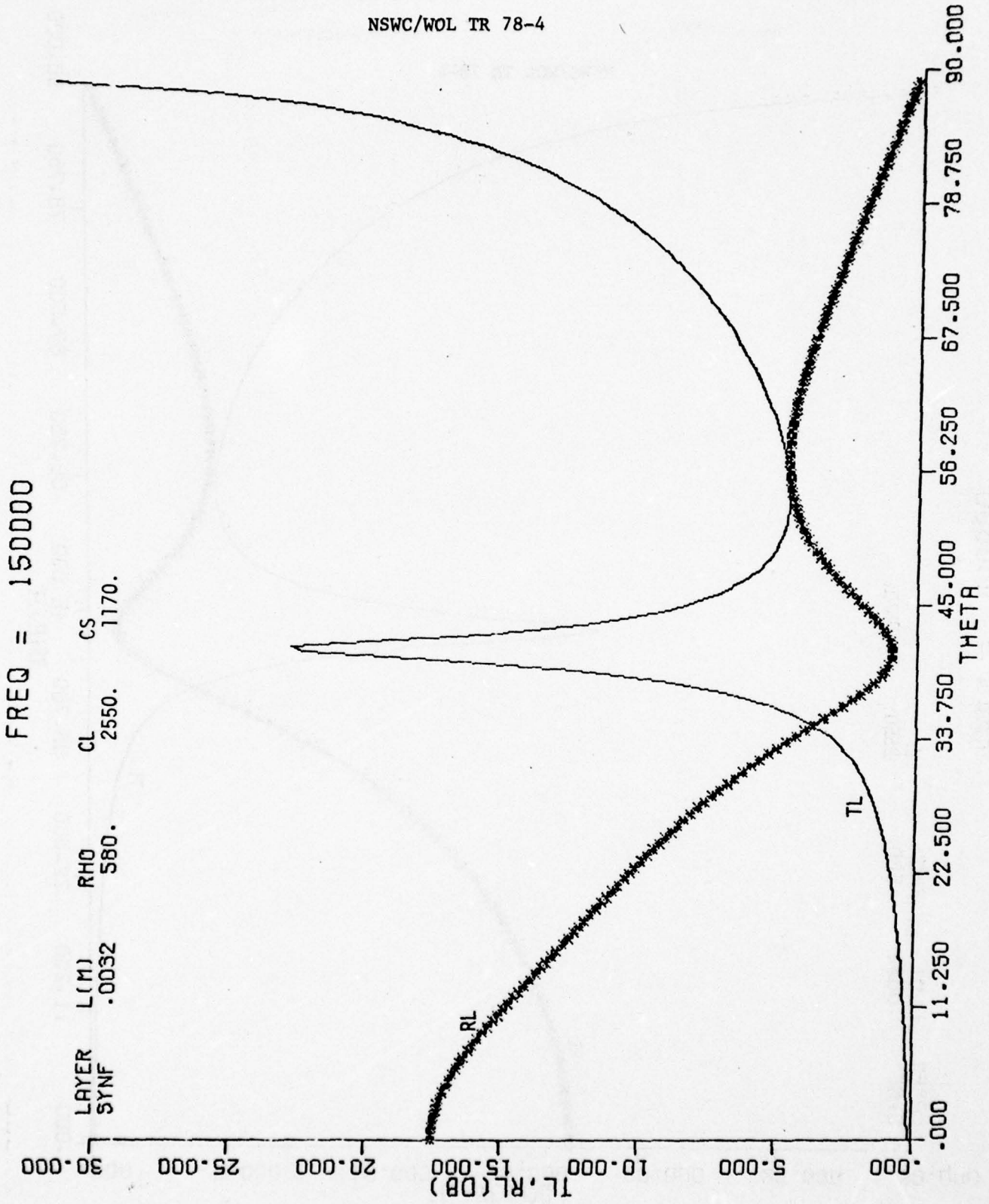


Figure 7(d). Transmission and Reflection Loss vs θ for Water/Syntactic Foam/FC-75

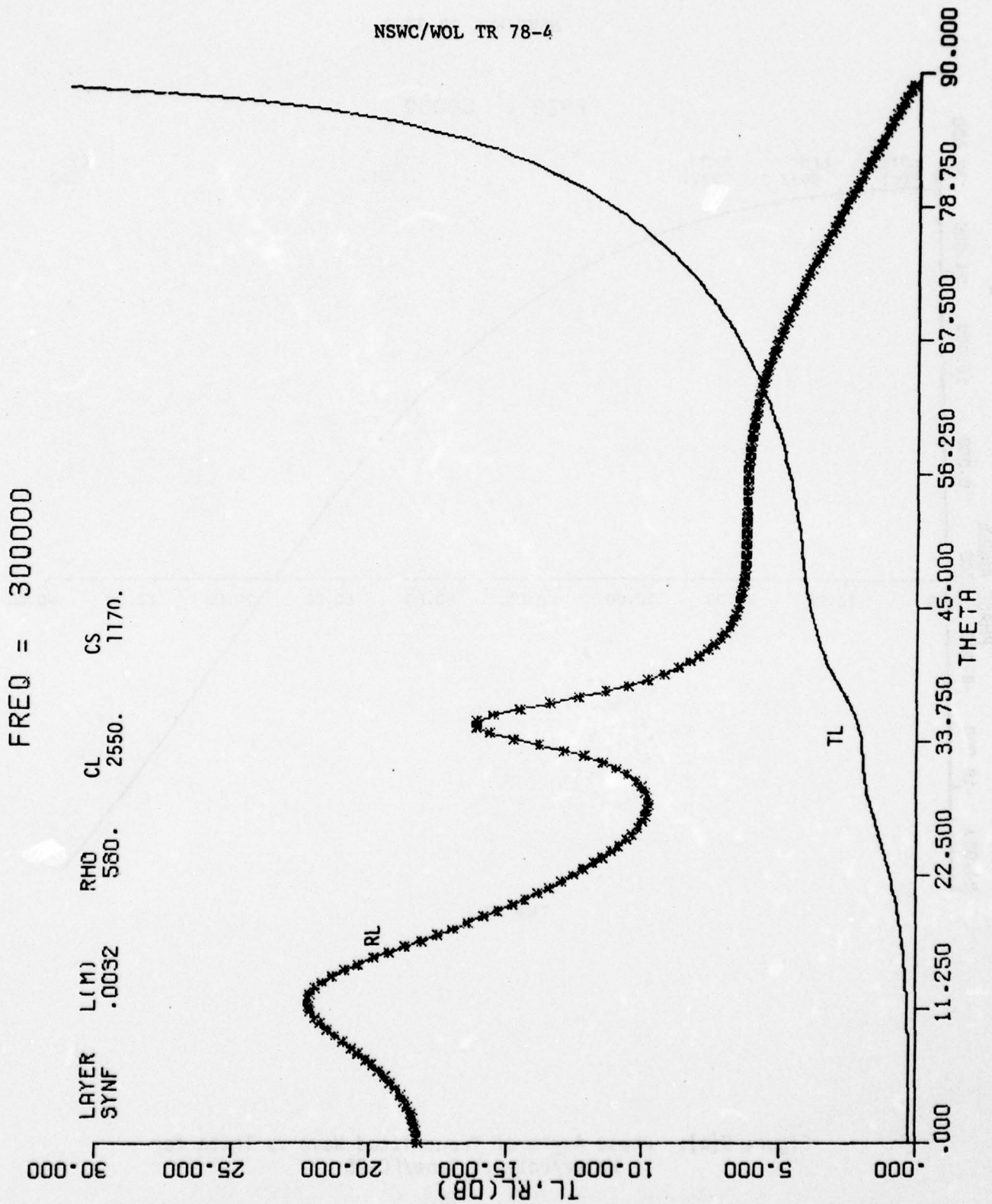


Figure 7(e). Transmission and Reflection Loss vs θ for Water/Syntactic Foam/FC-75

FREQ = 50000

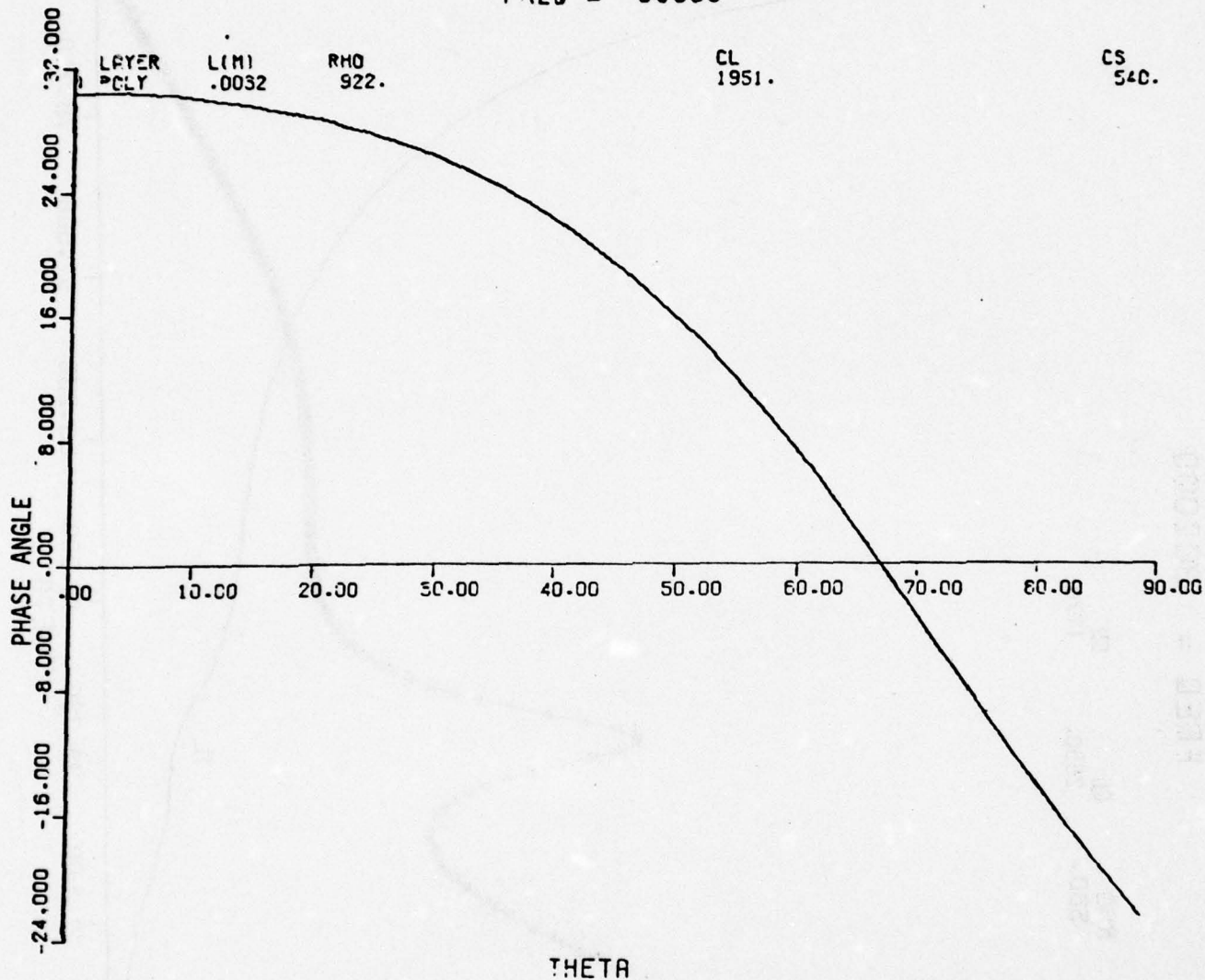


Figure 8(a). Phase Angle of Transmitted Wave vs Theta for Water/Polyethylene/FC-75

FREQ = 75000

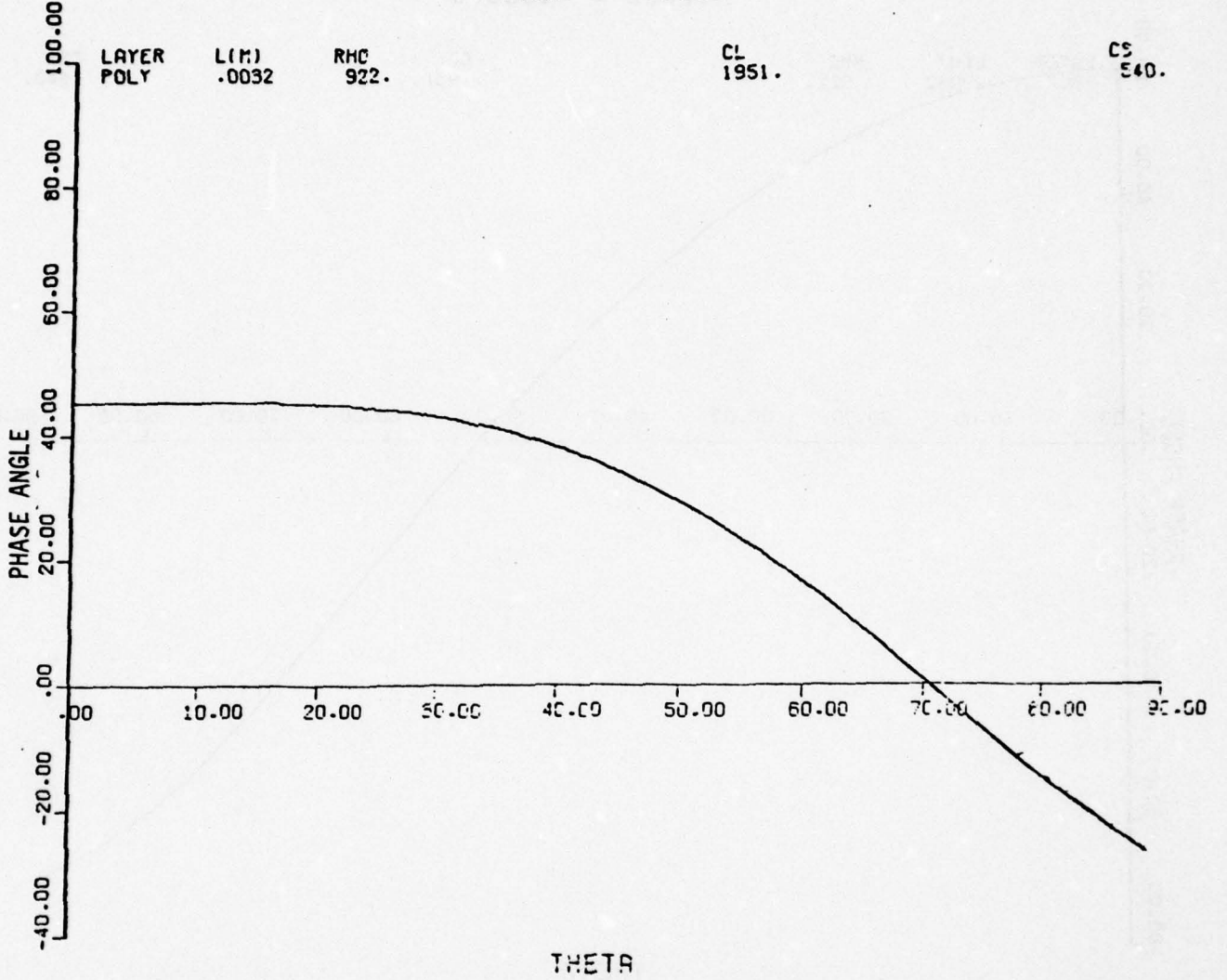


Figure 8(b). Phase Angle of Transmitted Wave vs Theta for Water/Polyethylene/FC-75

NSWC/WOL TR 78-4

FREQ = 100000

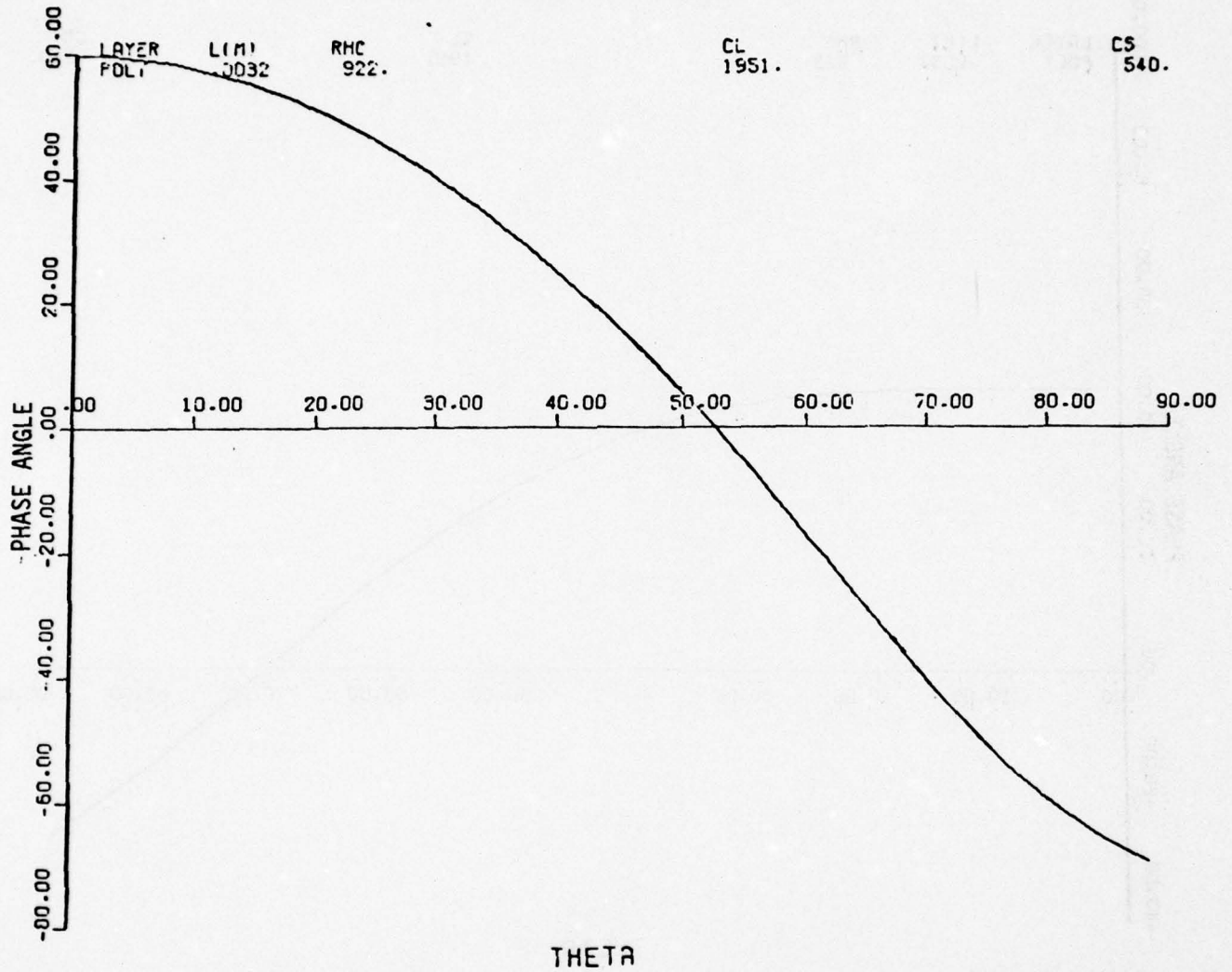


Figure 8(c). Phase Angle of Transmitted Wave vs Theta for Water/Polyethylene/FC-75

NSWC/WOL TR 78-4

FREQ = 150000

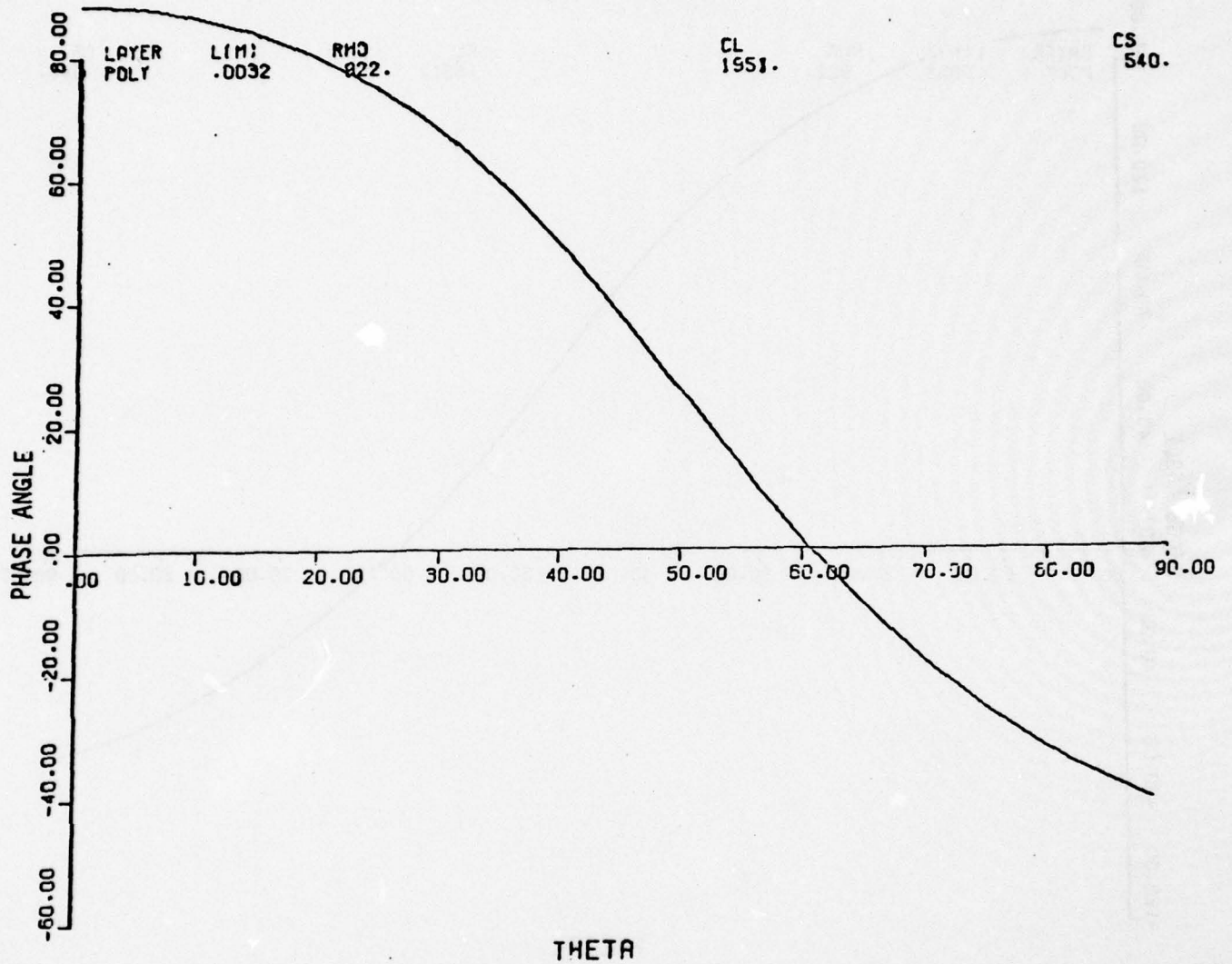


Figure 8(d). Phase Angle of Transmitted Wave vs Theta for Water/Polyethylene/FC-75

FREQ = 350000

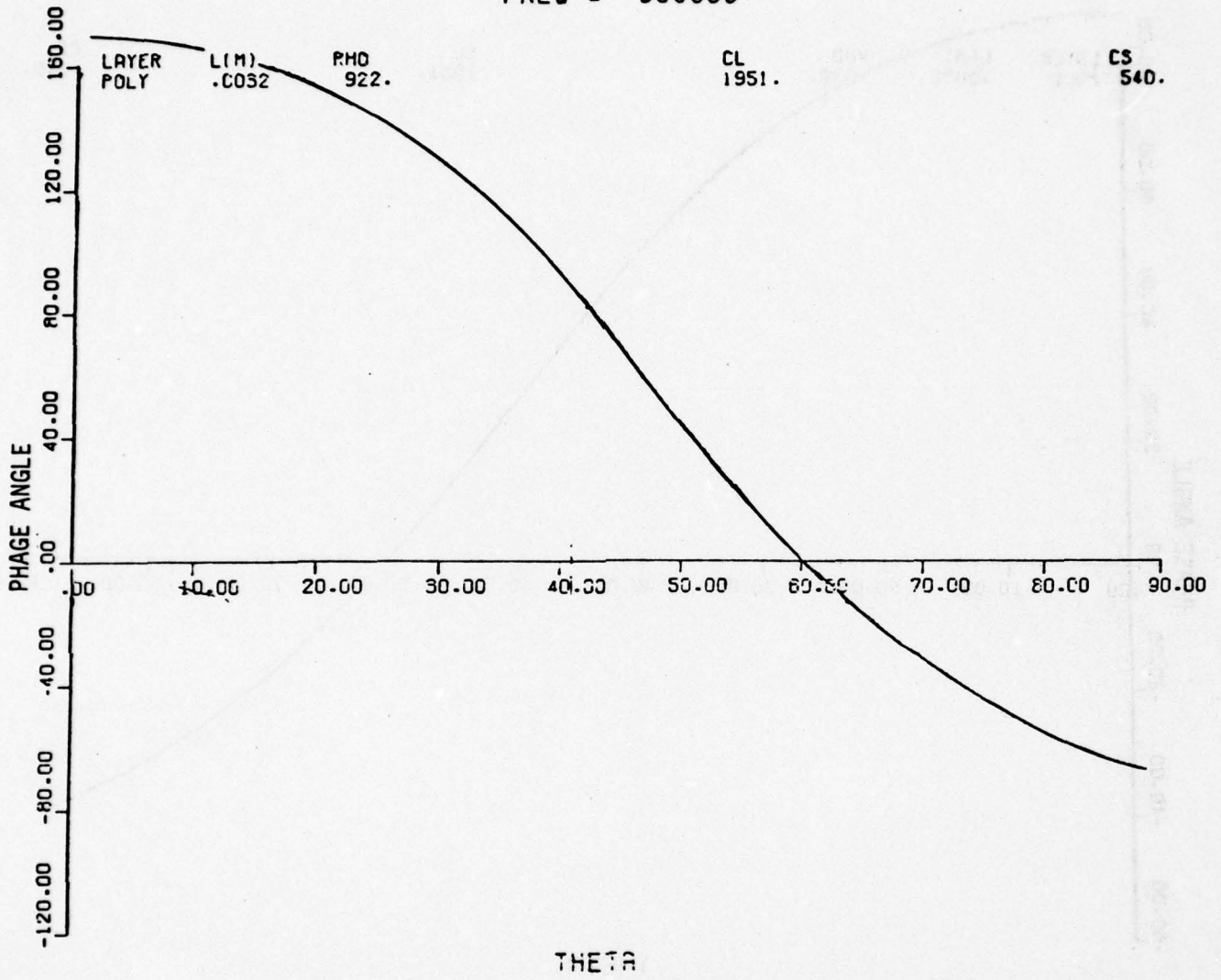


Figure 8(e). Phase Angle of Transmitted Wave vs Theta for Water/Polyethylene/FC-75

NSWC/WOL TR 78-4

FREQ = 50000

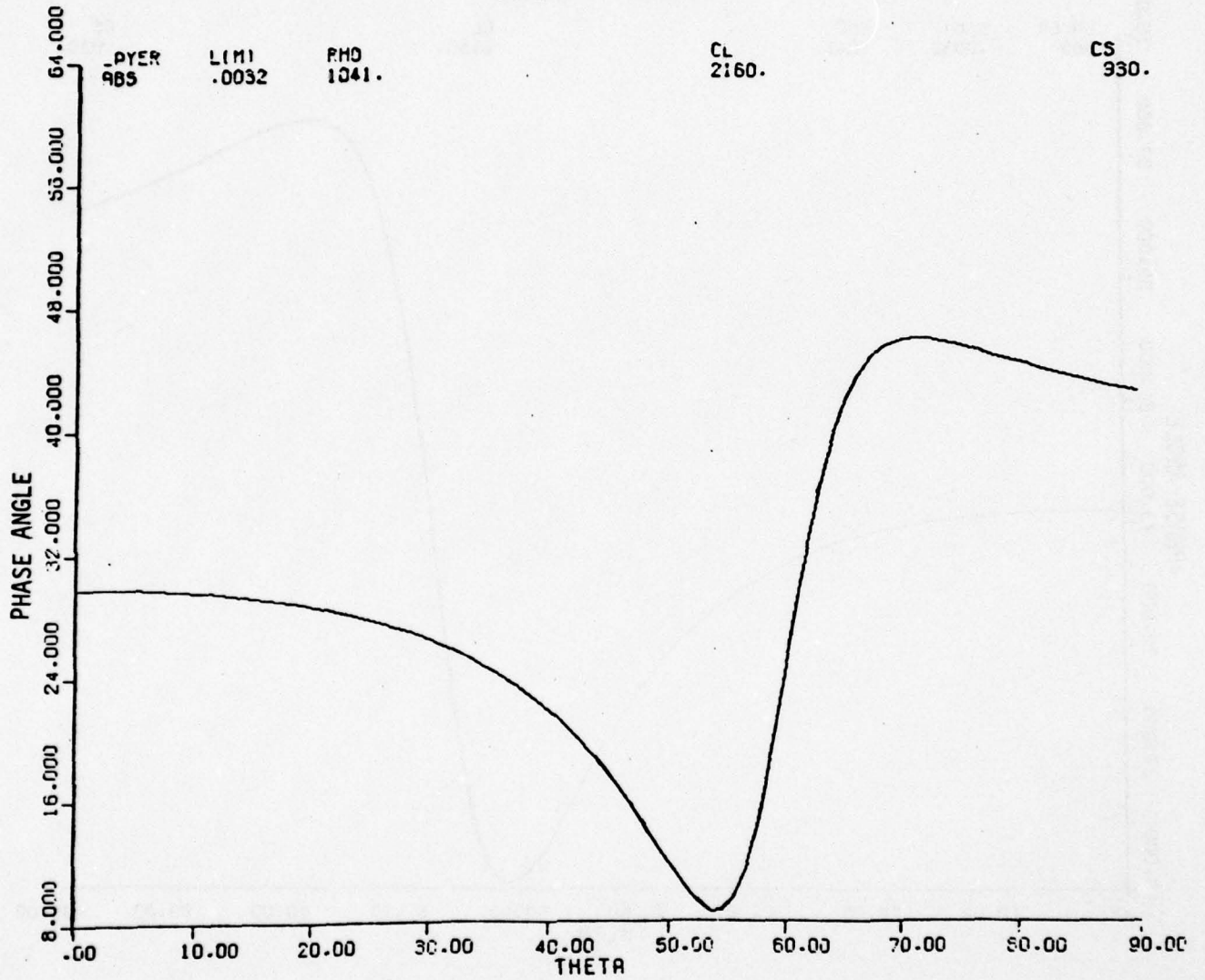


Figure 9(a). Phase Angle of Transmitted Wave vs Theta for Water/ABS/FC-75

NSWC/WOL TR 78-4

FREQ = 75000

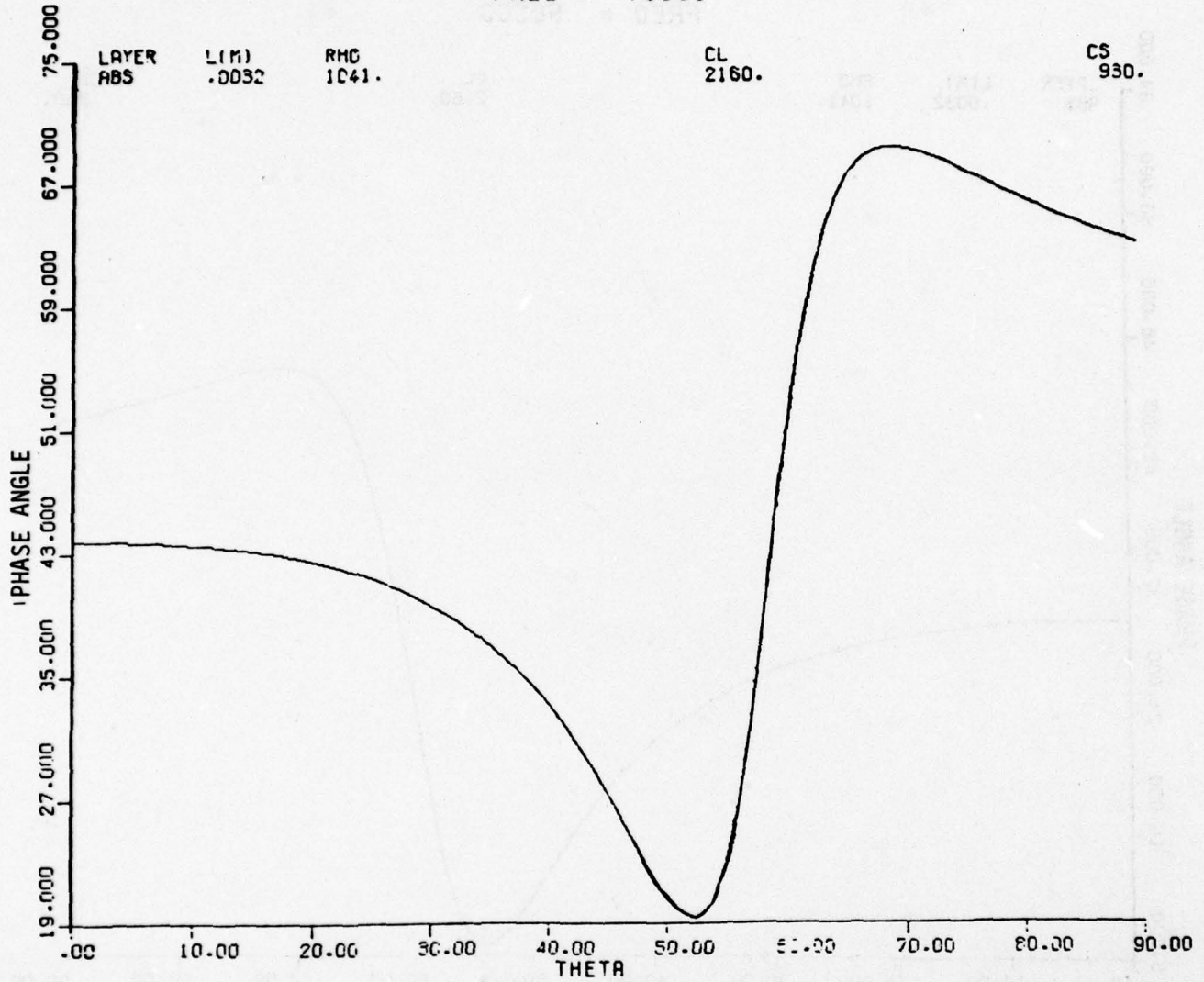


Figure 9(b). Phase Angle of Transmitted Wave vs Theta for Water/ABS/FC-75

NSWC/WOL TR 78-4

FREQ = 100000

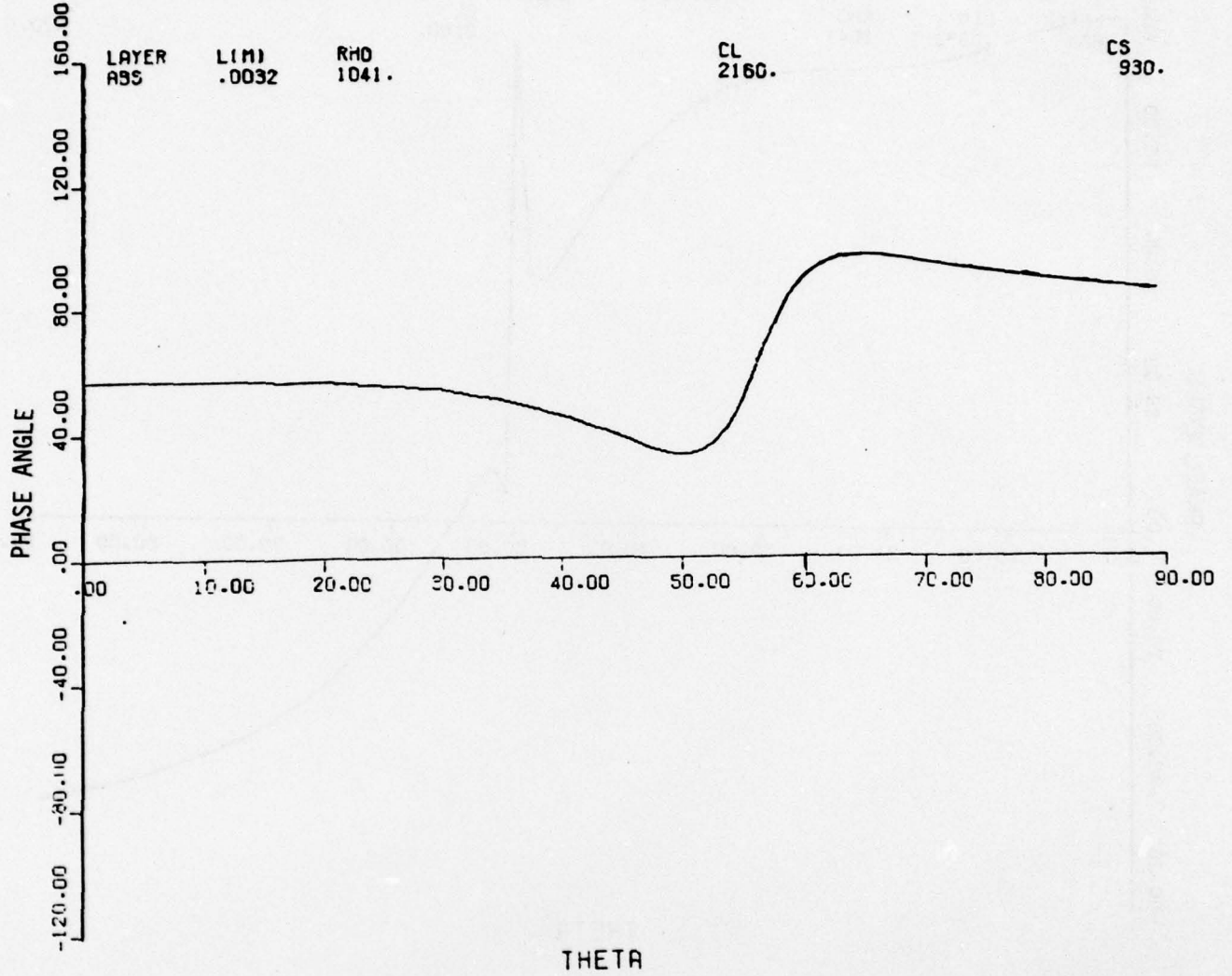


Figure 9(c). Phase Angle of Transmitted Wave vs Theta for Water/ABS/FC-75

NSWC/WOL TR 78-4

FREQ = 150000

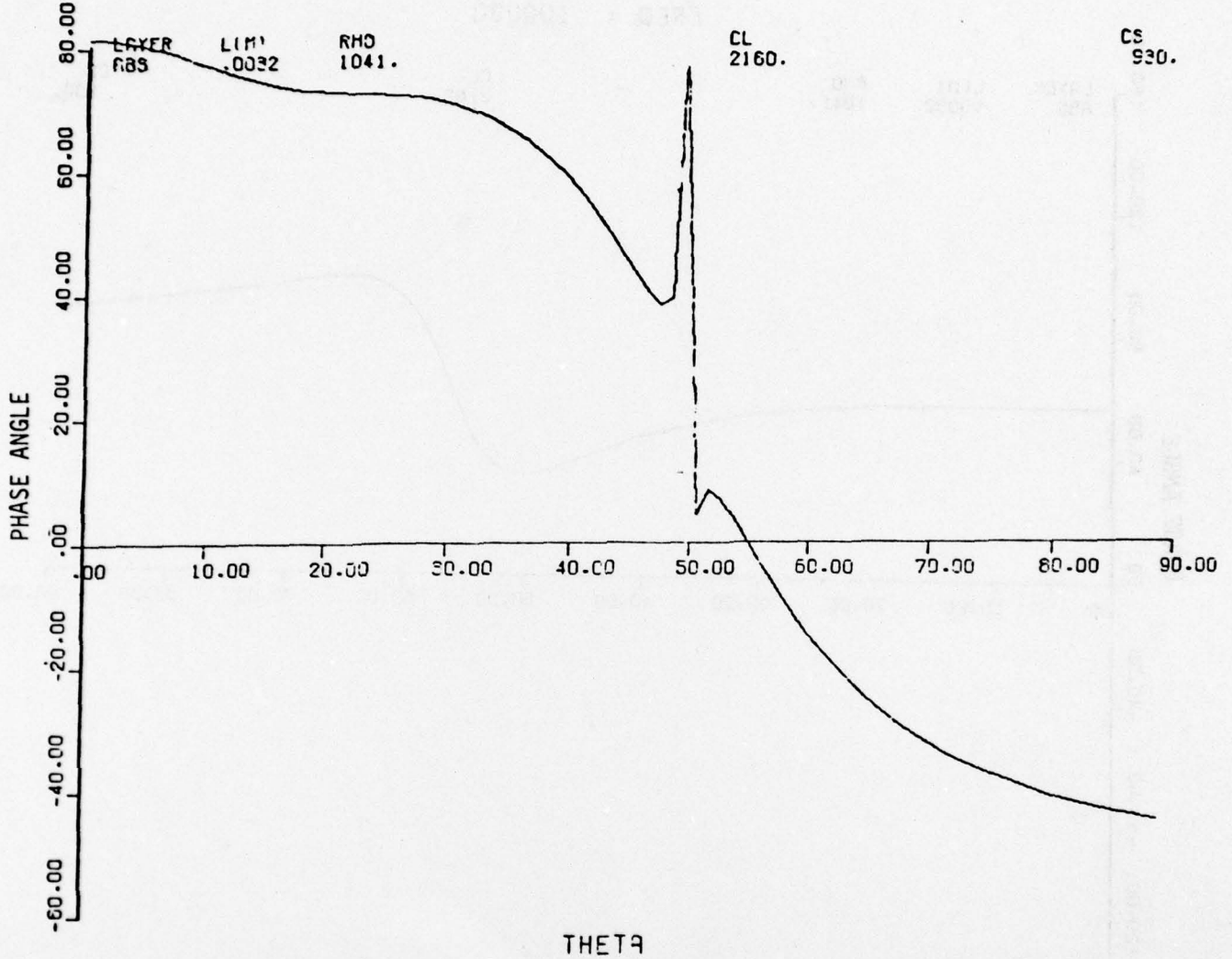


Figure 9(d). Phase Angle of Transmitted Wave vs Theta for Water/ABS/FC-75

NSWC/WOL TR 78-4

FREQ = 300000

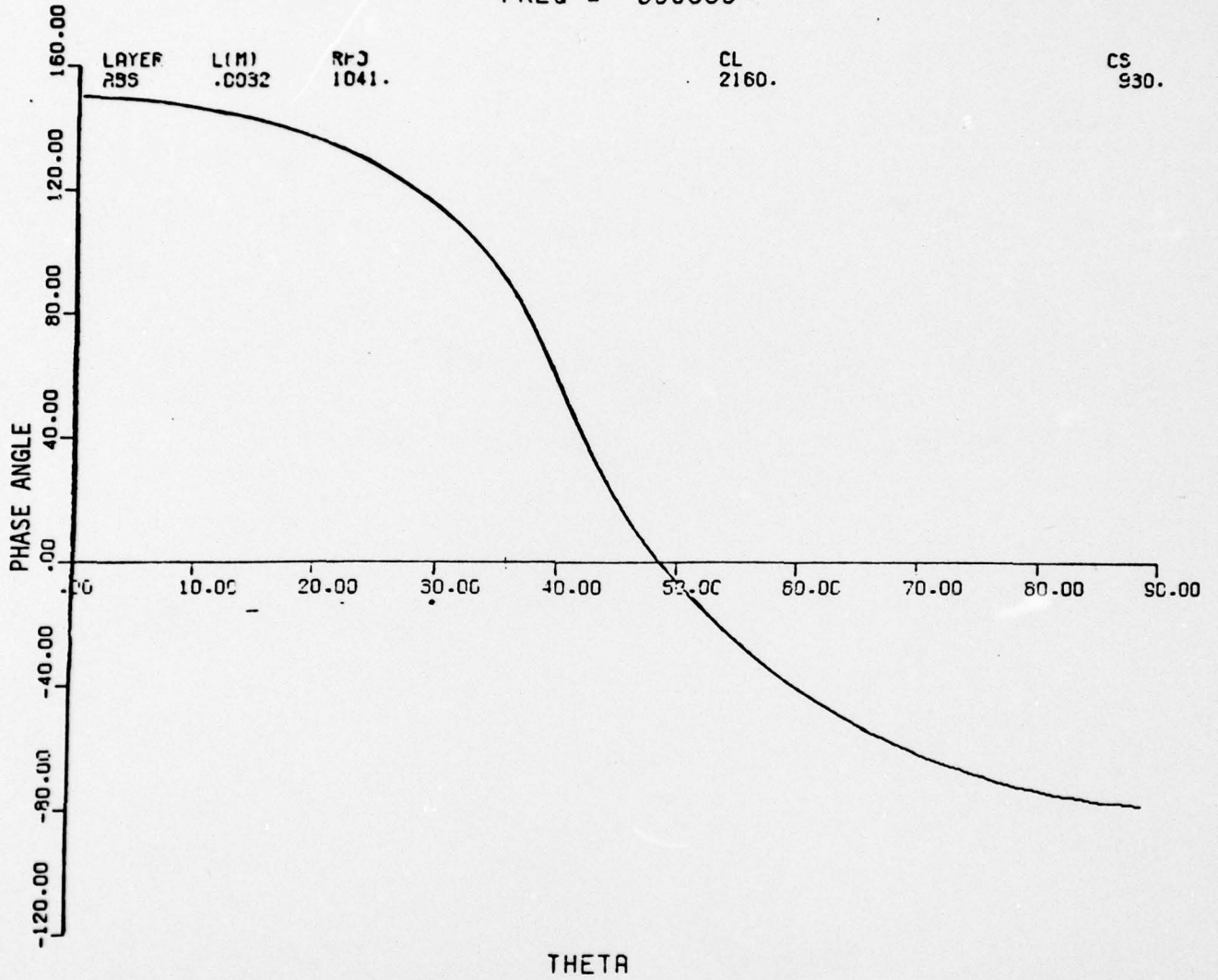


Figure 9(e). Phase Angle of Transmitted Wave vs Theta for Water/ABS/FC-75

Section 4

CONCLUSIONS

The data generated by the described method for computing transmission and reflection losses in multilayered media do show the coincidence rule to be effective in explaining the observed extrema. The cases where maxima are observed when minima are expected can be explained in terms of interaction between closely spaced modes.

Although the ABS exhibits a greater transmission loss than polyethylene over the whole spectrum because of its higher absorption, at low and moderate frequencies they both have good low loss characteristics and the sonar designer might select ABS because of its better structural properties. At higher frequencies the situation is different and the designer must be aware of the sensitivity of the transmission characteristics to the frequency, thickness of material and angle of incidence, factors which are somewhat controllable. By careful selection of frequency and thickness of material, "windows" of low transmission loss can be obtained. Care should be taken to avoid regimes where higher angles of incidence produce extreme peaks in the transmission loss curves.

Also of interest to the sonar designer is the change in phase of the transmitted wave as a function of the angle of incidence, particularly where beam forming is a consideration. The fluctuation in phase angle exhibited by ABS would make it a less satisfactory selection for a window material than the polyethylene which shows a smooth variation in phase over the range of incidence angles.

REFERENCES

- (1) Thomson, W. T., "Transmission of Elastic Waves Through a Stratified Solid Medium," J. Appl. Phy. 21, 89 (1950)
- (2) Young, J. W., J. Acoust. Soc. Am. 59, 1500 (1976)
- (3) Waterman, H. A., "Determination of the Complex Moduli of Viscoelastic Materials With the Ultrasonic Pulse Method," Part 1 and 2 Kolloid - Z.a.Z. Polymere 192, 1-16 (1963)
- (4) Hartmann, B., and Jarzynski, J., "Ultrasonic Hysteresis Absorption in Polymers," J. Appl. Phys. 43, 4304 (1972)
- (5) Madigosky, W. M., and Fiorito, R., "Transmission and Reflection Characteristics of Single and Multilayered Viscoelastic Plates," J. Acoust. Soc. Am. 62, S83 (1977)
- (6) Hartmann, B., and Jarzynski, J., "Polymer Sound Speeds and Elastic Constants," NOL TR 72-269, (1972), NSWC, White Oak, Maryland
- (7) Measured Data on 3M Syntactic Foam, NSWC, White Oak, Maryland
- (8) Brekhovskikh, L. M., Waves in Layered Media, (Academic Press, New York, 1960)

Appendix A
TRANSFER MATRIX ELEMENTS

For a single solid layer, the elements of the transfer matrix [M] are:

$$M_{11} = \frac{2K^2}{k_S^*} \cos \xi^* + \left(1 - \frac{2K^2}{k_S^*}\right) \cos \eta^*$$

$$M_{12} = \frac{iK}{\rho\omega} (\cos \eta^* - \cos \xi^*)$$

$$M_{13} = \frac{iK}{K_Z^*} \left(\frac{2K^2}{k_S^*} - 1\right) \sin \xi^* + \frac{2iK K_S^*}{k_S^*} \sin \eta^*$$

$$M_{14} = \frac{-1}{\rho\omega} \left(\frac{K^2}{K_Z^*} \sin \xi^* + K_S^* \sin \eta^*\right)$$

$$M_{21} = 2i\rho\omega^2 \frac{K}{k_S^*} \left(\frac{2K^2}{k_S^*} - 1\right) (\cos \eta^* - \cos \xi^*)$$

$$M_{22} = \left(1 - \frac{2K^2}{k_S^*}\right) \cos \xi^* + \frac{2K^2}{k_S^*} \cos \eta^*$$

$$M_{23} = \frac{\rho\omega^2}{K_Z^*} \left(\frac{2K^2}{k_S^*} - 1\right)^2 \sin \xi^* + \frac{4K^2 K_Z^* K_S^*}{k_S^*} \sin \eta^*$$

$$M_{24} = M_{13}$$

$$M_{31} = \frac{-iK}{k_S^*} \frac{2k_S^* k_Z^*}{k_S^*} \text{SIN} \xi^* + \left(\frac{2K^2}{k_S^*} - 1 \right) \text{SIN} \eta^*$$

$$M_{32} = \frac{-1}{\rho \omega^2} \left(k_Z^* \text{SIN} \xi^* + \frac{K^2}{k_S^*} \text{SIN} \eta^* \right)$$

$$M_{33} = \left(1 - \frac{2K^2}{k_S^*} \right) \text{COS} \xi^* + \frac{2K^2}{k_S^*} \text{COS} \eta^*$$

$$M_{34} = M_{12}$$

$$M_{41} = \frac{\rho \omega^2}{k_S^*} \frac{4K^2 k_Z^* k_S^*}{k_S^*} \text{SIN} \xi^* + \left(\frac{2K^2}{k_S^*} - 1 \right)^2 \text{SIN} \eta^*$$

$$M_{42} = M_{31}, M_{43} = M_{21}, M_{44} = M_{11}$$

where:

$$K = k_I \text{SIN} \theta_I = (\omega / C_I) \text{SIN} \theta_I$$

$$k_Z^* = (k_L^*{}^2 - K^2)^{1/2}$$

$$k_S^* = (k_S^*{}^2 - K^2)^{1/2}$$

$$k_L^* = \omega / C_L$$

$$k_S^* = \omega / C_S$$

$$\xi^* = k_Z^* d$$

$$\eta^* = k_S^* d$$

θ_I = angle of incidence

C_I = velocity in input fluid

C_L^* = longitudinal velocity in solid layer

C_S^* = shear velocity in solid layer

ρ = density of solid layer

d = thickness of solid layer

Applying the fluid-solid boundary conditions to the resulting matrix equation, the reflection and transmission coefficients in terms of displacement potentials can be computed as follows:

$$R = \frac{X - Y}{X + Y} \text{ and } S = \frac{2}{X + Y}$$

where:

$$X = \frac{1}{\rho_I \omega^2} \left(\rho_F \omega^2 A + iK_Z^{FB} \right)$$

$$Y = \frac{1}{iK_Z^I} \left(\rho_F \omega^2 C + iK_Z^{FD} \right)$$

$$A = M_{22} - \frac{M_{21} M_{42}}{M_{41}}$$

$$B = \frac{M_{21} M_{43}}{M_{41}} - M_{23}$$

$$C = \frac{M_{31} M_{42}}{M_{41}} - M_{32}$$

$$D = M_{33} - \frac{M_{31} M_{43}}{M_{41}}$$

$$K_Z^I = \left(k_I^2 - K^2 \right)^{1/2} = k_I \cos \theta_I$$

$$K_Z^F = \left(k_F^2 - K^2 \right)^{1/2}$$

$$k_F = \omega / C_F$$

C_F = velocity in final fluid

ρ_I = density of initial fluid

ρ_F = density of final fluid

The displacement potentials are (Figure A-1):

$$\phi_I = e^{i\vec{k}_I \cdot \vec{r}} \text{ for the incident wave,}$$

$$\phi_R = R e^{i\vec{k}_R \cdot \vec{r}} \text{ for the reflected wave,}$$

$$\phi_T = S e^{i\vec{k}_F \cdot \vec{r}} \text{ for the transmitted wave,}$$

where in general, the displacement is

$$\xi = \nabla\phi,$$

and the amplitude of the acoustic pressure is given by,

$$|P| = \rho C \omega |\xi| = \rho \omega^2 |\phi|.$$

Since $TL = 10 \log \frac{I_F}{I_I}$,

where I_F and I_I are the respective acoustic intensities,

and $I = \frac{|P|^2}{2\rho C}$,

then

$$\begin{aligned} TL &= 10 \log \left[\frac{\rho_F C_I}{\rho_I C_F} |\phi_T|^2 \right] \\ &= 10 \log \left[\left(\frac{\rho_F}{\rho_I} \right) \left(\frac{C_I}{C_F} \right) |S|^2 \right]. \end{aligned}$$

Similarly, $RL = 10 \log |R|^2$.

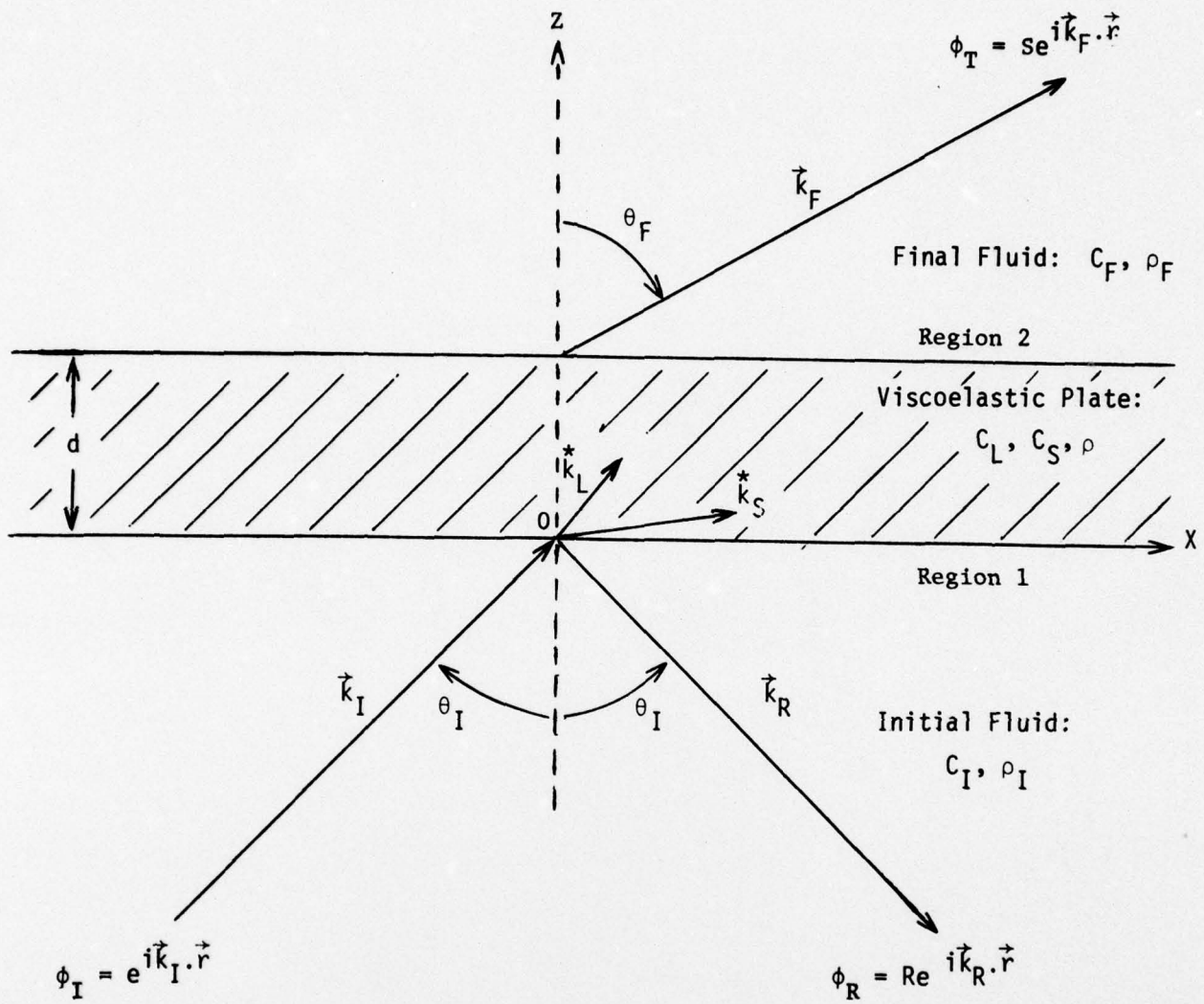


Figure A-1. Single Layer Problem

DISTRIBUTION

Chief of Naval Material
Department of the Navy
Attn: MAT-03
Washington, DC 20360

Commander
Naval Sea Systems Command
Department of the Navy
Attn: SEA-03B
Edward Liszka, Code 03421
Chris Taylor, Code 03724
Washington, DC 20362

Commander, Naval Ship Engineering Center
Prince Georges Center
Attn: P. Gauthier, Code 6101E
Hyattsville, MD 20782

Commander
David W. Taylor Naval Ship Research and Development Center
Department of the Navy
Attn: D. Feit
Richard Biancardi
Wayne Reader
Mel Rummerman
Bethesda, MD 20084

Commander, Naval Ship Research and Development Center
Attn: J. Eynck
Annapolis, MD 21404

Commander
Office of Naval Research
800 North Quincy Av.,
Attn: Dr. Nicholas Perrone, Code 474
Arlington, VA 22217

Commander
Naval Ocean Systems Center
Department of the Navy
Attn: James Brown
Peter Barrakos
San Diego, CA 92150

Commander
Naval Research Laboratory
Attn: C. M. Davis
Washington, DC 20375

Commander
Naval Underwater Systems Center
Newport Laboratory
Attn: Fred Cancilieri
Dwain Hartge
Newport, RI 02840

Commander
Naval Underwater Systems Center
New London Laboratory
Attn: R. Radlinsky
New London, CT 06321

Commander
Naval Coastal Systems Laboratory
Attn: Bruce Nolte
Don Folds
Panama City, FL 32401

Naval Oceanographic Office
Technical Library (Code 1640)
Suitland, MD
(Mail: Washington, DC 20373)

Naval Ordnance Station
Technical Library
Indian Head, MD 20640

Naval Postgraduate School
Technical Library (Code 0212)
Monterey, CA 93940

Defense Documentation Center
Cameron Station
Alexandria, VA 22314

12

Director National Bureau of Standards
Attn: Technical Library
Washington, DC 20234

Applied Research Laboratory
Pennsylvania State University
P.O. Box 30
Attn: S. Hayek
A. Stuart
State College, PA 16801

Bolt, Beranek and Newman, Inc.
50 Moulton St.,
Attn: E. Berkman
Cambridge, MA 02138

NSWC/WOL TR 78-4

AMETEK
Straza Division
790 Greenfield Drive
P.O. Box 666
Attn: Joel Young
El Cajon, CA 92022

TO AID IN UPDATING THE DISTRIBUTION LIST
FOR NAVAL SURFACE WEAPONS CENTER, WHITE
OAK LABORATORY TECHNICAL REPORTS PLEASE
COMPLETE THE FORM BELOW:

TO ALL HOLDERS OF NSWC/WOL TR 78-4
by W. Madigosky, Code CR-31
DO NOT RETURN THIS FORM IF ALL INFORMATION IS CURRENT

A. FACILITY NAME AND ADDRESS (OLD) (Show Zip Code)

NEW ADDRESS (Show Zip Code)

B. ATTENTION LINE ADDRESSES:

C.

REMOVE THIS FACILITY FROM THE DISTRIBUTION LIST FOR TECHNICAL REPORTS ON THIS SUBJECT.

D. NUMBER OF COPIES DESIRED _____