Technical Report
To
NASA
Patterns Of Residual Stresses Due To
Welding
BY
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P.E., C. Mfg. E.

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Final Inventory of Residual Equipment and Property

Subject: - NASA Research Grant NSG 1516 - Patterns of Residual Stresses Within Complex Welded Metallic Structures

Principal Investigator: - Dr. B. M. Botros - Professor, Mechanical Engineering

Item Number	Date Purchased	Description	Original Price
1	April 25, 1978	BLH Portable Digital strain indicator - Solid State Model 1200	

TELEPHONE 379-7995
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NORTH CAROLINA AGRICULTURAL AND TECHNICAL STATE UNIVERSITY
GREENSBORO 27411

OFFICE OF THE
DIRECTOR OF RESEARCH

February 3, 1983

NASA Scientific and Technical
Information Facility
Post Office Box 8757
Baltimore and Washington International Airport, MD 21240

Dear Sir:

Re: NASA Research Grant NSG 1516 - Patterns of Residual Stresses Within Complex Welded Metallic Structures

Enclosed you will find two (2) copies of the final technical report for the subject grant under the direction of Dr. B. M. Botros.

Kindly contact me if I can be of further assistance in this regard.

Sincerely,

Marvin H. Watkins

Marvin H. Watkins, Acting Director
Research Administration

MHW:b

Enclosures (2)

cc: Dr. B. M. Botros

TECHNICAL REPORT

TO THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SUBJECT:- NASA RESEARCH GRANT NSG-1516

PATTERNS OF RESIDUAL STRESSES WITHIN COMPLEX WELDED METALLIC STRUCTURES

BY

B. M. BOTROS, Ph.D., P.E.

January 19, 1983

INTRODUCTION

INTRODUCTION

Residual stresses caused by welding result from the nonuniform rate of cooling and the restrained thermal contraction or non-uniform plastic deformation.

From the zone of extremely high temperature at the weld, heat flows into both the adjoining cool body and the surrounding atmosphere. The weld metal solidifies under very rapid cooling. The plasticity of the hot metal allows adjustment initially, but as the structure cools the rigidity of the surrounding cold metal inhibits further contraction. The zone is compressed and the weld is put under tensile stresses of high magnitude(1). The danger of cracking in these structural elements is great(2).

Change in specific volume is caused by the change in temperature. The following simple analysis helps to visualize the action of temperature change in a confined body on stress operation(3):

A reduction of the temperature (t) of a confined body by (Δt) would decrease the body's original length (ℓ) by ($\Delta \ell$). To restore the original length, a tensile stress (σ) must be applied.

Hooke's law gives $\frac{\sigma}{E} = \frac{\Delta \ell}{\ell}$, and the expression for temperature expansion is $\alpha . \Delta t = \frac{\Delta \ell}{\ell}$. By substitution therefore, $\frac{\sigma}{E} = \alpha . \Delta t$, where α is the temperature expansion coefficient, and E is the body's modulus of elasticity.

Assuming $E = 30 \times 10^6$ psi for steel and $\alpha = 6.3 \times 10^{-6}$ per ^oF, the temperature reduction necessary to reach the yield point of about 30,000 psi is:

$$\Delta t = \frac{\sigma}{E} . \frac{1}{\alpha} = \frac{30 \times 10^3}{30 \times 10^6} . \frac{10^6}{6.3} \cong 160 \ ^oF$$

This indicates how a relatively small temperature change in a confined body can give rise to an intense stress, and of course stresses will result from any temperature gradient regardless of whether the body is confined or not.

In the case of large and complex structural frames, residual stresses will definitely be high because of the confinement of the individual members. Also the proportions of components have significant effect on the stresses.

As a result of the highly localized heat input, followed by the rapid cooling, specific effects are introduced into the regions adjacent to the weld. The sudden variation in temperatures between the weld zone and adjacent parts, Figs.1 & 2, can cause non-uniformity in grain structure, and the formation of hard Martensite or Bainite, Figs.3, 4 & 5, which are brittle and; with the interplay of thermal stresses, contribute to cracking under external factors. The sharpness of the variation in the microstructure can be reduced by preheating the basic metal adjacent to the weld, to about $400^{o}F$ just prior to welding. This preheating produces more gradual change in the microstructure and thereby eliminate the metallurgical stress-raiser.

In many projects where stiffness and dimensional stability are essential, the removal or at least a significant reduction of such stresses is necessary.

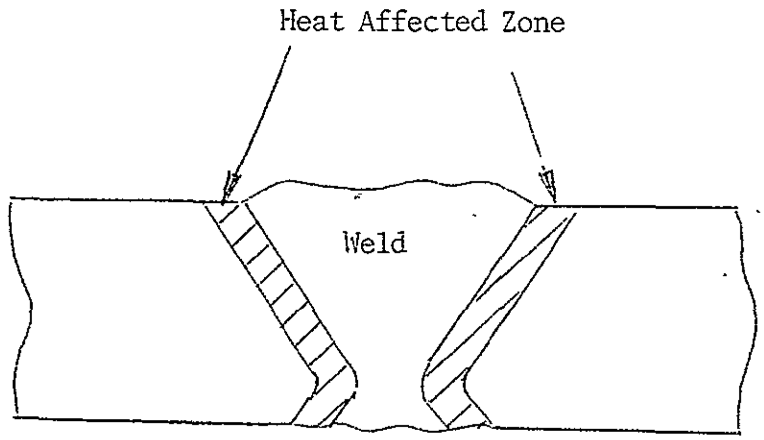


Figure 1

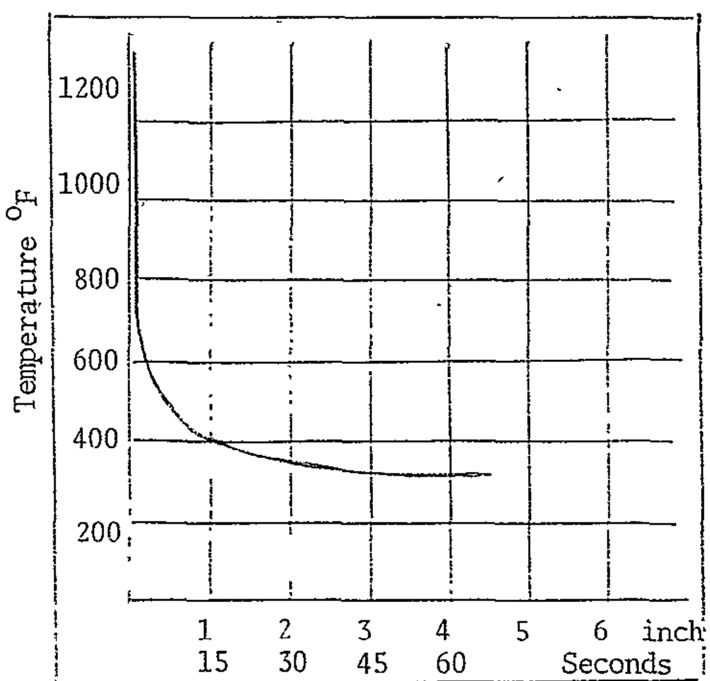
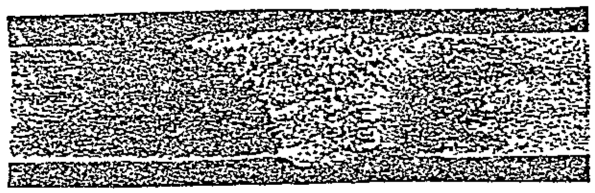


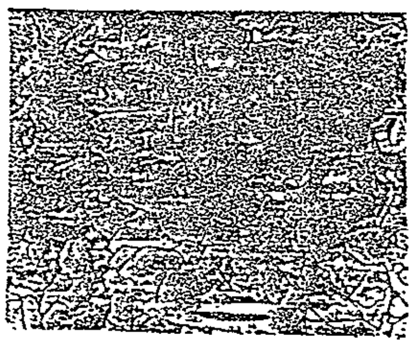
Figure 2

Oxy-Acetylene Welded Mild Steel Plate (0.2%C)



Macrostructure - Section Of Weld 5X

Coarse grains in the heat affected zones (in excess of 1000°C)
Excessive austenite grain growth near the fusion boundary



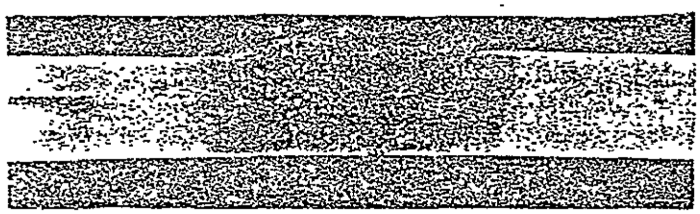
Microstructure
Parent Material
Ferrite + Pearlite

500 X

Microstructure
Heat Affected Zone
Upper Bainite (Cementite
Separated by wide bands
of ferrite (E))
500 X

Figure 3

Manual Metal-Arc Welded Mild Steel (0.2%C)

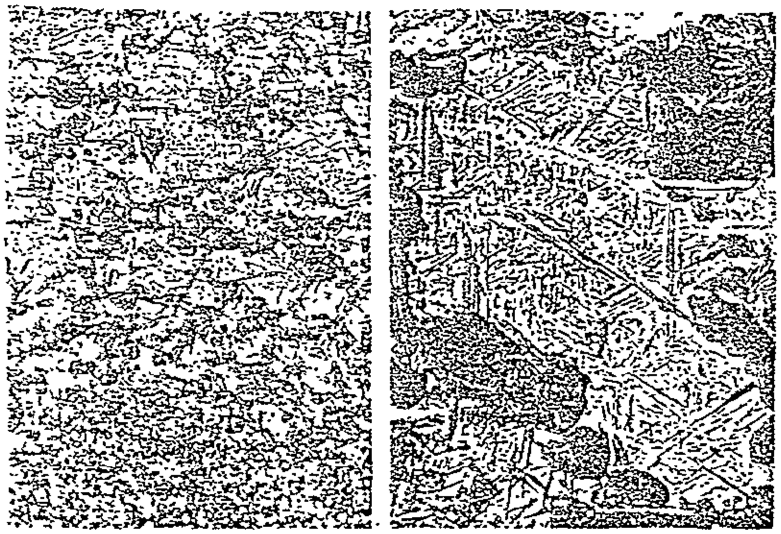


Macro structure - Section Of Weld 5 X
Less extensive heat-affected zone compared to Oxy-Acetylene Welding material subjected to high temperatures for very long. Small region of coarse grains

Heat affected Zone 500 X
The large coarsened grains (G) probably troostite or lower bainite, are surrounded in the boundaries by bands of proeutectoid ferrite (H), on which upper bainite (J) has nucleated.

Figure 4

Metal-Arc Fillet Welds In "40" Carbon Steel (0.41%C)



Heat affected zone near the fusion boundary. Martensitic structure with small islands of dark etching constituent in the prior austenite grain boundaries.
The right figure shows a part in greater detail.
Light acicular structure of martensite within the body of the grain - Dark etching pools in the grain boundaries may be troostite or very fine pearlite.

Figure 5

Some of the patterns of residual stresses are understandable, especially when a metallic solid is exposed to a homogeneous treatment. Various theories that depend upon layer removal (4-6) have been developed to analyse uniform stress distributions.

The decision was made to release the embeded residual stresses by removing successive layers off the metallic surface using diluted nitric acid solution or caustic soda solution. Although such a technique is time consuming, yet it is preferred to the mechanical methods where excess heat and vibrations can affect the pattern of the existing residual stresses.

Fusion welding is generally used because it is rigid and simple, as compared to rivetting or bolting techniques. In fusion welding tensile stresses of high magnitude are always developed within or near a weld(7) and the danger of cracking in these structural elements is great.

Thermal treatment is currently applied to relieve such stresses. The technique of inducing mechanical vibrations, through a variable speed eccentric motor, has been tried with simple metallic shapes to reduce or eliminate residual stresses developed by welding(8-10). The effect of such a technique on complex structures, however, is not clear and needs investigation. One major project affected by fusion welding is the Lawrence Livermore Laboratory's Shiva project in California(11).

THEORY

Stablein,(12) Davidenkow and Shevadin,(13) Letner,(14) and Frisch and Thomsen,(15) all tried to deduce mathematical equations for predicting residual stresses in bar specimens, applying the deflection technique. The most suitable analysis is the one developed by Frisch and Thomsen. If a straight metallic bar of rectangular cross section is subjected to such loads that stresses are induced in one of its surface, the stressed surface of the unrestrained bar will become curved upon release of the load. Furthermore, if the induced stresses are tension stresses and are constant at any particular depth in the stressed layer, the bar will assume a concave curvature of radius R,

The analysis deals with longitudinal stresses only, and it has been assumed that the effects of possible transverse stresses, if present, are negligible.

$$\sigma_n = \frac{E}{3L^2} \left(\frac{H^2}{1 + \frac{\Delta h_1}{H - \Delta h_1}} \right) \left(\frac{\Delta f}{\Delta h} \right)_1 \qquad \text{----------- } 1$$

Where:

σ_n = Original stress in the infinitesimal layer Δh_n which is n arbitrary infinitesimal layers of thickness Δh below the surface of the original bar

E = Modulus of elasticity

$2L$ = Central portion of the bar between supports

H = Initial depth or thickness of test specimen

Δh_1 = First layer to be removed

Δf = The change in deflection after the first layer is removed

Successive layers of thickness Δh are to be removed from the bar until h_s is completely removed. From the observed changes in deflection of the bar, it is possible to reconstruct the original stress distribution in the stressed layer h

The above relationship can be simplified to give

$$\sigma = K\, L^{-2}\, H^2 \left(\frac{df}{dh}\right) \qquad \text{---------------------2}$$

Where:

$K = \frac{4}{3} E$ = A constant for anyone material

$\frac{df}{dh}$ = The slope of deflection as a function of the depth of the layer

Also it may be written in a logarithmic form while replacing σ by η, the true response of the residual stress (psi)

$$\eta = B_o + B_1X_1 + B_2X_2 + B_3X_3 \qquad \text{------------------ 3}$$

or

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + \varepsilon \qquad \text{------------------ 4}$$

Where:

B_o, B_1, B_2, & B_3 = Parameters

b_o, b_1, b_2, & b_3 = Estimates of the parameters

ε = Experimental error

X_1, X_2, and X_3 = Logarithmic transformation of L^2, H^2 and $\frac{df}{dh}$

Y = The observed residual stress on the logarithmic scale

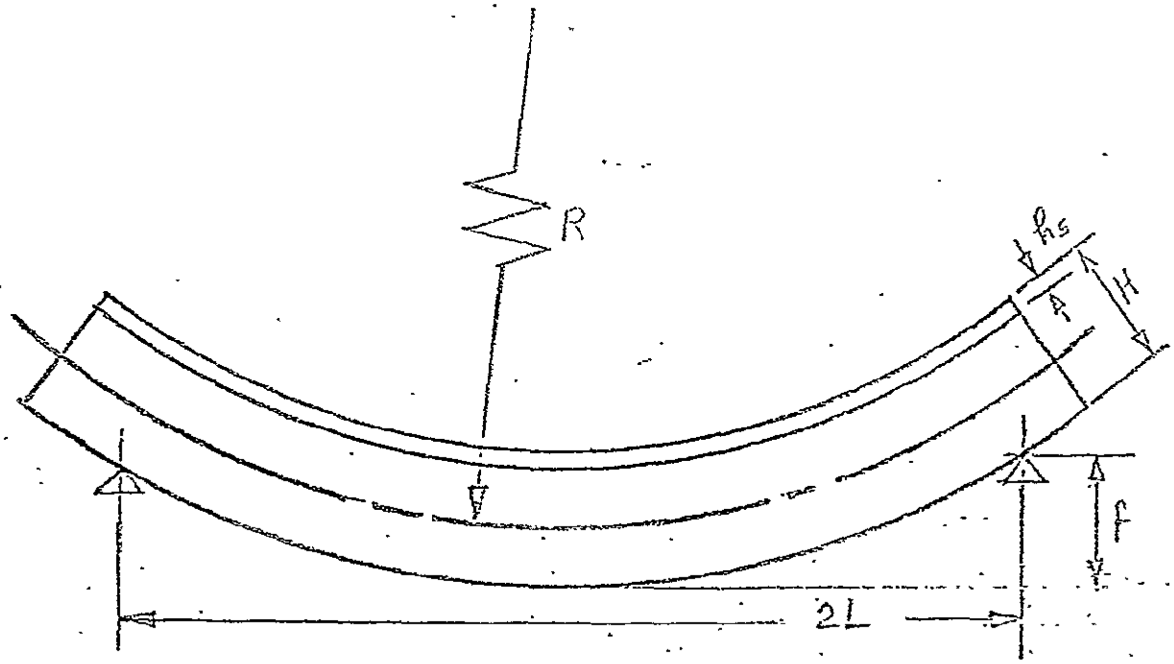
The stress in the first layer can be obtained by obtaining the slope of the deflection versus depth-of-layer curve at the surface and letting $\Delta h \to 0$, Thus

$$\sigma_1 = \frac{E}{3}\,\frac{H^2}{L^2}\left(\frac{df}{dh}\right)_{\text{surface}} \qquad \text{-------------- 5}$$

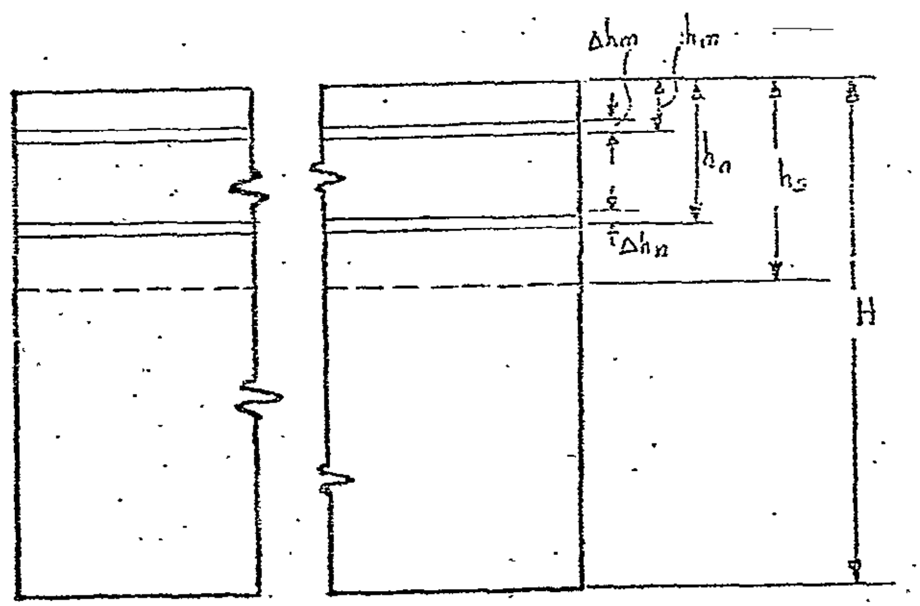
Where:

$\left(\frac{df}{dh}\right)$ surface = Slope of deflection as a function of depth of layer at h=0, or surface of bar

Revealing the pattern of the residual stress distribution for each of the geometrical shapes under consideration will help to develop a new set of analytical formulas to represent such stress patterns as found in complex frame structures by welding.



Configuration Of An Initially Straight Bar



Location Of Layers Below Surface Of Bar Containing Residual Stresses.

Figure 6

THEORY

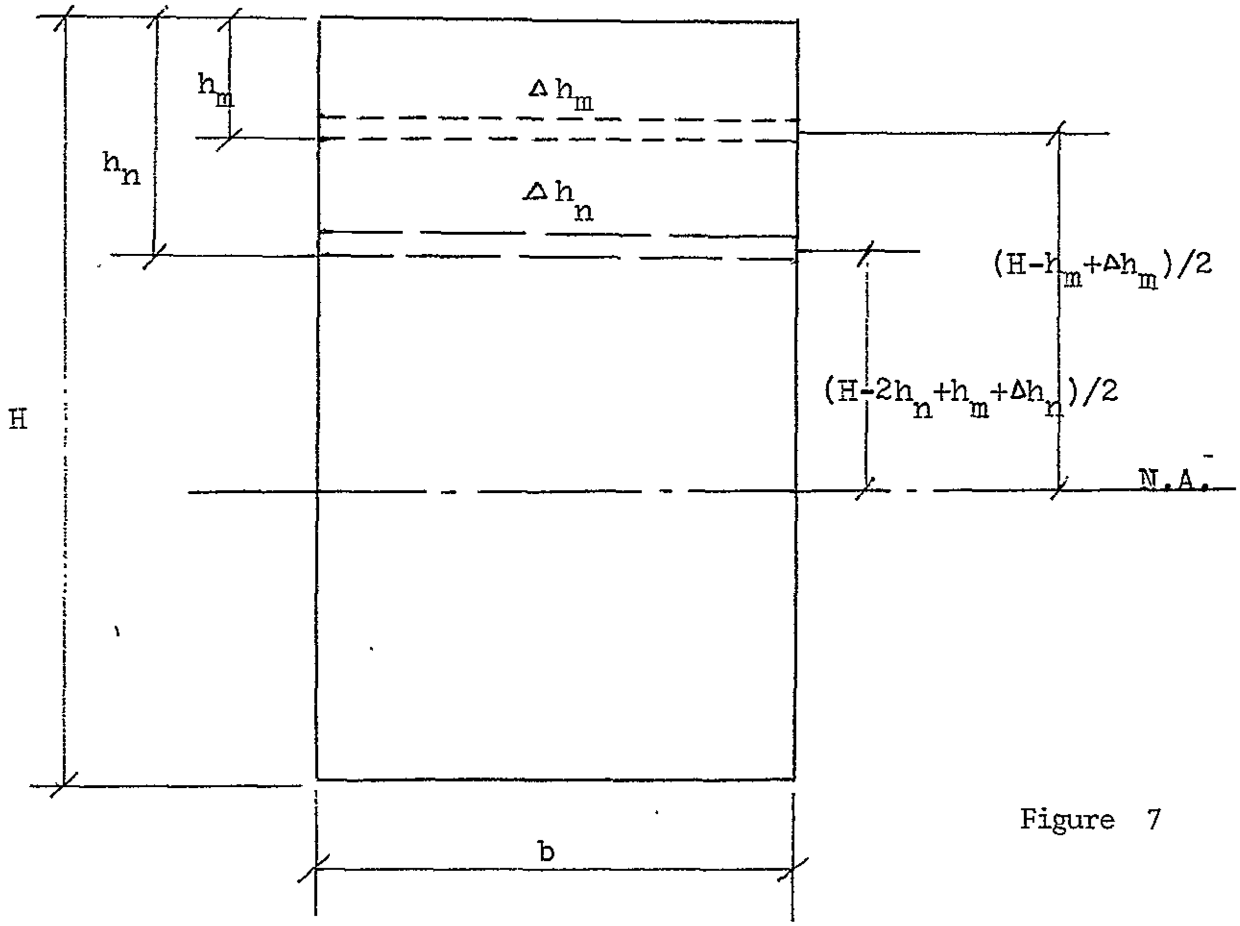


Figure 7

Assume the body of a bar is formed of infinitesimal layers of thickness Δh each.

Let σ'_n be the stress generated by welding in a layer (n) below the original surface of the bar and of thickness Δh_n.

Following the removal of all layers above Δh_n, the original stress σ'_n in that layer will be changed to σ_n.

This change is caused by the redistribution of the stresses following the removal of (n-1) layers above the layer (n) and in order to restores the balance of stresses across the bar section.

In order to visualize the effect of the removal of any specific layer, Δh_m at depth h_m, upon the stress σ_n in the layer Δh_n:-

Let σ_m be the stress in the layer Δh_m at the time this layer is removed.

The removal of the layer Δh_m causes two changes upon the stress σ'_n:-

1- Inducing a stress σ_{nA} because of the removal of the axial force in the layer Δh_m

2- Inducing a stress σ_{nB} because of the removal of the bending moment effect of the force removed in the layer Δh_m

Therefore, the original stress σ'_n in the layer Δh_n caused by the welding is composed of:- σ_n, which is the stress in that layer at the time of its removal + $\sum_0^{n-1}(\sigma_{nA} + \sigma_{nB})$ which is the total stress induced in that layer Δh_n because of the removal of all previous stressed layers.

$$\therefore \sigma_n = \sigma_{nR} + \sum_0^{n-1}(\sigma_{nA} + \sigma_{nB}) \qquad \text{----------} \quad (6)$$

If F_m = The axial force in the layer removed, it balances the remaining axial force F_s

$$F_s = - F_m$$

Assuming the width of the bar = b

$$\therefore F_m = \sigma_m \times \text{cross sectional area of the layer}$$

$$= \sigma_m . \Delta h_m . b \qquad \text{---------------------} \quad (7)$$

The remaining axial force F_s is worked from the balancing axial stress σ_{nA} appearing at layer n.

$$\therefore F_s = \sigma_{nA}.(H - h_m).b \quad \text{------------------} \quad (8)$$

$$\therefore \underline{\underline{\sigma_{nA}}} = \frac{F_s}{(H-h_m).b} = -\frac{F_m}{(H-h_m).b} = -\sigma_m.\frac{\Delta h_m}{H-h_m} \quad \text{-----} \quad (9)$$

The second reaction is the bending reaction

$$\sigma_{nB} = -\frac{M_s.C_n}{I_s} \quad \text{------------------------} \quad (10)$$

Where:-

$$I_s = \frac{b(H-h_m)^3}{12} \quad \text{------------------------} \quad (11a)$$

C_n = The distance of the layer n from the N.A. of the remaining section

$$= \frac{H-2h_n+h_m+\Delta h_n}{2} \quad \text{-----------------------} \quad (11b)$$

M_s = The bending moment in section remaining

= F_m . Its arm from the N.A.

$$= F_m.\frac{H-h_m+\Delta h_m}{2} \quad \text{------------------------} \quad (12)$$

Substituting (11a), (11b) and (12) in (10)

$$\therefore \sigma_{nB} = \frac{-F_m.\frac{H-h_m+\Delta h_m}{2}.\frac{H-2h_n+h_m+\Delta h_n}{2}}{\frac{b(H-h_m)^3}{12}}$$

$$= \frac{-3F_m(H-h_m+\Delta h_m)(H-2h_n+h_m+\Delta h_n)}{b(H-h_m)^3} \quad \text{-------} \quad (13a)$$

And substituting for F_m from equation (7)

$$\therefore \quad \underline{\underline{\sigma_{nB}}} = \frac{-3\sigma_m .\ \Delta h_m (H-h_m+\Delta h_m)(H-2h_n+h_m+\Delta h_n)}{(H-h_m)^3} \quad \text{-------} \quad (13b)$$

Stress at the outer fiber

$$\sigma_o = E.\ \epsilon_o \quad \text{---------------------------------} \quad (14)$$

<u>Where</u>

E = Modulus of Elasticity

ϵ_o = Strain measured using electric strain gages

$\therefore$ The total change at layer n, due to the removal of Δh_m

$$\sigma_{n_1} = \sigma_{nA} + \sigma_{nB} \quad \text{---------------------------------} \quad (15)$$

From equations (9) and (13b)

$$\therefore \sigma_{n_1} = -\frac{\sigma_m .\ \Delta h_m}{H - h_m} - \frac{3\sigma_m .\ \Delta h_m (H-h_m+\Delta h_m)(H-2h_n+h_m+\Delta h_n)}{(H - h_m)^3} \quad (16a)$$

$$\underline{\text{Or}}\ \sigma_m = -\frac{\sigma_{n1}}{\dfrac{\Delta h_m}{H - h_m} + \dfrac{3\Delta h_m (H-h_m+\Delta h_m)(H-2h_n+h_m+\Delta h_n}{(H - h_m)^3}} \quad \text{----} \quad (16b)$$

And for the outer fiber

$$\sigma_{n_1} = \sigma_o, \quad h_n = H \quad \text{And} \quad \Delta h_n = 0$$

$$\therefore \sigma_o = -\frac{\sigma_m .\ \Delta h_m}{H - h_m} - \frac{3\ \ _m .\ \Delta h_m (H-h_m+\Delta h_m)(-H+h_m)}{(H - h_m)^3}$$

$$= -\frac{\sigma_m .\ \Delta h_m}{H - h_m} + \frac{3\sigma_m .\ \Delta h_m (H-h_m+\Delta h_m)}{(H - h_m)^2} \quad \text{-----} \quad (17a)$$

Or $$\sigma_m = - \frac{\sigma_o}{\frac{\Delta h_m}{H-h_m} - \frac{3\Delta h_m(H-h_m+\Delta h_m)}{(H-h_m)^2}} \quad \text{------------} \quad (17b)$$

$$= - \frac{E.\epsilon_o}{\frac{\Delta h_m}{H-h_m} - \frac{3\Delta h_m(H-h_m+\Delta h_m)}{(H-h_m)^2}} \quad \text{------------} \quad (17c)$$

From equations (16b) & (17b)

$$\therefore \sigma_{n1} = \frac{\sigma_o}{\frac{\Delta h_m}{H-h_m} - \frac{3\Delta h_m(H-h_m+\Delta h_m)}{(H-h_m)^2}} \times$$

$$\times \left[\frac{\Delta h_m}{H-h_m} + \frac{3\Delta h_m(H-h_m+\Delta h_m)(H-2h_n+h_m+\Delta h_n)}{(H-h_m)^3}\right]$$

$$= \frac{\sigma_o(H-h_m)^2}{\Delta h_m(H-h_m) - 3\Delta h_m(H-h_m+\Delta h_m)} \times$$

$$\times \frac{\Delta h_m(H-h_m)^2 + 3\Delta h_m(H-h_m+\Delta h_m)(H-2h_n+h_m+\Delta h_n)}{(H-h_m)^3}$$

$$\therefore \sigma_{n1} = \sigma_o . \left[\frac{(H-h_m)^2 + 3(H-h_m+\Delta h_m)(H-2h_n+h_m+\Delta h_n)}{(H-h_m)^2 - 3(H-h_m+\Delta h_m)(H-h_m)}\right] \text{-----} \quad (18a)$$

And $$\sigma_{n1} = E.\epsilon_o . \left[\frac{(H-h_m)^2 + 3(H-h_m+\Delta h_m)(H-2h_n+h_m+\Delta h_n)}{(H-h_m)^2 - 3(H-h_m+\Delta h_m)(H-h_m)}\right] \text{----} \quad (18b)$$

This equation can be put in the form

$$\sigma_{n1} = E.\epsilon_o . \frac{A^2 + 3BC}{A^2 - 3BA}$$

Where

$A = \underline{H - h_m}$

$B = H - h_m + \Delta h_m = \underline{A + \Delta h_m}$

$C = H - 2h_n + h_m + \Delta h_n = \underline{A + 2(h_m - h_n) + \Delta h_n}$

Since we need to know the change in stress at each level for each layer removed, $\Delta\epsilon_o$ and $\Delta\sigma_{n1}$ are introduced as the change in strain at the outermost fiber and the change in the stress at level n respectively

From equation (18b)

$$\therefore \; \sigma_{n1} = E.\,\Delta\epsilon_o \left[\frac{(H-h_m)^2 + 3(H-h_m+\Delta h_m)(H-2h_n+\Delta h_n+h_m)}{(H-h_m)^2 - 3(H-h_m+\Delta h_m)(H-h_m)}\right] \quad (19)$$

Procedure:-

1- Remove a layer by etching

2- Calculate the stress in that layer using equation (17c) $\therefore$

It will be the residual stress in that first layer

3- When removing each subsequent layer, the stress in each layer is the sum of the residual stress in the layer plus the change in the stress due to the removal of the previous layers.

Equation to be used is equivalent to equation (6)

$$\text{i.e.,} \quad \sigma_n = \sigma_{nR} + \sum_1^{n-1} \Delta\sigma_{n1} \quad (20a)$$

Or

$$\sigma_{nR} = \sigma_n - \sum_1^{n-1} \Delta\sigma_{n1} \quad (20b)$$

This means that equation (19) is used to find the changes in stress at any level. Sum them. And upon the removal of layer n, equation (20b) is used to find the residual stress in the nth. layer.

Example

$H = 0.2505$ inch

First layer removed $\Delta h_m = 0.0006$ $h_m = 0.0006$ inch

$\Delta h_m = \Delta h_n$ $h_n = h_m$

$\epsilon_o = 0.0000 = 4 \times 10^{-6}$ in/in $E = 29 \times 10^6$ psi

From equation (12c)

$$\sigma_m = - \frac{29 \times 10^6 \times 4 \times 10^{-6}}{\dfrac{0.0006}{(0.2505-0.0006)} - \dfrac{3 \times 0.0006(0.2505 - 0.0006 + 0.0006)}{(0.2505 - 0.0006)^2}}$$

$$= - \frac{116 \times 0.062}{0.0005} = + 24{,}000 \text{ psi}$$

Since this is the first layer, this is the residual stress in that layer.

For the change in stress in the next layer

$\Delta h_n = 0.0059$

$h_n = 0.0059 + 0.0006 = 0.0065$

From equation (14)

$$\Delta \sigma_{n1} = 29 \times 10^6 \times 4 \times 10^{-6} \left[\frac{0.2499^2 + 3 \times 0.2505 \times 0.2440}{0.2499^2 - 3 \times 0.2505 \times 0.2499} \right]$$

$$\therefore \Delta\sigma_{n1} = 29 \times 4 \times \frac{0.062 + 0.183}{0.062 - 0.188} = -226 \text{ psi}$$

Second layer removed:-

$$\Delta h_m = 0.0059 \quad , \quad h_m = 0.0065 \quad , \quad \epsilon_o = 1 \times 10^{-6}$$

From equation (12c)

$$\sigma_n = -\frac{29 \times 10^6 \times 1 \times 10^{-6}}{\frac{0.0059}{0.2440} - \frac{3 \times 0.0059 \times 0.2499}{(0.2440)^2}}$$

$$= \frac{1.74}{0.003} = 580$$

And from equation (20b)

$$\sigma_{nR} = 580 - (-226)$$

$$= 806 \text{ psi}$$

which will be the residual stress in this second (nth) layer.

The basis for the calculations of welding heat originated in the work of Roberts And Rosenthal (16,17).Various assumptions were necessary in the derivation of the mathematical formulae, including the possible radiation and convention losses(18). Heat is lost by conduction into the adjacent parts of the metallic bars; in addition, the bars lose heat from its surfaces by convection and radiation, which was proved previously to be negligible(19). Radiation loss can be calculated from "Stefans Law" to be about 1.8 cal/square centemeter or 7.5 watts/square centemeter, if the temperature is 800°C. If the remainder of the surface reaches 200°C, the radiation loss will be 0.3 w/sq.cm. Convection loss will be of the same order(20).

In a theoretical analysis it is necessary to know accurately the amount of heat reaching the work-piece. Efficiency with Vee-Groove and a good arc may reach 90%, while it may drop to 30% with simple melt-run on a flat plate with poor flames.

In their mathematical analyses the above authors aimed at throwing some light on the effect of the material characteristics and welding conditions on the temperature distribution, but it is not intended to supplant experimental measurements, they related heat input to $vd/4\alpha$

Where - v = welding velocity

d = fused width

α = theoretical diffusivity of the parent material

Example:

	α e.g.s units	arc-volt	thermal conductivity
Mild steel	0.082	30.4	$\sim$ 0.10
Aluminum Alloy	0.88	25	$\sim$ 0.45

If $vd/4\alpha$ is >1, the heating is efficient with not much losses

Also $Q = 8kT_m(1/5 + 4d/4\alpha)$

Where Q = rate of heat input to plate (cal/sec/cm)

k = thermal conductivity

PROJECT DESIGN

PROJECT DESIGN

The suggested investigation will cover structural steels, Type ASTM A36, with flat and W-cross sectional shape, up to 1/4" thick. Reinforced box geometric structures will be built using the semi automatic solid wire arc welding technique, to conform to AWS D1.0 standards, (21) using Hobart wire #28, AWS E70s-6, size 0.035 as filler metal (Consumable wire AWS A5-18 for mild steel electrodes) with maximum current of 100/225 amps and maximum voltage of 19/28 volts. Edges will be brush free of mill scale, rust and other foreign matter. The base metal will be dry and free of all oils, paints and foreign matter. Temperatures will be checked by the use of temperature indicating crayons.

All joints will be of the Groove-fillet type. The filler metal will eliminate possible variation in the coefficient of linear expansion of the parts and prevent complications in the stress analysis.

The geometry of the structure will be studied closely. Marks will be made at certain distances around the welded zones and accurate measurements will be taken.

Electric strain gages will be fixed on the metallic surfaces, protected by suitable adhesives against the acid treatment which is to be used to remove successive layers for releasing residual stresses.

Several frames of the same structural shape are to be prepared and used for the various phases of the study that will include:

(a) Comparison of the original and welded shape and dimensions

(b) Sectioning and releasing of the residual stresses by layer removal with diluted nitric acid solution, a technique that has been developed by Waisman and Phillips.(5) This layer removal method is most useful in determining the residual stresses in flat plates or beams in which the stress varies with the thickness, particularly if the stress gradient is sharp. This method consists of removing thin layers in the region of interest and observing the dimensional chages in the part from which the layers were removed. The average stress in each layer can be calculated and a plot of the residual stress distribution obtained. The same chemical etching technique has proved suitable and effective for other shapes including the cylindrical, solid and hollow geometries.(22-27)

(c) Exposure to vibrational conditioning as a stress relief technique, by attaching a stress relief vibrator to a central area of the frame, in a working cycle of fifteen minutes.

Dasgupta, Baker and Weiss (28) have studied the vibrational technique to relieve residual stresses. They learned that dynamic surface stresses are induced in or near a weld.

The basic stress relieving method employed will be that is referred to by The Stress Relief Engineering Co. of Costa Mesa, California and The Rigging International Of Oakland, California, as The Formula 62 System.

The procedure recommended is to relieve stress immediately after the frame is completely welded by placing it on level rubber pads and running vibration thru its 15-minute automatic mode. The technique is a non-thermal method of relieving the residual stresses in metals or metal weldments without distorting or changing the tensile strength, fatigue, or yeild point of the work piece. It is necessary to prove that the vibrational technique is reproducible and capable of being monitored and effective at all critical locations within a part being so processed.

In the thermal stress relieving process, energy in the form of heat is introduced into the workpiece to reduce stresses. In the mechanical process energy is introduced into the workpiece by means of vibrations in a low frequency range of 0 to 100 cps, which will generate enough dynamic stresses to interact with the high intensity surface tensile residual stresses, and at the same time eliminate the side effect of vibrations using up a large fraction of the fatigue life of the part being processed. It is important for this investigation to establish relationships among stresses, forces, amplitudes and accelerations developed during vibration.

Relationships between force and deflection characteristics should also be experimentally investigated.

An accelerometer can be used to monitor acceleration of a vibrating part. Electric strain gages can be used to measure about half the yield strength of the material as an indication of the level of vibrations to be applied for stress relief.

The resistance strain gage can be used in conjunction with the accelerometers to characterize the vibrational act for complex shapes and to monitor the vibrational stress relief operation. It may also be helpful in indicating vibrational stress relief when oriented parrallel to the direction of maximum residual stresses.

Combining measurement and analysis to characterize the vibrational behavior of a given shape, and monitoring the vibrational stress relief treatment, requires a spectrum analyser. Such an instrument exists at N. C. Agricultural and Technical University, similar to the more expensive Fourier Analyzer, except that it needs continuous vibrational source applied to the structure. The accelerometers and strain gages are affixed to the part, which is then subjected to a continuous vibration. Signals are processed by the analyser and the modes associated with the natural frequency, characteristic of the part, are determined and displayed in animated isometric form on a cathode ray tube and photographed.

The frames, vibrationally conditioned, will be checked for stress relief in two ways:

(a) Tolerances, squareness and parallelism will be measured and compared with a similar frame untreated by vibrations.

(b) A full stress investigation by sectioning and layer removal will be made as explained before.

PART ONE

Work on the project started in April, 1978 and has continued for six months. The first two and one half months were spent purchasing equipment, strain gages, accessories and steel bars. A stand for etching the metallic bars and a tray for holding the acid solution were designed and built of plexyglass sheets, 3/8 inch thickness, cemented together by ethelyne dichloride, Fig. 8

Carolina Steel Co. of Greensboro,N.C. through Mr. Robert Sherman, Vice President for Engineering has encouraged the project, showing support by offering to cut, weld and recut the steel and boxes free of charge when I purchased the required steel from their company.

Electric strain gages were supplied by the BLH Co. They are designated SR-4, FAE-50-35 SX (350 Ohm) with a length of 0.500 inch (Gage Factor 2.07) and 0.250 inch (2.04). The gages are encapsulated with a 0.001 inch polyimide film that provides protection for the sensing element during insulation handling. The film also promotes better long term stability as the foil grid is protected from air borne contaminants or fingerprints.

The gages are self temperature compensated; They automatically cancel unwanted changes in gage resistance, due to temperature, so that only stress produced strains are measured. The degree and accuracy of self temperature compensation is defined in terms of a chord slope temperature coefficient; apparent strain is (U in/in) per degree F temperature change over a specific temperature range on a material having a specific coefficient of expansion over the same range.

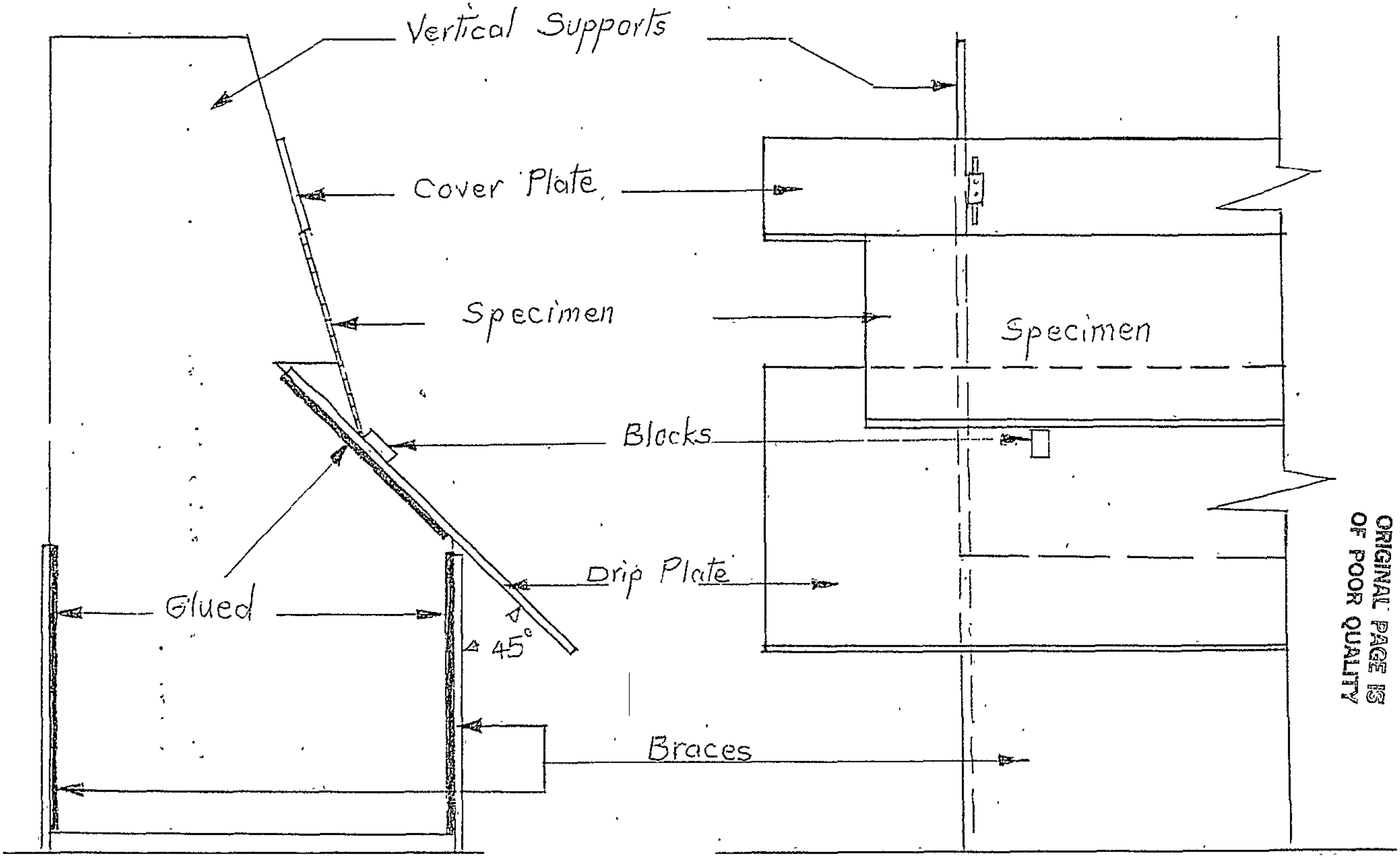


FIG 8 PLEXIGLASS SUPPORT For Etching Steel Bars

Recommended temperature range of these gages is -100 to 400 °F. The gages are made of constantan on polyimide carrier. They were provided with nickel-clad copper-ribbon leads soldered to the gage tabs (one inch long) with 425 °F tin-silver solder.

To prepare the metallic surface at the spots where the gages are to be fixed, the steel is smoothed with a sanding disc fixed to a portable rotor. The surface is cleaned with Methyle Ethyl Keton. The surface is next roughened with sand paper and re-cleaned with MEK.

A layer of EPY-500 adhesive is used to adhere the gages to the metallic surface. The adhesive must be cured at about 170 °F for 24 hours using electric heaters under slight pressure of about 20 psi, using pads and wooden blocks wrapped with string. This type of adhesive can stand a strain of about 5% at room temperature. It has an excellent moisture and chemical resistance and is useful over a temperqture range of -450 to 600 °F. When the wrapping is removed, the gages are checked for adhesion. A gage tester, is used to check on gage adhesion and insulation. Readings should show less than 1/10 % deviation from a resistance of 350 Ohm, which shows that the gage is within the range that the bridge can balance. Lead wires with polyvinal chloride tephlone are next soldered in place. Nylon plastic tape is used to isolate the wire ends off the metallic surface.

A barrier D which is a two component semi-rigid epoxy system, is spread on the gages to protect them against water and chemicals. It has a temperature range of -100 to 225°F. It has to be cured at a temperature of about 150°F for one hour using the electric heaters. The layer is thin in order to not stiffen the gage.

The recording equipment is composed of a portable BLH digital strain indicator, model 1200A solid state, and a switching and balancing unit model 1225 that can provide up to ten input channels. The recorder has an accurate setting of gage factor of 0.001 and a four-way display of $\pm 10,000$ μ inch per inch.

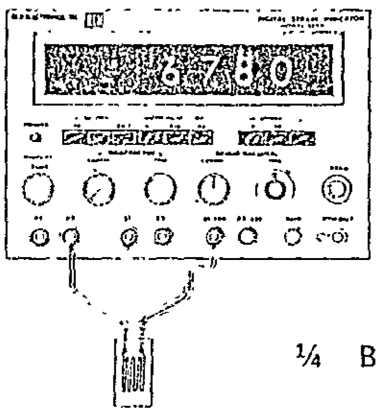
Before etching takes place, the gages are connected to the strain indicator through the switching and balancing unit. The gage factor is adjusted and the indicator is balanced for each gage. To compensate for the temperature effect, three leading wires are soldered; two to one side and the third to the other side of the gage leads, Fig. 9

Structural A36 steel bars, hot rolled, 6 inch wide by $\frac{1}{2}$ inch thick are sawed to a length of 3 feet each. All cutting is done by means of a saw. No flame cutting is used. This eliminates any heating other than the welding itself.

One bar is tested as received in order to investigate any possible residual stresses while forming. The analysis showed negligible residual stresses in that bar.

Square boxes, 3 feet by 3 feet, Fig. 10 were formed by welding the hot rolled bars together either by continuous real

STANDARD STRAIN GAGE CONNECTIONS



¼ BRIDGE

FIG. 9

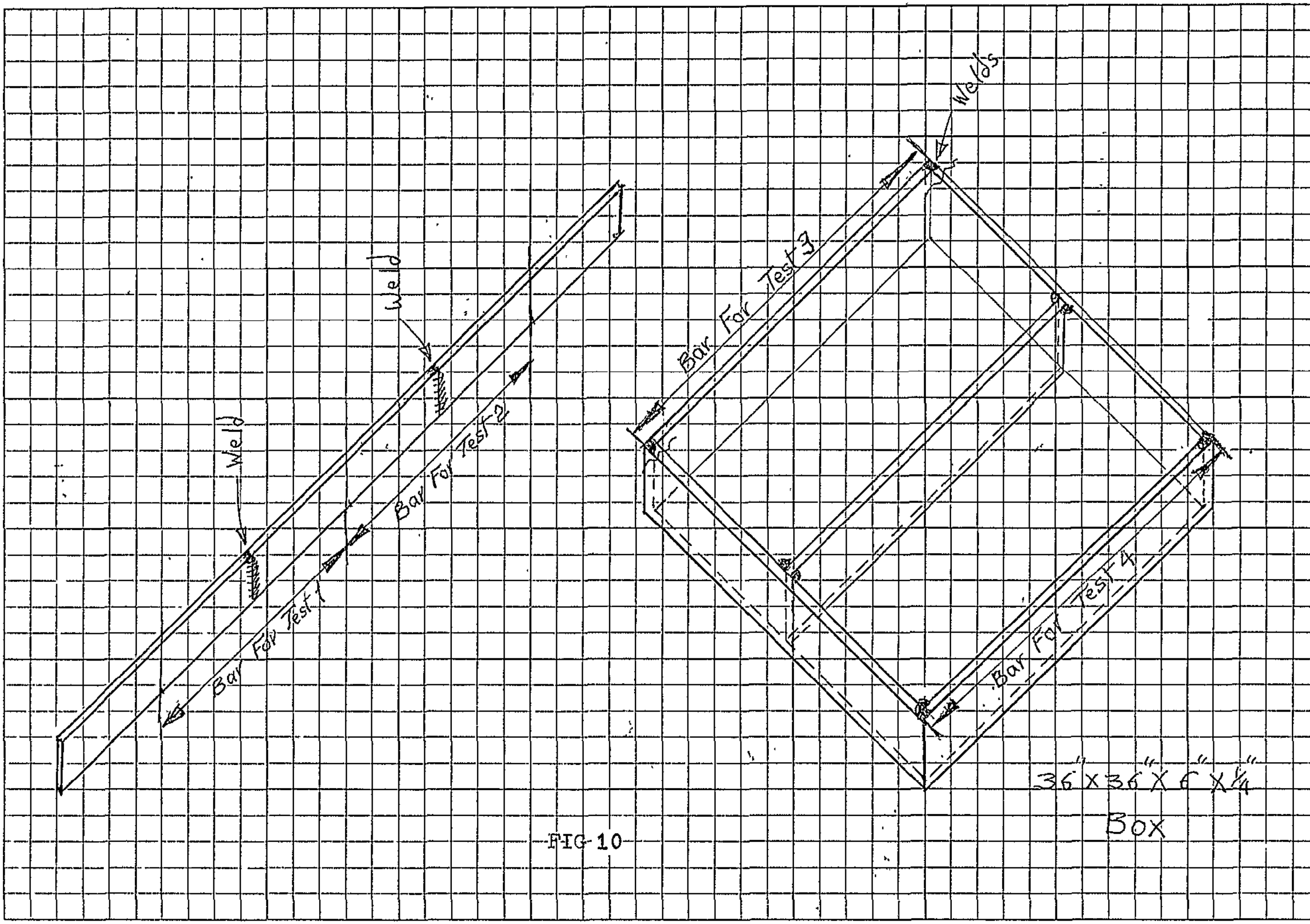

Weld
Weld
Bar For Test 1
Bar For Test 2
Welds
Bar For Test 3
Bar For Test 4
36"X36"X6"X1/4"
Box

FIG 10

intershield welding technique using 26 volts, 275 amps., 3/32 inch bare wire and powder flux, or by an AC welder using 225 amp., 5/32 inch rod. Such shapes simulate some of the conditions in built-up structures.

The sides of the box used are sufficiently long to obtain a unifrom state of stress distribution. Strain gages are fixed along the bar and simultaneous measurements are taken after each etch. One gage is fixed across each bar.

Future studies will cover thicknesses up to one inch and the width of plates up to 15 inch. Such study will reveal any plate distortion that may take place beside the actual residual patterns generated in such plates.

At present a set of tests is being performed on 4 inch bars welded together in various ways to form square boxes and then sawed and analyzed as has been done before.

A third group of tests is planned to weld unequal sections together in order to study the effect of various widths when welded together and if such a structure may develop concentrated residual stresses.

Sectioning and releasing residual stresses by means of layer removal, was performed using nitric acid solution of 30% concentration. This technique has been developed and proved to be most useful in determining the residual stresses in flat plates as well as many other sectional forms.[5,22,25]

Etching precautions include wearing respirators for toxic fumes and gas, rubber gloves and rubberized apron on top of lab coat. The stand and the acid tray are supported on a table under a hood with an outlet fan running continuously.

Nylon scrub brushes and paint brushes are used to continuously brush the metallic surface with the acid solution; because of the inclination of the supported bar the residue drops into the acid tray.

The bar is etched. After 24 hours measurements of strains and thicknesses are taken, to be followed by a second etching and so on.

Magnetic surface temperature thermometers are fixed to the back side of the bar while etching. No excess heat is registered (170 to 180°F).

3 inch and 6 inch deep throat micrometers are used to measure the bar thickness at various locations.

The average stress in each layer is calculated using the theory explained and presented in this report, together with a developed computer program, a copy of which is enclosed.

Results of the residual stress distributions in the bars cut from the welded straight and box shapes are shown in Figs. 11 to 18, High tensile residual stresses are found at the weld (about 25,000 psi) dropping sharply to compressive stresses in the range of 3,000 to 5,000 psi which spreads for some depth through the bar section. Surface stresses change gradually along each bar, from maximum tensile of about 25,000 psi to maximum compressive of about the same value at a distance of about 7 to 8 inches away from the weld.

The similarity between the patterns of stresses obtained from the flat welded bars and the box welding indicates that the stress distribution in various shapes can be obtained approximately by superposition. These stresses can, therefore, be considered as the cumulative sum of the thermal stresses set up by welding.

In order to judge the reaction on the strain gage fixed across the bar, other tests are planned with various bar widths and with more than one gage fixed across the span.

Both tests No. 1 & 2 are performed on bars sawed from a set of three bars, 3 feet each, welded together end to end as shown in Fig. 10. Welding is carried out with the #3 AC Jet Welder mentioned before.

Test No.3 is performed on a bar sawed from a square box welded together using the Inter Shield Technique.

Test No.4 is performed on a bar sawed from a square box welded together using #3 AC Jet welder.

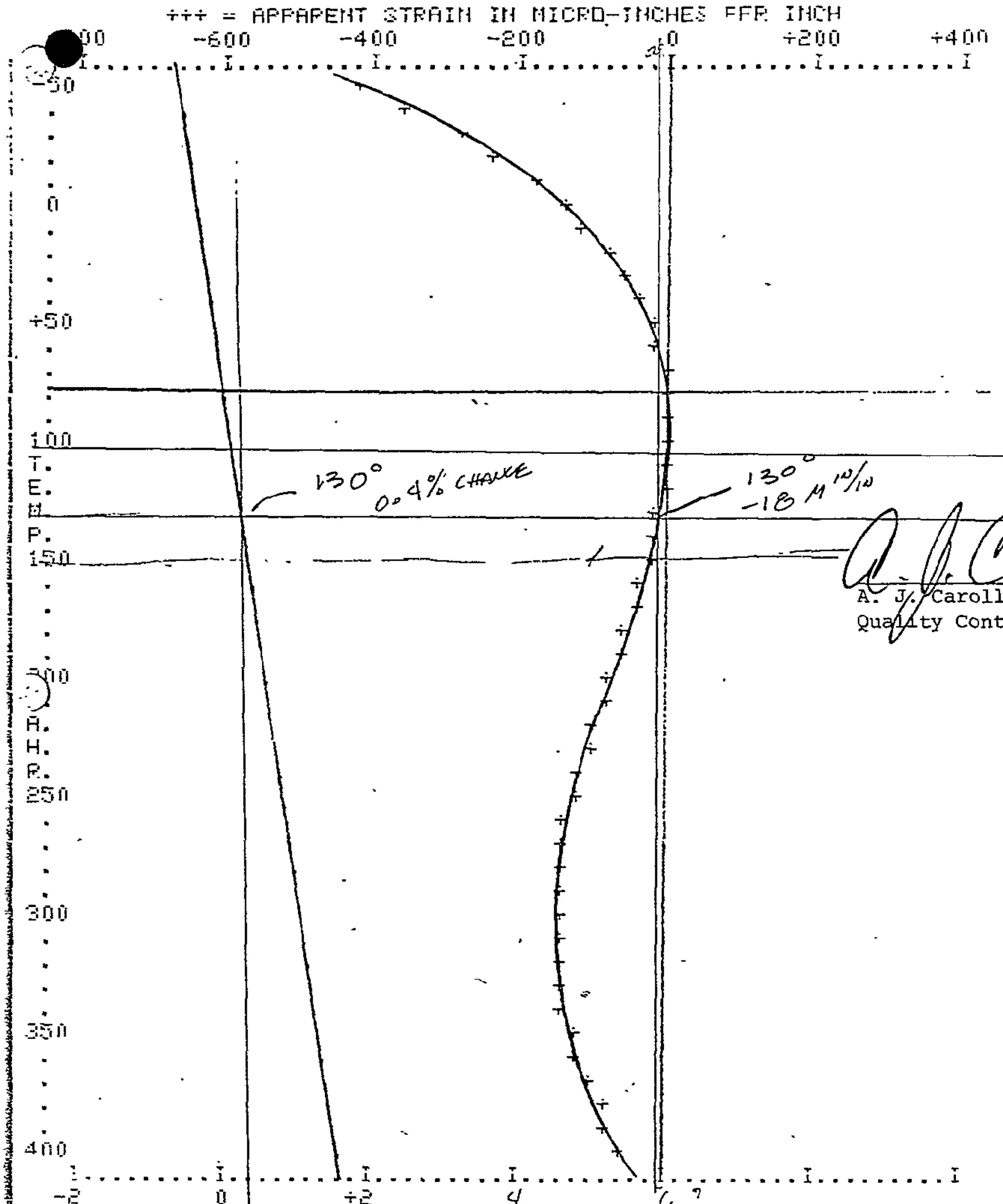
With these results and with what may be revealed in the further built-up shapes planned and under study at present it will be possible to estimate the general stress distribution in welded built-up shapes.

This is essential before going through the second phase of of the study that will deal with shaking the various shapes of built-up shapes, registering the spectrum and analyzing it through a Fourier Analyzer using both a load cell with strain gages, and an accelerometer with a suitable amplifier. It is possible to register such spectrum and then feed it into an analyzer using a suitable computer program. The structure is to be shaken for about 15 minutes at the frequency that shows maximum amplitude, and then will be tested by a complete residual stress analysis to investigate how the welding stresses can be relaxed by the vibrations.

Standard tensile test specimens $\frac{1}{2}$ inch x $\frac{1}{4}$ inch are prepared lengthwise and crosswise from one of the bars as received. Strain gages are cemented on the specimens and calibrated against load. Results are as shown in Fig. 19 The calibration was carried out on a 10 ton tensile testing machine.

Fatigue testing specimens are prepared from one side of a welded box as near to the weld as possible. These specimens are being tested at the present time. Similar analysis will be carried out on specimens from a box after vibration, in order to investigate how such vibrations may affect the fatigue life of the steel. This is considered as an essential study especially where the steel is to be exposed to dynamic loading in practice.

Definite conclusions cannot be made at this early stage of the study.



A. J. Carollo
Quality Control Department

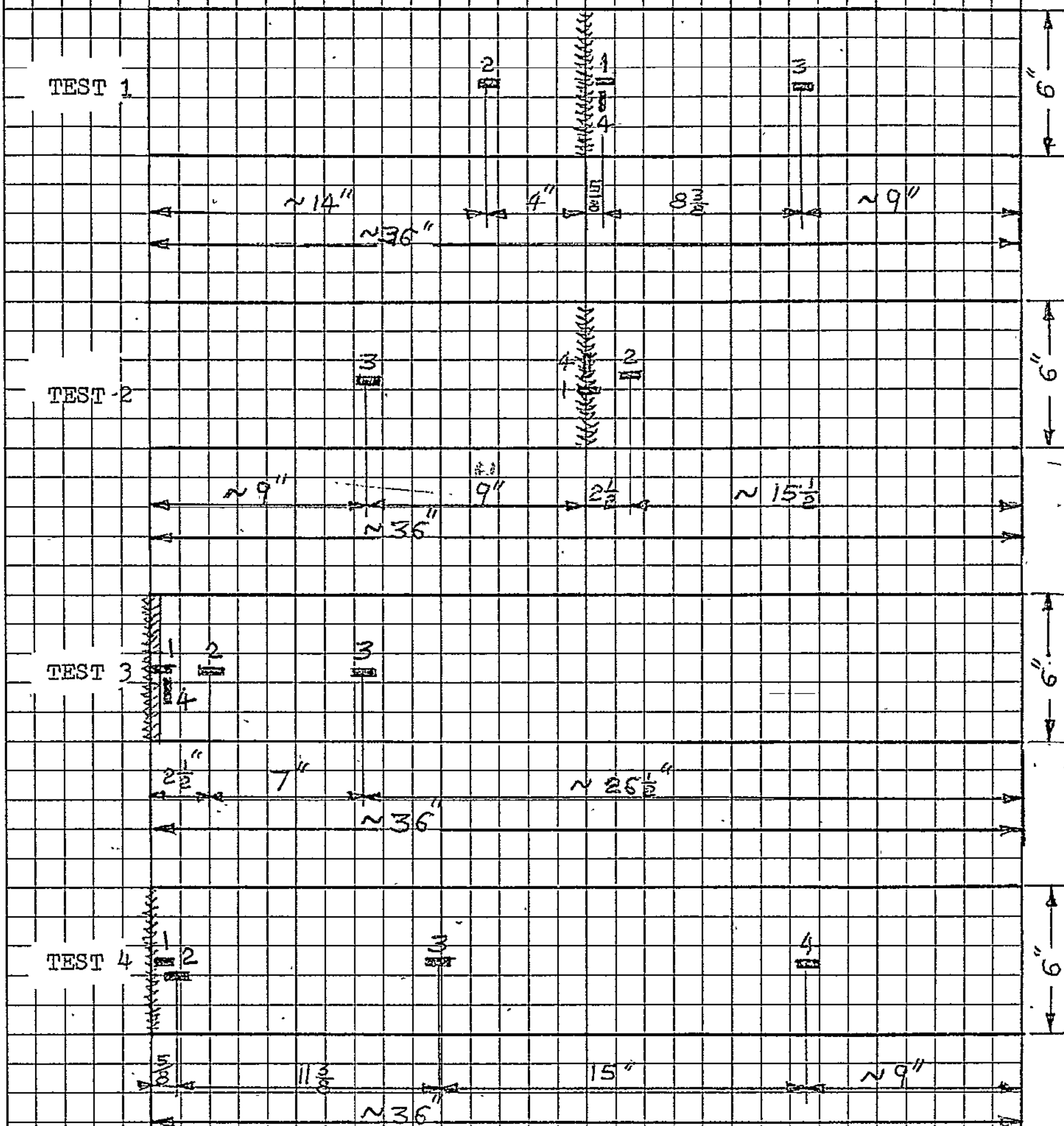
C O M P U T E R   P R O C E S S E D   D A T A

GAGE FAMILY FAB,FAE   LOT NUMBER 313-4   SERIAL NUMBER BN

TEMPERATURE ERROR (APPARENT STRAIN) EQUATION

$$E_{ap.} = -148.69 + 3.77T - 2.89 \times 10^{-2}T^2 + 6.78 \times 10^{-5}T^3 - 4.43 \times 10^{-8}T^4$$

1018 STEEL TEST SPECIMEN


TEST 1
2
1
4
3
6"
~14"
4"
8 3/4
~9"
~36"
TEST 2
3
4
1
2
6"
~9"
9"
2 1/2
~ 15 1/2
~36"
TEST 3
1
2
4
3
6"
2 1/2"
7"
~ 26 1/2"
~36"
TEST 4
1
2
3
4
6"
5/8
11 3/4
15"
~9"
~36"

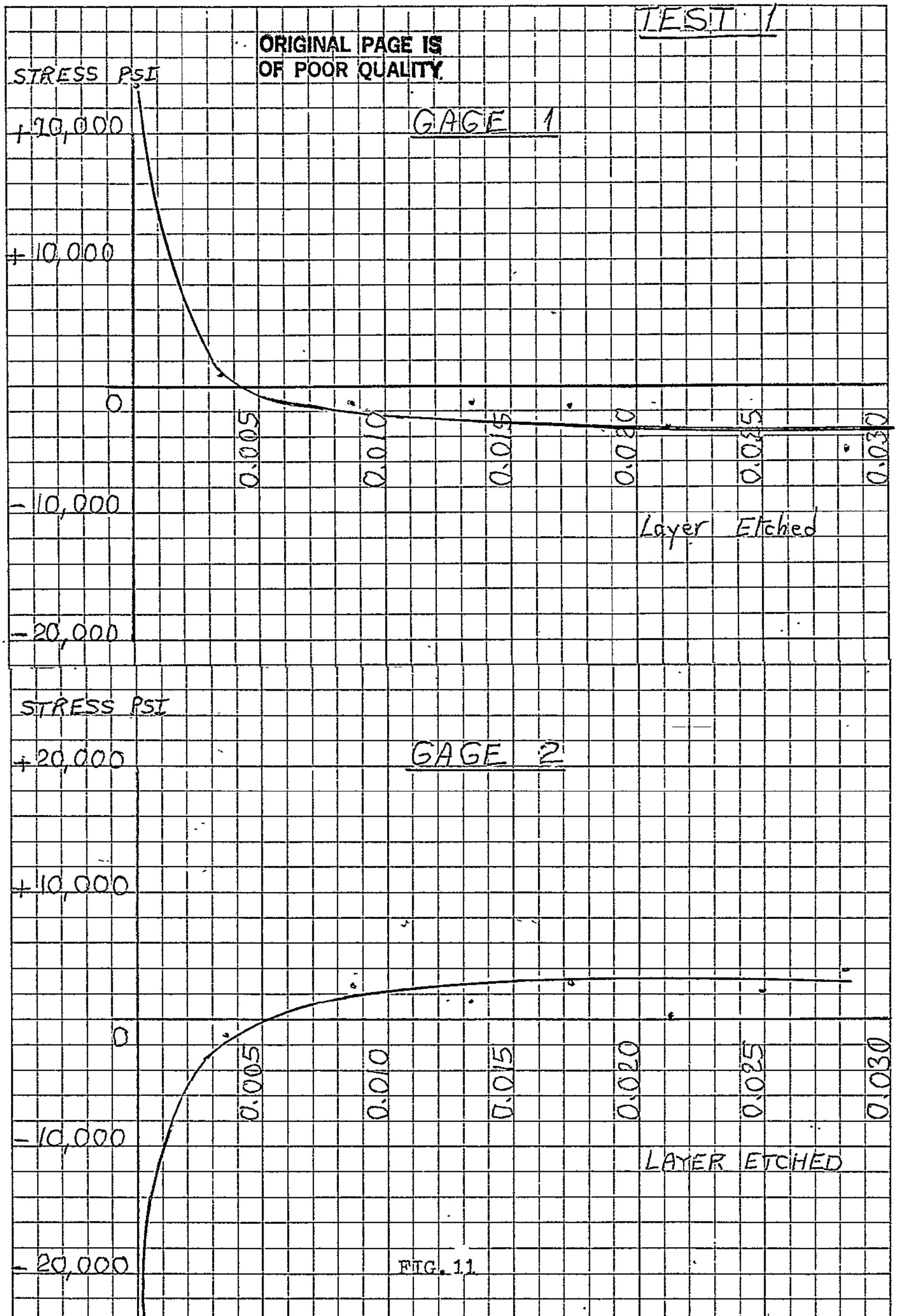

TEST 1
GAGE 1
STRESS PSI
+20,000
+10,000
0
-10,000
-20,000
0.005
0.010
0.015
0.020
0.025
0.030
Layer Etched
GAGE 2
STRESS PSI
+20,000
+10,000
0
-10,000
-20,000
0.005
0.010
0.015
0.020
0.025
0.030
LAYER ETCHED

FIG. 11

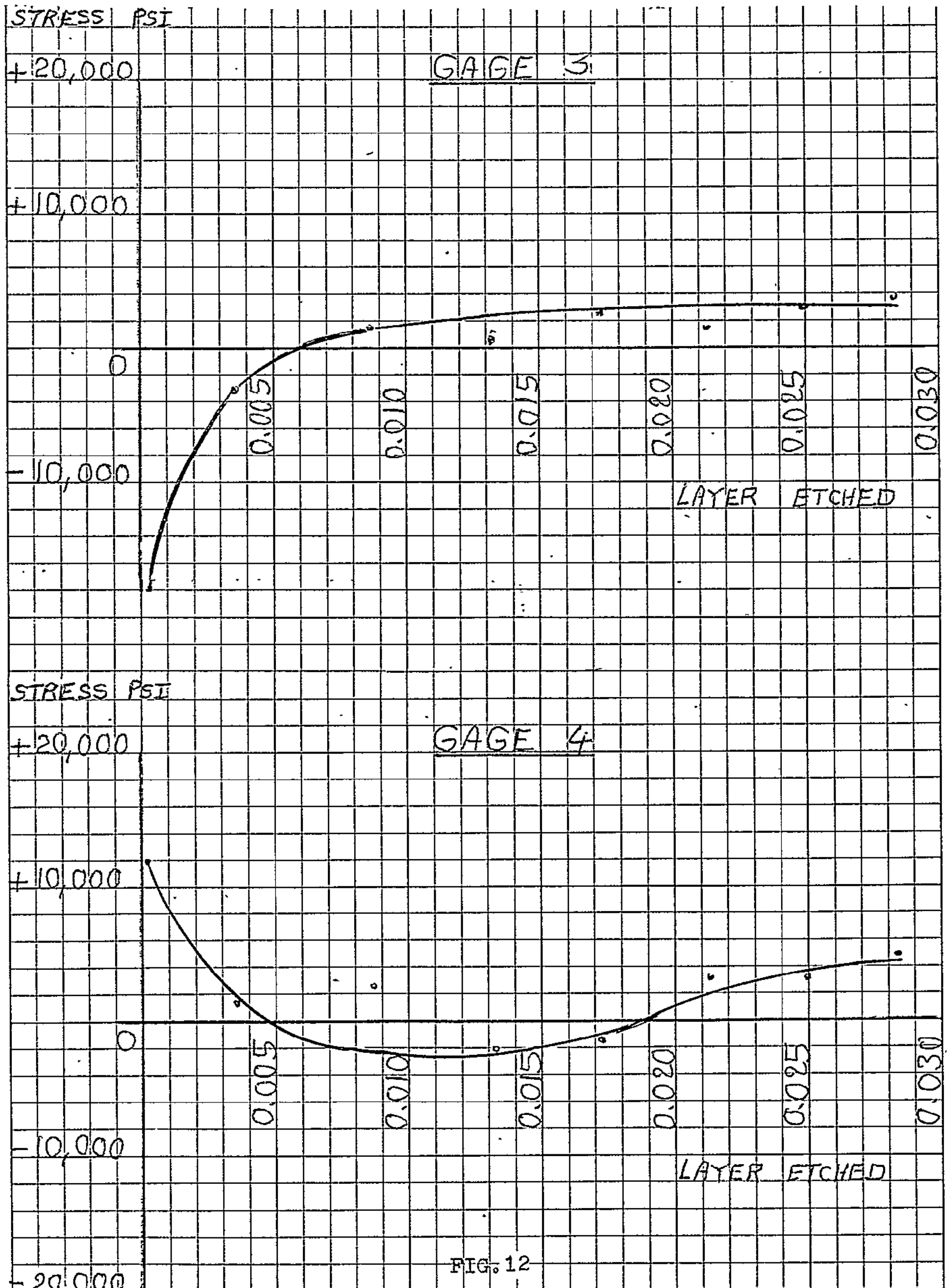

STRESS PSI
+20,000
GAGE 3
+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
STRESS PSI
GAGE 4
+20,000
+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000

FIG. 12

```
.TYPE TST1B.RES
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0      ,   42.00000     ,   38.00000     ,
   41.00000     ,   33.00000     ,   34.00000     ,  -3.000000     ,   4.000000     ,
   2.000000     ,  -4.000000     ,  -5.000000     ,
   1.000000     ,   2.000000     ,  -2.000000     ,   3.000000     ,  -3.000000     ,
   3.000000     ,   4.000000     ,   1.000000     ,
  -2.000000     ,  -3.000000     ,   2.000000     ,   3.000000     ,  -2.000000     ,
  -2.000000     ,   3.000000     ,   2.000000     ,
  -4.000000     ,   4.000000     ,  0.0000000E+00,   3.000000     ,  -4.000000     ,
   3.000000     ,   2.000000     ,   4.000000     ,
  -5.000000     ,   5.000000     ,   4.000000     ,   2499.000     ,   2440.000     ,
   2393.000     ,   2351.000     ,   2313.000     ,
   2272.000     ,   2239.000     ,   2205.000     ,  -18052.73     ,   24070.31     ,
   12035.16     ,  -24070.31     ,  -3063.972     ,
   806.1529     ,   1271.085     ,  -1384.825     ,   1705.549     ,  -1875.149     ,
   2373.783     ,   2536.131     ,   526.3311     ,
  -1481.678     ,  -1986.038     ,   1483.504     ,   2383.400     ,  -1739.208     ,
  -1516.912     ,   2602.368     ,   1538.952     ,
  -3258.616     ,   3216.633     ,   187.5758     ,   2975.954     ,  -4202.783     ,
   3198.955     ,   2108.191     ,   3933.228     ,
  -5167.281     ,   5069.873     ,   3969.003     ,
```

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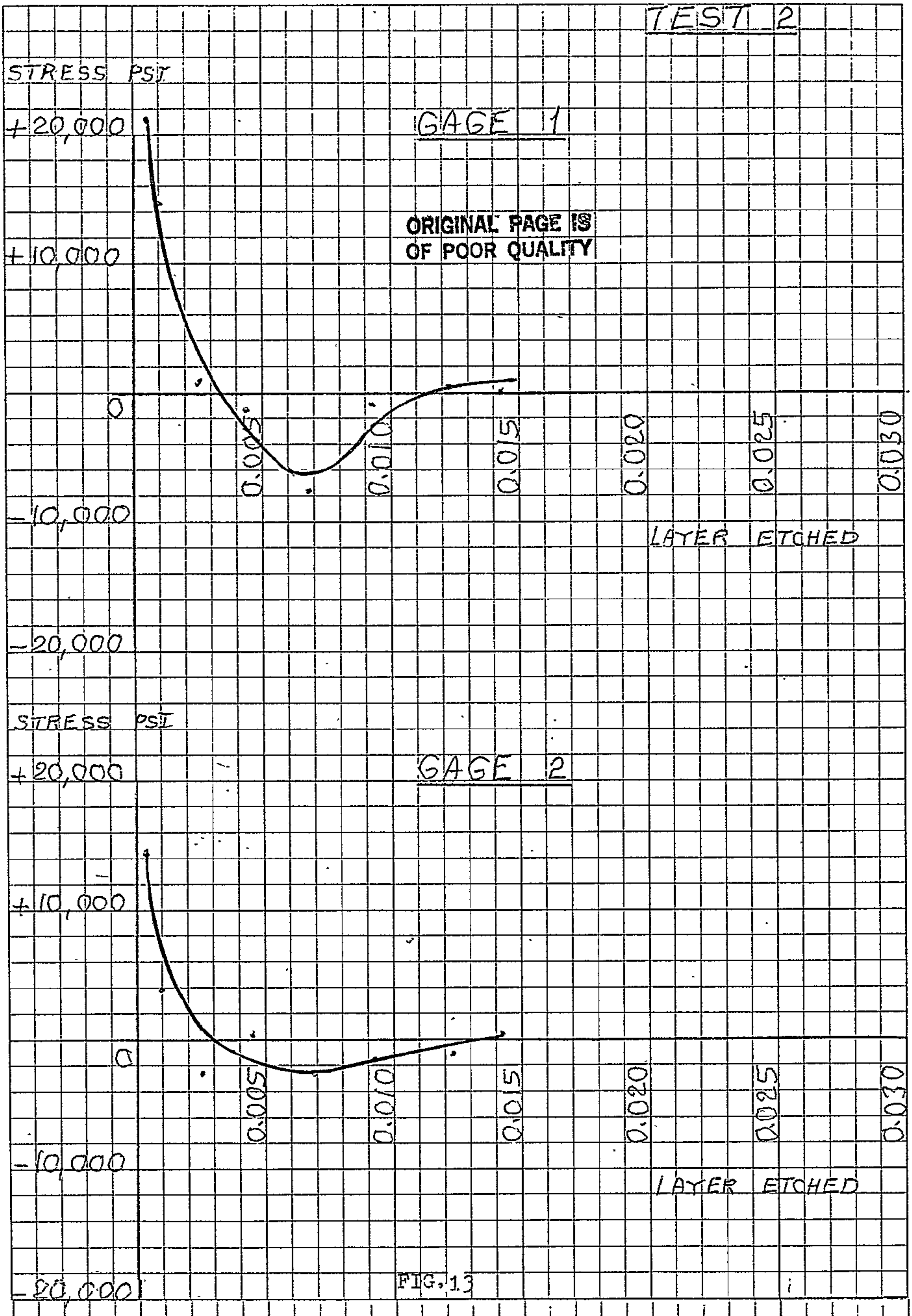
TEST 2
STRESS PSI
GAGE 1
+20,000
+10,000
0
-10,000
-20,000
0.005
0.010
0.015
0.020
0.025
0.030
LAYER ETCHED
STRESS PSI
GAGE 2
+20,000
+10,000
0
-10,000
-20,000
0.005
0.010
0.015
0.020
0.025
0.030
LAYER ETCHED

FIG. 13

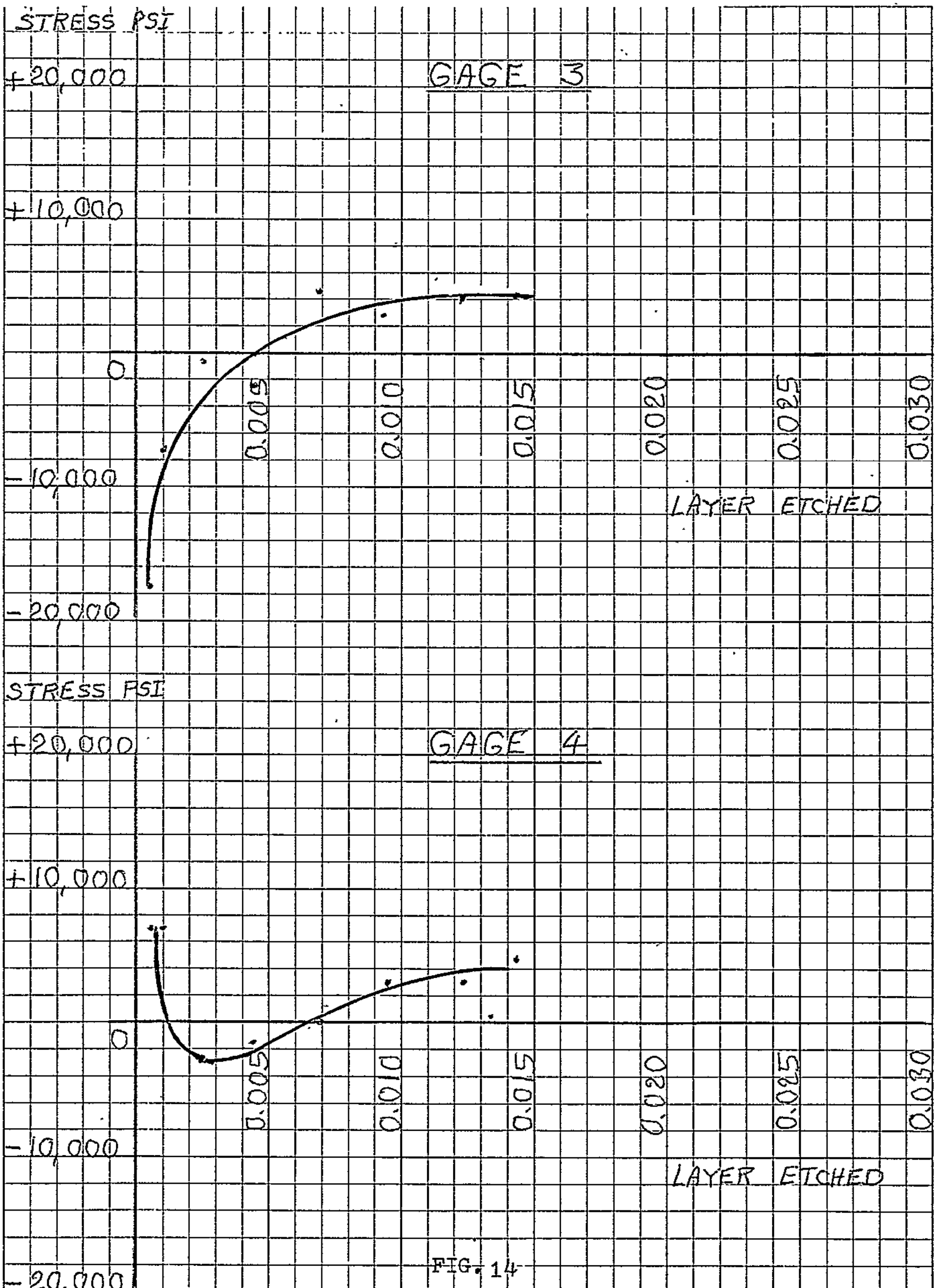
STRESS PSI
+20,000
GAGE 3
+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000
STRESS PSI
+20,000
GAGE 4
+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000

FIG. 14

```
TYPE TST2B.RES
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   35.00000     ,  24.00000      ,  15.00000      ,  -5.000000     ,  2.000000      ,
   6.000000     ,  4.000000      ,  2.000000      ,
   2.000000     ,  4.000000      ,  1.000000      ,  0.0000000E+00,  -2.000000      ,
 0.0000000E+00, -2.000000      , -2.000000      ,
 -2.000000      , -2.000000      , 0.0000000E+00,  2.000000      ,  0.0000000E+00,
 -3.000000      , -1.000000      ,  3.000000      ,
   3.000000     , -1.000000      , -2.000000      ,  3.000000      ,  2.000000      ,
 0.0000000E+00,  1.000000      ,  2.000000      ,
   2.000000     , 0.0000000E+00, 0.0000000E+00,  2470.000      ,  2460.000      ,
   2439.000     ,  2402.000      ,  2389.000      ,
   2354.000     ,  2330.000      ,  2315.000      , -17799.41      ,  7119.763      ,
   21359.29     , -14239.53      , -7379.010      ,
  -7206.062     ,  14527.42      ,  3775.979      , -400.4290      , -3096.082      ,
   572.4406     , -3039.326      , -2233.416      ,
 -1729.047      , -1277.901      ,  166.8236      ,  4784.811      , -4.885372      ,
 -7490.035      , -2478.878      ,  2482.407      ,
   2857.023     , -692.8616      ,  1803.351      ,  3957.442      ,  2938.583      ,
   199.1129     ,  1374.969      ,  4405.643      ,
   4711.044     ,  196.4892      ,  46.05377      ,
```

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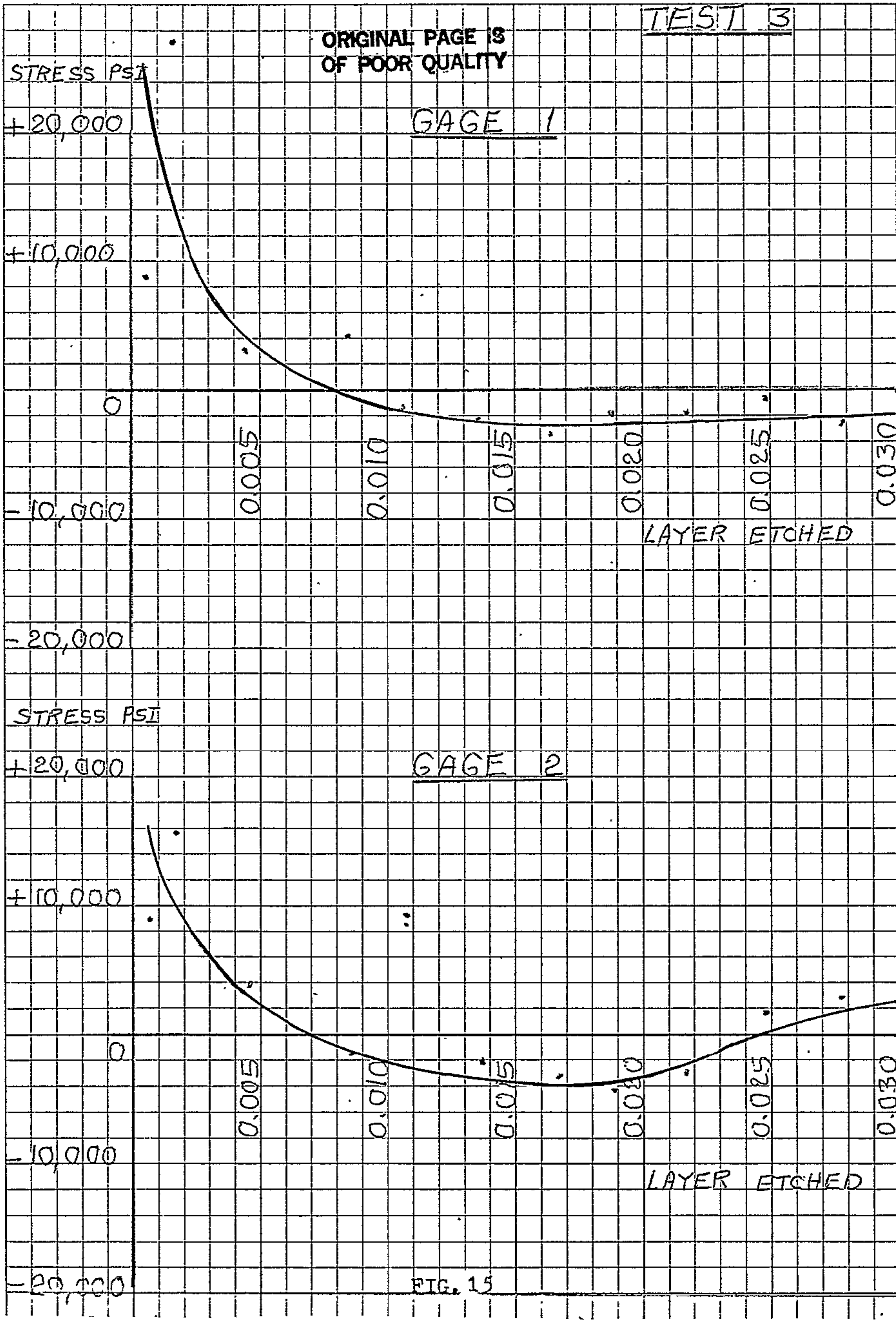
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STRESS PSI
+20,000
GAGE 1
+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000
STRESS PSI
+20,000
GAGE 2
+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000

FIG. 15

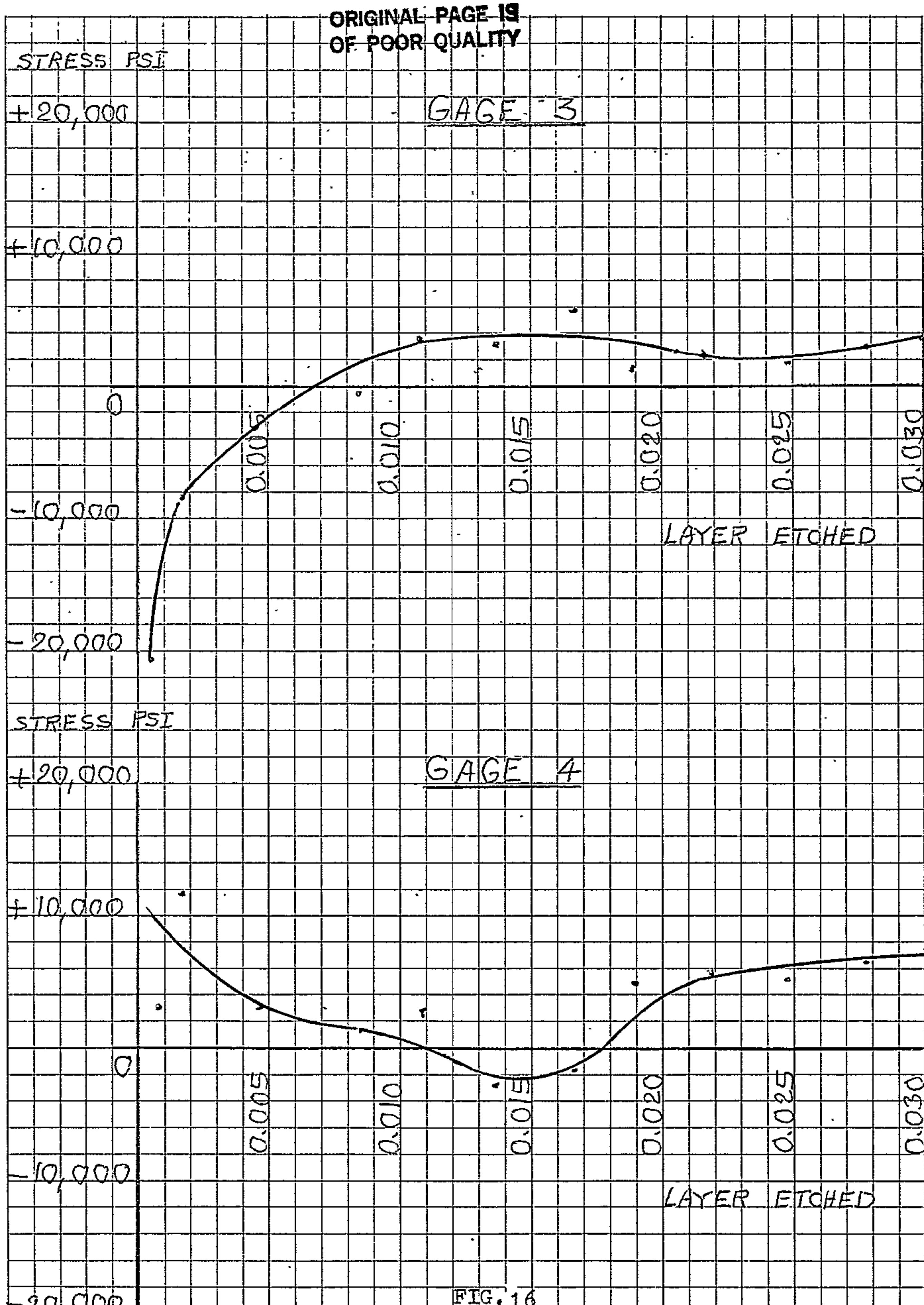
STRESS PSI
GAGE 3
+20,000
+10,000
0
-10,000
-20,000
0.005
0.010
0.015
0.020
0.025
0.030
LAYER ETCHED
STRESS PSI
GAGE 4
+20,000
+10,000
0
-10,000
-20,000
0.005
0.010
0.015
0.020
0.025
0.030
LAYER ETCHED

FIG. 16

```
.TYPE TSTSB.RES
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00     ,    30.00000     ,    15.00000     ,
   44.00000     ,    16.00000     ,    28.00000     ,    29.00000     ,    34.00000     ,
   23.00000     ,    28.00000     ,   -7.000000     ,
   3.000000     ,    1.000000     ,    3.000000     ,   -2.000000     ,    4.000000     ,
   3.000000     ,    7.000000     ,   -4.000000     ,
   5.000000     ,    4.000000     ,    3.000000     ,  0.0000000E+00,   -2.000000     ,
   1.000000     ,    3.000000     ,    2.000000     ,
   4.000000     ,    1.000000     ,   -1.000000     ,    5.000000     ,   -4.000000     ,
  -4.000000     ,   -4.000000     ,    3.000000     ,
  -2.000000     ,   -1.000000     ,   -2.000000     ,    1.000000     ,   -4.000000     ,
   4.000000     ,   -2.000000     ,    2.000000     ,
  -3.000000     ,    5.000000     ,   -2.000000     ,    2.000000     ,    2.000000     ,
   5.000000     ,   -1.000000     ,    2.000000     ,
   2.000000     ,    4.000000     ,   -2.000000     ,    3.000000     ,    1.000000     ,
   6.000000     ,  0.0000000E+00,    2454.000     ,
   2445.000     ,    2396.000     ,    2366.000     ,    2351.000     ,    2307.000     ,
   2291.000     ,    2263.000     ,    2234.000     ,
   2200.000     ,    2177.000     ,    2149.000     ,   -20605.61     ,    8830.975     ,
   2943.658     ,    8830.975     ,   -8238.480     ,
   15843.03     ,    11810.24     ,    27595.64     ,   -3261.841     ,    3837.283     ,
   2979.187     ,    2632.359     ,   -723.9754     ,
  -1573.565     ,    1570.523     ,    4091.055     ,    3788.608     ,    9551.240     ,
   2750.146     ,   -1365.556     ,    3109.478     ,
  -2192.396     ,   -2410.002     ,   -2144.725     ,    5874.111     ,   -3587.970     ,
  -1746.584     ,   -3541.286     ,    1036.533     ,
  -4202.913     ,    4848.556     ,   -1855.839     ,    2136.741     ,   -3123.253     ,
   5947.427     ,   -1868.731     ,    1894.520     ,
   1823.415     ,    5327.703     ,   -715.3185     ,    2875.660     ,    2805.097     ,
   6416.686     ,   -2561.780     ,    3559.478     ,
   1306.315     ,    7771.501     ,    23.34309     ,
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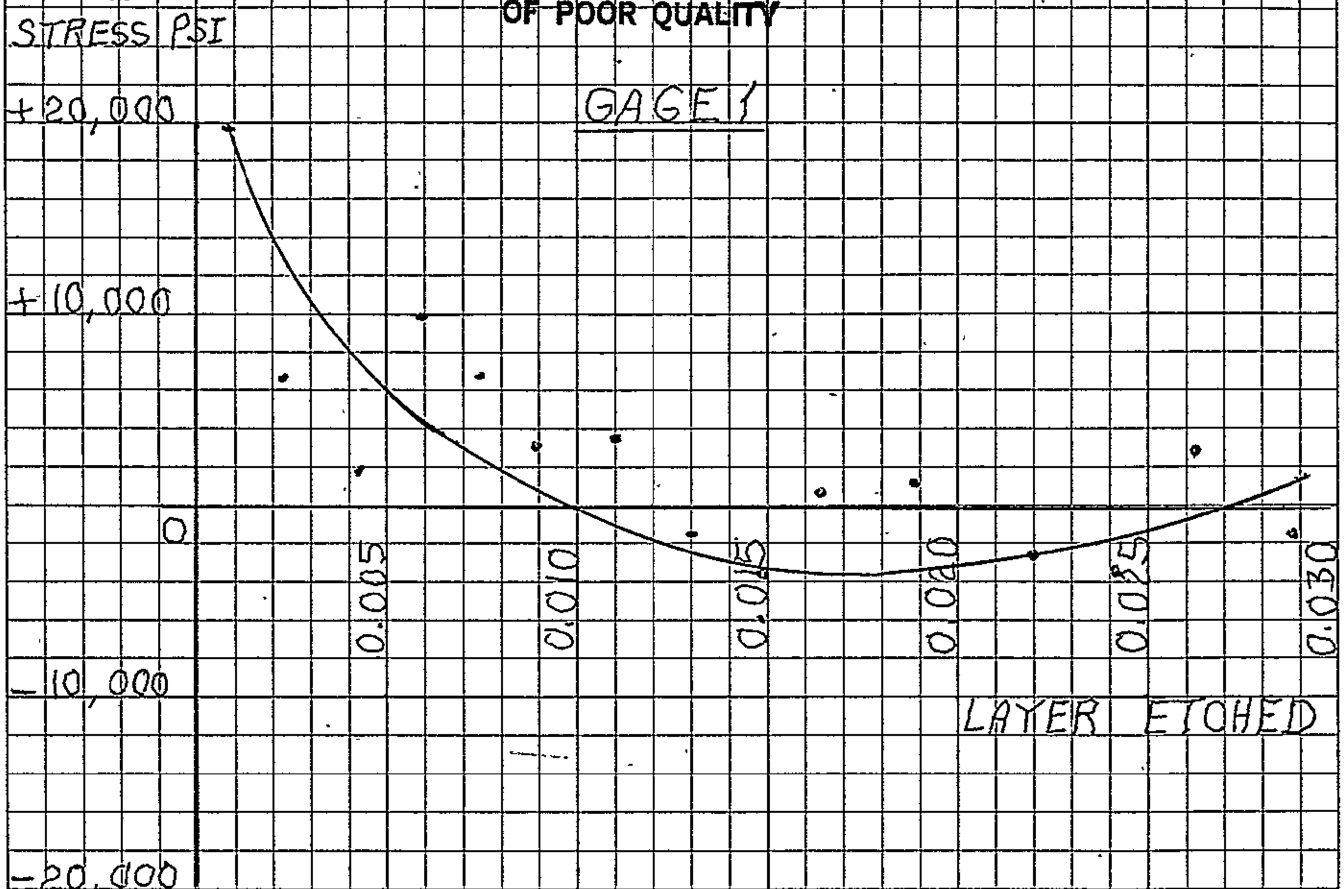
TEST 4



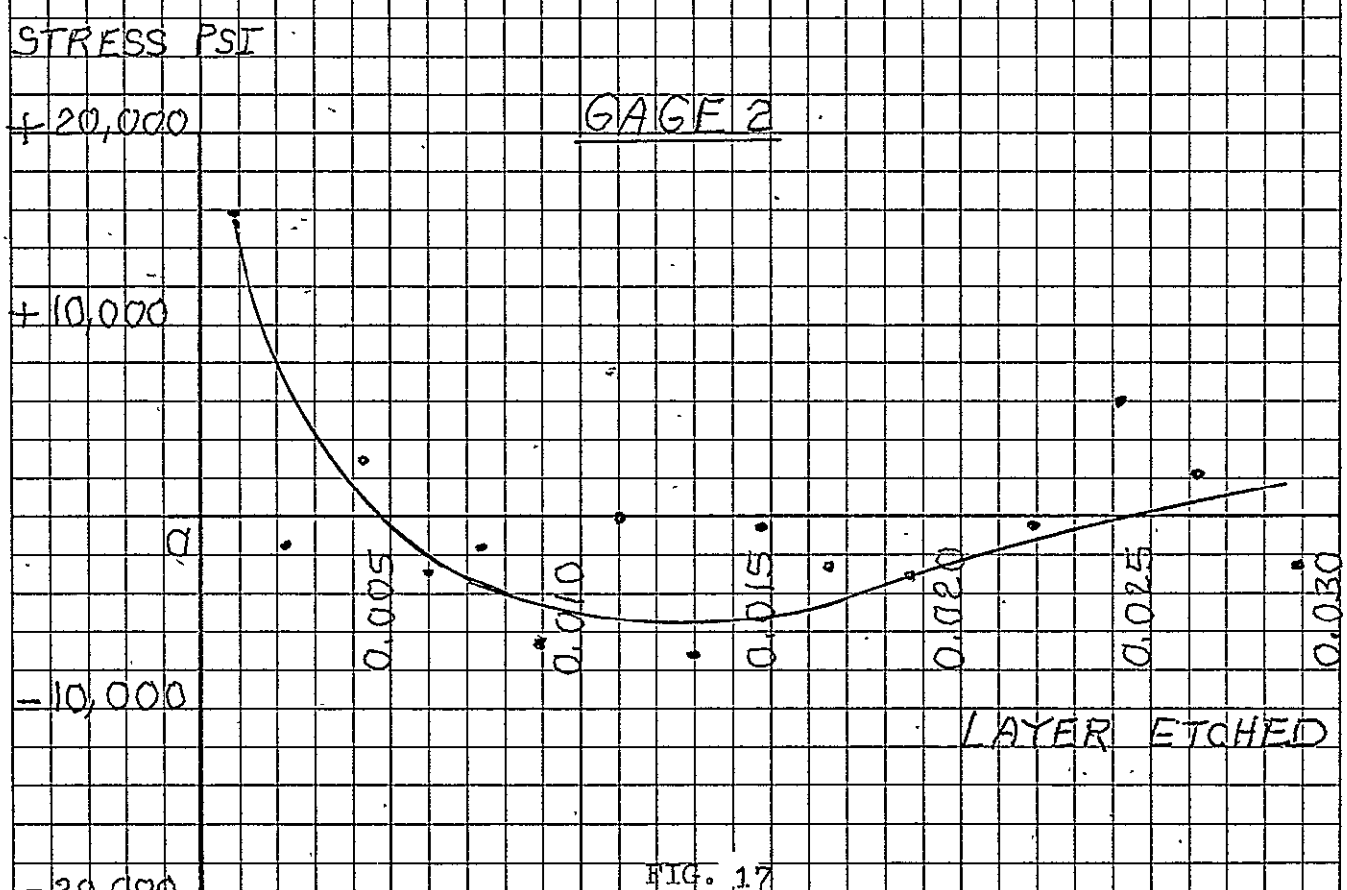


FIG. 17

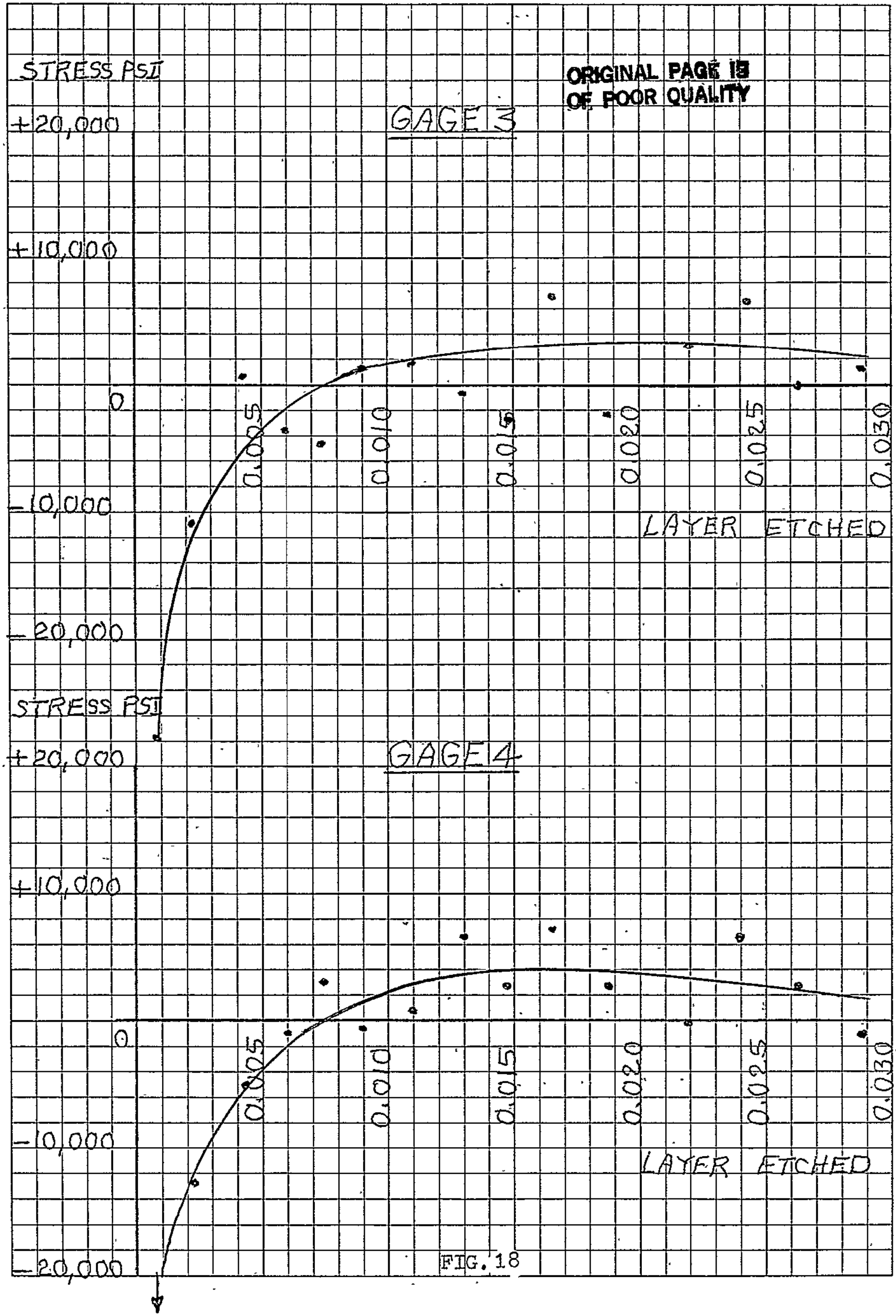

STRESS PSI
GAGE 3
+20,000
+10,000
0
-10,000
-20,000
0.005
0.010
0.015
0.020
0.025
0.030
LAYER ETCHED
STRESS PSI
GAGE 4
+20,000
+10,000
0
-10,000
-20,000
0.005
0.010
0.015
0.020
0.025
0.030
LAYER ETCHED

FIG. 18

TYPE T4R.RES

```
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00  , 11.00000  , 17.00000  ,
 15.00000  ,  26.00000  ,  14.00000  ,  21.00000  ,  13.00000  ,
 35.00000  ,  28.00000  ,  15.00000  ,
 27.00000  ,  26.00000  ,  5.000000  ,  4.000000  , -7.000000  ,
-8.000000  ,  3.000000  , -1.000000  ,
-5.000000  , -6.000000  ,  1.000000  ,  2.000000  ,  1.000000  ,
-3.000000  ,  3.000000  , -1.000000  ,
-1.000000  , 0.0000000E+00,  3.000000  , -1.000000  , -2.000000  ,
 2.000000  ,  1.000000  , -3.000000  ,
 1.000000  , 0.0000000E+00,  2.000000  , 0.0000000E+00,  2.000000  ,
 1.000000  , -1.000000  , -3.000000  ,
0.0000000E+00,  3.000000  , -3.000000  , 0.0000000E+00,  2.000000  ,
 2.000000  , 0.0000000E+00, -1.000000  ,
 3.000000  ,  3.000000  ,  1.000000  , -3.000000  , -2.000000  ,
 3.000000  , -3.000000  , 0.0000000E+00,
-3.000000  , 0.0000000E+00, -2.000000  ,  3.000000  ,  3.000000  ,
 3.000000  ,  2.000000  ,  2.000000  ,
0.0000000E+00,  2.000000  , -2.000000  , -2.000000  ,  1.000000  ,
-1.000000  ,  2485.000  ,  2468.000  ,
 2444.000  ,  2433.000  ,  2416.000  ,  2401.000  ,  2375.000  ,
 2361.000  ,  2340.000  ,  2327.000  ,
 2292.000  ,  2264.000  ,  2249.000  ,  2222.000  ,  2196.000  ,
 19909.89  ,  15927.91  , -27873.85  ,
-31855.83  ,  6538.325  , -1853.346  , -10820.48  , -12961.56  ,
 1911.144  ,  3080.336  ,  770.9309  ,
-5163.777  ,  10065.08  , -2902.558  , -3805.012  , -961.9011  ,
 6794.112  , -1816.167  , -4749.958  ,
 3124.818  ,  3141.504  , -6734.905  ,  1519.699  , -829.1460  ,
 3494.718  , -10.56369  ,  1893.875  ,
 484.7344  , -1432.061  , -7281.765  , -588.6897  ,  6520.677  ,
-3859.602  , -182.4735  ,  2606.525  ,
 2618.517  ,  740.7924  , -2754.455  ,  7261.075  ,  7272.981  ,
-1657.278  , -3019.719  , -2138.534  ,
 2514.649  , -2682.884  , -400.5633  ,  3063.823  , -93.66317  ,
-3717.590  ,  6062.629  ,  6245.516  ,
 6365.538  ,  2808.190  ,  2126.145  , -37.08179  ,  2425.155  ,
-1837.317  , -2506.464  ,  1167.367  ,
-1009.051  ,
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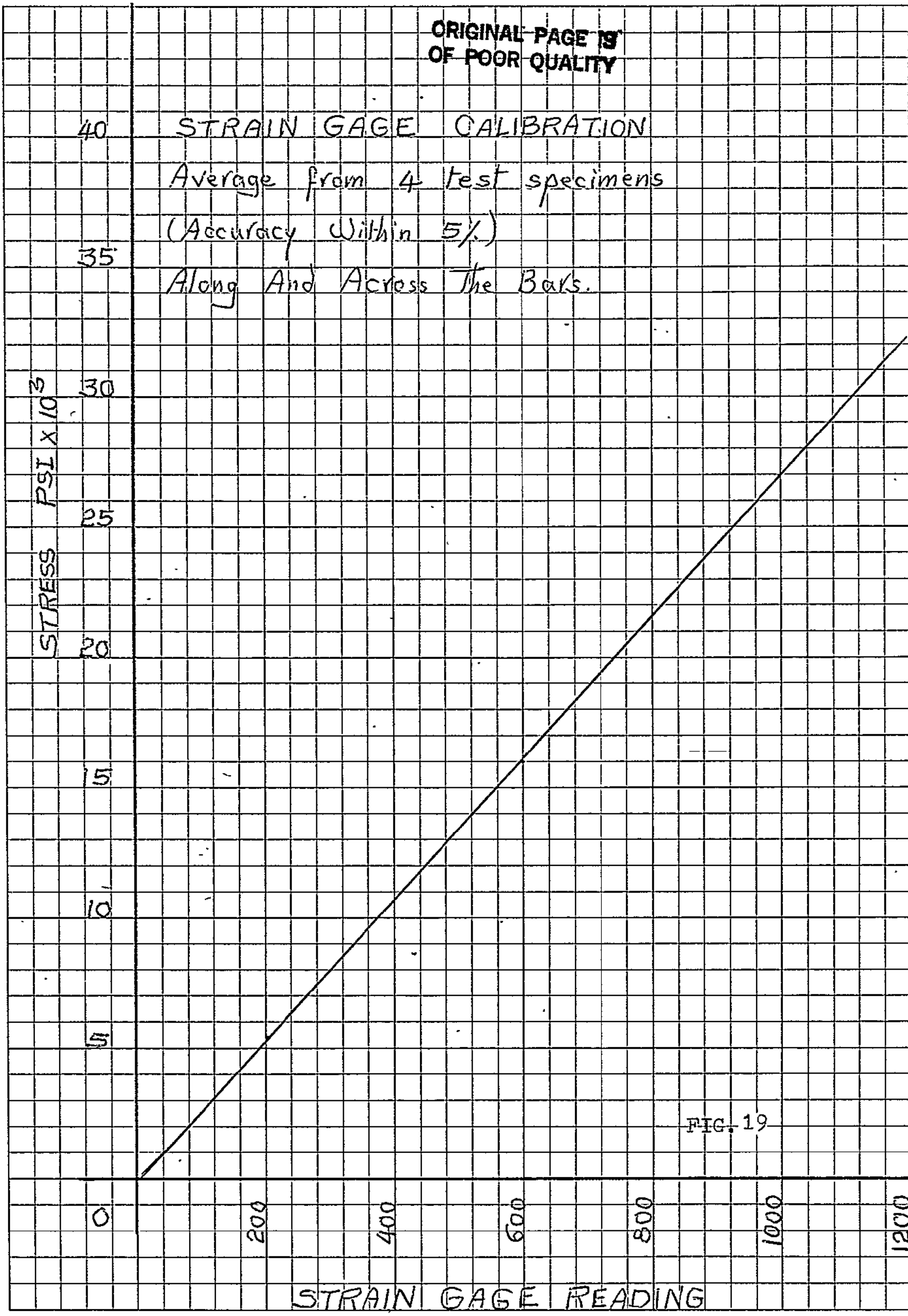

STRAIN GAGE CALIBRATION
Average from 4 test specimens
(Accuracy Within 5%)
Along And Across The Bars.
STRESS PSI X 10^3
40
35
30
25
20
15
10
5
0
200
400
600
800
1000
1200
STRAIN GAGE READING

FIG. 19

The objective of the first phase of the program is to determine experimentally the magnitude and distribution of stresses lengthwise and across the thickness of each member. The use of electric strain gages eliminates the need for straightening steel members following the welding.

1:3 by volume diluted nitric acid solution is used to etch successive layers off surfaces opposite the gages. The rate of metal removal is 2 to 3 mills/15 minutes. Dimensions and strains are measured after a period of 24 hours following each etching process. This arrangement permits measurement under stabilized conditions.

The stresses are next calculated using the theoretical approach that we developed

6 inch and 4 inch wide by ½ inch thickness hot rolled steel bars are used in the first and second phases of the study. The bars are cut to a length of 3 feet by means of a saw. No flame cutting is used, eliminating any heating other than that from the welding itself.

Bars are also tested as received to investigate any possible residual stresses from the milling. The study showed negligible stresses in such bars.

Square boxes 3 ft x 3 ft are formed by welding which simulates some of the conditions in built-up structures.

Future investigations will study multi-pass welding, weld widths up to 15 inches, and unequal section welds to determine the effect of such connections on concentrated residual stresses.

Current results indicate high tensile stresses at the weld of about 25,000 psi, dropping sharply across the bar thickness to compressive stresses of about 3,000 to 5,000 psi. Surface stresses showed more gradual changes along each bar, from the maximum tensile of 25,000 psi to maximum compression of about the same magnitude at a distance of 7 to 8 inches away from the weld.

Some flat bars were welded end to end; a length of 3 ft. sawed with the weld central. Patterns of stresses obtained from this study are similar to those obtained with box welding. This similarity may indicate that the stress distribution in various shapes can be obtained by superposition.

How to relieve such stresses? Traditionally, residual stresses are relieved through thermal treatment, suitable for simple and symmetric structures. Complex and heavy structures, however, cannot be thermally stress-relieved.

The technique of inducing mechanical vibrations in the weld to reduce or eliminate residual stresses has been tried with various metallic shapes. Consideration must be taken of the fact that a continuous application of vibrations or vibrating near resonance, may lead to metal fatigue, and a possible spreading of any embeded cracks. For this reason it is planned to vibrate at a frequency within 100 cps, which would generate enough dynamic stresses to interact with the high intensity tensile stresses and at the same time eliminate metal fatigue.

In the second phase of the study which is in progress at the present time, a load cell is fixed to steel structures similar to those already analyzed for stress patterns. A hammer is used to strike the cell generating an impulse to the system, Figs.20,21. It is important to observe the frequency response of the force input before proceeding with the test.

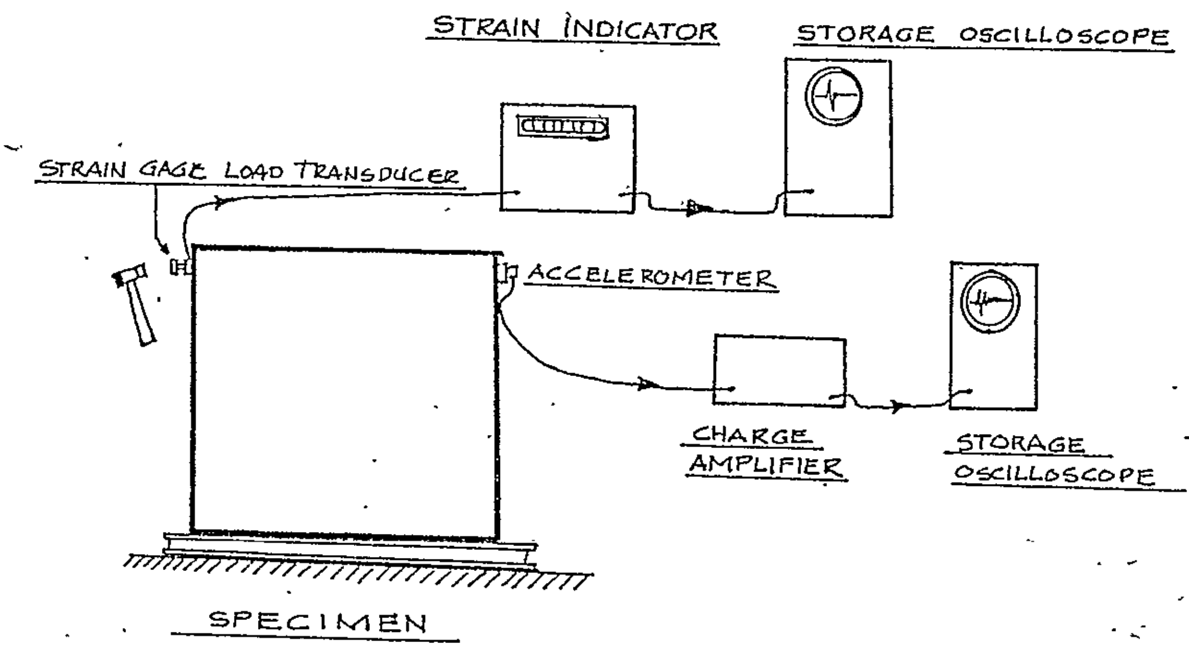
The signal will be treated in either one or both the following two ways:-

1- The signal will be sent into a channel of a Fourier analyzer. The acceleration response is measured through an accelerometer, amplified and sent to a second channel of the analyzer, Figs. 22,23.

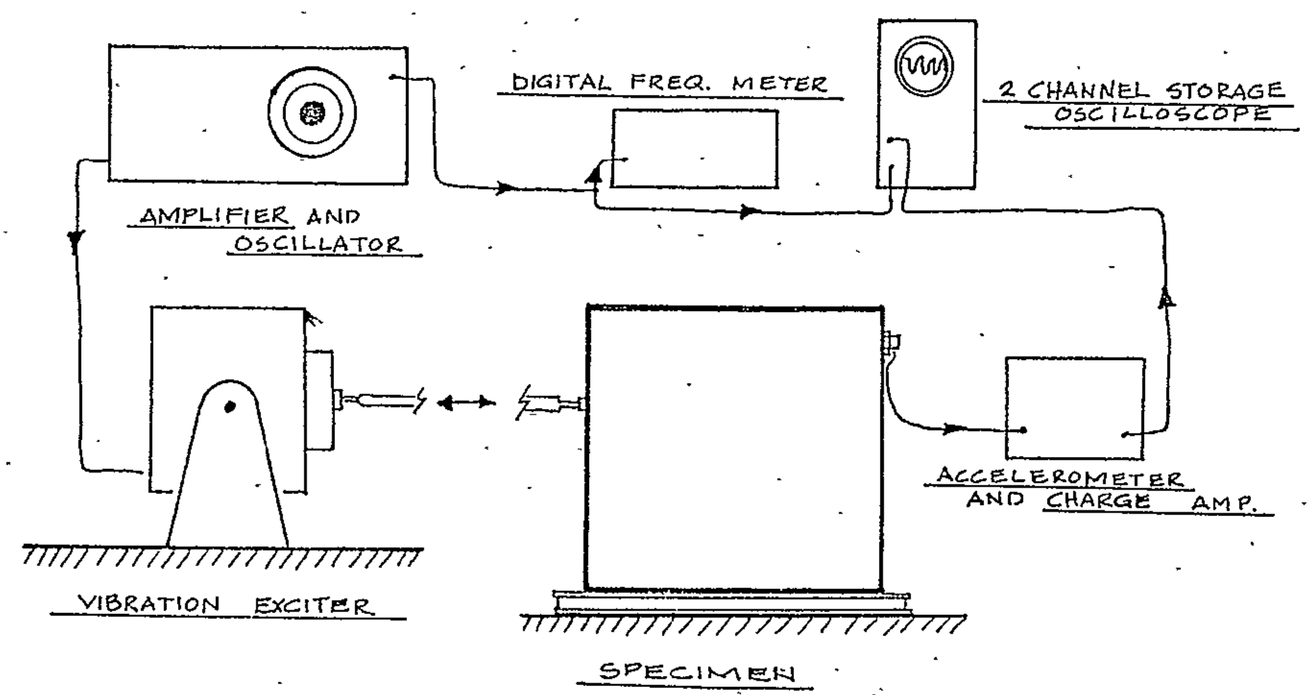
The impulse should have a low enough frequency input to excite the system sufficiently at low frequencies. A softer or harder hammer may be indicated by the observed frequency content of the impulse.

2- A second method, which is being applied at the present time is to read the data of the pulse and feed this information into a Dec.10 computer available on campus, through a suitably developed program that uses data digitized manually and stored on a magnetic disk. It is designed for the joint analysis of two random, stationary, ergodic processes containing significant noise. The frequency analysis consists of Fourier transformed probability functions and statistical smoothing.

The fundamental utility of the program is in the analysis of frequency response characteristics.

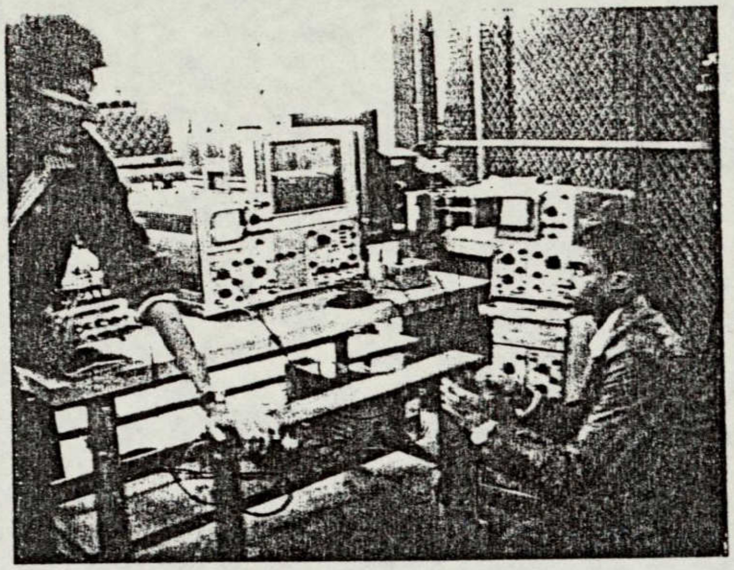


I. FREQUENCY ANALYSIS



II. VIBRATION

FIG. 20



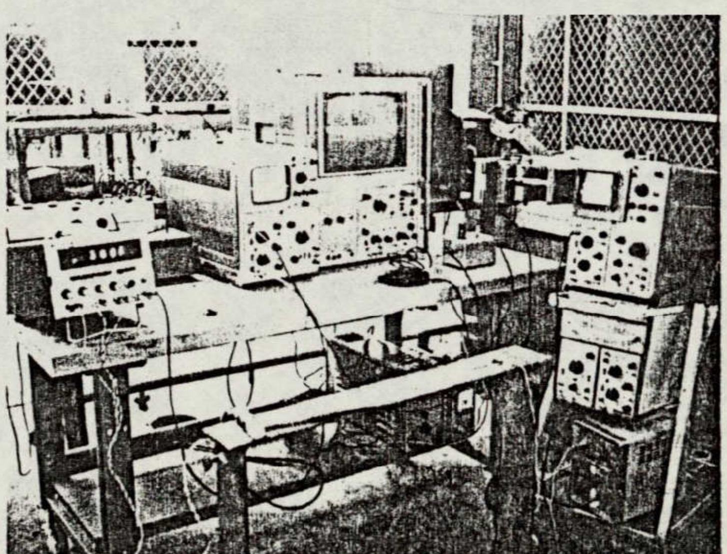
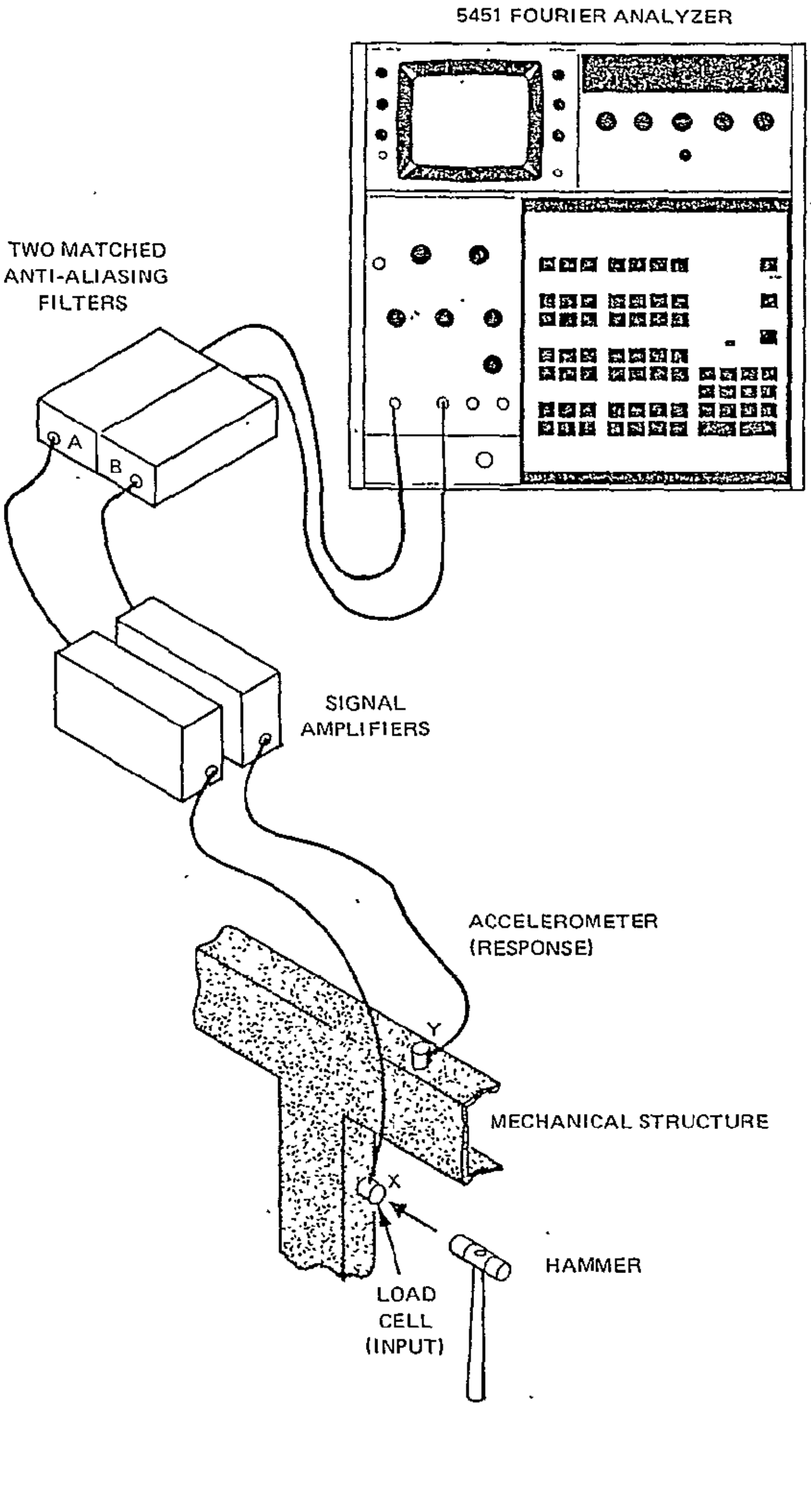


FIG.21



TYPICAL IMPULSE TEST

FIG. 22

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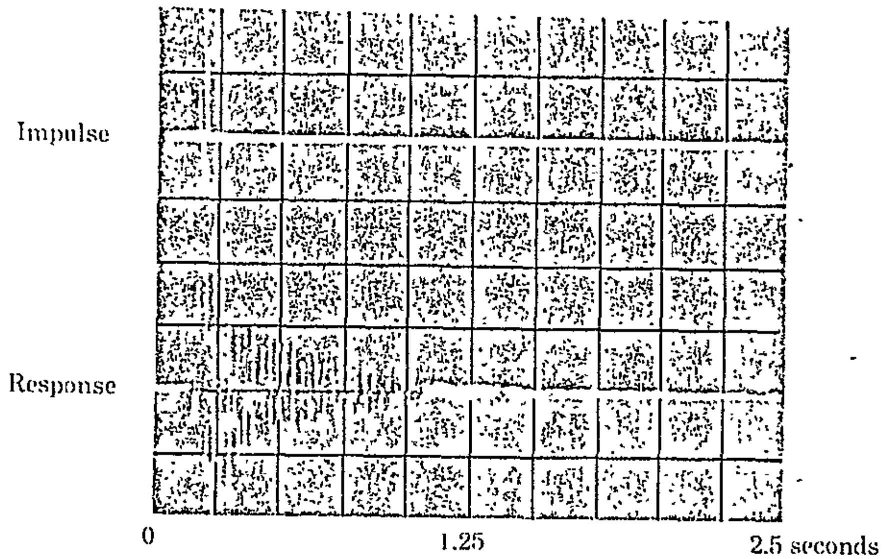
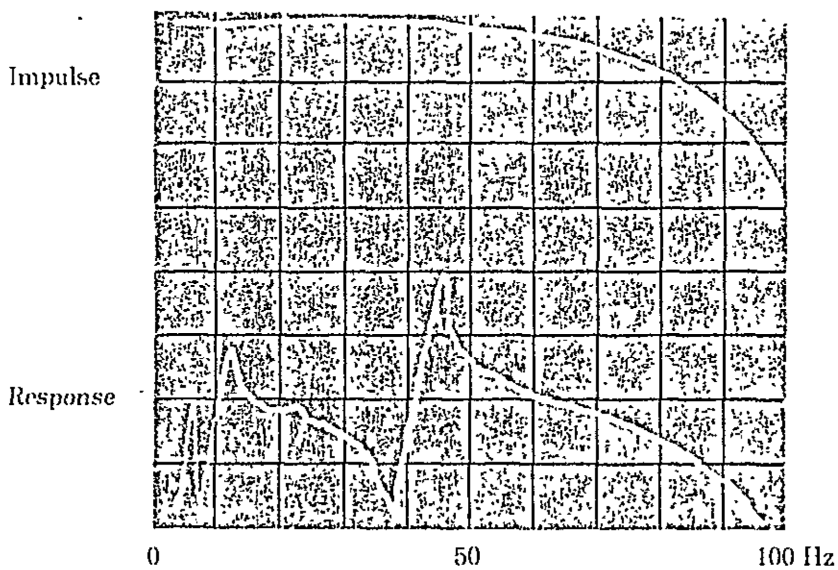


TYPICAL TIME WAVEFORMS OF THE IMPULSE
AND SYSTEM RESPONCE



TYPICAL FREQUENCY PLOT OF THE IMPULSE
AND RESPONSE

FIG. 23

The routines used include: Power spectrum density, cross-spectral density, Transfer function analysis, Coherence analysis, Hanning window smoothing and Parzen lag smoothing [30,31]

The structure will be shaken for about 15 minutes, using a mechanical shaker, Fig.[24] at the frequency that will show maximum amplitude, according to the previous shock study.

The third phase of the program will be to test the vibrated structure and carry out a complete residual stress analysis, as in phase one, to reveal the effectiveness of the vibration technique on the embeded residual stresses.

It is also important and necessary to prove that the vibrational technique is reproducible and capable of being monitored and effective at all critical locations within a part being so treated.

Fatigue test specimens will be prepared from the welded structures and tested for fatigue life, and similar analyses will be carried out on specimens to be prepared from similar structures after vibration.

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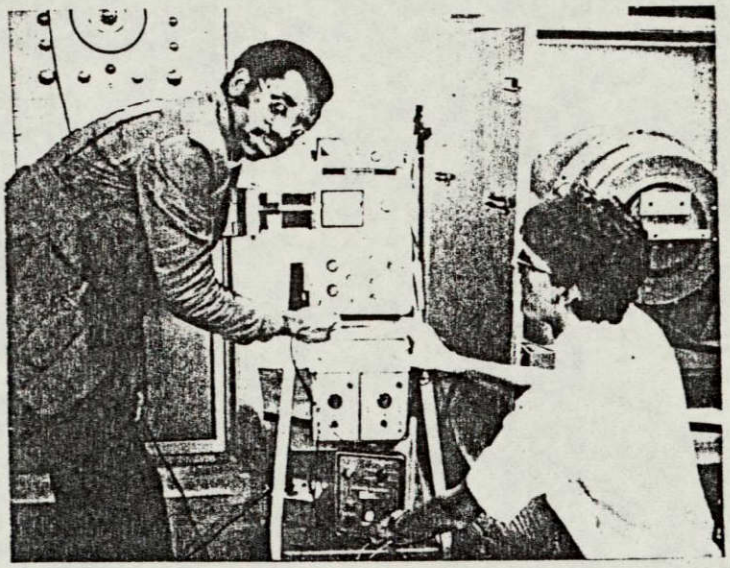


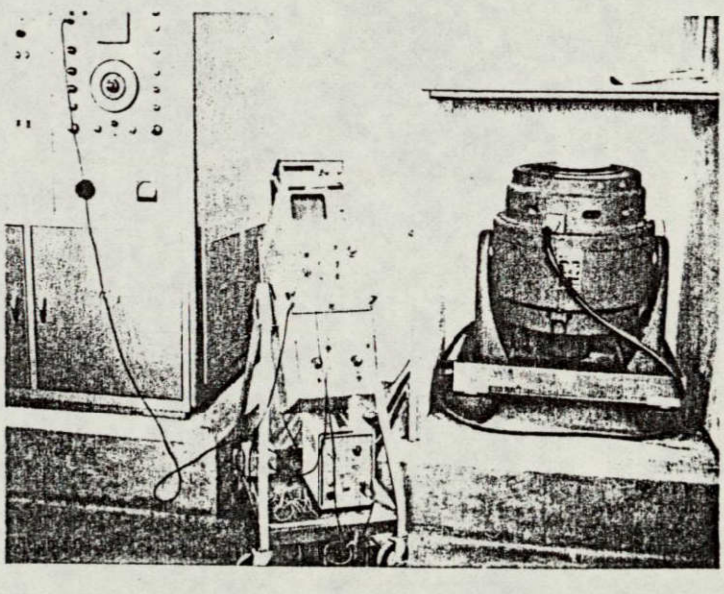


FIG. 24

Future Work Plan

Study multi-pass welding with bar thickness up to 1 inch, weld widths up to 15 inches, and unequal section welds to determine the effect of such connections on concentrated residual stresses.

A load cell will be fixed to steel structures similar to those already analyzed for stress patterns. A hammer will strike the cell generating an impulse to the system. The signal will be treated in either one or both of two ways:-

1- Amplify load cell and accelerometer signals and send to two channels of a Fourier analyzer. A softer or harder hammer may be indicated by the observed frequency content of the impulse.

2- Read the data of the pulse and feed the information into the Dec10 computer through a suitably developed program.

The structure will be shaken for about 15 minutes, using a mechanical shaker, at the frequency that will show maximum amplitude, according to the shock study.

Next the vibrated structure will be analyzed for stresses, as in phase one, to reveal the effectiveness of the vibration technique on the embeded residual stresses.

Fatigue test specimens will be prepared from the welded structures and tested for fatigue life, and similar analysis will be carried out on specimens to be prepared from similar structures after vibration.

PART TWO

A second set of steel boxes was formed by welding bars $4 \times \frac{1}{2}$ inch section. Details of shapes and dimensions of these boxes, referred to as tests No.5, 6, and 7, are given in Fig. 25 The results of the stress distribution measured as before are presented in Figures 26 to 31.

Test 5 was stopped short due to an apparatus failure, yet the general trend of its results together with those of test 7 are similar to the previous results of tests 1 to 4 of the first report.

The second phase of the study developed a set of computer programs to analyse the load pulse and the acceleration response that were obtained when steel frames similar to those studied for stress analysis were secured to the ground through brackets. A copy of these programs, together with the theoretical analysis and a key to applying these programs are presented later in this report.

Vibrational characteristics of a part have to be analysed experimentally. If the part is vibrated near its natural frequency, vibration amplitudes become quite large, even though the input forces or displacements are relatively small. Correspondingly large dynamic stresses can be developed, which interact with residual stresses. A typical set-up for impulse testing the steel frames is shown in Fig. 32-I

A load cell provided with an electric strain gage, and an accelerometer were attached at opposite ends of the top side of the frame. A plastic hammer applied a force to the load cell at point X, Fig.32-I and the signal was sent into channel 1 of an oscilloscope. The acceleration response was measured at point Y using the accelerometer and sent to channel 2 of the oscilloscope. A photograph was taken of the display.

Results of treating a frame similar to the one tested for stress distribution No.7 are shown in Fig. 33. A blow-up of the photograph was prepared, from which measurements of both the load and acceleration frequencies were taken. These values represent the X-data and Y-data for the computer programs. The output of these programs give statistical analysis of the frequencies, while the Trans. results give the frequencies in cps against the magnitude of deflection. Results of the Trans. values are presented in Fig.34 showing the prominent periodic frequency component that may help reduce the stresses and may reveal the frequency of the structure.

The frequency chosen for vibrating the frame in test8 was about 1.62 cps. An MB model C10 vibration exciter, tilted to a horizontal position was used. The frame was connected to the exciter with a solid rod, as shown in Fig. 32-II . This arrangement was necessary because the heavy weight of the steel frames prevents placing them on top of the vertically positioned exciter. The exciter used has a frequency range of 5 to 3000 cps that can be controlled through an attached panel. The vibration is accomplished principally by means of an induced electromagnetic force which is localized in the region of the basic structure or body casting.

The frame under study was vibrated at 162 cps for 15 minutes. It was removed, the sides were sawed apart and a stress analysis was performed on the top side that was exposed to the heaviest vibration.

Results of this study are presented under test8, in Figs. 36 & 37. These results indicate that the vibration affected the stress distribution at the critical location, i.e., at the weld. Vibrating the box developed sufficient dynamic stresses to reduce the intensity and general distribution characteristics of the residual stresses generated by the original welding.

Quantitative data from measuring residual stress patterns both after welding and after vibration are needed in order to state some definite conclusions. Also it is important to determine how vibration treatments effect the various steel structures to relieve welding stresses.

Although experiments performed up to the present time are limited, the results demonstrate that applying a suitable vabration amplitude to low carbon steel weldments significantly reduces peak residual stresses in the weldment. Such vibration seemed to smooth out the pattern of residual stresses by reducing the localized high stresses due to welding.

Such findings were expected due to the fact that residual stresses are the result of internal nonuniform plastic deformation and that the vibration reduces the disorder by changing the dimension of the structure. The procedure, however, is expected to be more complicated with complex shapes and multiple modes of vibration may be needed to allow all junctions of the structure to be exposed to the suitable vibrational amplitude.

The effects of the vibrational technique and the corresponding induced cyclic stresses on the fatigue of steel is still under investigation and no conclusions can yet be presented at this stage.

The boxes formed and studied are of comparatively simple shape. The following studies will cover more complex shapes; pulses will be induced at various locations and analysed. It is hoped that through such studies, a standard type of treatment can be formulated.

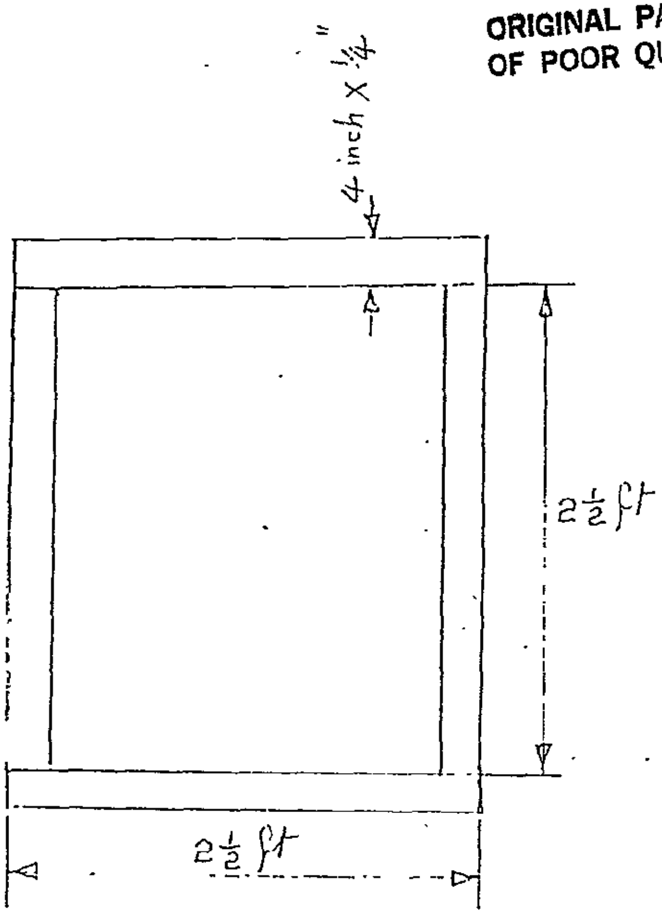


FIG.25(a)

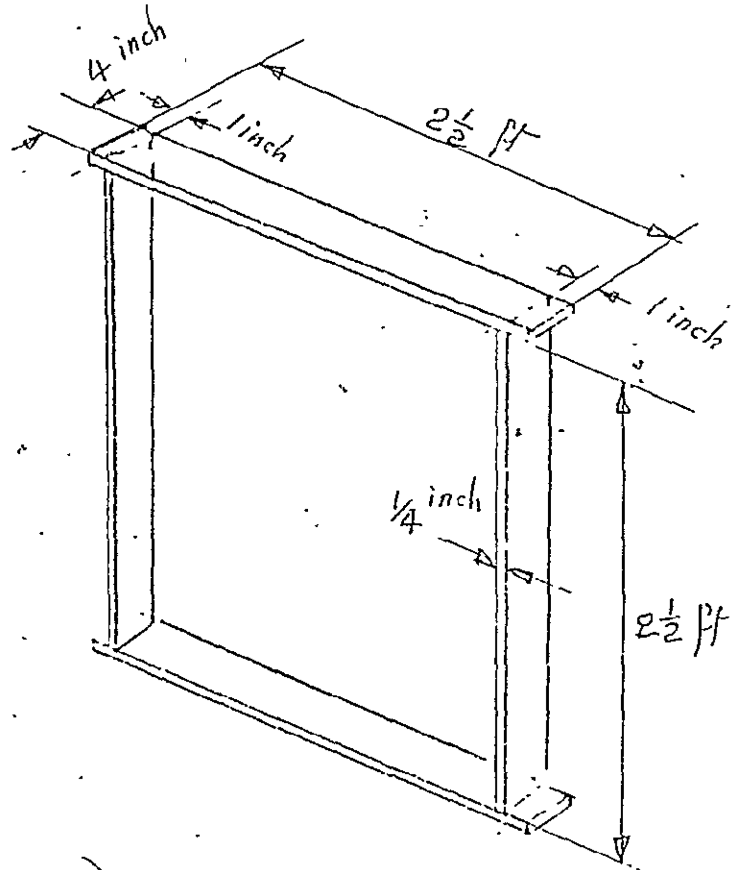


FIG.25(c)

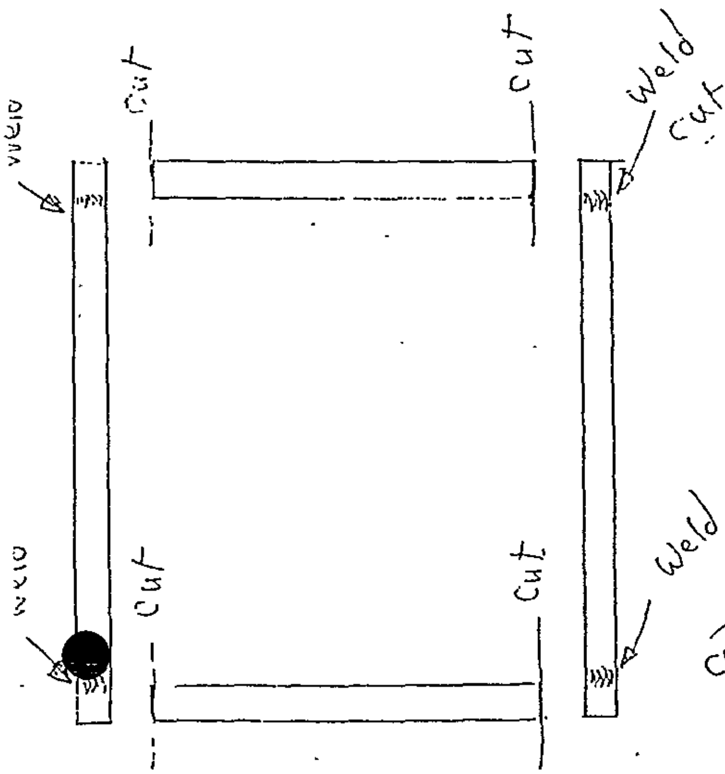


FIG.25(b)

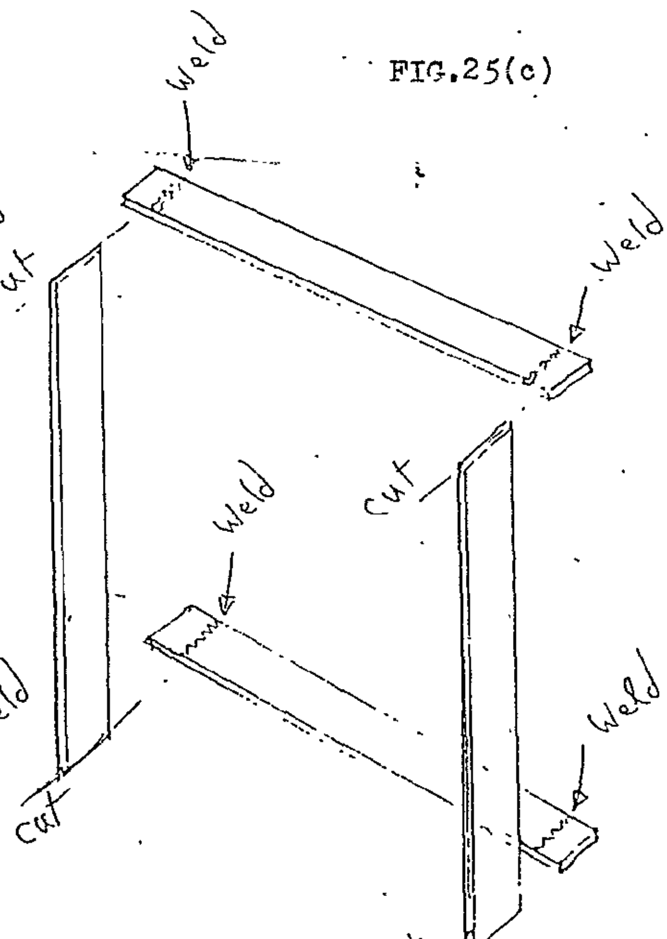
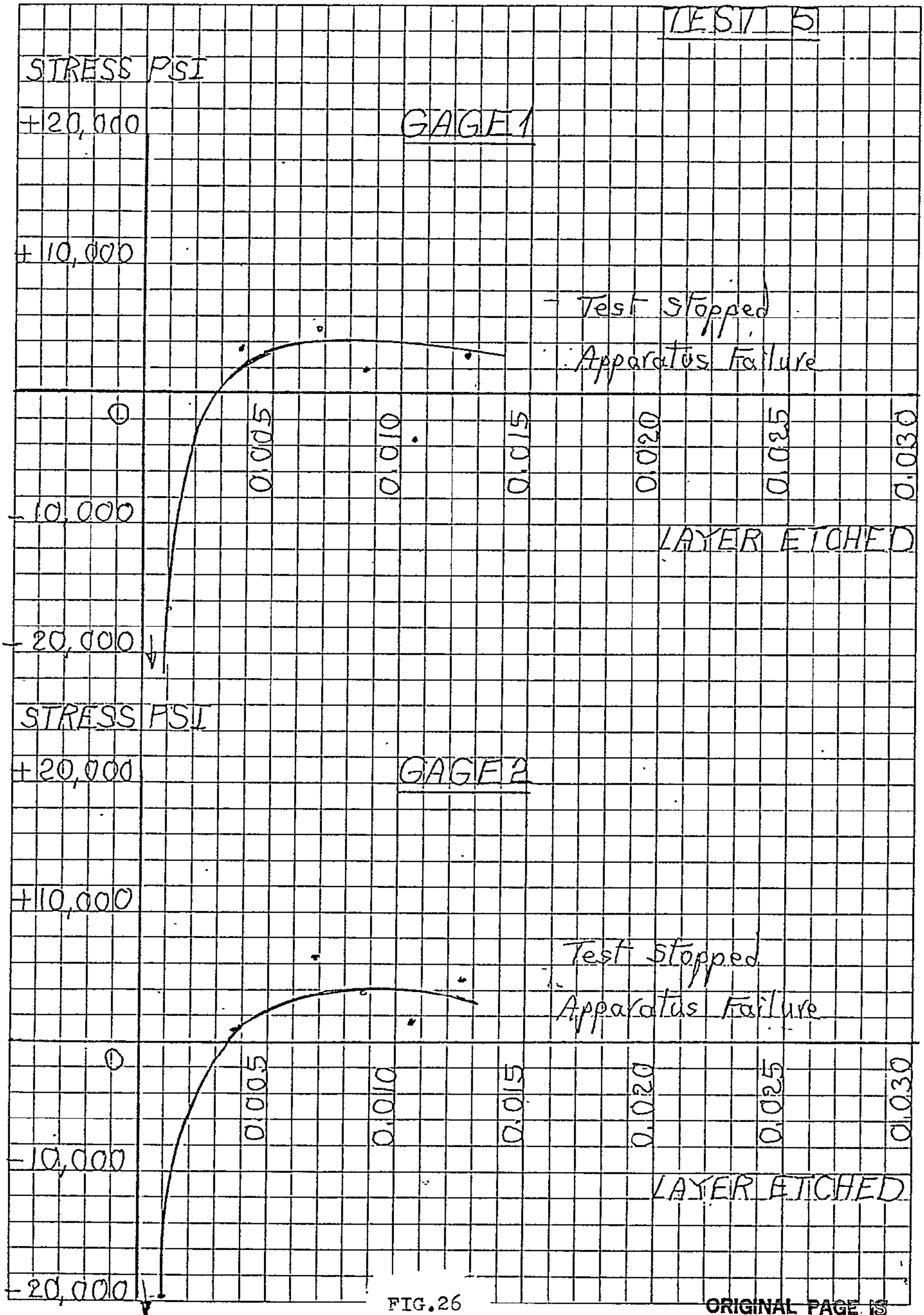


FIG.25(d)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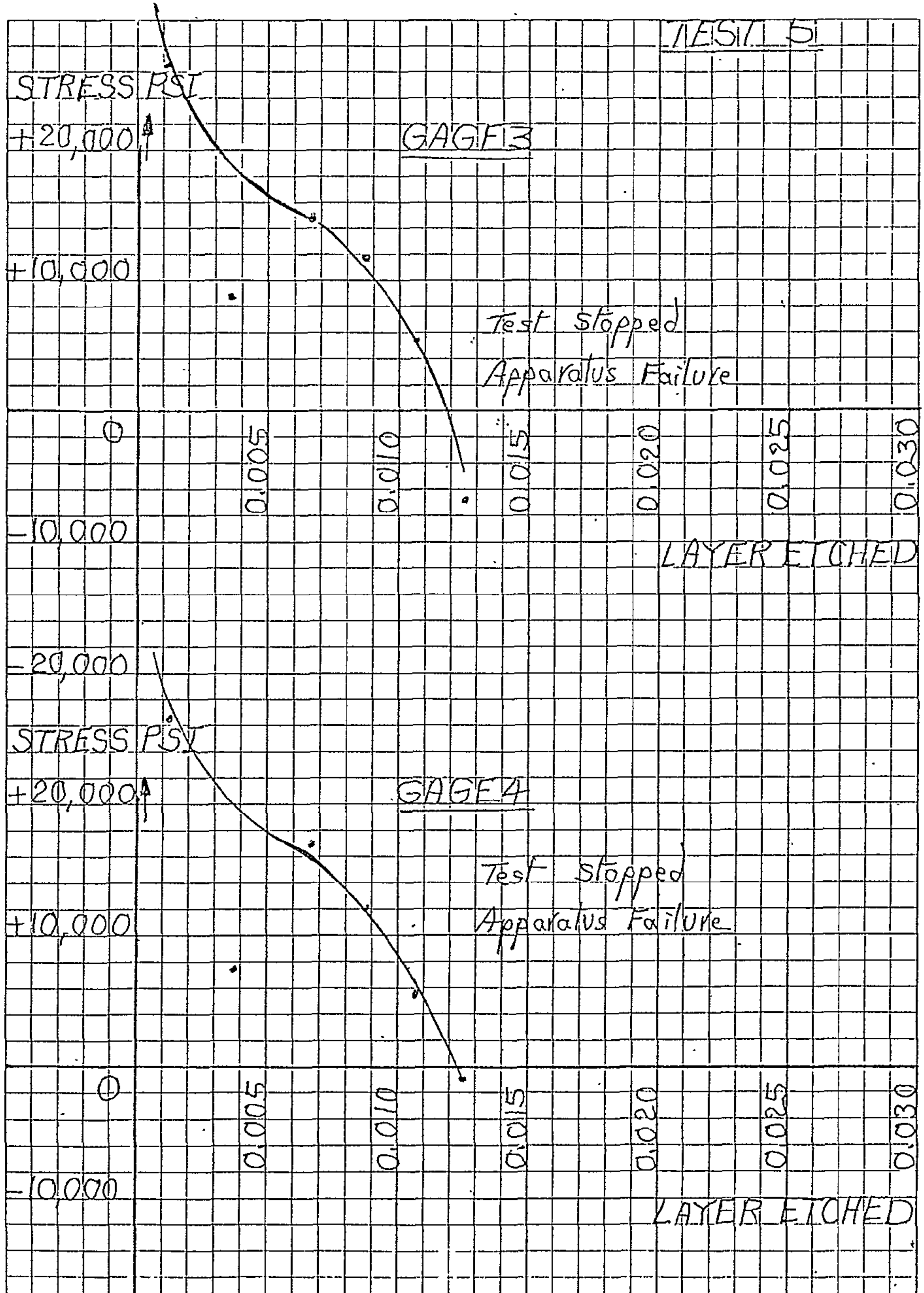
STRESS PSI
+20,000
GAGE 1
+10,000
Test Stopped
Apparatus Failure
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000
STRESS PSI
+20,000
GAGE 2
+10,000
Test stopped
Apparatus Failure
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000

FIG.26


TEST 5
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GAGE 3
+10,000
Test stopped
Apparatus Failure
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0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000
STRESS PSI
+20,000
GAGE 4
Test stopped
Apparatus Failure
+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000

FIG.27

GAGE #		1	2	3	4
LAYER	1	-66142.	-43070.	43370.	50098.
LAYER	2	-16585.	-19902.	26421.	26479.
LAYER	3	3653.	1006.	8399.	7611.
LAYER	4	4942.	6398.	15467.	16943.
LAYER	5	1936.	3749.	11856.	11970.
LAYER	6	-1556.	1509.	5373.	5485.
LAYER	7	2903.	1477.	-2202.	-232.

ENTER THE NAME FOR A NEW FILE FORSTORAGE
TS13.RES

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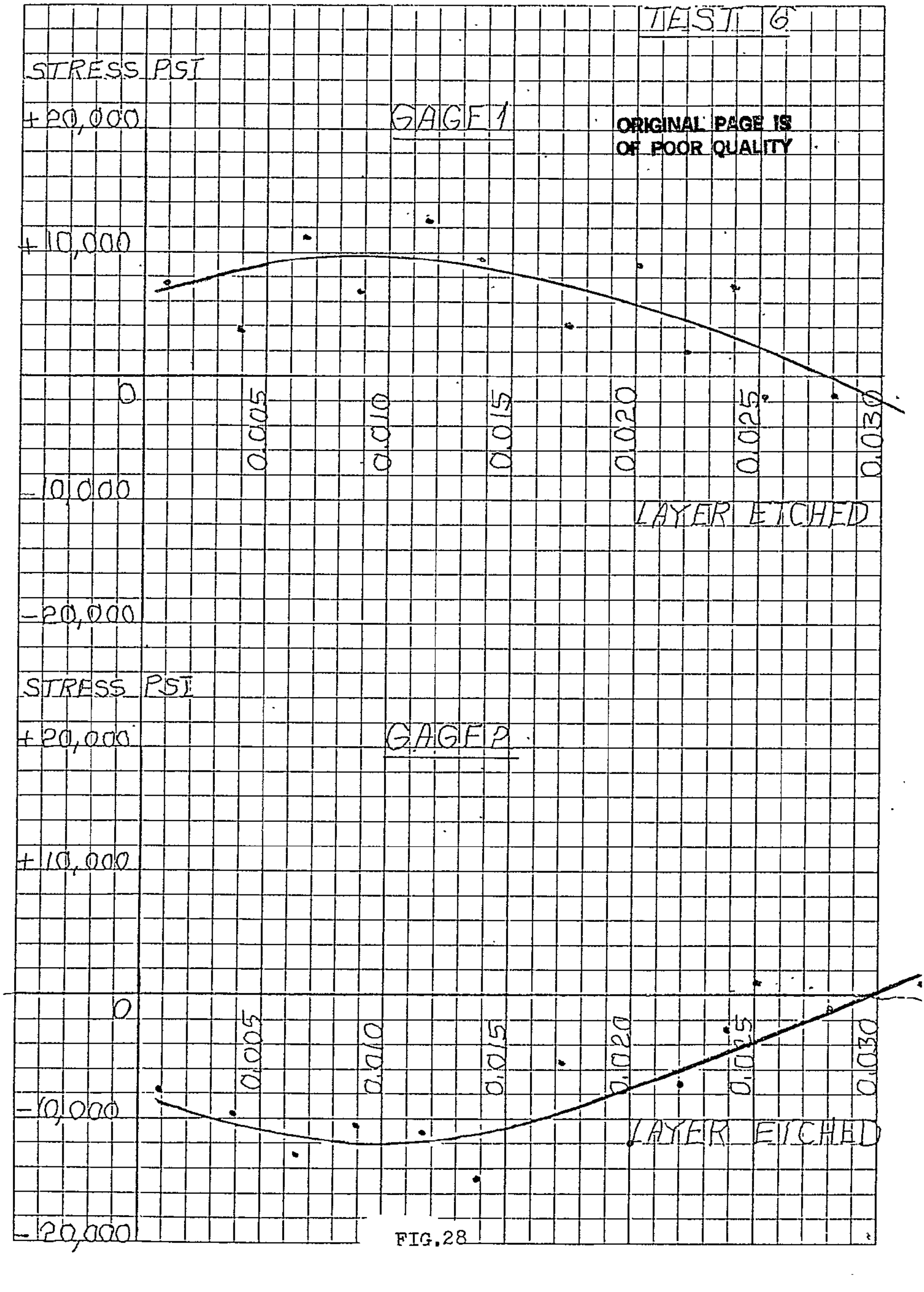
EXIT


TEST 6
STRESS PSI
+20,000
GAGE 1
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+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000
STRESS PSI
+20,000
GAGE 2
+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000

FIG.28

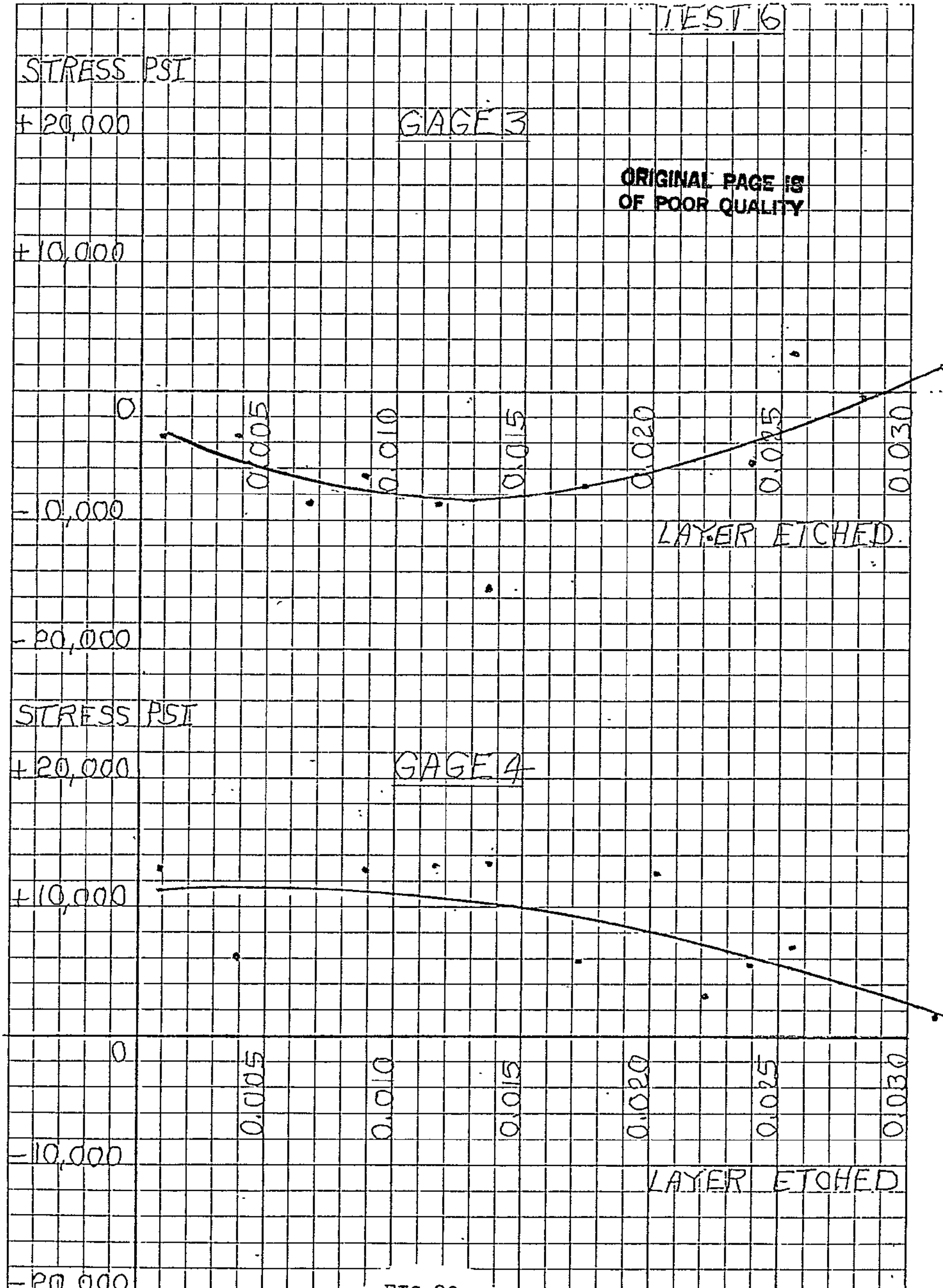

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FIG.29

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	GAGE #	1	2	3	4	5
LAYER	1	7563.	-7564.	-3792.	13257.	
LAYER	2	6910.	-9433.	-3796.	5922.	
LAYER	3	10798.	-13209.	-8616.	21425.	
LAYER	4	6476.	10317.	-6308.	12764.	
LAYER	5	12455.	11379.	9019.	13296.	
LAYER	6	9499.	-14877.	-15706.	13571.	
LAYER	7	4067	-5528.	-7245.	5799.	
LAYER	8	8940.	-12034.	-21060.	13301.	
LAYER	9	1942.	-7180.	-11386.	2955.	
LAYER	10	2411.	-2031.	-5474.	5667.	
LAYER	11	-1018.	1028.	2992.	6785.	
LAYER	12	-1164.	-1128.	-987.	11994.	
LAYER	13	1568.	670.	1069.	1525.	

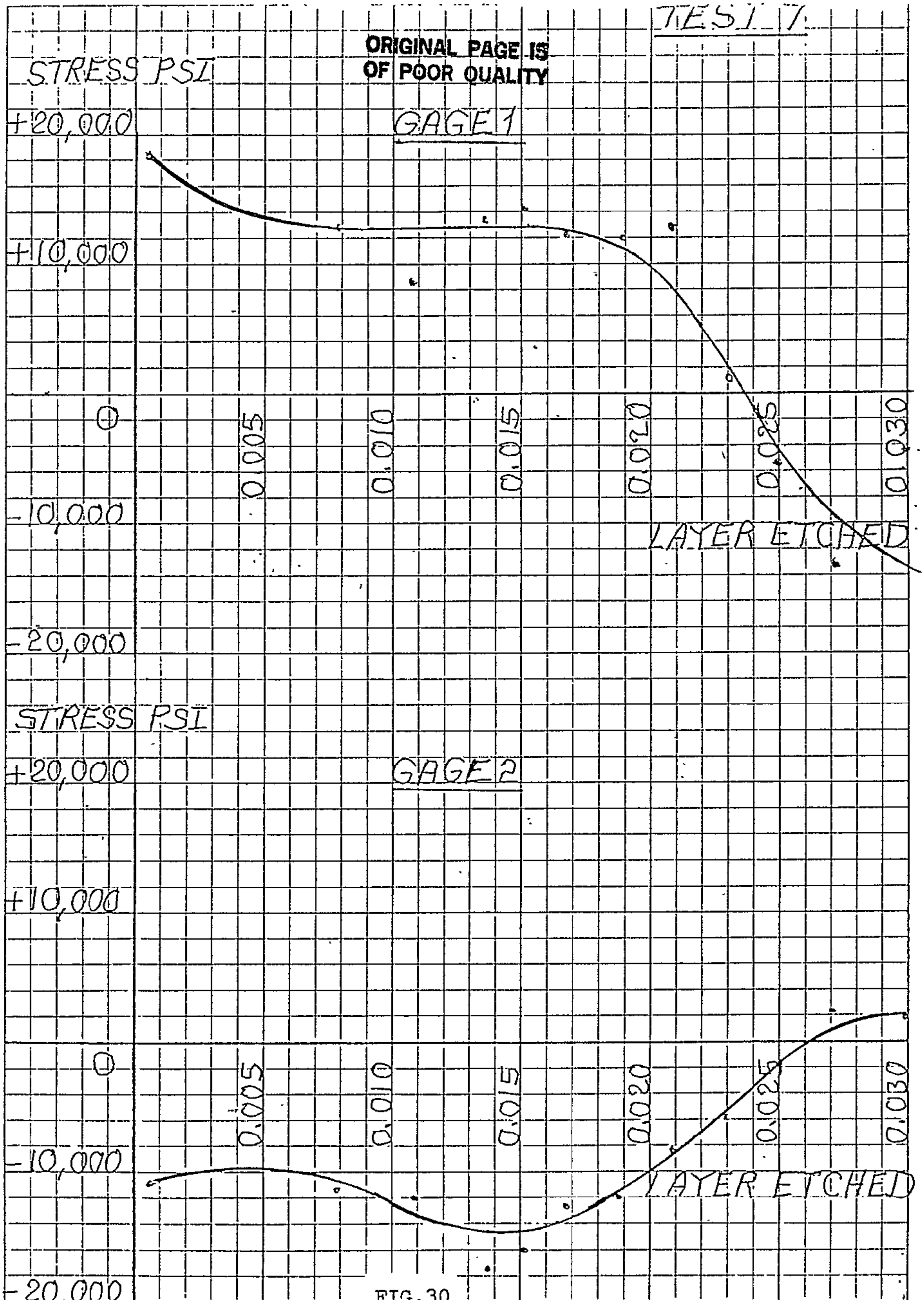
TEST 7
STRESS PSI
+20,000
GAGE 1
+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000
STRESS PSI
+20,000
GAGE 2
+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000

FIG. 30

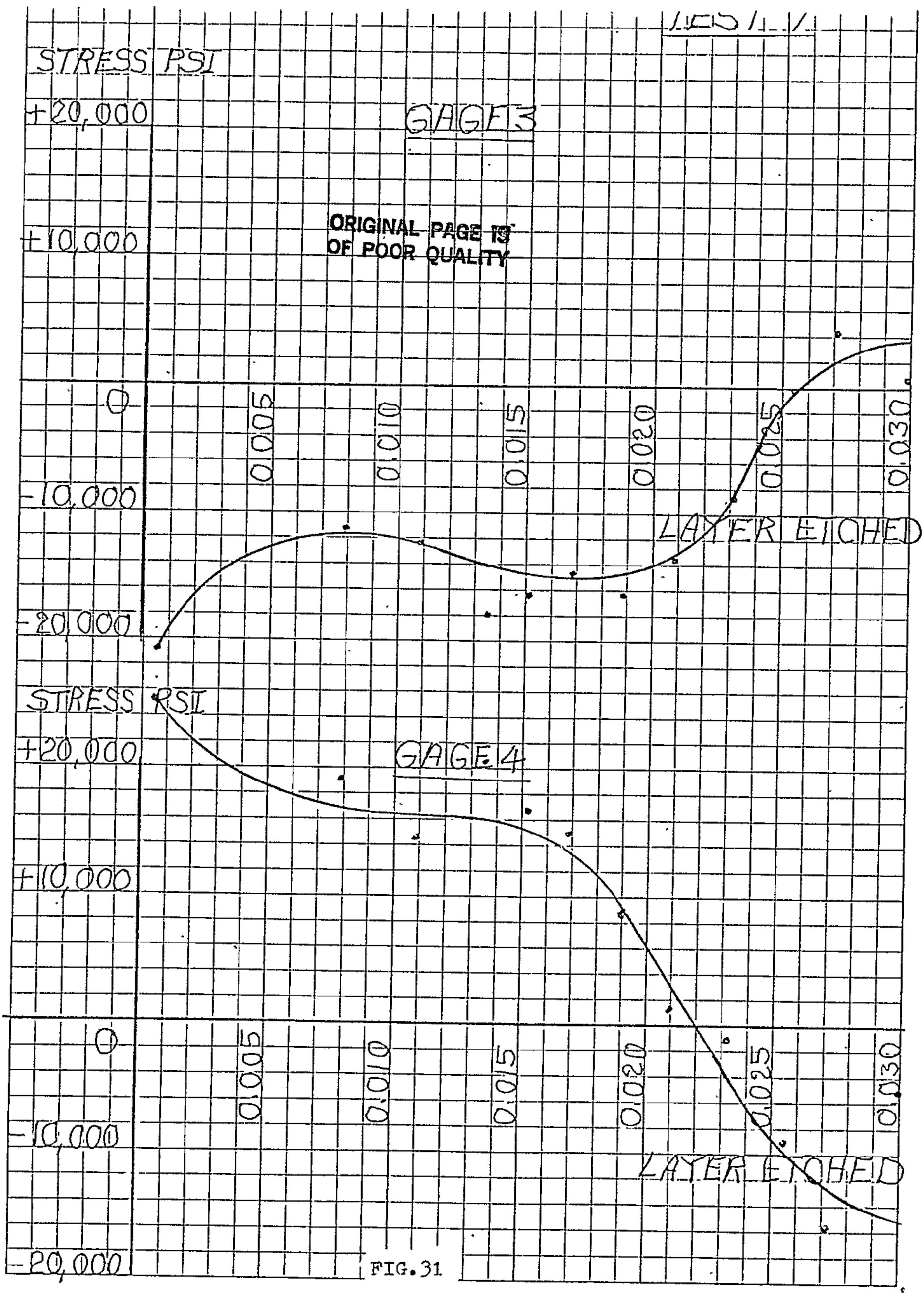
TEST 7
STRESS PSI
+20,000
GAGE 3
+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000
STRESS PSI
+20,000
GAGE 4
+10,000
0
0.005
0.010
0.015
0.020
0.025
0.030
-10,000
LAYER ETCHED
-20,000

FIG. 31

```
LAYER   1   18133.-10880.-21759. 25386.
LAYER   2    6444. -5098. -6500.  5941.
LAYER   3   12963.-11224.-11504. 19077.
LAYER   4    8638.-12038.-12313. 14435.
LAYER   5   13784.-17762.-18032. 20436.
LAYER   6   14023.-16091.-16358. 16804.
LAYER   7   12276.-12404.-14650. 15091.
LAYER   8   11905.-12032.-16329.  8805.
LAYER   9   13213. -8225.-13823.  1128.
LAYER  10    1271. -6028. -8520. -1179.
LAYER  11   -7789. -1496.  -394. -9366.
LAYER  12  -13536.  2184.  4246.-16068.
LAYER  13   -4336.  1896.   511. -5056.

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TST7.RES

END OF EXECUTION
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EXIT
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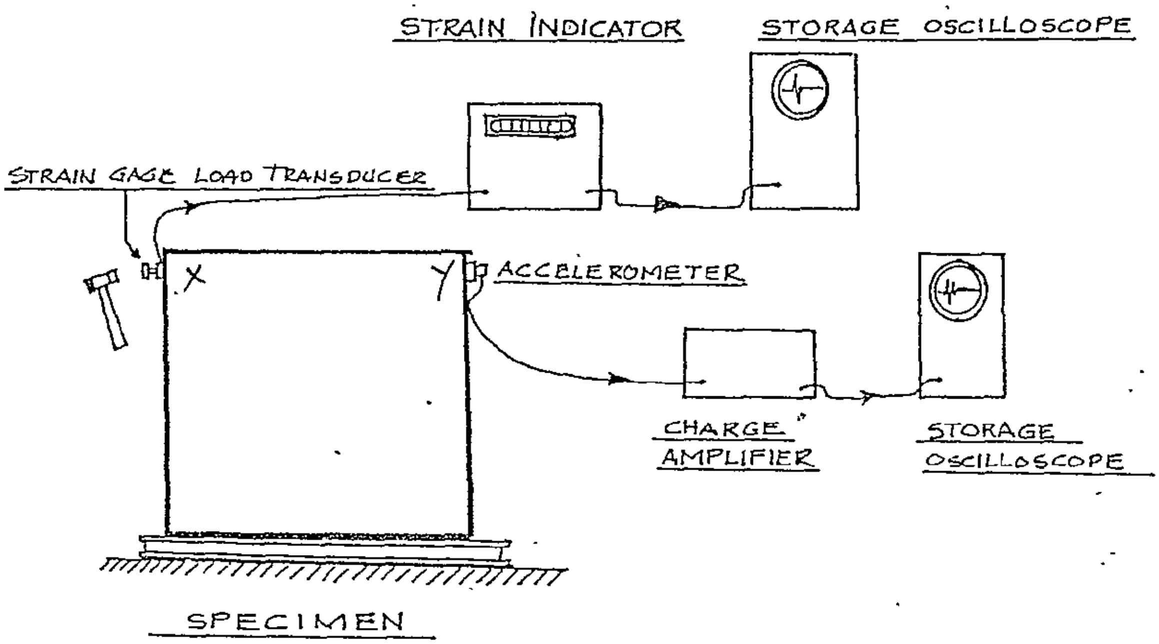
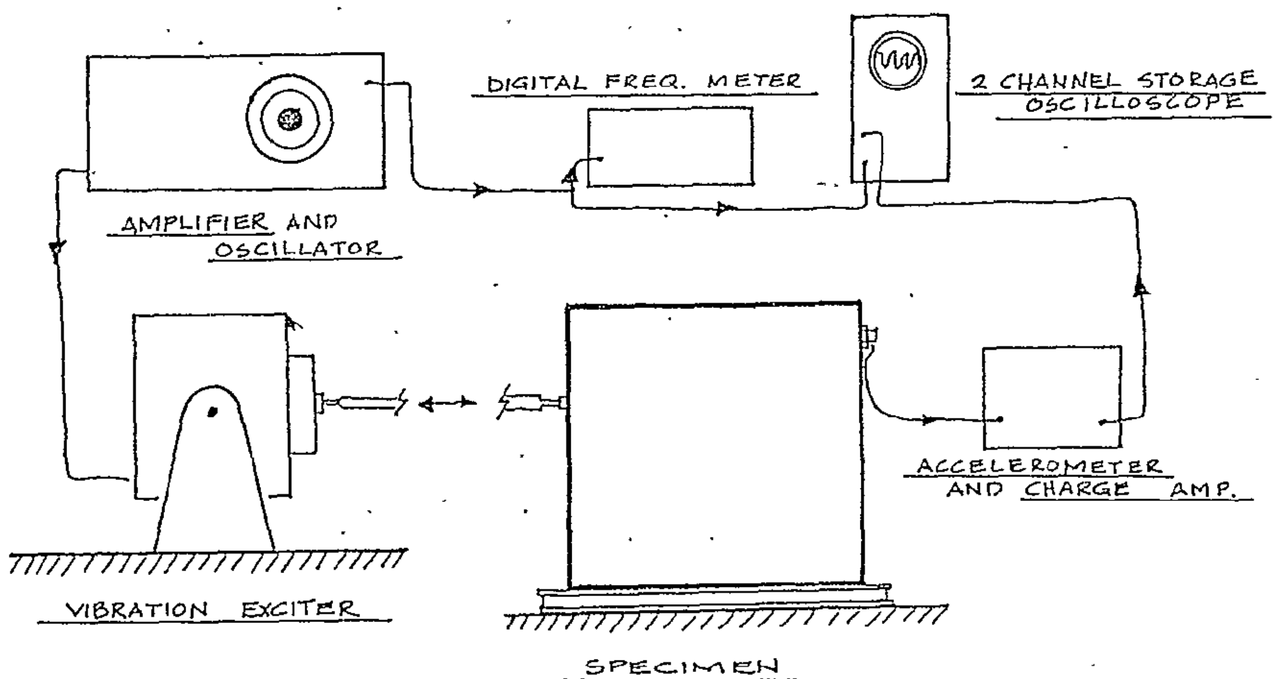


I. FREQUENCY ANALYSIS



II. VIBRATION

FIG. 32

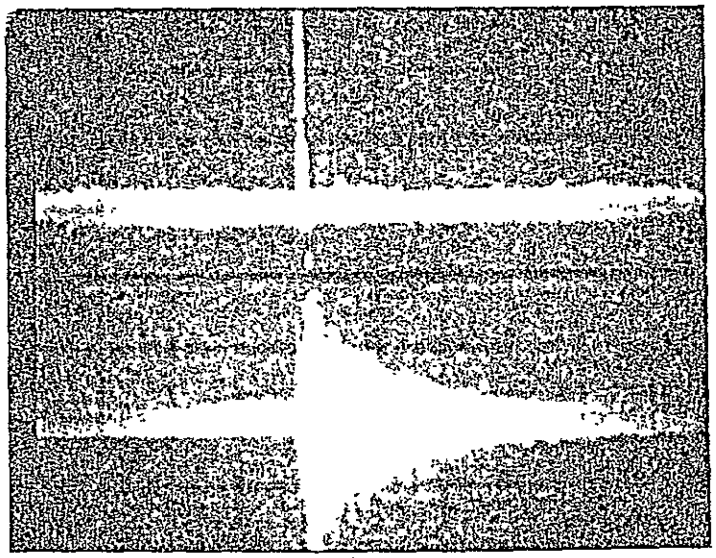


FIG. 33

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 125.00001    E=          0.31623
                 UT                        US(I)                        C(I)
       CS(I)

      0.241544  0.002881     0.608313  0.136984     0.085014      0.09777
  8

      0.905302  0.248880    -0.987671 -0.222238     0.208769      0.64760
  2

      0.013664 -0.326009     0.481282  0.022956     0.121537      0.06432
  9

     -0.833476 -1.058601    -0.298581  0.039087     0.047018      0.06127
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  5

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  3

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  1

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  3

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     -7.204051  2.752593     0.038155  0.002441     0.189442      0.00030
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11.538108	3.132050	0.049656	0.001565	0.344490	0.00068	5
3.677828	-30.716488	0.058047	0.002430	12.257801	0.00235	2
10.696361	2.466761	0.052577	0.001582	0.327823	0.00076	9
-21.783019	138.697460	-0.060146	0.001726	52.440475	0.00252	8
11.740766	2.014545	0.053590	0.001215	0.371586	0.00079	9
-14.205511	-84.279397	-0.060741	0.001310	29.701223	0.00257	9
11.208734	1.381945	0.053815	0.000834	0.361601	0.00080	6
3.468986	-25.119526	-0.060671	0.000960	8.479313	0.00257	3
11.584917	1.034872	0.053905	0.000746	0.378632	0.00080	0
2.707635	-13.013425	-0.060671	0.000549	5.100894	0.00257	4
10.795040	0.487078	0.054185	0.000410	0.355188	0.00081	7
12.061397	-9.991795	-0.060019	0.000201	1.378977	0.00251	9
10.020042	0.072639	0.061553	0.000046	1.481004	0.00105	5

NX=240 H= 0.00033 M= 8 FC= 1200.00010 BE= 375.00004 E= 0.18257

HT		HS(I)		C(I)	CS(I)
0.451908	-0.000312	0.416366	-0.045561	0.028219	0.036160
-0.010567	-0.161158	-0.126140	0.103135	0.006205	0.000954
1.875225	-0.353666	-0.044466	-0.035834	0.022090	0.000146
-1.251191	-0.444802	0.112383	0.035611	0.002823	0.002055
1.302220	-0.112088	-0.075498	-0.010375	0.073307	0.001181
-0.324424	-0.456504	0.103622	0.009900	0.000571	0.001924
1.488197	-0.048239	-0.068860	-0.002534	0.314333	0.001000
-0.199735	-0.160803	0.096749	0.002511	0.000094	0.001692
1.591380	-0.001024	-0.084116	-0.000703	0.082279	0.001494

[illegible]

12.50000	0.7861853E-04	-0.1564026E-03	-1.989386
25.00000	0.1000000E-02	0.0000000E+00	0.0000000E+00
~~37.50000~~	~~-150.9785~~	~~139.0576~~	~~0.9210420~~
50.00000	111.8163	-63.26190	-0.5657661
62.50000	-82.74754	-85.11066	1.028558
75.00000	45.71558	-324.8166	-7.105162
87.50000	-173.6392	-422.6140	2.433863
100.0000	46.19609	18.09390	0.3916761
112.5000	-119.2011	-242.3333	1.624205
125.0000	192.5251	236.0914	1.226289
137.5000	8.198017	51.83154	6.322448
150.0000	187.9613	225.0673	1.197413
162.5000	-0.9405687	263.4407	-280.0866
175.0000	82.68034	-292.6387	-3.539399
187.5000	-53.19046	-323.6385	6.084521
200.0000	151.6819	-224.8064	-1.482091
212.5000	76.18889	12.51051	0.1642038
225.0000	199.6640	-27.67320	-0.1385989
237.5000	136.1775	-112.6739	-0.8274047
250.0000	71.35597	-7.937418	-0.1112369
262.5000	53.99740	245.4271	4.545165
275.0000	42.51398	291.8554	6.864927
287.5000	94.39206	455.5269	4.825903
300.0000	97.52081	-242.4269	-2.485899
312.5000	160.0996	25.07870	0.1566443
325.0000	11.31685	-188.9824	-16.26795
337.5000	84.03408	-145.5217	-1.731698
350.0000	-59.75730	5.382805	-0.9007778E-01
362.5000	44.49602	-60.72386	-1.364703
375.0000	-15.09106	22.07986	-1.463109
387.5000	78.57802	-254.6479	-3.240702
400.0000	-20.61485	212.9392	-10.32941
412.5000	56.17418	177.8973	3.166887
425.0000	-61.24784	184.5940	-3.013887
437.5000	21.42395	-105.3154	-4.915782
450.0000	-53.58968	-168.6844	3.147703
462.5000	11.05934	-82.97371	-7.502595
475.0000	-43.45011	57.39591	-1.320961
487.5000	-0.6453957	81.81208	-126.7627
500.0000	-28.93555	-107.7104	3.722424
512.5000	11.73539	-0.8802552	-0.7500862E-01
525.0000	-14.26173	-84.46985	5.922835
537.5000	15.49726	54.20937	3.497998
550.0000	-28.59888	36.74725	-1.284919
562.5000	-3.449380	200.4197	-58.10312
575.0000	-18.94477	-19.66747	1.038148
587.5000	17.30794	-36.09905	-2.085693
~~600.0000~~	~~2.330848~~	~~-32.73435~~	~~14.04396~~
612.5000	38.12707	139.6453	3.662629

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625.0000 ,	-24.99107 ,	222.5470 ,	-8.905060 ,
~~637.5000~~ ,	~~11.93198~~ ,	~~94.35165~~ ,	~~7.907461~~ ,
650.0000 ,	-41.88533 ,	-138.8071 ,	3.313980 ,
662.5000 ,	5.385611 ,	-162.8133 ,	-30.23117 ,
~~675.0000~~ ,	~~-22.54707~~ ,	~~108.0099~~ ,	~~-4.790420~~ ,
687.5000 ,	20.16100 ,	-93.65978 ,	-4.645592 ,
700.0000 ,	-30.23576 ,	1.572905 ,	-0.5202133E-01 ,
712.5000 ,	4.366481 ,	-148.5256 ,	-34.01494 ,
725.0000 ,	-45.90525 ,	90.68083 ,	-1.975391 ,
737.5000 ,	-10.40945 ,	-25.91076 ,	2.489157 ,
750.0000 ,	-33.51018 ,	206.2403 ,	-6.154558 ,
762.5000 ,	-5.197509 ,	242.8108 ,	-46.71676 ,
775.0000 ,	-27.61350 ,	19.77407 ,	-0.7161016 ,
787.5000 ,	-9.874155 ,	10.87199 ,	-1.101055 ,
800.0000 ,	-32.09090 ,	-253.7132 ,	7.906079 ,
812.5000 ,	-18.21086 ,	0.9956197 ,	-0.5467175E-01 ,
825.0000 ,	-25.96596 ,	11.32470 ,	-0.4361362 ,
837.5000 ,	-19.21392 ,	53.65513 ,	-2.792513 ,
850.0000 ,	-18.80778 ,	-21.48460 ,	1.142325 ,
862.5000 ,	-19.47731 ,	-136.1321 ,	6.989265 ,
875.0000 ,	-12.75355 ,	221.8886 ,	-17.39818 ,
887.5000 ,	-15.11855 ,	209.0619 ,	-13.82818 ,
900.0000 ,	-8.093527 ,	99.98973 ,	-12.35428 ,
912.5000 ,	-14.31376 ,	58.95194 ,	-4.118549 ,
925.0000 ,	-10.49673 ,	-184.1631 ,	17.54480 ,
937.5000 ,	-19.81569 ,	-308.1110 ,	15.54884 ,
950.0000 ,	-5.002851 ,	13.33428 ,	-2.665337 ,
962.5000 ,	-12.11855 ,	-429.6819 ,	35.45655 ,
975.0000 ,	4.570205 ,	284.2736 ,	62.20151 ,
987.5000 ,	-3.072534 ,	-307.9075 ,	100.2129 ,
1000.000 ,	-2.882151 ,	406.1298 ,	-140.9121 ,
1012.500 ,	-11.96455 ,	-86.44149 ,	7.224801 ,
1025.000 ,	-8.237401 ,	1175.530 ,	-142.7064 ,
1037.500 ,	-14.57576 ,	1153.159 ,	-79.11487 ,
1050.000 ,	2.722073 ,	-1386.622 ,	-5[illegible]0

12.50000 ,	0.9536743E-06,	0.0000000E+00,	0.0000000E+00,
37.50000 ,	-54.24877 ,	47.42885 ,	-0.8742844 ,
62.50000 ,	-29.24072 ,	-16.64006 ,	0.5690713 ,
87.50000 ,	-56.99455 ,	-140.9965 ,	2.473858 ,
112.5000 ,	-56.77778 ,	-80.15561 ,	1.411743 ,
137.5000 ,	-4.512192 ,	23.81135 ,	-5.277114 ,
162.5000 ,	5.146555 ,	141.1951 ,	27.43488 ,
187.5000 ,	-18.84820 ,	-46.67597 ,	2.476416 ,
212.5000 ,	13.15314 ,	13.08460 ,	0.9947892 ,
237.5000 ,	50.58742 ,	-14.64900 ,	-0.2895780 ,
262.5000 ,	28.87008 ,	-0.3034998 ,	-0.1051261E-01,
287.5000 ,	24.20383 ,	142.2461 ,	5.877008 ,
312.5000 ,	56.07147 ,	-23.70649 ,	-0.4227906 ,
337.5000 ,	47.29784 ,	-84.33347 ,	-1.783030 ,
362.5000 ,	19.30187 ,	-50.49999 ,	-2.616326 ,
387.5000 ,	25.67358 ,	-72.92706 ,	-2.840548 ,
412.5000 ,	30.21515 ,	7.464522 ,	0.2470456 ,
437.5000 ,	15.33736 ,	-96.77225 ,	-6.309578 ,
462.5000 ,	7.715114 ,	-38.39276 ,	-4.976305 ,
487.5000 ,	3.225154 ,	12.40730 ,	3.847043 ,
512.5000 ,	1.059259 ,	-22.48950 ,	-21.23136 ,
537.5000 ,	7.400002 ,	-55.50004 ,	-7.500004 ,
562.5000 ,	4.095055 ,	-14.91915 ,	-3.643211 ,
587.5000 ,	-0.9974161 ,	26.91895 ,	-26.98868 ,
612.5000 ,	11.20194 ,	-24.05212 ,	-2.147138 ,
637.5000 ,	15.54183 ,	104.4684 ,	6.721759 ,
662.5000 ,	3.511331 ,	25.97452 ,	7.397344 ,
687.5000 ,	3.852908 ,	-33.09186 ,	-8.588801 ,
712.5000 ,	9.800625 ,	-42.00000 ,	-4.285441 ,
737.5000 ,	1.654088 ,	-68.72238 ,	-41.54698 ,
762.5000 ,	-4.561670 ,	-9.552348 ,	2.094046 ,
787.5000 ,	-1.999923 ,	120.5270 ,	-60.26585 ,
812.5000 ,	-4.480295 ,	9.347021 ,	-2.086251 ,
837.5000 ,	-9.190781 ,	-4.180703 ,	0.4548800 ,
862.5000 ,	-10.28128 ,	22.37312 ,	-2.176104 ,
887.5000 ,	-11.05180 ,	-116.8240 ,	10.57059 ,
912.5000 ,	-9.470908 ,	91.50858 ,	-9.662071 ,
937.5000 ,	-8.621144 ,	37.65340 ,	-4.367564 ,
952.5000 ,	-12.75634 ,	-226.7350 ,	-17.77430 ,
987.5000 ,	-10.82858 ,	-298.1550 ,	27.53409 ,

25.00000	0.1000000E-02	0.0000000E+00	0.0000000E+00
50.00000	36.46849	-19.62529	-0.5381439
75.00000	15.92929	-110.0183	-6.906667
100.0000	10.49614	-18.25453	-1.739165
125.0000	56.99547	58.36524	1.024033
150.0000	66.17998	67.27688	1.016575
175.0000	28.82285	51.31708	-1.780430
200.0000	39.69564	-106.6420	-2.686491
225.0000	68.77678	52.03100	0.7565199
250.0000	36.26049	26.46629	0.7298932
275.0000	8.701916	150.1402	17.25369
300.0000	29.80191	40.48984	1.358632
325.0000	19.88465	-87.31516	-4.391083
350.0000	-17.45667	-64.09554	3.671694
375.0000	-13.85749	-9.526278	0.6874462
400.0000	-1.496063	-33.65305	22.49441
425.0000	-15.64992	99.52728	-6.359603
450.0000	-22.06526	-33.38540	1.513030
475.0000	-16.67005	14.62798	-0.8775005
500.0000	-14.00691	66.00872	-4.712583
525.0000	-6.658938	-9.801565	1.471941
550.0000	-5.500004	-2.500011	0.4545471
575.0000	-11.25104	8.877078	-0.7890005
600.0000	-3.312222	-74.69887	22.55250
625.0000	0.9359885	-3.712527	-3.966424
650.0000	-13.28712	38.96610	-2.932623
675.0000	-16.90037	-88.33668	5.226908
700.0000	-8.987985	57.63683	-6.412654
725.0000	-14.72352	8.660257	-0.5881922
750.0000	-21.28416	54.08127	-2.540916
775.0000	-15.35607	105.3673	-6.861604
800.0000	-13.08668	4.758537	-0.3636169
825.0000	-15.63874	-135.9833	8.695286
850.0000	-12.91840	9.171346	-0.7099443
875.0000	-9.238415	3.005097	-0.3252827
900.0000	-6.199382	95.14196	-15.34701
925.0000	-3.252385	78.96177	-24.27811
950.0000	-4.558754	-110.5741	24.25533
975.0000	-3.021162	-93.85307	31.06523
1000.000	3.830004	13.40832	3.500863

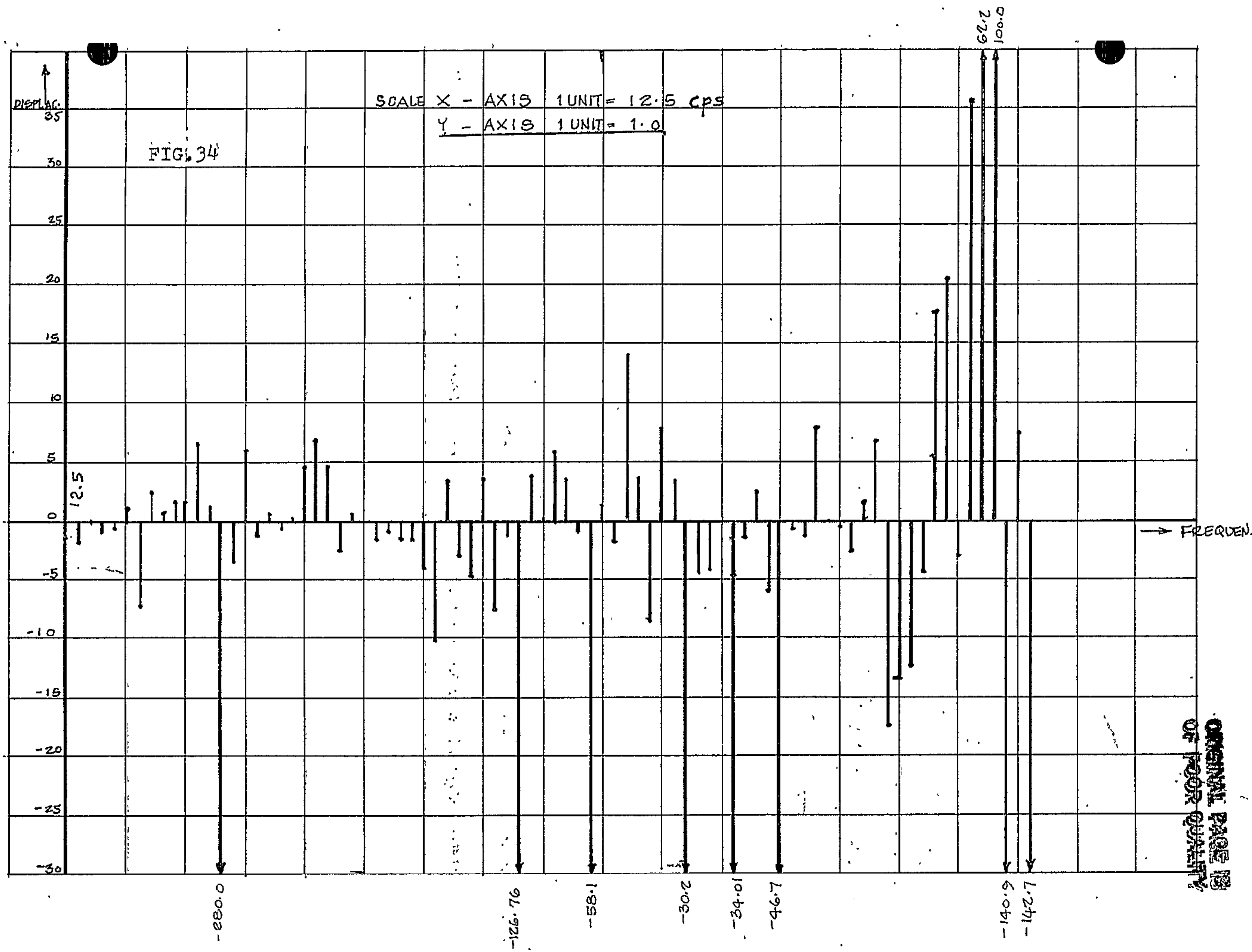
SCALE X - AXIS 1 UNIT = 12.5 CPS
Y - AXIS 1 UNIT = 1.0
DISPLAC.
FREQUEN.
12.5
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
62.2
100.0
-280.0
-126.76
-58.1
-30.2
-34.01
-46.7
-140.9
-142.7

FIG. 34

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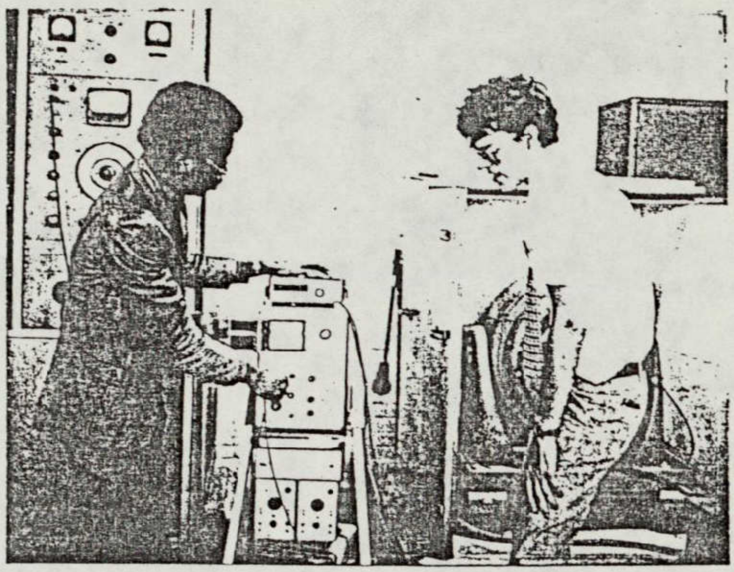
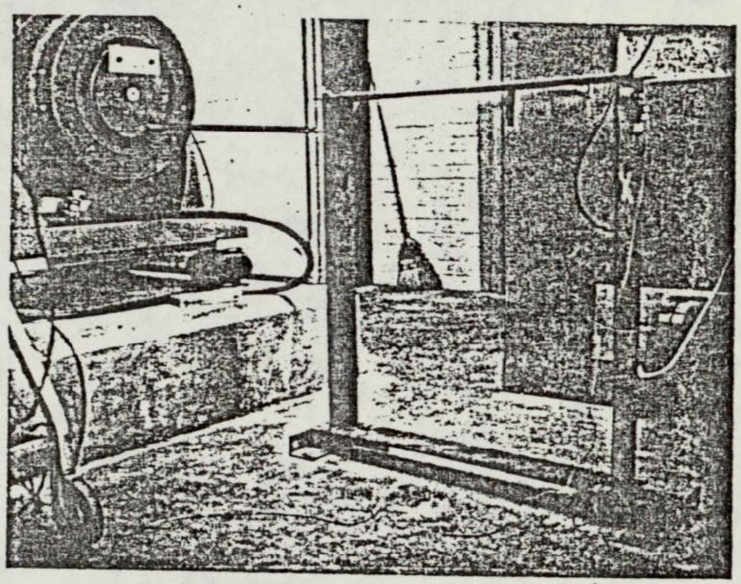


	GAGE #	1	2	3	4	5
LAYER	1	2216.	-1478.	0.	2216.	
LAYER	2	3254.	915.	-1028.	3254.	
LAYER	3	2791.	-1691.	-1694.	1973.	
LAYER	4	3485.	1826.	1823.	2433.	
LAYER	5	2489.	563.	1172.	2377.	
LAYER	6	3519.	2722.	4132.	3410.	
LAYER	7	4243.	-989.	2457.	1912.	



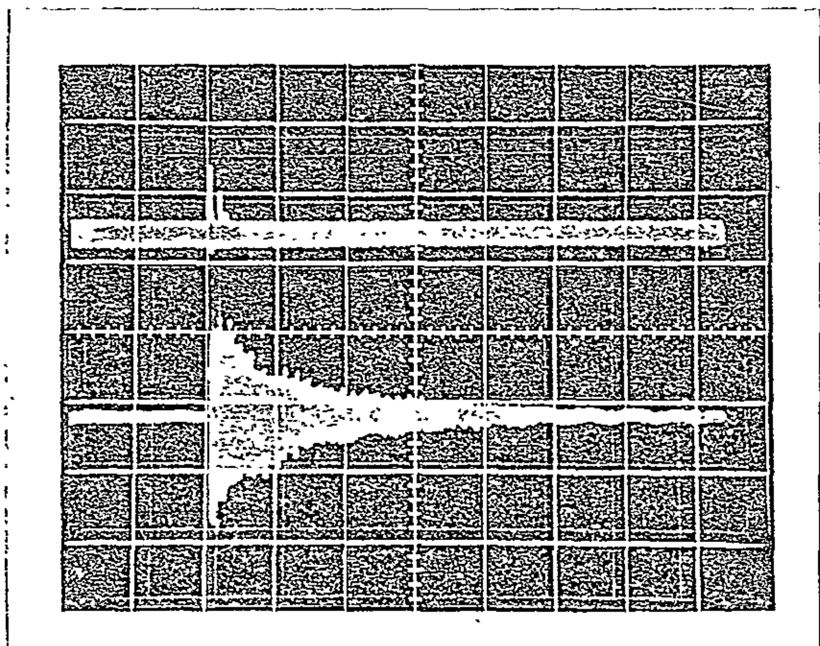


FIG.35

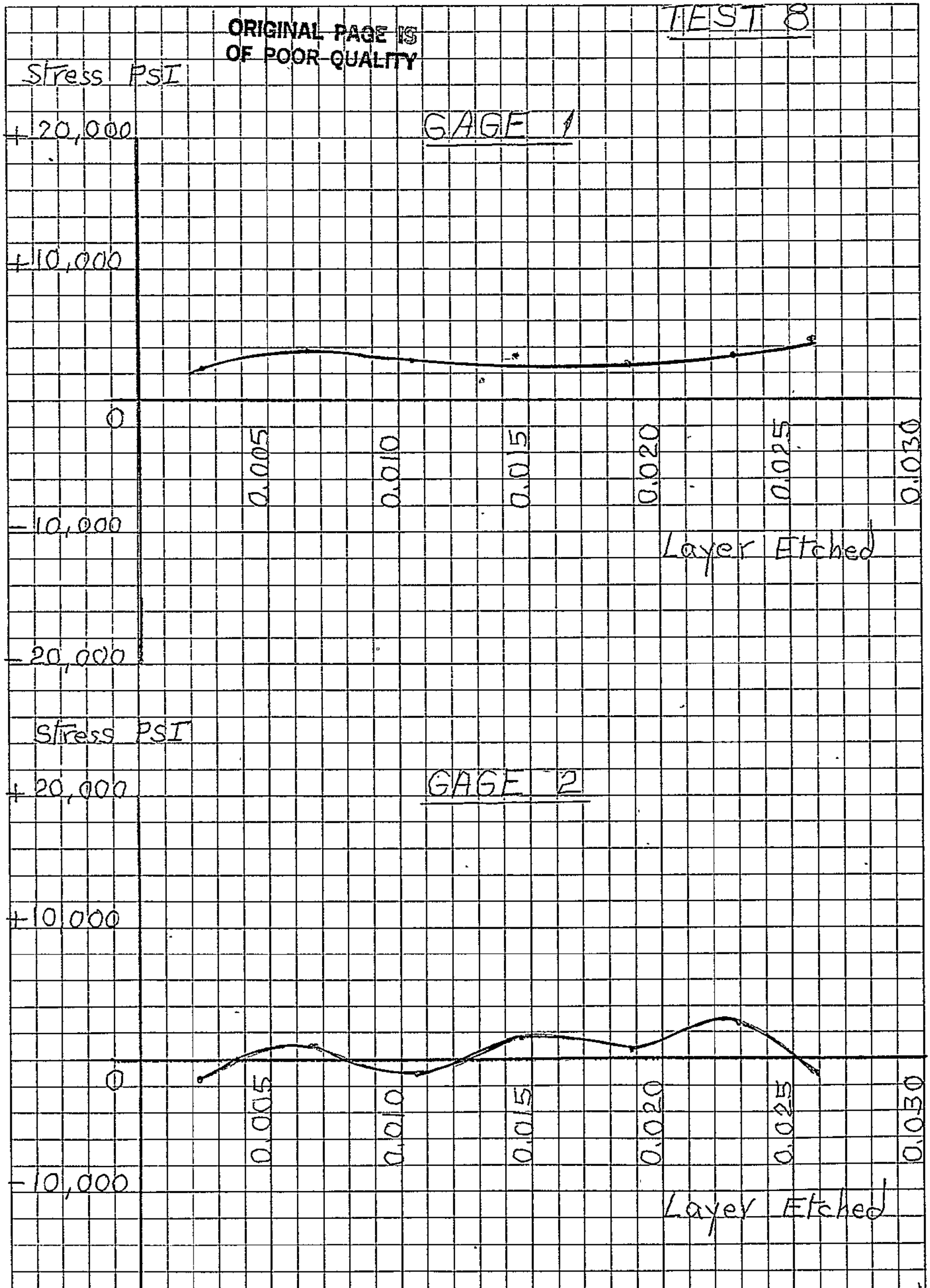

TEST 8
Stress PSI
GAGE 1
+20,000
+10,000
0
-10,000
-20,000
0.005
0.010
0.015
0.020
0.025
0.030
Layer Etched
Stress PSI
GAGE 2
+20,000
+10,000
0
-10,000
-20,000
0.005
0.010
0.015
0.020
0.025
0.030
Layer Etched

FIG. 36

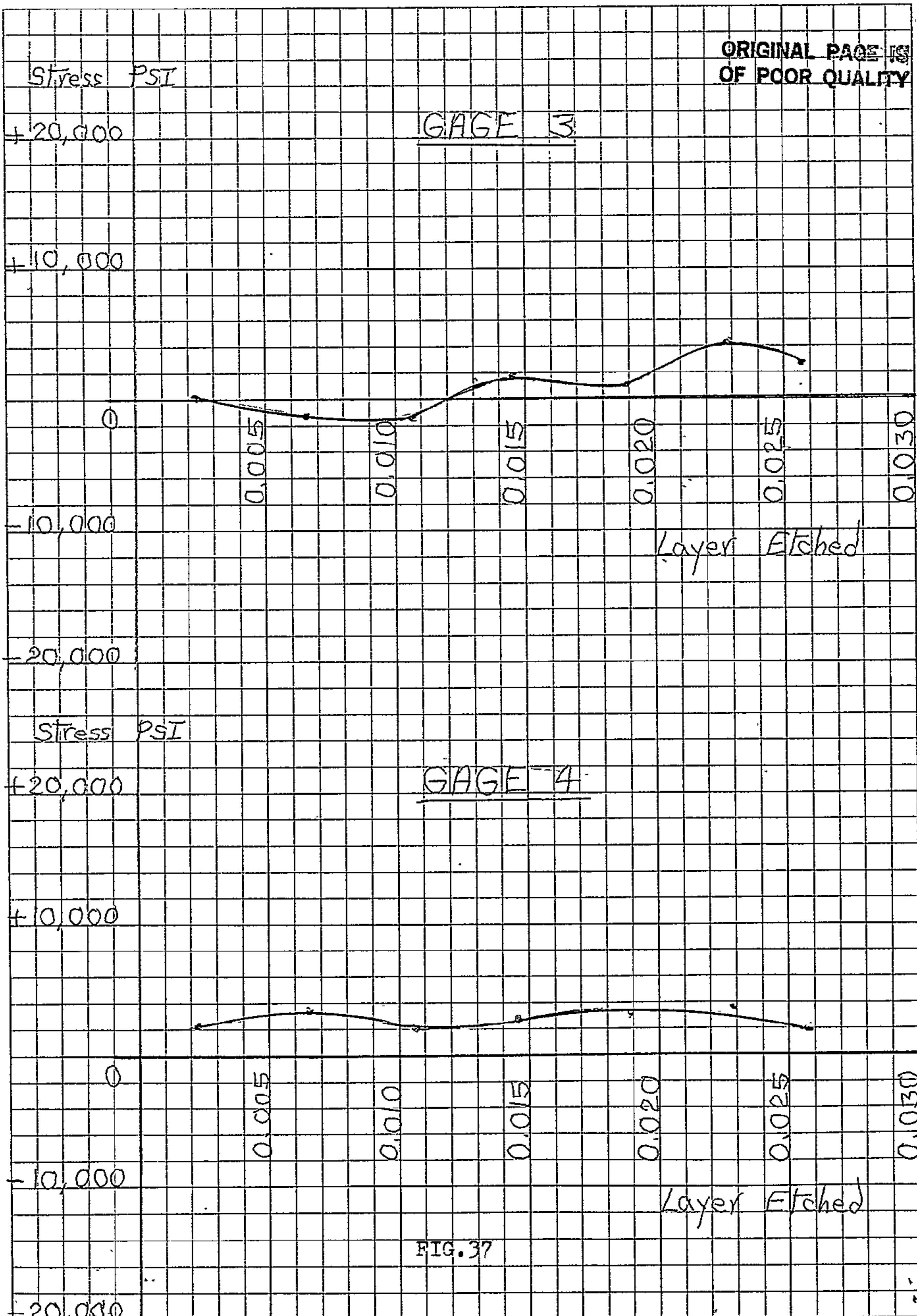

Stress PSI
GAGE 3
+20,000
+10,000
0
-10,000
-20,000
0.005
0.010
0.015
0.020
0.025
0.030
Layer Etched
Stress PSI
GAGE 4
+20,000
+10,000
0
-10,000
-20,000
0.005
0.010
0.015
0.020
0.025
0.030
Layer Etched

FIG. 37

PART THREE

The welded steel boxes studied during the period from April 15 to November 15, 1979 were formed of bars 4, 6 and 8 inches wide and $\frac{1}{4}$ and $\frac{1}{2}$ inch thick. They had various shapes, Table 1, and other complex shapes are planned for the coming study period.

Figs. 38-58 show the results of the tests conducted on seven sets of boxes. Each set of boxes was subjected to three phases of testing. The first phase of the study examined the residual stress distribution across the thickness of each bar and at various locations along the bar directly after welding. Both the theory and the technique for such analysis together with the developed computer program for stress calculation have been presented.

The second phase showed the results of impact testing using a load cell, an accelerometer and an oscilloscope. The study was performed on a second box identical to the one examined in the first phase. This phase also analyzed the pulses, applying the computer programs presented at the end of this report & the chart of displacement vs, the frequency of vibration. A specific frequency was chosen to be within 100 cps that showed a peak displacement.

For the third phase of the study the second box was fixed on the floor facing the mechanical vibrator. A steel rod of L-section, with welded studs at both ends, was used to connect the box to the vibrator. Other designs will also be used to suit other shapes of boxes for future investigation. Each box was vibrated at the chosen frequency for 15 minutes. The vibration was resonant and was felt through the metallic frame. Following the vibration, the box was sectioned and studied for stress distribution as previously carried out in the first phase.

Tests numbers 3 and 7 are not complete yet; with phases 2 and 3 of test 3 and phase 3 of test 7 still under investigation.

Handling the vibrator was very successful during this period of the study and its manual control confirmed the peak that was chosen from the pulse analysis for each box.

Most of the pulse results indicated that a suitable frequency within 100 cps can be used to give a peak displacement which reduces fatigue of the metal to a minimum level.

SUMMARY OF TESTS PRESENTED IN THIS REPORT

TEST NO.		FIG. NO.	BOX SHAPE	NATURE OF TEST	LENGTH x WIDTH x DEPTH x WALL THICK.	STRAIN GAUGE ARRANGEMENT	REMARKS
1	a	1		(a) Stresses Before Vibration (b) Impact Test (c) Stresses After Vibration	36"x36x6"x¼"		Tests 3&4 1st report
	b	2					Fig.11 of 2nd rep.
	c	3					
2	a	4			36"x36"x4"x½"		Test 7 of 2nd.rep.
	b	5					
	c	6					Figs.13&14 of 2nd.R
3	a	7			36"x36"x6"x¼"		Test 5 of 2nd. rep.
	b	8					
	c	9					
4	a	10			36"x36"x4"x½"		
	b	11					
	c	12					
5	a	13			36"x36"x4"x¼" Flat		Test 6 of 2nd rep.
	b	14					
	c	15					
6	a	16			36"x36"x8"x¼"		
	b	17					
	c	18					
7	a	19			36"x36"x8"x½"		
	b	20					
	c	21					

TABLE 1

```
TYPE TST2B.RES
  2480.000     , 8, 4,   2.070000     ,   10.00000     ,   10.00000     ,   21.0000
0     ,   37.00000     ,   13.00000     ,
  35.00000     ,   24.00000     ,   15.00000     ,  -5.000000     ,   2.000000     ,
  6.000000     ,   4.000000     ,  -2.000000     ,
  2.000000     ,   4.000000     ,   1.000000     ,  0.0000000E+00,  -2.000000     ,
 0.0000000E+00,  -2.000000     ,  -2.000000     ,
 -2.000000     ,  -2.000000     ,  0.0000000E+00,   2.000000     ,  0.0000000E+00,
 -3.000000     ,  -1.000000     ,   3.000000     ,
  3.000000     ,  -1.000000     ,  -2.000000     ,   3.000000     ,   2.000000     ,
 0.0000000E+00,   1.000000     ,   2.000000     ,
  2.000000     ,  0.0000000E+00,  0.0000000E+00,   2470.000     ,   2460.000     ,
  2439.000     ,   2402.000     ,   2389.000     ,
  2354.000     ,   2330.000     ,   2315.000     ,  -17799.41     ,   7119.763     ,
  21359.29     ,   14239.53     ,  -7379.010     ,
  7206.062     ,   14527.42     ,   3775.979     ,  -400.4290     ,  -3096.082     ,
  572.4406     ,  -3039.326     ,  -2233.416     ,
 -1729.047     ,  -1277.901     ,   166.8236     ,   4784.811     ,  -4.885372     ,
 -7490.035     ,  -2478.878     ,   2482.407     ,
  2857.023     ,  -692.8616     ,  -1803.351     ,   3957.442     ,   2938.583     ,
  199.1129     ,   1374.969     ,   4405.643     ,
  4711.044     ,   196.4892     ,   46.05377     ,
```


TABLE 2

TEST 1-a

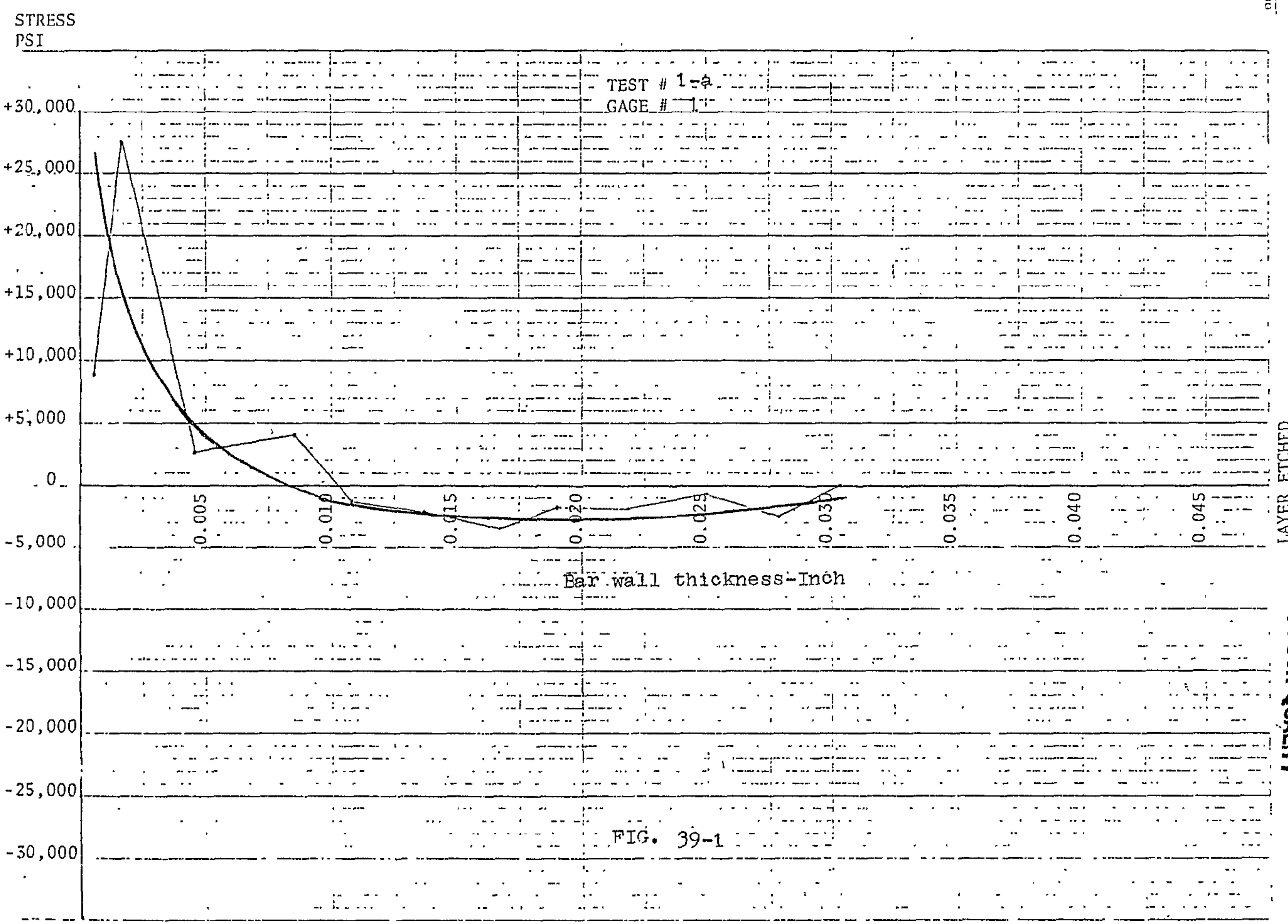


FIG. 39-1

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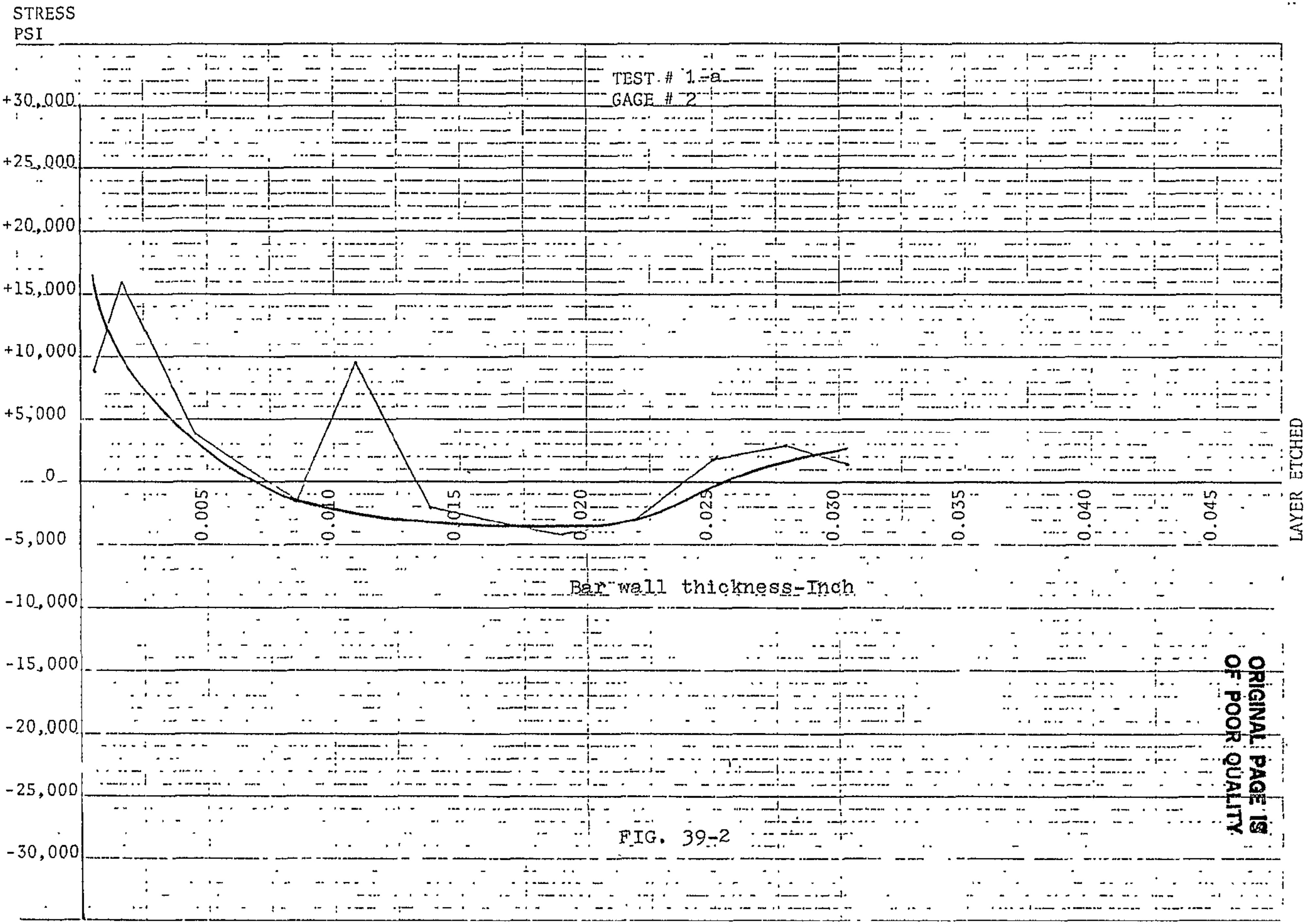
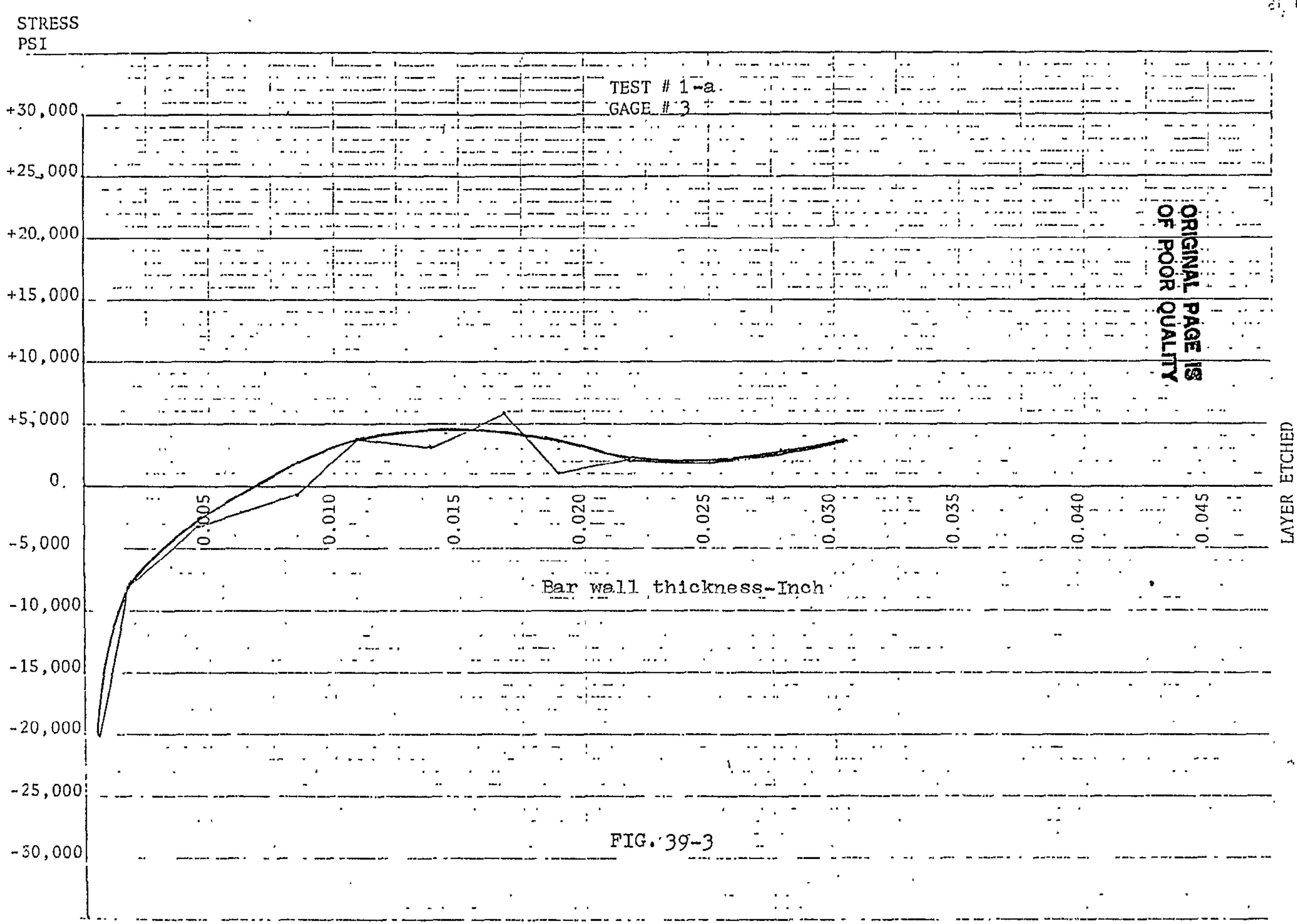
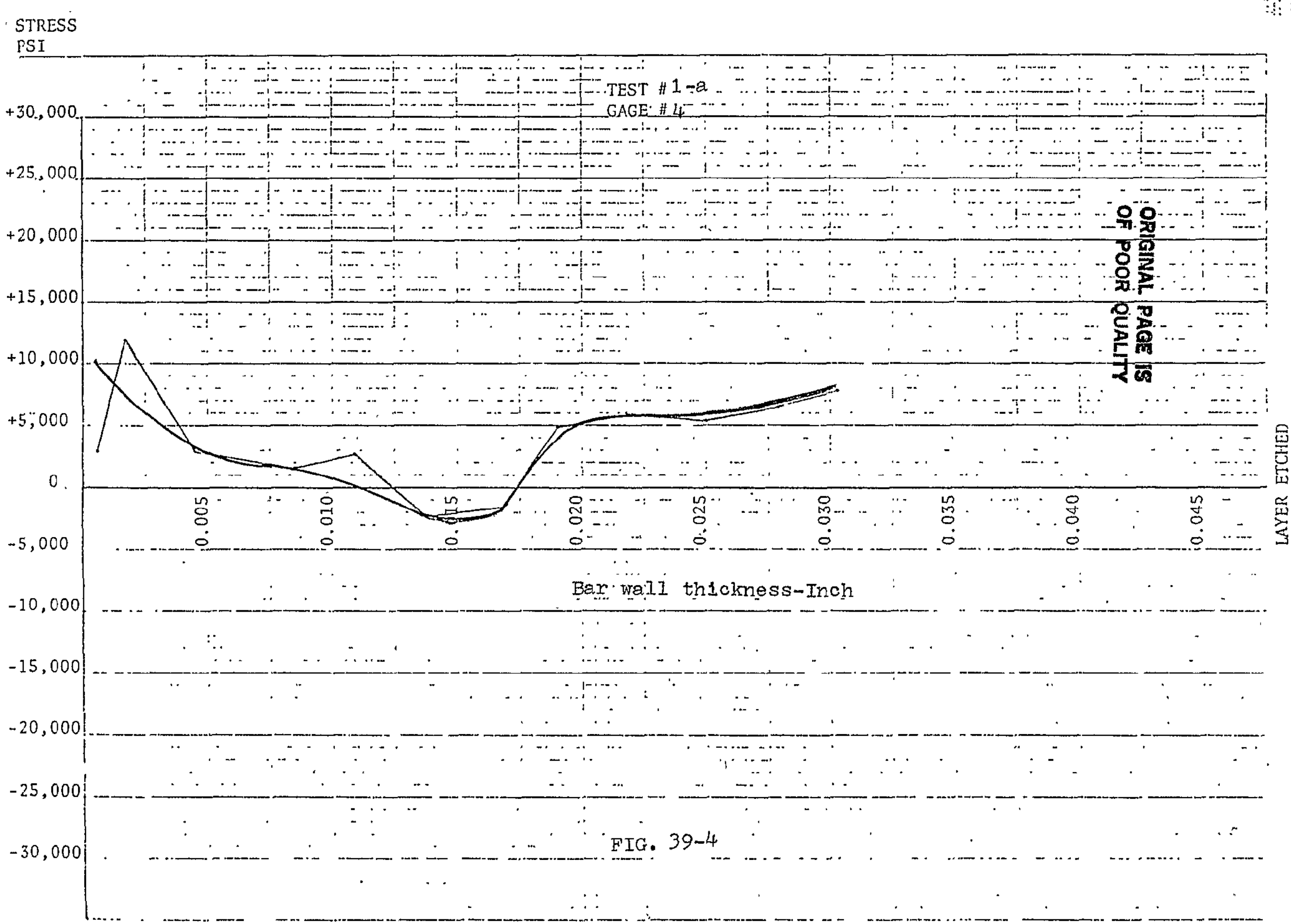

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 1-a
GAGE # 2
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 39-2



ORIGINAL PAGE IS OF POOR QUALITY

FIG. 39-3



ORIGINAL PAGE IS OF POOR QUALITY

FIG. 39-4

A(I)	X(I)	Y(I)	H(I)
6.250000	-0.2384186E-06	-0.7152557E-06	3.000000
18.75000	0.9833372	0.1075997	0.1094230
31.25000	0.6914301	1.724155	2.453606
43.75000	0.8398896	1.366369	1.626844
56.25000	0.8151027	0.6853779	0.8408485
68.75000	0.6502647	-0.6003598	-0.9232545
81.25000	0.7261916	0.1711077	0.2356233
93.75000	0.7040228	0.5059855	0.7187061
106.2500	0.5368714	0.6672617	1.242871
118.7500	0.5769966	0.7055878	1.222863
131.2500	0.5849083	0.4145351	0.7087182
143.7500	0.4282232	0.7494897	1.750231
155.2500	0.4449825	0.5328878	1.197548
168.7500	0.4980600	0.1766498	0.3546758
181.2500	0.3792500	-0.1304374	-0.3439352
193.7500	0.3853321	0.3216789	0.8348095
206.2500	0.4873621	0.4079997	0.8371594
218.7500	0.4298063	0.4056497	0.9437964
231.2500	0.4360173	0.7306882	1.675824
243.7500	0.5767210	0.1924005	0.3336110
256.2500	0.5889772	0.2948212	0.5005647
268.7500	0.5999999	0.5199999	0.8666665
281.2500	0.7551037	0.8824280	1.168618
293.7500	0.8264285	0.1404550E-02	0.1699542E-02
306.2500	0.8397724	1.029839	1.226330
318.7500	0.9767942	1.313309	1.344510
331.2500	1.080510	1.101322	1.019261
343.7500	1.090489	0.8932404	0.8191194
356.2500	1.179750	1.353188	1.147012
368.7500	1.282958	1.177456	0.9177670
381.2500	1.287791	0.6382032	0.4955799
393.7500	1.314538	1.013230	0.7707877
406.2500	1.389013	1.007265	0.7251665
418.7500	1.396544	0.5028600	0.3600745
431.2500	1.368611	0.3045326	0.2225122
443.7500	1.395977	0.8401453E-01	0.6018331E-01
456.2500	1.424245	0.4900246	0.3440592
468.7500	1.373045	0.5502490	0.4007510
481.2500	1.335186	1.688463	1.264590
493.7500	1.410748	1.010261	0.7161170

TABLE 3
TEST 1-b

ORIGINAL PAGE IS
OF POOR QUALITY

12.50000	0.1000000E-02	0.0000000E+00	0.0000000E+00
25.00000	0.5272845	0.4818015	0.9137409
37.50000	-0.5065518E-01	0.5136341E-02	-0.1013981
50.00000	-0.1631070	-0.6726932	4.124246
62.50000	-0.1465611	-1.529976	10.43917
75.00000	-0.1860366	-0.3838884	2.063510
87.50000	-0.3128683	-0.3905305E-01	0.1248226
100.0000	-0.1031660	0.8288511	-8.034153
112.5000	-0.1159012	-0.1802419E-01	0.1555135
125.0000	-0.9059032E-01	0.9891857E-01	-1.091933
137.5000	0.9163210E-01	0.6853241	7.479083
150.0000	0.2284940	0.3368694	1.474303
162.5000	0.2056261	0.1554980	0.7562170
175.0000	0.4181224	0.6727870	1.609067
187.5000	0.5200483	0.7219404	1.388218
200.0000	0.5075308	1.132041	2.230487
212.5000	0.5871127	1.237647	2.108024
225.0000	0.7045789	1.023640	1.452839
237.5000	0.6023633	0.6701418	1.112521
250.0000	0.6320537	0.8319549	1.316273
262.5000	0.6819789	0.8966627	1.314795
275.0000	0.6199999	0.9499995	1.532257
287.5000	0.5673879	0.7449587	1.312962
300.0000	0.6704643	0.8615016	1.284933
312.5000	0.6333963	1.396817	2.205282
325.0000	0.6443007	1.197079	1.857951
337.5000	0.7477511	0.7457528	0.9973276
350.0000	0.8493792	1.187297	1.397841
362.5000	0.8664584	1.674568	1.932659
375.0000	1.033867	1.145503	1.107979
387.5000	1.147131	1.768219	1.541427
400.0000	1.229702	2.453279	1.995018
412.5000	1.289278	2.228246	1.728289
425.0000	1.422773	2.496836	1.754908
437.5000	1.396311	3.026324	2.167370
450.0000	1.384666	3.882024	2.803582
462.5000	1.313934	3.976814	3.026647
475.0000	1.288917	5.269501	4.088318
487.5000	1.020052	4.499320	4.410872
500.0000	0.8983795	5.749107	6.399419

TABLE 3 Cont.
TEST 1-b

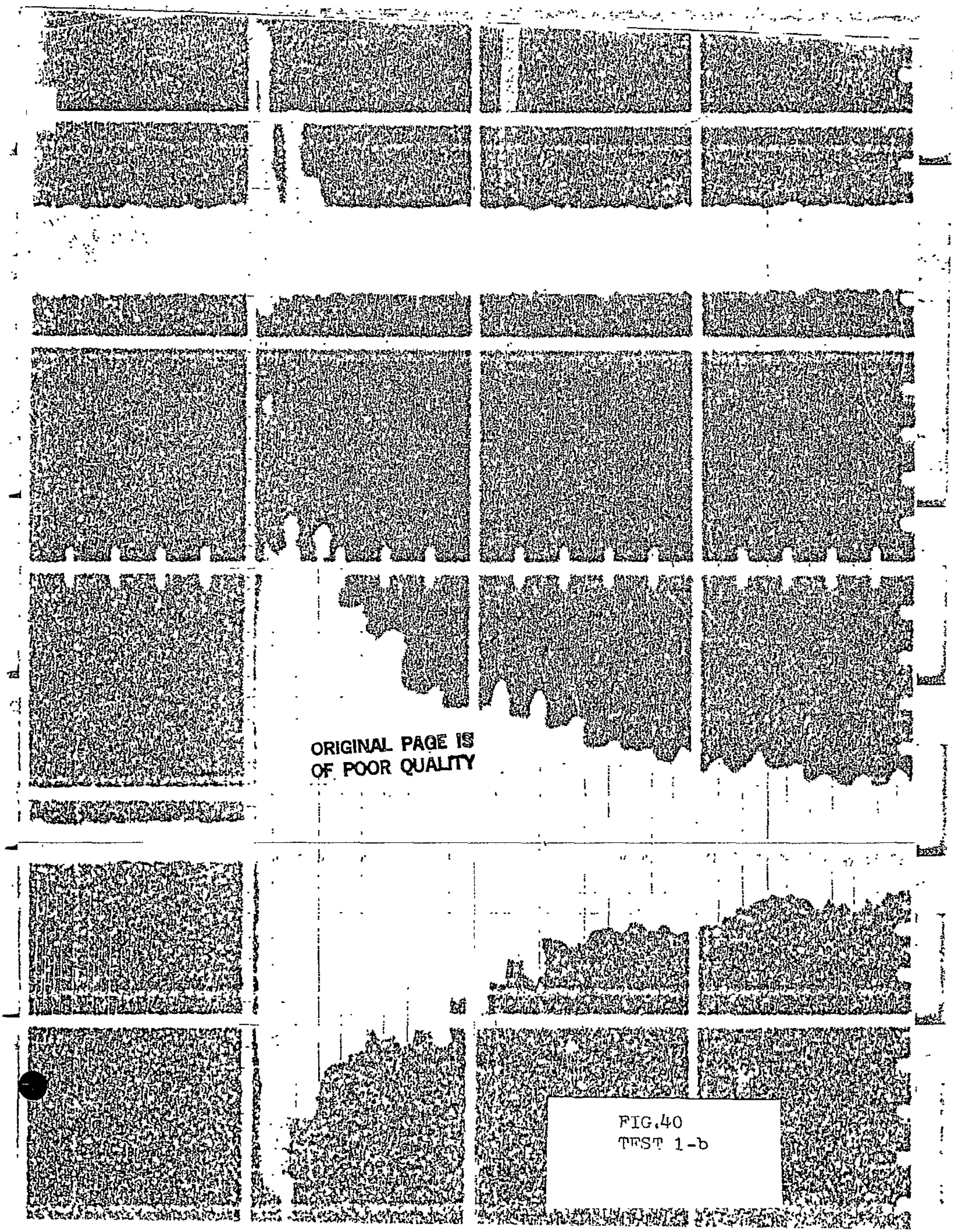


FIG.40
TEST 1-b

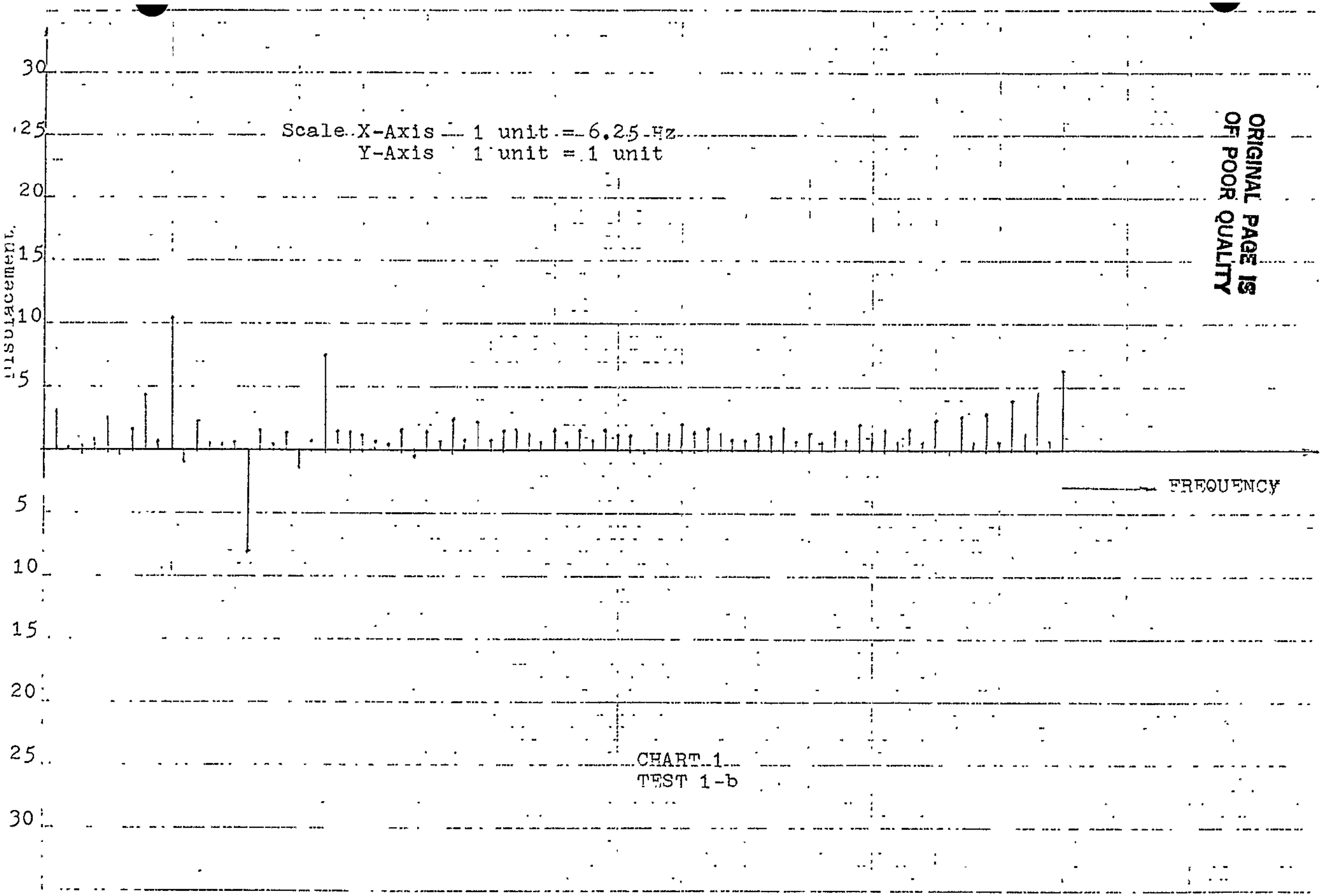
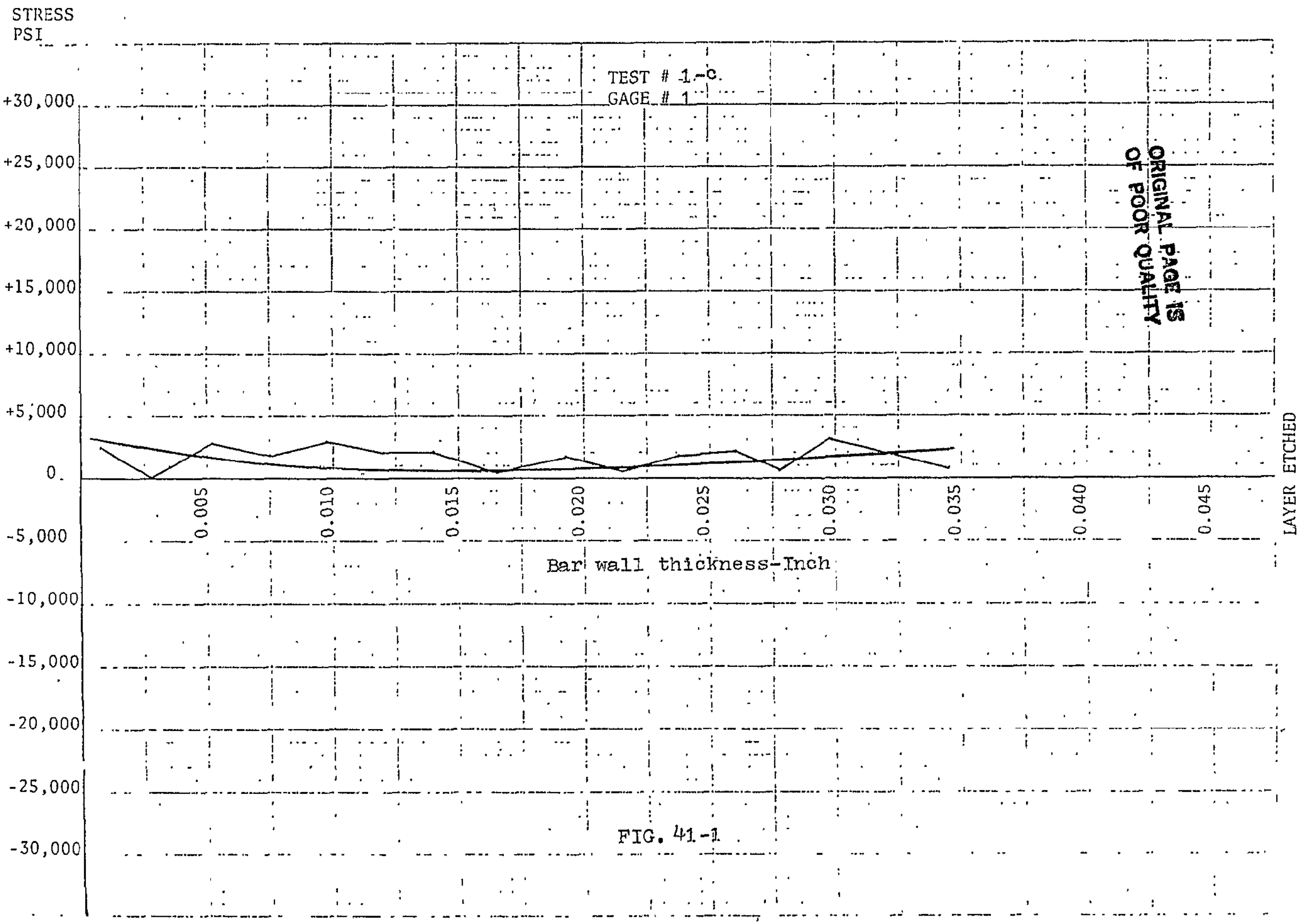


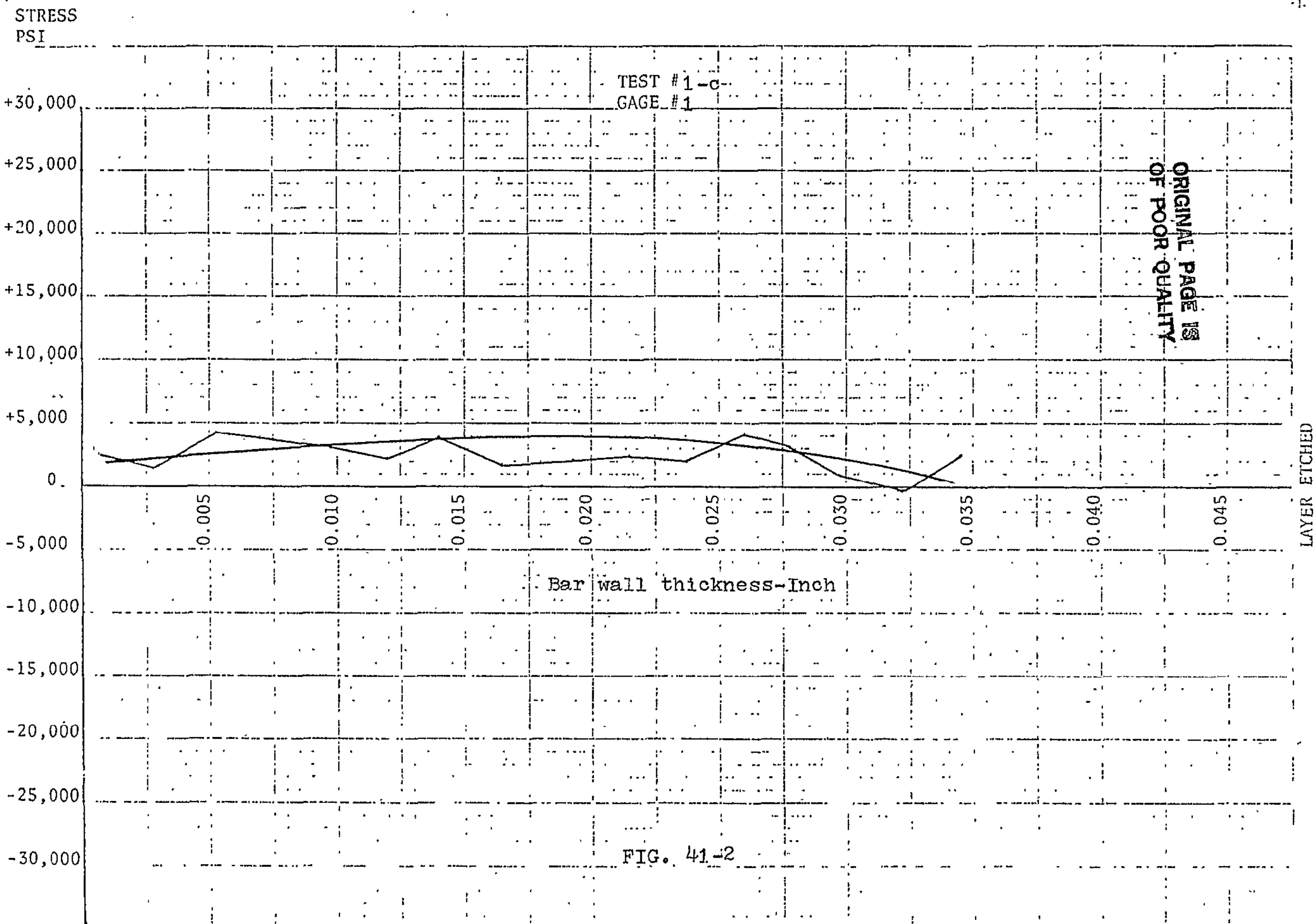
CHART 1
TEST 1-b

ORIGINAL PAGE IS
OF POOR QUALITY

	GAGE #	1	2	3	4	5	6	7	8
LAYER	1	2381.	2381.	4761.	-2381.				
LAYER	2	57.	1463.	2925.	-2868.				
LAYER	3	2838.	4286.	1618.	-171.				
LAYER	4	1899.	3742.	3740.	1561.				
LAYER	5	2954.	3124.	3121.	-109.				
LAYER	6	2033.	2200.	2197.	1590.				
LAYER	7	2071.	3918.	3916.	-49.				
LAYER	8	440.	1759.	657.	-48.				
LAYER	9	1742.	2014.	1954.	-1357.				
LAYER	10	483.	2379.	2320.	-103.				
LAYER	11	1759.	2080.	739.	1182.				
LAYER	12	2120.	4032.	2323.	-43.				
LAYER	13	576.	3065.	-1344.	2077.				
LAYER	14	3066.	990.	-541.	1264.				
LAYER	15	1906.	-262.	638.	72.				
LAYER	16	718.	2433.	2161.	1605.				

TABLE 4
TEST 1-c


STRESS
PSI
TEST # 1-c
GAGE # 1
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch
FIG. 41-1



STRESS
PSI
TEST #1-c
GAGE #1
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 41-2

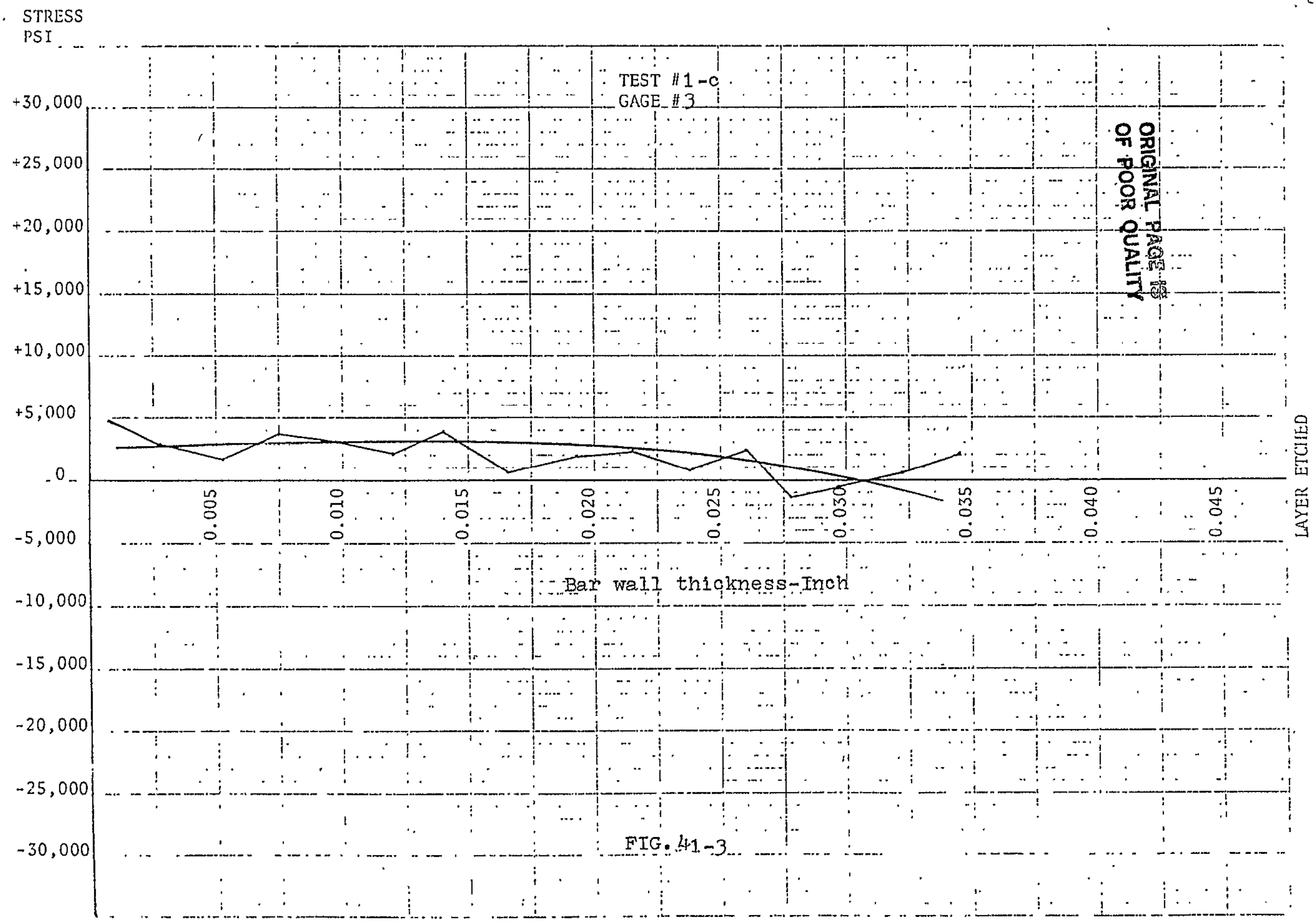

STRESS PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST #1-c
GAGE #3
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 41-3

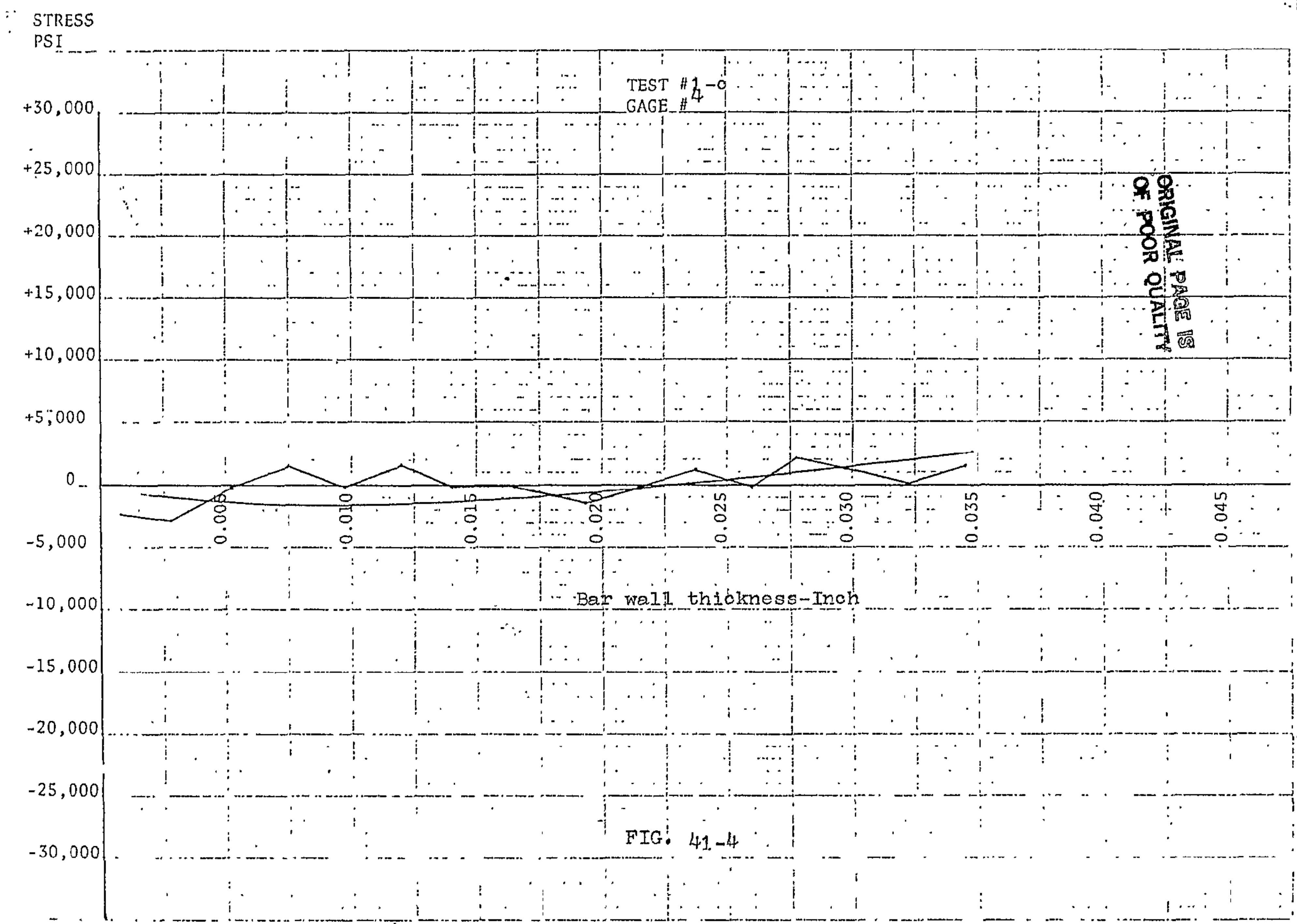

STRESS
PSI
TEST #1-c
GAGE #4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 41-4

```
LAYER   1    18133.-10880.-21759. 25386.
LAYER   2     6444. -5098. -6500.  5941.
LAYER   3    12963.-11224.-11504. 19077.
LAYER   4     8638.-12038.-12313. 14435.
LAYER   5    13784.-17762.-18032. 20436.
LAYER   6    14023.-16091.-16358. 16804.
LAYER   7    12276.-12404.-14650. 15091.
LAYER   8    11905.-12032.-16329.  8805.
LAYER   9    13213. -8225.-13823.  1128.
LAYER  10     1271. -6028. -8520. -1179.
LAYER  11    -7789. -1496.  -394. -9366.
LAYER  12   -13536.  2184.  4246.-16068.
LAYER  13    -4336.  1896.   511. -5056.

ENTER THE NAME FOR A NEW FILE FORTORAGE
TSTZ.RES

END OF EXECUTION
CPU TIME: 1.40  ELAPSED TIME: 2:3.98
EXIT
```


TABLE 5
TEST 2-a

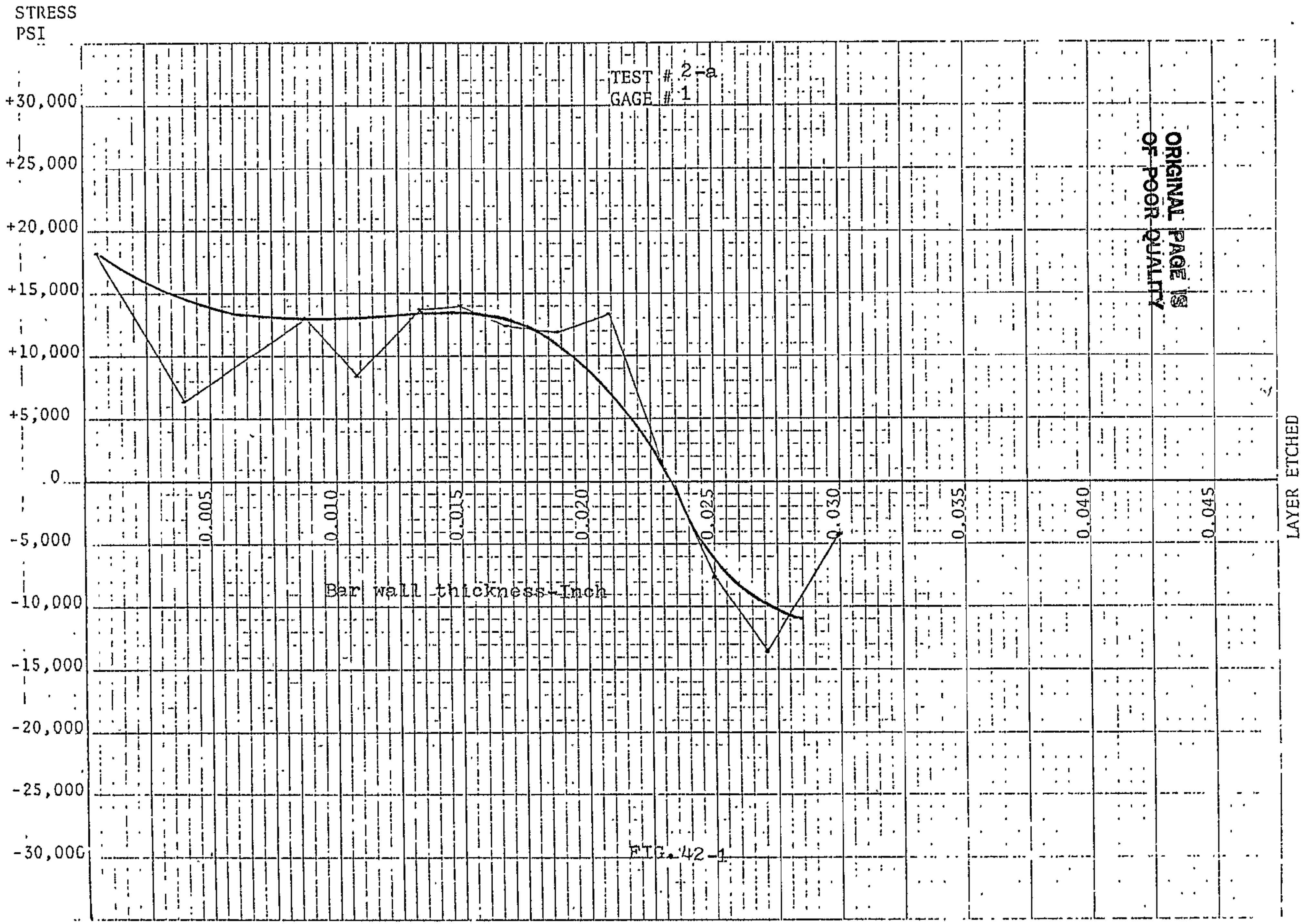

STRESS
PSI
TEST # 2-a
GAGE # 1
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 42-1

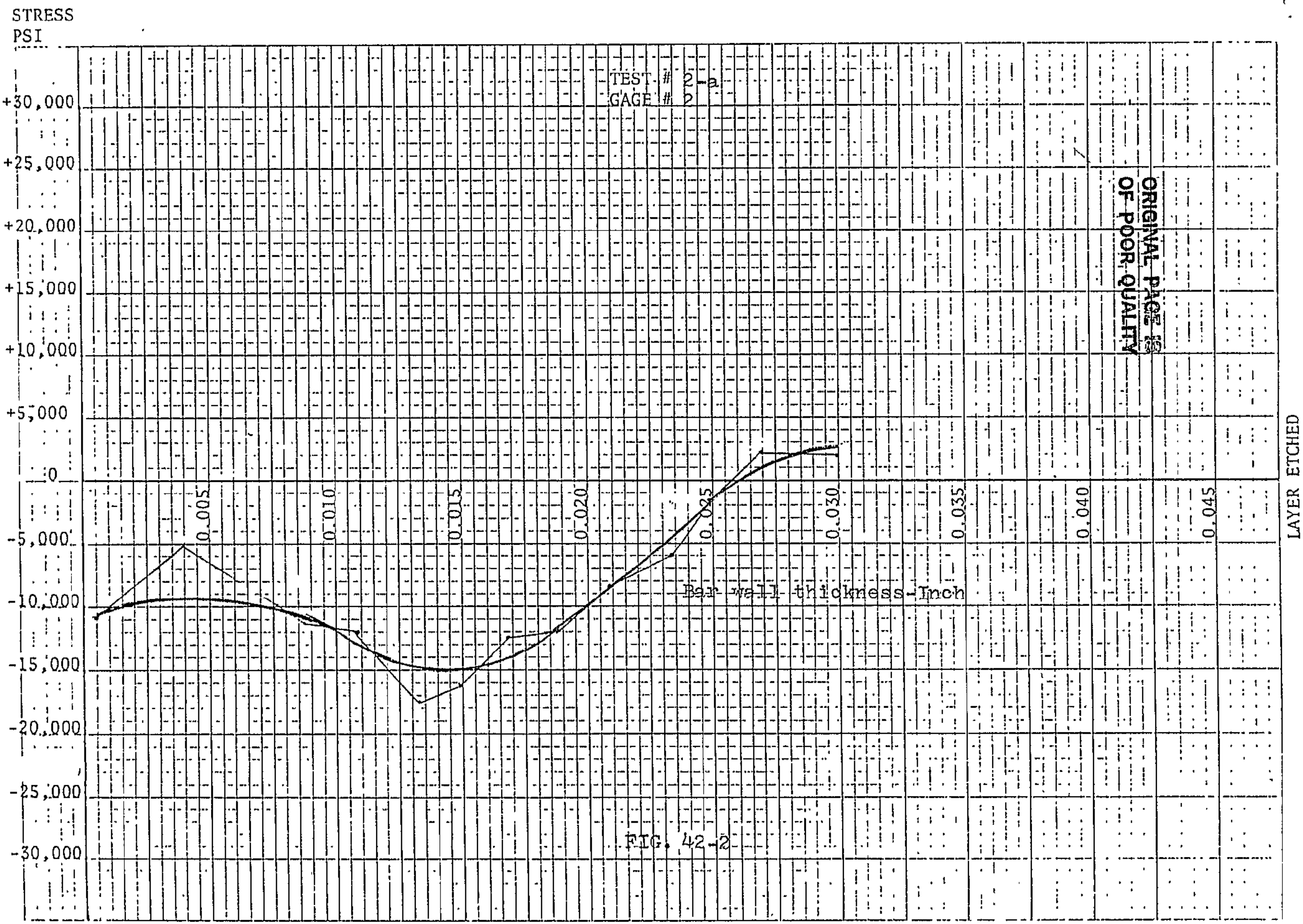

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 2-a
GAGE # 2
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
Bar wall thickness-Inch
LAYER ETCHED
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 42-2

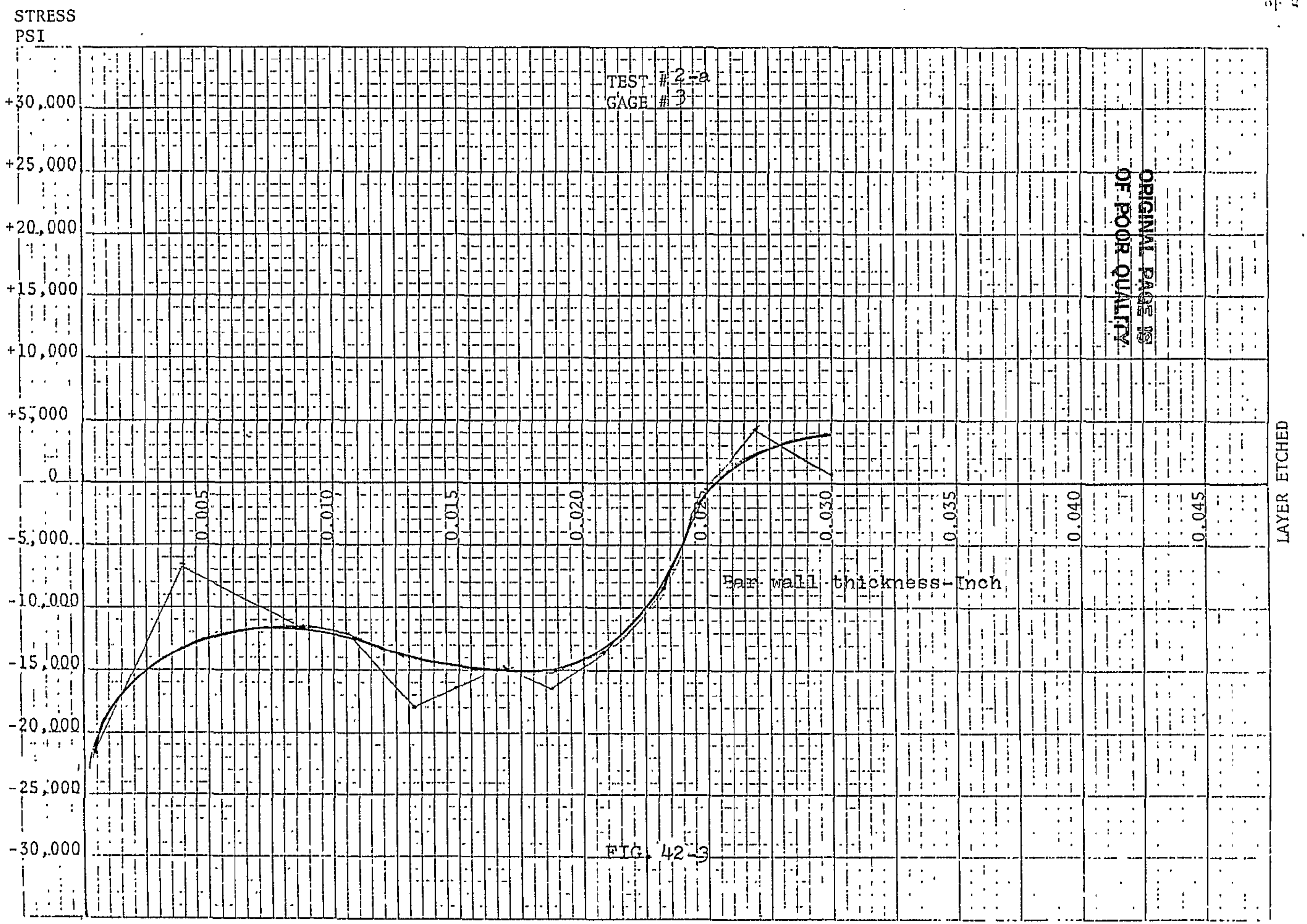

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST #2-a
GAGE #3
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
Bar wall thickness-Inch
LAYER ETCHED
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 42-3

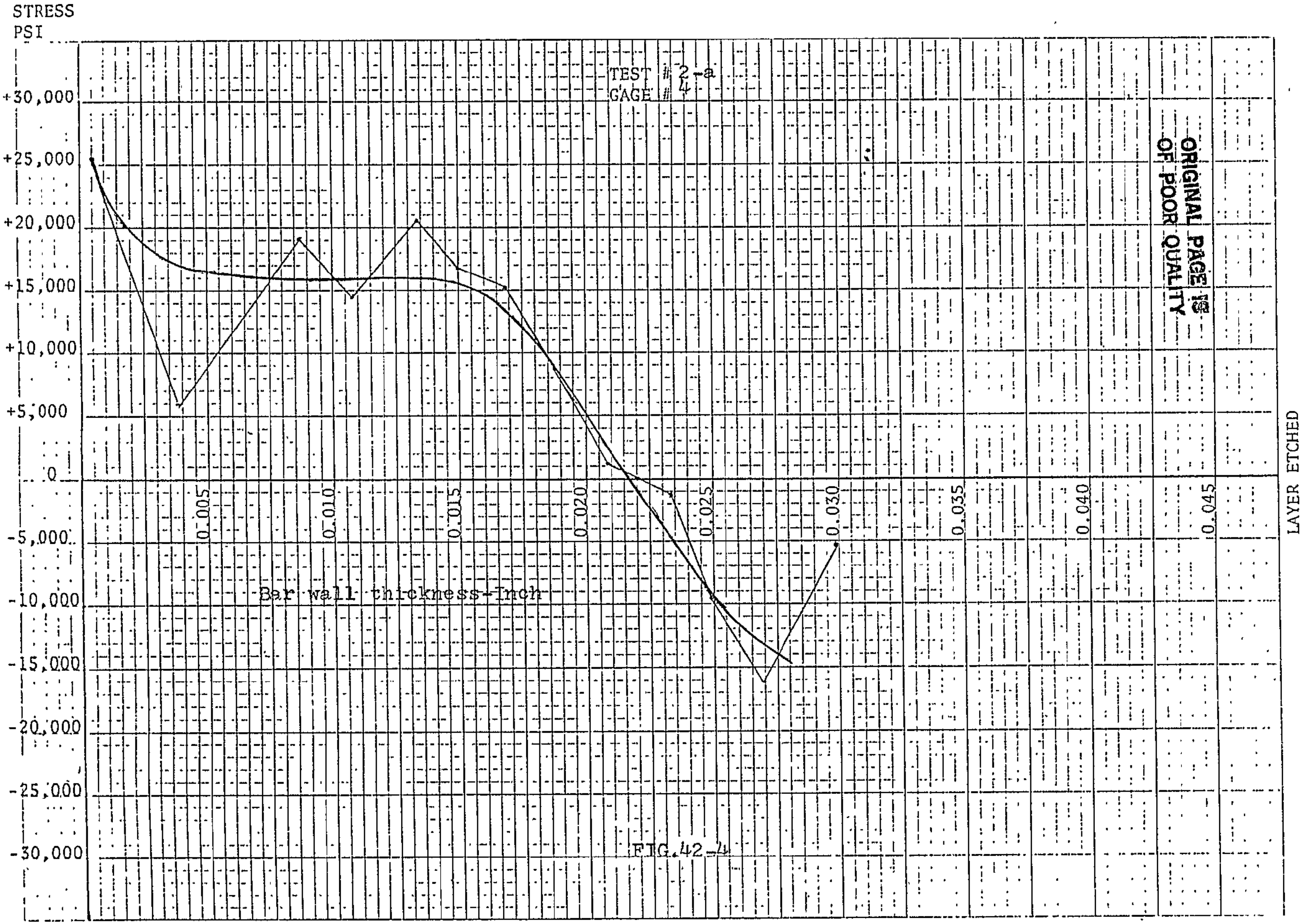

STRESS PSI
TEST # 2-a
GAGE # 4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch
ORIGINAL PAGE IS OF POOR QUALITY

FIG. 42-4

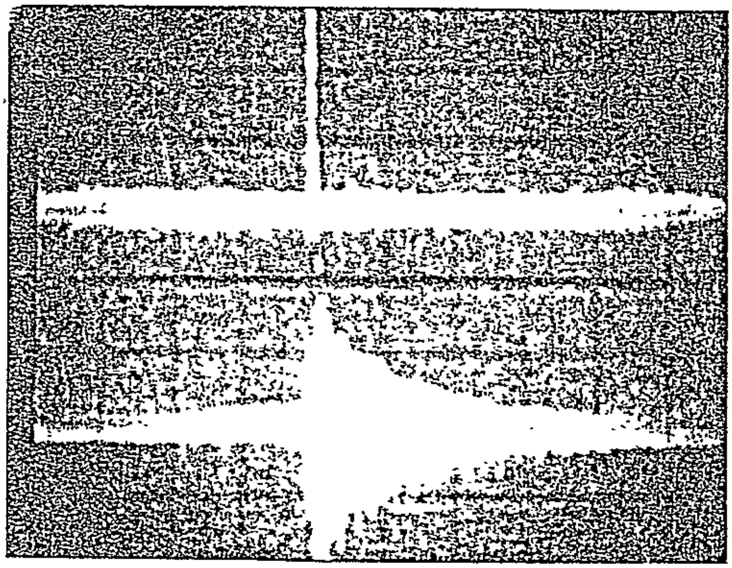


FIG. 43
TEST 2-b

12.50000	0.9536743E-06	0.0000000E+00	0.0000000E+00
37.50000	-54.24877	47.42885	-0.8742844
62.50000	-29.24072	-16.64006	0.5690713
87.50000	-56.99455	-140.9965	2.473858
112.5000	-56.77778	-80.15561	1.411743
137.5000	-4.512192	23.81135	-5.277114
162.5000	5.146555	141.1951	27.43488
187.5000	-18.84820	-46.67597	2.476416
212.5000	13.15314	13.08460	0.9947892
237.5000	50.58742	-14.64900	-0.2895780
262.5000	28.87008	0.3034998	0.1051261E-01
287.5000	24.20383	142.2461	5.877008
312.5000	56.07147	-23.70649	-0.4227906
337.5000	47.29784	-84.33347	-1.783030
362.5000	19.30187	-50.49999	-2.616326
387.5000	25.67358	-72.92706	-2.840548
412.5000	30.21515	7.464522	0.2470456
437.5000	15.33736	96.77225	6.309578
462.5000	7.715114	-38.39276	-4.976305
487.5000	3.225154	12.40730	3.847043
512.5000	1.059259	-22.48950	-21.23136
537.5000	7.400002	-55.50004	-7.500004
562.5000	4.095055	14.91915	-3.643211
587.5000	-0.9974161	26.91895	-26.98868
612.5000	11.20194	-24.05212	-2.147138
637.5000	15.54183	104.4584	6.721759
662.5000	3.511331	25.97452	7.397344
687.5000	3.852908	-33.09186	-8.588801
712.5000	9.800625	-42.00000	-4.285441
737.5000	1.654088	-68.72238	-41.54698
762.5000	-4.561670	-9.552348	2.094046
787.5000	-1.999923	120.5270	-60.26585
812.5000	-4.480295	9.347021	-2.086251
837.5000	-9.190781	-4.180703	0.4548800
862.5000	-10.28128	22.37312	-2.176104
887.5000	-11.05180	-116.8240	10.57059
912.5000	-9.470908	91.50858	-9.662071
937.5000	-8.621144	37.65340	-4.367564
952.5000	-12.75634	226.7350	17.77430
987.5000	-10.82858	-298.1550	27.53409

TABLE 6

TEST 2-b

25.00000	0.1000000E-02	0.0000000E+00	0.0000000E+00
50.00000	36.46849	-19.62529	-0.5381439
75.00000	15.92929	-110.0183	-6.906667
100.0000	10.49614	-18.25453	-1.739165
125.0000	56.99547	58.36524	1.024033
150.0000	66.17998	67.27688	1.016575
175.0000	28.82285	51.31708	-1.780430
200.0000	39.69564	-106.6420	-2.686491
225.0000	68.77678	52.03100	0.7565199
250.0000	36.26049	26.46629	0.7298932
275.0000	8.701916	150.1402	17.25369
300.0000	29.80191	40.48984	1.358632
325.0000	19.88465	-87.31516	-4.391083
350.0000	-17.45667	-64.09554	3.671694
375.0000	-13.85749	-9.526278	-0.6874462
400.0000	-1.496063	-33.65305	22.49441
425.0000	-15.64992	99.52728	-6.359603
450.0000	-22.06526	-33.38540	1.513030
475.0000	-16.67005	14.62798	-0.8775005
500.0000	-14.00691	66.00872	-4.712583
525.0000	-6.658938	-9.801565	1.471941
550.0000	-5.500004	-2.500011	0.4545471
575.0000	-11.25104	8.877078	-0.7890005
600.0000	-3.312222	-74.69887	22.55250
625.0000	0.9359885	-3.712527	-3.966424
650.0000	-13.28712	38.96610	-2.932623
675.0000	-16.90037	-88.33668	5.226908
700.0000	-8.987985	57.63683	-6.412654
725.0000	-14.72352	8.660257	-0.5881922
750.0000	-21.28416	54.08127	-2.540916
775.0000	-15.35607	105.3673	-6.861604
800.0000	-13.08668	4.758537	-0.3636169
825.0000	-15.63874	-135.9833	8.695286
850.0000	-12.91840	9.171346	-0.7099443
875.0000	-9.238415	3.005097	-0.3252827
900.0000	-6.199382	95.14196	-15.34701
925.0000	-3.252385	78.96177	-24.27811
950.0000	-4.558754	-110.5741	24.25533
975.0000	-3.021162	-93.85307	31.06523
1000.000	3.830004	13.40832	3.500863

TABLE 6 Cont.
TEST 2-b

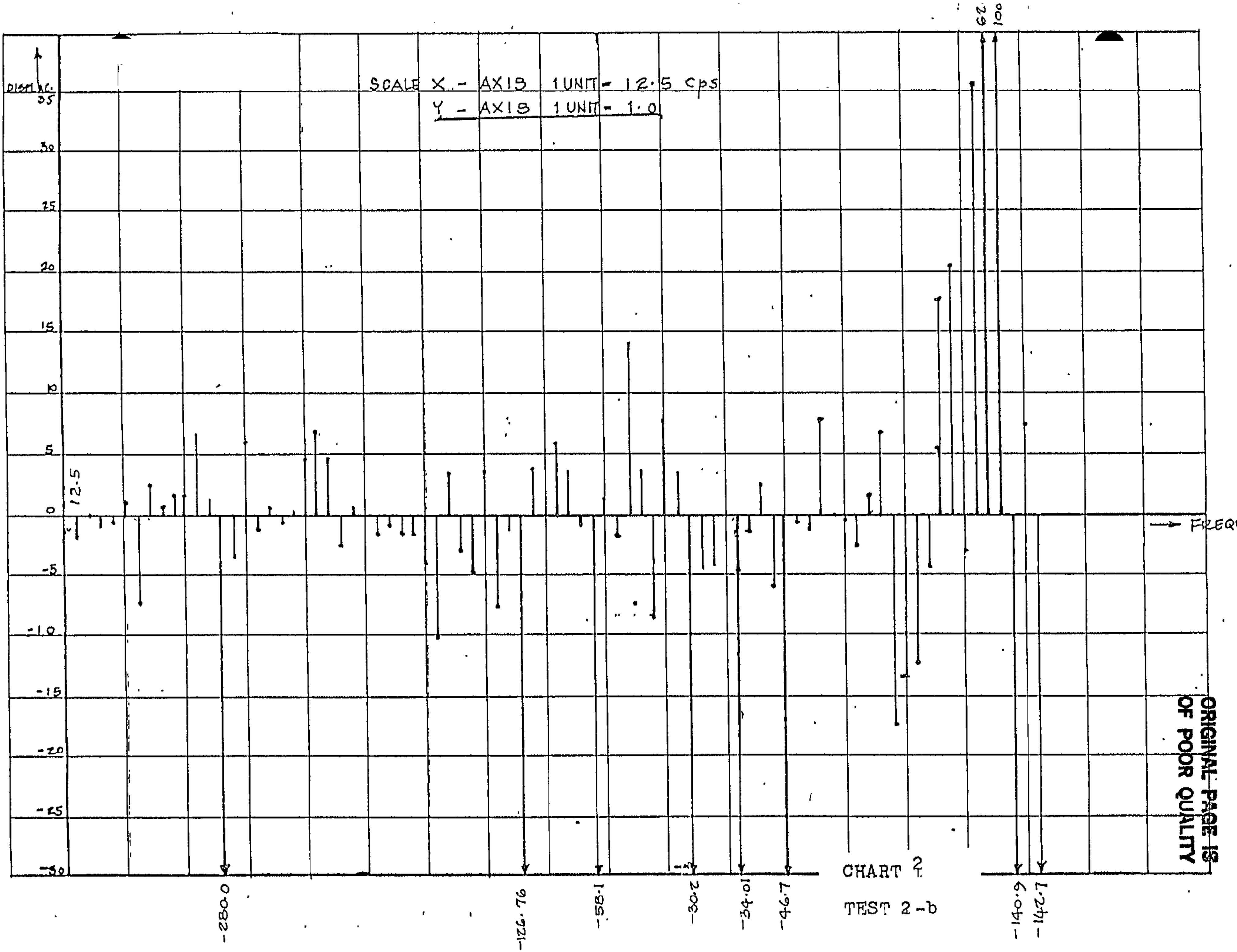


CHART 2
TEST 2-b

GAGE #		1	2	3	4	5	6
LAYER	1	2216.	-1478.	0.	2216.		
LAYER	2	3254.	915.	-1028.	3254.		
LAYER	3	2791.	-1691.	-1694.	1973.		
LAYER	4	3485.	1826.	1823.	2433.		
LAYER	5	2489.	563.	1172.	2377.		
LAYER	6	3519.	2722.	4132.	3410.		
LAYER	7	4243.	-989.	2457.	1912.		

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 7
TEST 2-c

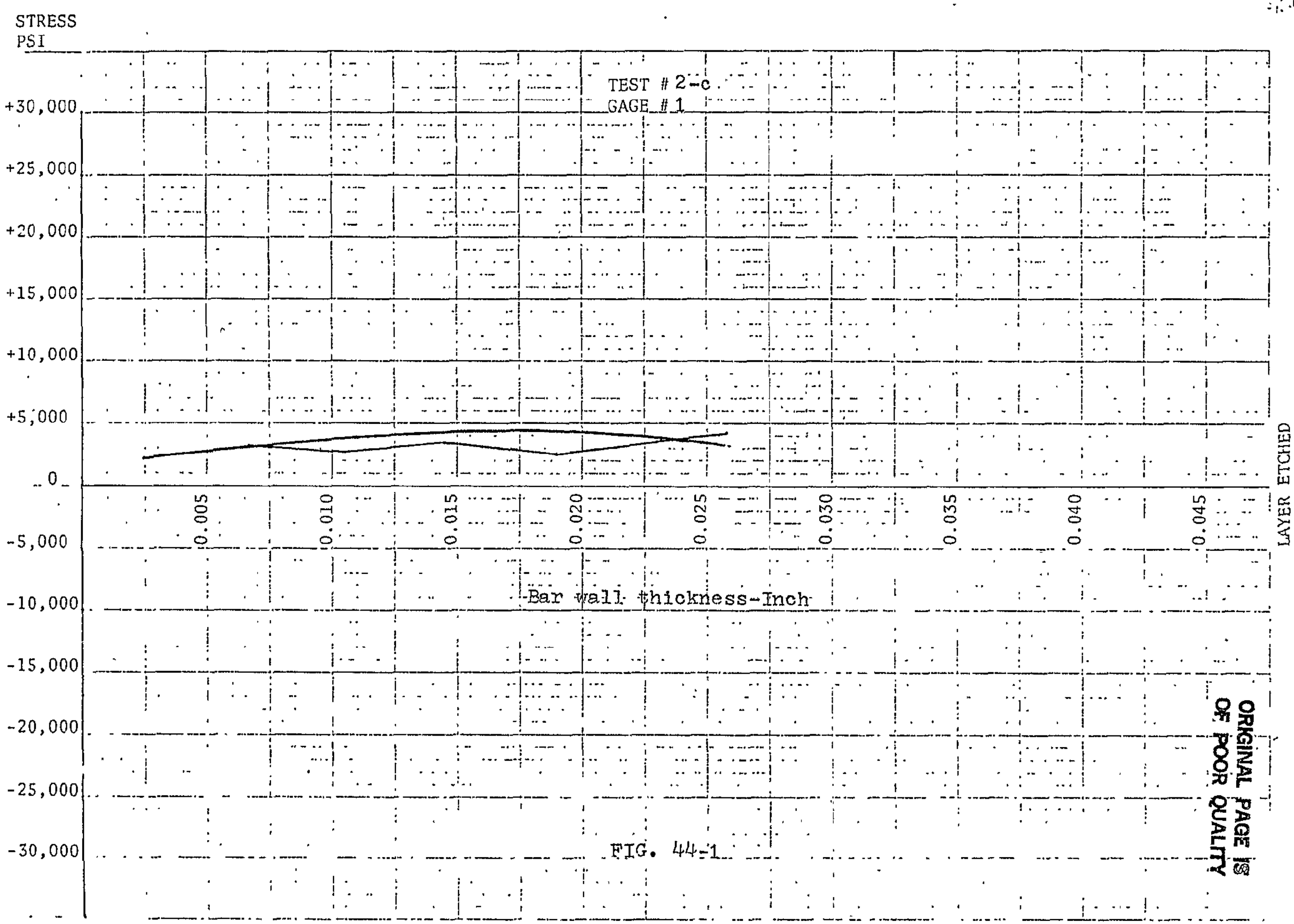


FIG. 44-1

ORIGINAL PAGE IS OF POOR QUALITY

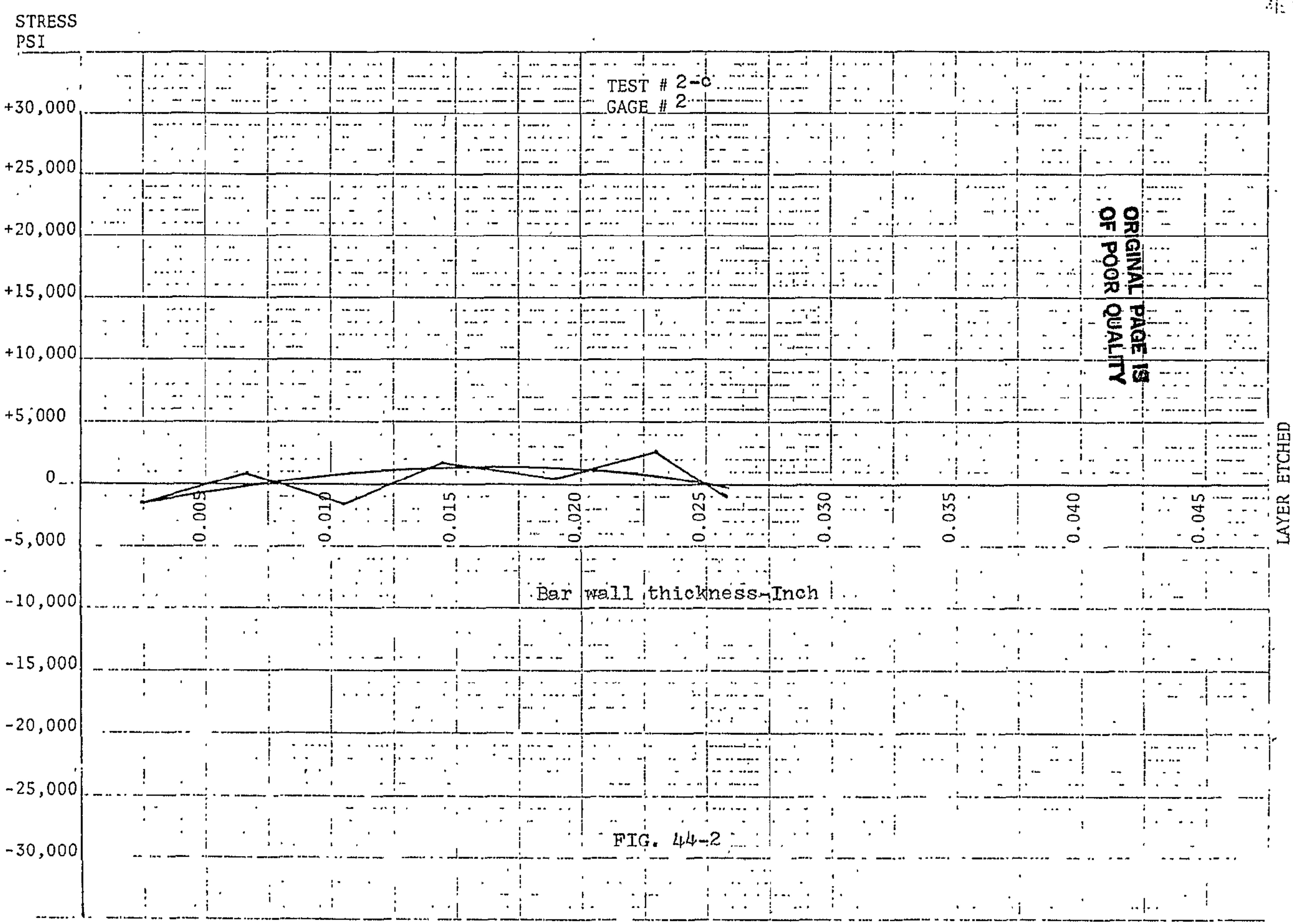

STRESS
PSI
TEST # 2-c
GAGE # 2
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 44-2

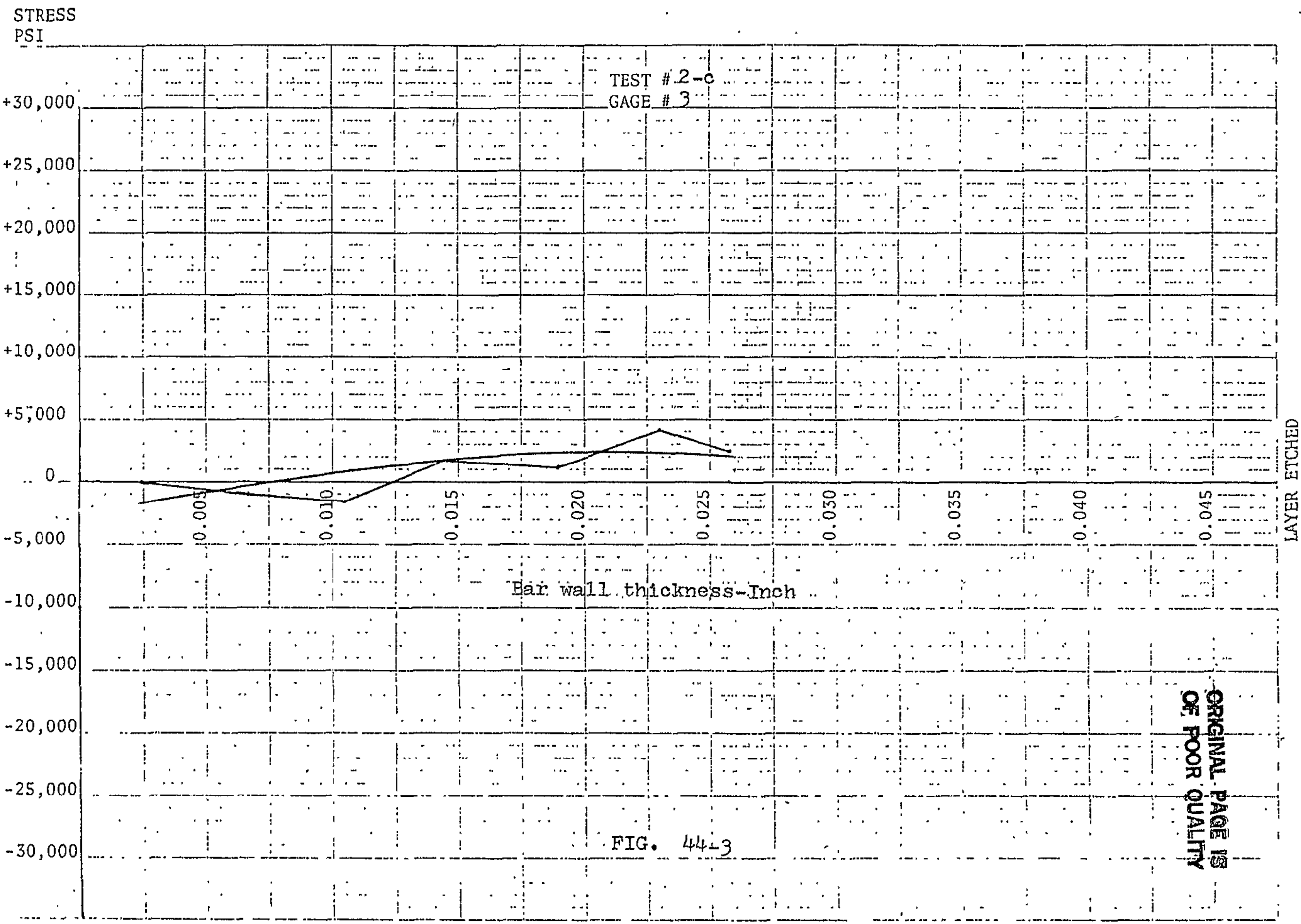

STRESS
PSI
TEST # 2-c
GAGE # 3
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 44-3

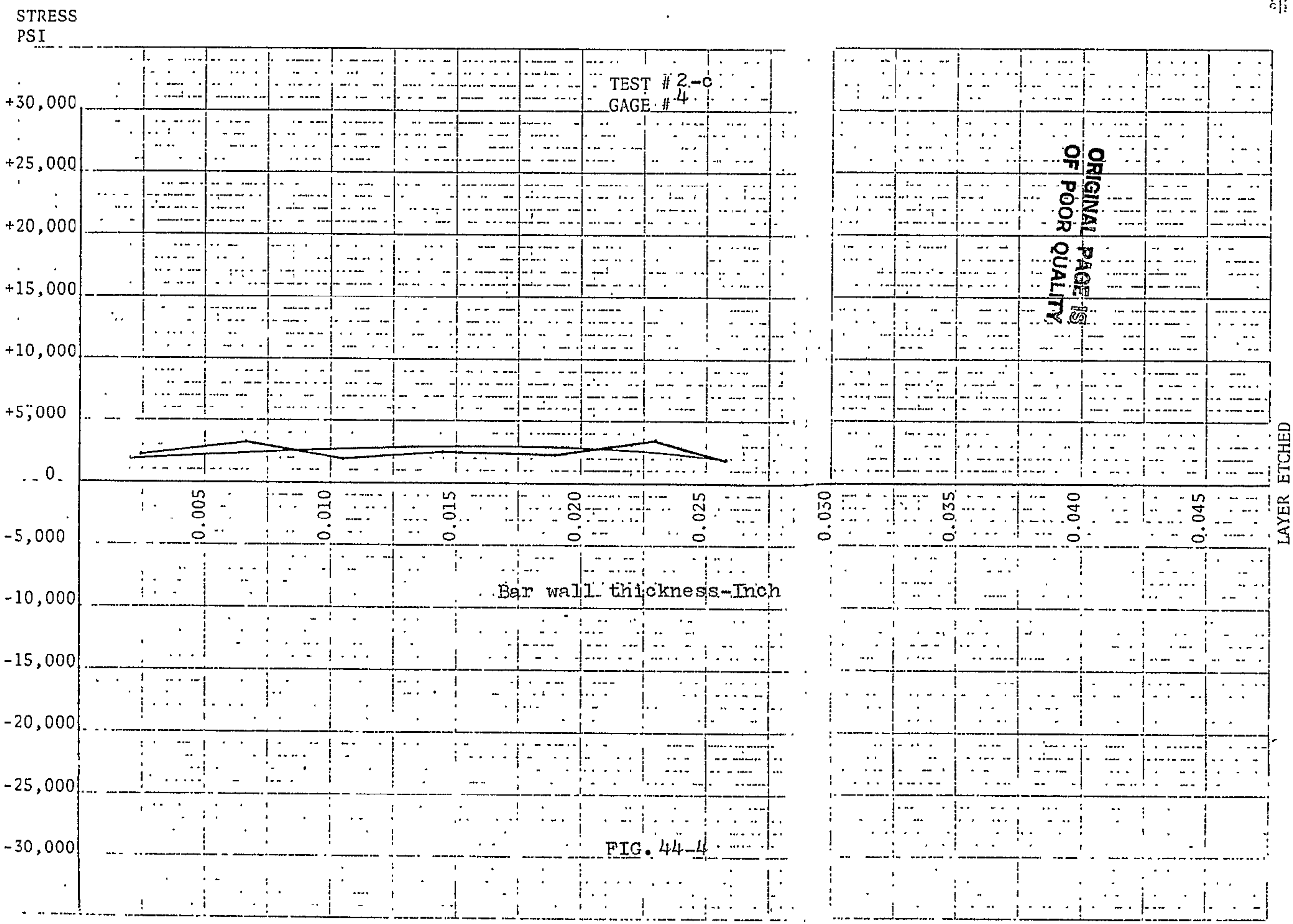

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 2-c
GAGE # 4
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 44-4

ORIGINAL PAGE IS
OF POOR QUALITY

	BAND [illegible]				
LAYER	1	[illegible]12.	43[illegible]0.	4[illegible]0.	50[illegible]
LAYER	2	16185.	19902.	26421.	2647[illegible].
LAYER	3	3653.	1006.	8399.	7611.
LAYER	4	4942.	6598.	15467.	16943.
LAYER	5	1933.	3749.	11086.	11970.
LAYER	6	1[illegible].	1507.	5378.	5486.
LAYER	7	2903.	[illegible]	[illegible]	[illegible]

ENTER THE NAME FOR A NEW FILE FORTORAGE
TSTG.RES

END OF EXECUTION
CPU TIME: 0.80 ELAPSED TIME: 1:15.38
EXIT

TABLE 8
TEST 3-a .

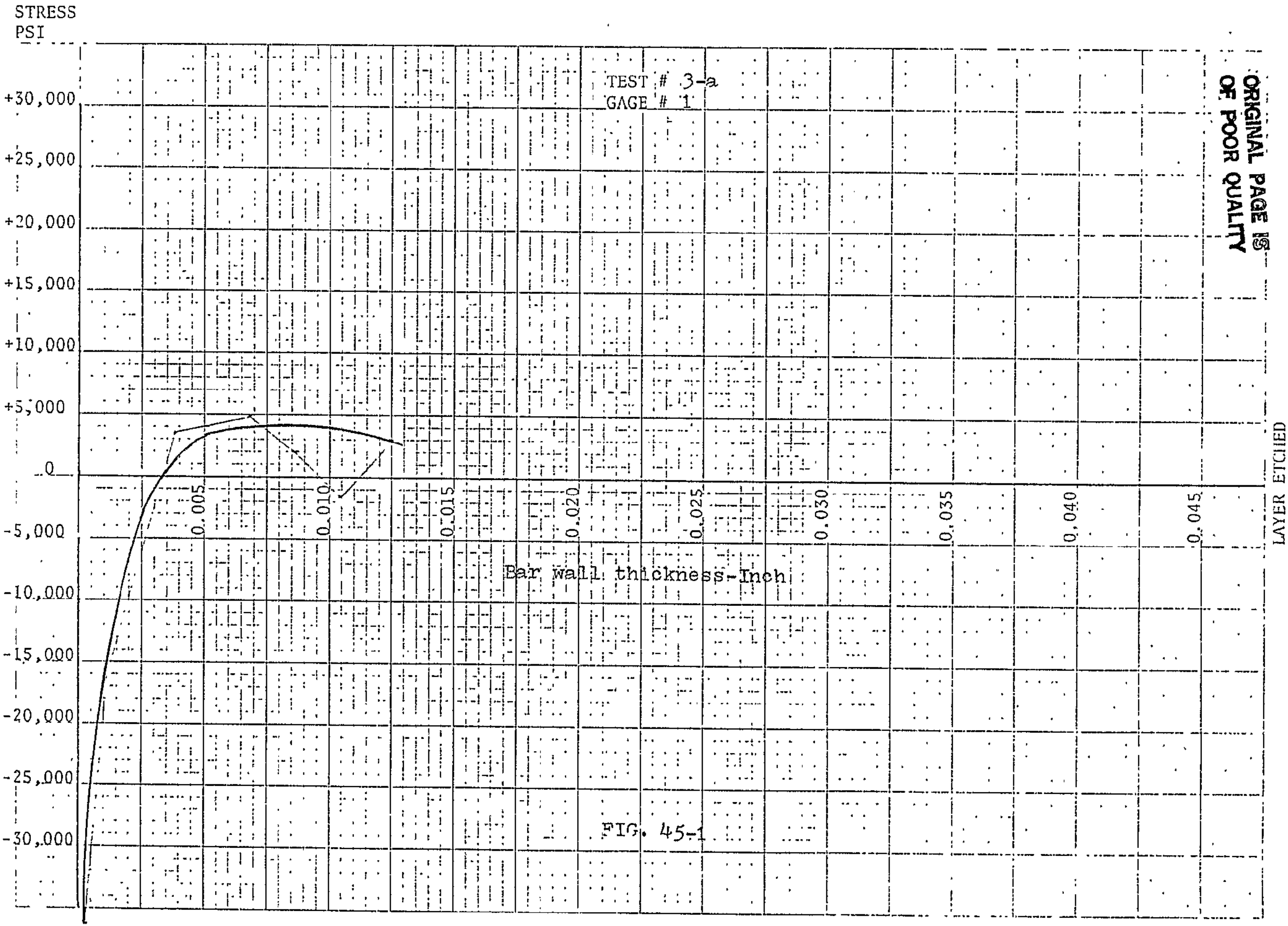


FIG. 45-1

ORIGINAL PAGE IS OF POOR QUALITY

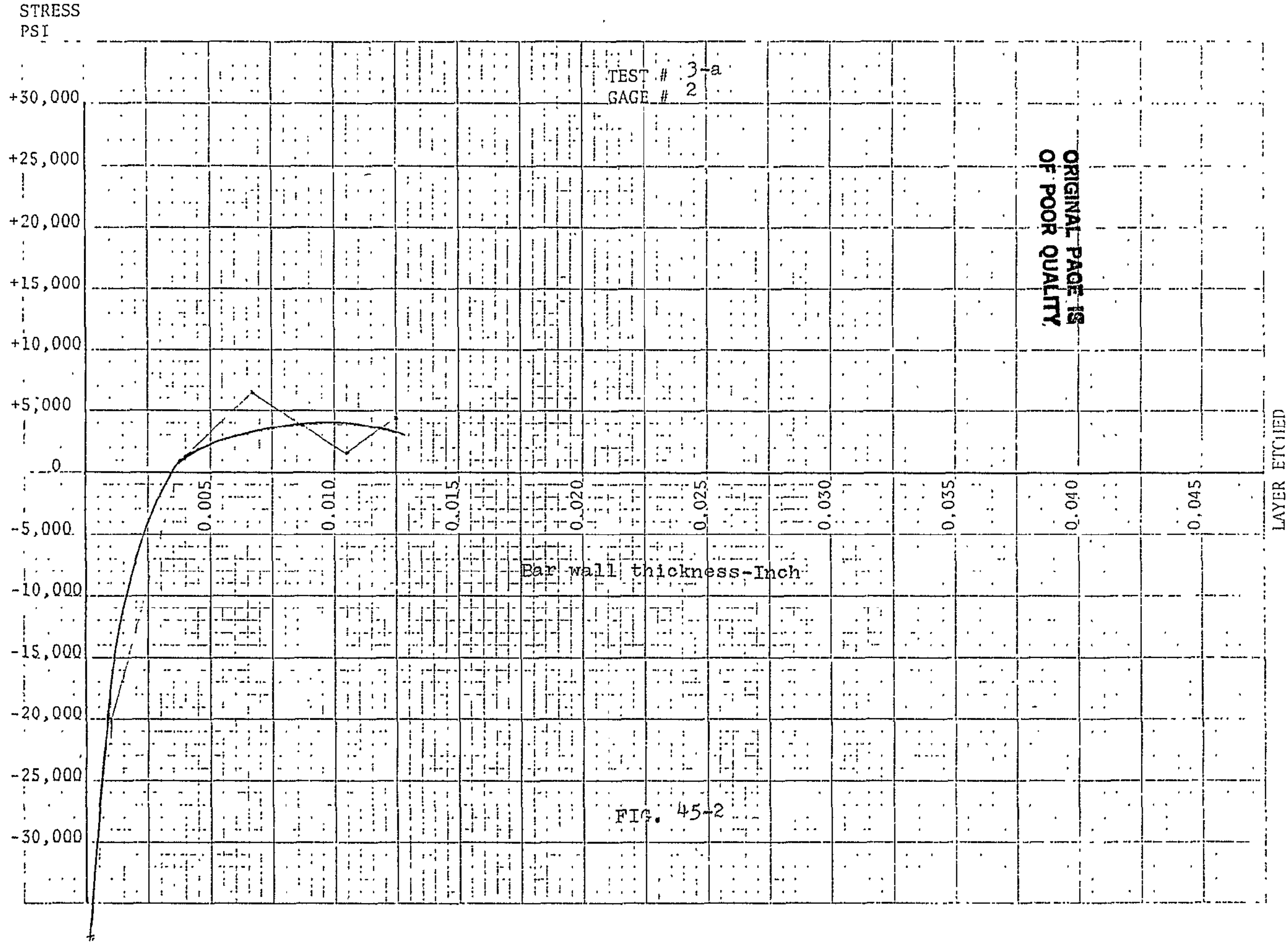

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 3-a
GAGE # 2
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 45-2

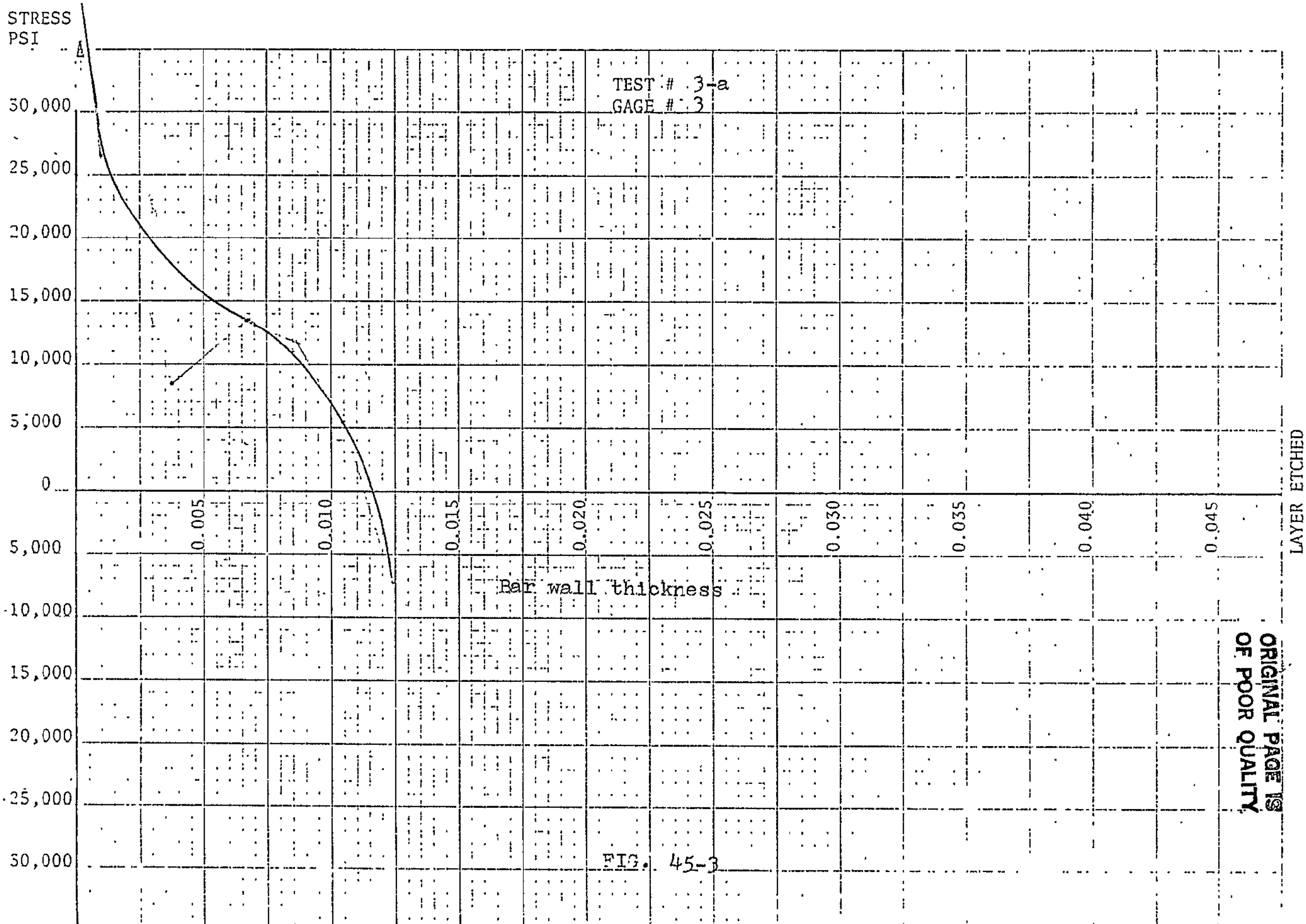
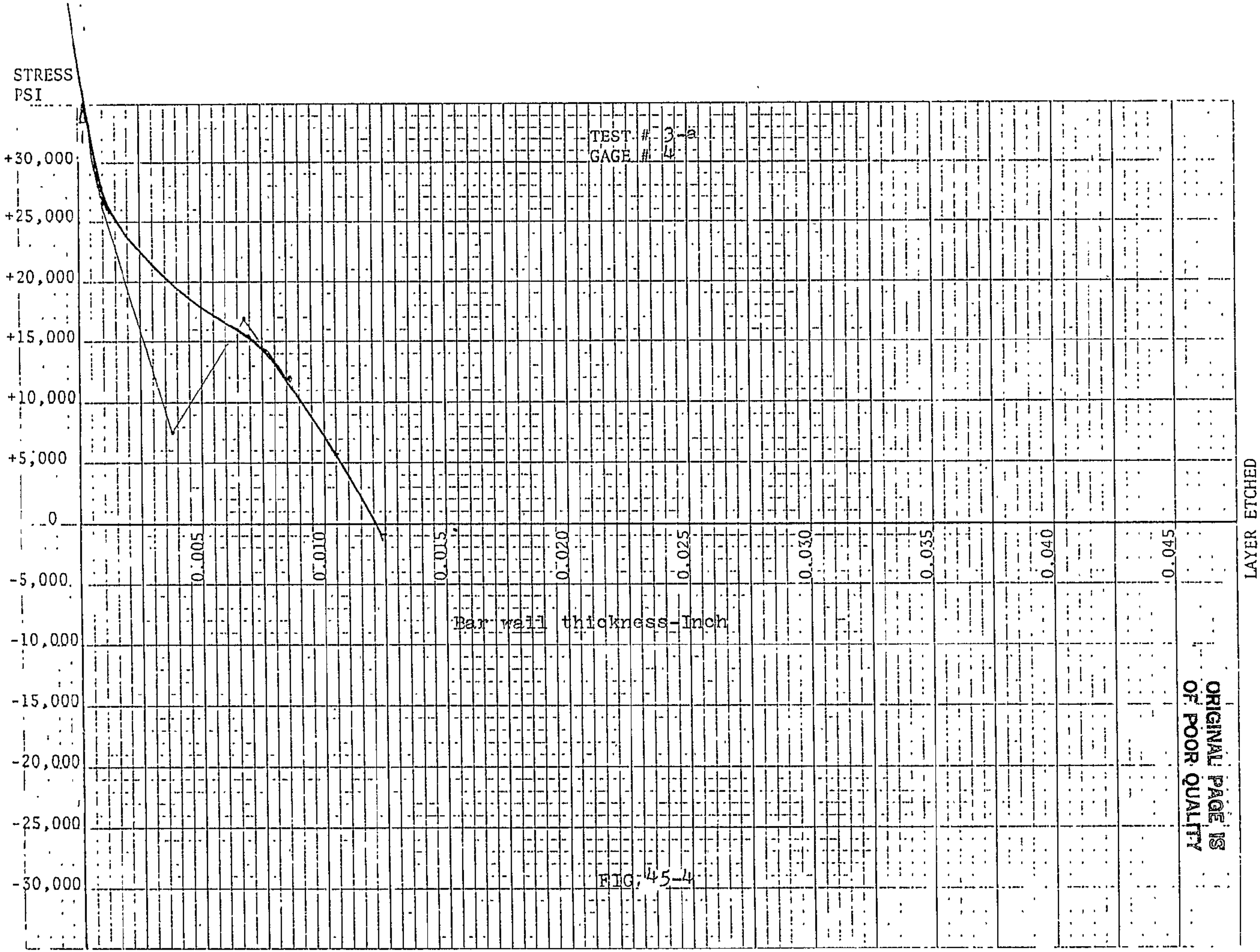

STRESS PSI
30,000
25,000
20,000
15,000
10,000
5,000
0
5,000
10,000
15,000
20,000
25,000
30,000
TEST # 3-a
GAGE # 3
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness

FIG. 45-3



STRESS
PSI
TEST # 3-a
GAGE # 4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 45-4

ORIGINAL PAGE IS
OF POOR QUALITY

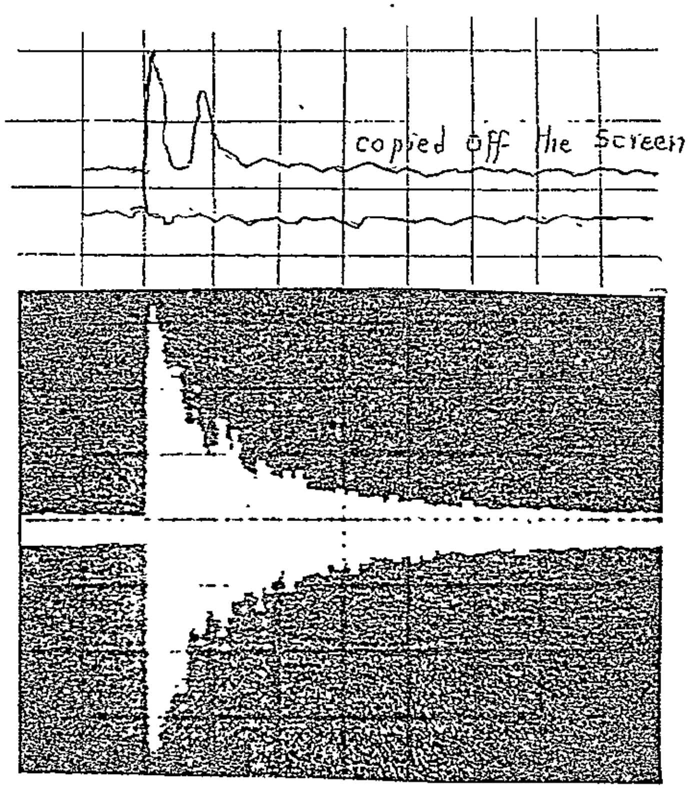


FIG. 46
TEST 3-b

A(I)	X(I)	Y(I)	H(I)
6.250000	-0.7152557E-06	-0.9536743E-06	1.333333
18.75000	4.124232	-2.150216	-0.5213617
31.25000	2.747234	1.386169	0.5045692
43.75000	1.051820	2.749330	2.613887
56.25000	0.6784344	5.149467	7.590221
68.75000	-0.3109391	4.488403	-14.43499
81.25000	-0.2292619	4.541687	-19.81004
93.75000	0.3696476	3.336830	9.027057
106.2500	0.5287182	1.707470	3.229452
118.7500	0.7847478	-1.190125	-1.516570
131.2500	0.8223593	0.8875925	1.079215
143.7500	0.8886834	-0.5147218	-0.5791959
156.2500	0.4481144	1.834173	4.093091
168.7500	0.2778947	1.951367	7.021965
181.2500	0.8437526E-02	3.367813	399.1469
193.7500	-0.2114844	2.972814	-14.05690
206.2500	-0.9878509	0.7176146	-0.7264402
218.7500	-1.322884	-1.341268	1.013896
231.2500	-1.859032	-2.516194	1.353497
243.7500	-2.231308	-2.233206	1.000851
256.2500	-2.819940	-2.895390	0.9948402
268.7500	-2.600000	-3.550002	1.365385
281.2500	-2.567862	-2.826384	1.100676
293.7500	-2.343365	-6.257913	2.670098
306.2500	-1.989987	-5.525238	2.776520
318.7500	-1.649659	-6.284113	3.809343
331.2500	-0.9258670	-6.277784	6.780436
343.7500	-0.8035762	-5.784917	7.198965
356.2500	-0.1471875	-4.544062	30.87262
368.7500	-0.3391682E-01	-5.743323	169.3355
381.2500	-0.3670735E-01	-4.125495	112.3888
393.7500	0.1056297	-6.608572	-62.56359
406.2500	-0.2175731	-6.284007	28.88228
418.7500	-0.5318579	-6.695921	12.58963
431.2500	-0.8194151	-5.193827	6.338457
443.7500	-0.9196477	-4.436830	4.824489
456.2500	-2.071877	-3.335186	1.609741
468.7500	-1.953140	-4.391899	2.248635
481.2500	-1.189889	-3.068493	2.578808
493.7500	-0.8396516	-1.101198	1.311494

TABLE 9
TEST 3-b

ORIGINAL PAGE IS
OF POOR QUALITY

12.50000	0.1000000E-02	0.0000000E+00	0.0000000E+00
25.00000	-1.043946	2.567167	-2.459099
37.50000	-3.194663	5.071345	-1.587443
50.00000	-2.735263	2.282261	-0.8343844
62.50000	-2.287580	1.653251	-0.7227074
75.00000	-2.109373	-2.231176	1.057743
87.50000	-0.7970164	-1.641514	2.059569
100.0000	-0.7355198	-4.339789	5.900302
112.5000	-0.4909324	-4.710217	9.594431
125.0000	-0.6085354	-3.559978	5.850075
137.5000	-1.217066	-2.055547	1.687827
150.0000	-0.5552960	-1.317670	2.372914
162.5000	-1.317557	0.2928590	-0.2222743
175.0000	-1.087387	-0.3220639	0.2961815
187.5000	-1.563717	-1.655733	1.058844
200.0000	-1.720666	-3.825556	2.223299
212.5000	-1.953788	-5.666648	2.900339
225.0000	-2.042970	-4.774841	2.337205
237.5000	-1.746810	-5.758968	3.296849
250.0000	-1.335433	-3.672426	2.749989
262.5000	-1.139783	-3.642472	-3.195759
275.0000	-0.5500002	-4.000001	7.272727
287.5000	-0.3191622	-3.622559	11.35021
300.0000	0.4624953	-4.281540	-9.257478
312.5000	0.8064399	-2.856713	-3.542375
325.0000	1.297757	-1.453863	-1.120290
337.5000	1.290461	0.6105119E-01	0.4730960E-01
350.0000	1.346008	1.358312	1.009141
362.5000	1.640577	1.635164	0.9967007
375.0000	1.210134	3.012193	2.489140
387.5000	1.824541	2.693707	1.476375
400.0000	1.965223	2.952728	1.502490
412.5000	2.006026	5.629253	2.806171
425.0000	1.772548	7.079271	3.993840
437.5000	1.589309	9.244121	5.816441
450.0000	1.968645	9.904164	5.030955
462.5000	1.951084	11.49004	5.889057
475.0000	2.918747	11.65166	3.992008
487.5000	3.217090	15.54790	4.832907
500.0000	3.373931	20.35427	6.032805

TABLE 9-Cont.
TEST 3-b

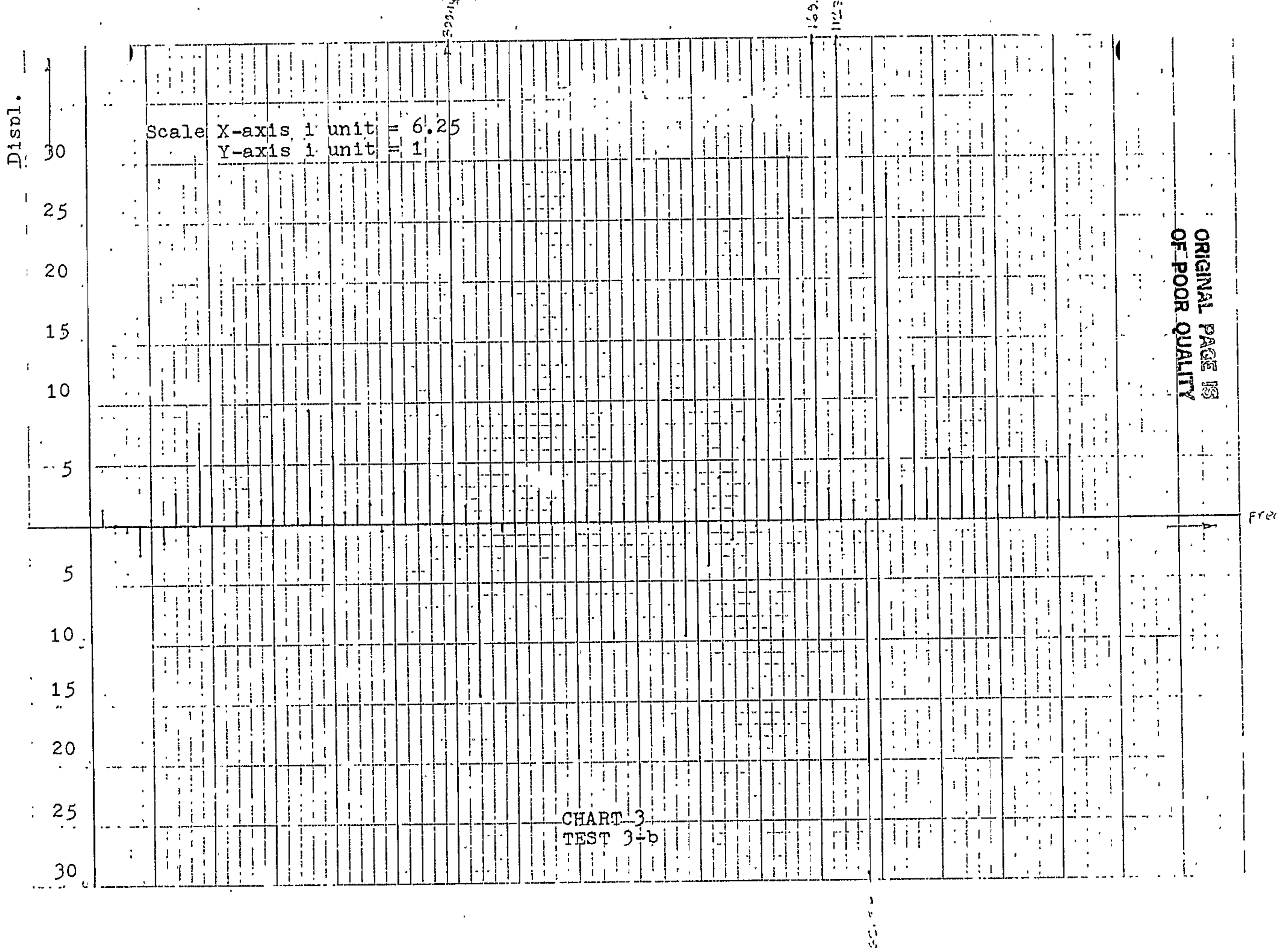


CHART 3
TEST 3-b

GAGE #		1	2	3	4	5	6	7	8
LAYER	1	0.	-1265.	-1265.	-1265.				
LAYER	2	-822.	-879.	-879.	-57.				
LAYER	3	-736.	-791.	-791.	-55.				
LAYER	4	-650.	-704.	-164.	487.				
LAYER	5	-164.	-1545.	-1489.	-1325.				
LAYER	6	-160.	-1009.	-212.	689.				
LAYER	7	571.	-316.	-206.	1459.				
LAYER	8	1970.	724.	832.	1151.				
LAYER	9	688.	424.	528.	1506.				
LAYER	10	1657.	610.	712.	1070.				

TABLE 10
TEST 3-c

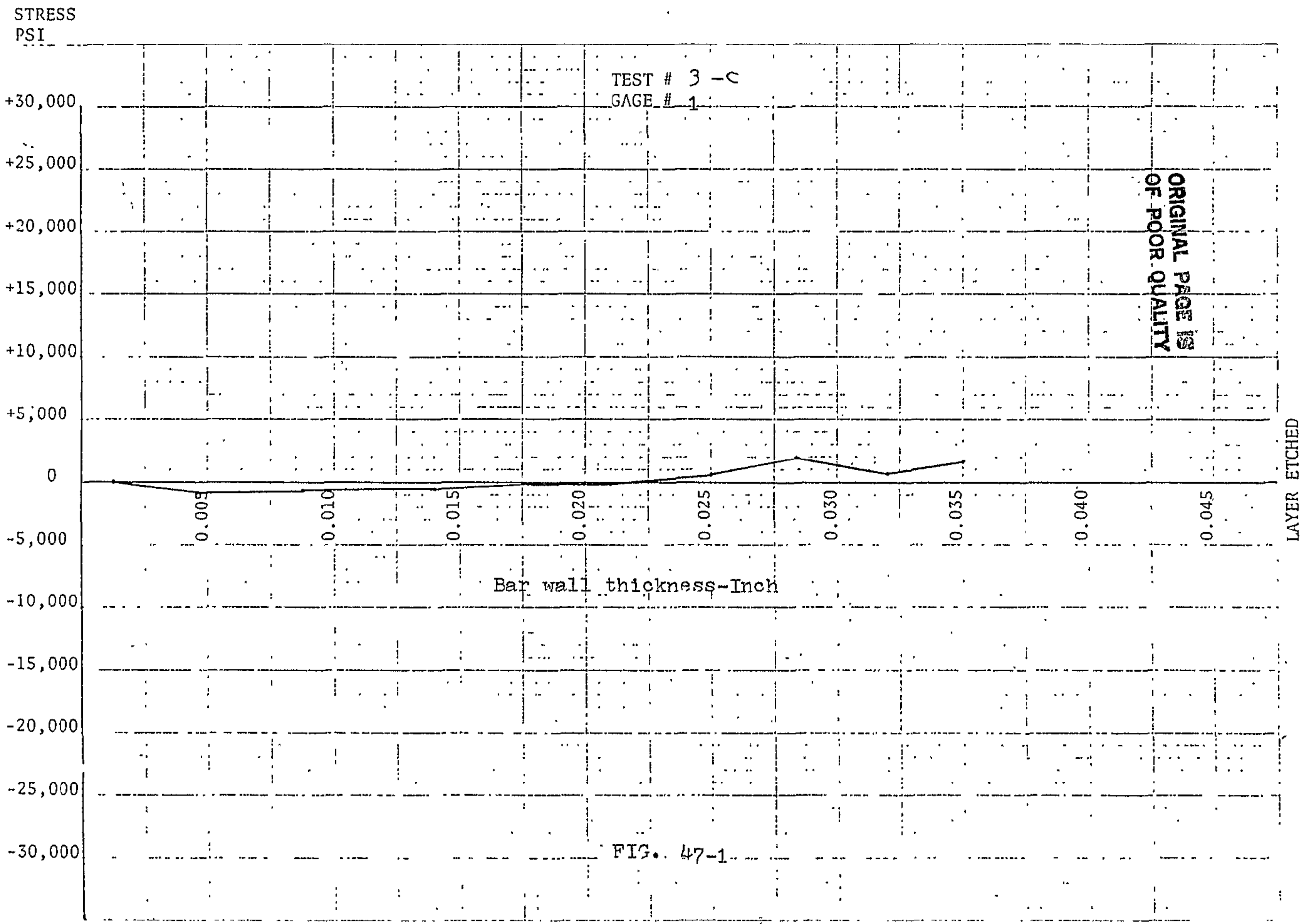

STRESS PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 3 -C
GAGE # 1
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch
ORIGINAL PAGE IS OF POOR QUALITY

FIG. 47-1

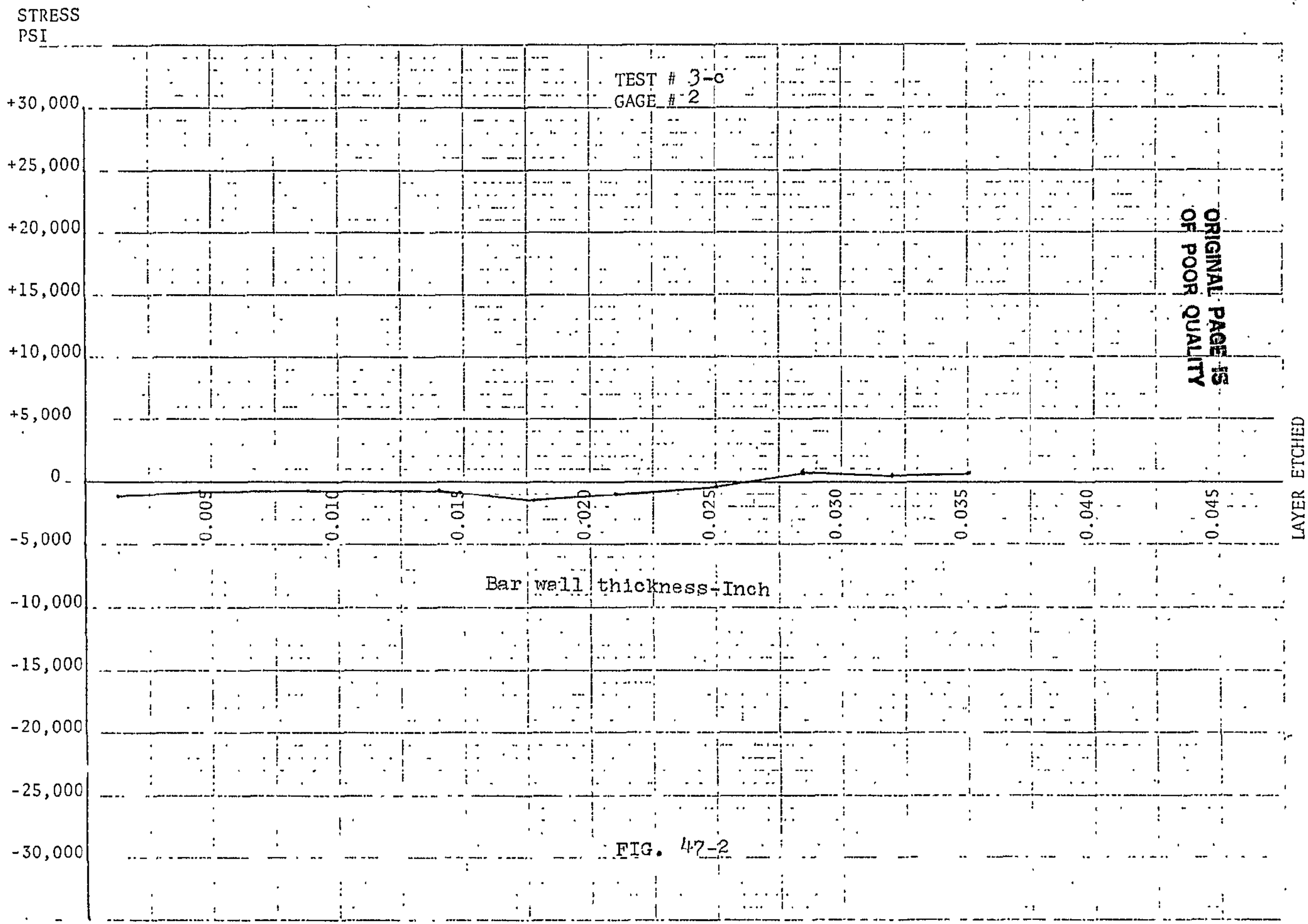
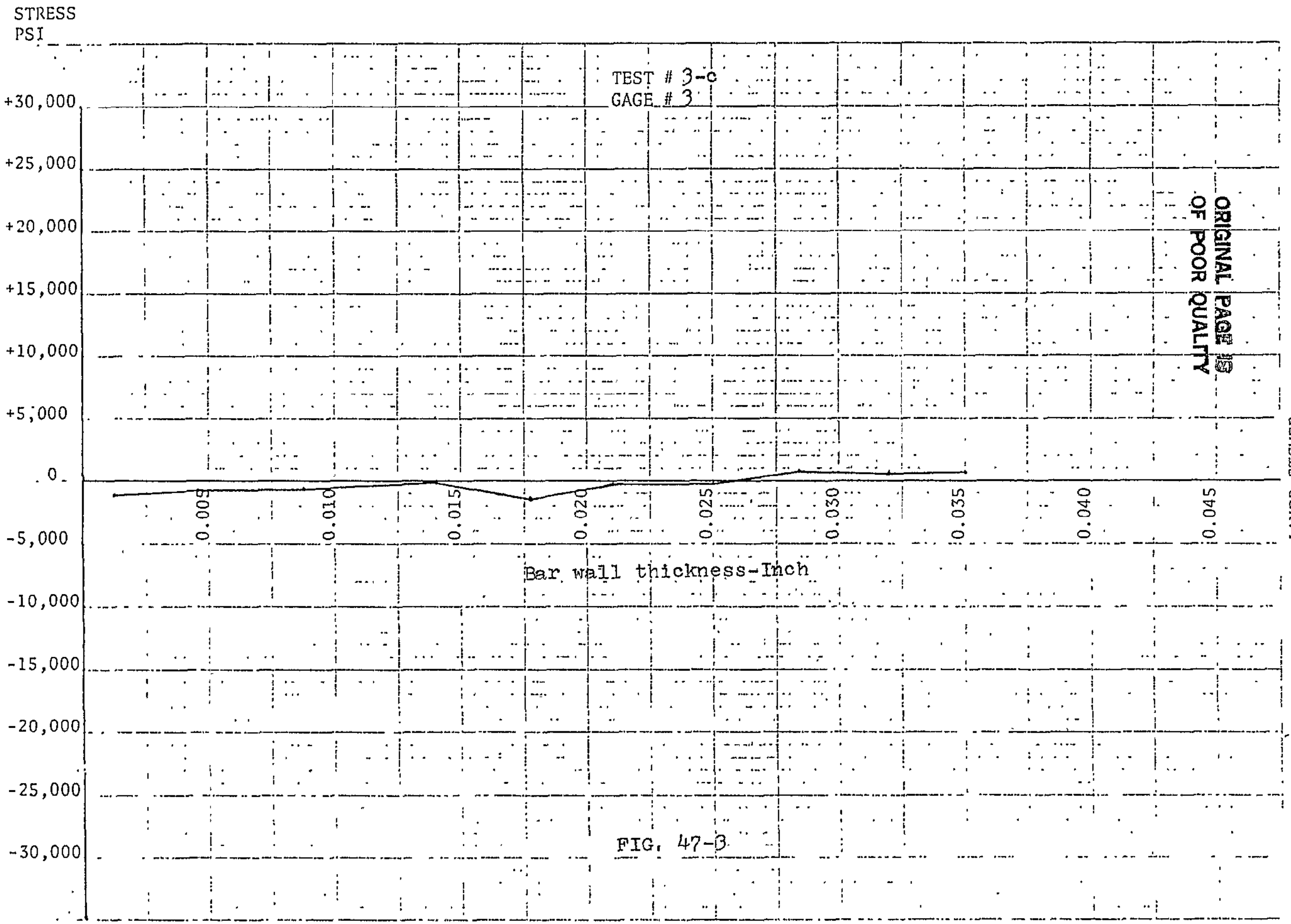


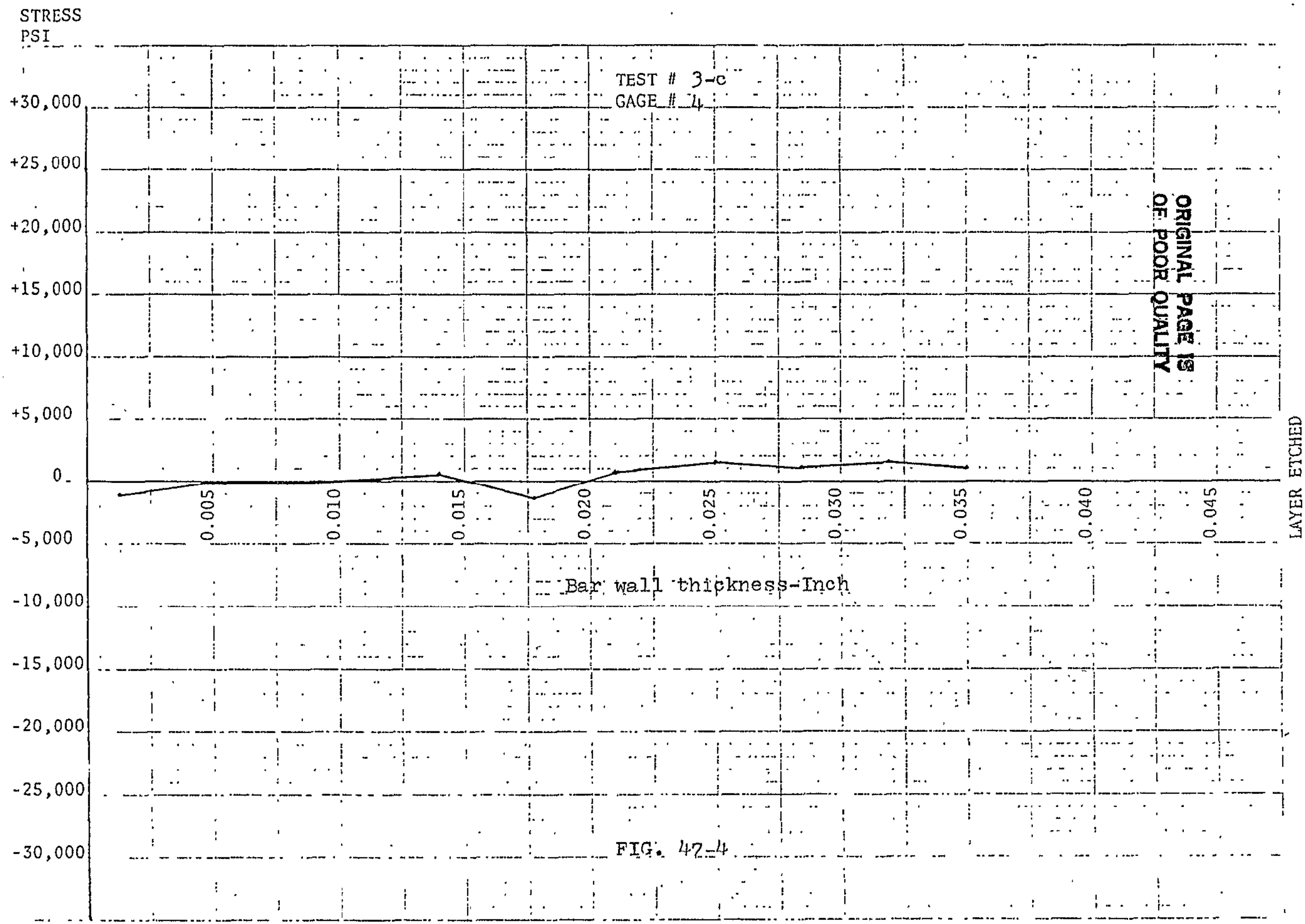
FIG. 47-2

ORIGINAL PAGE IS OF POOR QUALITY



STRESS
PSI
TEST # 3-c
GAGE # 3
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 47-B


STRESS
PSI
TEST # 3-c
GAGE # 4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch
FIG. 47-4

LAYER	1	6936.	-3468.	-3468.	6936.
LAYER	2	13965.	-4674.	-4674.	9348.
LAYER	3	4716.	-115.	-1591.	6135.
LAYER	4	5231.	2276.	-170.	5232.
LAYER	5	15160.	4831.	-9823.	19988.
LAYER	6	4205.	-3297.	-13716.	905.
LAYER	7	-4196.	1700.	-509.	7686.
LAYER	8	-2163.	60.	-504.	9752.
LAYER	9	-1397.	60.	-500.	9473.
LAYER	10	-1514.	-2041.	-2595.	9898.
LAYER	11	-5008.	-3686.	-4234.	9083.
LAYER	12	-2230.	5036.	-3231.	12221.
LAYER	13	2412.	6386.	3549.	8516.
LAYER	14	2691.	7231.	4119.	9341.
LAYER	15	4128.	11548.	10736.	9908.
LAYER	16	447.	3557.	2754.	5572.

TABLE 11
TEST 4-a

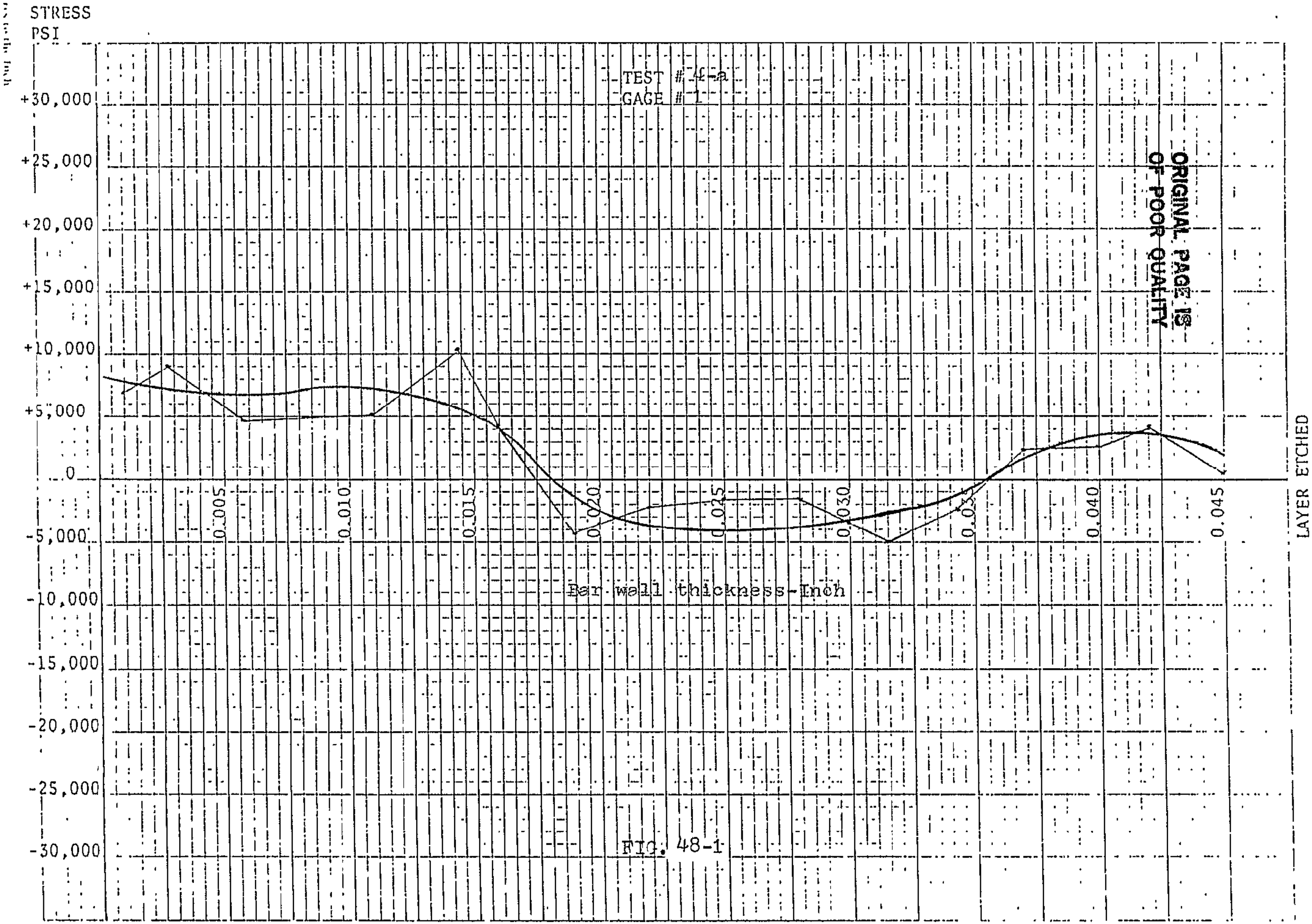

STRESS
PSI
TEST # 4-a
GAGE # 1
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 48-1

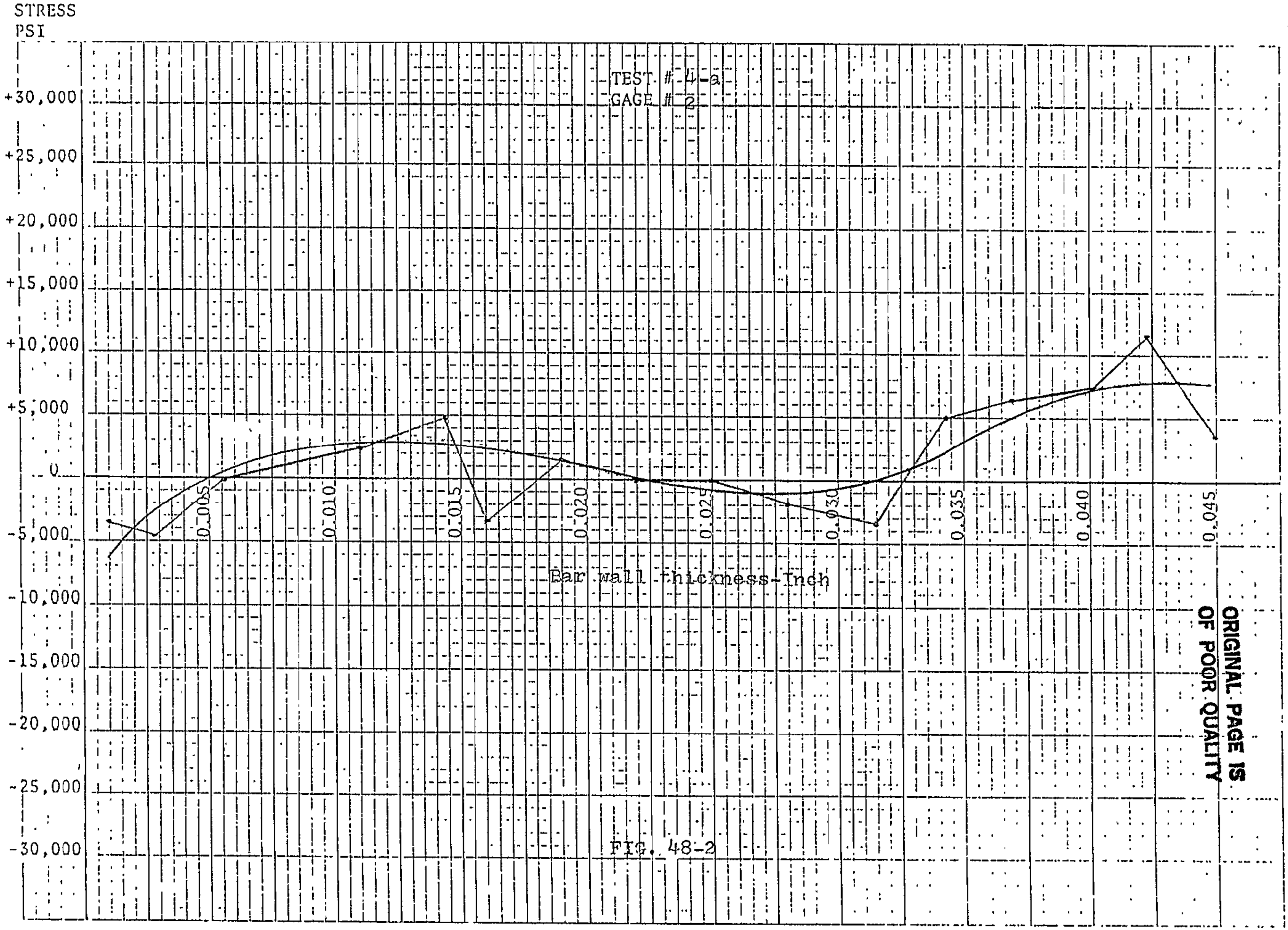


FIG. 48-2

ORIGINAL PAGE IS
OF POOR QUALITY

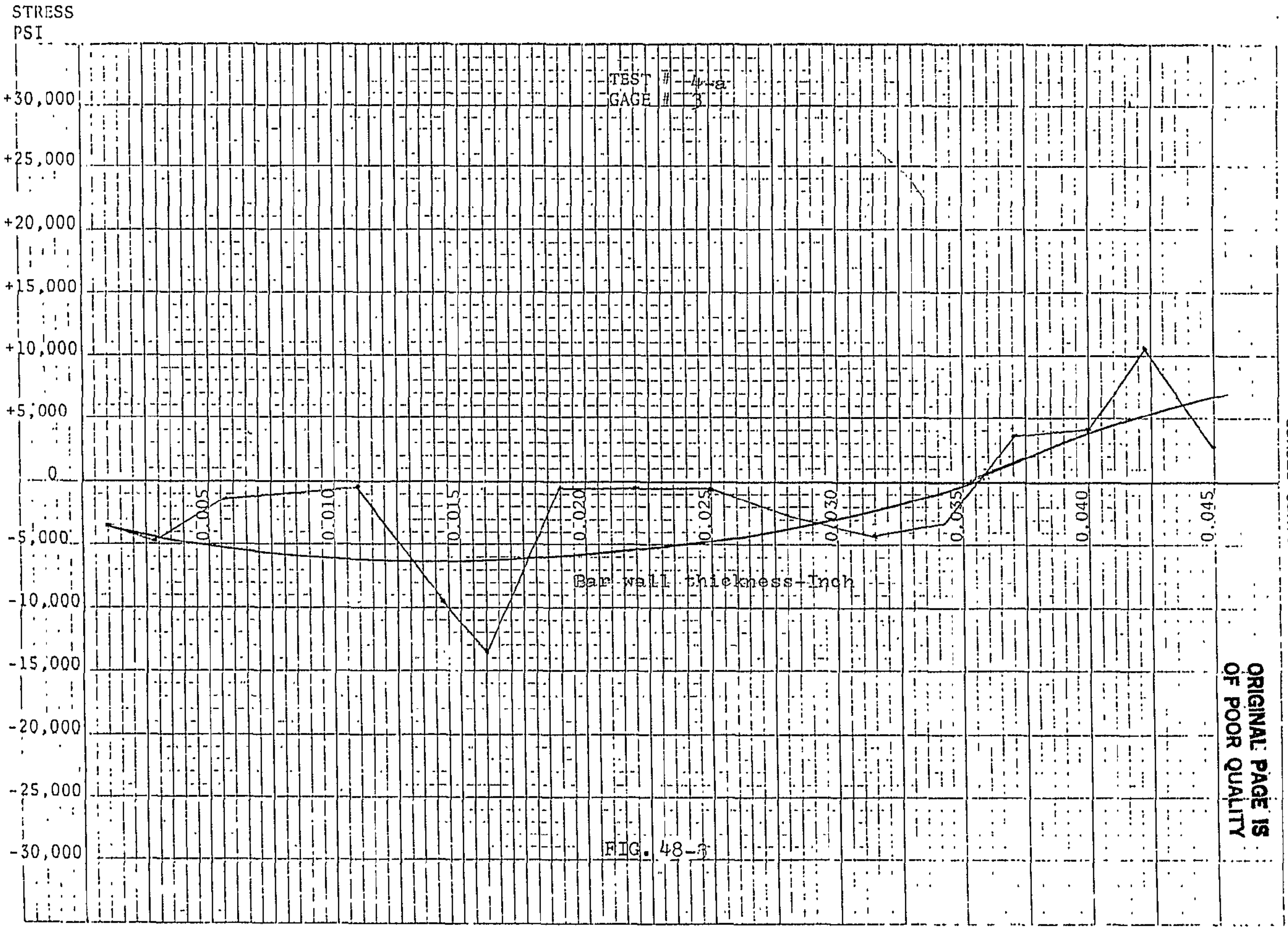

STRESS
PSI
TEST # 4-a
GAGE # 3
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 48-3

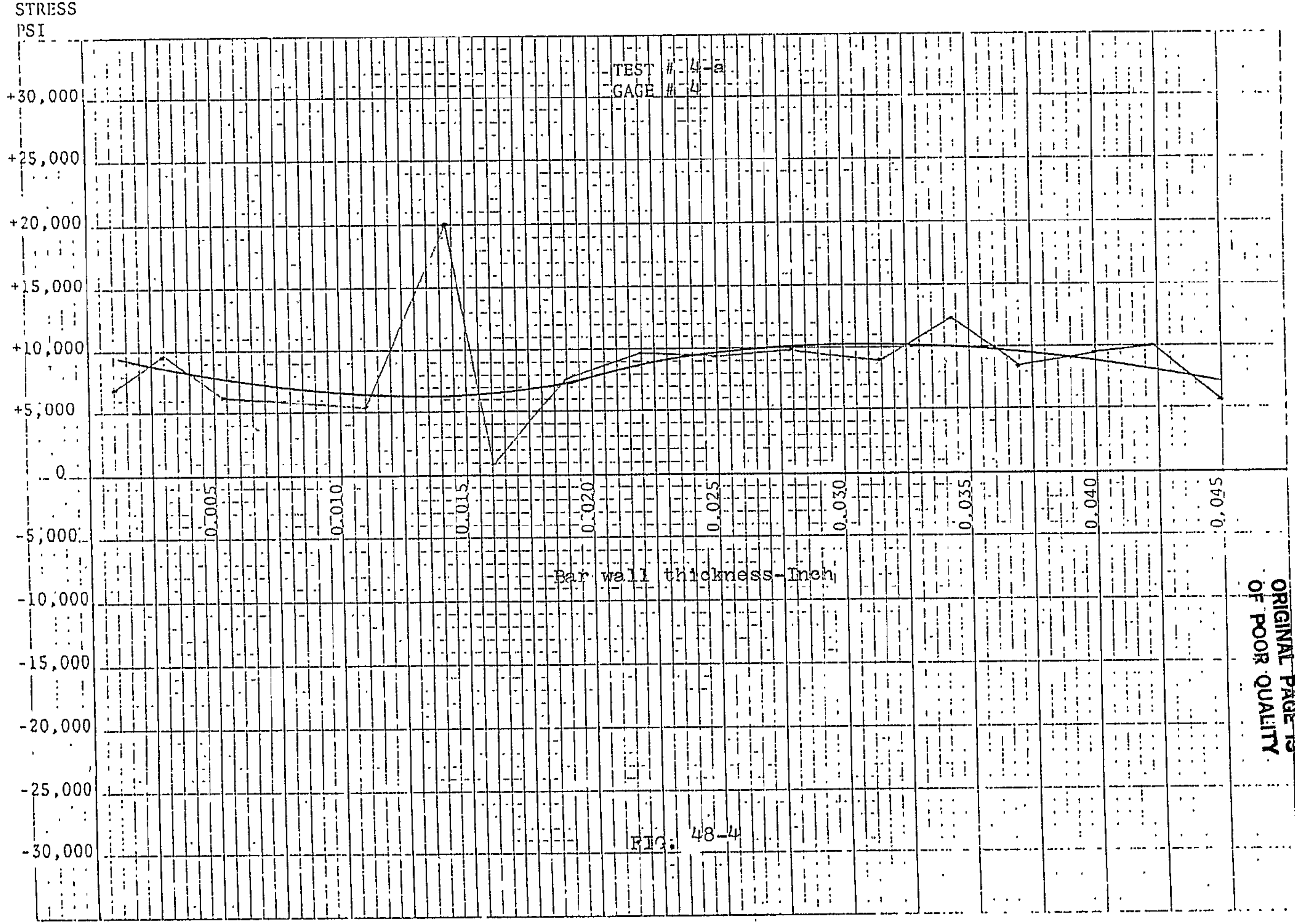


FIG. 48-4

ORIGINAL PAGE IS
OF POOR QUALITY

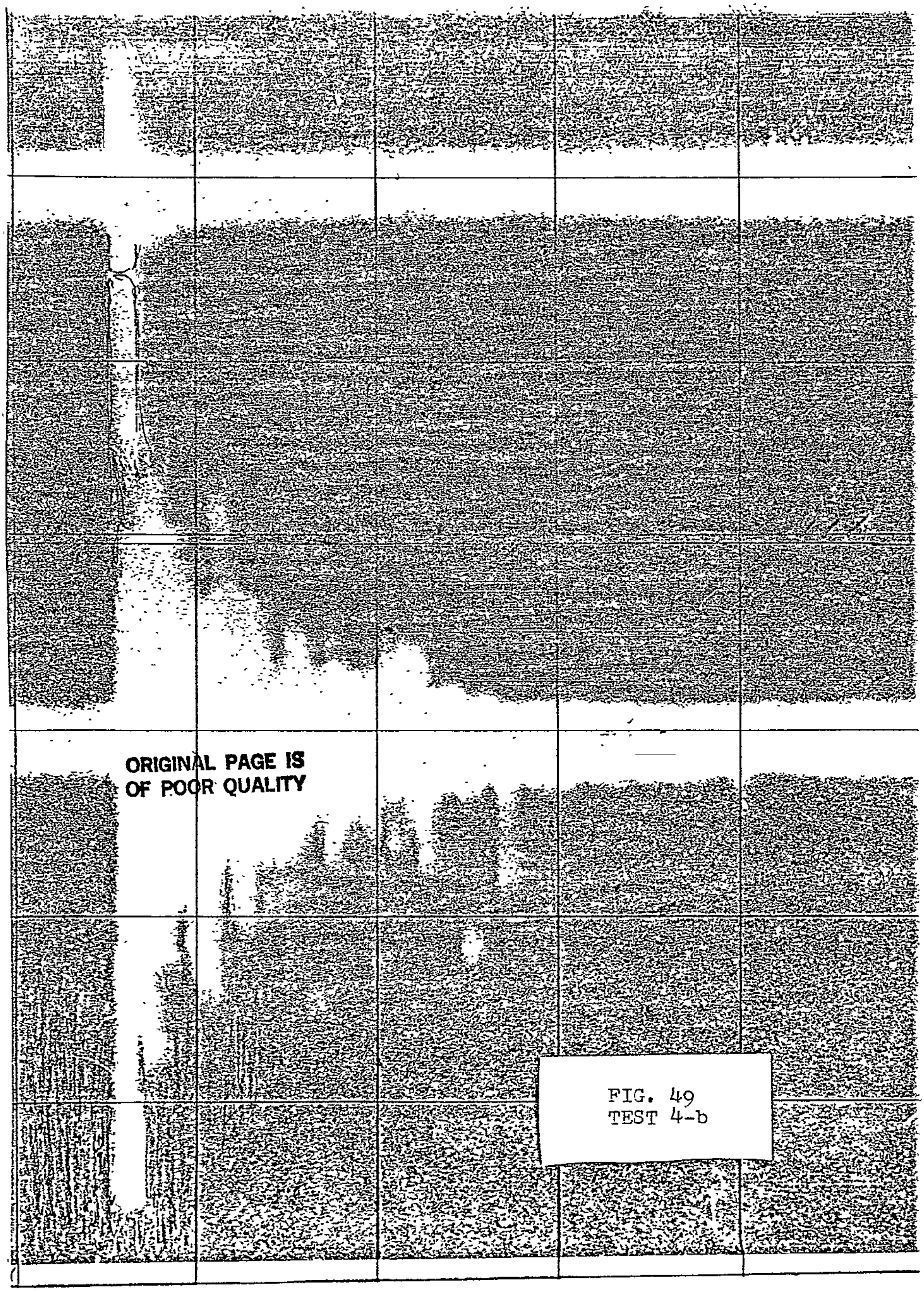


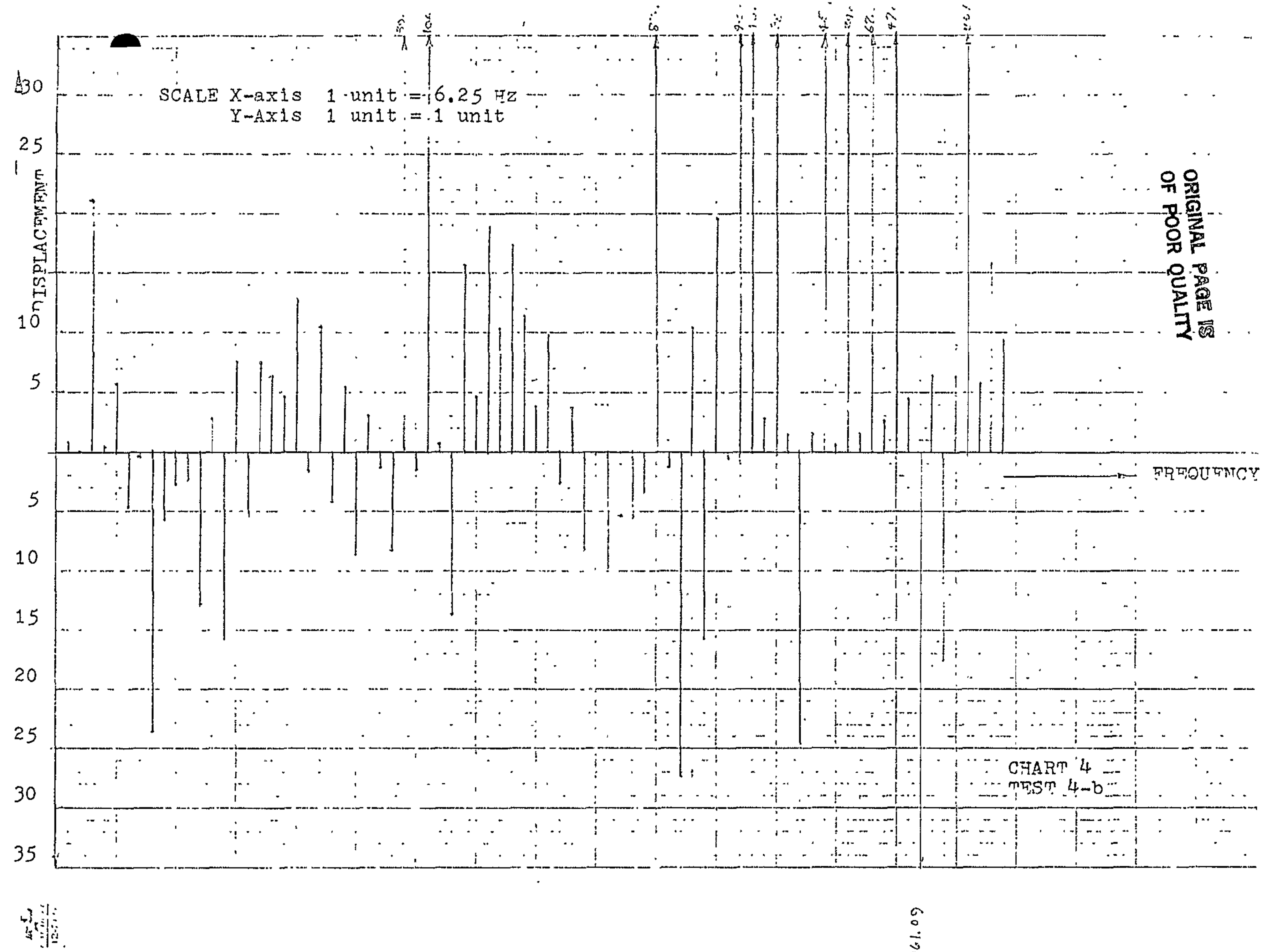
FIG. 49
TEST 4-b

A(I)	X(I)	Y(I)	H(I)
6.250000	-0.5960464E-06	-0.4768372E-06	0.8000000
18.75000	0.1422350	3.025710	21.27261
31.25000	0.1035034	0.6008103	5.804739
43.75000	0.1530738	-0.4747725E-01	-0.3101592
56.25000	0.3530619	-2.097229	-5.940116
68.75000	0.4636920	-0.9322674	-2.010532
81.25000	0.6124296	1.778944	2.904733
93.75000	0.6691294	4.909606	7.337305
105.2500	0.5985094	4.480725	7.486473
118.7500	0.5771630	2.577475	4.465766
131.2500	0.5081584	-0.8742760	-1.720479
143.7500	0.3569202	-1.445958	-4.051208
155.2500	0.3067014	-2.693244	-8.781325
168.7500	0.1319940	-0.1417594	-1.073984
181.2500	0.3868750E-01	1.528063	39.49758
193.7500	0.2482751E-01	2.696932	108.6268
206.2500	-0.1252199	1.699881	-13.57517
218.7500	-0.1356764	-0.6496987	4.788592
231.2500	-0.2483852	-2.505574	10.08745
243.7500	-0.3615775	-4.002553	11.06970
255.2500	-0.3721835	-3.425724	9.204395
268.7500	-0.4800001	-1.800000	3.749999
281.2500	-0.5270284	0.5250531E-01	-0.9962520E-01
293.7500	-0.5069322	2.634300	-5.196552
306.2500	-0.5321749	1.769805	-3.325607
318.7500	-0.4183192	-0.4726929	1.129981
331.2500	-0.2923848	-2.985789	10.21185
343.7500	-0.2638633	-5.040104	19.10119
356.2500	-0.8043749E-01	-3.427313	42.60840
368.7500	-0.6234031E-01	-2.895551	46.44750
381.2500	-0.4044751E-02	-1.568370	387.7544
393.7500	0.8384279E-01	-2.077255	-24.77559
406.2500	-0.5606281E-01	-2.544590	45.38819
418.7500	-0.1999991E-01	-4.977800	248.8911
431.2500	-0.7657378E-01	-5.177842	67.61899
443.7500	-0.1291295	-6.079607	47.08147
455.2500	0.1372340E-01	-2.210812	-161.0979
468.7500	-0.6609529E-01	1.140132	-17.24983
481.2500	0.6369241E-03	1.641525	2577.270
493.7500	0.2187983	3.370970	15.40675

TABLE 12
TEST 4-b

12.50000	0.1000000E-02	0.0000000E+00	0.0000000E+00
25.00000	1.206526	0.4028735	0.3339120
37.50000	0.4280995	-2.051101	-4.791178
50.00000	0.4125961E-01	-0.9722238	-23.56358
62.50000	0.2118492	-0.5496376	-2.594476
75.00000	-0.1891608	2.443632	-12.91828
87.50000	-0.1805338	2.842466	-15.74478
100.0000	-0.1831975	0.9678778	-5.283248
112.5000	-0.3996087	-2.430842	6.083057
125.0000	-0.3349030	-4.173017	12.46037
137.5000	-0.3907262	-4.034981	10.32688
150.0000	-0.3926228	-1.997907	5.088618
162.5000	-0.2618207	-0.7891093	3.013930
175.0000	-0.2722762	2.216675	-8.141274
187.5000	-0.2417294	0.3937156	-1.628750
200.0000	-0.1714505	-0.7588269E-01	0.4425924
212.5000	-0.2292777	-3.630111	15.83281
225.0000	-0.1806045	-3.422874	18.95232
237.5000	-0.2225881	-3.798648	17.06582
250.0000	-0.2959282	-1.129967	3.818384
262.5000	-0.2543463	0.6651324	-2.615066
275.0000	-0.2900000	2.349997	-8.103438
287.5000	-0.1991120	1.978463	-9.936432
300.0000	-0.1277306	0.6878973	-5.385534
312.5000	-0.4025210E-01	-3.505224	87.08176
325.0000	0.1232414	-3.370935	-27.35229
337.5000	0.2698410	-4.235034	-15.69455
350.0000	0.4599614	-0.1865638	-0.4056074
362.5000	0.6242960	0.7228066	1.157795
375.0000	0.7687280	2.144940	2.790246
387.5000	0.9392939	1.244772	1.325221
400.0000	1.107763	1.615122	1.458003
412.5000	1.251294	0.6437061	0.5144323
425.0000	1.413190	2.249764	1.591976
437.5000	1.446601	3.781776	2.614250
450.0000	1.545822	7.065997	4.571028
462.5000	1.574095	10.28475	6.533754
475.0000	1.467952	9.203225	6.269432
487.5000	1.431122	8.284515	5.788827
500.0000	1.018516	9.361416	9.191234

TABLE 12 Cont.
TEST 4-b



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GAGE #		1	2	3	4	5	6	7	8
LAYER	1	0.	-2784.	0.	0.				
LAYER	2	-3471.	-7000.	0.	0.				
LAYER	3	-58.	-172.	0.	-2459.				
LAYER	4	-3041.	-171.	2984.	-58.				
LAYER	5	-114.	2178.	4752.	4638.				
LAYER	6	-3064.	-111.	172.	58.				
LAYER	7	-2413.	-2353.	-2072.	-2185.				
LAYER	8	-5186.	-2646.	112.	-0.				
LAYER	9	-2349.	-2233.	111.	-0.				
LAYER	10	-4791.	-2476.	-2090.	-2199.				
LAYER	11	-4170.	-3998.	51.	-3723.				

TABLE 13
TEST 4-c

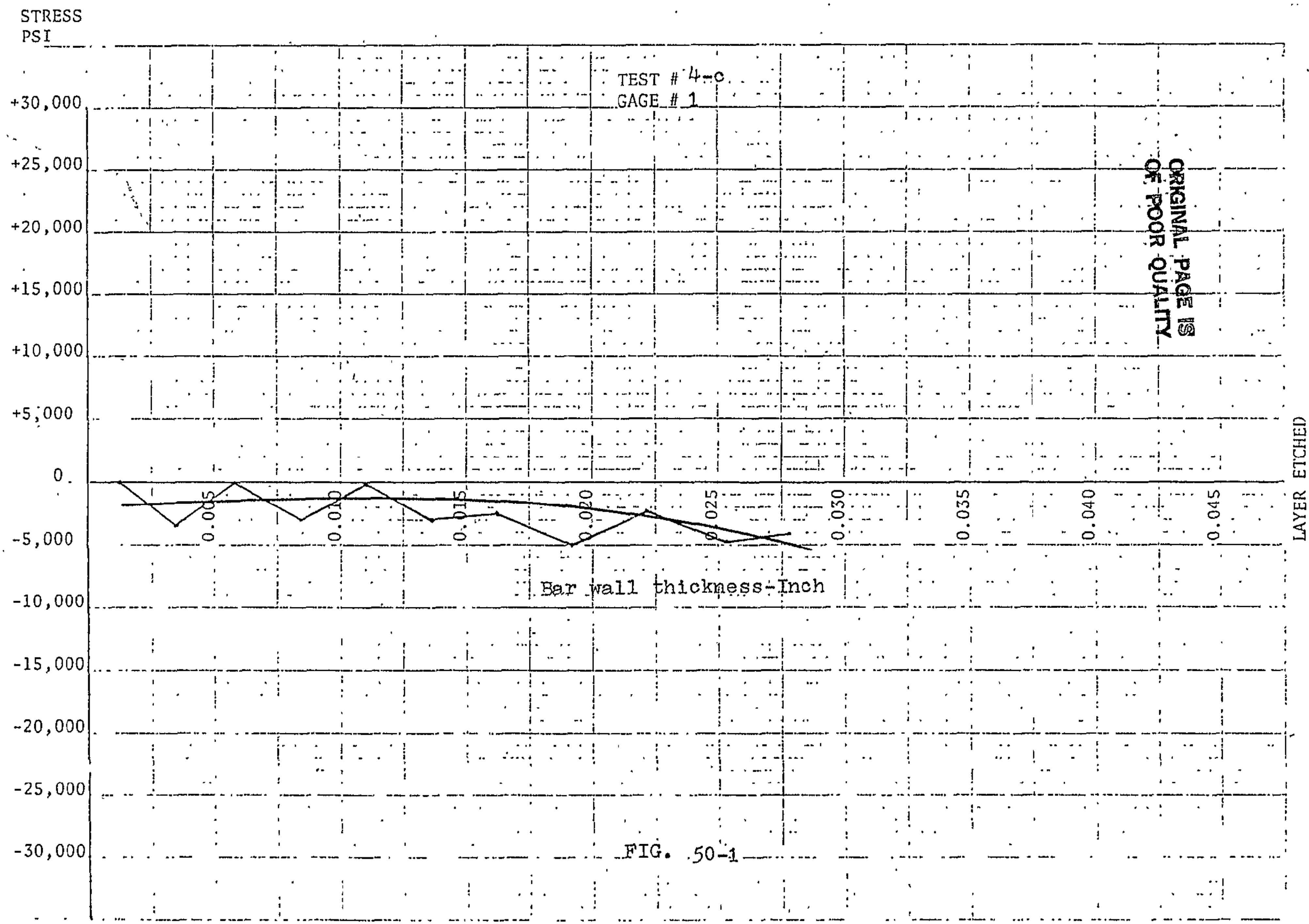
STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 4-c
GAGE # 1
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 50-1

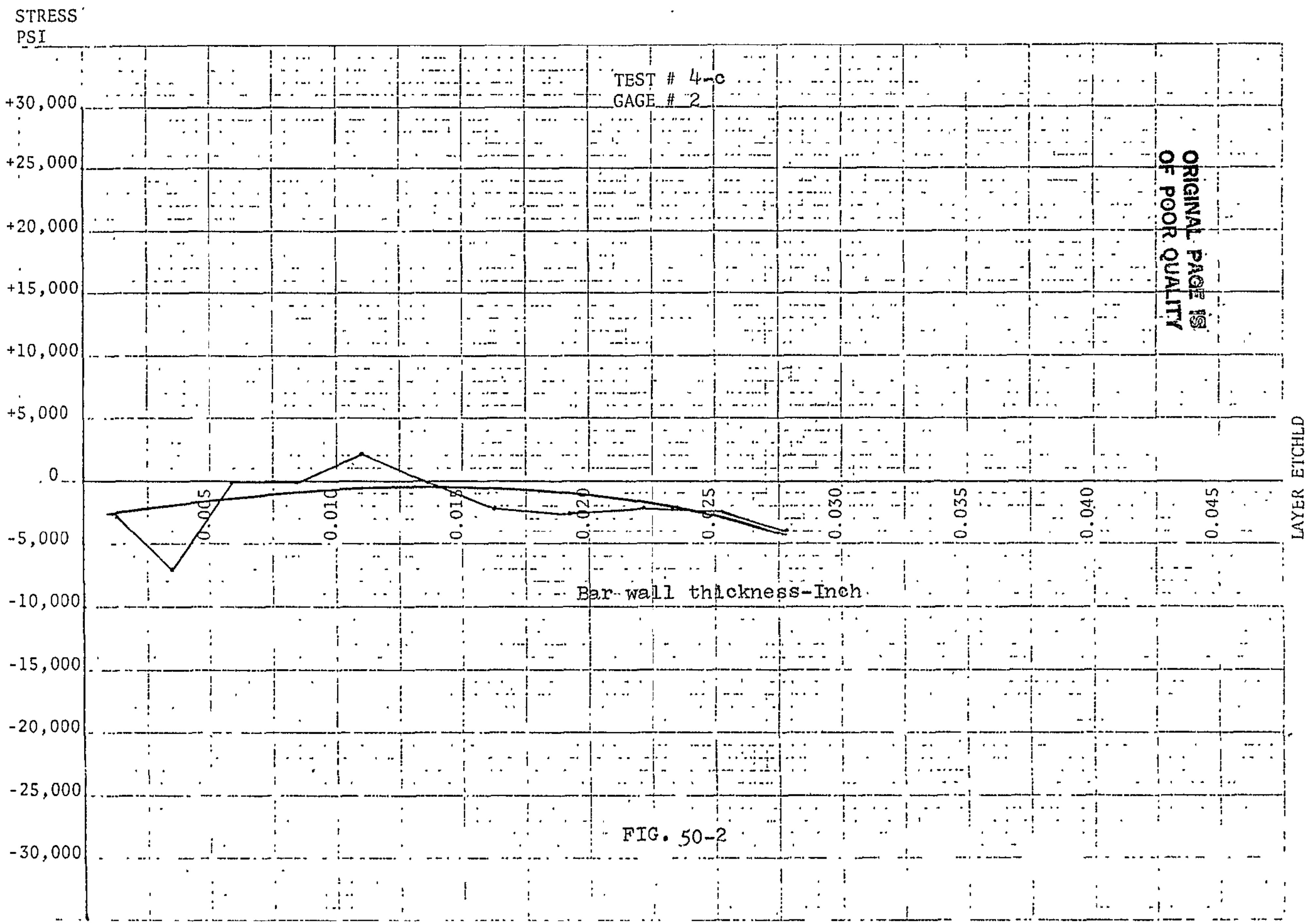
STRESS
PSI
TEST # 4-c
GAGE # 2
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 50-2

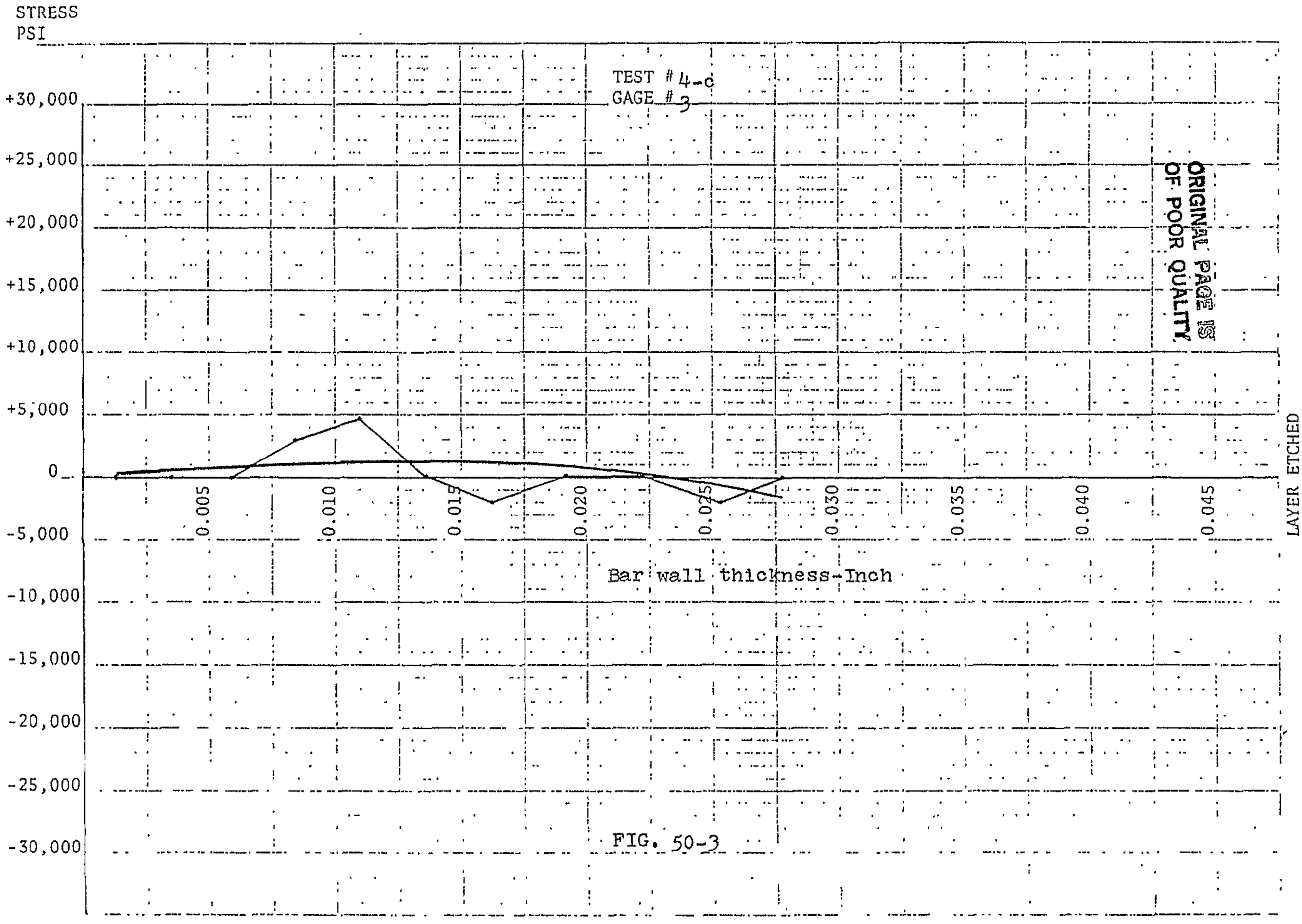
STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 4-c
GAGE # 3
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 50-3

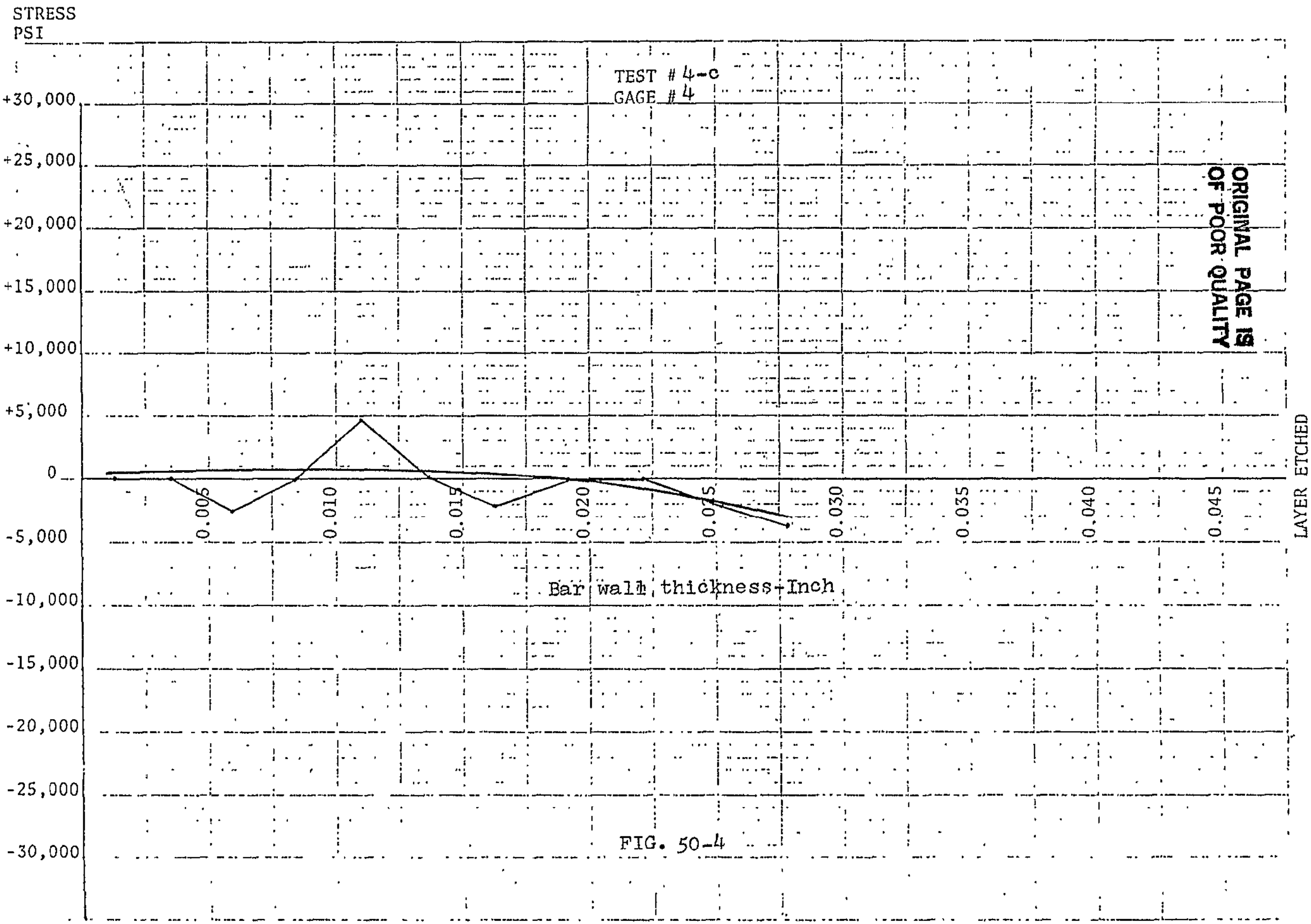
STRESS
PSI
TEST # 4-c
GAGE # 4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 50-4

	GAGE #	1	2	3	4
LAYER	1	7561.	7561.	6702.	15357.
LAYER	2	6910.	9433.	3794.	[illegible]
LAYER	3	10798.	13209.	-8616.	21425.
LAYER	4	6476.	10317.	-6308.	12704.
LAYER	5	12886.	11379.	9019.	13296.
LAYER	6	9497.	14857.	-11706.	14071.
LAYER	7	4067	[illegible]	[illegible]	5799.
LAYER	8	8948.	12034.	21060.	12301.
LAYER	9	1942.	-7180.	-11688.	2965.
LAYER	10	[illegible]	-2034.	-5171.	5667.
LAYER	11	-1018.	1030.	2992.	6705.
LAYER	12	1134.	-1128.	-982.	11994.
LAYER	13	[illegible]	[illegible]	[illegible]	[illegible]

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TABLE 14
TEST 5-a

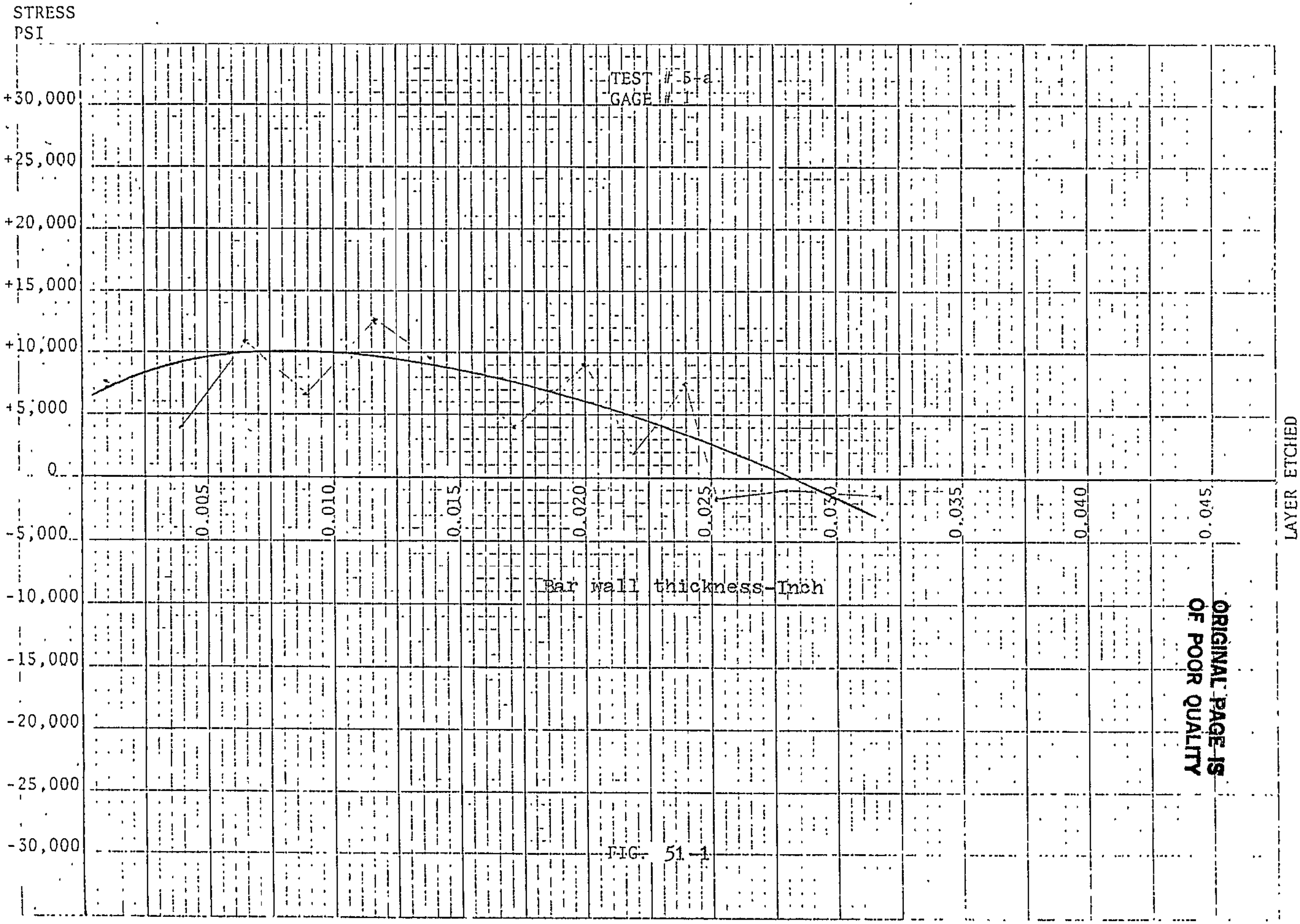

FIG. 51-1

ORIGINAL PAGE IS
OF POOR QUALITY

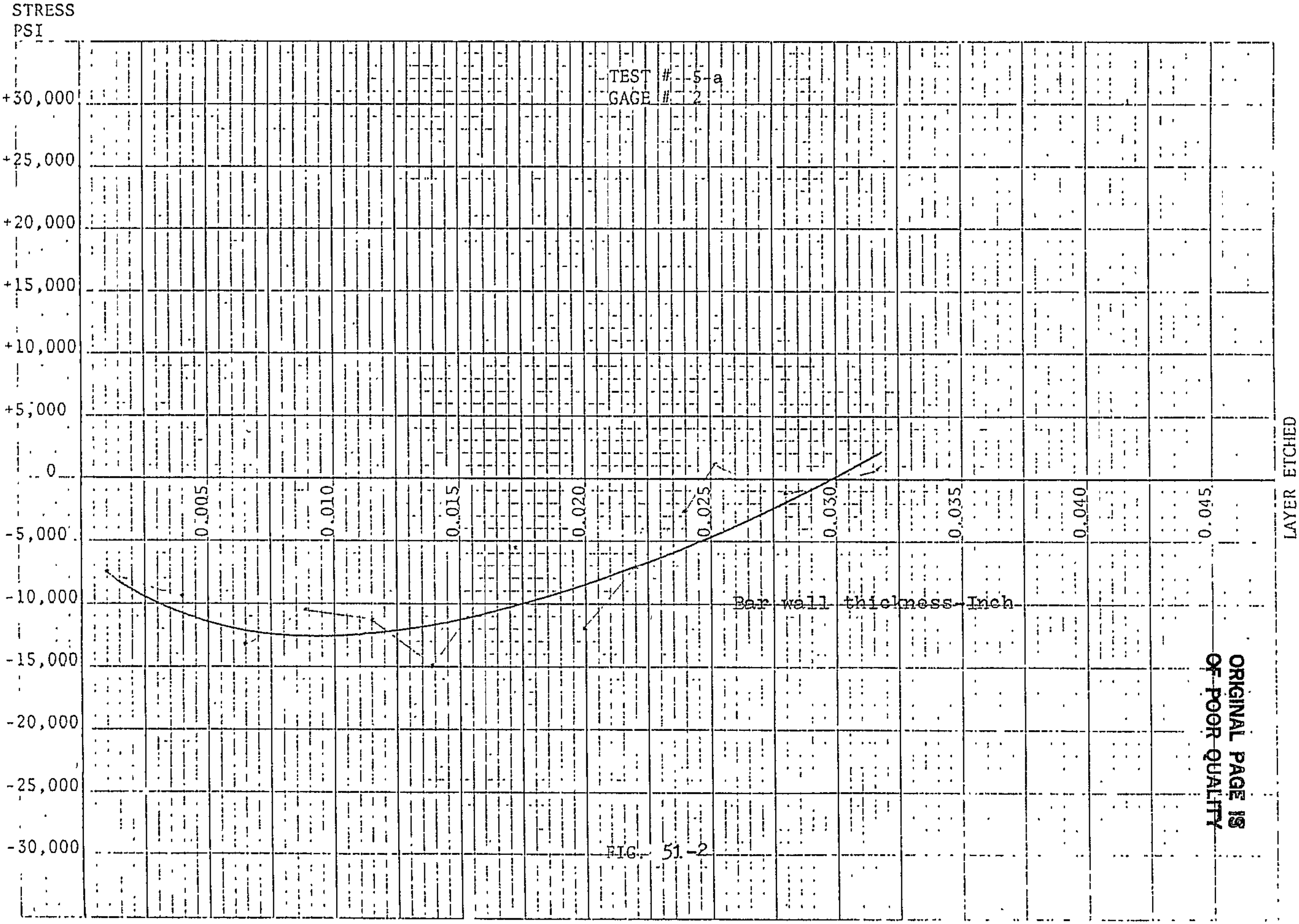
STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 5-a
GAGE # 2
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness Inch
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 51-2

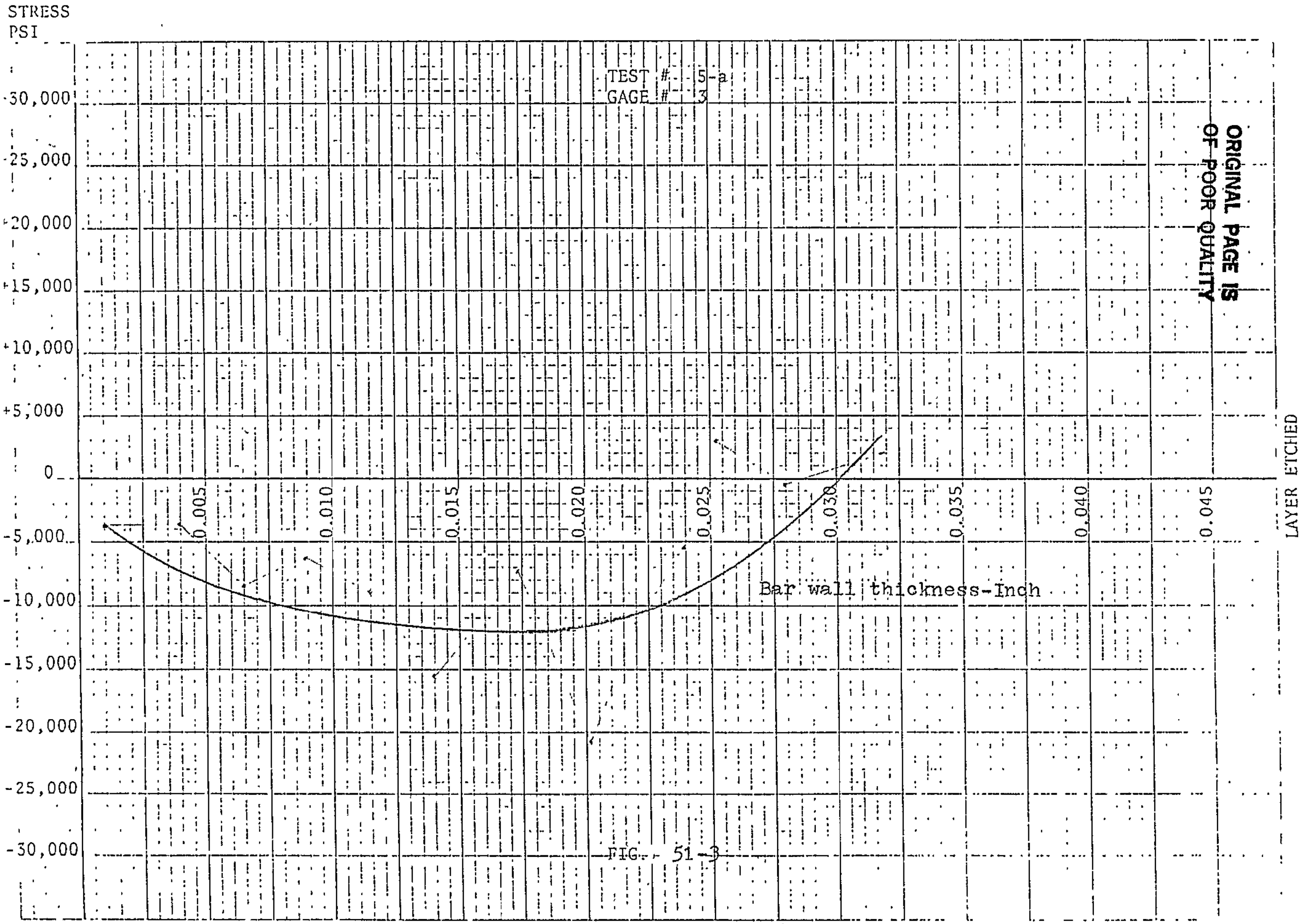

FIG. 51-3

ORIGINAL PAGE IS OF POOR QUALITY

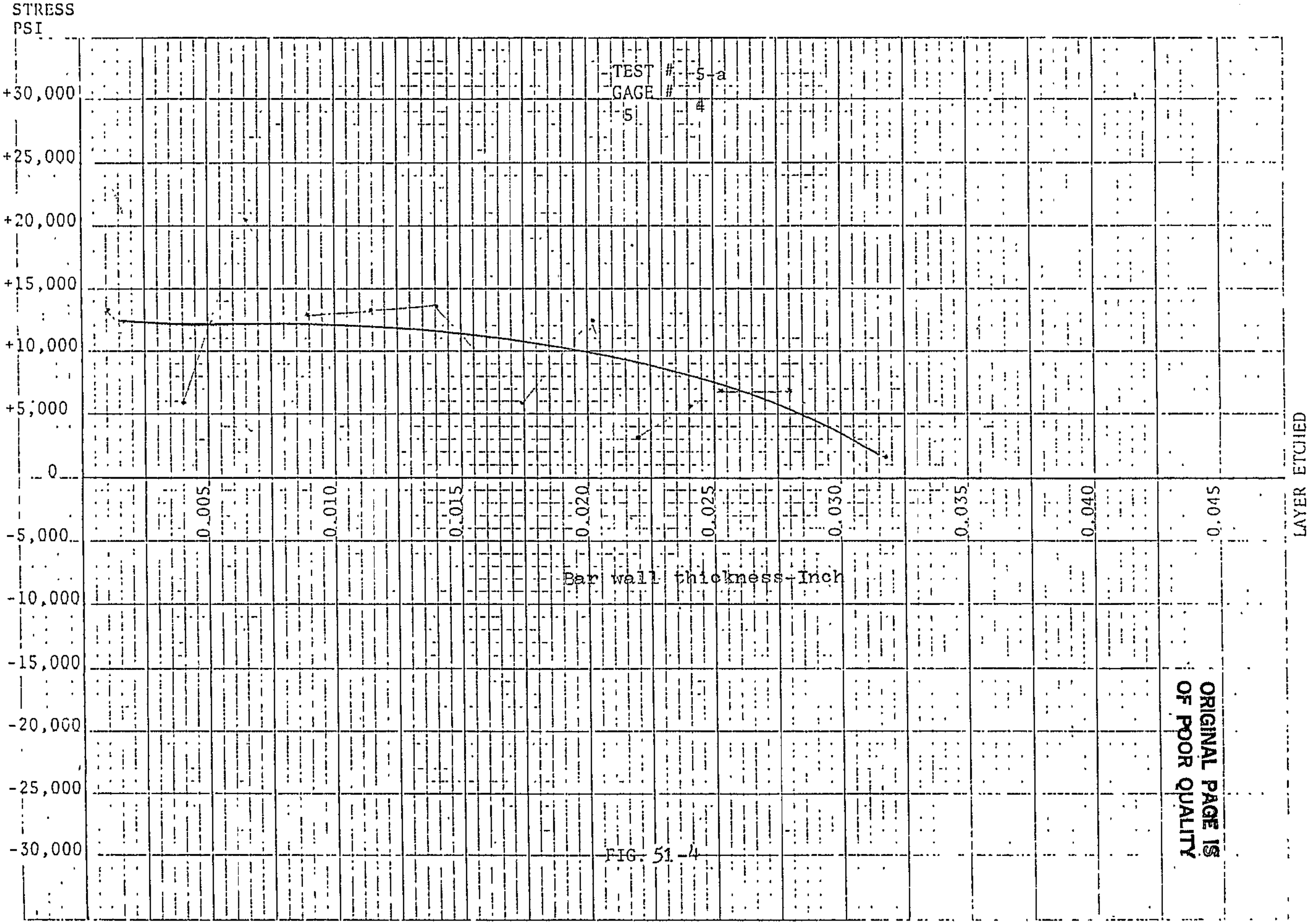

FIG. 51-4

ORIGINAL PAGE IS OF POOR QUALITY

GAGE #		1	2	3	4	5	6	7	8
LAYER	1	25737.	-19303.	-19303.	28955.	25737.	22520.	25737.	
LAYER	2	13744.	-8647.	-10308.	15462.	13744.	12026.	13744.	
LAYER	3	12397.	-7805.	-9298.	13947.	10961.	9412.	10961.	
LAYER	4	13785.	-8672.	-8785.	15508.	12174.	12005.	13728.	
LAYER	5	14108.	-10412.	-10524.	15872.	13995.	10749.	12513.	
LAYER	6	15330.	-8991.	-10973.	21223.	17090.	14939.	17089.	
LAYER	7	7633.	-4588.	-4753.	8798.	9023.	5806.	7579.	
LAYER	8	12179.	-7677.	-7838.	13826.	12241.	10533.	12127.	
LAYER	9	11035.	-6547.	-6705.	13777.	11095.	8294.	9881.	
LAYER	10	14817.	-10298.	-8859.	15460.	18064.	12583.	16303.	
LAYER	11	10881.	-6876.	-6110.	11511.	11053.	9334.	10832.	
LAYER	12	8611.	-5226.	-5262.	9836.	9392.	7890.	9790.	
LAYER	13	12713.	-7561.	-8756.	14524.	12933.	14330.	13940.	
LAYER	14	8412.	-5433.	-6114.	10283.	10398.	7252.	9125.	

TABLE 17
TEST 6-a

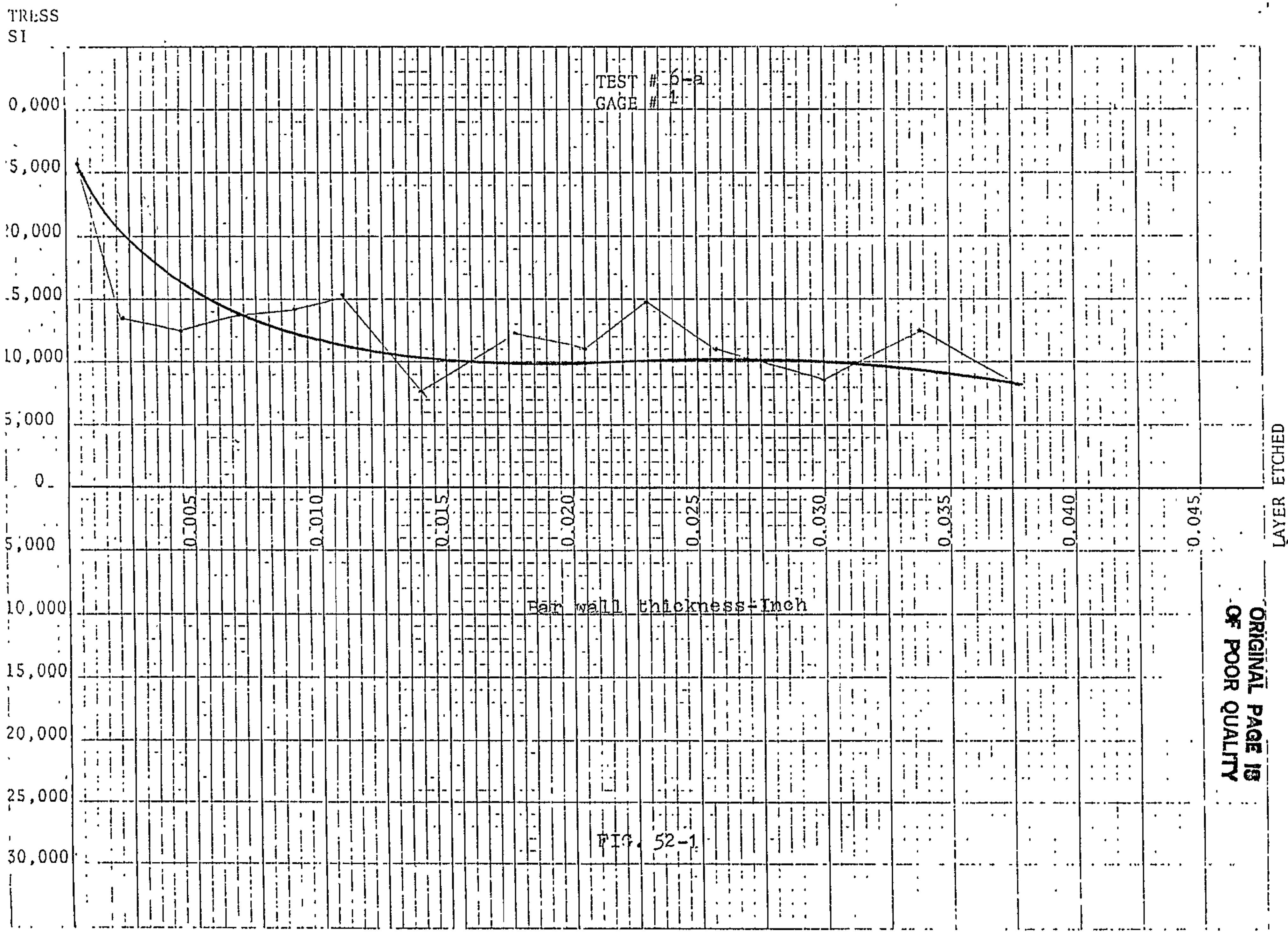

FIG. 52-1

ORIGINAL PAGE IS OF POOR QUALITY

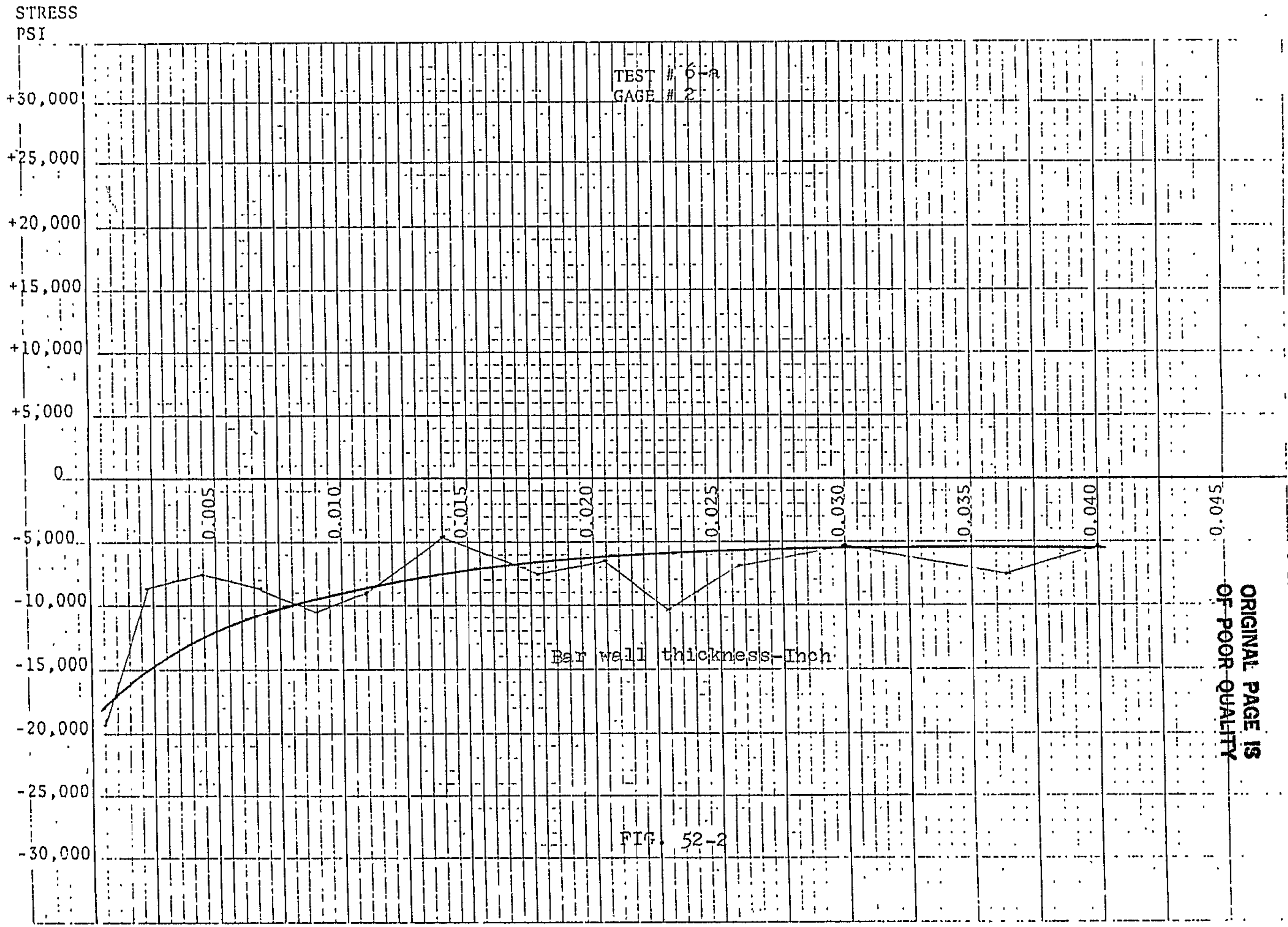

FIG. 52-2

ORIGINAL PAGE IS
OF POOR QUALITY

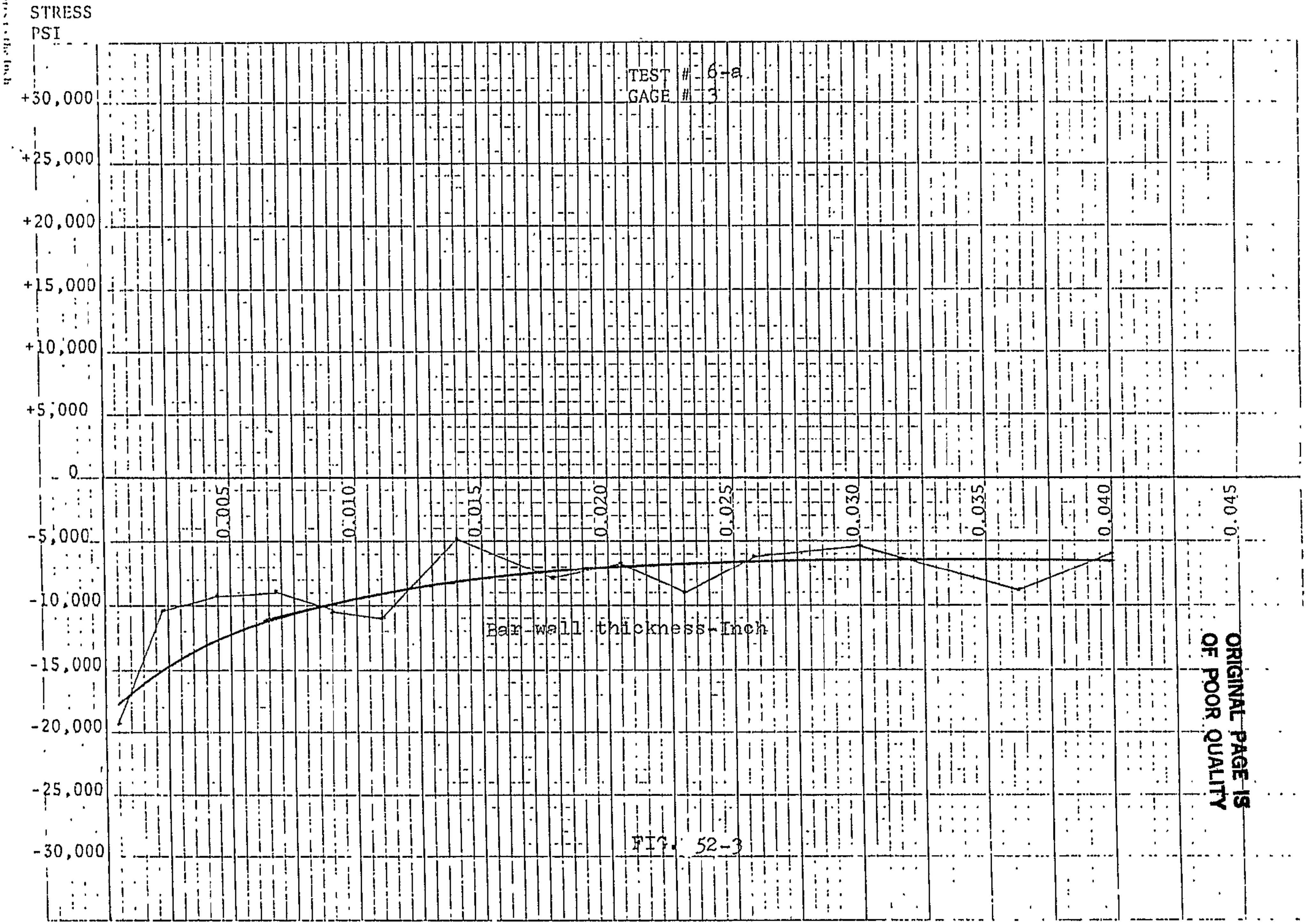
STRESS
PSI
TEST # 6-a
GAGE # 3
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
Bar wall thickness-Inch

FIG. 52-3

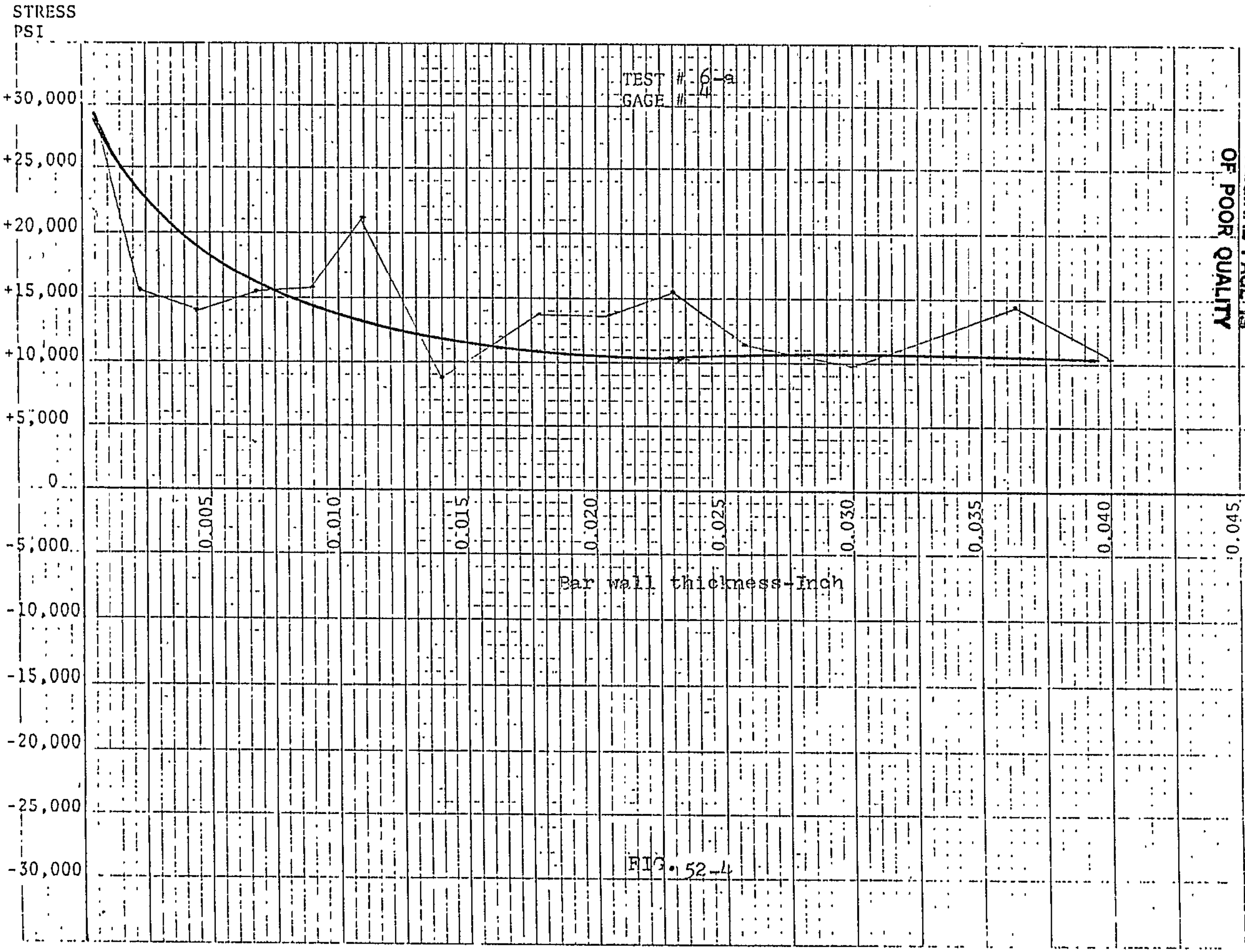

FIG. 52-4

ORIGINAL PAGE IS
OF POOR QUALITY

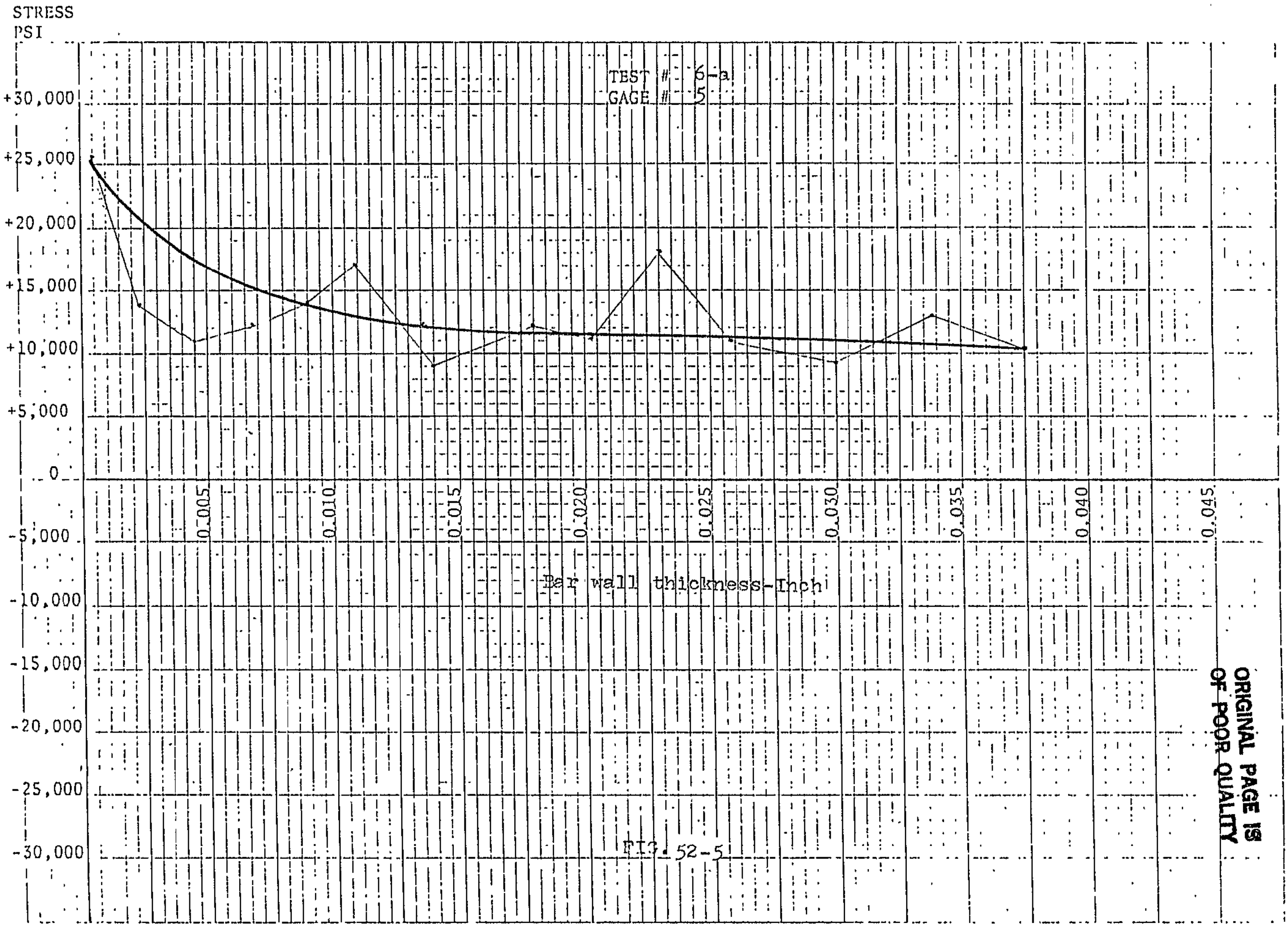

FIG. 52-5

ORIGINAL PAGE IS
OF POOR QUALITY

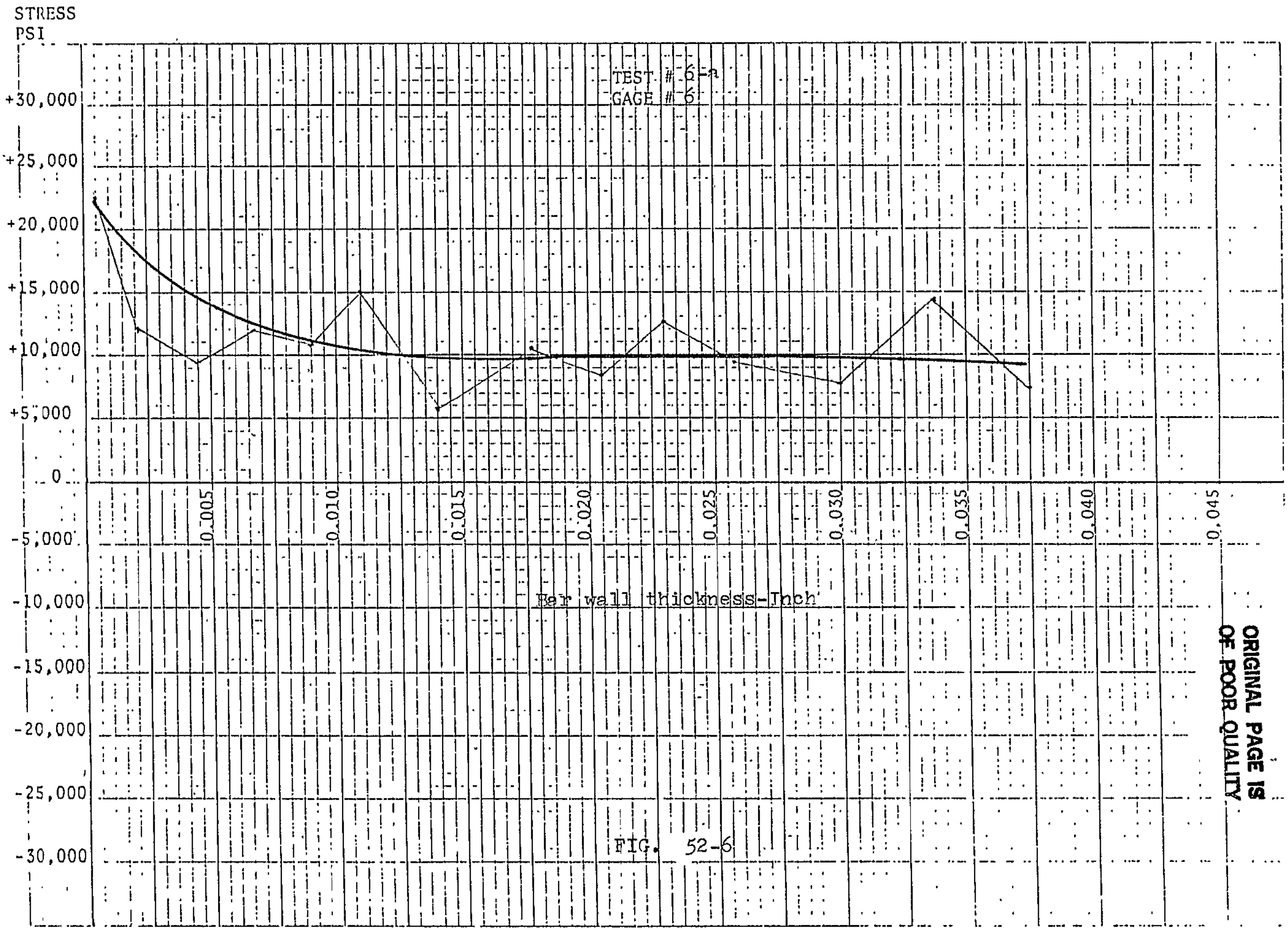

FIG. 52-6

ORIGINAL PAGE IS
OF POOR QUALITY

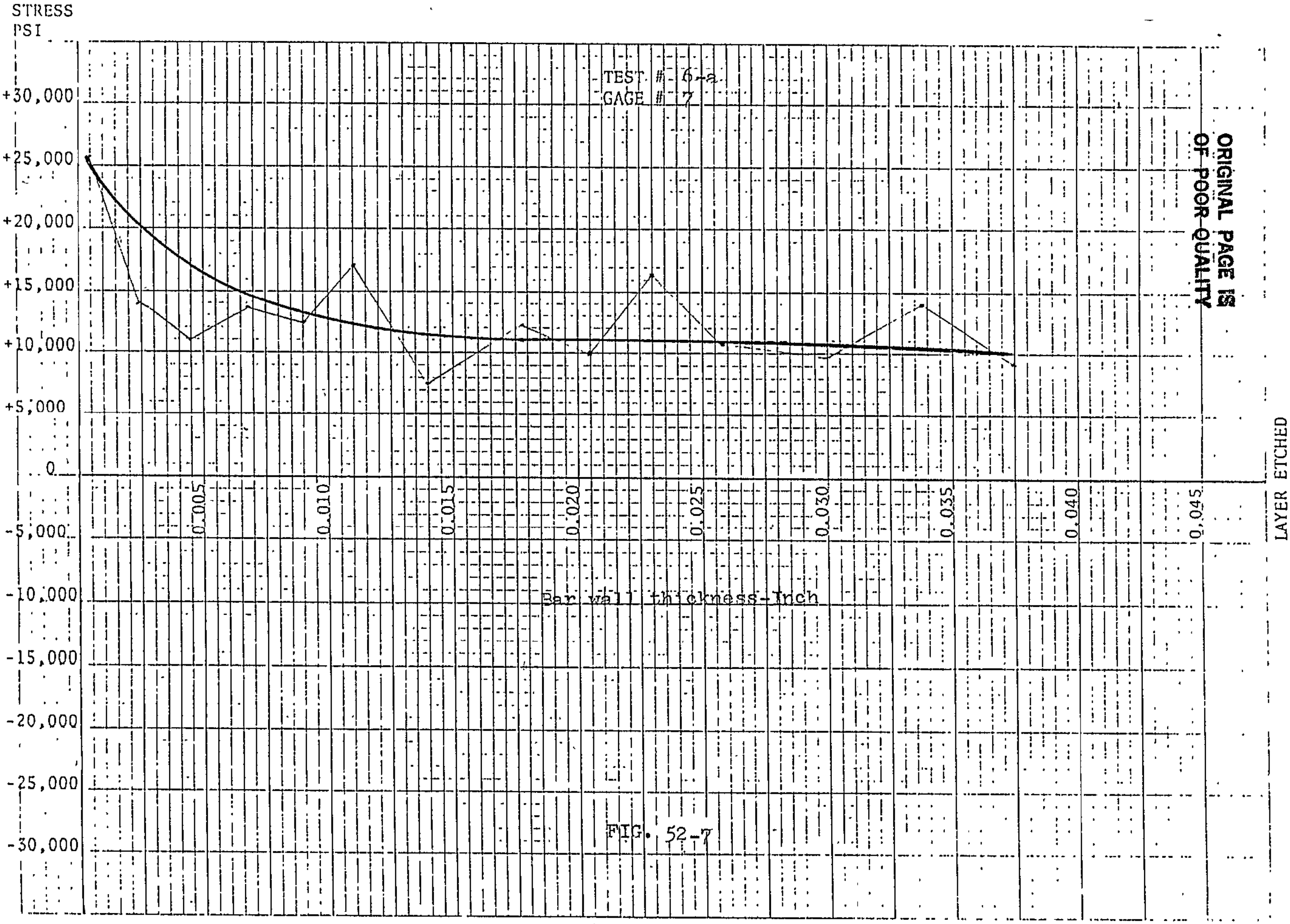

FIG. 52-7

ORIGINAL PAGE IS
OF POOR QUALITY

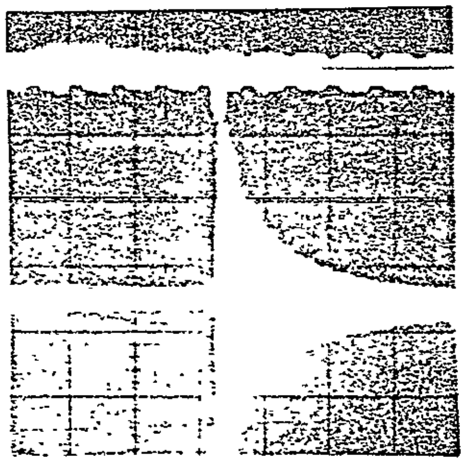

FIG. 53
TEST 6-b

A(I)	X(I)	Y(I)	H(I)
6.250000	0.3576279E-06	0.4768372E-06	1.333333
18.75000	-0.8449340	1.644052	-1.945660
31.25000	-0.7065322	1.886440	-2.669999
43.75000	-0.1239620	1.576438	-12.71711
56.25000	-0.8717401E-01	2.034061	-23.33334
68.75000	0.9474022E-01	1.602468	16.91433
81.25000	1.016656	1.310277	1.288811
93.75000	0.4175756	-0.1783623	-0.4271376
105.2500	0.5524458	-1.268218	-2.295643
118.7500	0.7550860	-0.7355450	-0.9741208
131.2500	0.8651939	-1.025375	-1.185139
143.7500	0.8954032	-0.8094013	-0.9039518
156.2500	0.6321129	-0.8289899	-1.311459
163.7500	0.2904840	-0.9887902	-3.403940
181.2500	0.1457250	-0.8115623	-5.569134
193.7500	0.2895272E-01	-0.8144311	-28.12969
205.2500	0.1436379E-02	-1.018542	-709.1039
218.7500	-0.1925933	-0.4994590	2.593335
231.2500	-0.3070853	-0.3824143	1.245303
243.7500	-0.1627415	0.3114054E-01	-0.1913496
255.2500	-0.2189682	0.9757568	-4.456158
268.7500	-0.1750000	1.075000	-6.142856
281.2500	0.2116939E-01	1.435429	67.80681
293.7500	0.3809455	2.533814	6.651381
305.2500	0.2277831	2.132142	9.360403
318.7500	0.4031679	2.470745	6.128328
331.2500	0.5712488	2.832443	4.958336
343.7500	0.3372043	2.434328	7.219150
356.2500	0.2925750	1.637812	5.597924
363.7500	-0.7832029E-01	0.9789069	-12.49877
381.2500	0.7442870E-01	0.8463519E-01	1.137131
393.7500	-0.3069351	-0.3953911	1.288191
405.2500	-0.7583357	-1.204067	1.587775
418.7500	-0.3693926	-2.129444	5.764717
431.2500	-0.7877651	-3.399868	4.315840
443.7500	-0.9175758	-5.546637	6.044882
455.2500	-1.105596	-7.489402	6.774084
463.7500	-0.8605505	-8.617260	10.01366
481.2500	-0.2840406	-8.180013	28.79874
493.7500	-0.2778889	-7.006353	25.21279

TABLE 18
TEST 6-b

ORIGINAL PAGE IS
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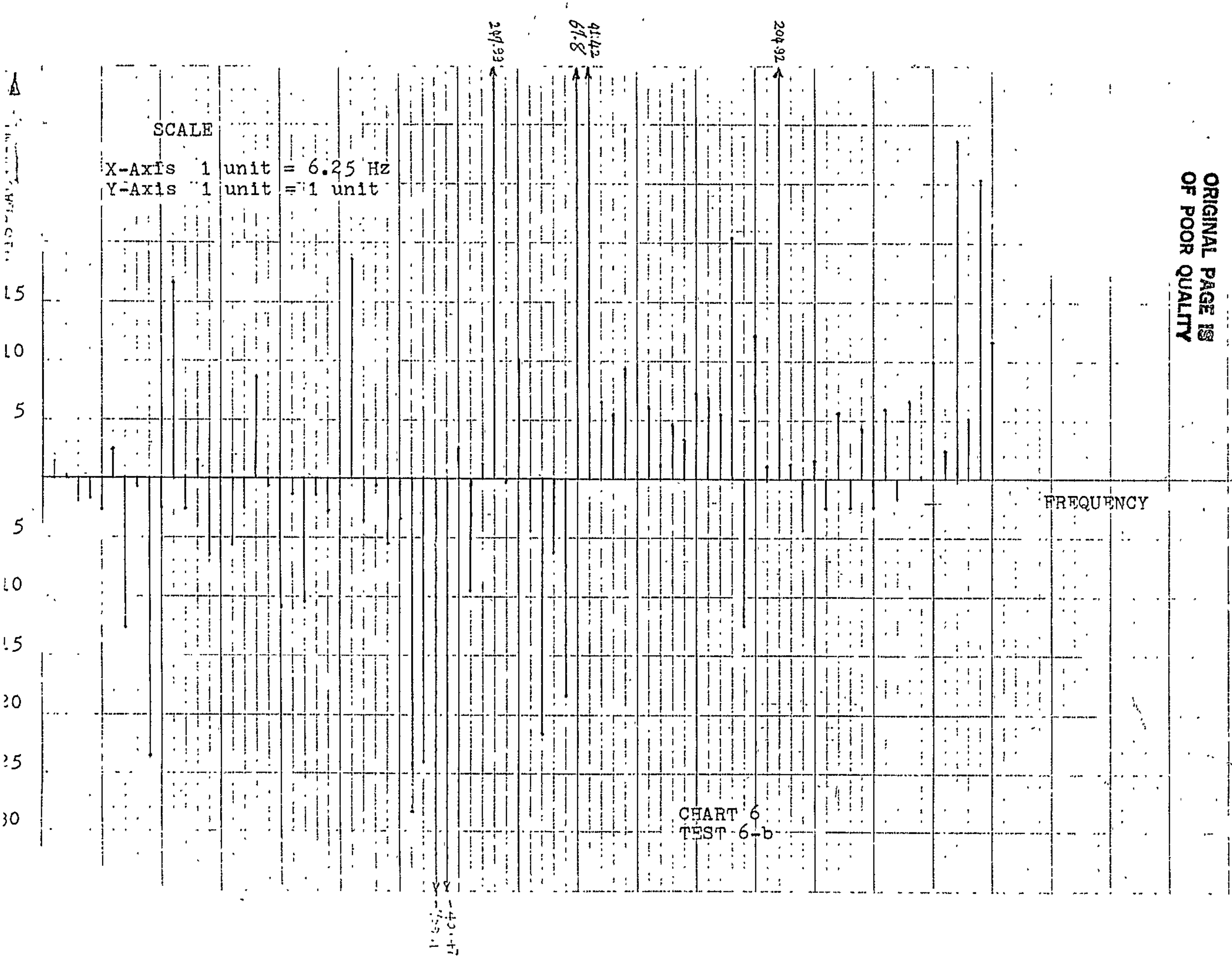
ORIGINAL PAGE IS OF POOR QUALITY

12.50000	0.1000000E-02	0.0000000E+00	0.0000000E+00
25.00000	-0.4093776	0.7032880	-1.717944
37.50000	0.1420565	0.3168283	2.230297
50.00000	0.4035198	-0.3506109	-0.8688816
62.50000	0.5346471	-1.184508	-2.215496
75.00000	0.6186816	-1.648966	-2.665290
87.50000	0.4352871	-2.817468	-6.472666
100.0000	0.4602023	-2.679888	-5.823283
112.5000	0.2020495	-1.783396	-8.826530
125.0000	0.7160344E-01	-0.7814512	-10.91360
137.5000	0.7565469E-01	-0.8211999	-10.85458
150.0000	-0.4800499E-01	0.1265418	-2.636013
162.5000	-0.2593980E-01	-0.4859872	18.73520
175.0000	-0.5133691	0.2592283	-0.5049550
187.5000	-0.1984497	0.6273271	-3.161138
200.0000	-0.4274627E-01	1.027417	-24.03524
212.5000	-0.2492783E-01	1.009048	-40.47875
225.0000	-0.1494069	1.428983	-9.564369
237.5000	0.6149814E-02	1.525096	247.9907
250.0000	0.2065626	2.089453	10.11535
262.5000	-0.6642997E-01	1.440320	-21.68178
275.0000	-0.6700003E-01	1.224999	-18.28356
287.5000	0.3207290E-01	1.328511	41.42159
300.0000	0.1034663	0.5864501	5.668033
312.5000	-0.8481196E-01	-0.5292915E-01	0.6240765
325.0000	-0.3950346	-0.4497278	1.138452
337.5000	-0.2736679	-0.8942394	3.267608
350.0000	-0.2779165	-1.949600	7.015057
362.5000	-0.1118472	-2.273858	20.33004
375.0000	-0.2268647	-2.757265	12.15378
387.5000	-0.1230699E-01	-2.521960	204.9209
400.0000	0.5906609	-2.527615	-4.279300
412.5000	0.8099376	-2.008877	-2.480286
425.0000	0.8810978	-2.186671	-2.481757
437.5000	0.9625416	-2.159704	-2.243751
450.0000	0.7863476	-1.421986	-1.808343
462.5000	2.680912	0.4879630	0.1820138
475.0000	1.681481	3.960007	2.355070
487.5000	1.400330	7.239397	5.169778
500.0000	0.9778438	11.60467	11.86761

TABLE 18 Cont.
TEST 6-b


SCALE
X-Axis 1 unit = 6.25 Hz
Y-Axis 1 unit = 1 unit
FREQUENCY
CHART 6
TEST 6-b

GAGE #		1	2	3	4	5	6	7	8
LAYER	1	-2933.	-2933.	-5866.	0.	-5866.	-2933.	-5866.	
LAYER	2	1448.	-57.	2896.	1505.	-115.	-1563.	-115.	
LAYER	3	1176.	-2407.	1176.	1232.	-2463.	-1289.	-3638.	
LAYER	4	1949.	-3953.	3842.	2005.	-4009.	-2061.	3501.	
LAYER	5	1800.	-283.	3544.	3541.	-3709.	-3596.	-5222.	
LAYER	6	1272.	-2483.	1386.	-1924.	-2651.	-2540.	-1436.	
LAYER	7	3217.	-3380.	1832.	-1334.	-5042.	-1940.	1112.	
LAYER	8	2489.	-2649.	1465.	-975.	-2869.	-1570.	1834.	
LAYER	9	4033.	-601.	4028.	43.	-4407.	-2337.	3388.	
LAYER	10	3922.	-594.	3917.	1728.	763.	-3962.	3285.	
LAYER	11	2902.	538.	1775.	2343.	1395.	-2941.	2275.	
LAYER	12	3150.	-2907.	1893.	1407.	1671.	-3189.	2536.	
LAYER	13	7823.	-7583.	4226.	28100.	6363.	-7861.	7216.	
LAYER	14	1947.	-2691.	-188.	2681.	-3415.	957.	1349.	

TABLE 19
TEST 6-c

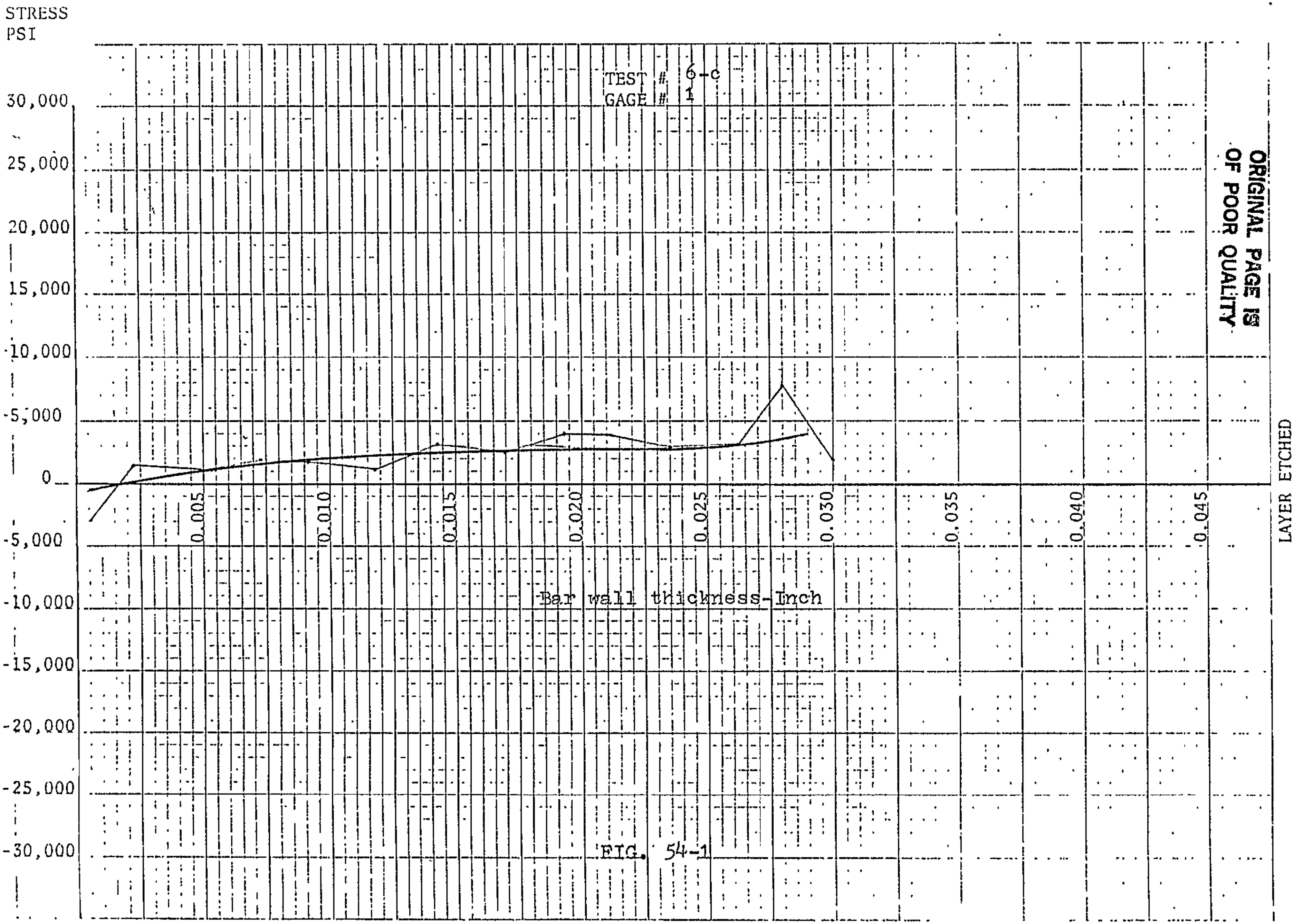


FIG. 54-1

ORIGINAL PAGE IS OF POOR QUALITY

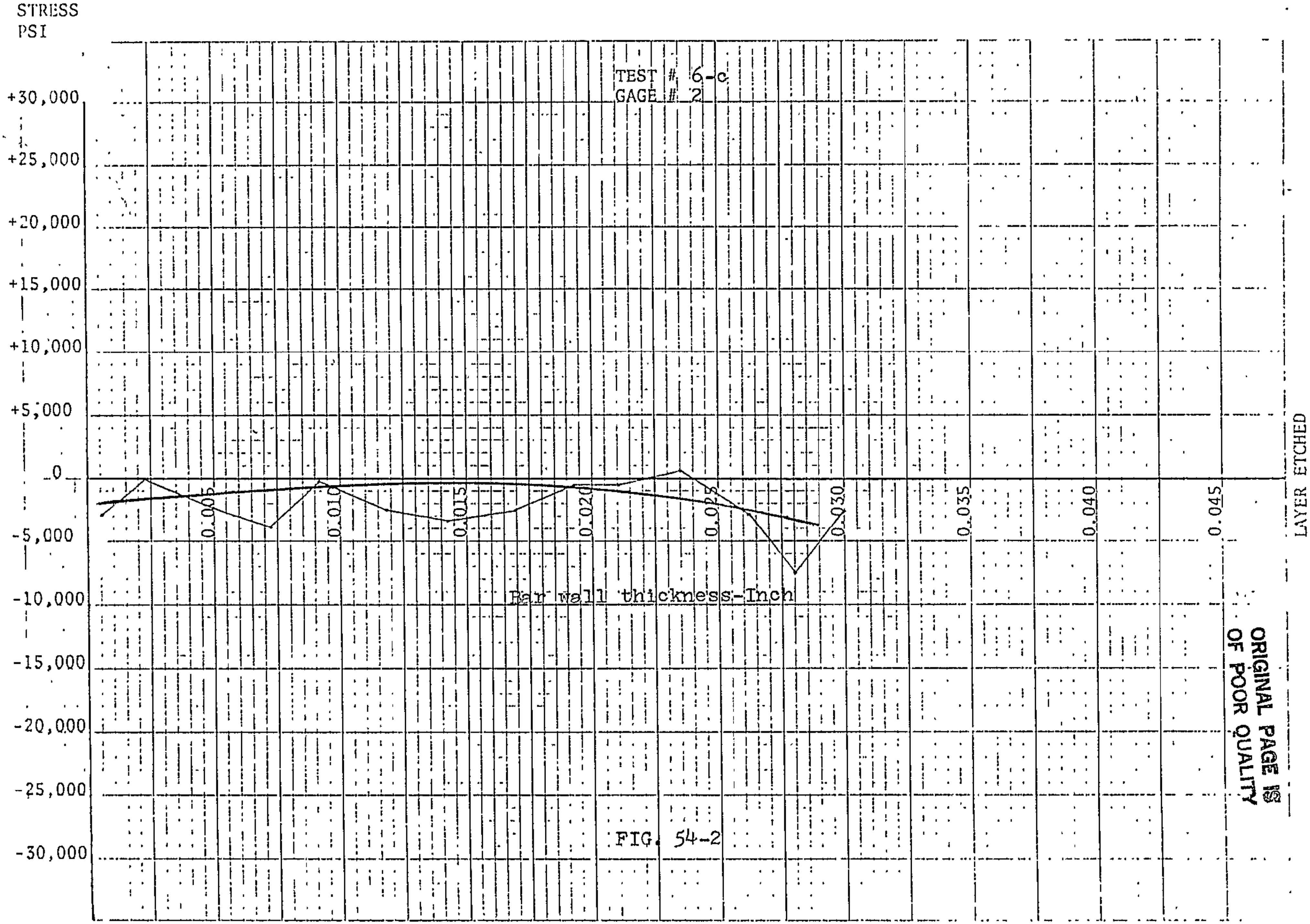


FIG. 54-2

ORIGINAL PAGE IS OF POOR QUALITY

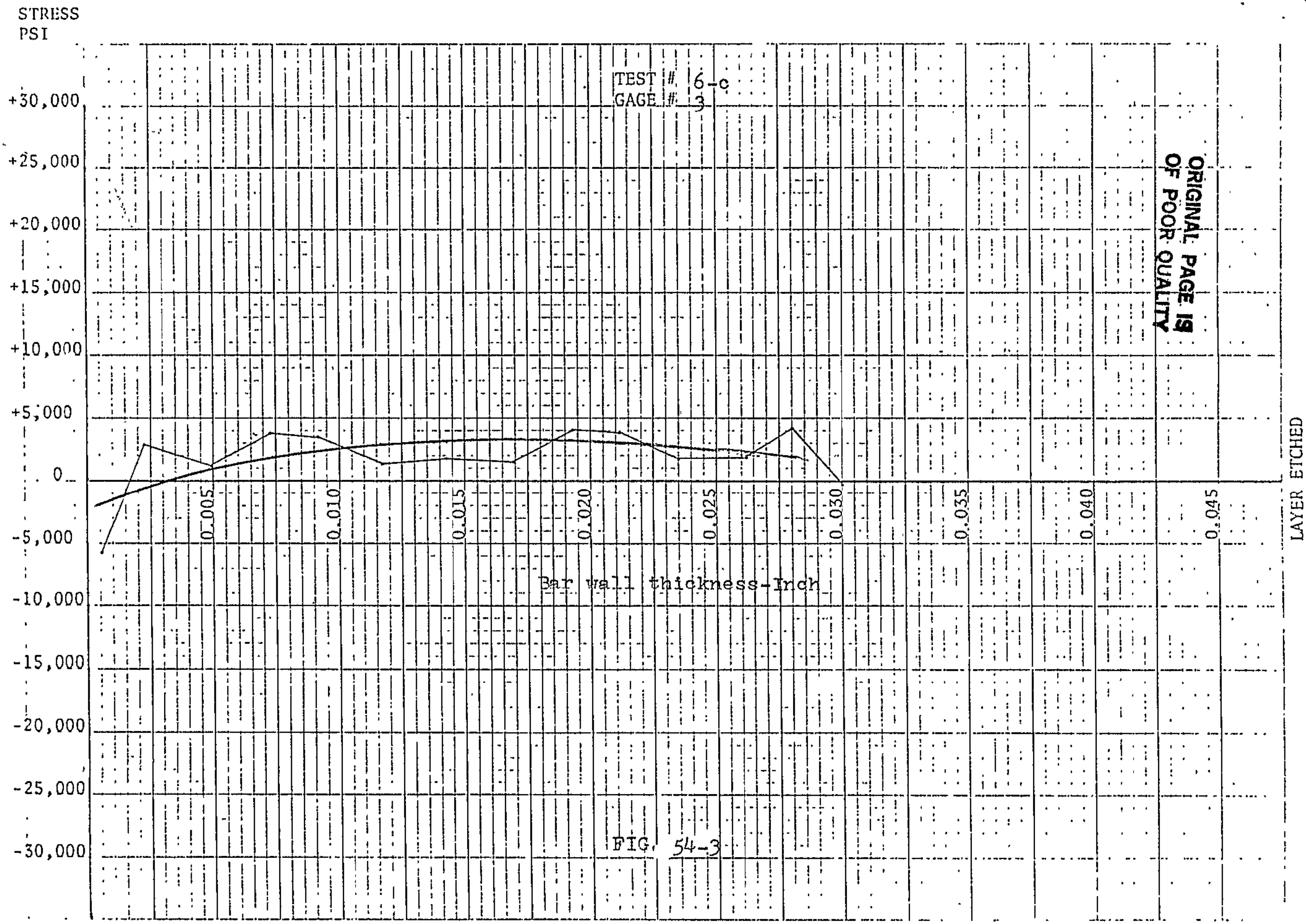

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 6-c
GAGE # 3
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 54-3

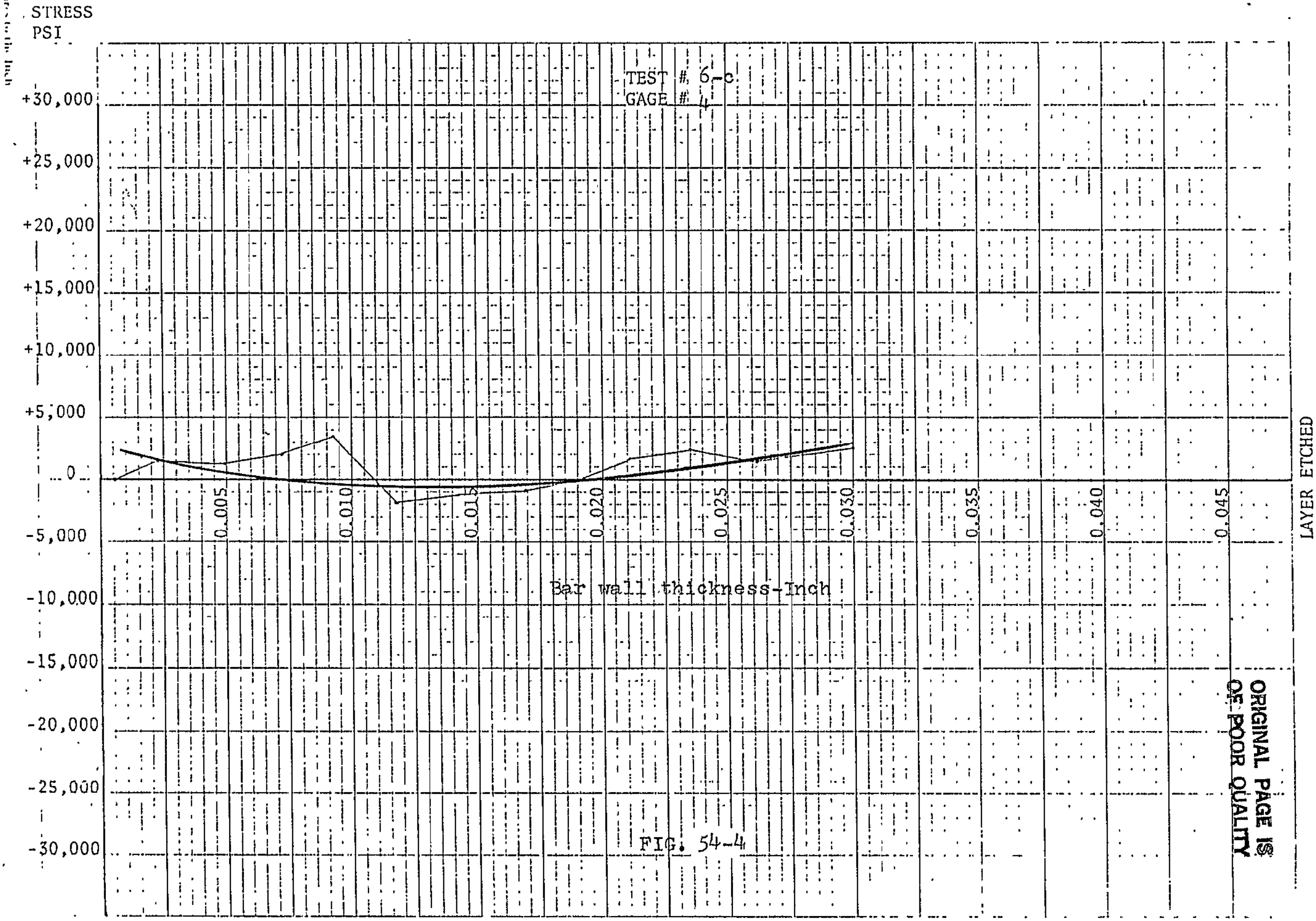


FIG. 54-4

ORIGINAL PAGE IS
OF POOR QUALITY

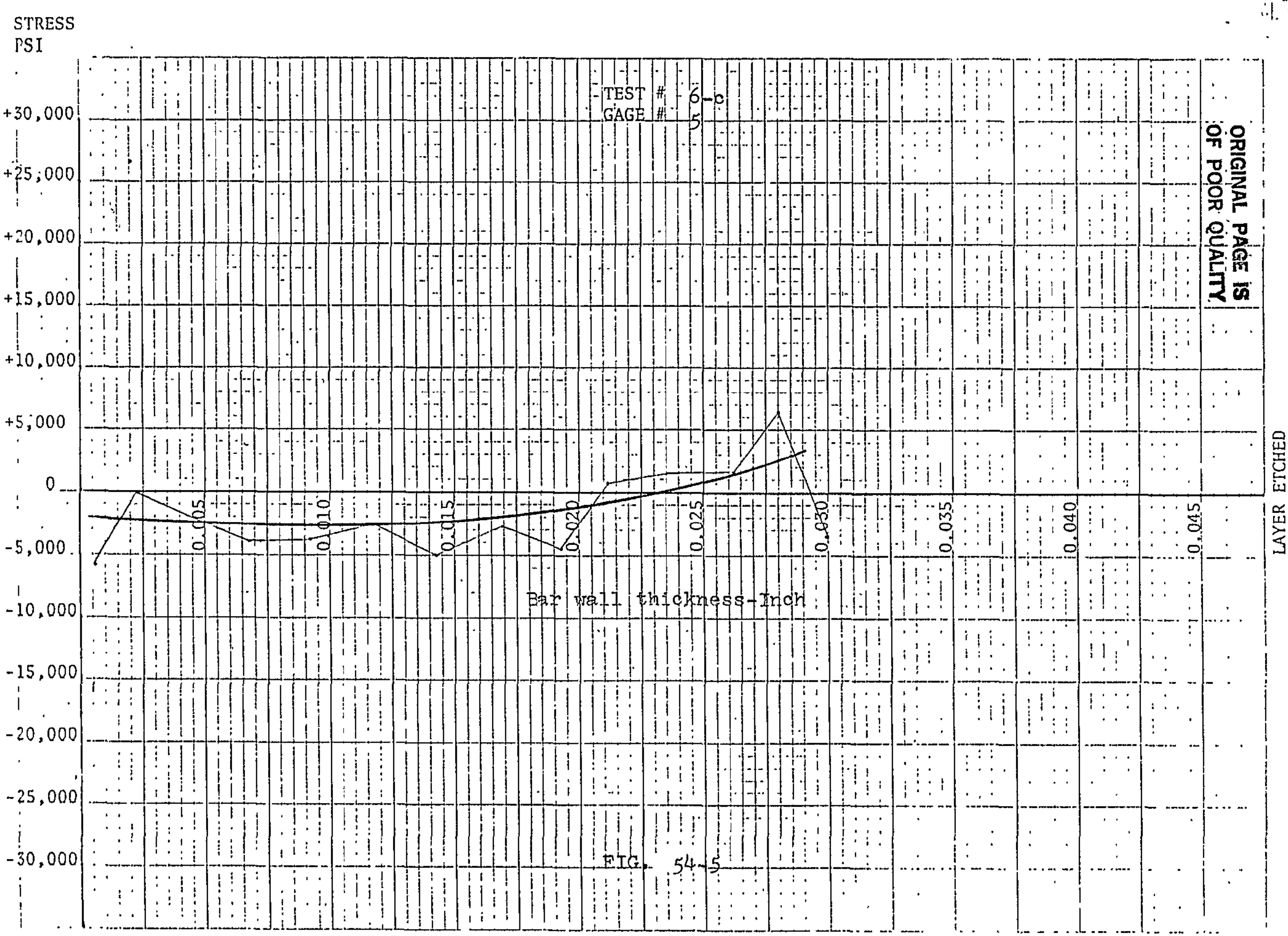

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 6-c
GAGE # 5
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
Bar wall thickness-Inch
LAYER ETCHED

FIG. 54-5

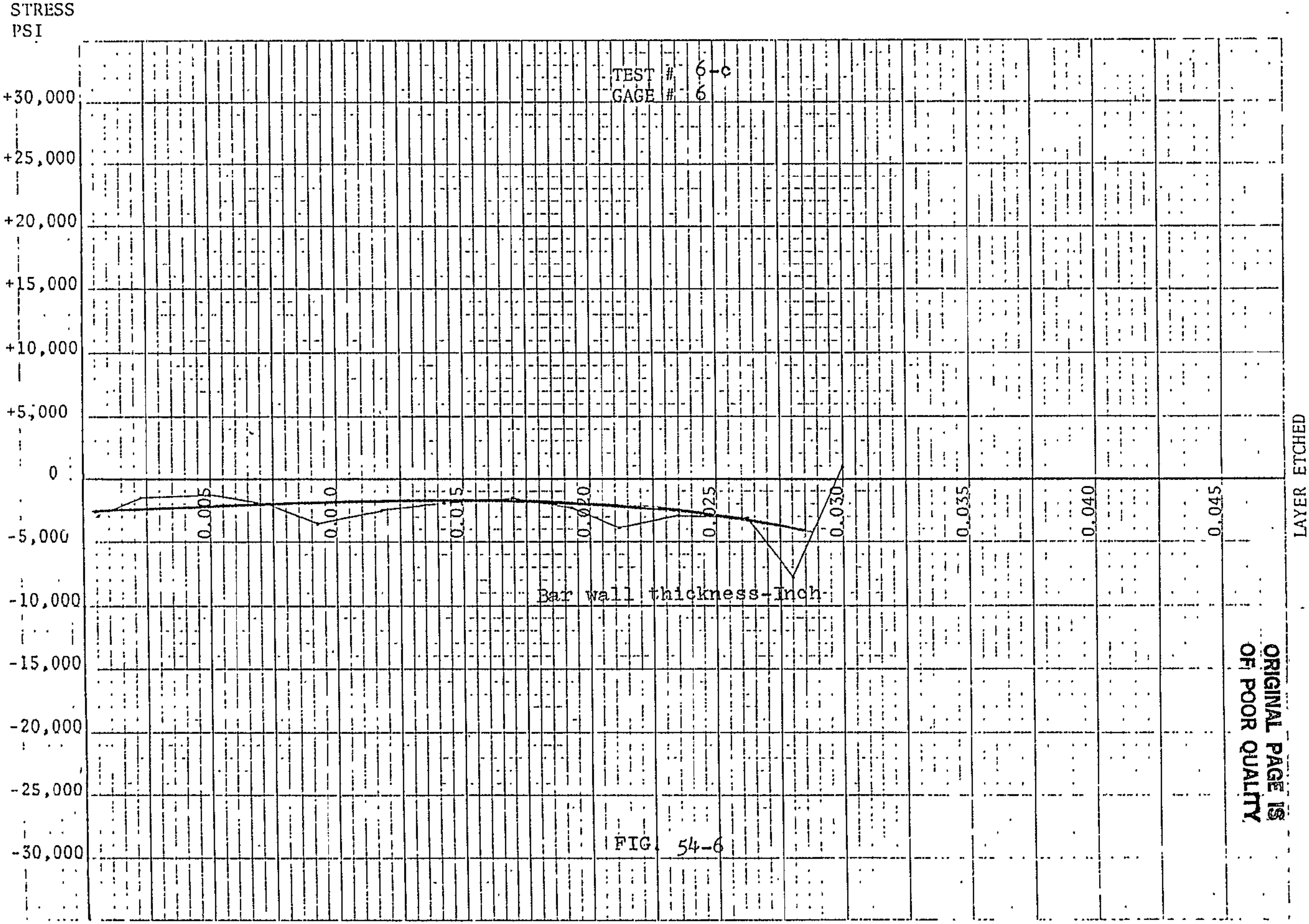


FIG. 54-6

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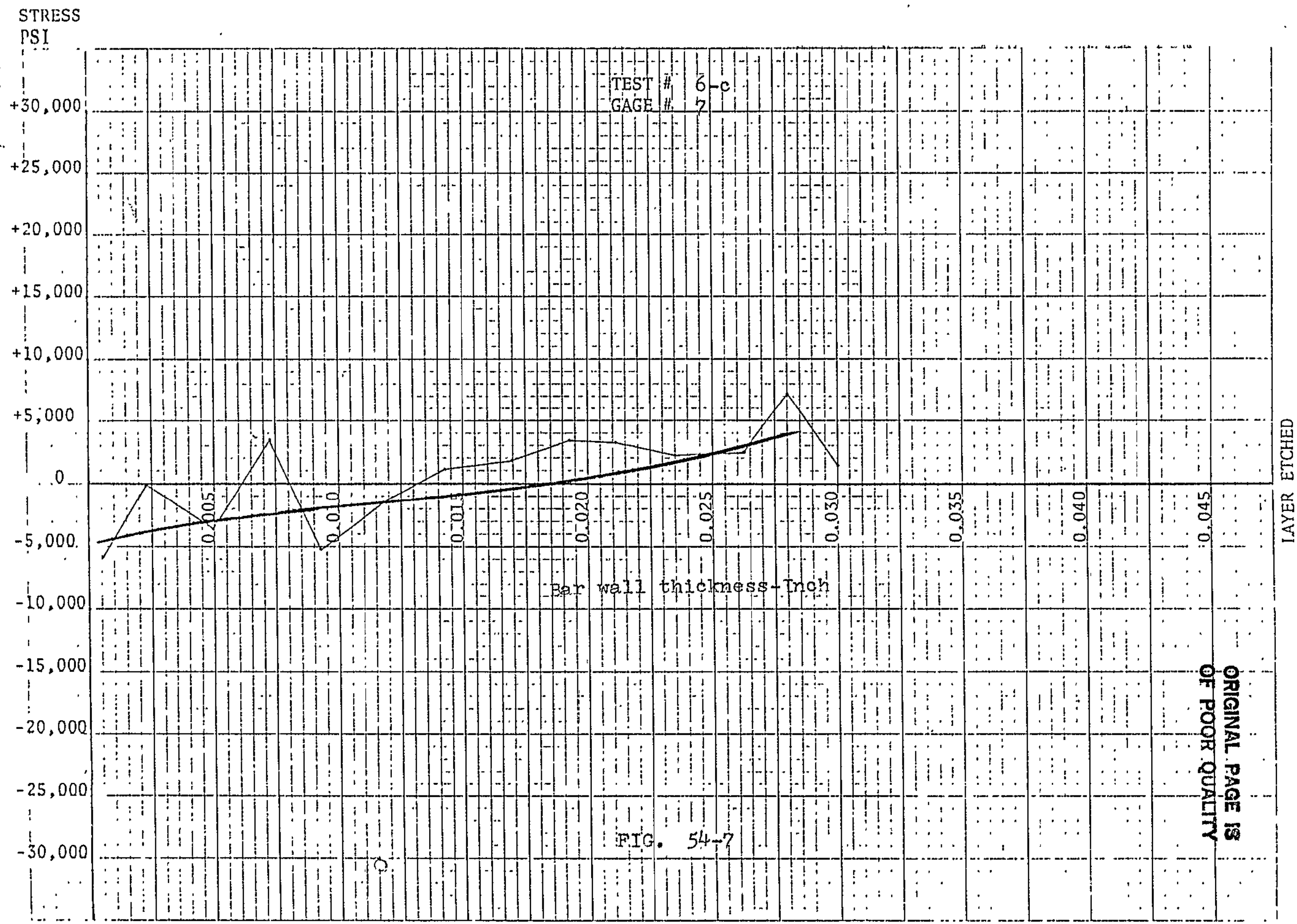

FIG. 54-7

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OF POOR QUALITY

LAYER	1	29713.	-29713.	-23771.	17828.	17828.	17828.	17828.
LAYER	2	44841.	-35930.	-35873.	26904.	26904.	35815.	35815.
LAYER	3	21797.	-18202.	-18145.	14493.	14493.	14550.	11014.
LAYER	4	11520.	-13525.	-11348.	9055.	11176.	9113.	9055.
LAYER	5	30471.	-30415.	-24446.	18363.	24275.	18420.	12508.
LAYER	6	22419.	-18873.	-15212.	14927.	22021.	14984.	11380.
LAYER	7	17805.	-15027.	-12135.	9187.	17411.	9243.	1077.
LAYER	8	20349.	-9259.	-1695.	4997.	19957.	12333.	1070.
LAYER	9	18808.	-5359.	1592.	-1871.	11865.	4853.	-5491.
LAYER	10	14813.	1911.	2422.	-6737.	10272.	5663.	-7136.
LAYER	11	19929.	-5472.	1865.	1217.	5713.	8503.	7650.
LAYER	12	18880.	-2104.	3767.	-4041.	18096.	12281.	11433.
LAYER	13	21420.	-6627.	-1419.	5680.	20639.	10953.	-3491.
LAYER	14	23416.	-10107.	-5395.	9164.	14673.	9958.	4962.
LAYER	15	12942.	-5301.	4656.	-1752.	8996.	2095.	-5086.
LAYER	16	15100.	1442.	2393.	-2488.	10433.	9538.	-10276.
LAYER	17	15869.	-2215.	2664.	1175.	14877.	10054.	-7138.
LAYER	18	11616.	-5902.	-1205.	4868.	14330.	9688.	4311.

TABLE 20
TEST 7-a

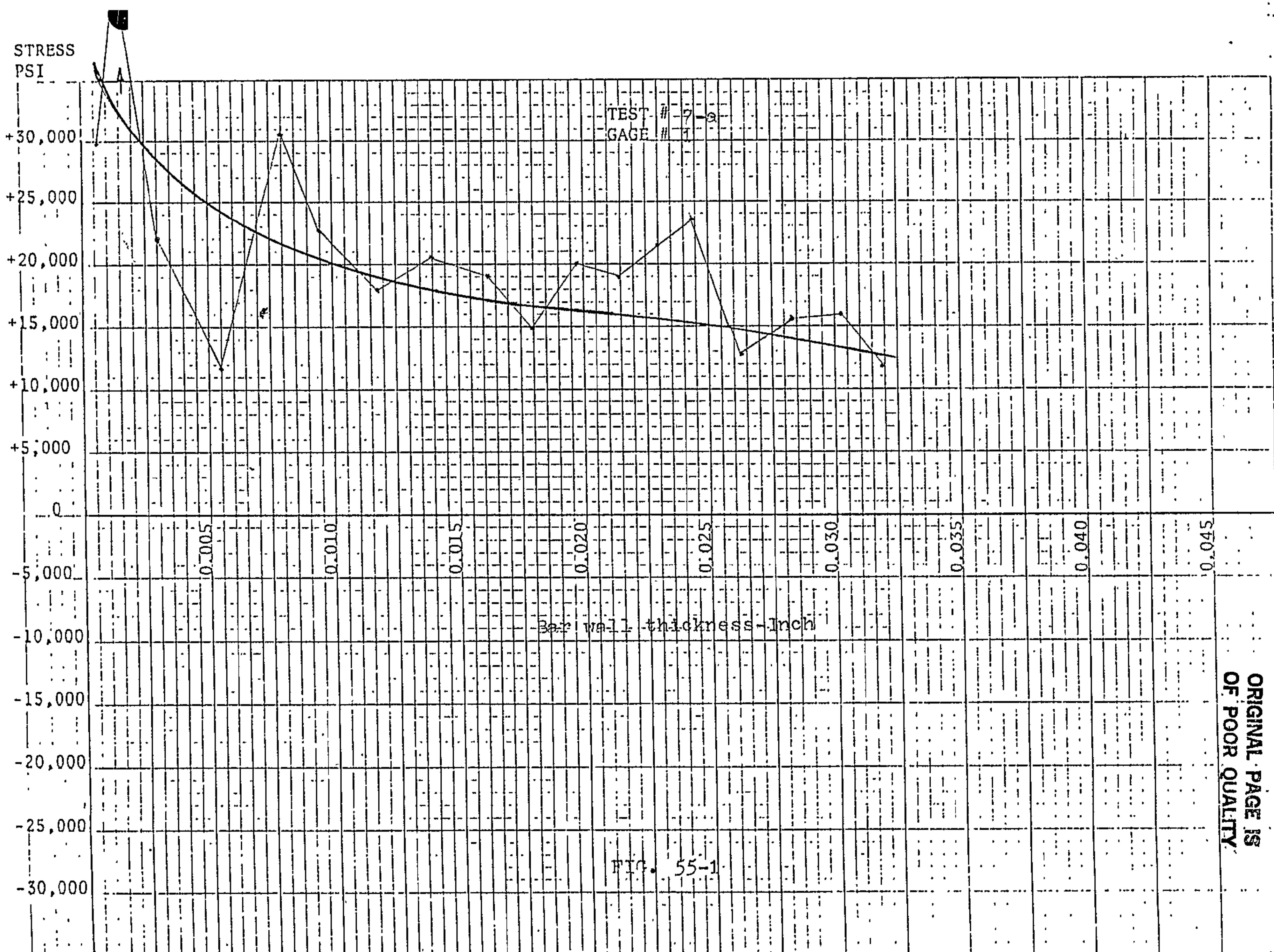

FIG. 55-1

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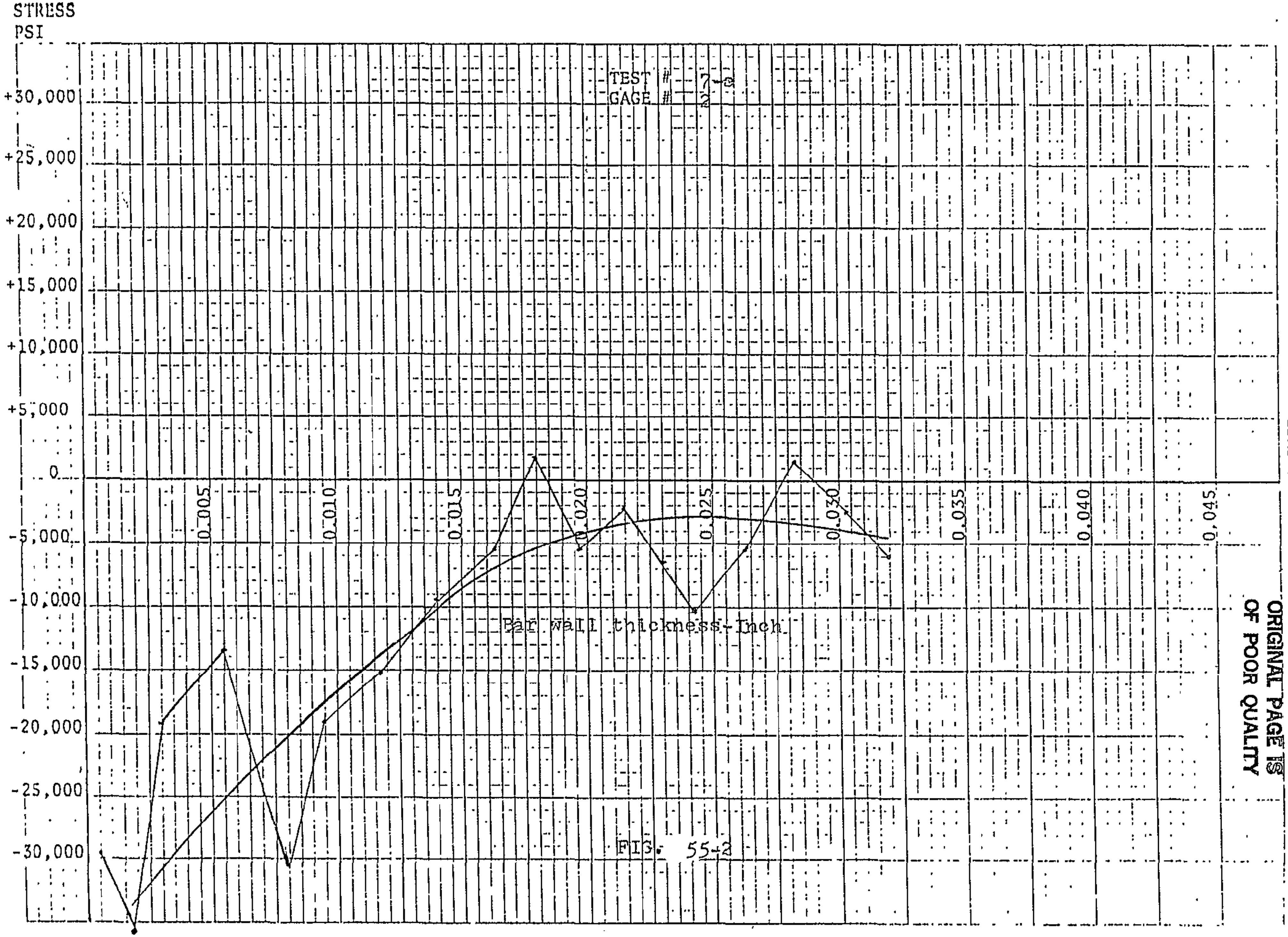

FIG. 55-2

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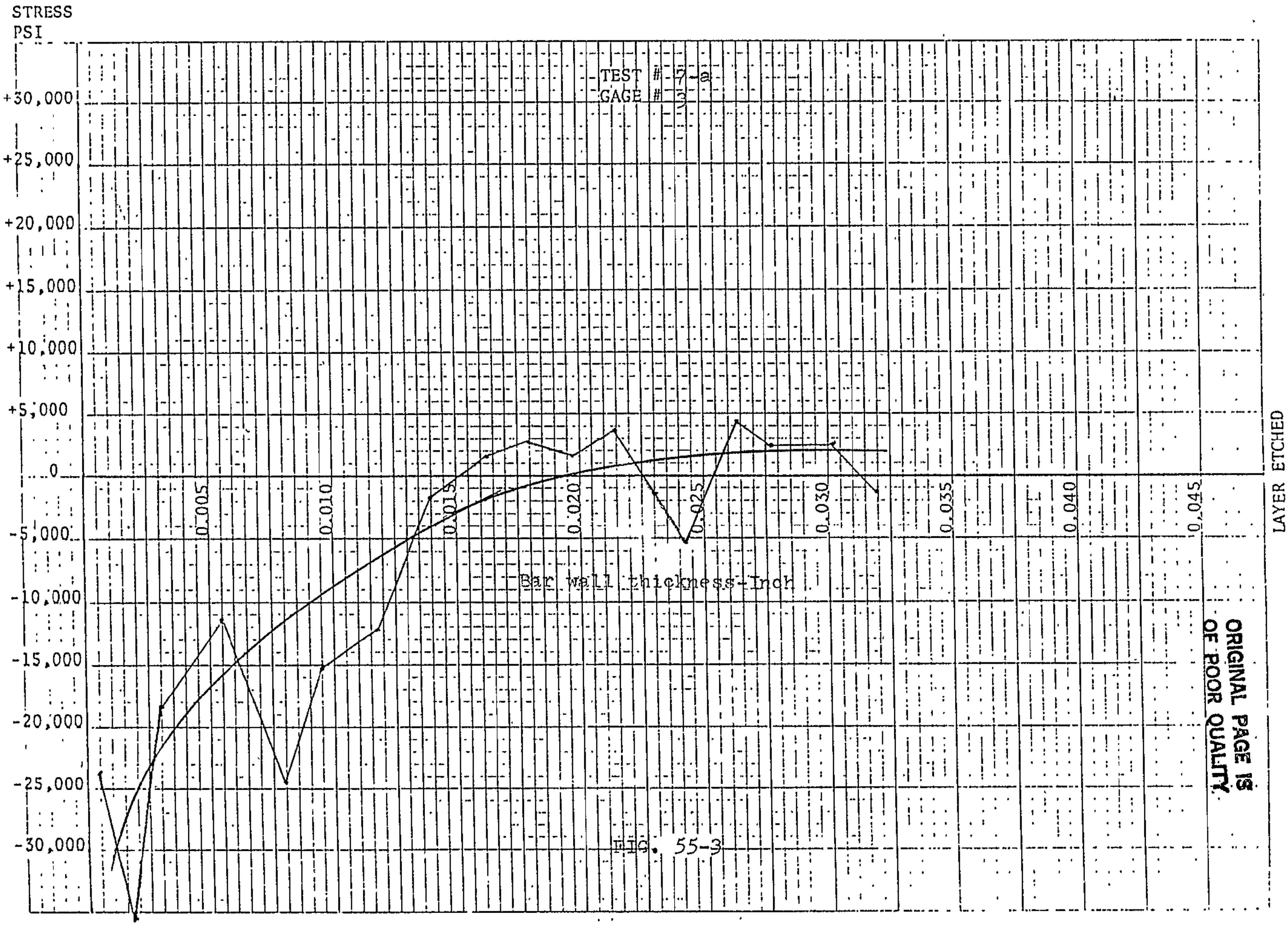

FIG. 55-3

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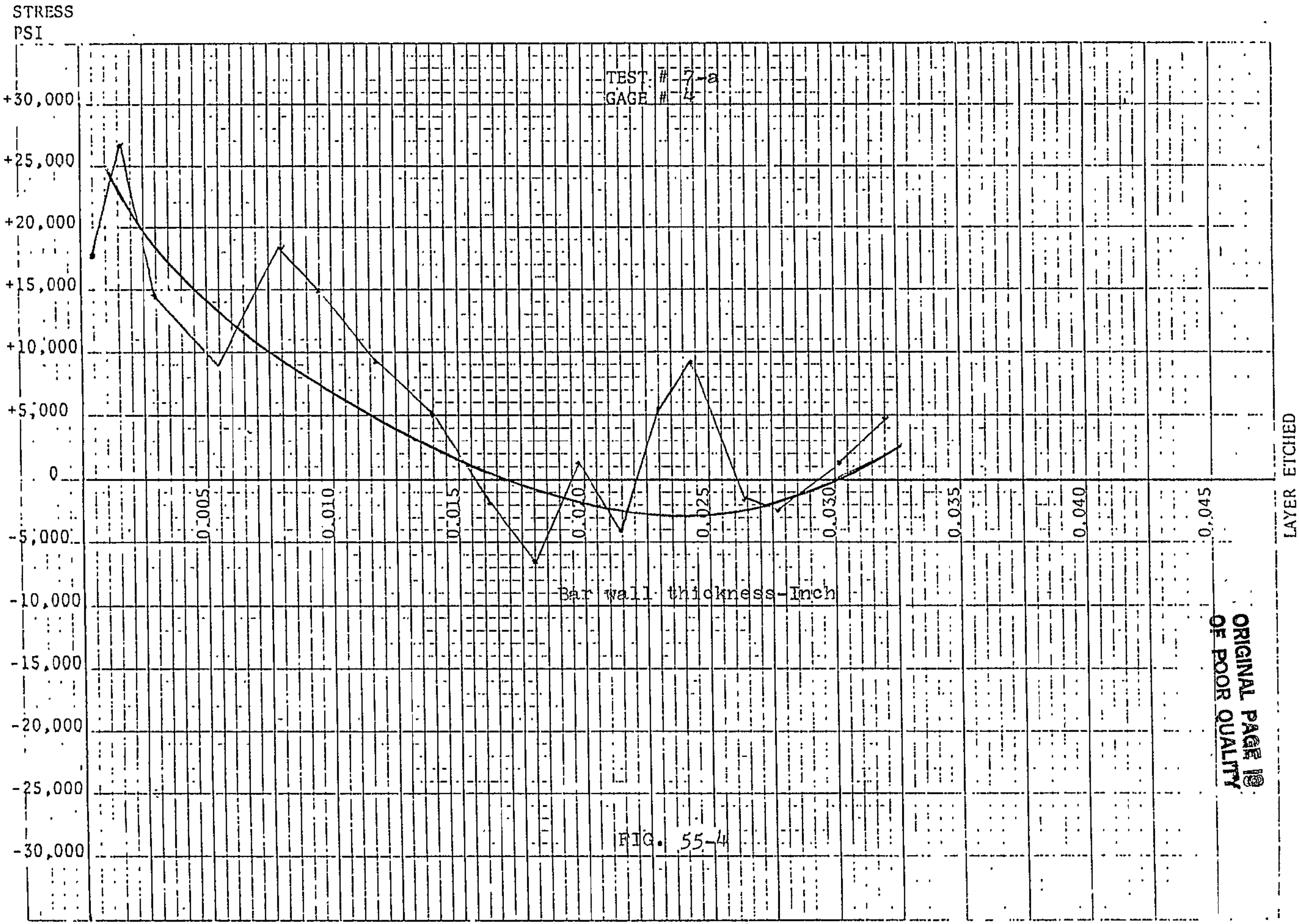
STRESS
PSI
TEST # 7-a
GAGE # 4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 55-4

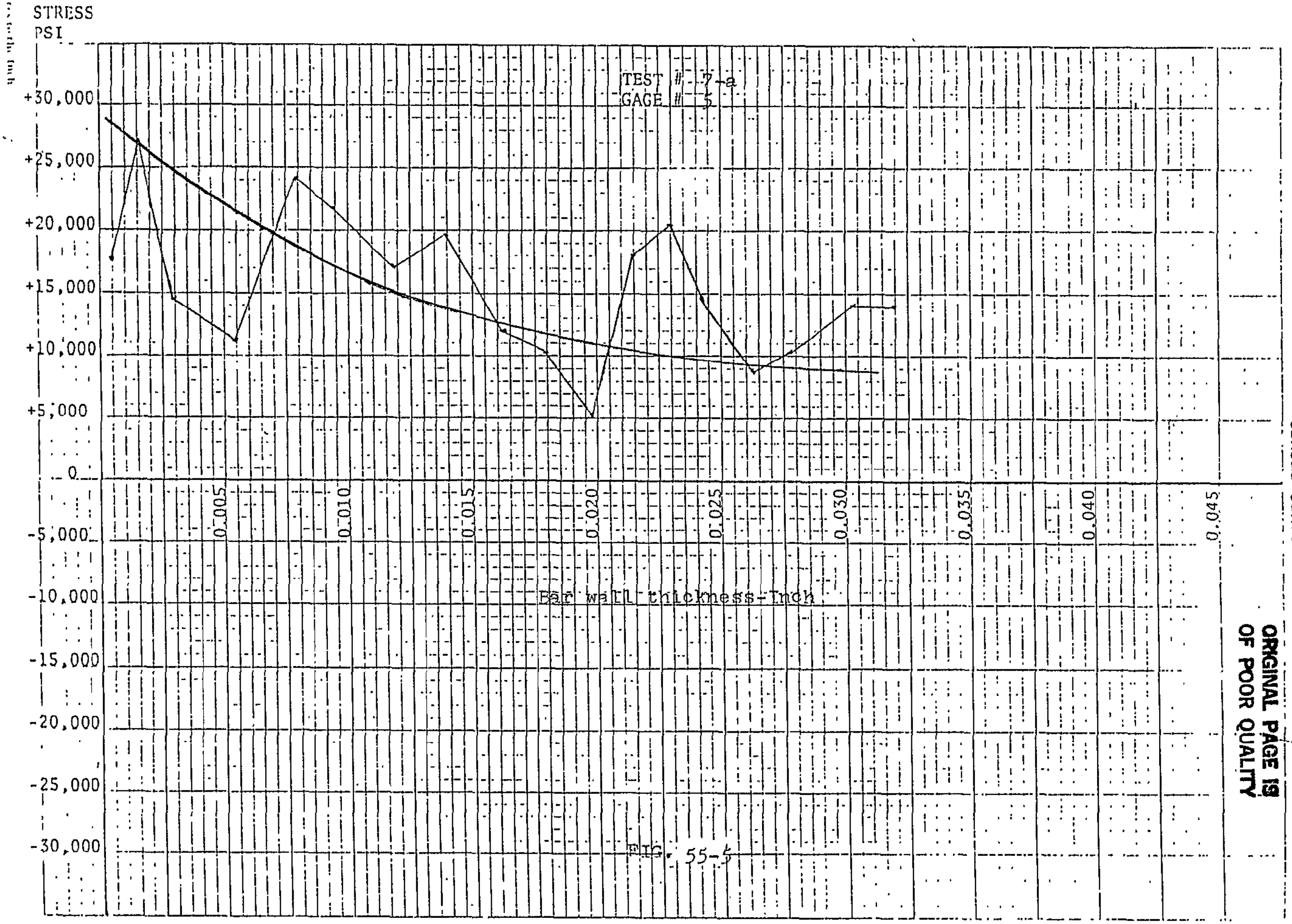

FIG. 55-5

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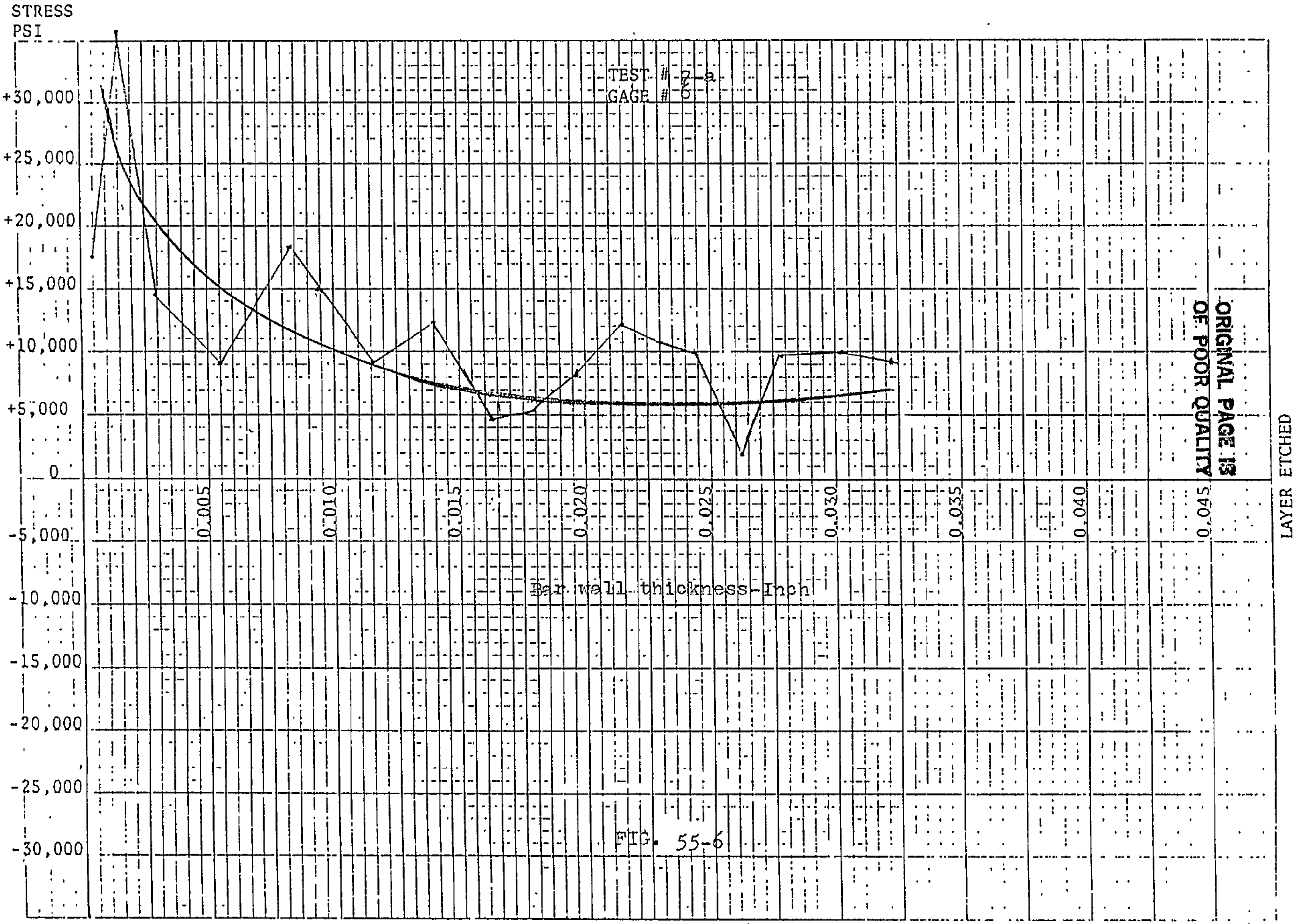
STRESS
PSI
TEST # 7-a
GAGE # 5
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
Bar wall thickness-Inch

FIG. 55-6

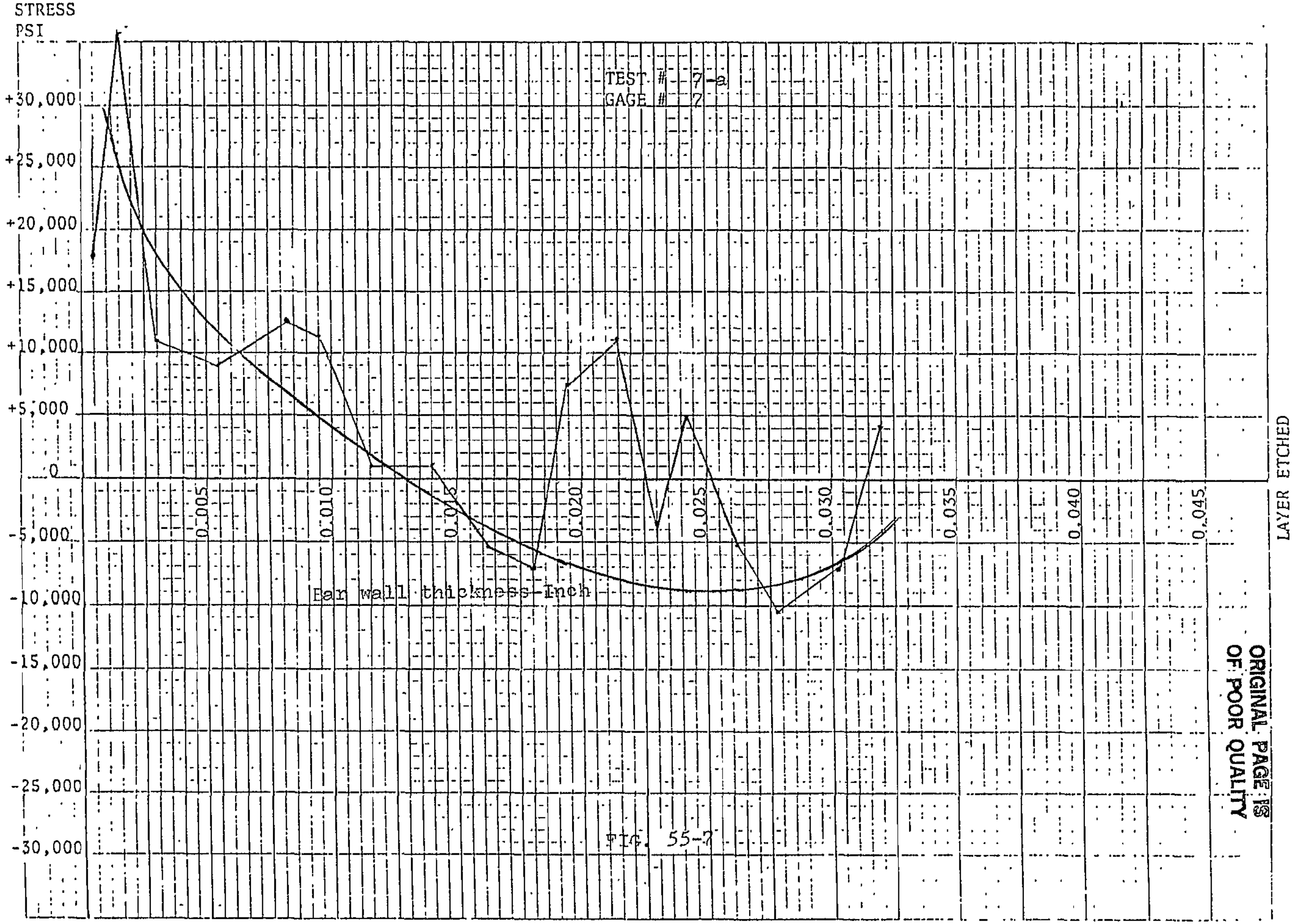

FIG. 55-7

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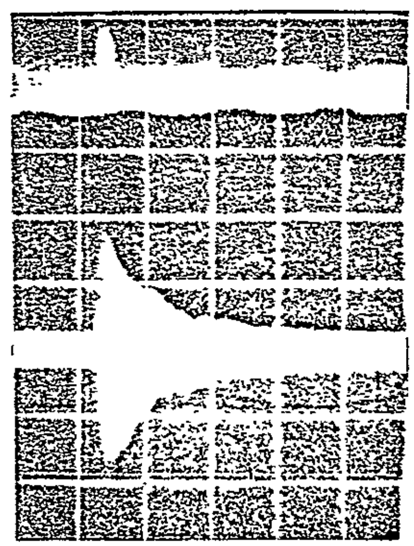

FIG. 56
TEST 7-b

A(I)	X(I)	Y(I)	[illegible]
6.250000	-0.1192093E-06	0.7152557E-06	-6.000000
18.75000	1.324972	1.735201	1.309613
31.25000	0.8268281	1.876595	2.269631
43.75000	-1.727668	0.4448196	-0.2574683
56.25000	-1.218540	-2.186089	1.794023
68.75000	-0.8199350	-1.791428	2.164841
81.25000	0.4339552E-01	-0.6402678	-14.75424
93.75000	0.5444562	0.2579578	0.4737899
106.2500	0.8148764	1.257541	1.543229
118.7500	0.8996522	0.9459059	1.051413
131.2500	0.6981044	1.285714	1.841722
143.7500	0.2337615	0.4986301	2.133072
156.2500	-0.1324508	0.1005131	-0.7588715
168.7500	0.6586843E-01	-0.2221962	3.373334
181.2500	0.1402501	0.1937502	1.381462
193.7500	0.1160381	0.1361681	1.173477
206.2500	0.1496218	-0.1079704E-01	-0.7216222E-01
218.7500	0.1050289	0.9879037E-01	0.9406021
231.2500	-0.7076846E-01	0.5840568E-02	-0.8253066E-01
243.7500	-0.1485789	-0.3410231	2.295233
256.2500	-0.1924364	-0.1418860	0.7373138
268.7500	-0.4000026E-01	-0.2500003	6.249966
281.2500	0.1330673	-0.3785491E-01	-0.2844795
293.7500	0.1082482	-0.3287502E-01	-0.3037003
305.2500	0.1626519	0.2590370	1.592586
318.7500	0.6152168	0.5895820	0.9583321
331.2500	0.6849760	0.9601308	1.401700
343.7500	0.5403027	0.5505469	1.018960
356.2500	0.5167500	0.2812501	0.5442672
368.7500	0.2099017	0.1777225	0.8466941
381.2500	0.8737256E-01	0.1344267	1.538546
393.7500	0.4199593	0.1204891	0.2869067
406.2500	0.5206719	0.2159201	0.4146952
418.7500	0.7044503	0.5389189	0.7650205
431.2500	0.5689838	0.9031010	1.587217
443.7500	0.6554378E-01	1.492043	22.76407
456.2500	-0.7932011	0.5154500	-0.6498352
468.7500	-2.518612	-1.426191	0.5662606
481.2500	-2.107212	-2.556440	1.213186
493.7500	-1.962778	-7.266361	3.702080

TABLE 21

TEST 7-b

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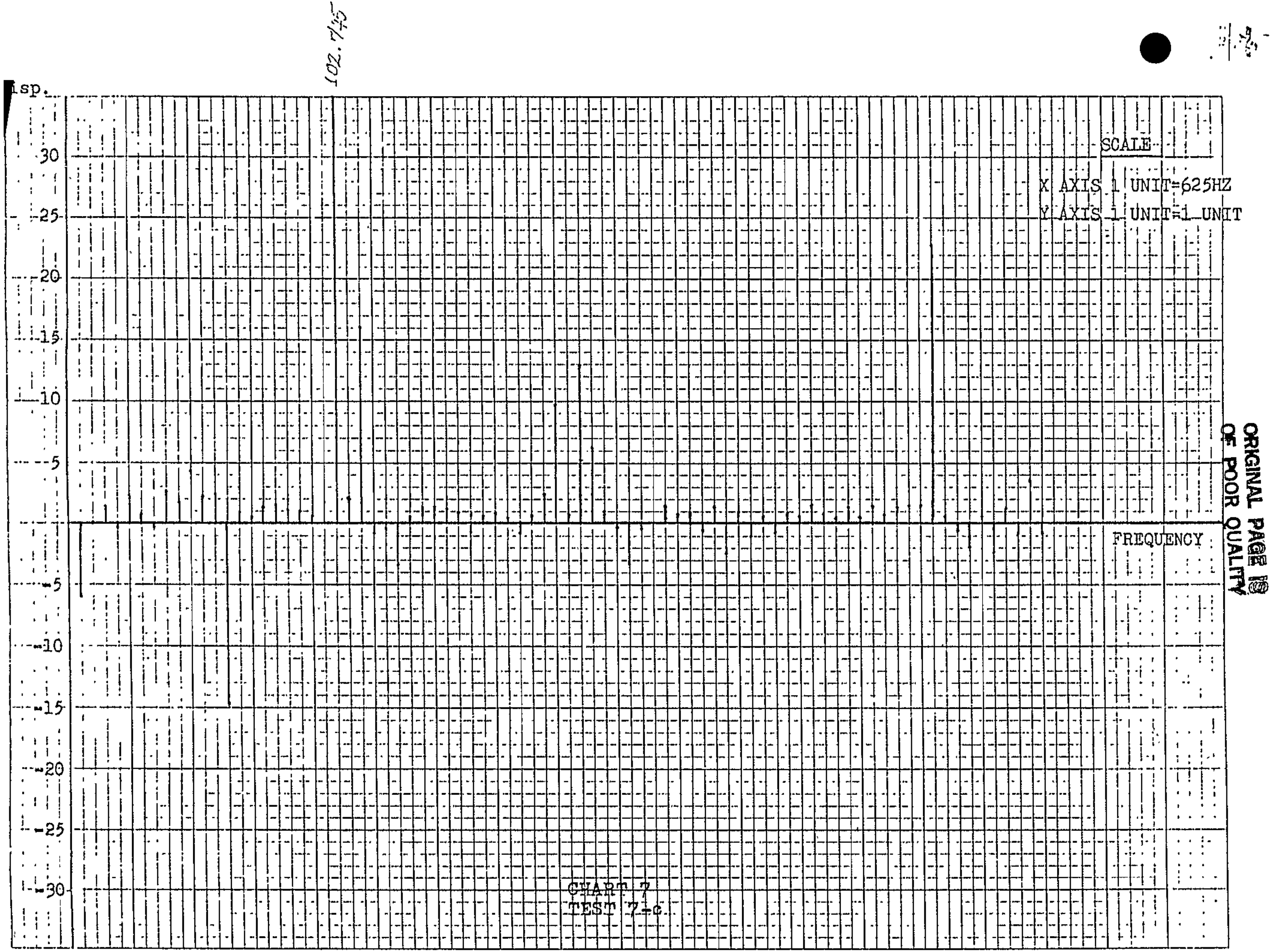
12.50000	0.1000000E-02	0.0000000E+00	0.0000000E+00
25.00000	-1.905247	0.4490613	-0.2356971
37.50000	-2.556141	-2.010060	0.7863652
50.00000	-1.035801	-2.723342	2.629213
62.50000	-0.4026100	-1.751148	4.349490
75.00000	0.2423844	0.5824272	2.402907
87.50000	1.134577	0.9987937	0.8803226
100.0000	0.9098348	1.185913	1.303438
112.5000	0.5232278	0.5836106	1.115405
125.0000	0.2520475	0.1581805	0.6275820
137.5000	-0.4268087E-02	-0.4385279	102.7458
150.0000	-0.4388625E-01	-0.7074940	16.12108
162.5000	0.2864071	0.1124433	-0.3925994
175.0000	0.5174829	0.1925565	0.3721022
187.5000	0.5079238	0.7252962	1.427962
200.0000	0.4265256	0.4066316	0.9533581
212.5000	0.3729886	0.1930622	0.5176089
225.0000	0.1971029	0.4643727E-01	0.2355991
237.5000	0.8756790E-01	0.5594628E-01	0.6388903
250.0000	-0.8440178E-02	-0.8230597E-01	9.751686
262.5000	-0.2309831E-01	-0.2991935	12.95304
275.0000	0.1399999	0.1499993	1.071424
287.5000	0.4183480E-01	-0.1363680	-3.259679
300.0000	0.5715900E-01	0.4089673	-7.154907
312.5000	0.1675933	0.1294436	0.7723672
325.0000	0.2760330	-0.1264660	-0.4581554
337.5000	0.1538582	-0.3545940	-2.304681
350.0000	0.2027971	-0.2127579	-1.049117
362.5000	0.3173983	-0.2273317	-0.7162348
375.0000	0.4586533	0.2853926	0.6222404
387.5000	0.6858622	0.5790534	0.8442708
400.0000	1.061981	1.528833	1.439605
412.5000	1.094164	1.601085	1.463295
425.0000	1.232552	1.672747	1.357141
437.5000	1.029447	1.546781	1.502536
450.0000	0.4196649	0.2765870	0.6590664
462.5000	0.3838868	-0.7436554	1.937174
475.0000	0.8264854	-1.942926	-2.345154
487.5000	1.567071	-1.329173	-0.8481893
500.0000	3.081077	-2.489605	-0.8080309

TABLE 21-Cont.

TEST 7-b

C-3



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SUMMARY OF VIBRATION FREQUENCIES OF TESTS

TEST NO.	VIBRATION FREQUENCY	FROM FIG. NO.
1	62	CHART 1
2	162	CHART 2
3	56 or 180	CHART 3
4	50	CHART 4
5	70	CHART 5
6	55	CHART 6
7	80 & 135	CHART 7

TABLE 23

PART FOUR

Summary Of Current Investigation

The research program currently underway investigates the patterns of residual stresses in welded A36 steel structures of various geometrical designs, formed of hot rolled bars of various widths and thicknesses. High tensile stresses of about 25,000 to 30,000 psi were found at the weld; these dropped rapidly to compressive stresses in the range of 3,000 to 5,000 psi which spread for some depth through the bar thickness.

The pattern of stresses at a distance from the weld was reversed, showing high compressive stresses at the outer layers. The outer layer stresses, however, were of a lesser degree than the stresses found at the weld.

In the second phase of the study, a load cell was used together with an accelerometer to generate an impulse and analyze the response. A vibration frequency within the range of 100 cps was chosen to generate a peak displacement. Such a limited frequency was chosen to reduce the damage to the steel by fatigue, due to the vibration. A set of computer programs was designed for choosing the appropriate frequency. This technique was found to be less expensive than using a commercial spectrum or Fourier analyzer. Results showed that the most effective pulse varies between 50 and 80 cps.

At present, the steel structures are vibrated using an MB model C10 mechanical vibrator with attached panel to control the frequency to the required value.

Future Work Plan

A new study is suggested using a variable speed motor with eccentric load.(32) The motor will be connected to a metallic frame fixed firmly to the ground. The motor speed can be adjusted to generate vibrations at the specified frequency. The study can be performed in the field, or where the frame is to be located. This technique presents a practical way to test the method away from laboratory facilities. The frequency should be determined using the same present load cell and the accelerometer. The pulse can be recorded on the screen of a portable oscilloscope and analyzed using the same computer programs already developed.

Fatigue testing of specimens prepared from the sides of the welded boxes showed a life span of a fatigue limit of 30,000 psi. This investigation needs to be continued. Similar studies are being carried out at present on specimens cut from boxes after vibration. Most of the vibrations so far are limited to a maximum of 80 cps. For the future investigations, similar boxes will be vibrated at higher frequencies chosen according to other peak values that were registered from the impulse analyses.

This study will examine the effect of high vibrations on the fatigue life of the steel and establish a relationship between the magnitude of the vibration and the fatigue life of the metal.

The study will be expanded to include aluminum which is used on a large scale in the aerospace industry. Aluminum can be etched using caustic soda solution, a technique that was applied in studying residual stresses in drawn tubes.[22] The study will use the same basic equipment, including the strain indicator, the resistance box and either the existing laboratory mechanical vibrator or the new planned variable speed motor. Basic and fundamental theories and computer programs presently developed will be used.

This project heretofore has examined the effectiveness of vibration in reducing residual stresses from welding various shapes of steel structures. The present activity, part of which is reported here, examined the pattern of stresses in some more steel structures, aluminum structures and the effectiveness of vibration in reducing these stresses. A second part of the activity studied the fatigue life of steel exposed to vibration treatment. Further, and as reported before, a variable speed motor has been added to our testing equipment and was used to vibrate some metallic frames at the required frequency.

A new set of steel frames was formed by welding bars 4 and 8 inch wide by $\frac{1}{4}$ and $\frac{1}{2}$ inch thick. Details of shapes and dimensions are given in Fig.57.

The results of stress distributions, measured as before, are presented in Figs.58-65, 76-82 and 92-96. The second phase covered the load pulse and the acceleration response analyses and their results are given in Figs.66-67, 83-84 and 97. The three frames were vibrated at 78, 63 and 112 cps for 15 minutes respectively.

It was noticed that when the frame was an open structure, test2, Figs.76-82, the peaks of the stresses were lower than when the frame was restricted and had a closed shape, test1, Figs.58-65.

The cross connection between the bars in test 3 helped to reduce the stresses and the results showed a maximum stress of about 5,000 psi only, Figs. 92-96.

The aluminum (6061T6) studies started by testing a bar as received and showed that the material was exposed to some residual stresses of about 3,000 to 4,000 psi which were mostly developed due to the straightening process following the extrusion and treatment of the bars. The few tests carried out so far show that the welding caused peak residual stresses of about 8 to 10 X10^3 psi that appeared at a certain depth from the outer surface. That may be due to the higher conductivity of aluminum to the heat of welding as compared to mild steel and such a behavior may reduce the risk of surface cracks. These conclusions however cannot be final. The experiments on welding are still in their first stage and further investigations are needed.

An investigation of how vibration affects the fatigue life of steel was carried out on steel specimens of the shape shown in Fig. 119. The investigation was essential particularly for steel exposed to dynamic loading.

The specimens were machined locally for both the non-vibrated and vibrated metal boxes. They were tested using a classical rotating beam, constant load fatigue testing machine, of the type shown in the same figure.

Each specimen was mounted between two rotating spindles. Stresses were continuously reversed and the steel was passed through complete cycles of flexural stress. The load consisted of accurately adjusted weights stacked on a hanger and the machine operated continuously at a speed of 10,000 rpm.

Stress was calculated from

$$S = 16\ wL/\pi D^3$$

Where:-

S=extreme fiber stress, psi
w=total load on the specimen in lbs.
L=moment arm,i.e., distance from end support to load point(in inches)
And D=minimum diameter of specimen(4 inch)

A maximum fiber stress of 30,000 psi was assumed for the structural steel under study, for which experiments showed a fatigue life span, or cycles to failure of $2x10^6$ cycles and higher. The microstructure analysis of the grain showed no effect of vibrations, Figs.120-123.

The conclusion as of now is that the vibration of steel structures within 100 cps and for a limited time period of about 15 minutes does not fatigue the steel while it significantly reduces the peaks of residual stresses at the weld zone.

Our school of engineering has received a new testing machine MTS-Type810 and I intend to use it in the near future for some further studies on the fatigue life of the vibrated metallic structures, both steel and aluminum.

As reported before, a variable speed motor with a speed range of 700 to 4500 rpm has been added to our testing equipment. It was mounted on a heavy channel-sections base, and provided with an eccentric at the end of its spindle.

The eccentric was connected to the side of the frame to be vibrated, Fig. 124. The vibration lasted for about 15 minutes at the required frequency dicided upon by the impulse study and the analysis of the signal registered on the oscilloscope. This technique proved successful and opens the way for a practical method of vibrating the metallic structures at the chosen frequency, in the field as well as in the laboratory.

In conclusion I can say that although the surface stresses due to welding mild steel structures are high, yet the design of the connections may limit the severity of these stresses. The technique of vibrating the structure at resonance whithin about 100 cps for a short period of about 15 minutes reduces the peak values of stresses in both steel and aluminum structures.

As far as fatigue life of the metal, there is no indication at the moment of any sound effect of a limited vibration on the fatigue of steel, especially if such vibration is performed within 100 cps.

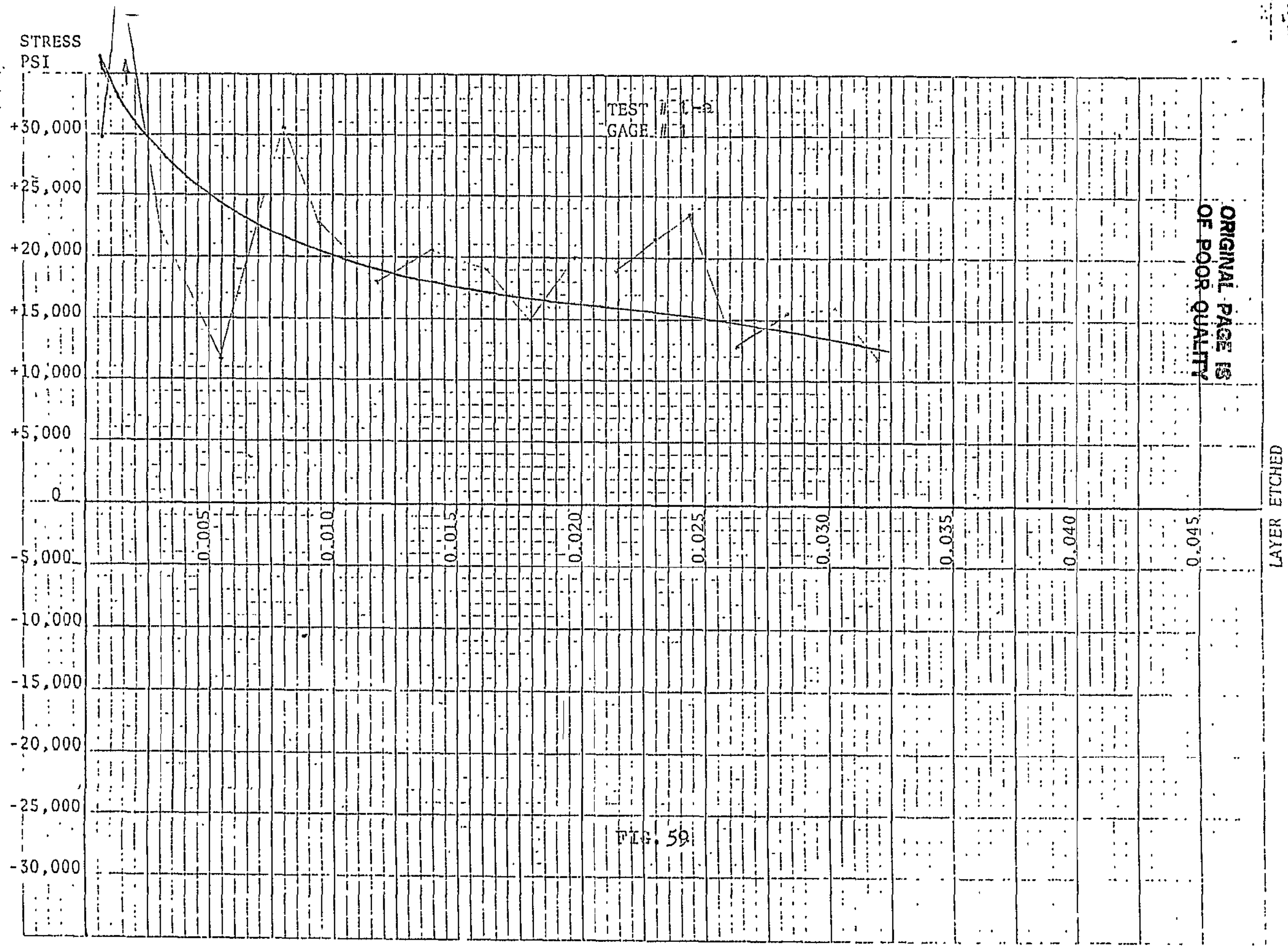
TEST NO.		FIG. NO.	BOX SHAPE	NATURE OF TEST	LENGTH x WIDTH x DEPTH x WALL THICKNESS	STRAIN GAUGE ARRANGEMENT	MATERIAL AND REMARKS
1	a	2-9		(a) Stresses Before Vibration (b) Impact Test (c) Stresses After Vibration.	36"x36"x8"x 1/2"		M.St.
	b	10-11					
	c	12-19					
2	a	20-26			36"x36"x36"x 4" x 1/4"		M.St.
	b	27-28					
	c	29-35					
3	a	36-40			36"x4"x36"x8" x 1/4		M.St.
	b	41					
	c	42-46					
4		47-49			36"x4"x 1/4"		Aluminum As Received
5	a	50-55			36"x36"x4"x1/4"		Aluminum
	b	56-57					
	c	58-62					

FIG. 57

	GAGE #	1	2	3	4	5	6	7	8
LAYER	1	29713.	-29713.	-23771.	17828.	17828.	17828.	17828.	
LAYER	2	44841.	-35930.	-35873.	26904.	26904.	35815.	35815.	
LAYER	3	21797.	-18202.	-18145.	14493.	14493.	14550.	11014.	
LAYER	4	11520.	-13525.	-11348.	9055.	11176.	9113.	9055.	
LAYER	5	30471.	-30415.	-24446.	18363.	24275.	18420.	12508.	
LAYER	6	22419.	-18873.	-15212.	14927.	22021.	14984.	11380.	
LAYER	7	17805.	-15027.	-12135.	9187.	17411.	9243.	1077.	
LAYER	8	20349.	-9259.	-1695.	4997.	19957.	12333.	1070.	
LAYER	9	18808.	-5359.	1592.	-1871.	11865.	4853.	-5491.	
LAYER	10	14813.	1911.	2422.	-6737.	10272.	5663.	-7136.	
LAYER	11	19929.	-5472.	1865.	1217.	5713.	8503.	7650.	
LAYER	12	18880.	-2104.	3767.	-4041.	18096.	12281.	11433.	
LAYER	13	21420.	-6627.	-1419.	5680.	20639.	10953.	-3491.	
LAYER	14	23416.	-10107.	-5395.	9164.	14673.	9958.	4962.	
LAYER	15	12942.	-5301.	4656.	-1752.	8996.	2095.	-5086.	
LAYER	16	15100.	1442.	2393.	-2488.	10433.	9538.	-10276.	
LAYER	17	15869.	-2215.	2664.	1175.	14877.	10054.	-7138.	
LAYER	18	11616.	-5902.	-1205.	4868.	14330.	9688.	4311.	

TEST 1-a

FIG. 58



STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 1-a
GAGE # 1
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 59

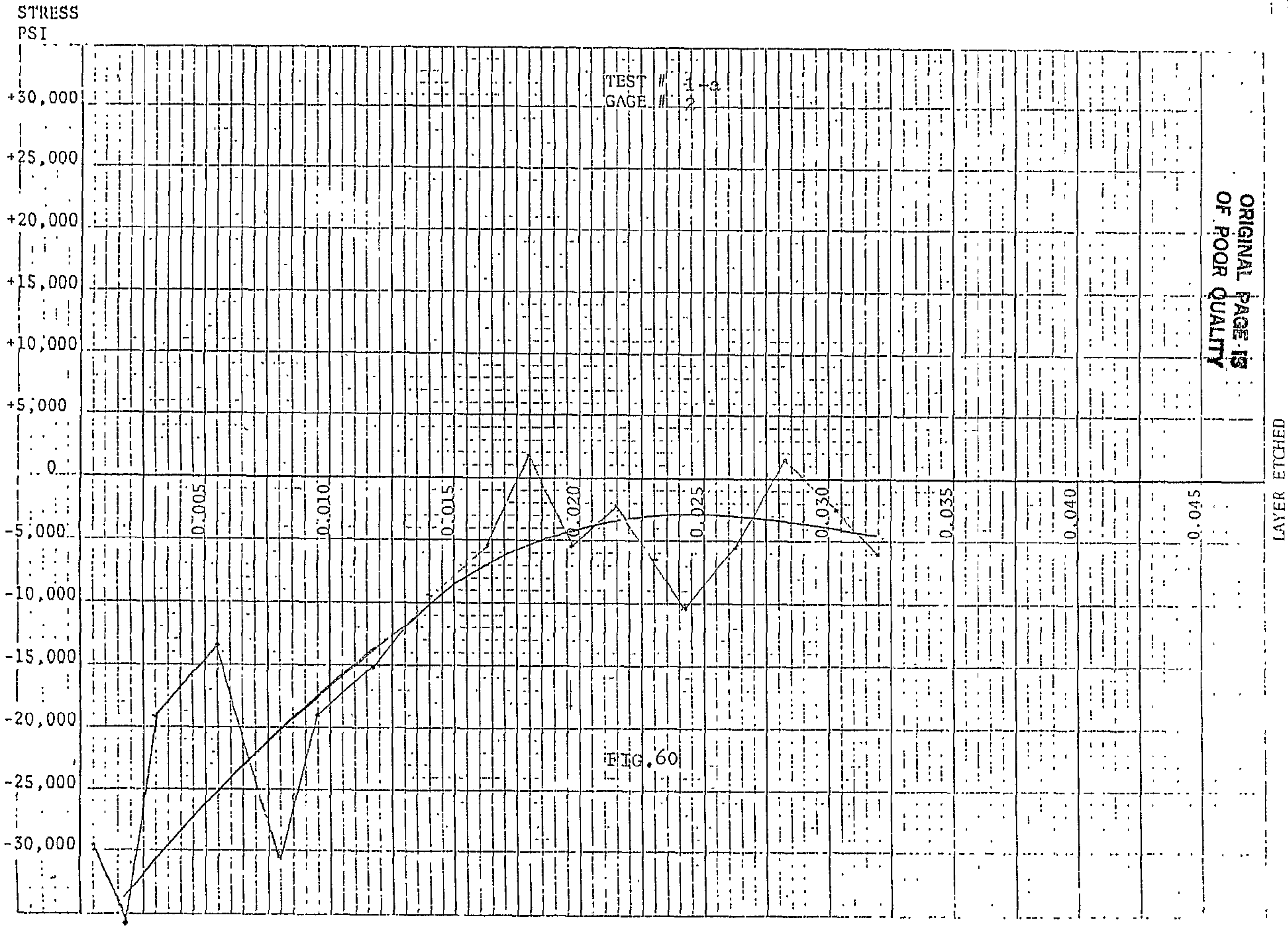


FIG. 60

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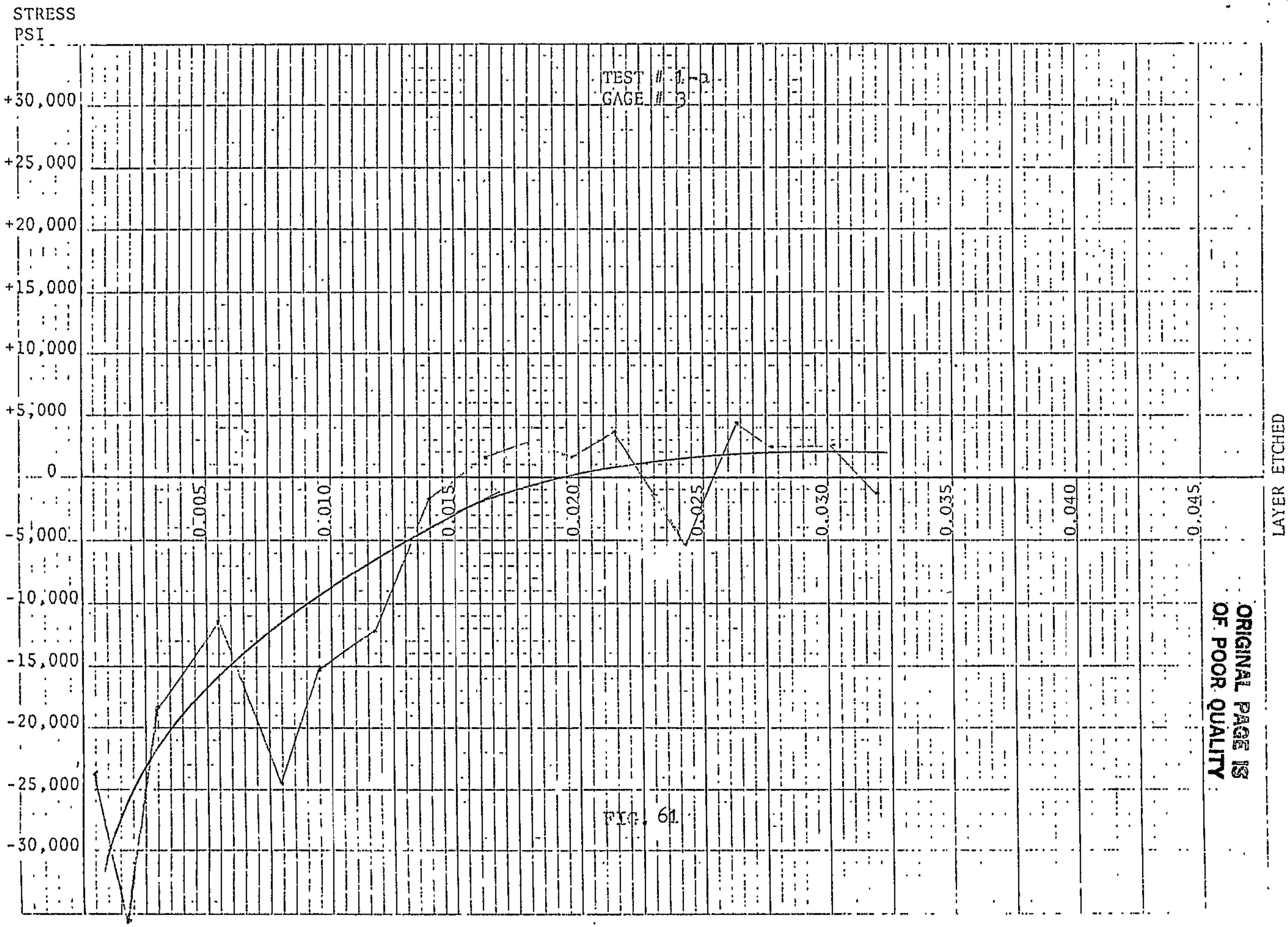

FIG. 61

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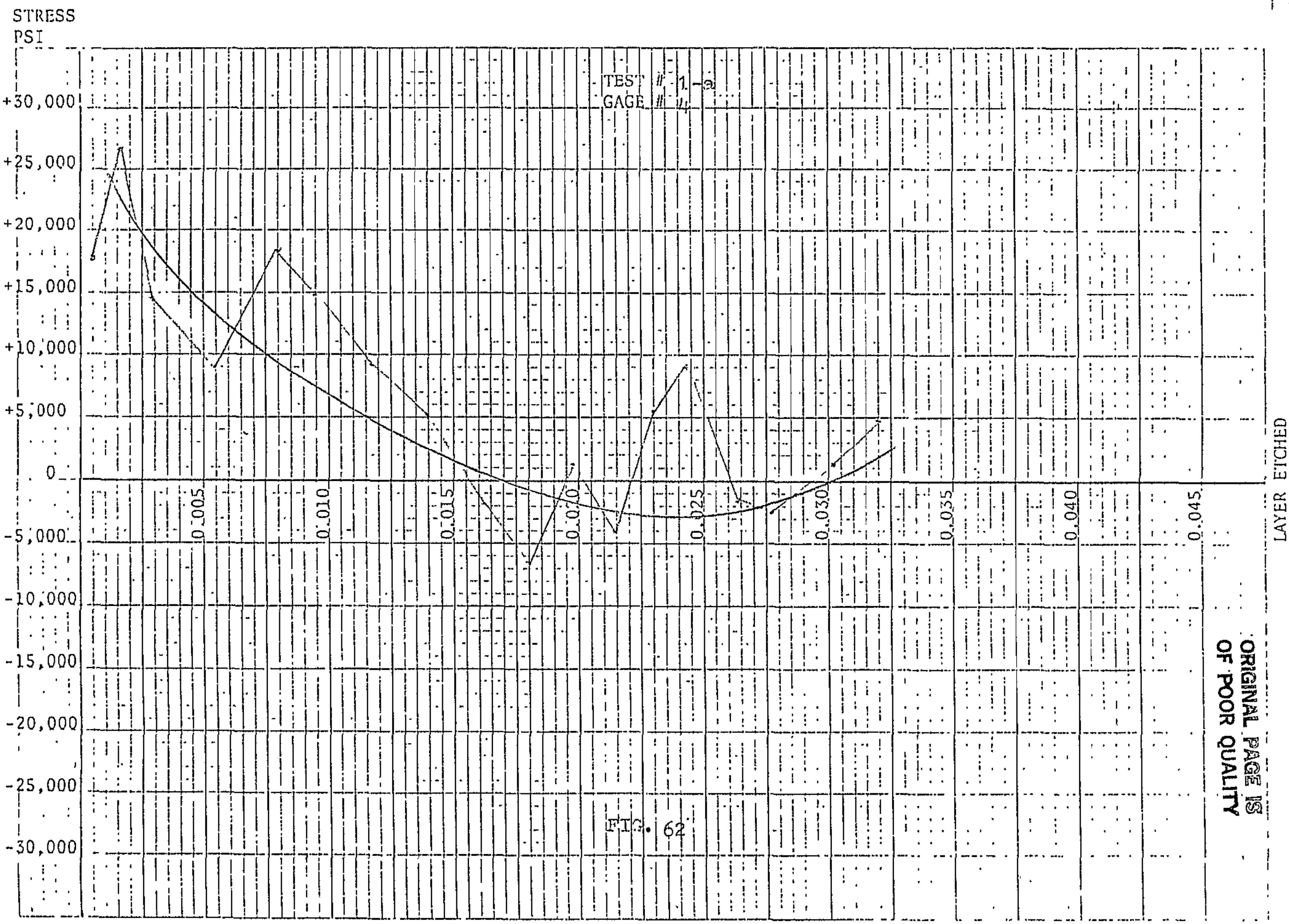
STRESS
PSI
TEST # 1-a
GAGE # 4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 62

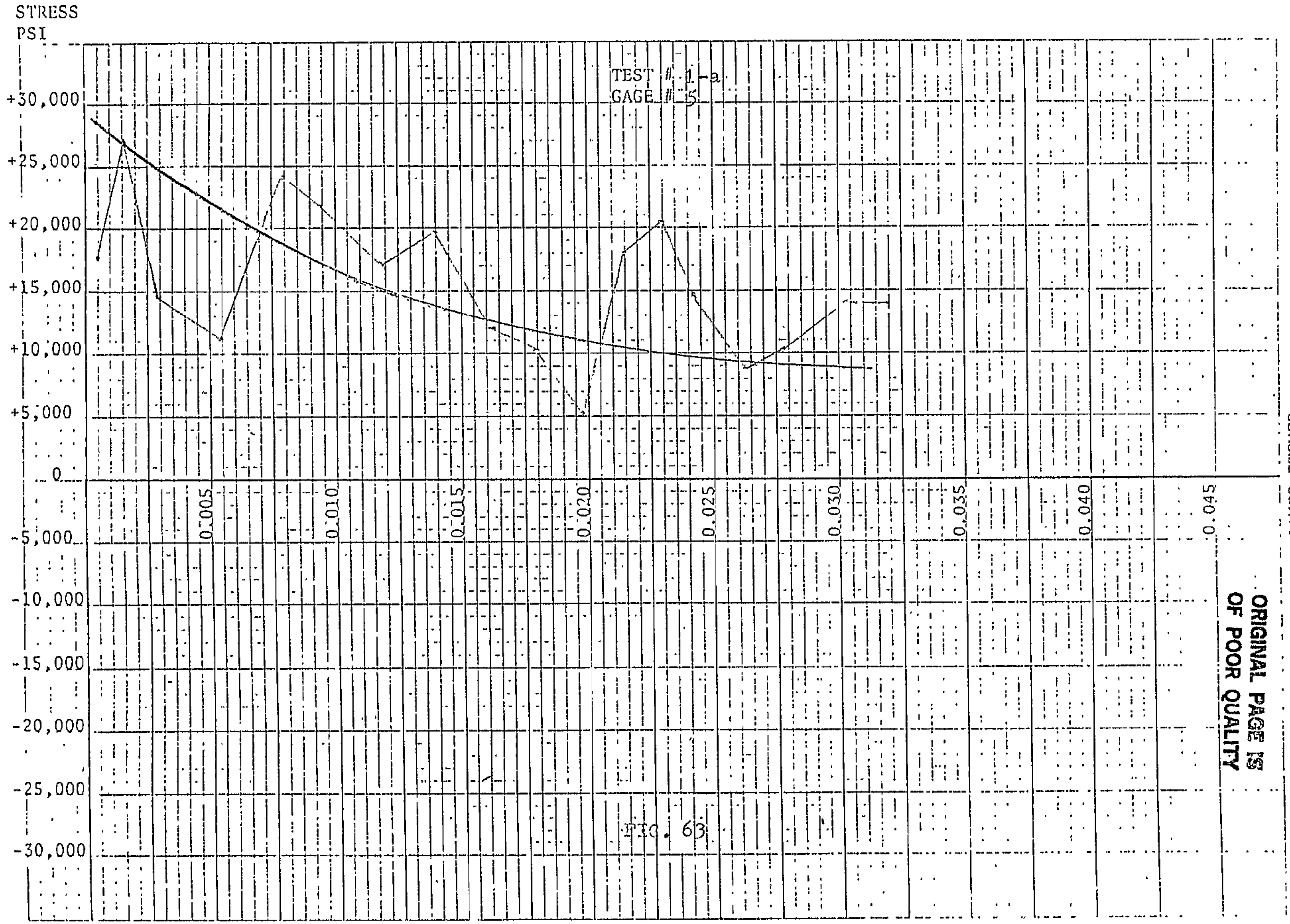

FIG. 63

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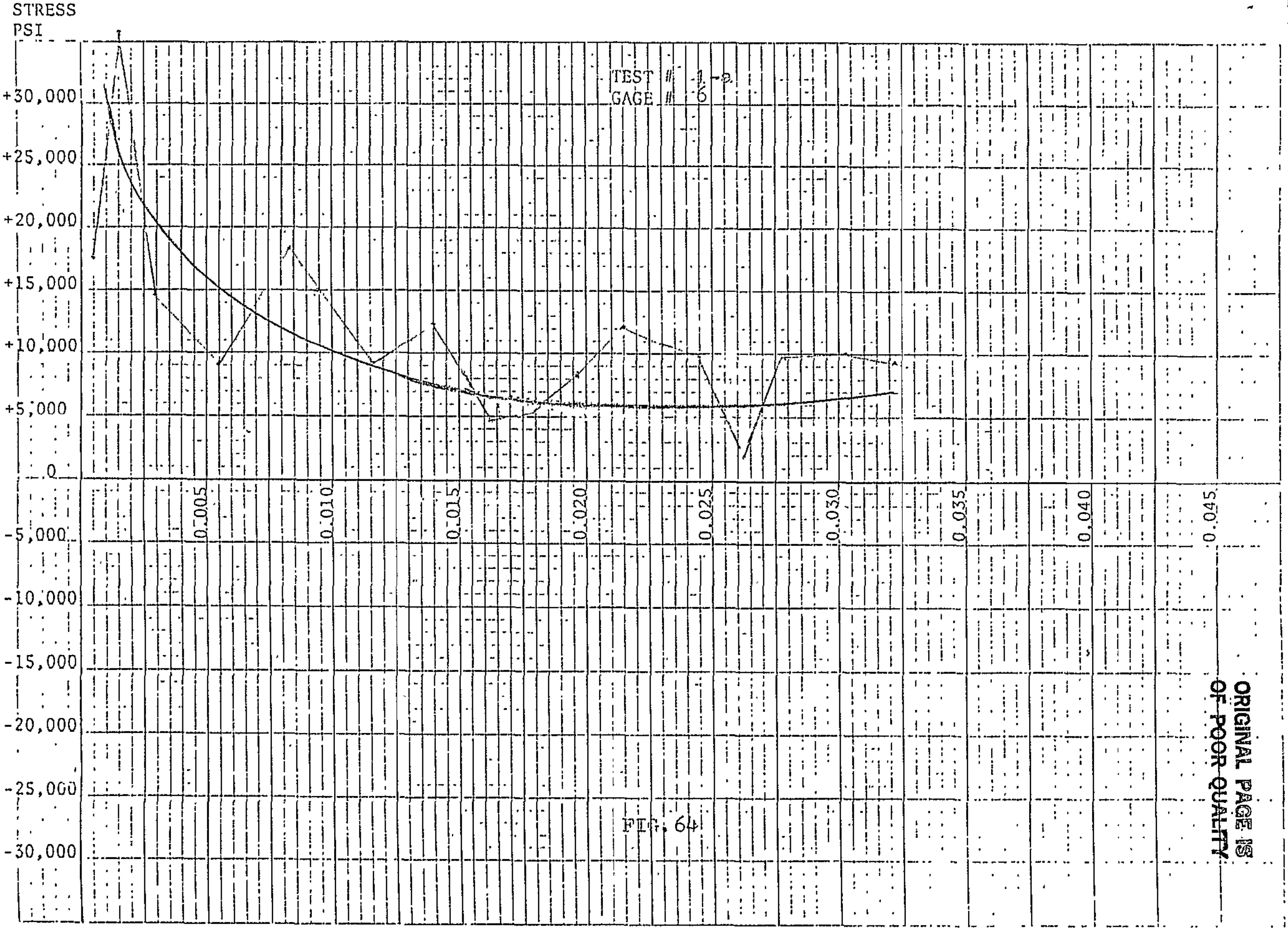

FIG. 64

ORIGINAL PAGE IS OF POOR QUALITY

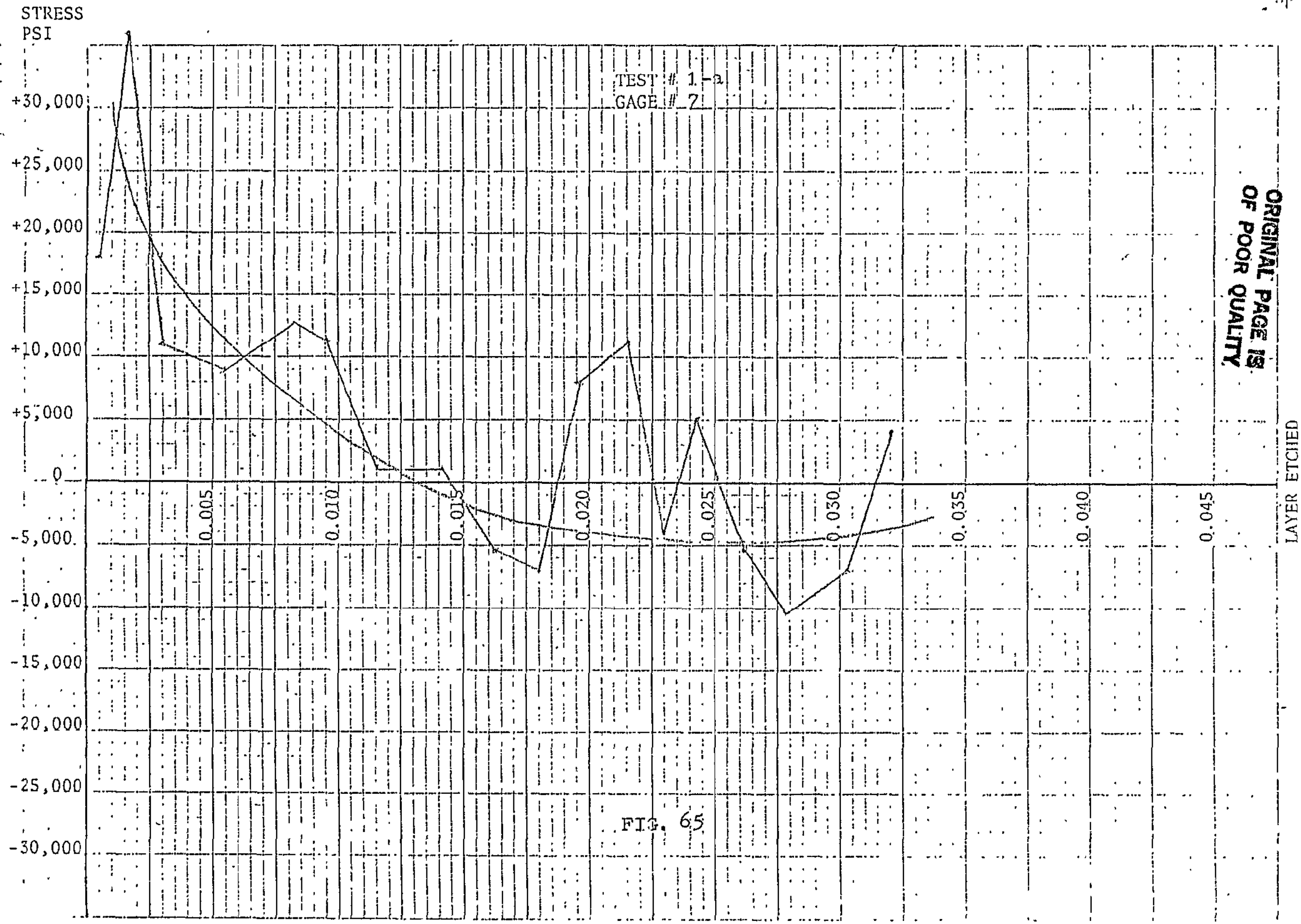

FIG. 65

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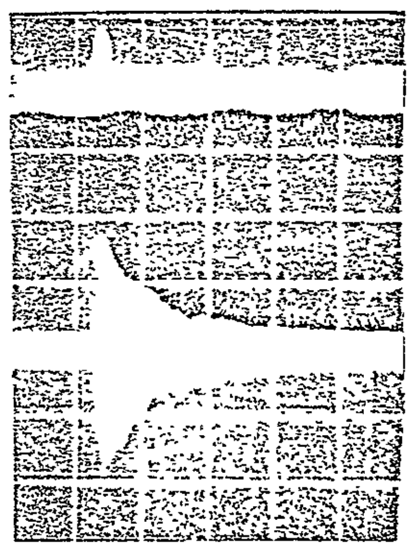
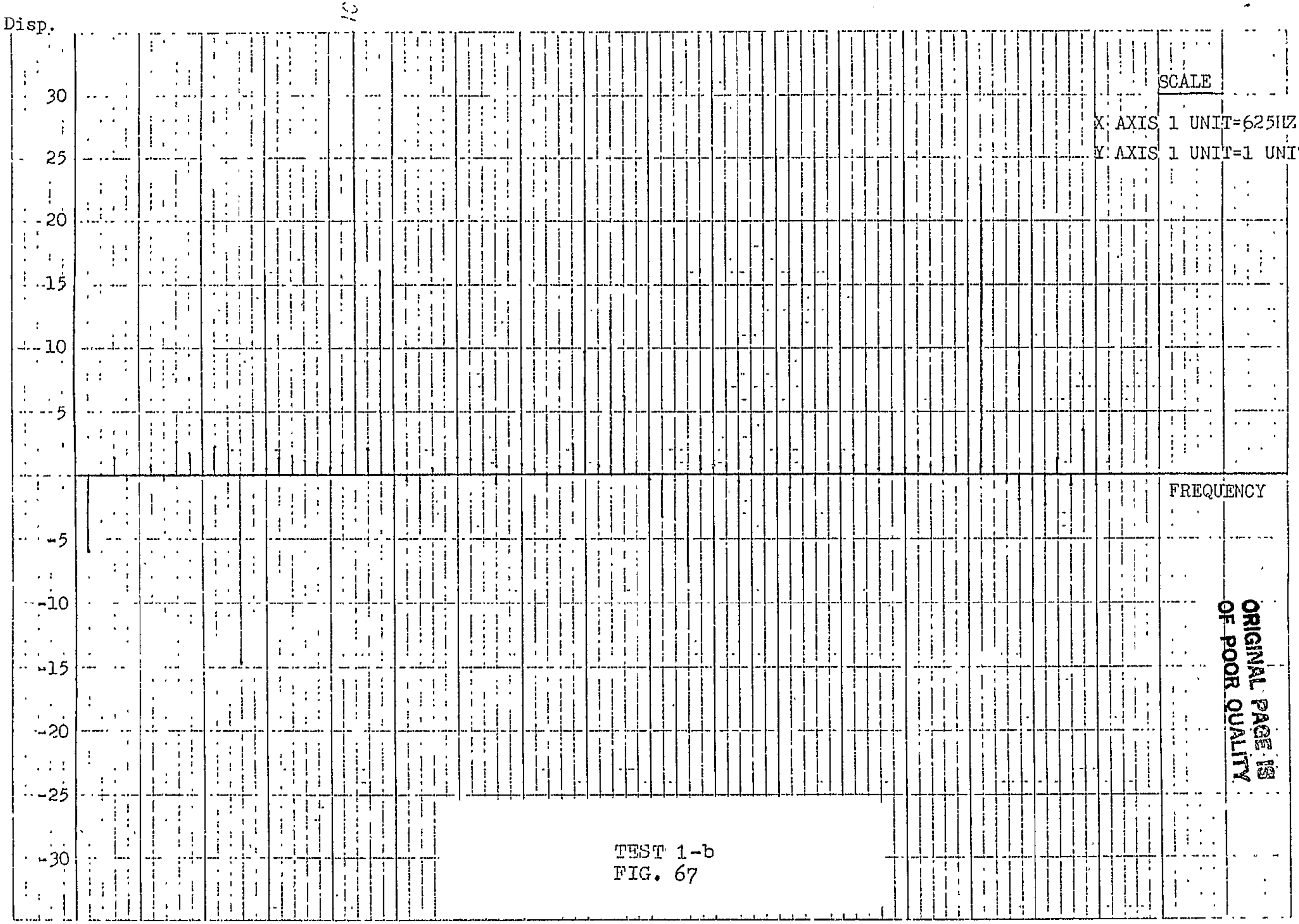


TEST 1-b
FIG. 66



TEST 1-b
FIG. 67

	GAGE #	1	2	3	4	5	6	7	8
LAYER	1	0.	4466.	4466.	4466.	4466.	4466.	8932.	
LAYER	2	-4452.	8961.	4509.	58.	58.	58.	4567.	
LAYER	3	2659.	5606.	5548.	5491.	2774.	5491.	2889.	
LAYER	4	0.	4997.	4940.	9593.	4825.	9593.	9649.	
LAYER	5	-3050.	-5757.	3336.	287.	6271.	287.	-2707.	
LAYER	6	3625.	225.	4024.	7649.	3968.	7649.	7647.	
LAYER	7	3163.	3386.	3560.	6723.	6667.	6723.	3559.	
LAYER	8	58.	3931.	4103.	7812.	7756.	7812.	4102.	
LAYER	9	58.	3972.	4143.	4259.	4203.	4259.	7779.	
LAYER	10	-2928.	6363.	3547.	3662.	3607.	3662.	3604.	
LAYER	11	-0.	5079.	5191.	9880.	5250.	5305.	5247.	
LAYER	12	-3593.	559.	670.	4434.	4322.	4377.	4319.	
LAYER	13	-4061.	4560.	4670.	4898.	4786.	4841.	8787.	

TEST 1-C
FIG 68

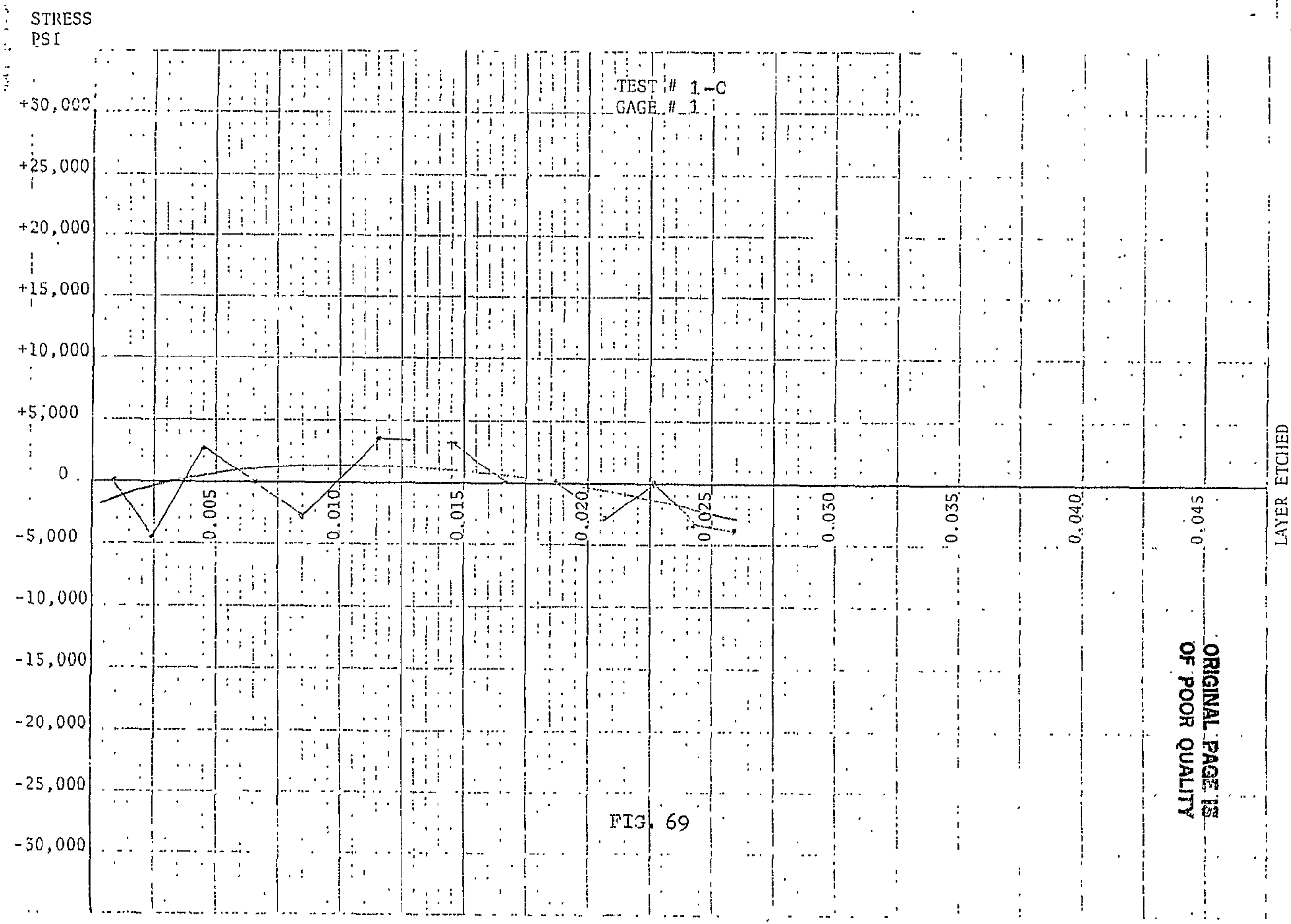


FIG. 69

ORIGINAL PAGE IS
OF POOR QUALITY

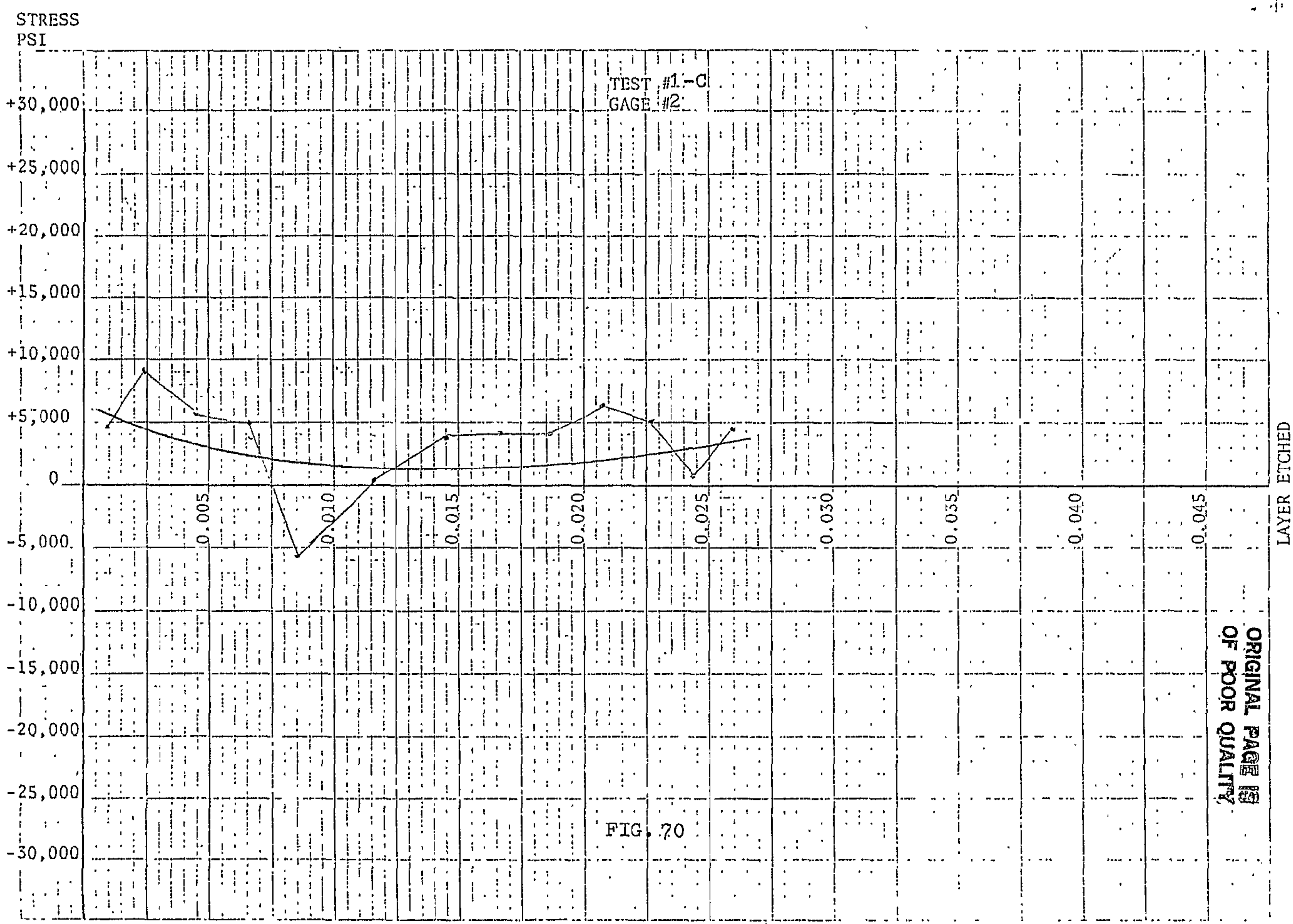


FIG. 70

ORIGINAL PAGE IS
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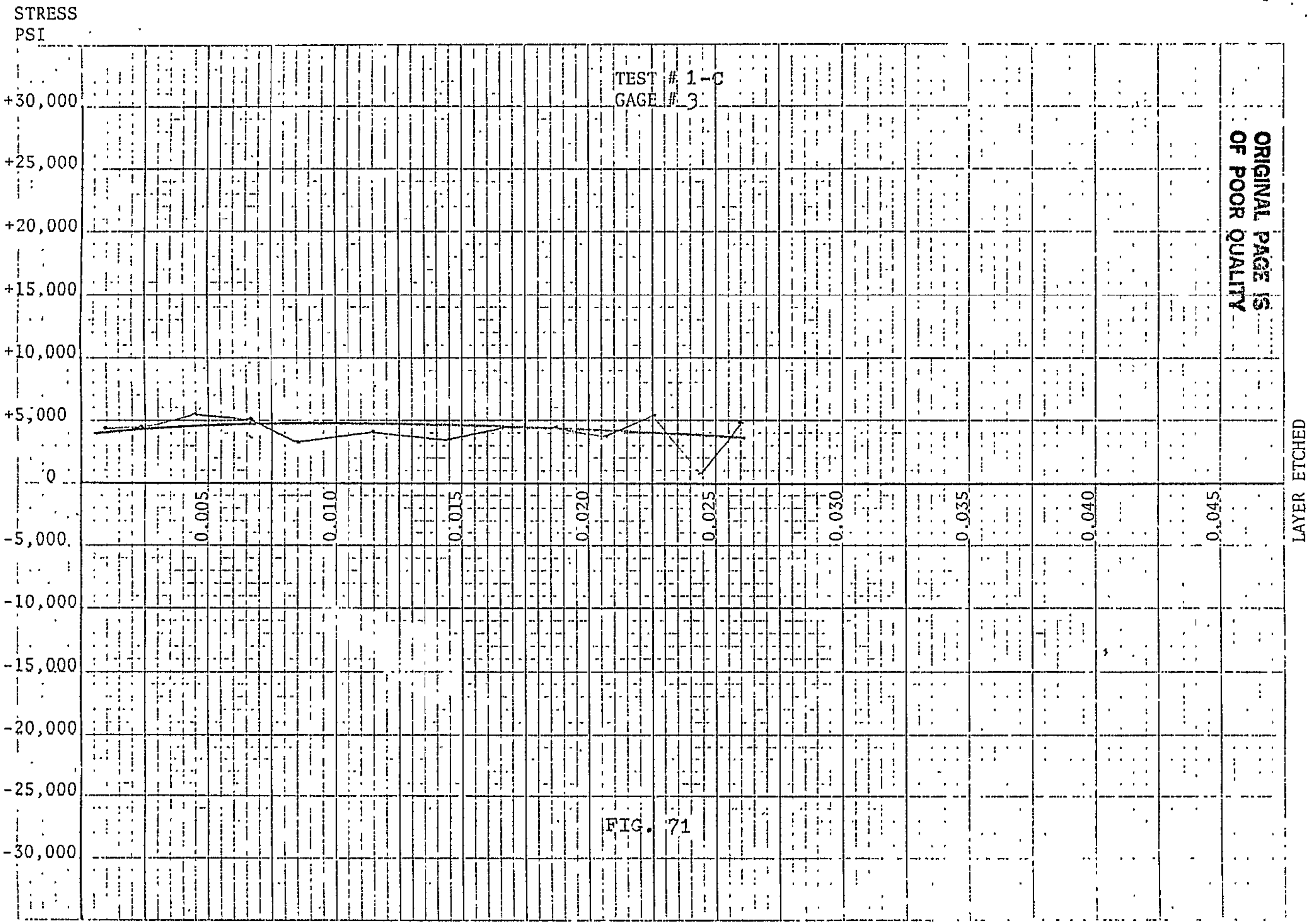
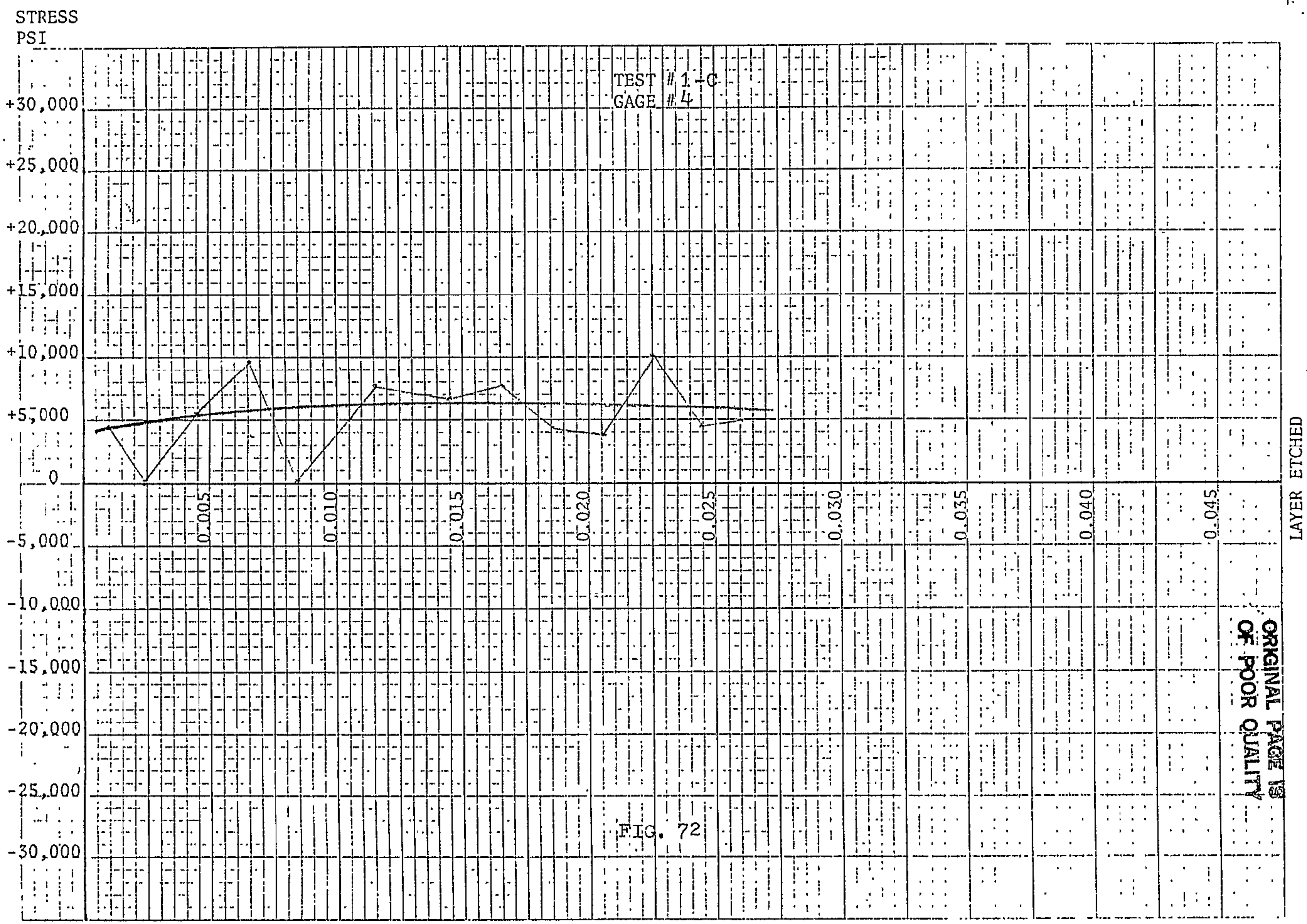


STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 1-C
GAGE # 3
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 71



STRESS
PSI
TEST #1-C
GAGE #4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 72

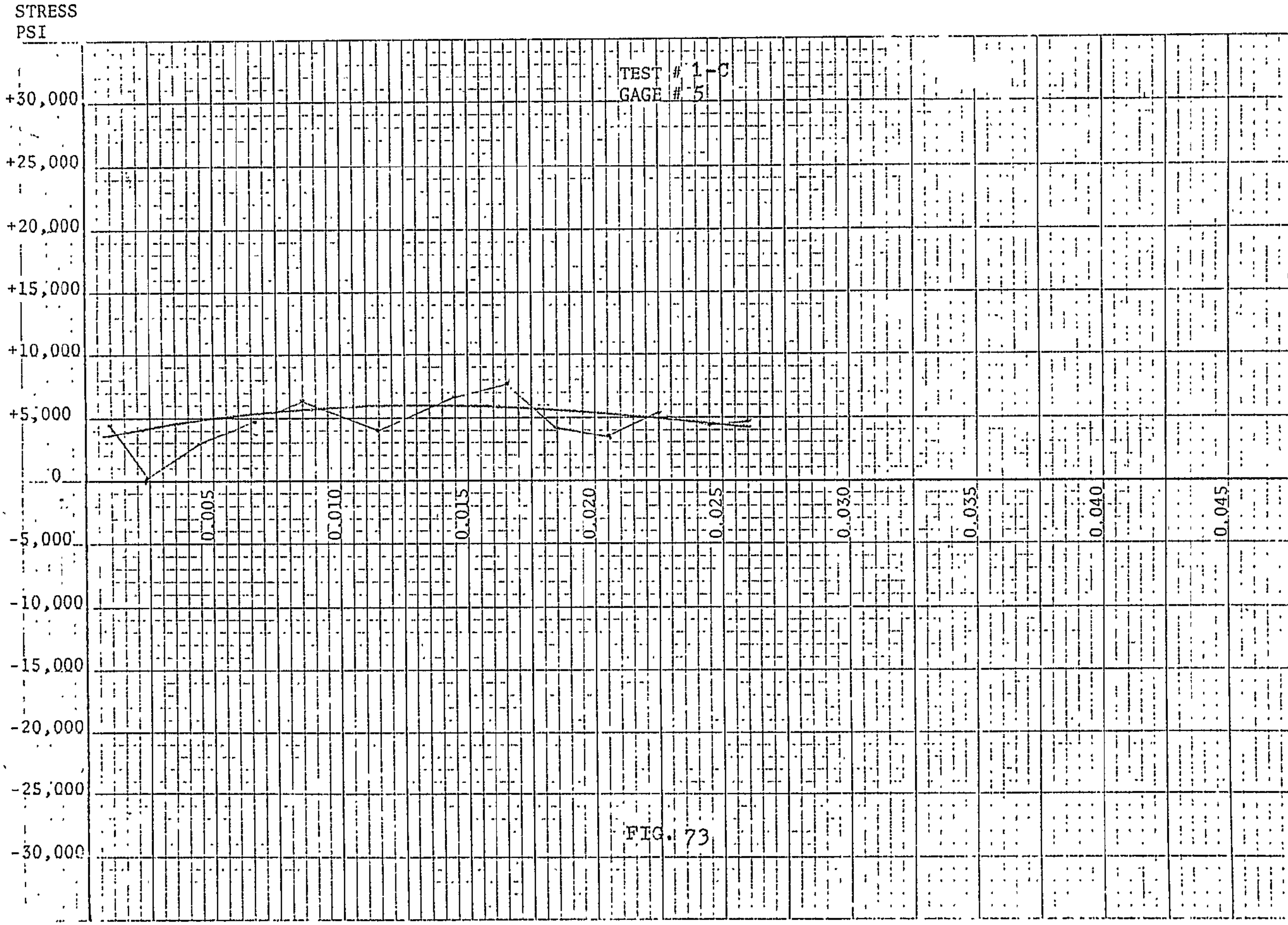

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 1-C
GAGE # 5
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 73

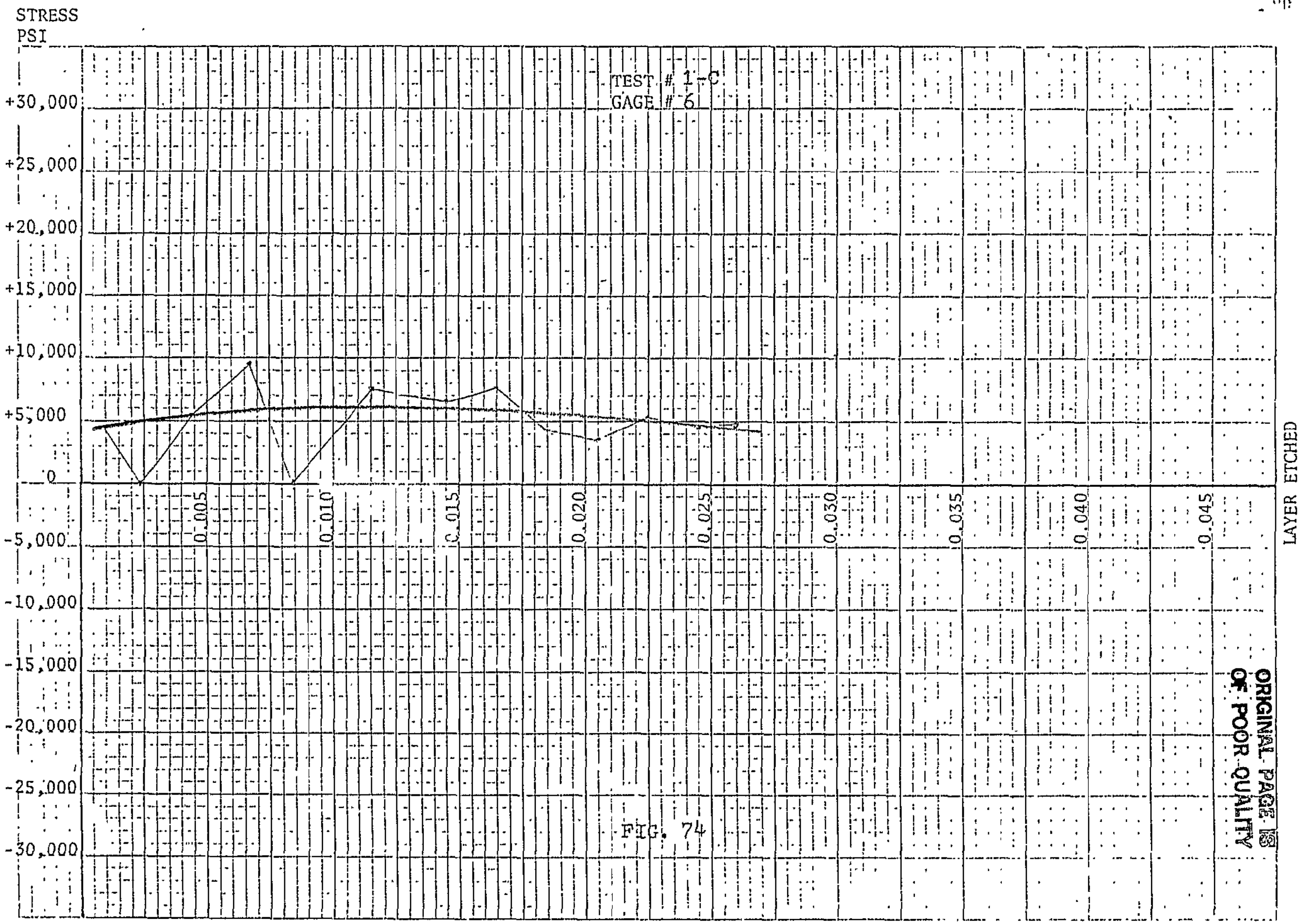
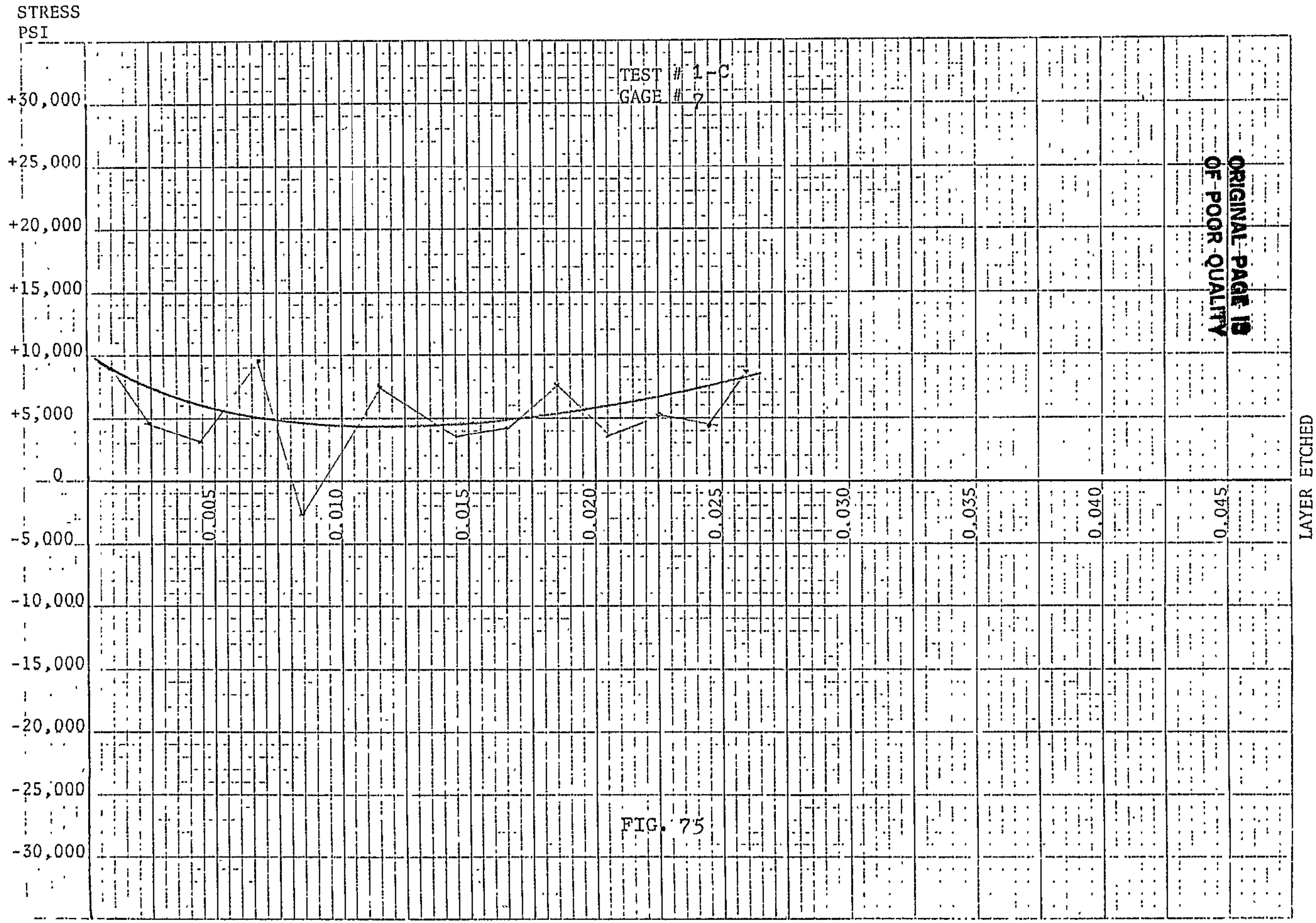


FIG. 74

ORIGINAL PAGE IS OF POOR QUALITY



STRESS
PSI
TEST # 1-C
GAGE # 7
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 75

GAGE #		1	2	3	4	5	6
LAYER	1	-12894.	-12894.	11461.	12894.	-12894.	-11461.
LAYER	2	-12986.	-12986.	11147.	11205.	-12986.	-12929.
LAYER	3	-12082.	-12082.	6382.	4577.	-12082.	-13887.
LAYER	4	-7158.	-6171.	-1019.	-1020.	-6171.	-6172.
LAYER	5	-7798.	-7742.	-966.	-967.	-6849.	-7743.
LAYER	6	-5979.	-6940.	-2362.	-2363.	-5866.	-4908.
LAYER	7	-5212.	-4435.	-1059.	-1060.	-4323.	-4323.
LAYER	8	-4011.	-3084.	-2246.	-2247.	-2975.	-2101.
LAYER	9	-503.	-2213.	-3445.	-3447.	-3017.	-2050.
LAYER	10	-1307.	-3004.	-4263.	-3419.	-2111.	-1999.
LAYER	11	257.	-2166.	-4927.	-3720.	-912.	-802.
LAYER	12	-198.	-1273.	[illegible]	-2962.	-272.	-1009.
LAYER	13	37.	-245	[illegible]	-2351.	-35.	13.

TEST 2-a
FIG. 76

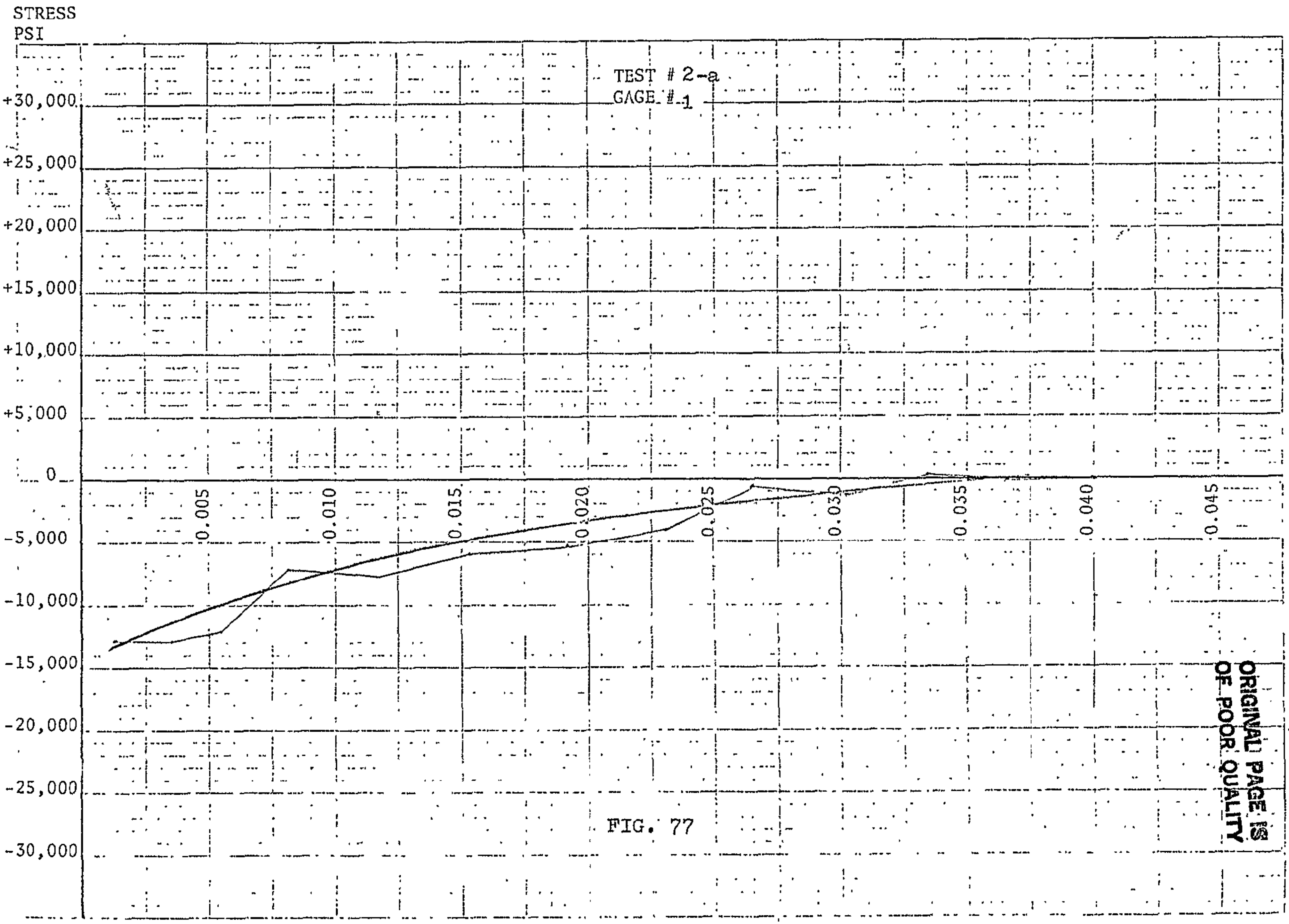


FIG. 77

ORIGINAL PAGE IS
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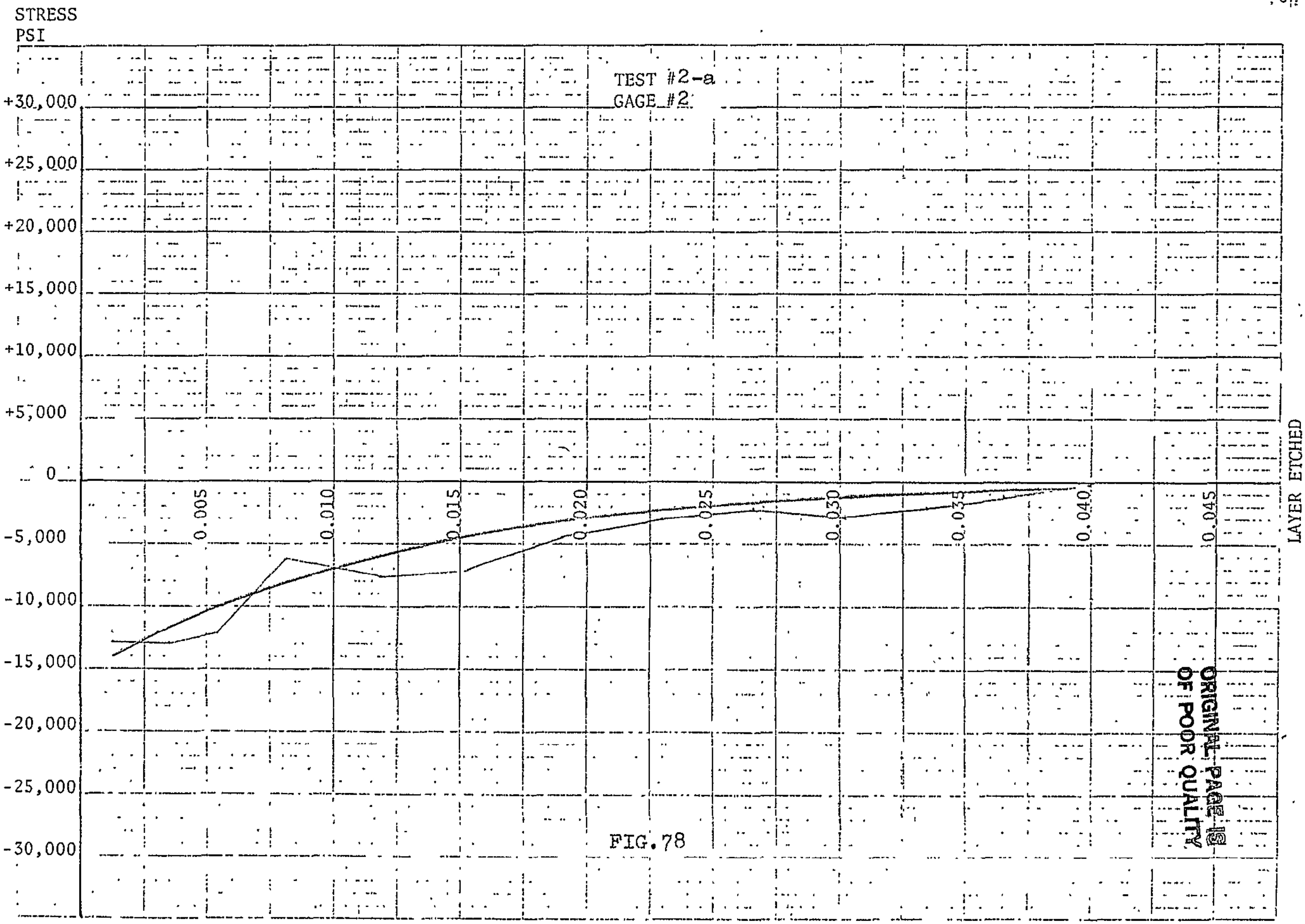

FIG. 78

ORIGINAL PAGE IS
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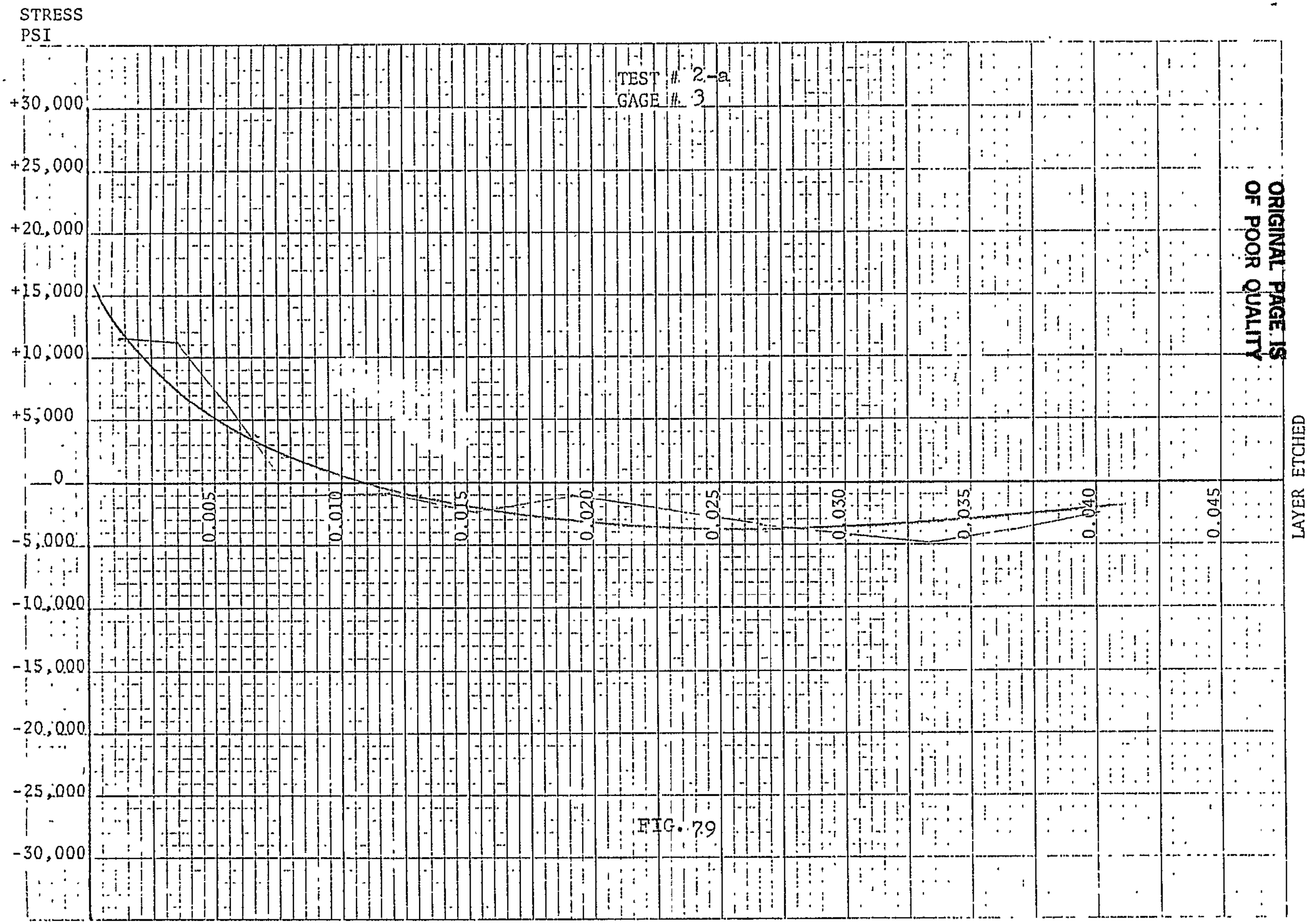

STRESS
PSI
TEST # 2-a
GAGE # 3
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 79

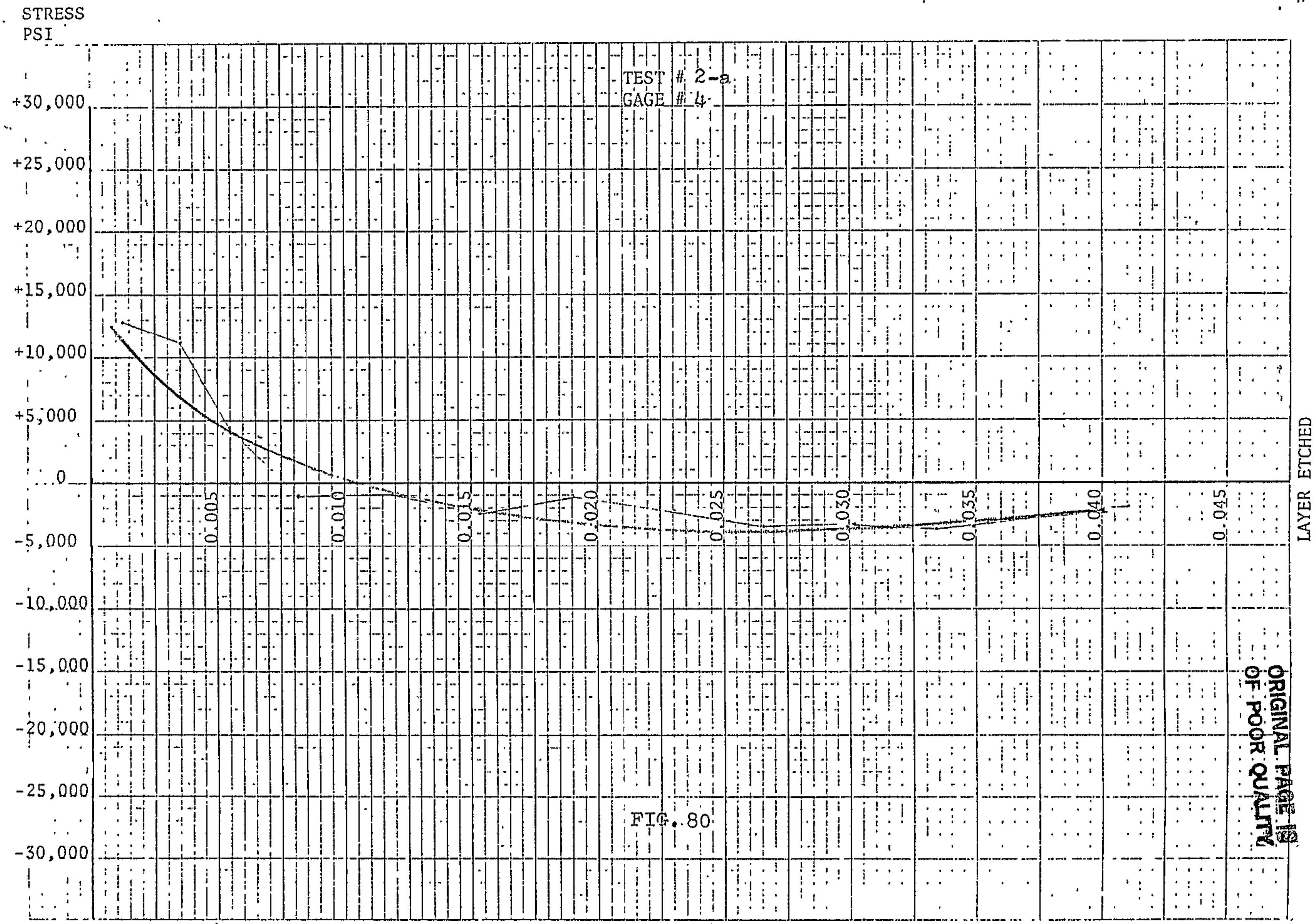

FIG. 80

ORIGINAL PAGE IS
OF POOR QUALITY

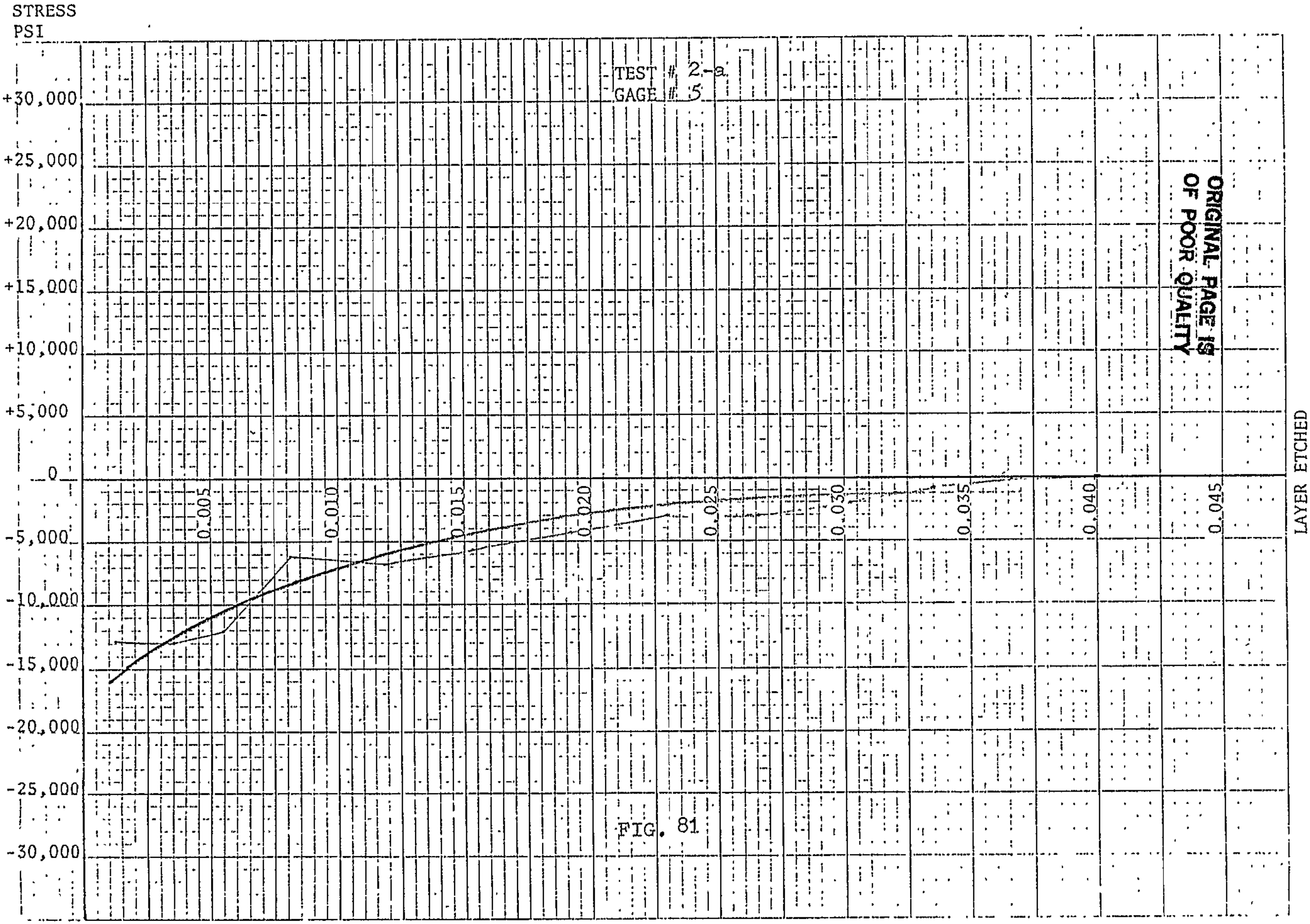
STRESS
PSI
TEST # 2-a
GAGE # 5
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 81

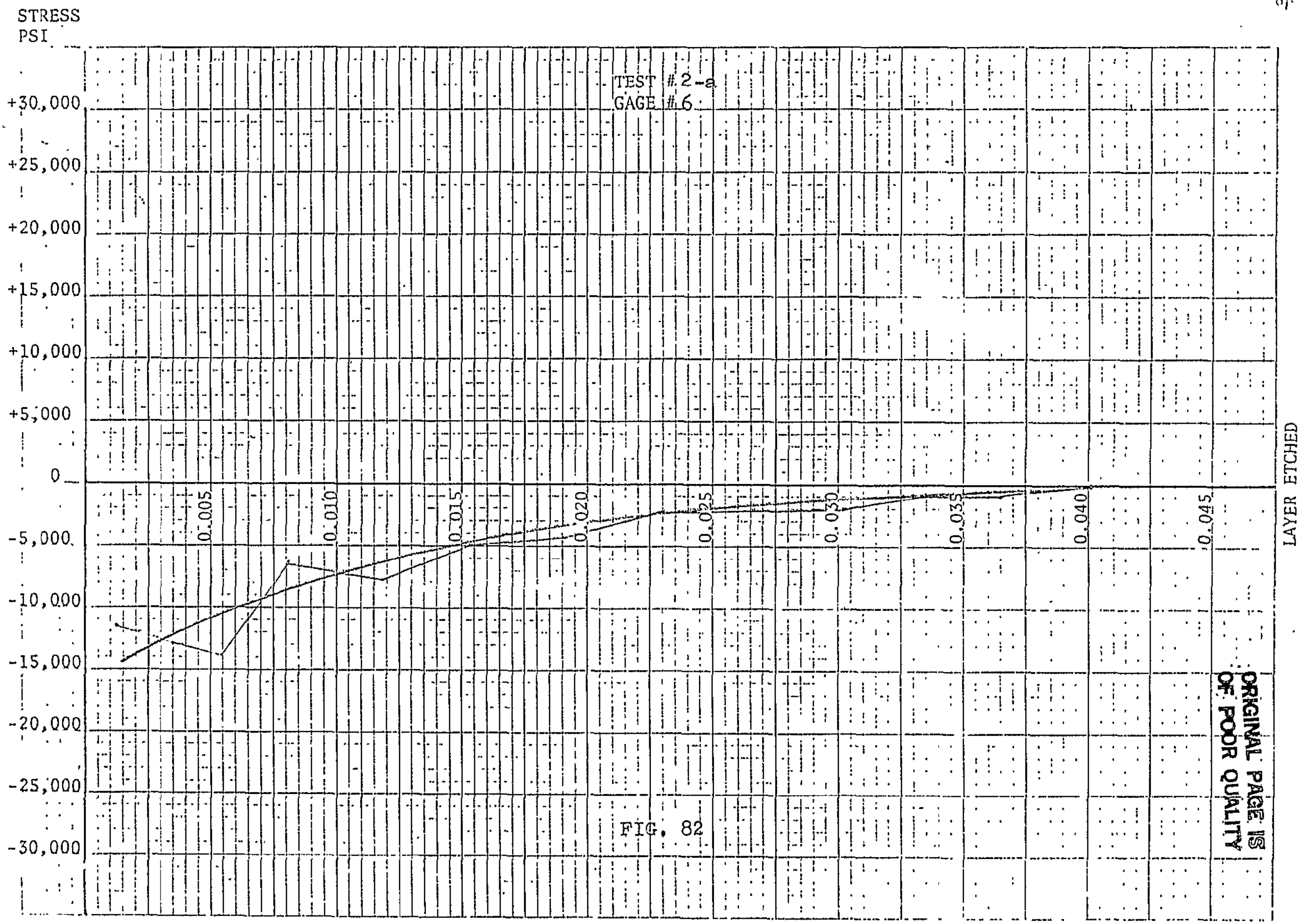

FIG. 82

ORIGINAL PAGE IS
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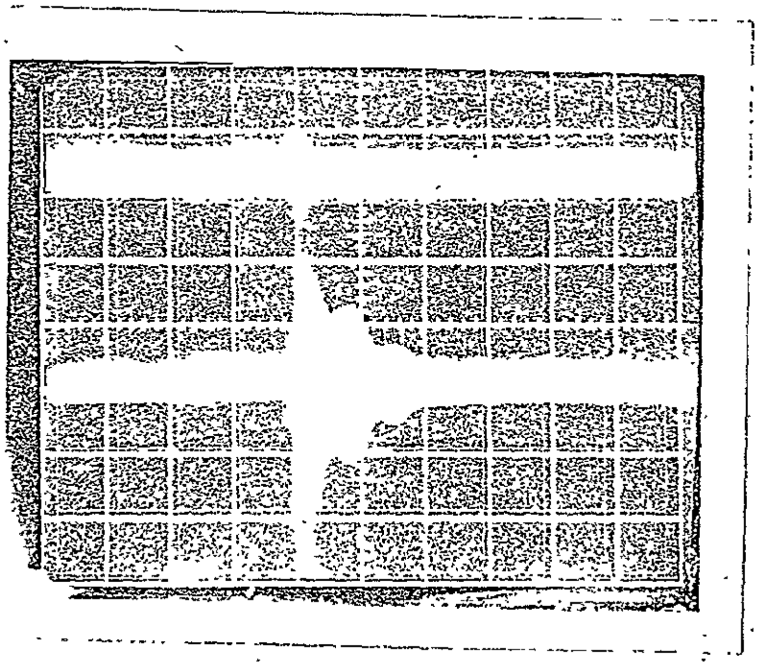
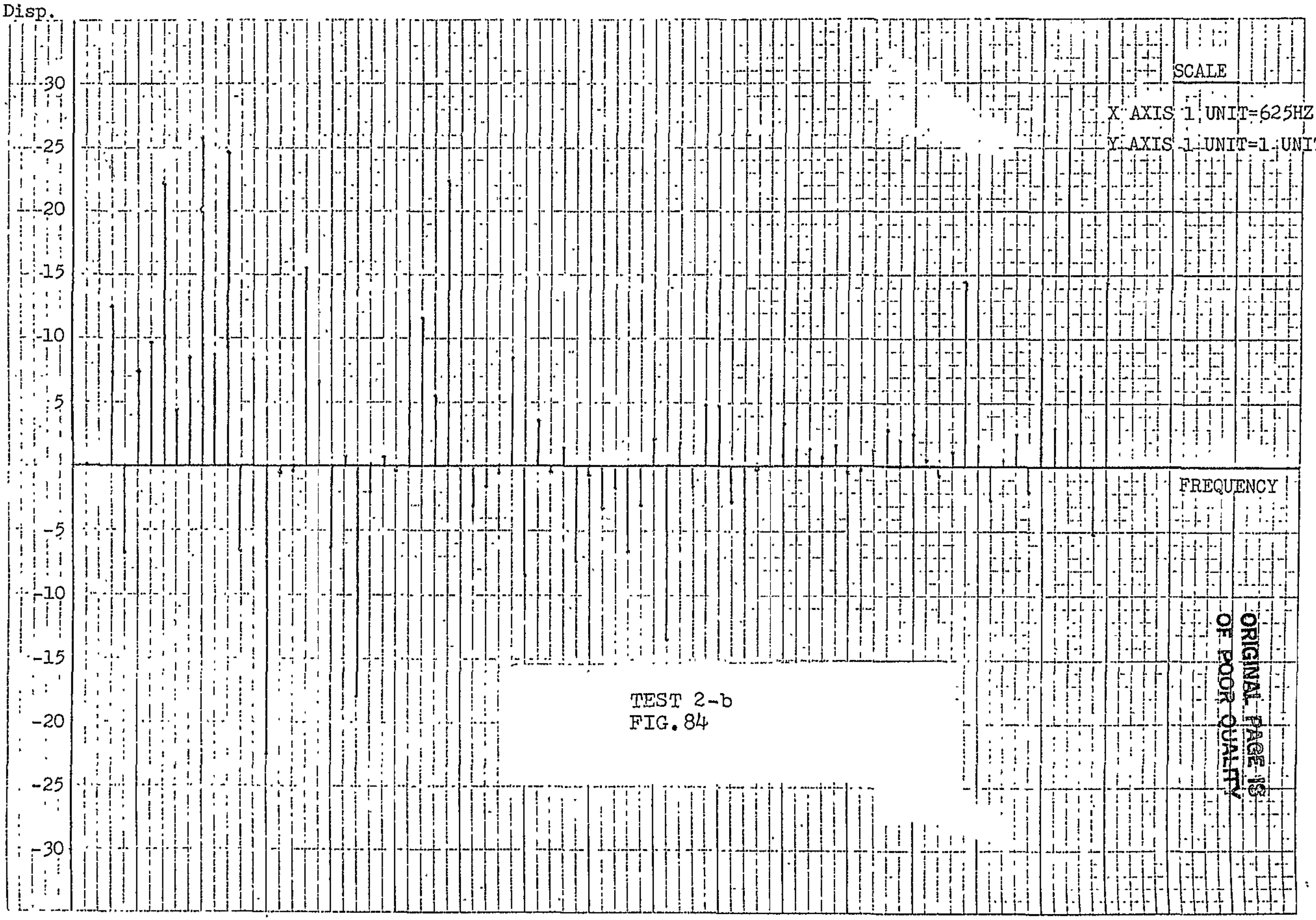
ORIGINAL PAGE IS
OF POOR QUALITY



TEST 2-b
FIG. 83



TEST 2-b
FIG. 84

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OF POOR QUALITY**

	GAGE #	1	2	3	4	5	6	7	8
LAYER	1	2107.	-4215.	-2107.	-2107.	2107.	4215.		
LAYER	2	3133.	-3190.	-3133.	-1595.	3133.	3190.		
LAYER	3	2660.	-2717.	-2660.	-2603.	2660.	2717.		
LAYER	4	1353.	-2481.	-2426.	-2369.	-1863.	1409.		
LAYER	5	2953.	-3064.	2229.	-2955.	-2457.	3007.		
LAYER	6	3255.	-3364.	2543.	-3257.	2858.	3308.		
LAYER	7	3457.	-3565.	2756.	-3459.	-1295.	3510.		
LAYER	8	3534.	-2201.	2844.	-2097.	100.	2147.		
LAYER	9	4852.	-4899.	2808.	-4797.	98.	3482.		
LAYER	10	3739.	-3786.	3013.	-3684.	-2723.	3676.		
LAYER	11	2415.	-3856.	1700.	-3756.	-2810.	3748.		
LAYER	12	4248.	-4350.	3544.	-4252.	-1727.	2651.		

TEST 2-C
FIG. 85

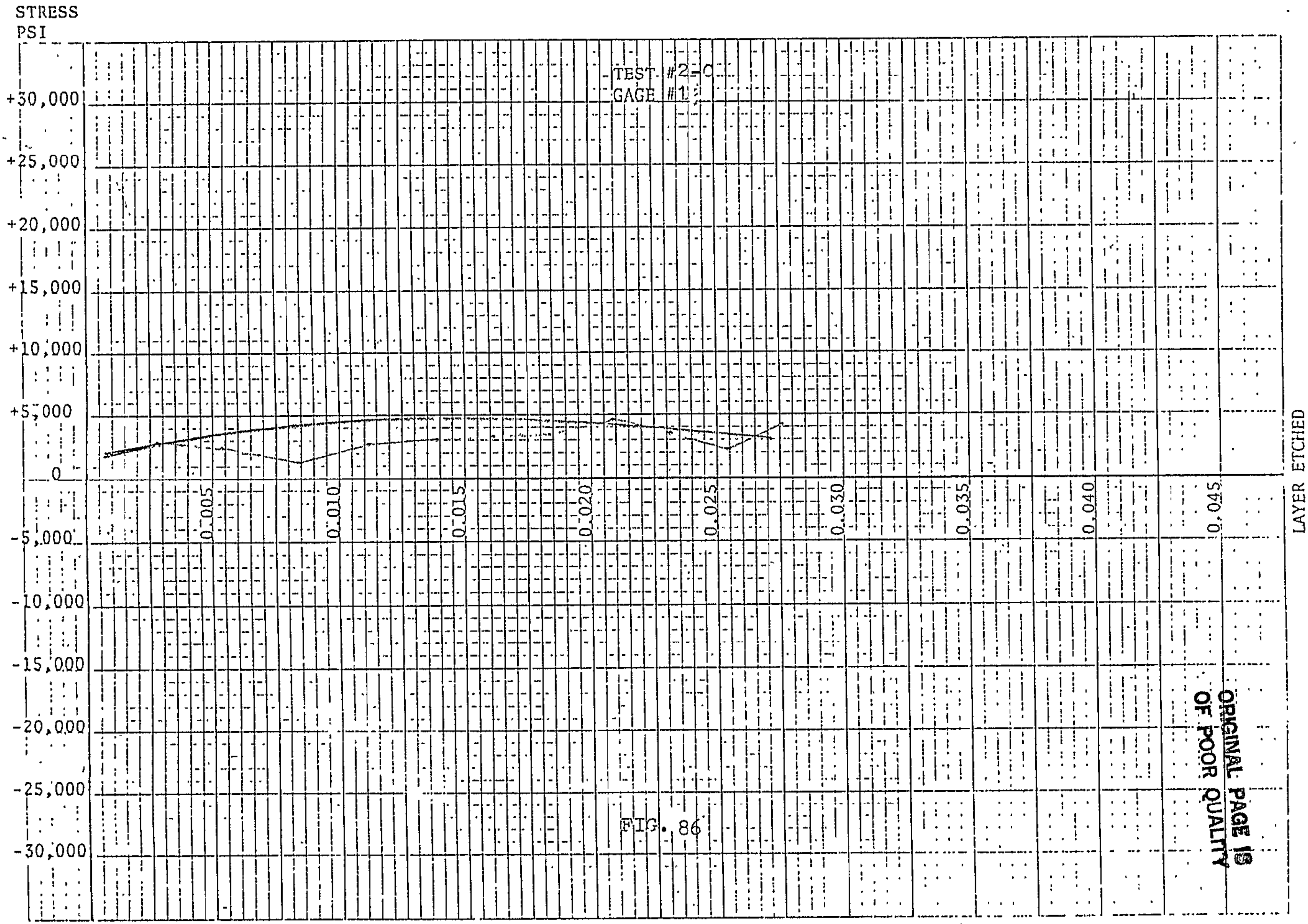

STRESS
PSI
TEST #2-C
GAGE #1
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 86

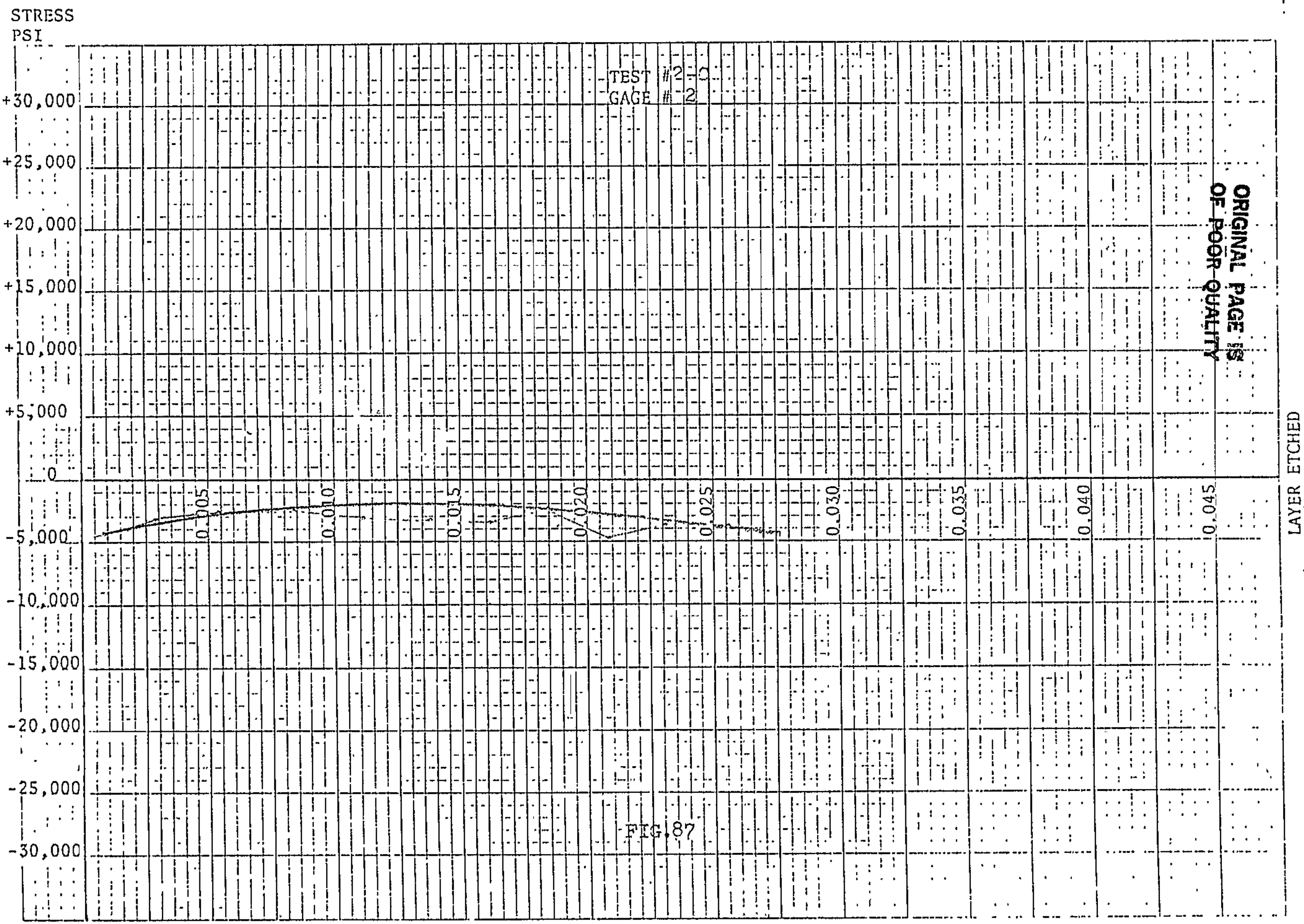
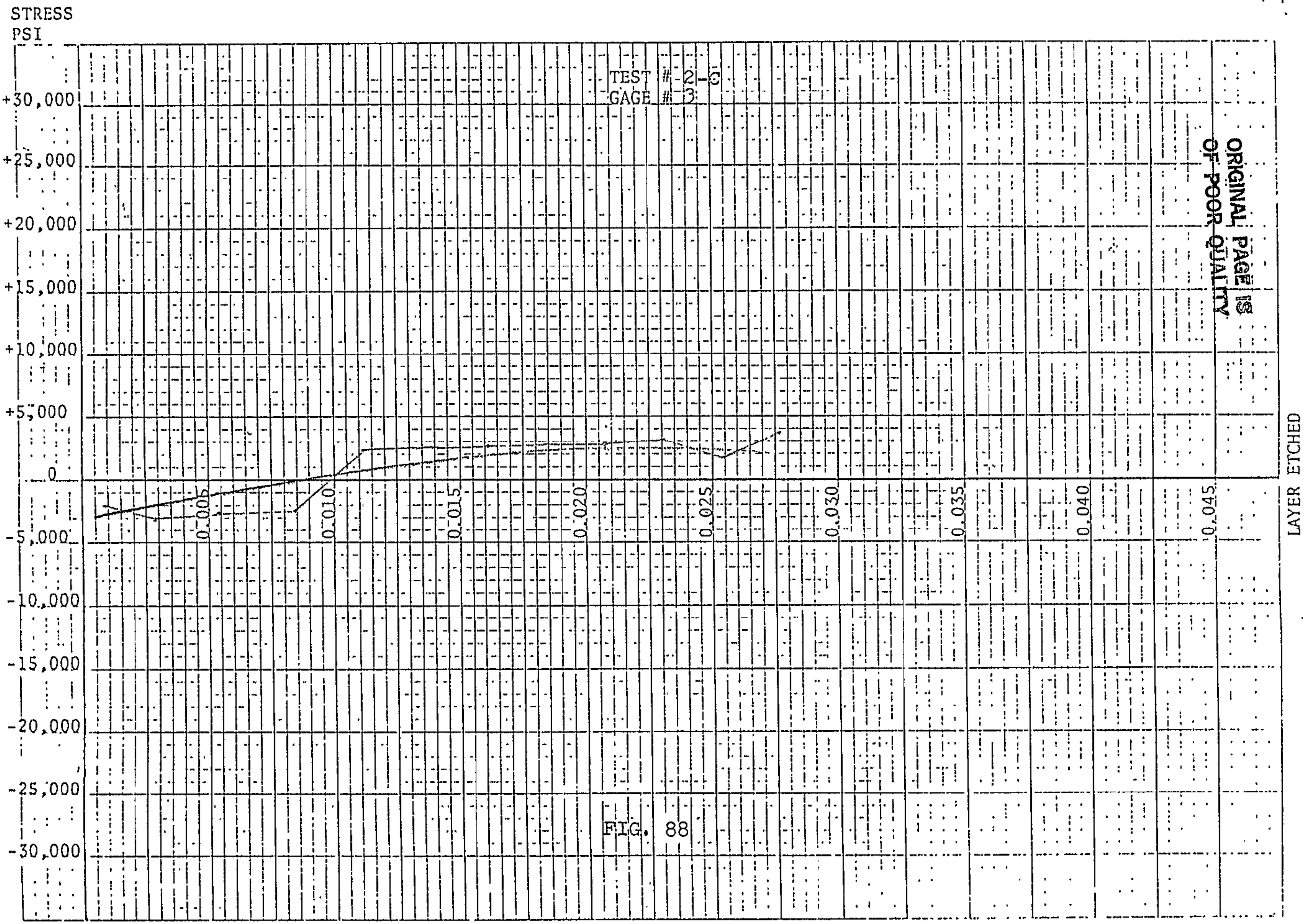


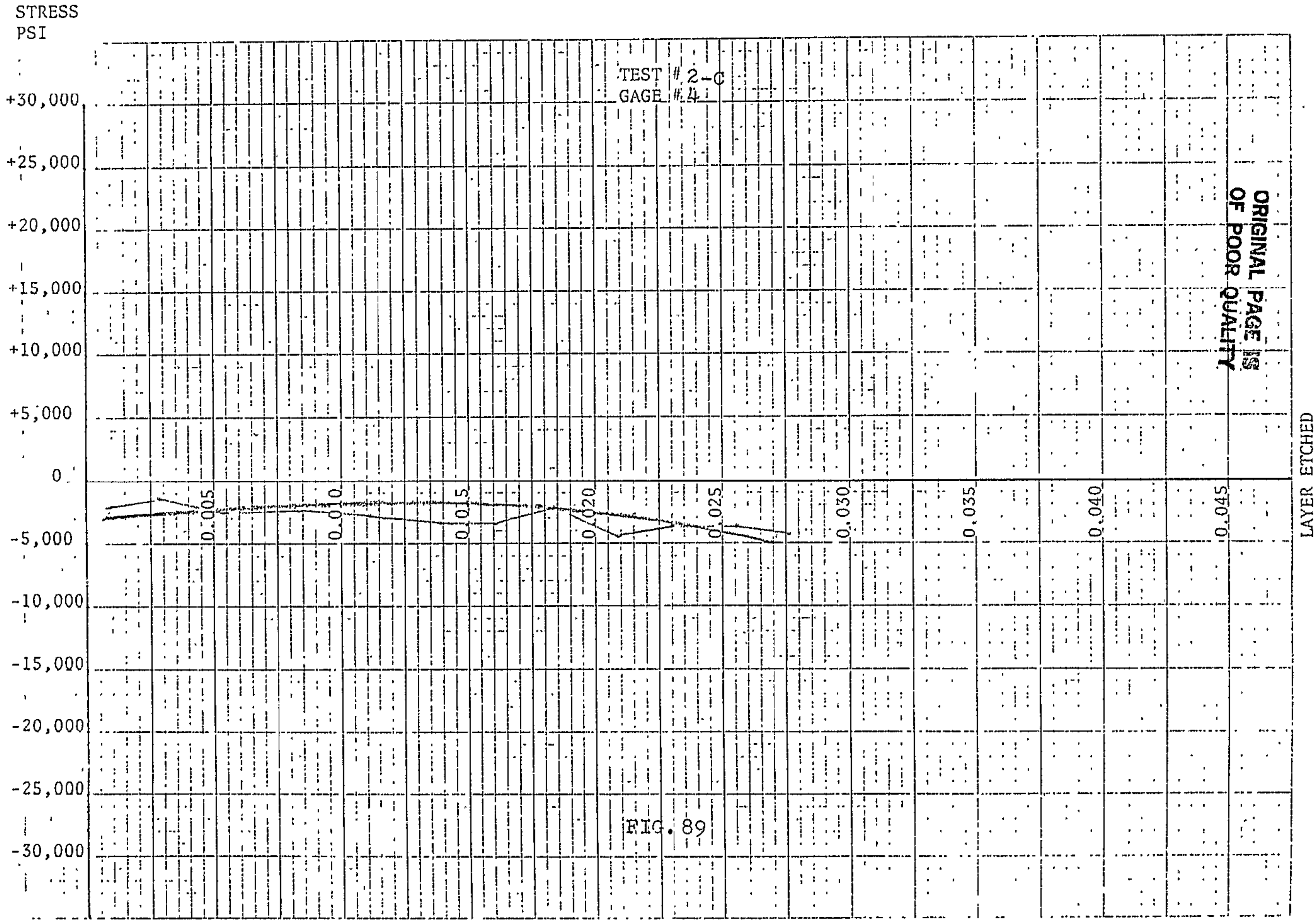
FIG. 87

ORIGINAL PAGE IS
OF POOR QUALITY



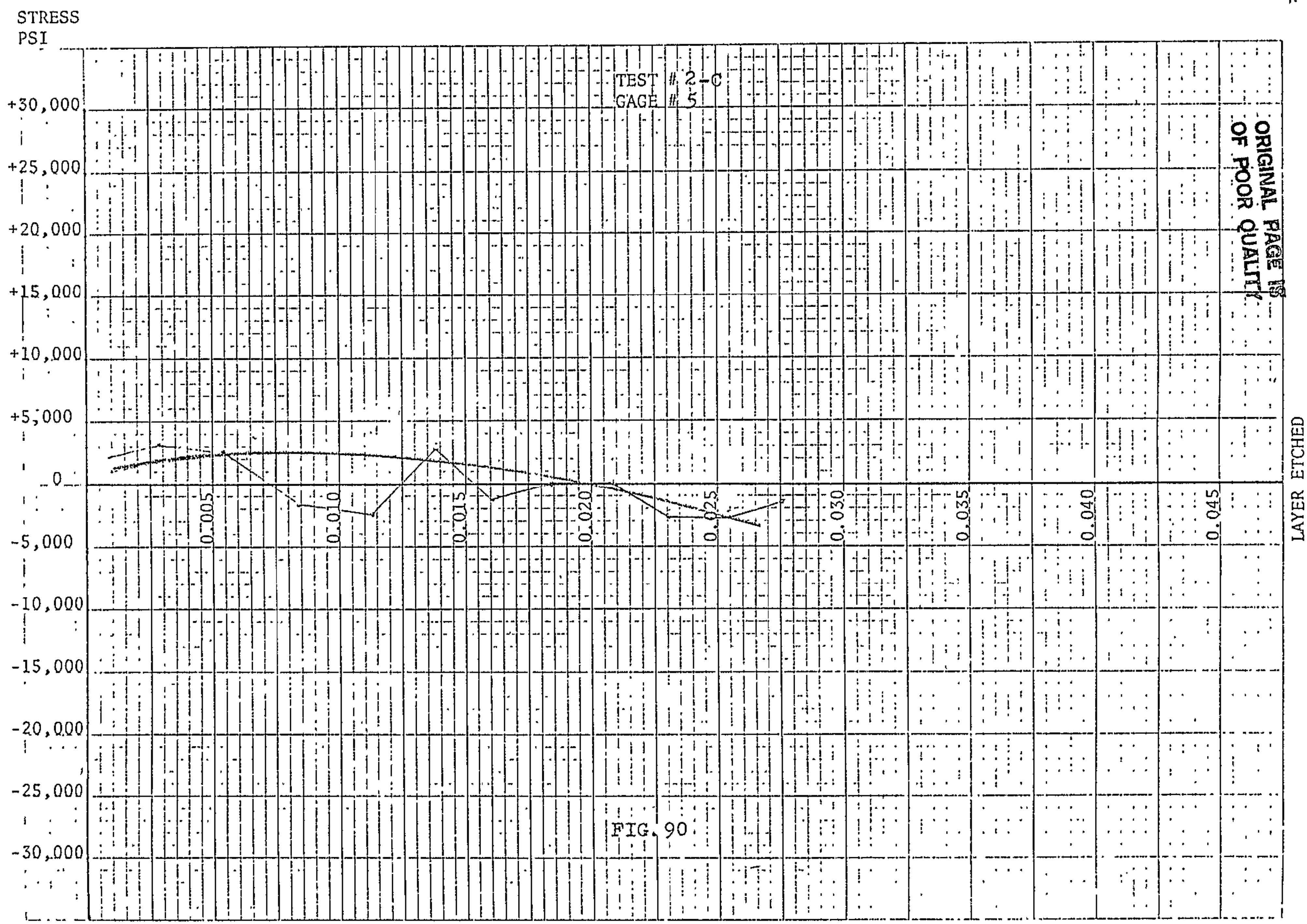
ORIGINAL PAGE IS OF POOR QUALITY

FIG. 88



STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 2-C
GAGE # 4
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 89


STRESS
PSI
TEST # 2-C
GAGE # 5
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
FIG. 90

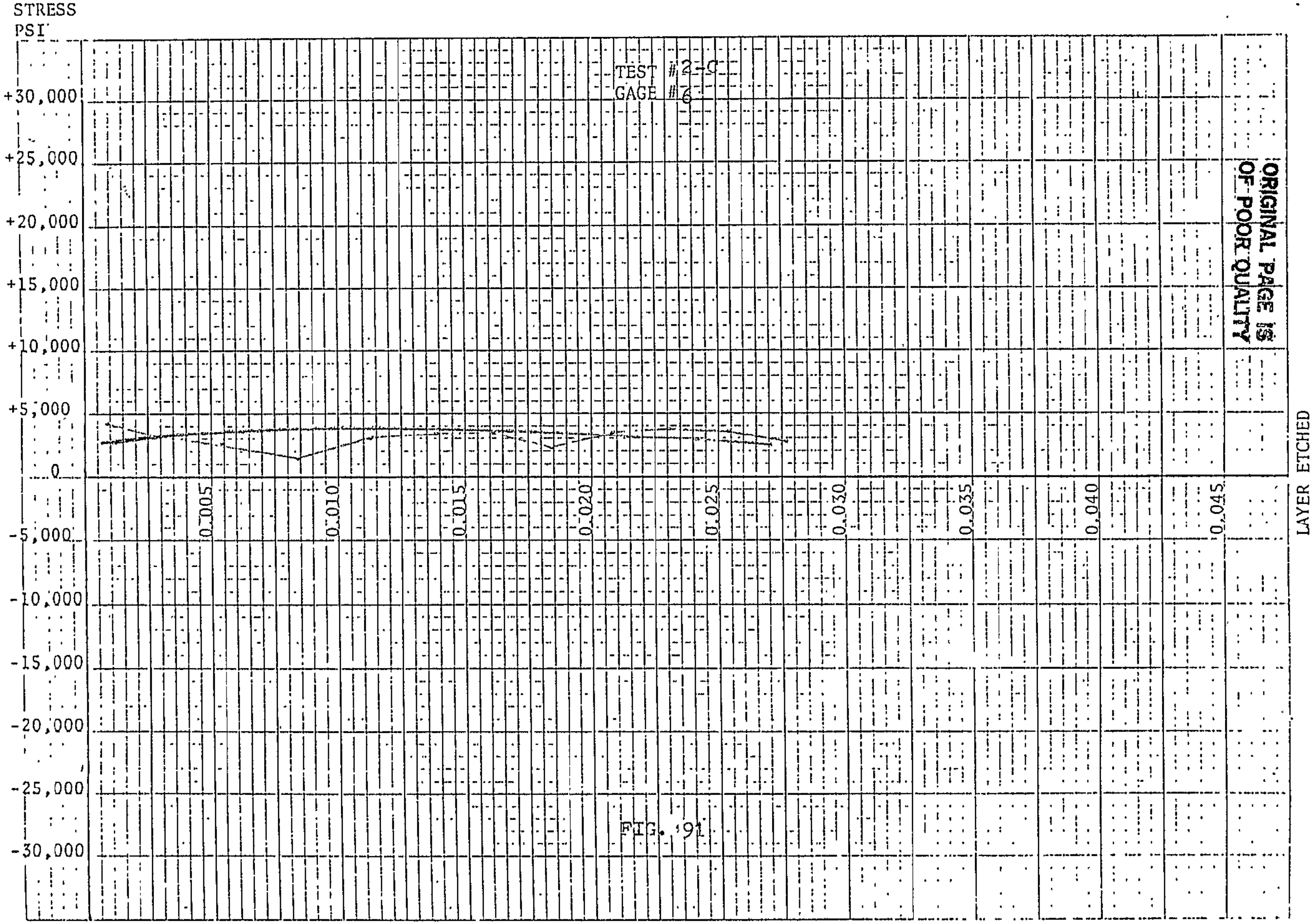

STRESS
PSI
TEST #2-C
GAGE #6
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 91

	GAGE #	1	2	3	4	5
LAYER	1	4776.	3184.	1592.	-1592.	
LAYER	2	5135.	3423.	1712.	-1712.	
LAYER	3	3789.	1951.	1837.	-114.	
LAYER	4	4054.	2083.	170.	-112.	
LAYER	5	3951.	3727.	1863.	-111.	
LAYER	6	2349.	446.	223.	-110.	
LAYER	7	2383.	440.	220.	-1775.	
LAYER	8	764.	-880.	-1098.	-1478.	
LAYER	9	-665.	-3878.	-1260.	-1634.	
LAYER	10	-2551.	-4658.	-1520.	-1889.	
LAYER	11	-2348.	-4342.	38.	-326.	
LAYER	12	-3687.	1222.	37.	-321.	
LAYER	13	-2590.	-94.	-1387.	1108.	

TEST 3-a
FIG. 92

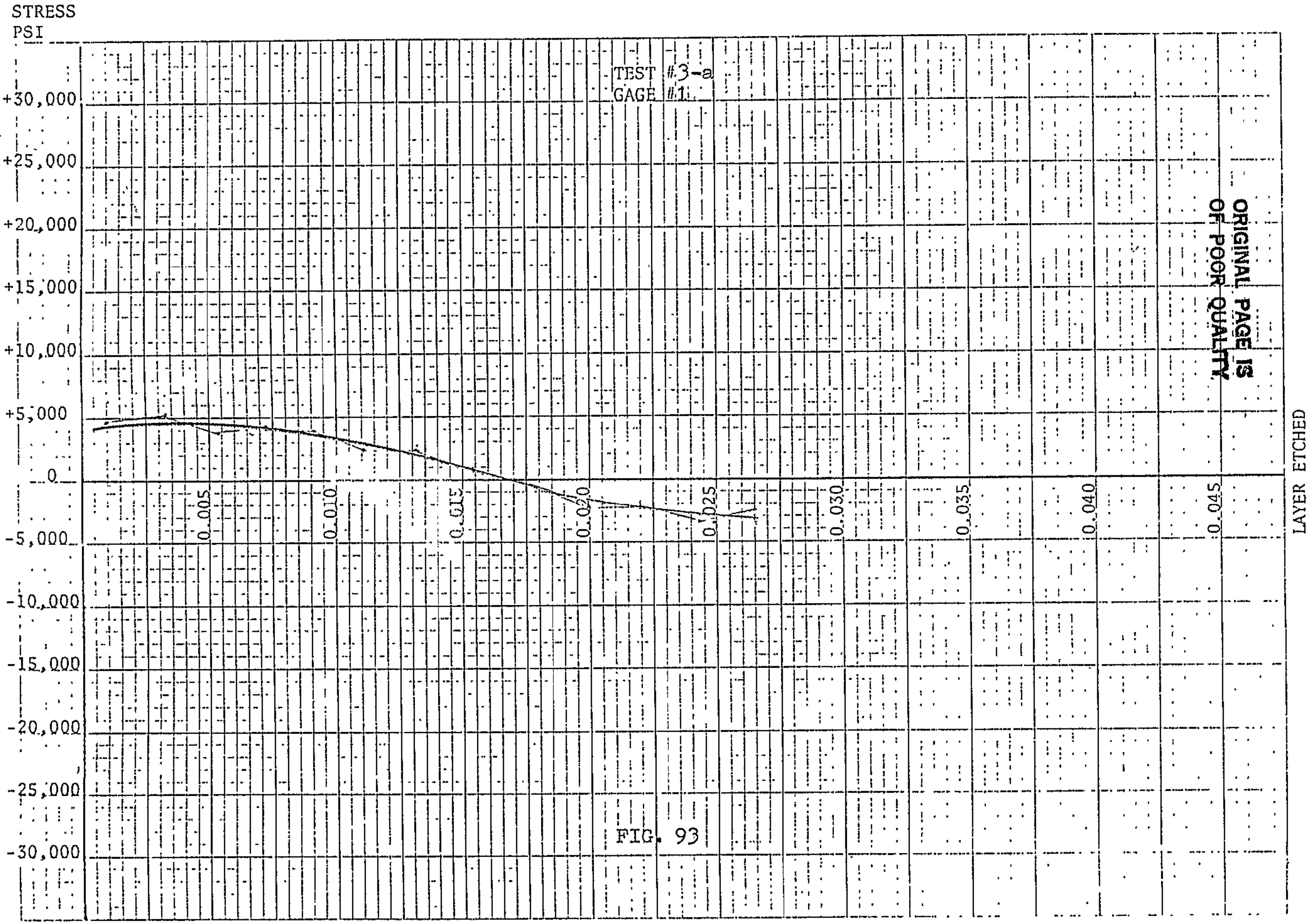


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FIG. 93

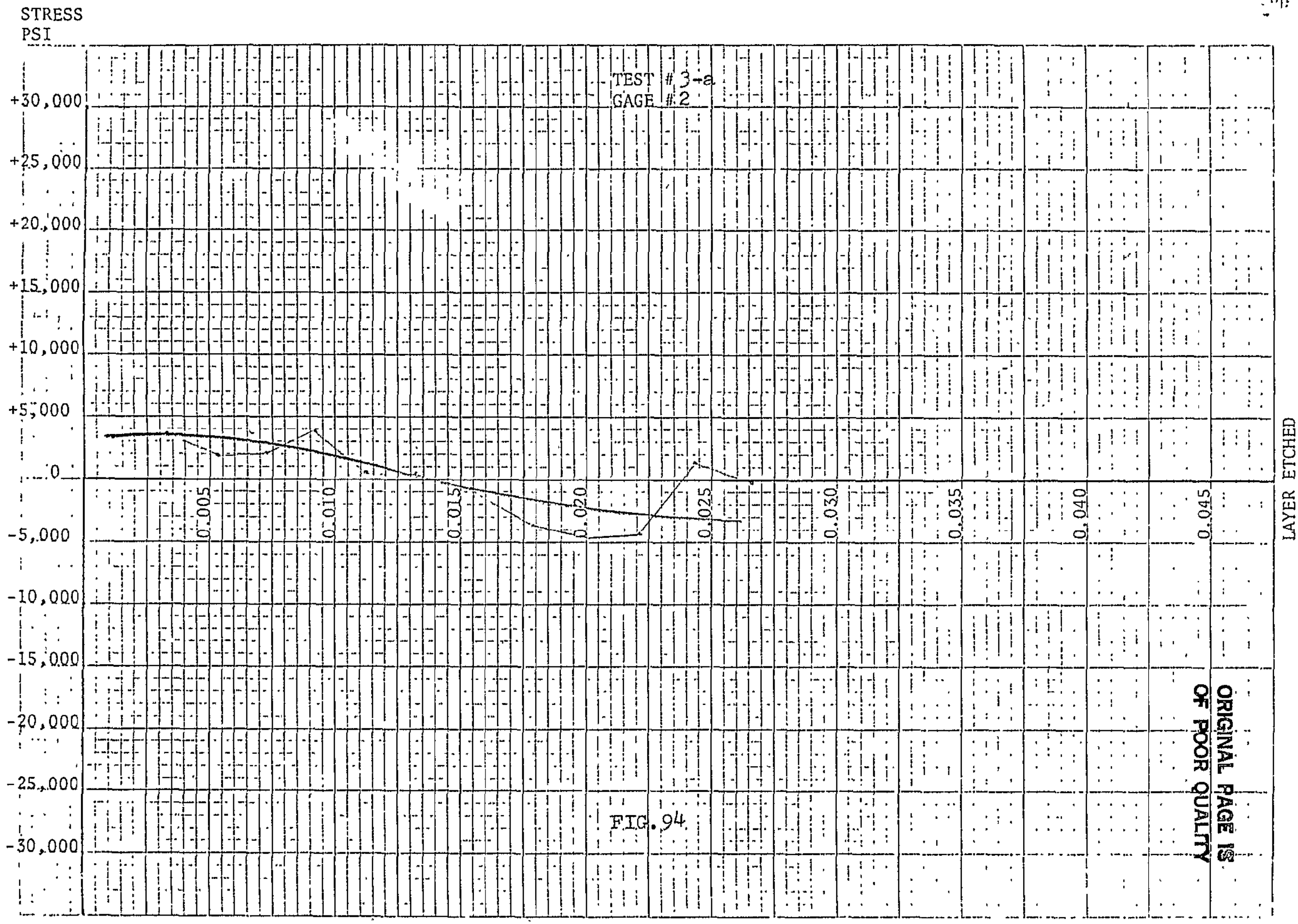

FIG. 94

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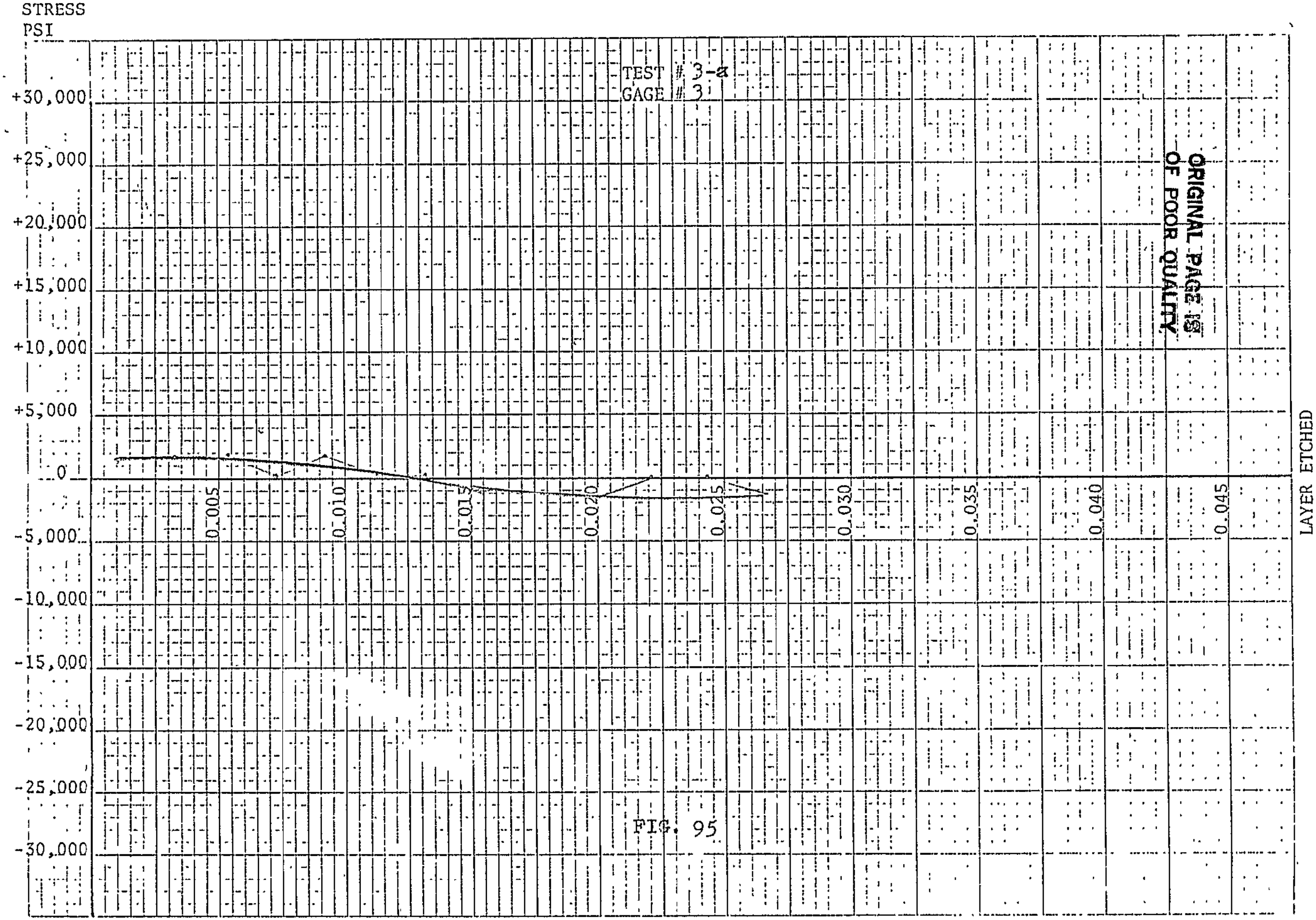

STRESS
PSI
TEST # 3-a
GAGE # 3
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 95

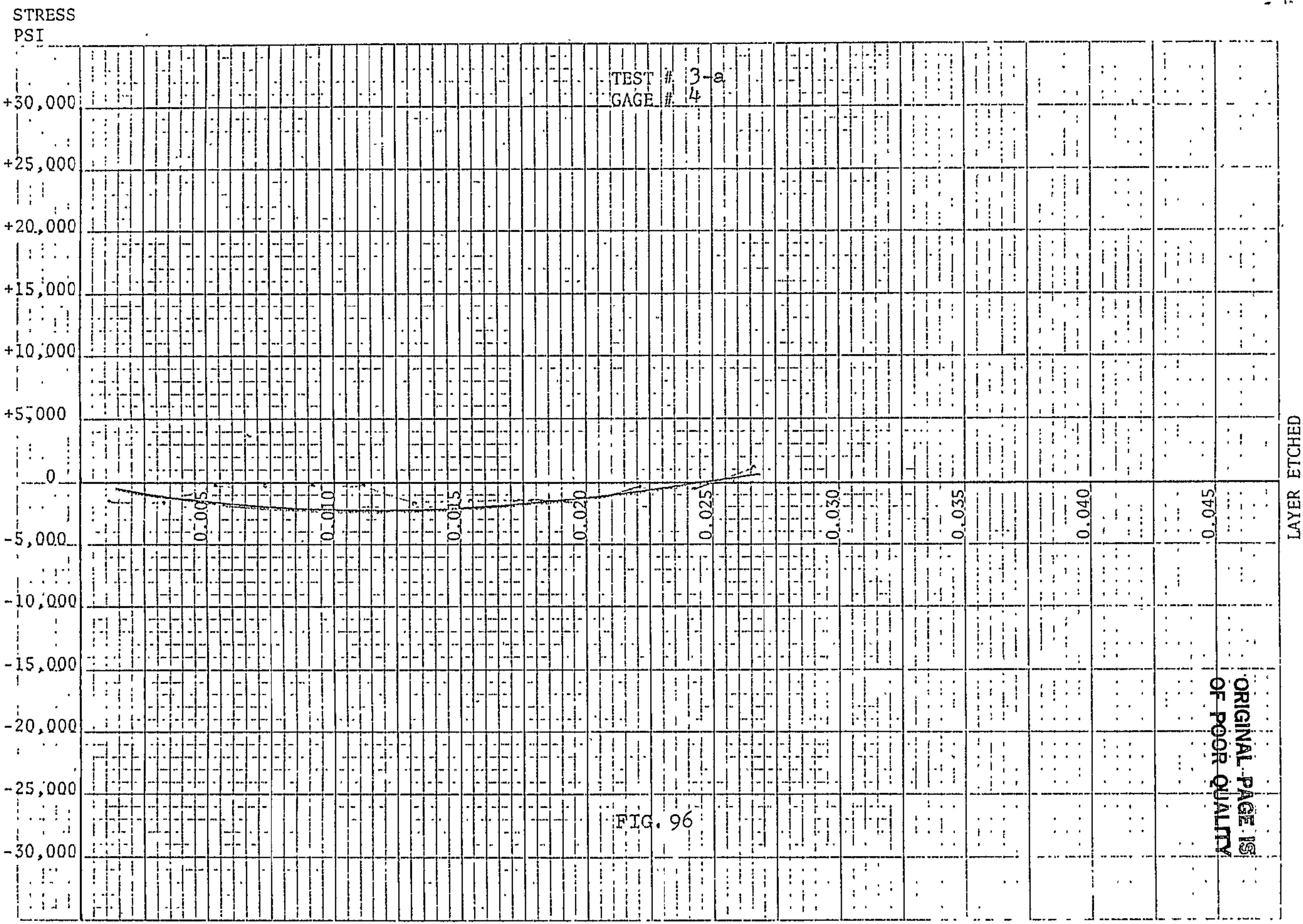

FIG. 96

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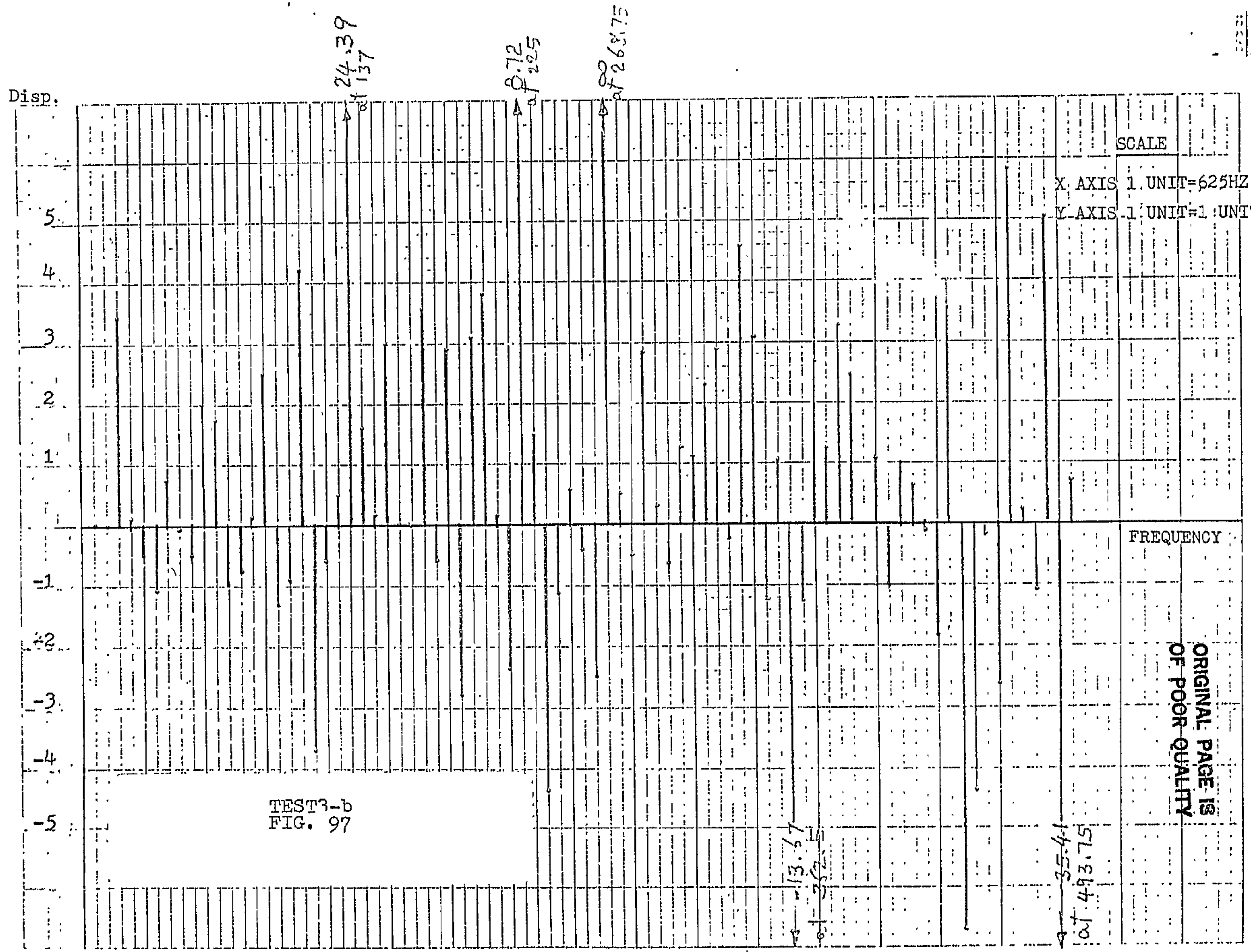

TEST3-b
FIG. 97

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ORIGINAL PAGE IS
OF POOR QUALITY

	GAGE #	1	2	3	4
LAYER	1	-1769.	-1769.	1769.	-1769.
LAYER	2	-57.	-964.	-850.	-1870.
LAYER	3	-1699.	-3399.	-3288.	-1813.
LAYER	4	-112.	-1938.	-1828.	-1937.
LAYER	5	-111.	-2069.	-1960.	-2068.
LAYER	6	-110.	-2018.	-1910.	-3701.
LAYER	7	-108.	-3726.	-1950.	-2113.
LAYER	8	-1762.	-2151.	-3644.	-2150.
LAYER	9	-1468.	-3157.	-1749.	-3155.
LAYER	10	-3029.	-3464.	-1900.	-3462.
LAYER	11	-3539.	-2362.	-2150.	-3966.
LAYER	12	1005.	-2246.	-2037.	-2302.
LAYER	13	991.	-848.	-3371.	-2268.
LAYER	14	1102.	579.	-746.	-2359.
LAYER	15	1088.	-764.	-734.	-988.

TEST 3-C
FIG. 98

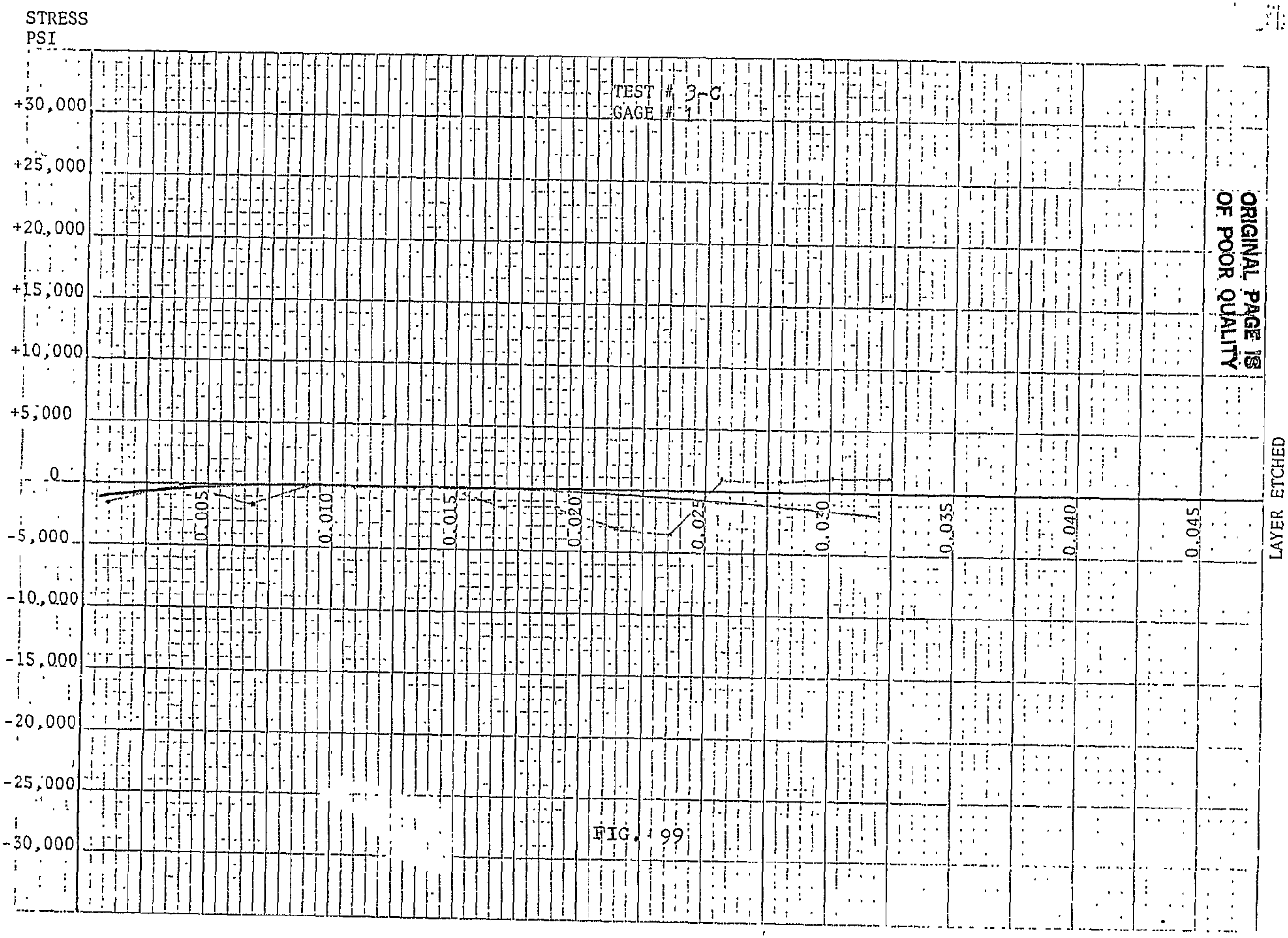

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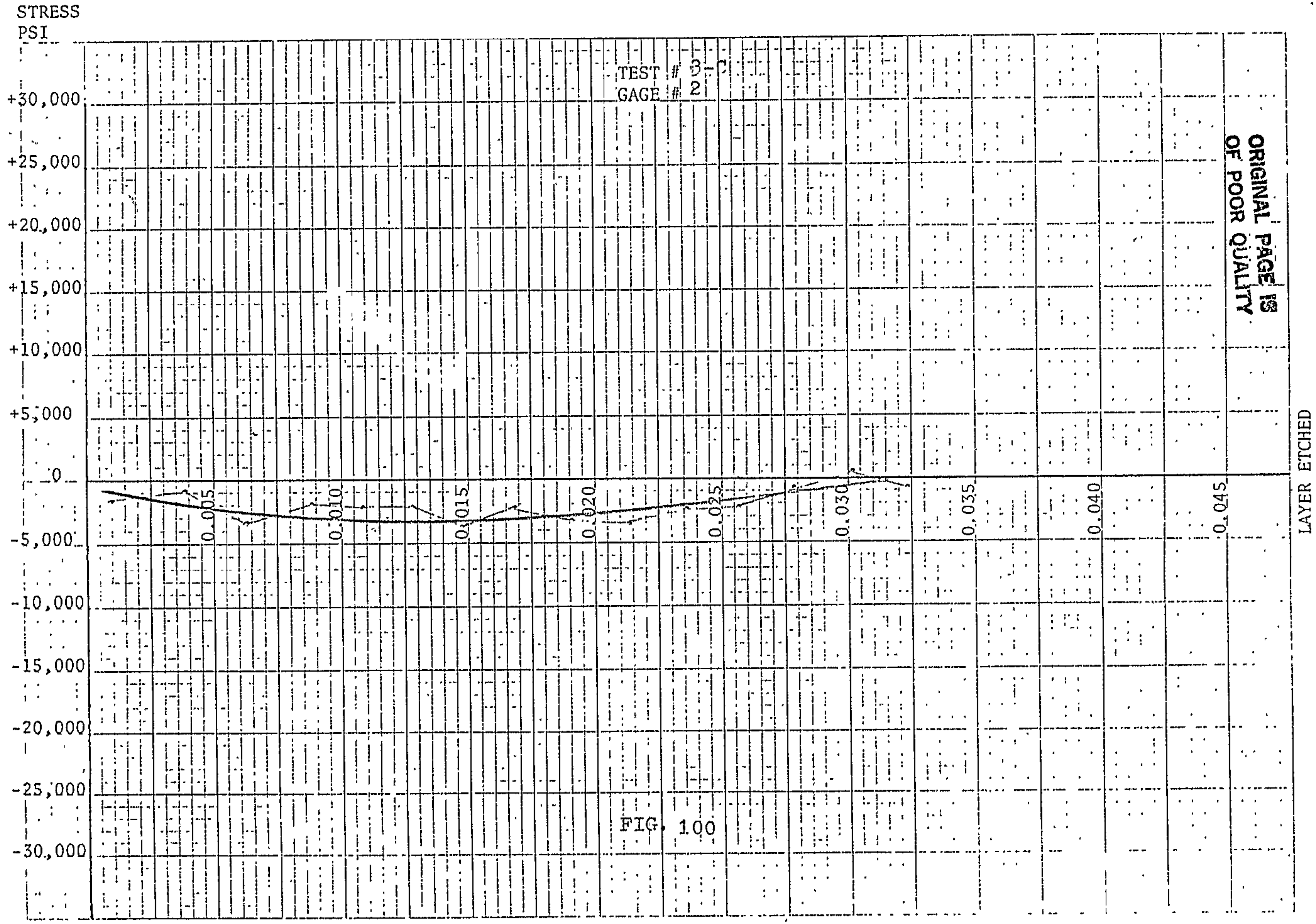
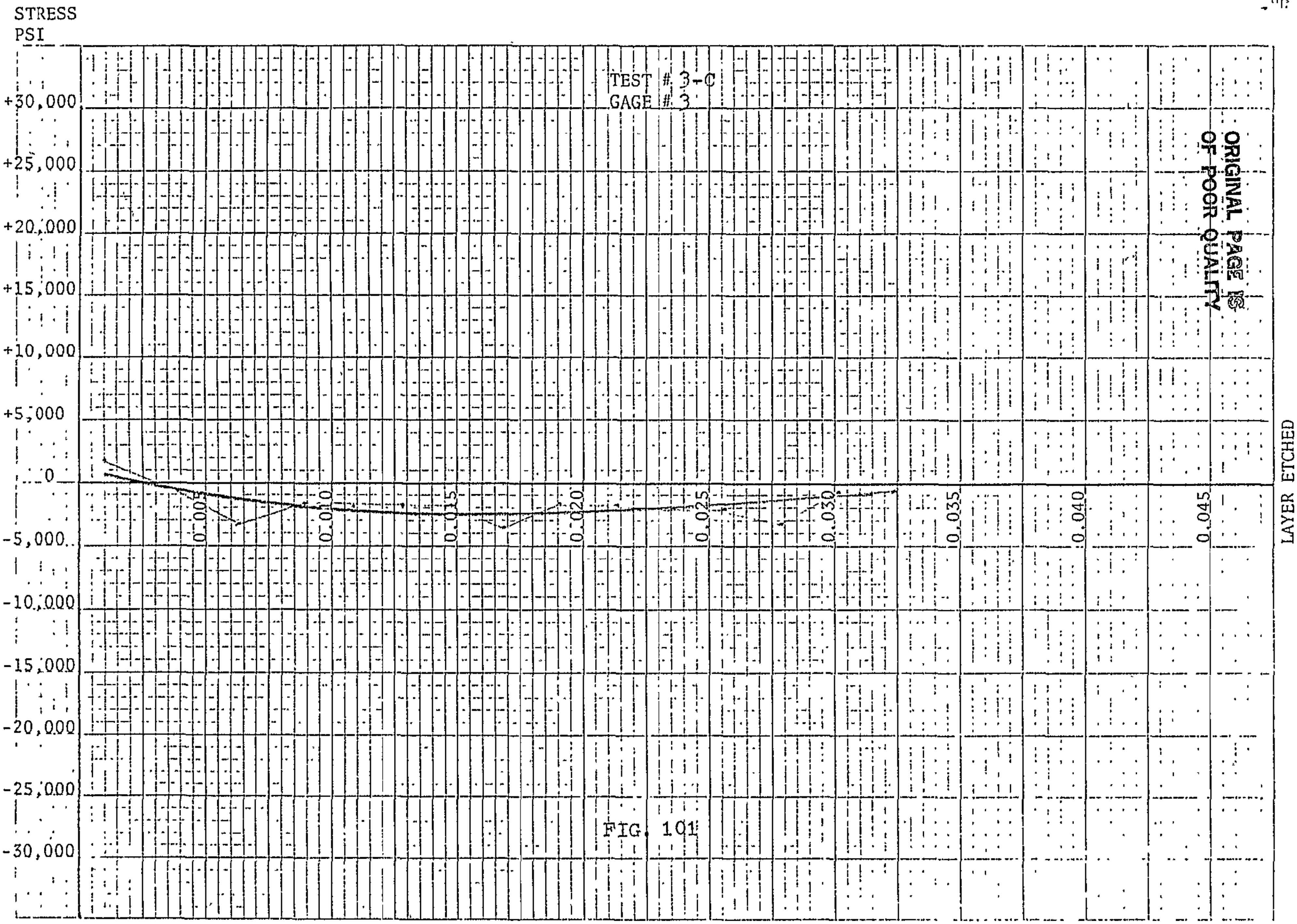
FIG. 99



ORIGINAL PAGE IS OF POOR QUALITY

FIG. 100



STRESS
PSI
TEST # 3-C
GAGE # 3
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 101

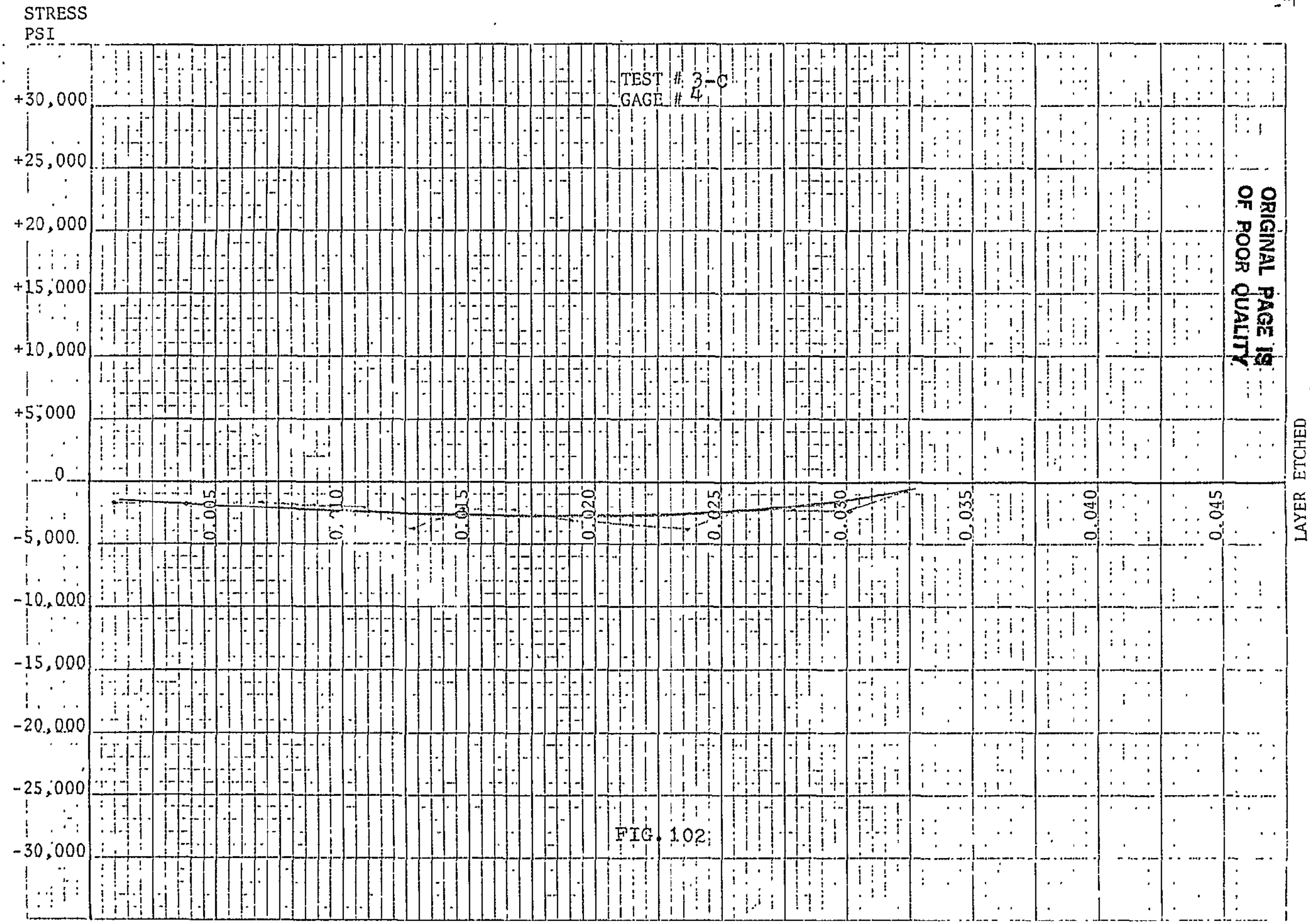

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 3-C
GAGE # 4
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 102

	GAGE #	1	2	3
AYER	1	-3594.	-2396.	
AYER	2	-2543.	-1695.	
AYER	3	-2653.	-1965.	
AYER	4	-4557.	-3976.	
AYER	5	-2841.	-3629.	
AYER	6	-2347.	-3972.	
AYER	7	-2937.	-3808.	
AYER	8	-3574.	-4705.	
AYER	9	-3841.	-4634.	
AYER	10	-2841.	-2429.	
AYER	11	-2149.	-259.	

TEST 4
FIG. 103

FIG. 104

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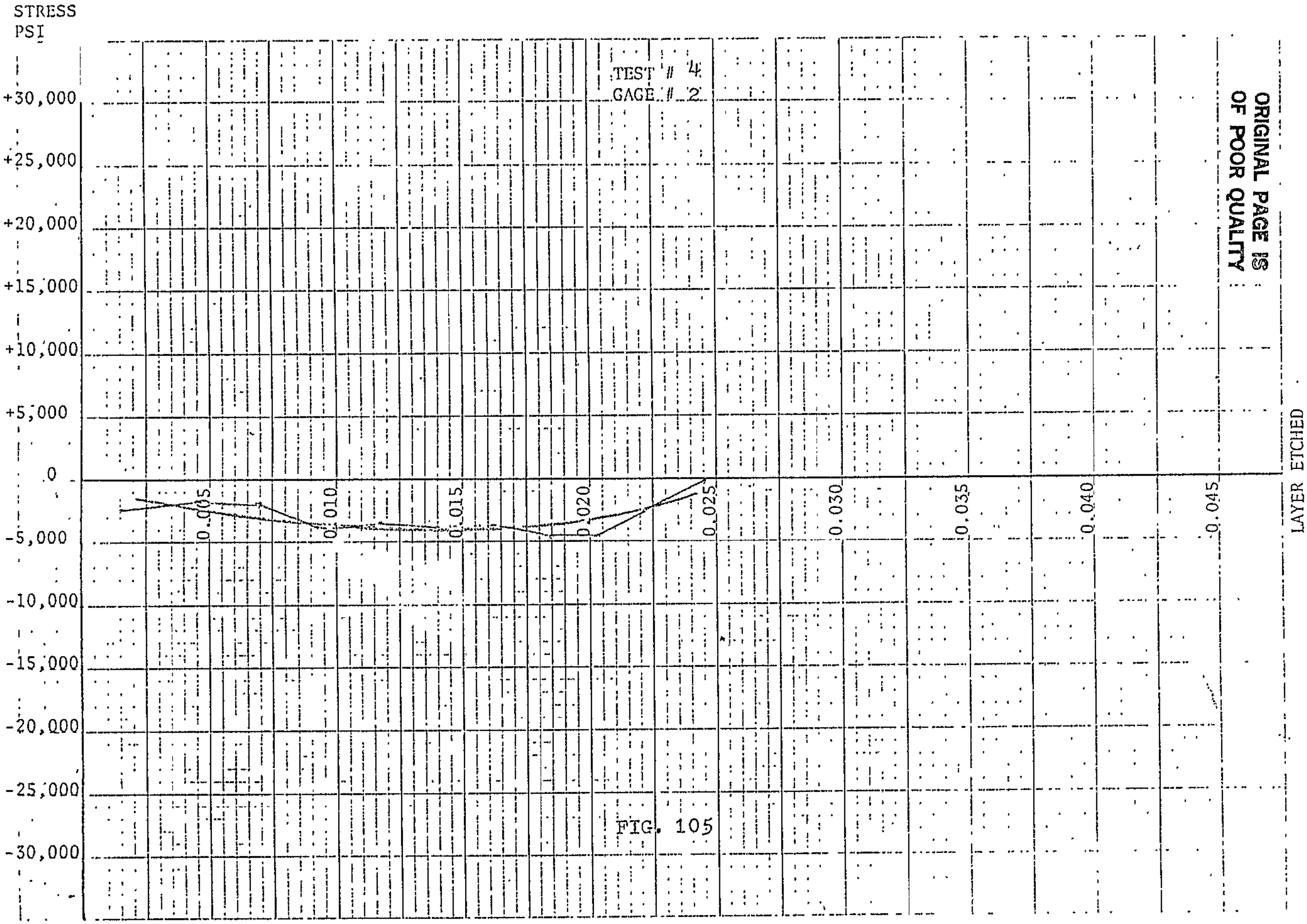

FIG. 105

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	GAGE #	1	2	3	4	5
AYER	1	-3355.	-2982.	-3728.	2982.	2982.
AYER	2	-4501.	-5022.	-6683.	4482.	5022.
AYER	3	-9001.	-7918.	-12350.	4648.	6835.
AYER	4	-4713.	-6383.	-9939.	5459.	7208.
AYER	5	-582.	-3728.	1376.	5416.	5067.
AYER	6	6570.	-3479.	3102.	8407.	7385.
AYER	7	8742.	-4937.	5162.	10858.	10894.
AYER	8	4413.	-3160.	2175.	4957.	4617.
AYER	9	7438.	-4988.	6320.	7347.	7362.
AYER	10	11607.	-5806.	9262.	10916.	9058.
AYER	11	10411.	-5134.	6635.	6310.	6939.
AYER	12	9258.	-4451.	6045.	5509.	5505.
AYER	13	11451.	-5518.	7343.	7433.	6745.
AYER	14	10507.	-4527.	6115.	5709.	5685.
AYER	15	10114.	-3984.	6239.	5771.	6942.

TEST 5-a

FIG. 106

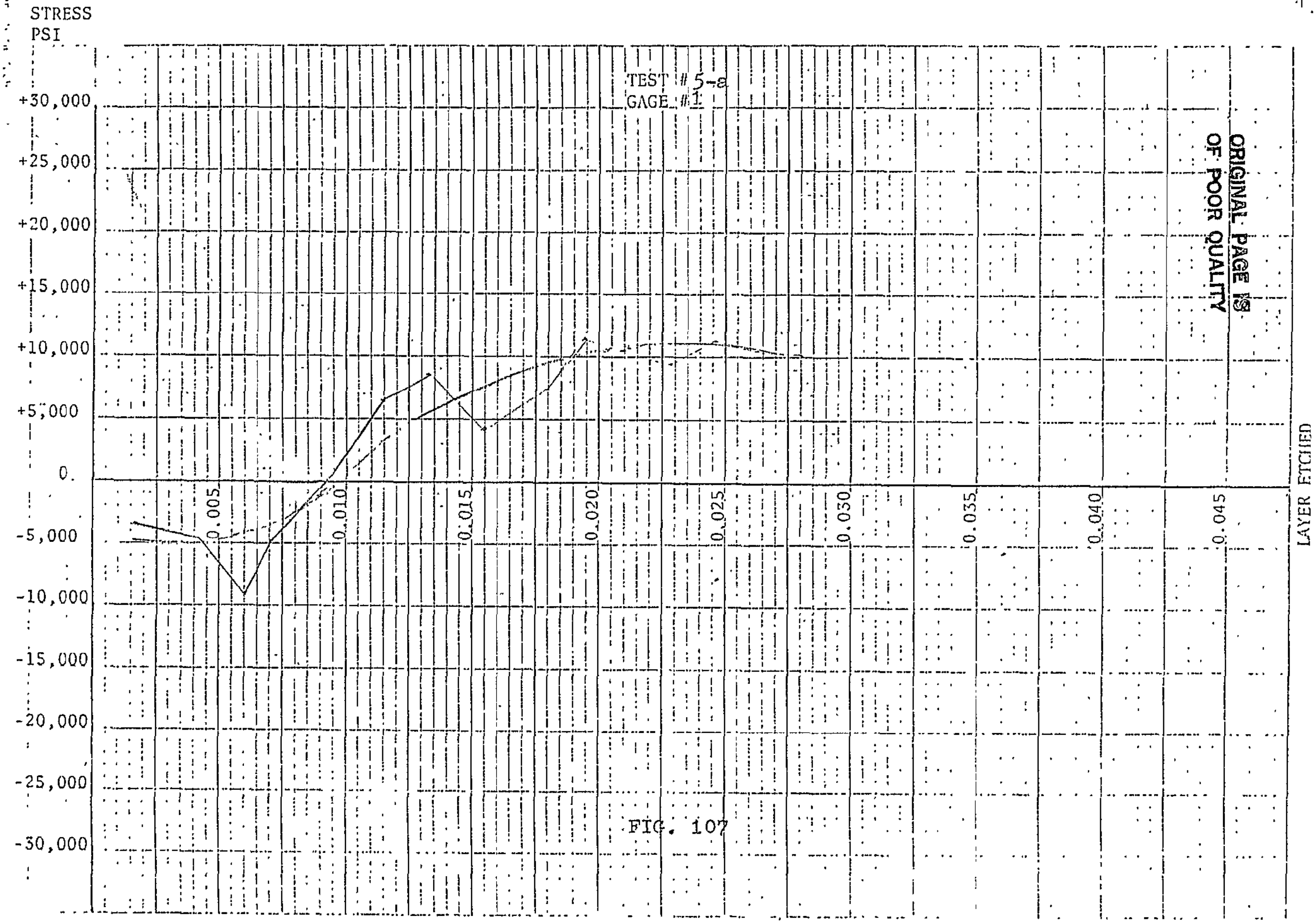

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FIG. 107

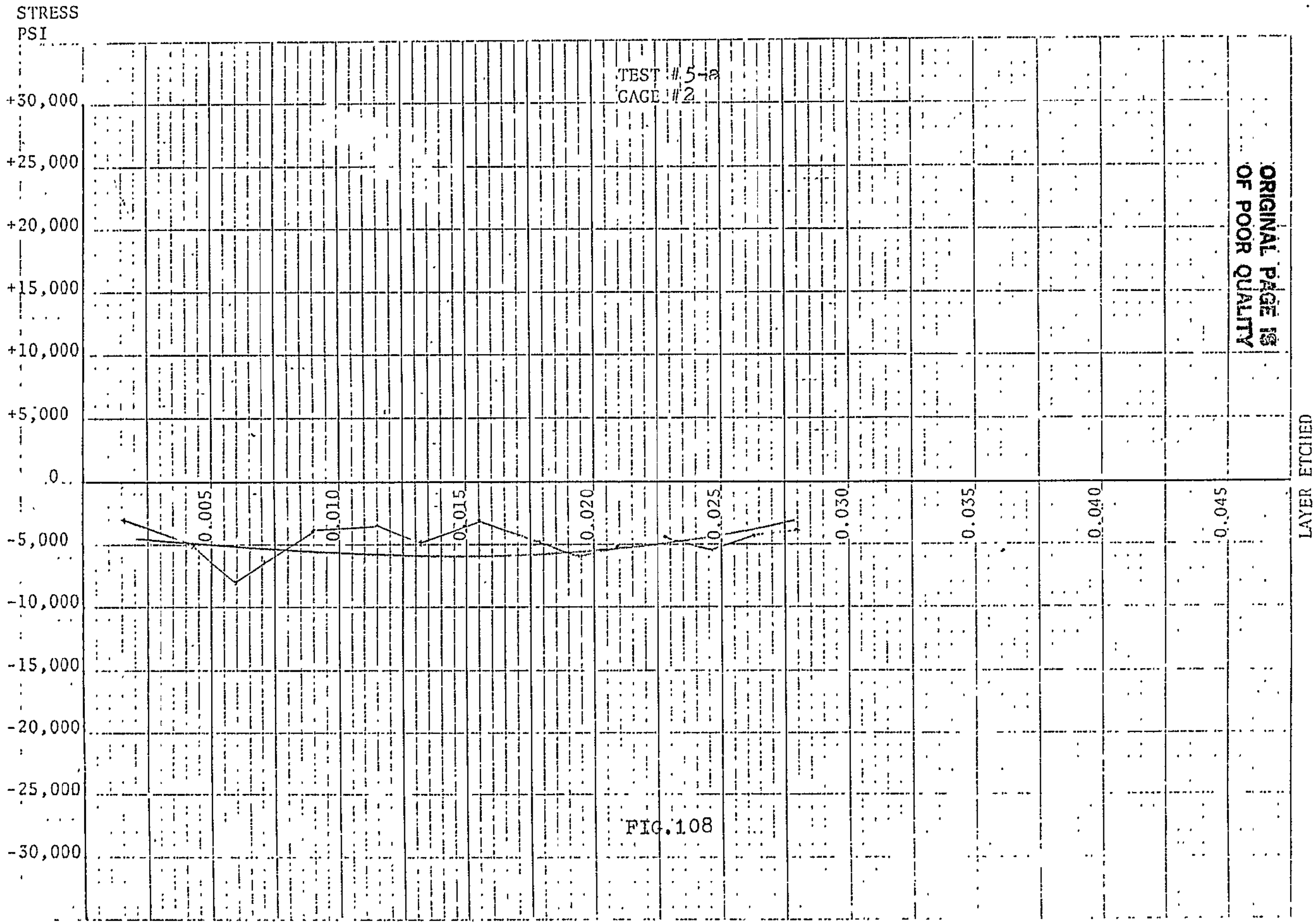

FIG. 108

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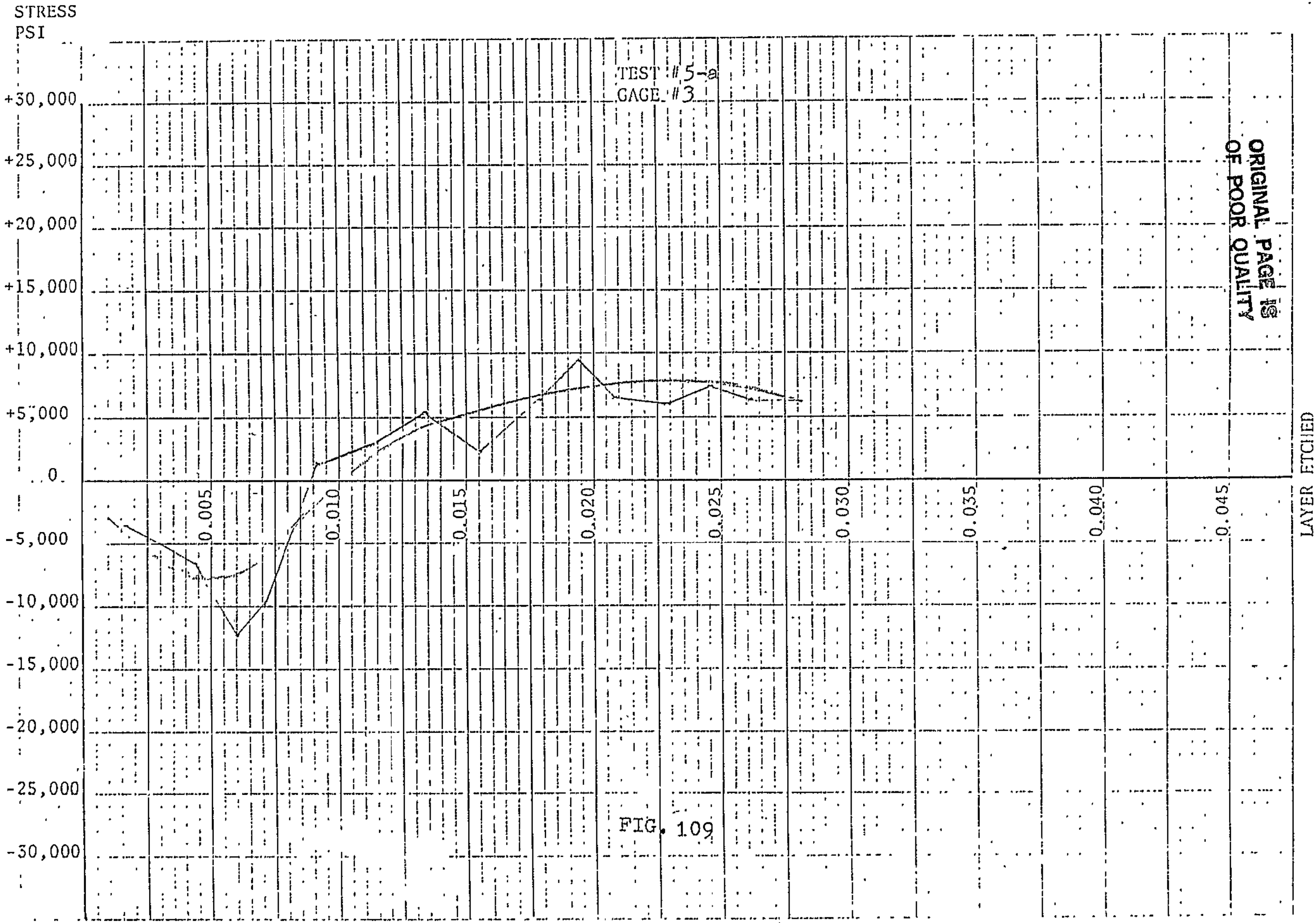

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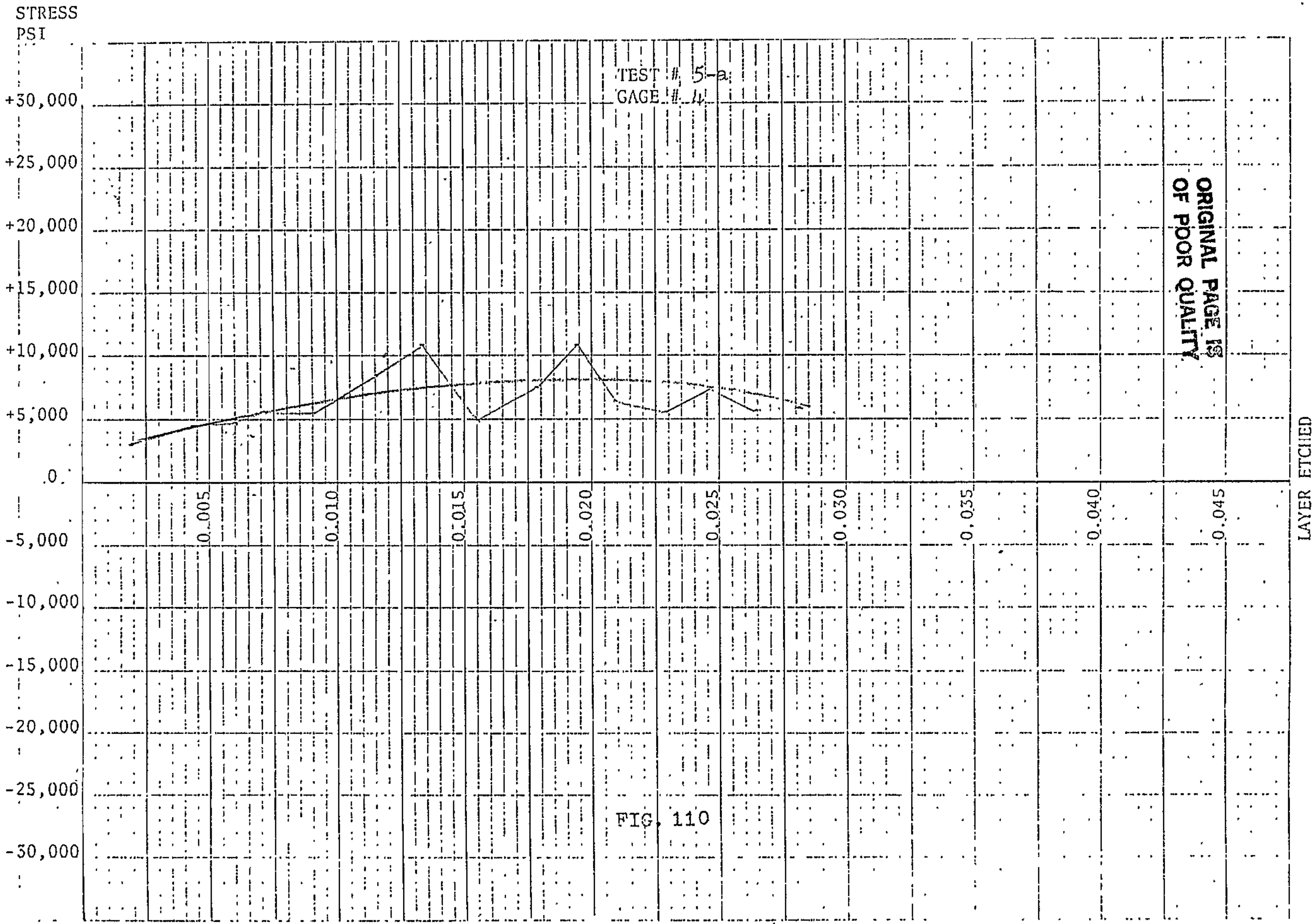
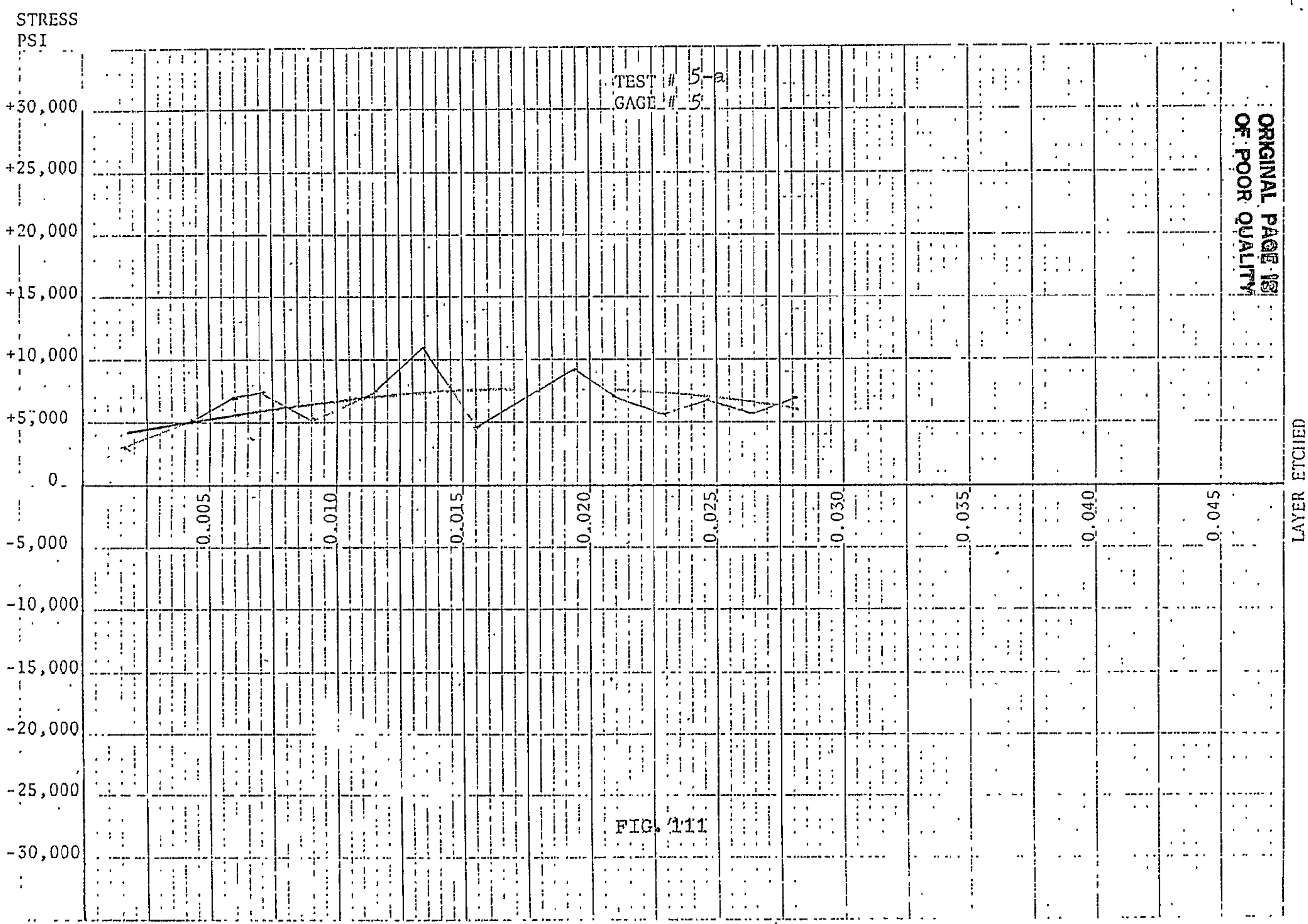
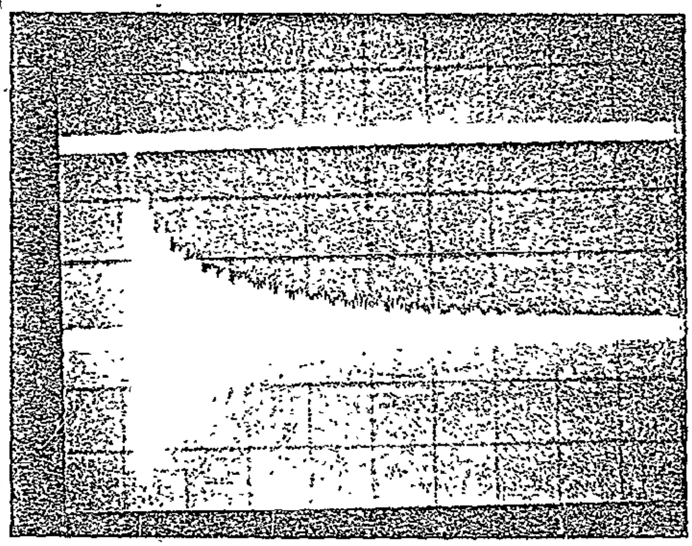
FIG. 109


STRESS PSI
TEST # 5-a
GAGE # 4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
ORIGINAL PAGE IS OF POOR QUALITY
FIG. 110



STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 5-a
GAGE # 5
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 111



TEST 5-b

FIG. 112

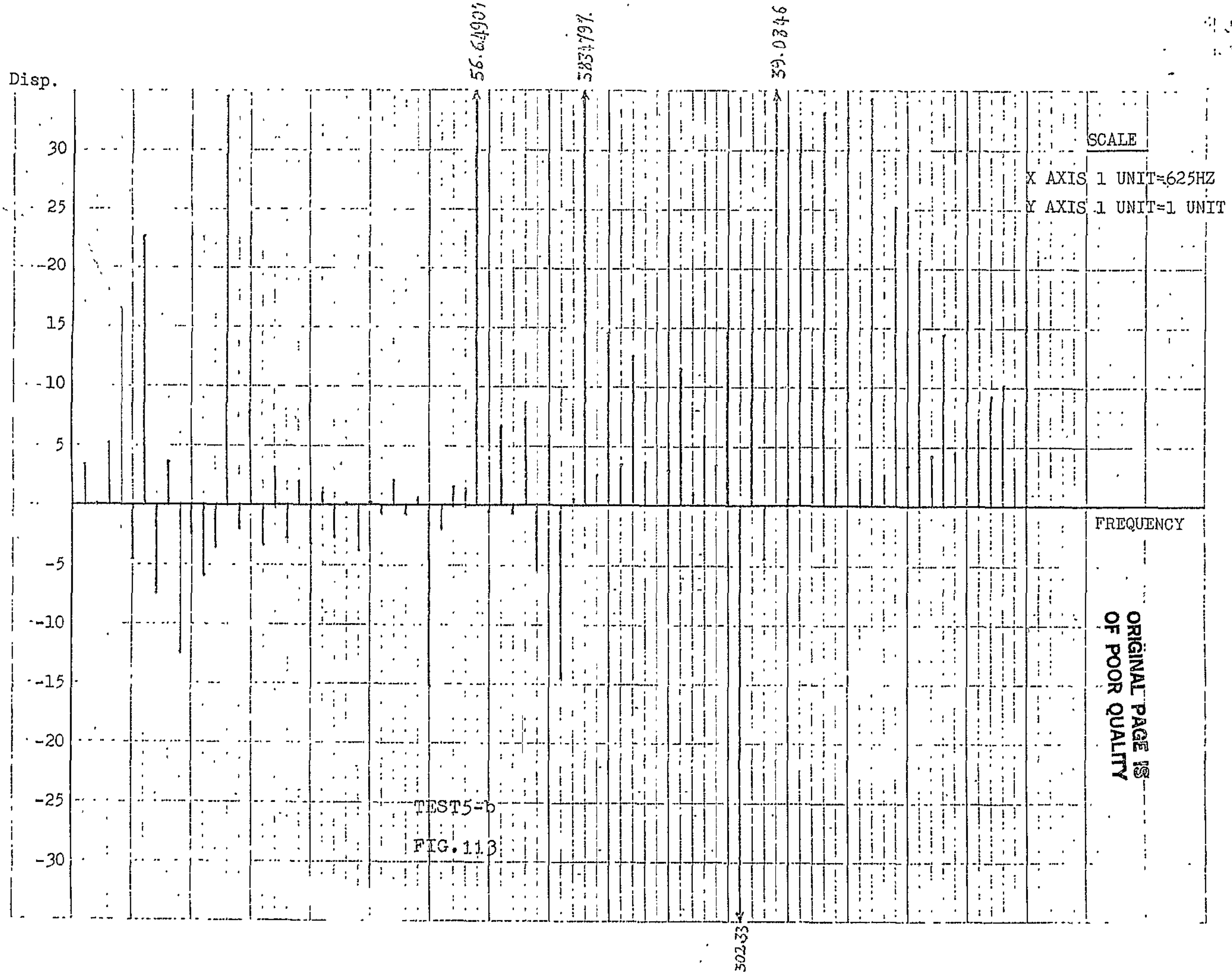


FIG. 113

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OF POOR QUALITY

	GAGE #	1	2	3	4
AYER	1	-2085.	-2607.	-2085.	1043.
AYER	2	-3504.	-4380.	-3504.	2608.
AYER	3	-2254.	-2293.	-2953.	99.
AYER	4	-1281.	-1320.	-3434.	-1502.
AYER	5	-5667.	-5706.	-3961.	-5378.
AYER	6	-2290.	-2328.	-2828.	-3446.
AYER	7	-2521.	-2558.	-2597.	-2818.
AYER	8	-5055.	-4524.	-3428.	-3153.
AYER	9	-7644.	-7661.	-5043.	-5643.
AYER	10	-3694.	-3710.	-2416.	-2990.
AYER	11	-6506.	-6522.	-4019.	-3813.
AYER	12	-6600.	-5827.	-8019.	-7815.
AYER	13	-5708.	-5060.	-6232.	-6031.
AYER	14	-4268.	-4735.	-5151.	-4953.
AYER	15	-4636.	-4096.	-5650.	-5454.

TEST 5-C
FIG.114

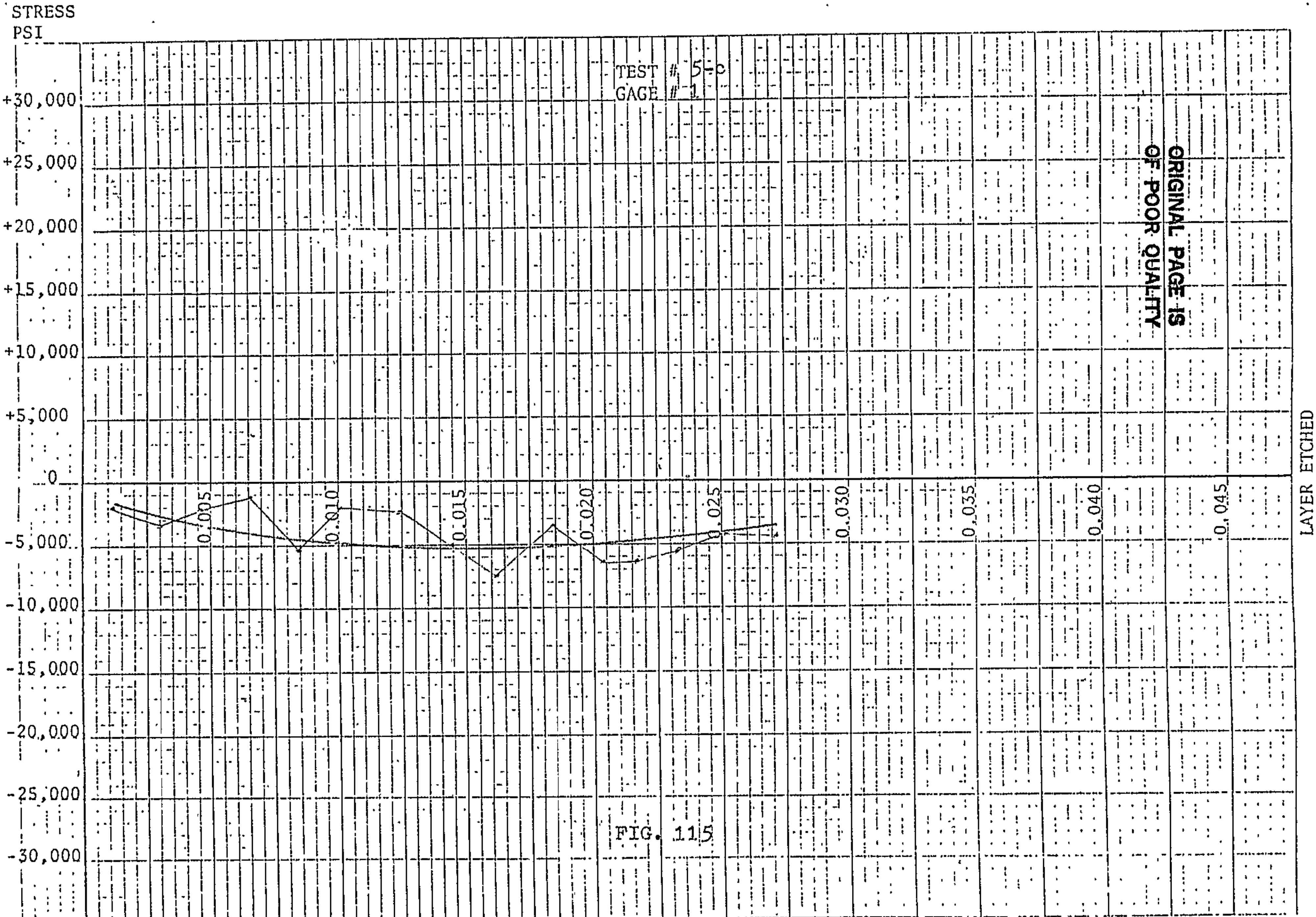

FIG. 115

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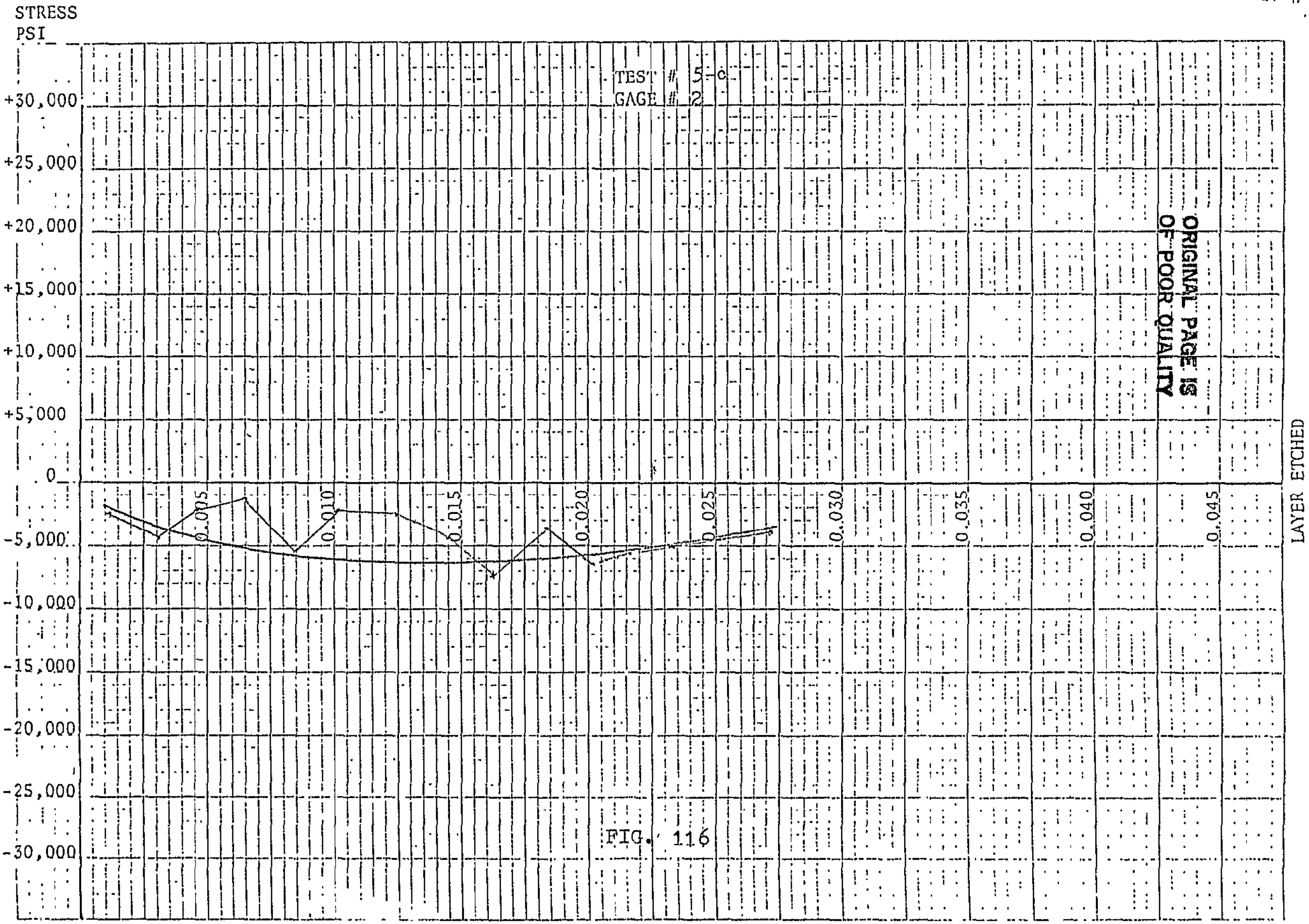
OF POOR QUALITY



STRESS
PSI
TEST # 5-c
GAGE # 2
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
ORIGINAL PAGE IS OF POOR QUALITY

FIG. 116

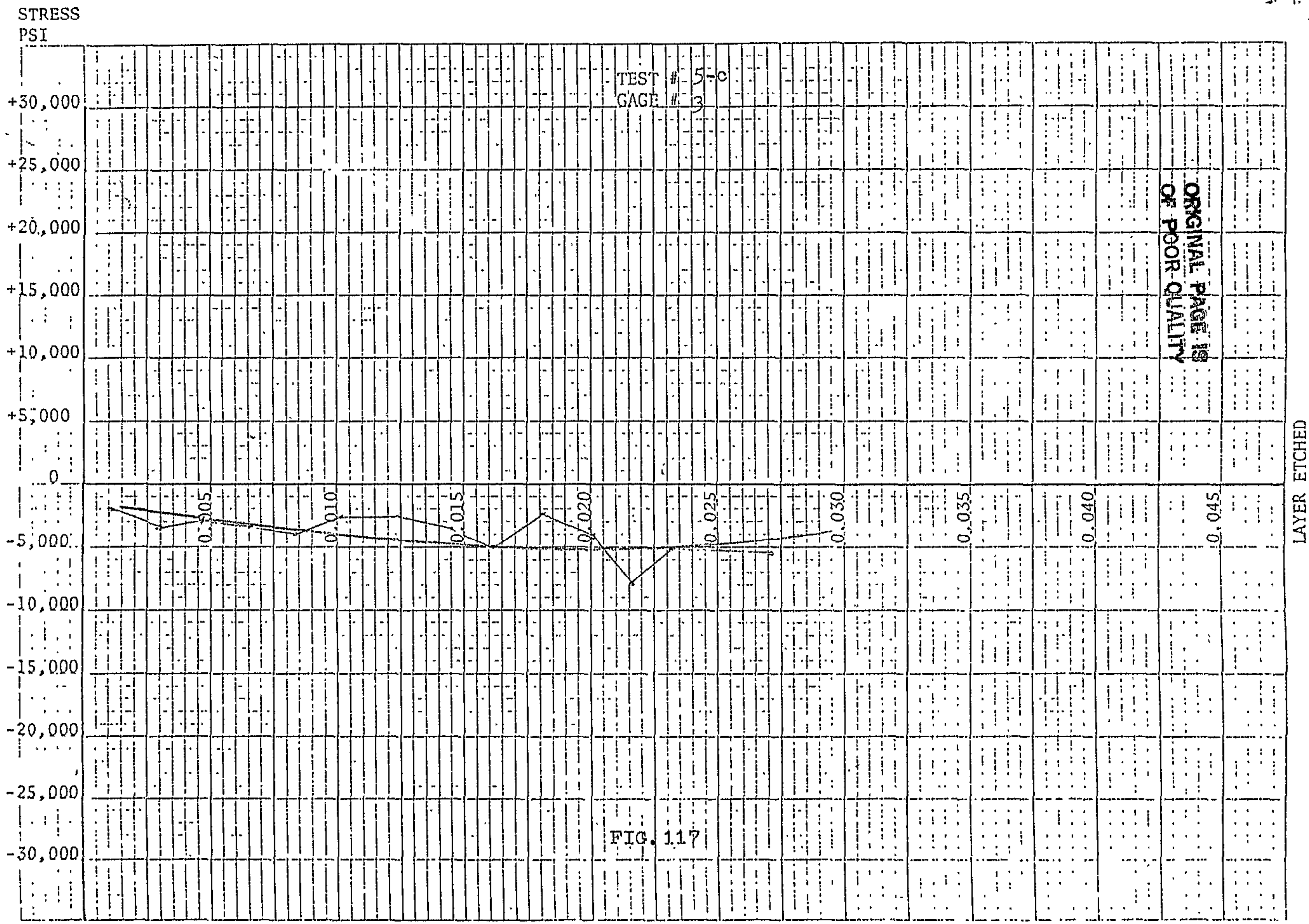


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FIG. 117

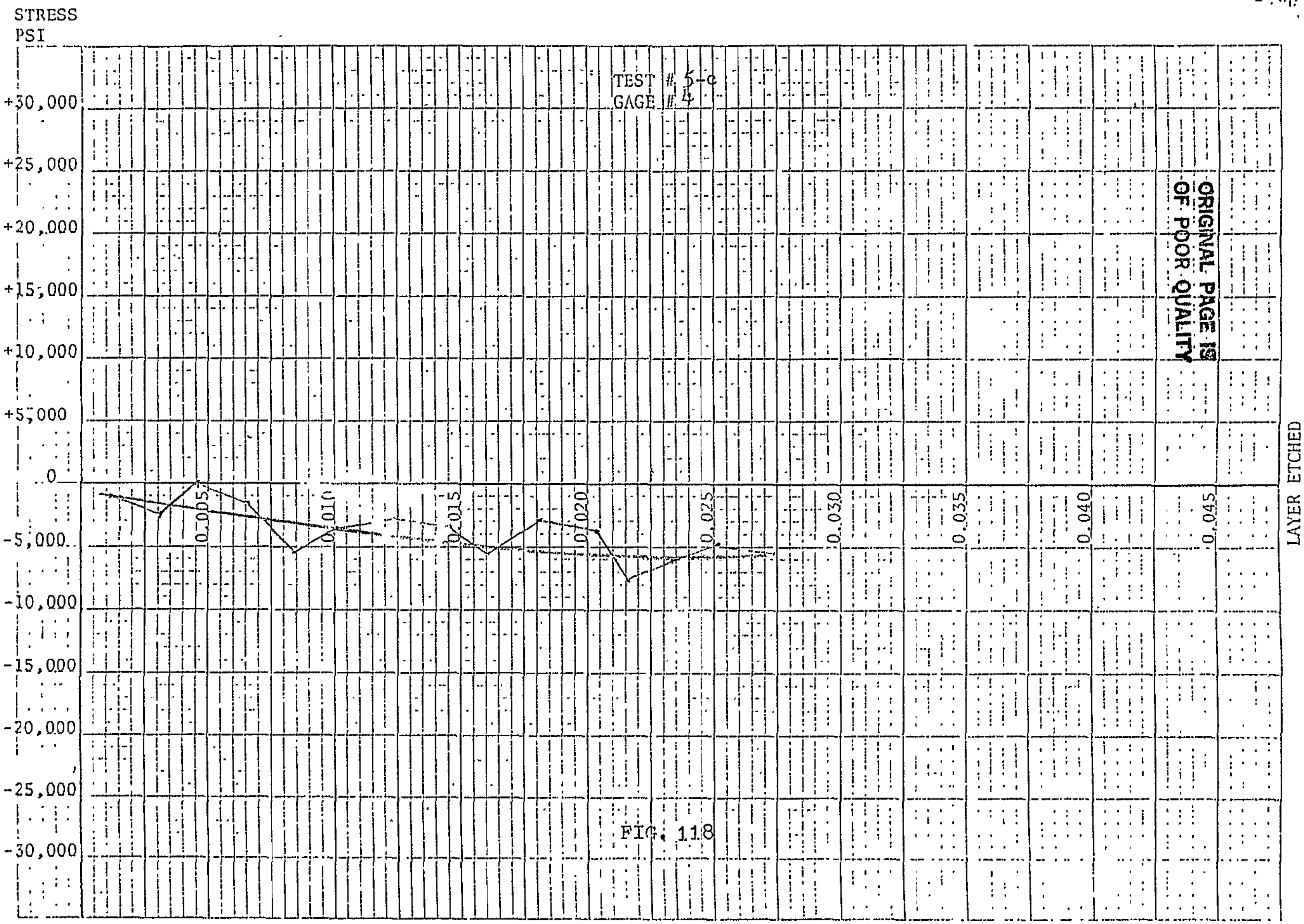

FIG. 118

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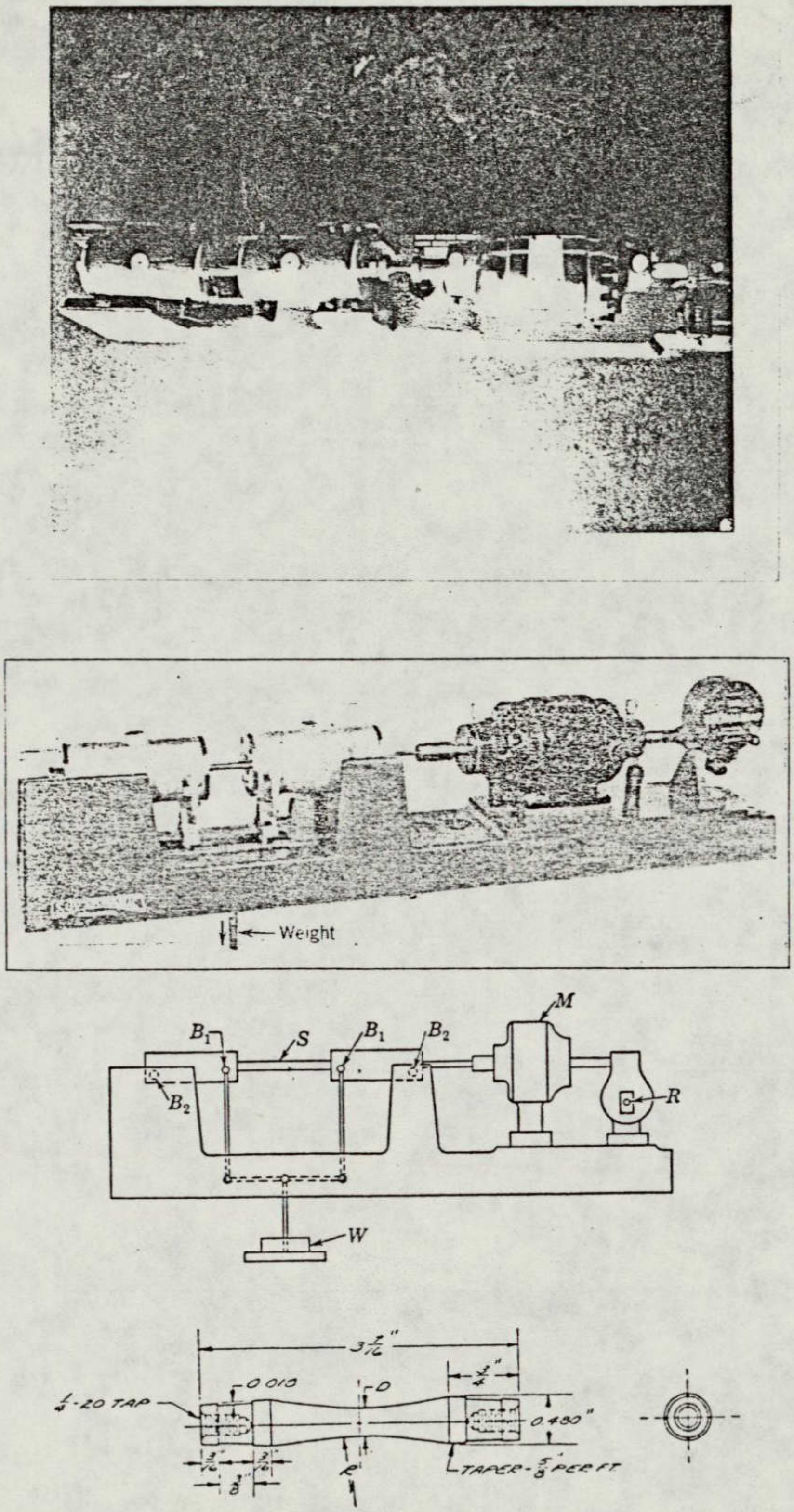
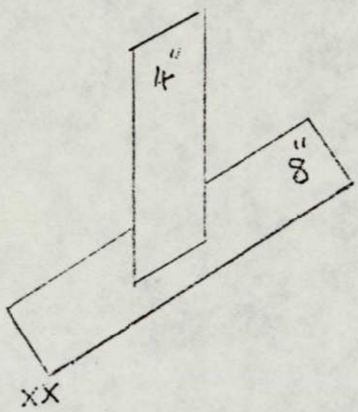


FIG. 119

Fatigue Testing Machine And Specimen

X400
As Received



X600
As Received

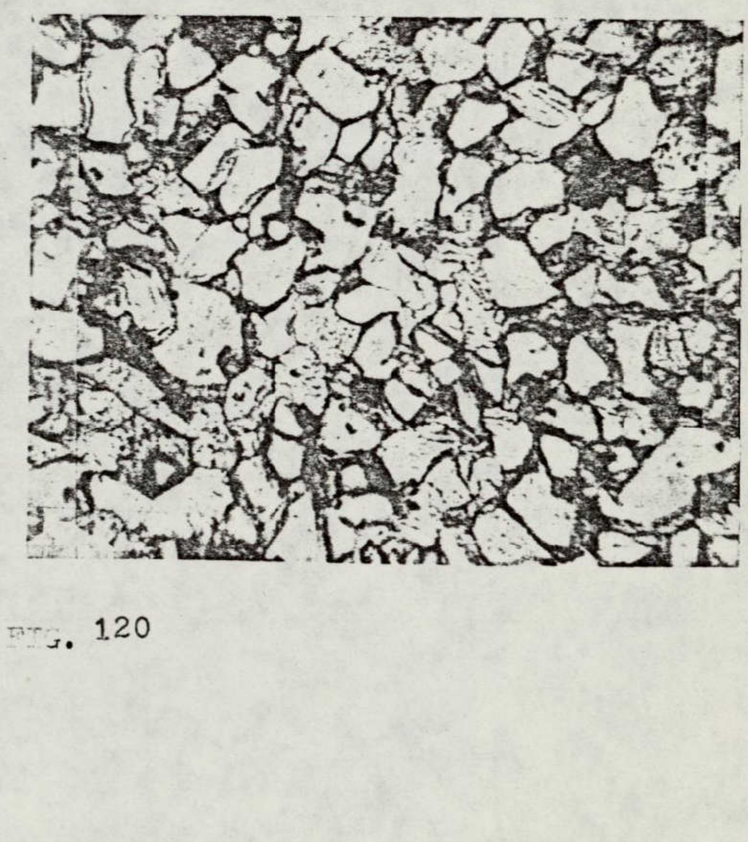
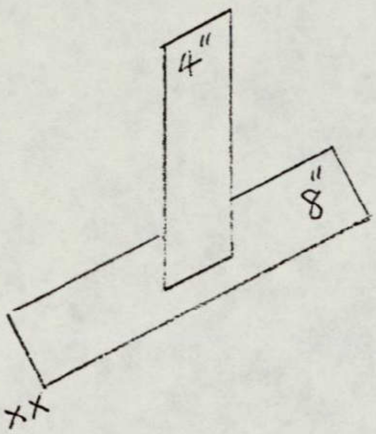


FIG. 120

X400
Vibrated



X600
Vibrated

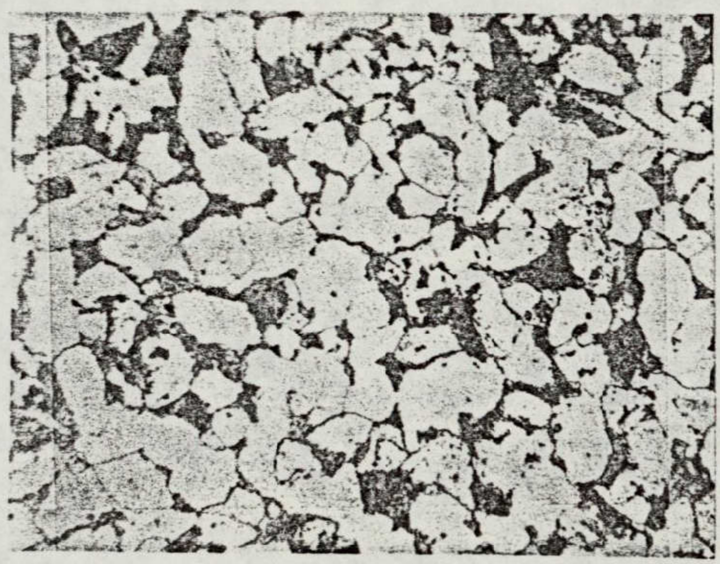
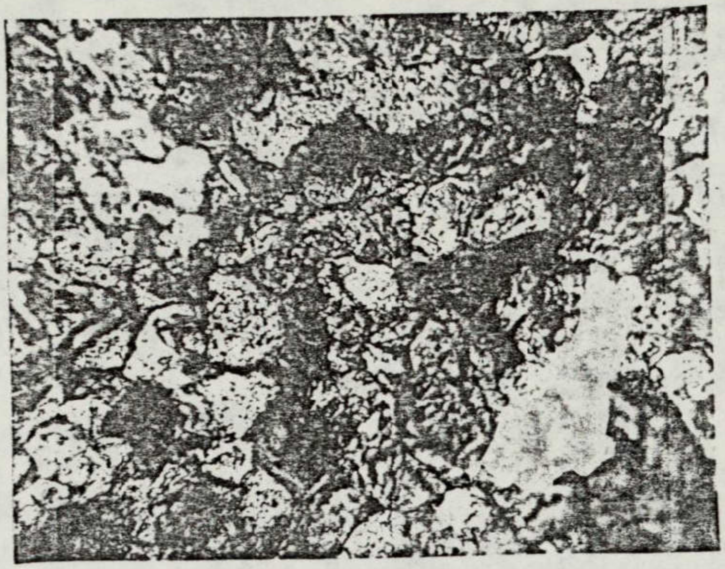
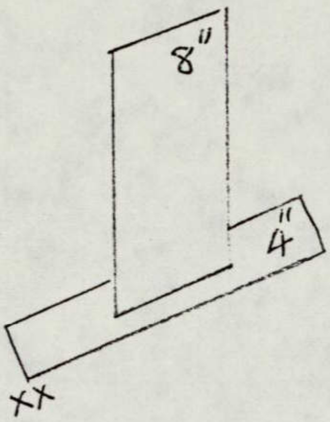


FIG. 121

X400
As Received





X400
Vibrated

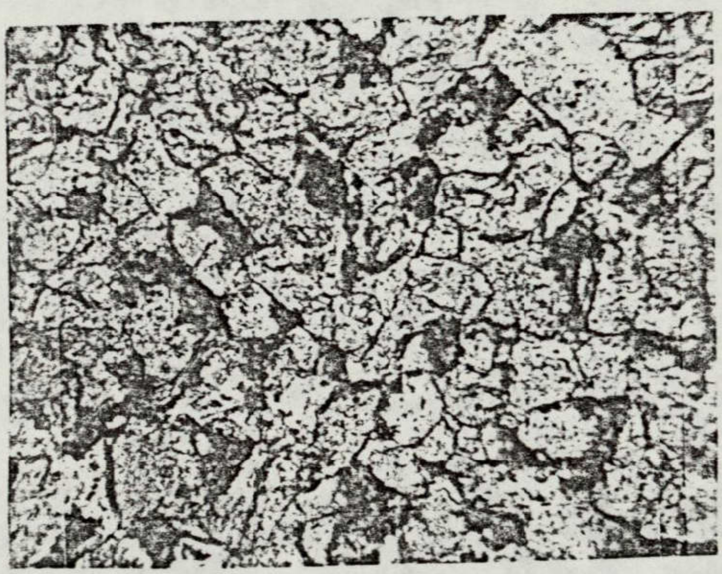
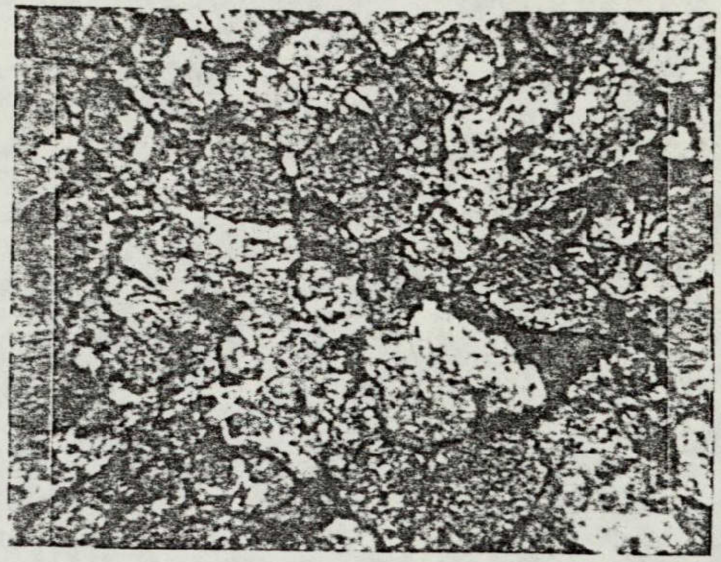
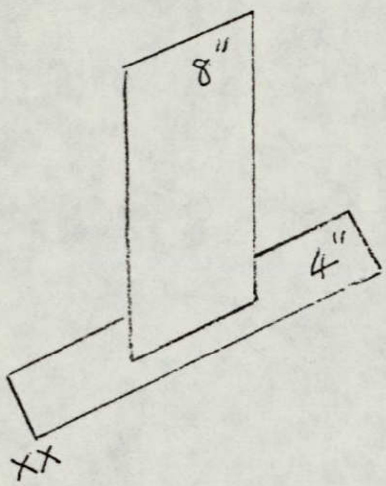


FIG. 122

X600
As Received





X600
Vibrated

FIG. 123

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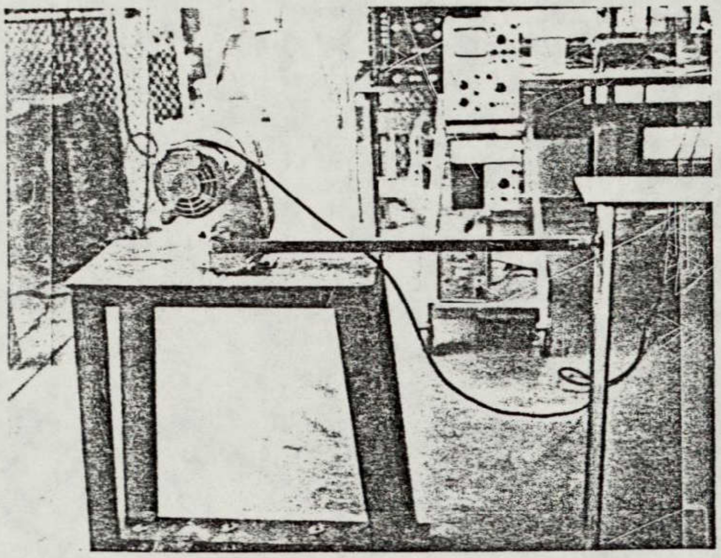


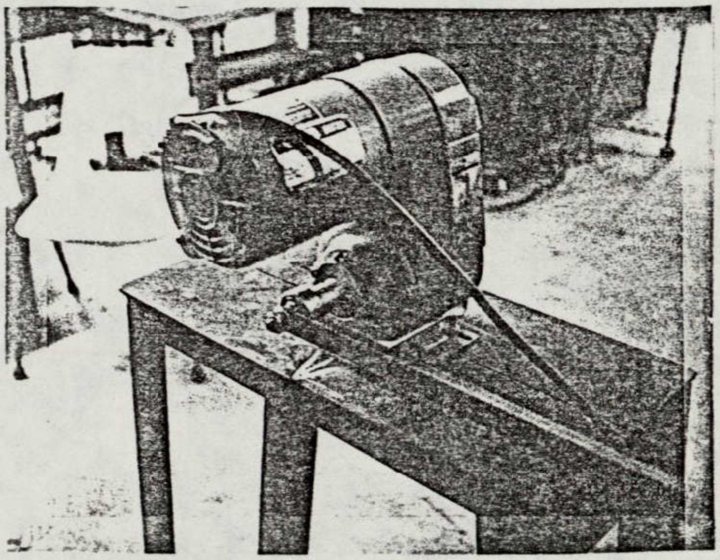


FIG. 124

Variable Speed Electric Motor
With Eccentric For Vibrations

PART FIVE

Summary of current investigations

The research project has examined the effectiveness of vibration in reducing residual stresses from welding various shapes of A36 steel structures(L-shape connections). It is currently investigating such patterns in welded 6061T6 aluminum, that had been cold extruded.

High tensile stresses of about 25,000 to 30,000 psi were found at the weld surface of the steel bars which dropped rapidly to compressive stresses in the range of 3,000 to 5,000 psi that spread for some depth through the bar thickness. A cross connection between the bars(T connections) helped to reduce the stresses and the results showed maximum surface stresses of about 5,000 psi only. It was noticed also that when the frame was an open structure, the peaks of the stresses were lower than when the frame was restricted and had a closed shape.

Patterns of stresses at a short distance from the weld were reversed, showing high compressive stresses at the outer layers, but to a lesser degree than those found at the weld.

A load cell and an accelerometer were used to generate an impulse in the steel frame and analyze the response picked on the screen of an oscilloscope. A vibration frequency within the range of 100 cps was chosen to generate a peak displacement.

Such a limited frequency was chosen to reduce the damage to the steel by fatigue, due to vibration. A set of computer programs was designed for choosing the appropriate frequency.

Results showed that the most effective pulse varied between 50 and 80 cps.

Originally the steel structures were vibrated using an MB model C10 mechanical vibrator with attached panel to control the frequency to the required cps. Later a variable speed motor with eccentric load was used and connected to the metallic frame. The motor speed could be adjusted to generate vibrations at the specified frequency. This new approach was to investigate the possibility of vibrating the metallic frames in the field. The pulse was recorded on the screen of a portable oscilloscope and analyzed using the same computer programs developed previously.

Fatigue testing of specimens prepared from the sides of the welded steel boxes were essential particularly for welded steel structures exposed to dynamic loading. Results showed a life span of a fatigue limit of 30,000 psi. The specimens for these tests were machined locally for both the non-vibrated and the vibrated metal boxes. They were tested using a classical rotating beam constant load fatigue testing machine, where the specimen was mounted between two rotating spindles and stresses were continuously reversed. This investigation needs to be continued and a more advanced testing machine MTS-Type810 that our department has purchased recently will be used. It is also planned to widen the study and examine the effect of higher vibrations on the fatigue life of the steel and establish a relationship between the magnitude of the vibration and the fatigue life of the metal.

The second phase of the project which started few months ago deals with the above mentioned aluminum which is being used on a large scale in the aerospace industry. While the stress distribution for the steel was studied by etching the metal in diluted nitric acid solution, the aluminum is being etched using caustic soda solution. Both techniques were used before studying the distribution of residual stresses in tubes and plates[22,24&25]. The study used the same equipment used for steel including electric strain gages, strain indicator and resistance box and similar computer programs modified to suit the aluminum.

Preliminary studies showed that the as received (cold extruded) aluminum bars were exposed to some residual stresses of about 3 to $4x10^3$ psi which were mostly developed due to the straightening process following the extrusion and treatment of the bars. The few tests carried out so far showed peak residual stresses of about 8 to $10x10^3$ psi that appeared at a certain depth from the outer surface at the weld. This may be due to the higher conductivity of aluminum to the heat of welding as compared to the mild steel and such a behavior may reduce the risk of surface cracks. Such studies are still in their first stage and the conclusions cannot be final.

Future Work Plan

To continue the investigations on aluminum structures.

To expand the fatigue testing analysis for both the steel and aluminum, using the new testing machine MTS-Type 810.

In order to support the findings of the patterns of stress distributions, it is necessary to continue the study by measuring temperature distribution that takes place while welding and to correlate the patterns of both the stress and temperature. Thermoelectric technique using thermocouple wires of 0.0005 inch introduced into holes drilled in the metallic bars or spot welded to the bar sides. Temperatures can be measured at successively decreasing distances from the outer surface, together with temperatures at various distances from the weld zone. The state of affair may necessitate carrying out extrapolation to find the temperature at the weld. In addition a radiation pyrometer will be used to check on the temperature at the weld.

This section of the project studied the effectiveness of vibration on releasing residual stresses generated by welding aluminum bars to various shapes. The frames were formed of bars 3 and 4 inch wide by $\frac{1}{4}$, $\frac{3}{8}$ and $\frac{1}{2}$ inch thick. Details are given in Fig.125

Results of the stress distribution were worked out as before, and are presented in Figures 126-130, 132-141, 143-152, 154-163 and 165-169.

The load pulse and acceleration response analyses are given in Figs. 131, 142, 153 and 164.

The four frames were vibrated at 82, 69, 85 and 50 cps respectively for 15 minutes. An unsuccessful trial of vibrating the frames at 26, 24, 35 and 27 cps, was performed for 15 minutes but the embeded stresses were not effectively reduced. It was found necessary to vibrate at the higher frequencies given above.

It was observed that the thicker the bars and the more restrained the structure (Tests 2&4) the higher the magnitude of the trapped stresses.

Both aluminum and mild steel structures showed comparatively high tensile residual stresses generated by welding. The main difference is that peak stresses appeared at the outer layers of the mild steel bars, while it appeared at a slight depth from the outer layer of the aluminum bars. Such a behavior is mostly due to the higher conductivity of the aluminum.

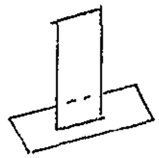
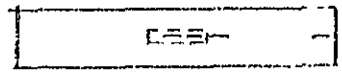
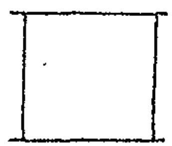
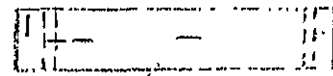
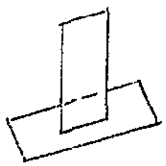
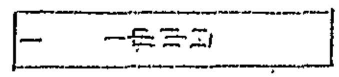
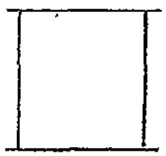
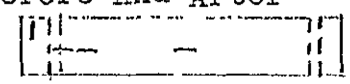
TEST NO.		FIG. NO.	BOX SHAPE	NATURE OF TEST	LENGTH X WIDTH X DEPTH X WALL THICKNESS	STRAIN GAUGE ARRANGEMENT	MATERIAL AND REMARKS
1	a			(a) Stresses Before Vibration (b) Impact Test (c) Stresses After Vibration	36"x36"x4"x$\frac{1}{4}$"	 Before (4)(3)(2) (1) After (3)(1)(2) (4)	Aluminum
	b						
	c						
2	a				36"x36"x4"x$\frac{3}{8}$"	Before And After  (3)(1)(2) (4)	Aluminum
	b						
	c						
3	a				36"x36"x3"x$\frac{1}{2}$"	Before And After  (4) (3)(2)(1)	Aluminum
	b						
	c						
4	a				36"x36"x3"x$\frac{1}{2}$"	Before And After  (3)(1)(2) (4)	Aluminum
	b						
	c						

FIG. 125

	GAGE #	1	2	3	4
AYER	1	-1209.	4837.	3023.	3023.
AYER	2	-1471.	2544.	2007.	99.
AYER	3	-3328.	-284.	-362.	-1518.
AYER	4	-3948.	-4569.	-2513.	-3163.
AYER	5	-5009.	-7520.	-4606.	-4159.
AYER	6	-5217.	-7016.	-6390.	-4933.
AYER	7	-4768.	-6830.	-5801.	-4489.
AYER	8	-5252.	-7592.	-5964.	-5467.
AYER	9	-5371.	-6816.	-6117.	-5605.
AYER	10	-5187.	-7246.	-6011.	-4960.
AYER	11	-5110.	-7138.	-5921.	-4886.
AYER	12	-4465.	-6396.	-5231.	-4244.
AYER	13	-4811.	-6485.	-5219.	-4594.

TEST 1-a
FIG. 126

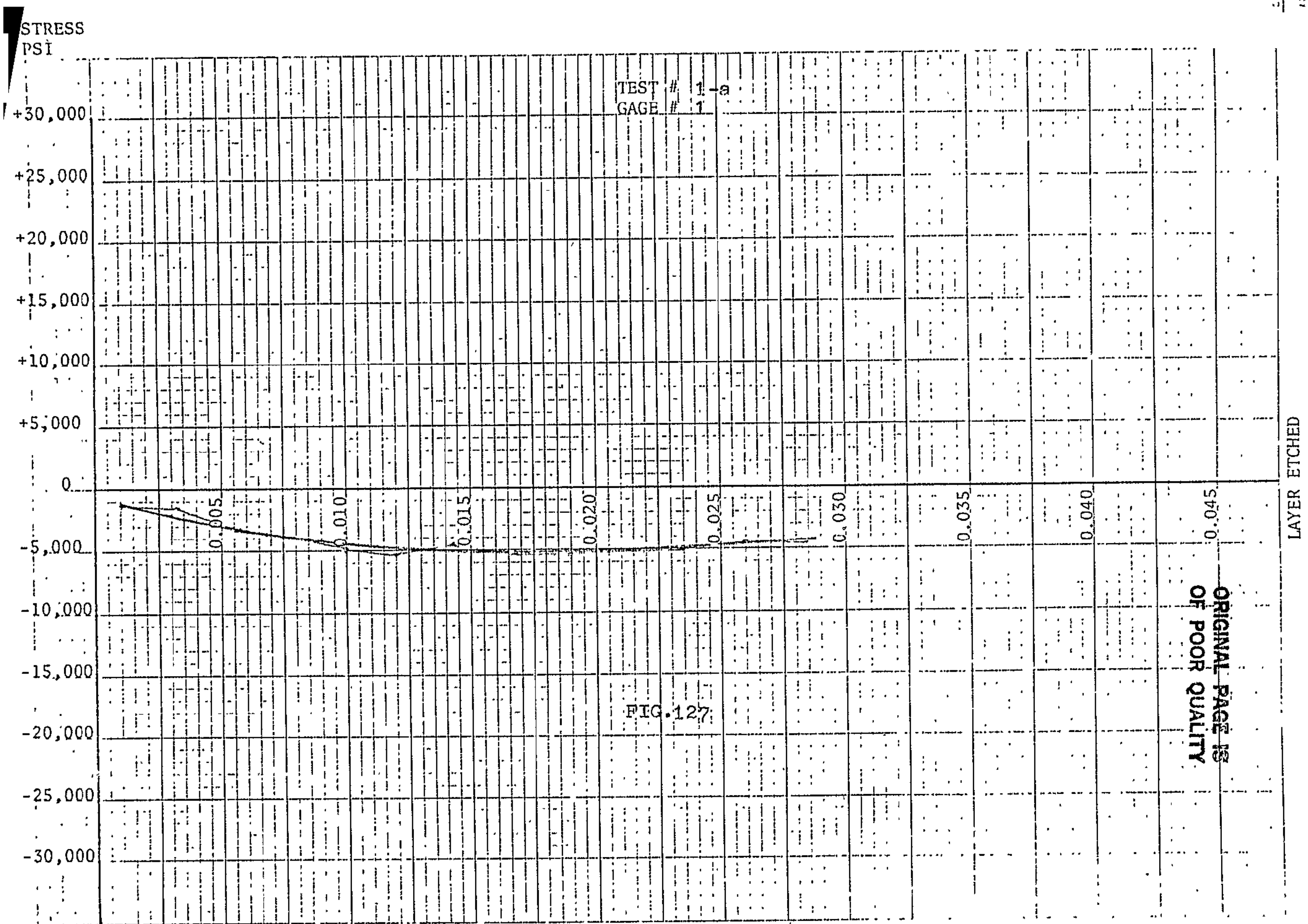


FIG.127

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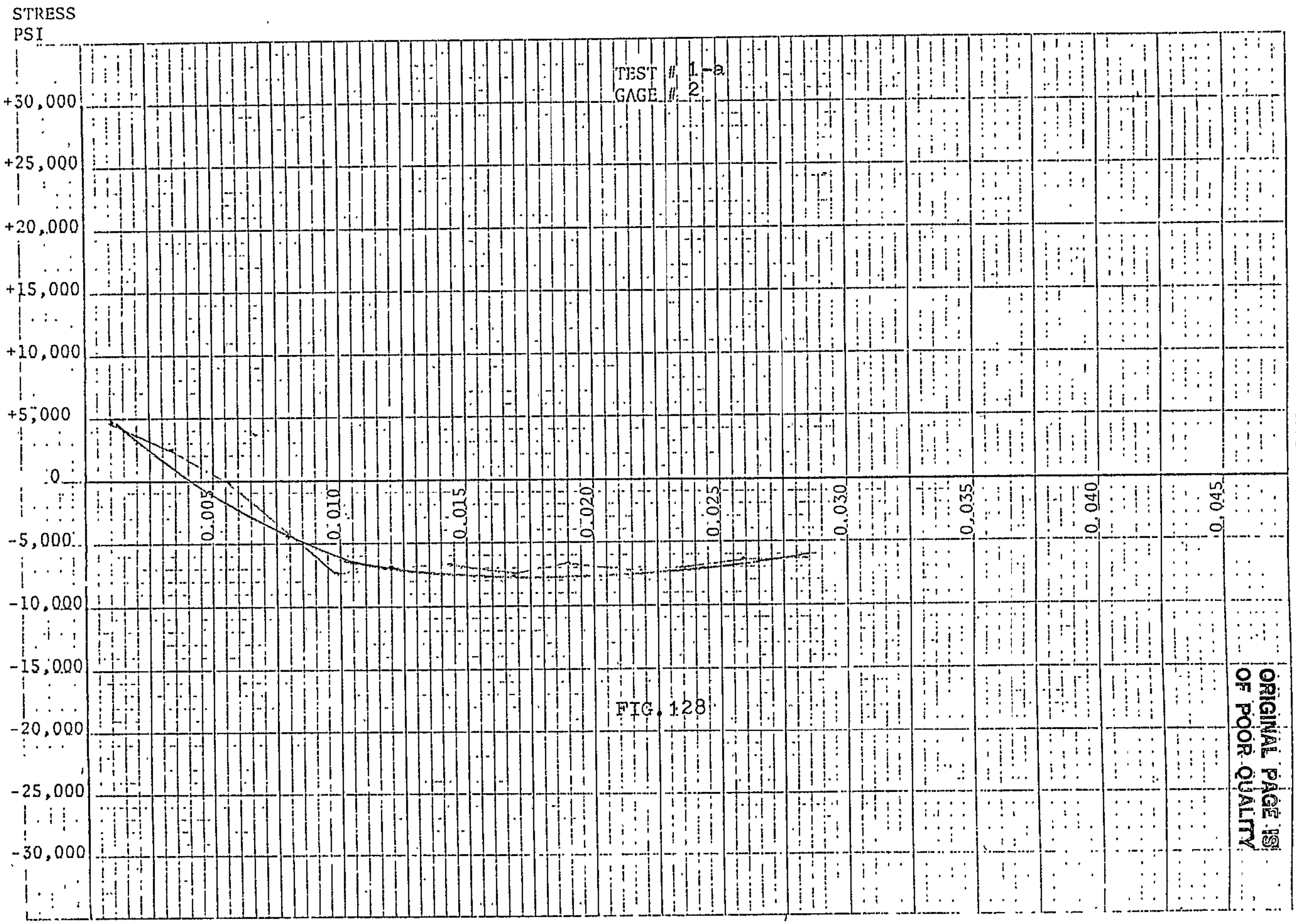
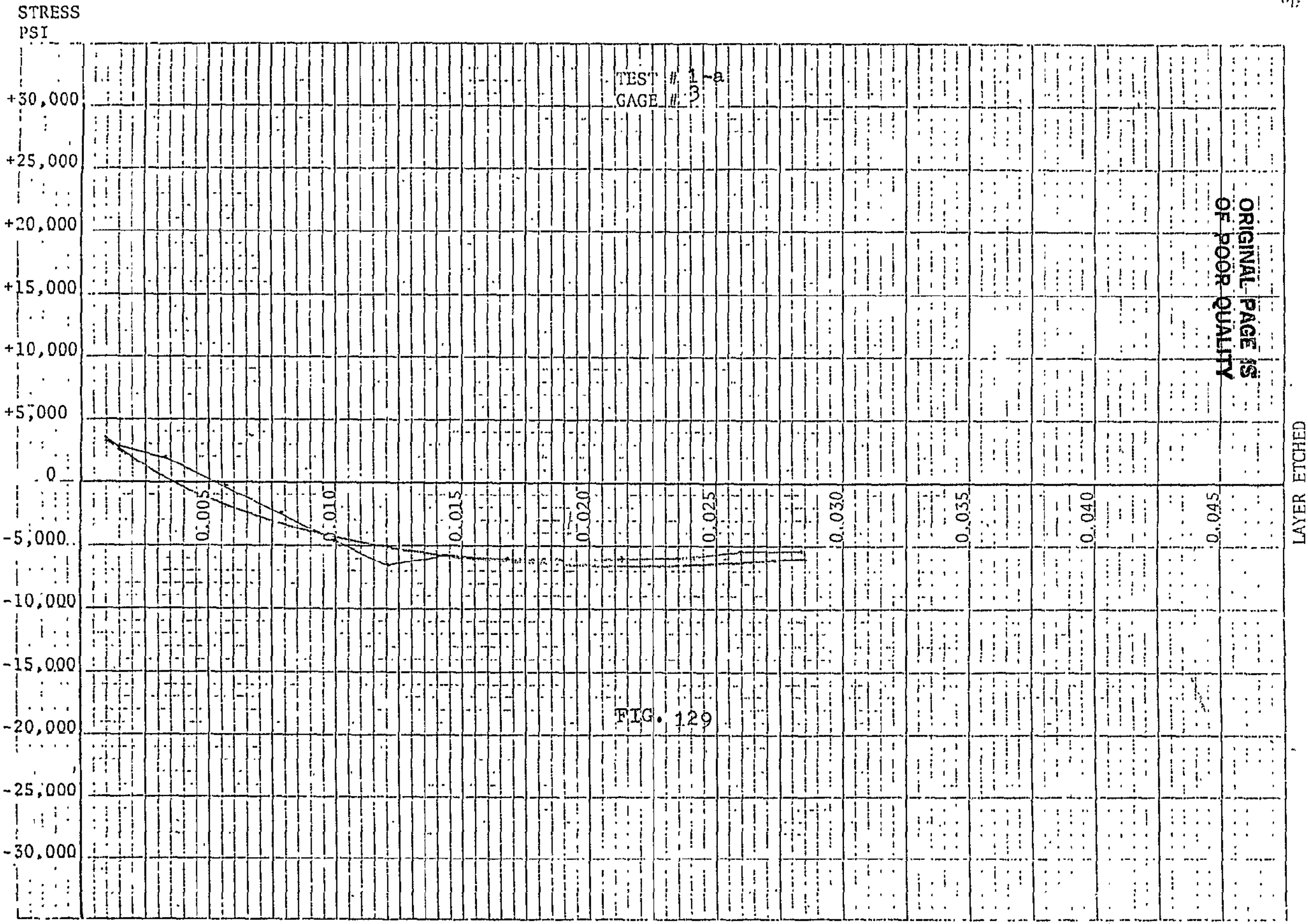
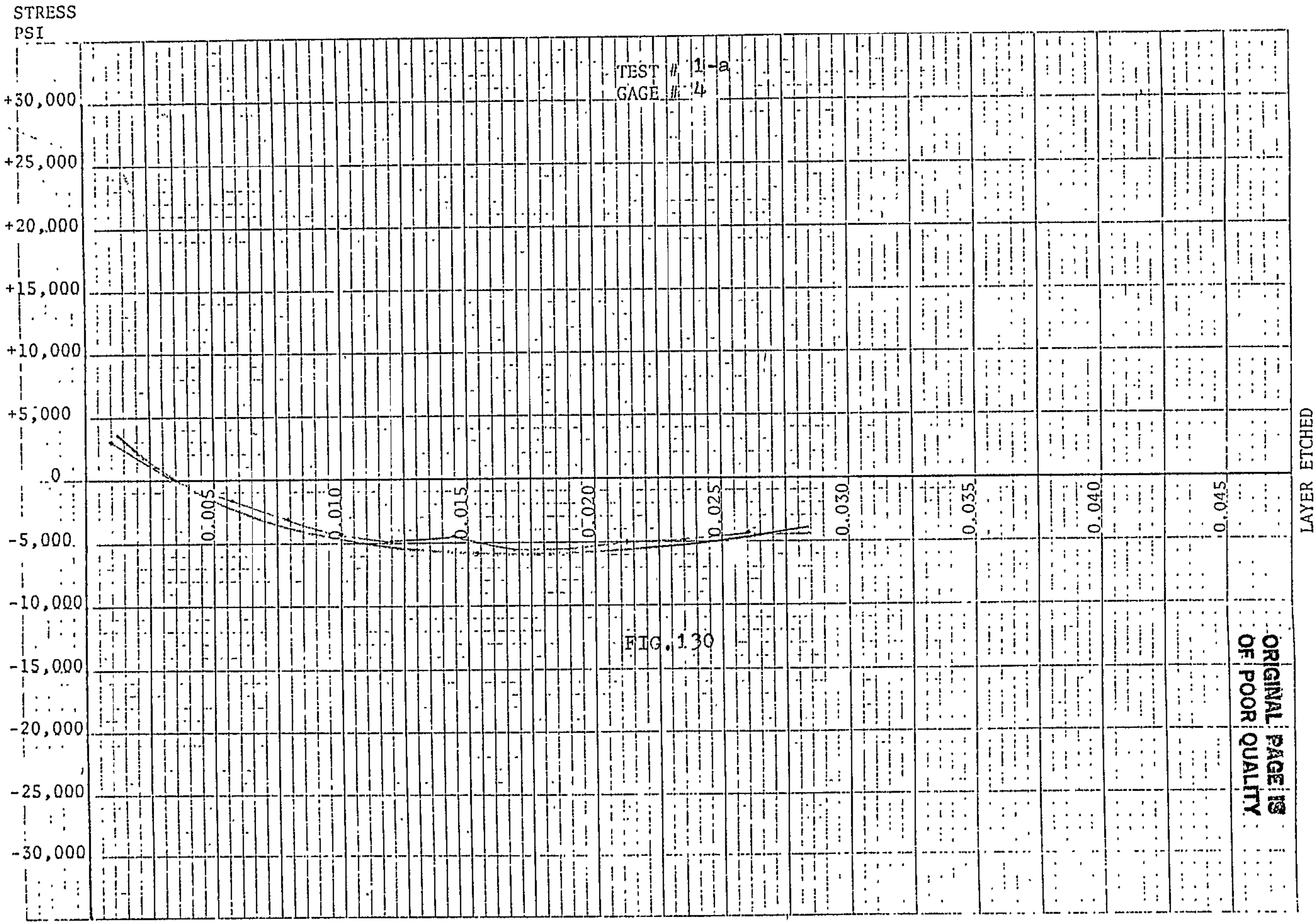
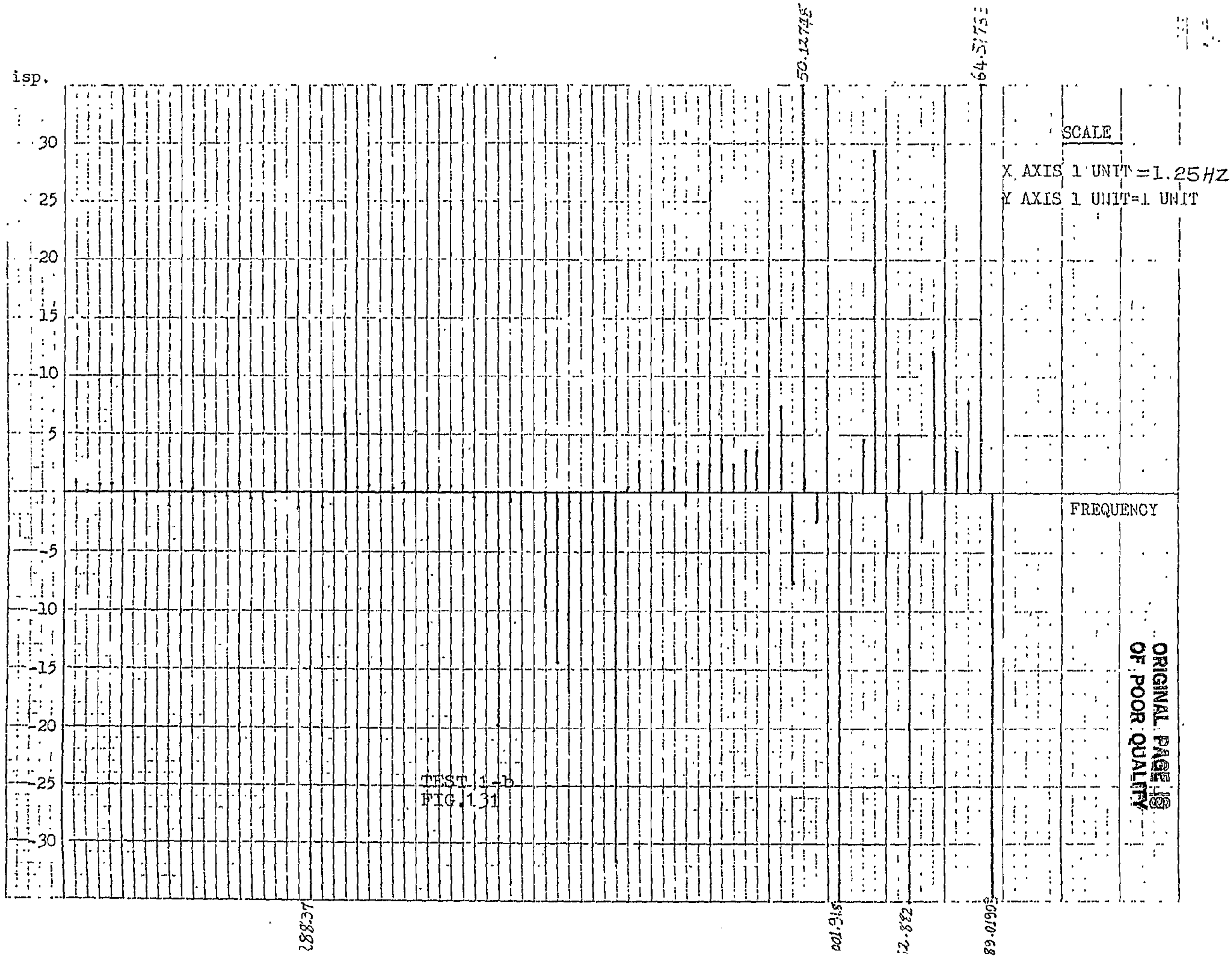


FIG. 128

ORIGINAL PAGE IS OF POOR QUALITY


STRESS PSI
TEST # 1-a
GAGE # 3
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
FIG. 129


STRESS
PSI
TEST # 1-a
GAGE # 4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
FIG. 130



TEST 1-b
FIG. 131

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY

	GAGE #	1	2	3	4
AYER	1	1099.	1099.	-1099.	1099.
AYER	2	-1161.	-2361.	-2440.	-2361.
AYER	3	1325.	-2690.	-3431.	-3353.
AYER	4	1220.	-3072.	-3168.	-3682.
AYER	5	2307.	-1887.	-3097.	-3041.
AYER	6	2477.	308.	-3888.	-2672.
AYER	7	912.	-2965.	-3915.	-3821.
AYER	8	-2034.	-3181.	-2897.	-1661.
AYER	9	1195.	-1960.	-2737.	-2606.
AYER	10	1326.	-1033.	-2995.	-2865.
AYER	11	242.	-1105.	-3297.	-3787.
AYER	12	-261.	0.	-2389.	-2283.
AYER	13	-304.	46.	-2493.	-2388.
AYER	14	-888.	-446.	-2602.	-3039.

TEST 1-c
FIG.132

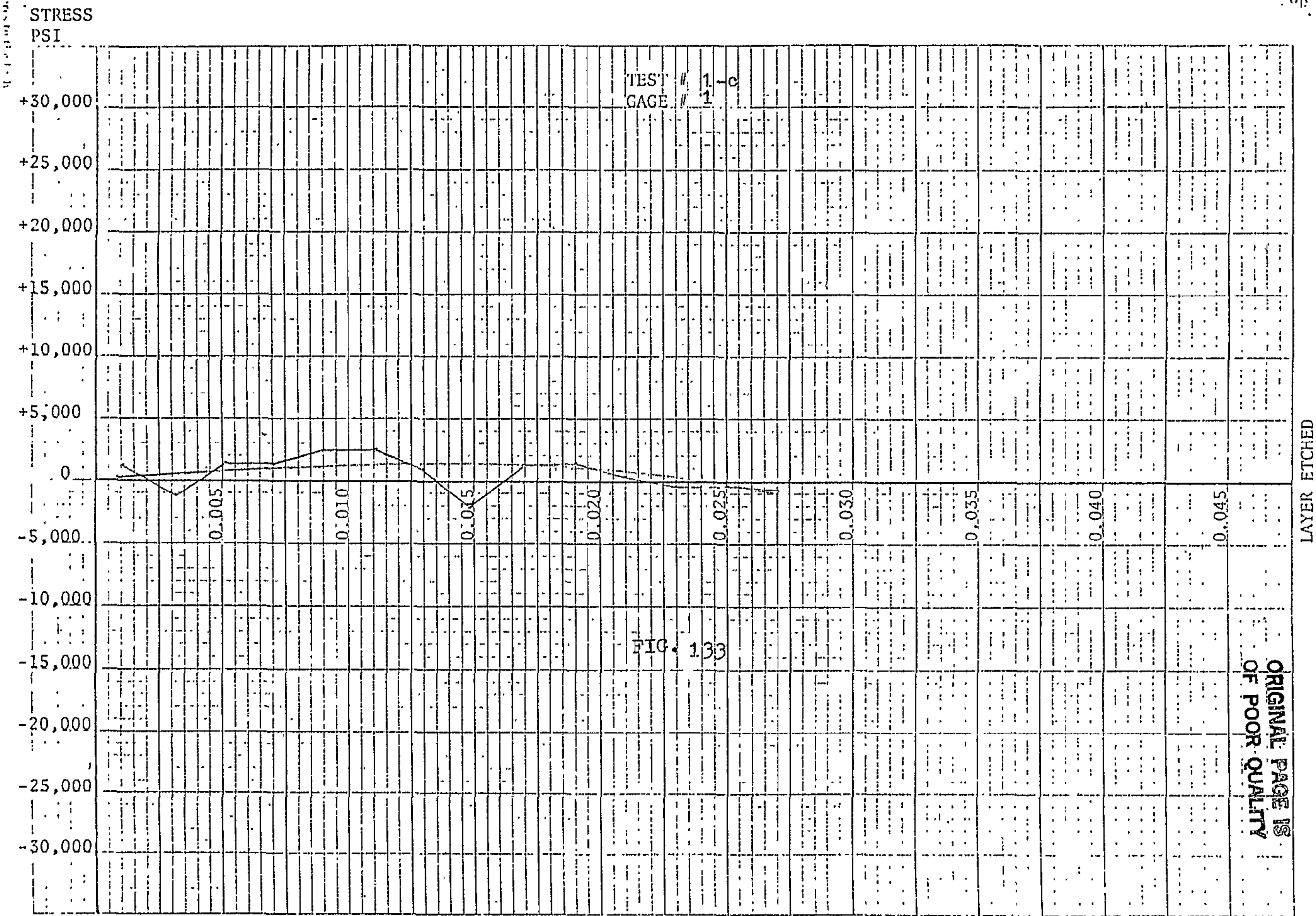


FIG. 133

ORIGINAL PAGE IS OF POOR QUALITY

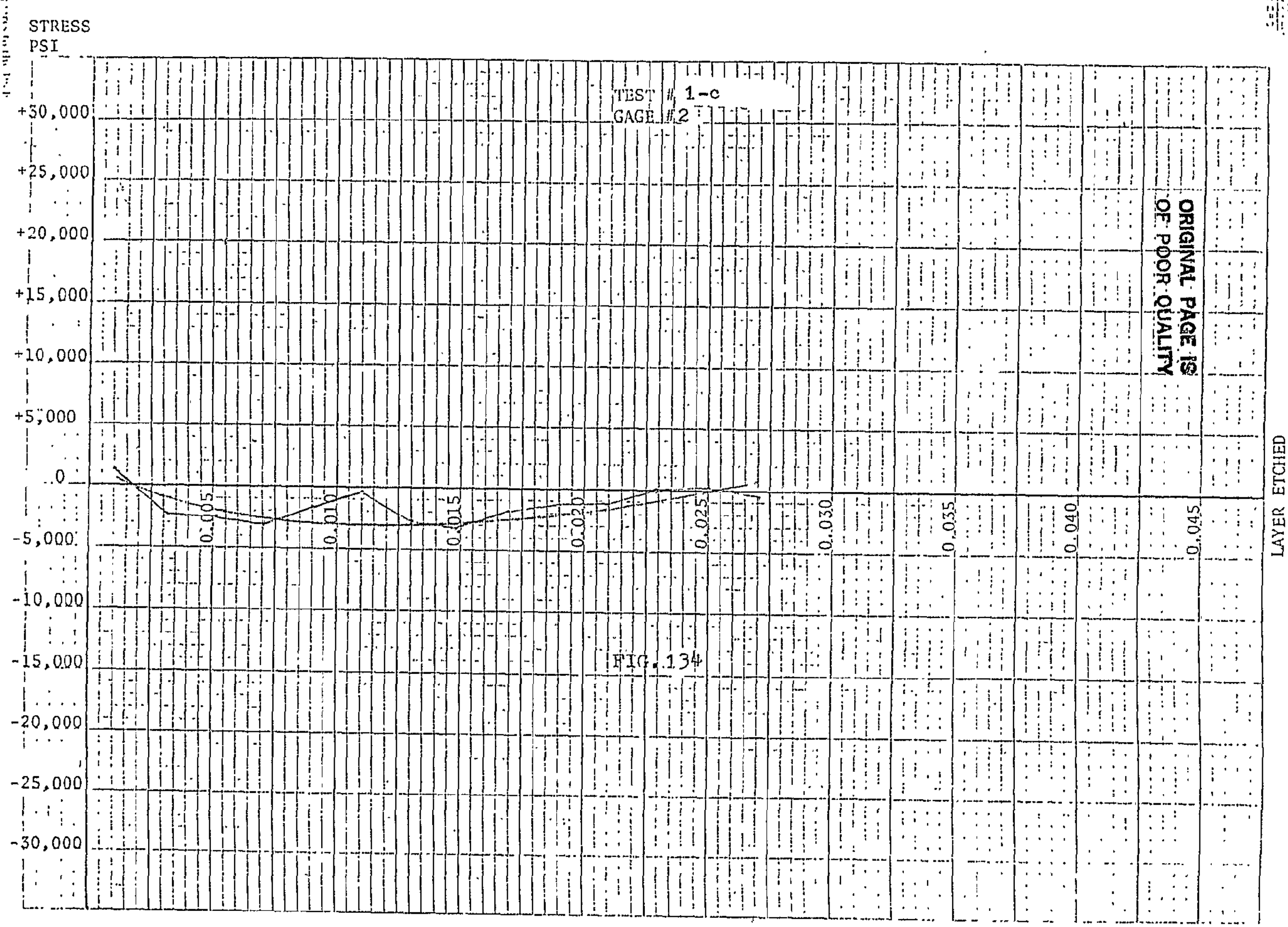


FIG. 134

ORIGINAL PAGE IS OF POOR QUALITY

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST #1-c
GAGE #3
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 135

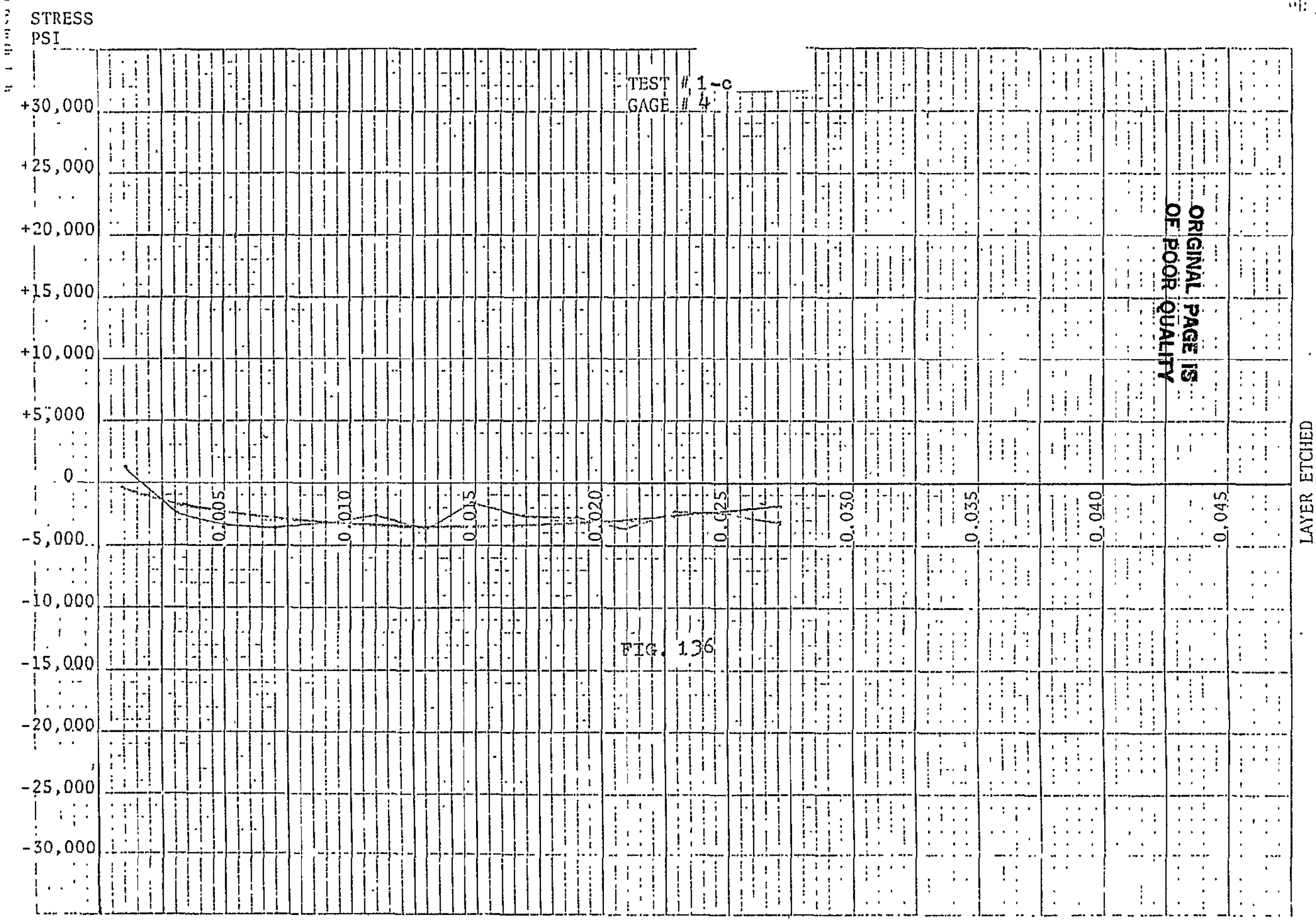


FIG. 136

ORIGINAL PAGE IS OF POOR QUALITY

	GAGE #	1	2	3	4
AYER	1	5821.	-8003.	5821.	-8731.
AYER	2	7564.	-9269.	7564.	-8466.
AYER	3	6081.	-9052.	4644.	-7615.
AYER	4	5363.	-8788.	6948.	-5500.
AYER	5	7158.	2419.	7158.	3848.
AYER	6	10873.	5127.	10873.	7803.
AYER	7	12174.	4968.	12970.	9164.
AYER	8	11715.	3708.	10346.	8189.
AYER	9	15251.	6955.	13408.	10117.
AYER	10	13522.	6685.	12091.	9912.
AYER	11	14586.	7780.	12937.	12215.
AYER	12	12048.	9061.	11911.	13394.
AYER	13	12824.	10575.	13532.	14691.
AYER	14	10619.	9035.	10505.	11776.
AYER	15	10031.	9923.	11299.	12861.

TEST 2-a
FIG.137

C-4

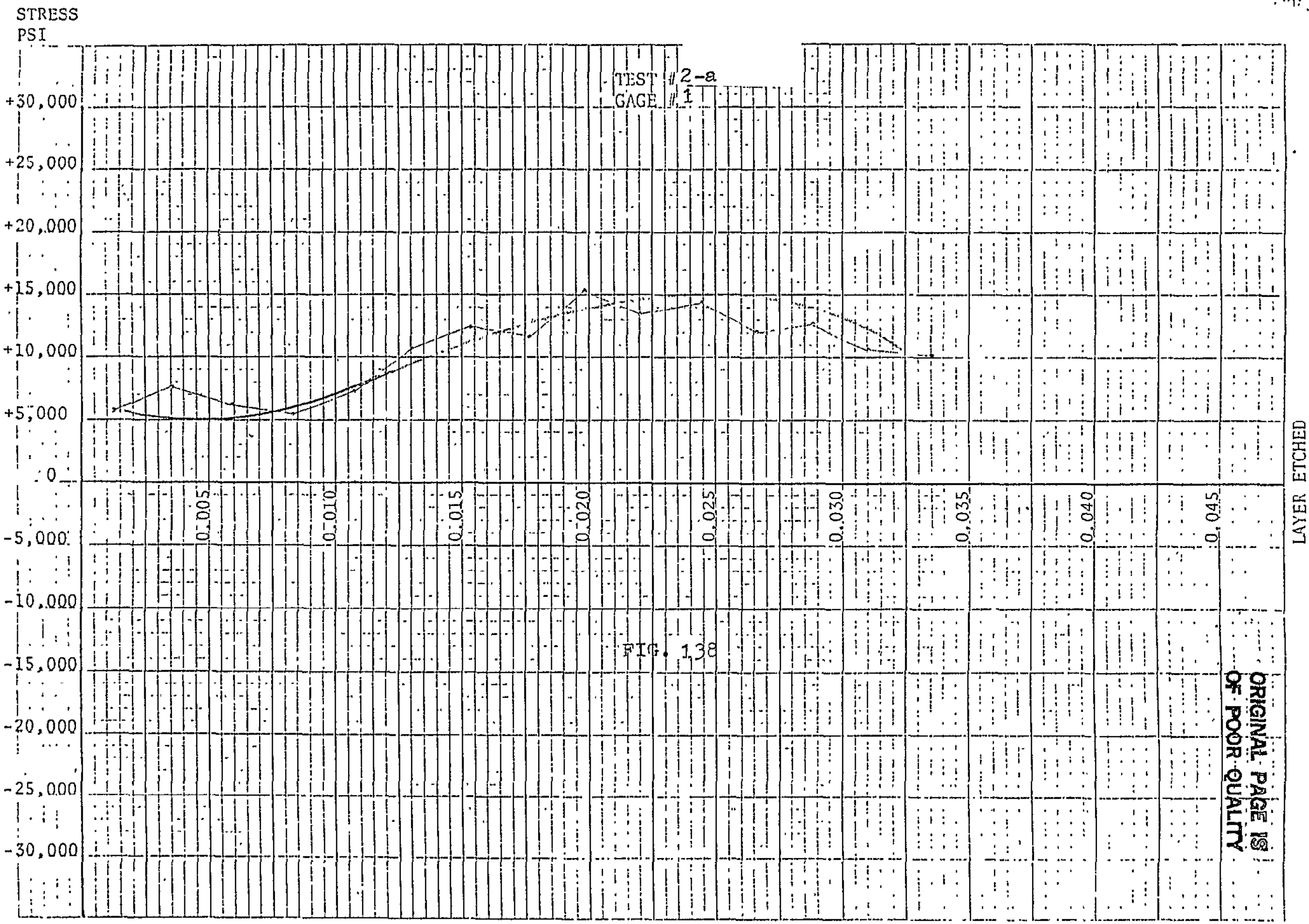


FIG. 138

ORIGINAL PAGE IS
OF POOR QUALITY

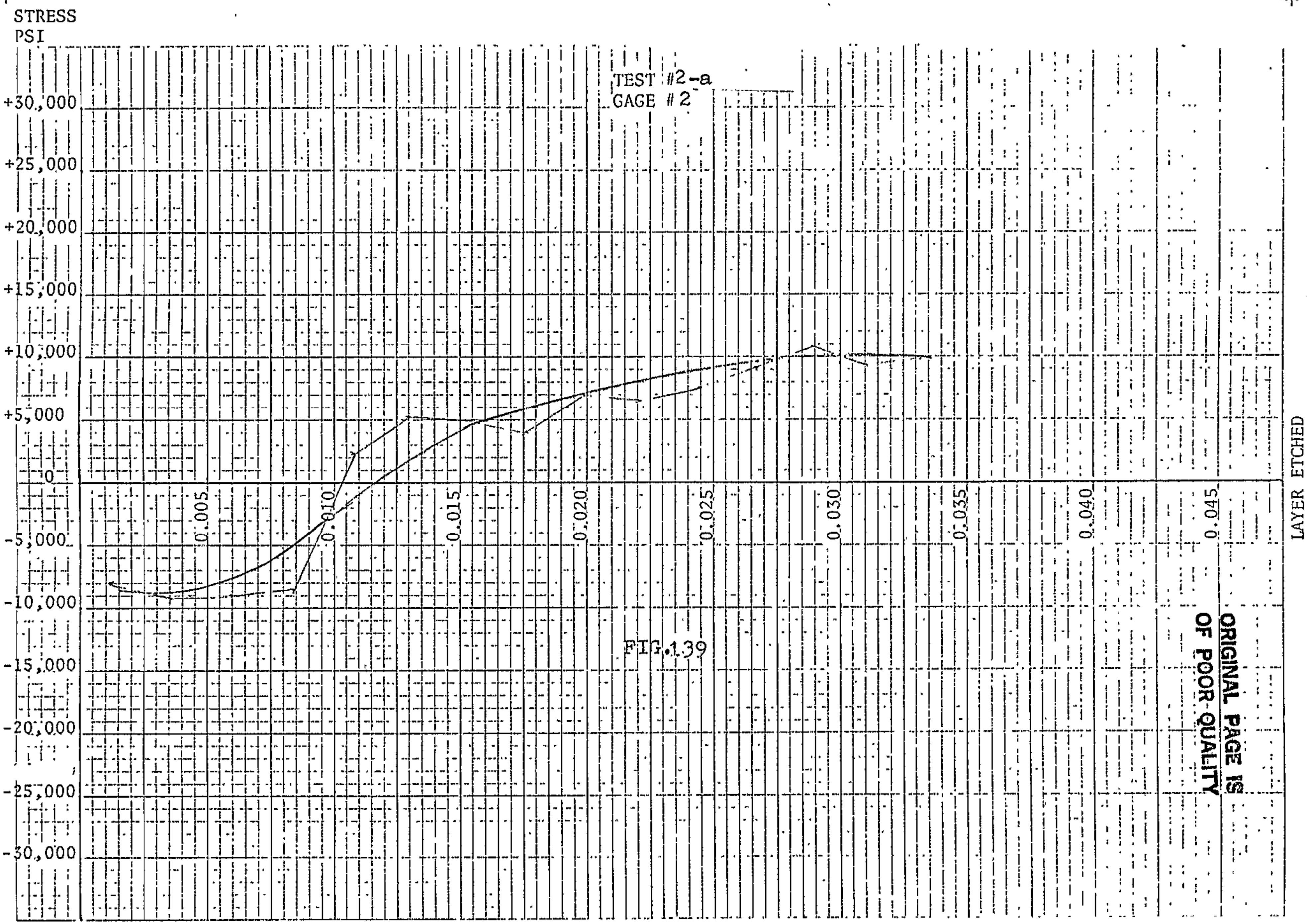

STRESS
PSI
TEST #2-a
GAGE #2
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 139

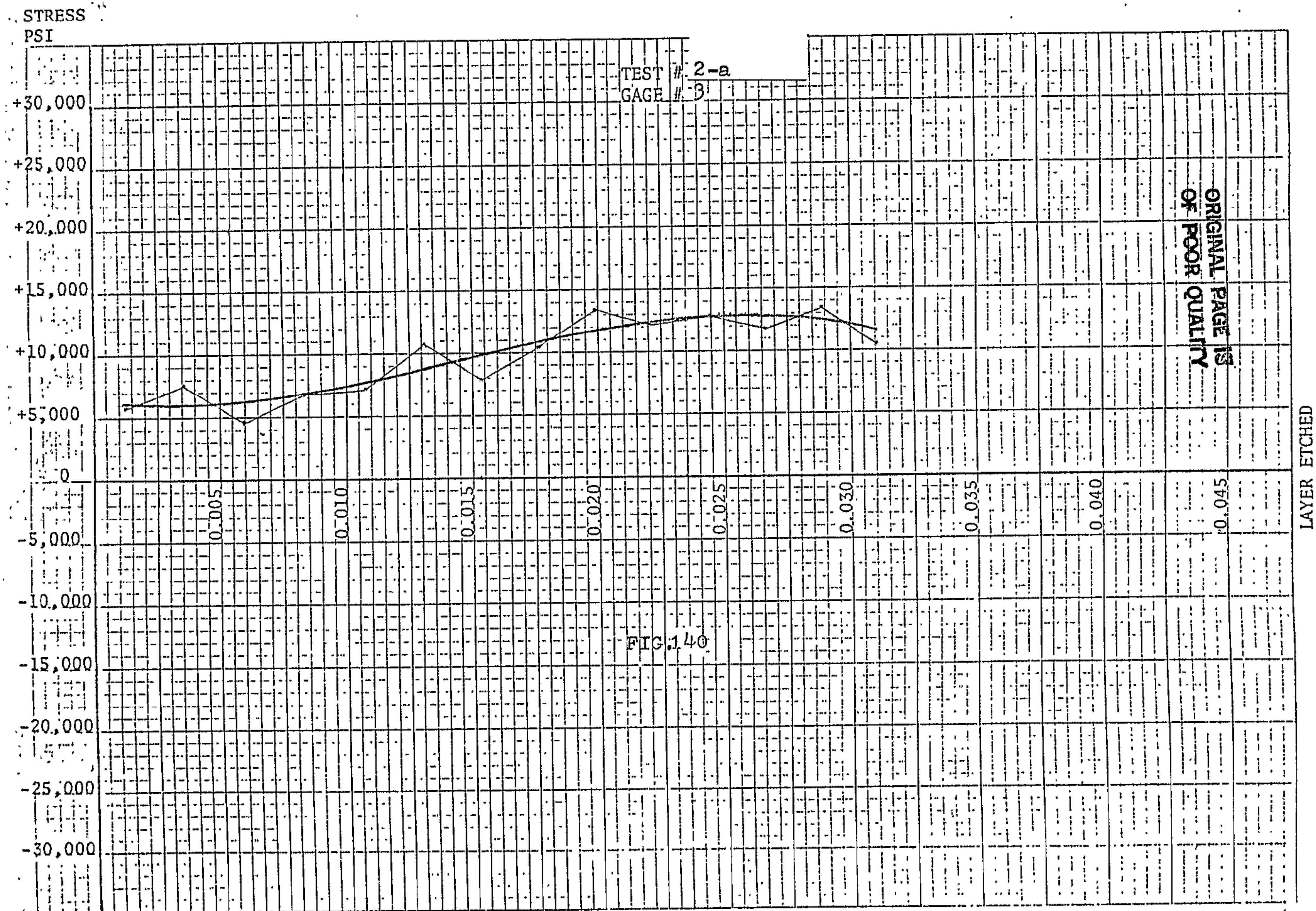

STRESS
PSI
TEST # 2-a
GAGE # 3
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
ORIGINAL PAGE IS
OF POOR QUALITY

FIG.140

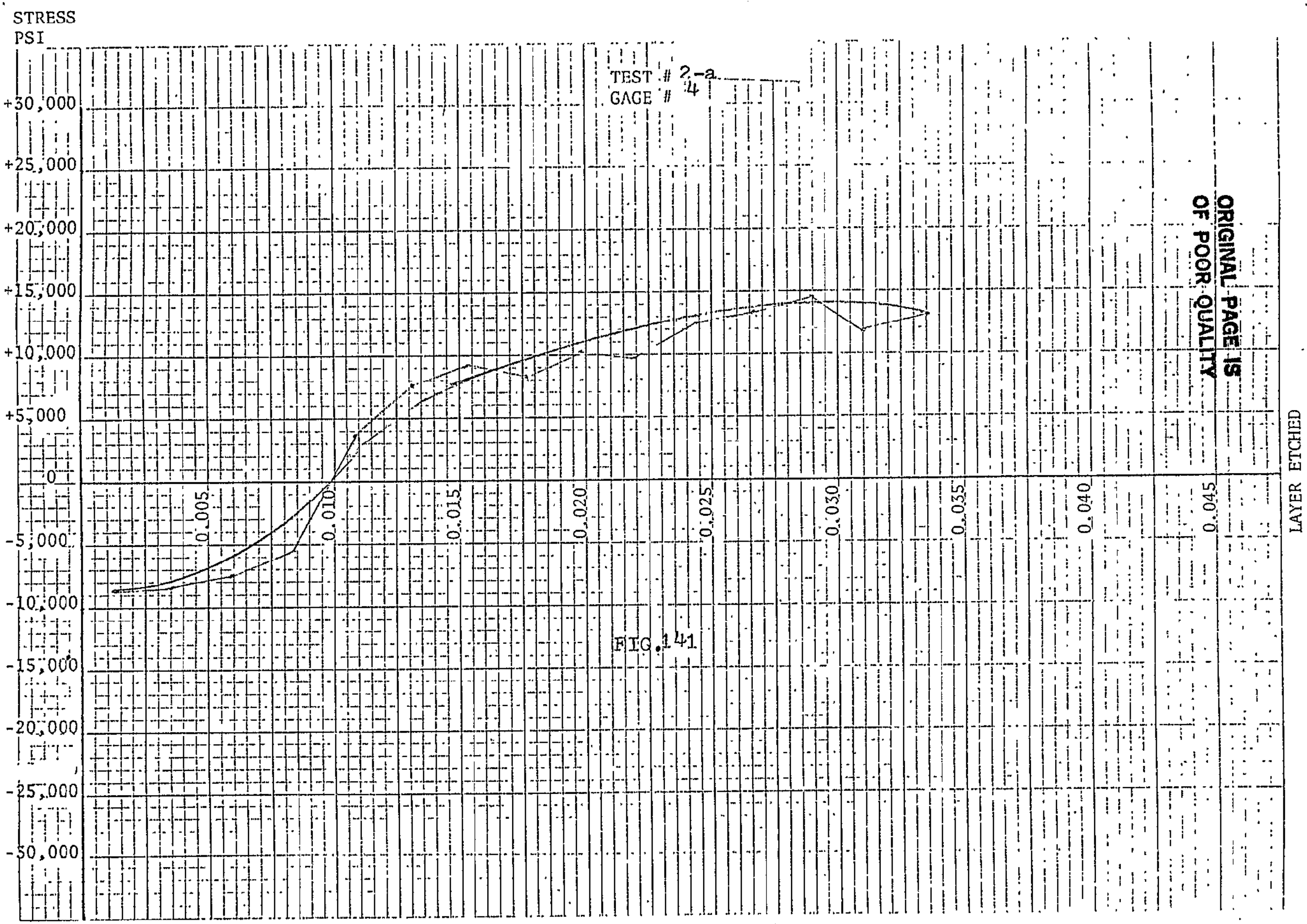
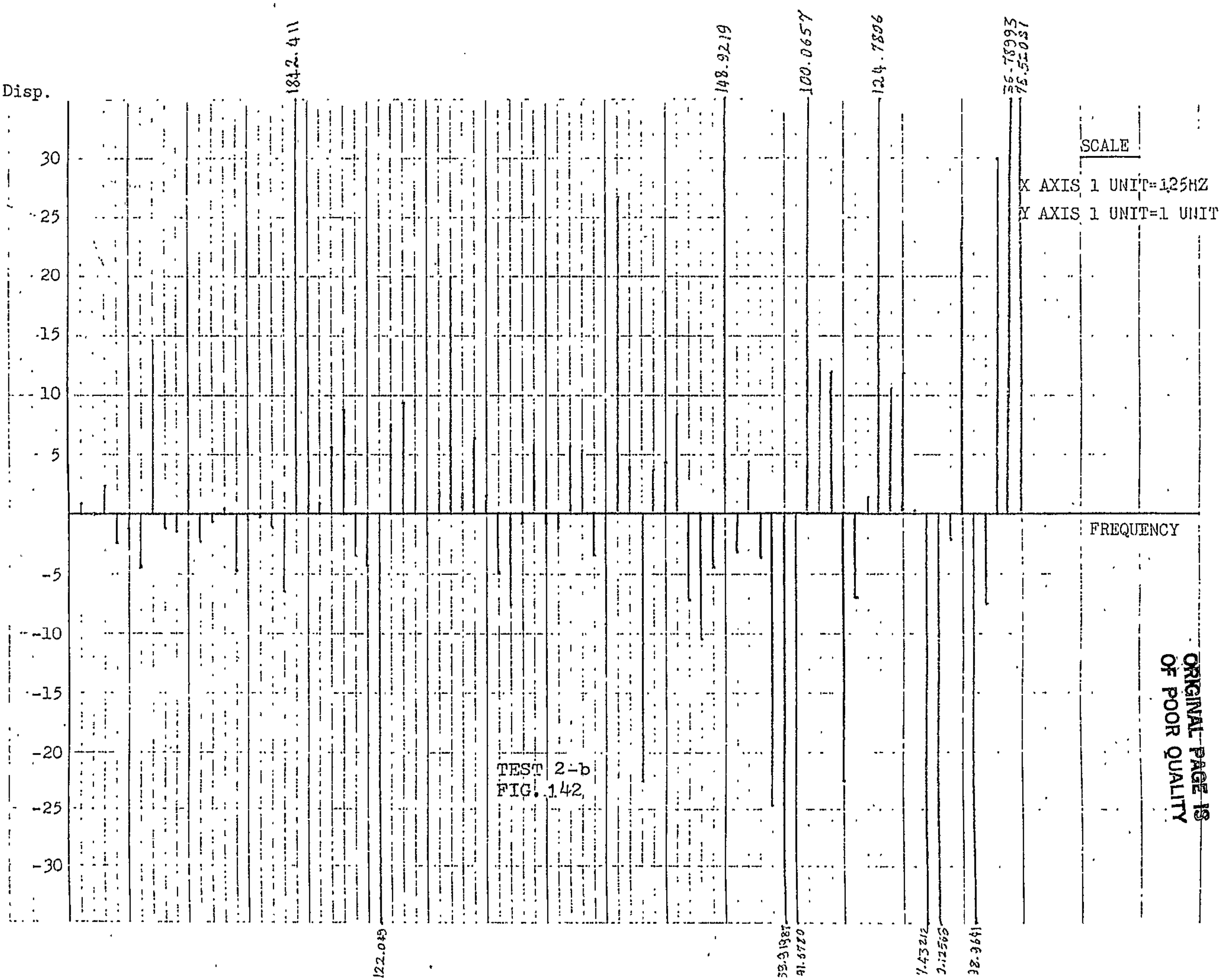

STRESS
PSI
TEST # 2-a
GAGE # 4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 141



TEST 2-b
FIG. 142

	GAGE #	1	2	3	4
AYER	1	1533.	767.	-1533.	-1533.
AYER	2	872.	-1644.	-2536.	-40.
AYER	3	1881.	-2753.	812.	-1861.
AYER	4	2457.	-2438.	1494.	-2437.
AYER	5	2310.	-856.	1398.	-1573.
AYER	6	3618.	-156.	2555.	675.
AYER	7	3520.	1459.	1676.	2267.
AYER	8	2891.	2408.	1782.	1588.
AYER	9	3356.	1900.	3071.	1901.
AYER	10	3384.	2164.	1650.	2165.
AYER	11	2918.	1621.	1811.	1622.
AYER	12	2042.	1518.	989.	802.
AYER	13	2689.	1489.	1655.	787.
AYER	14	2107.	2281.	1738.	830.

TEST 2-c
FIG. 143

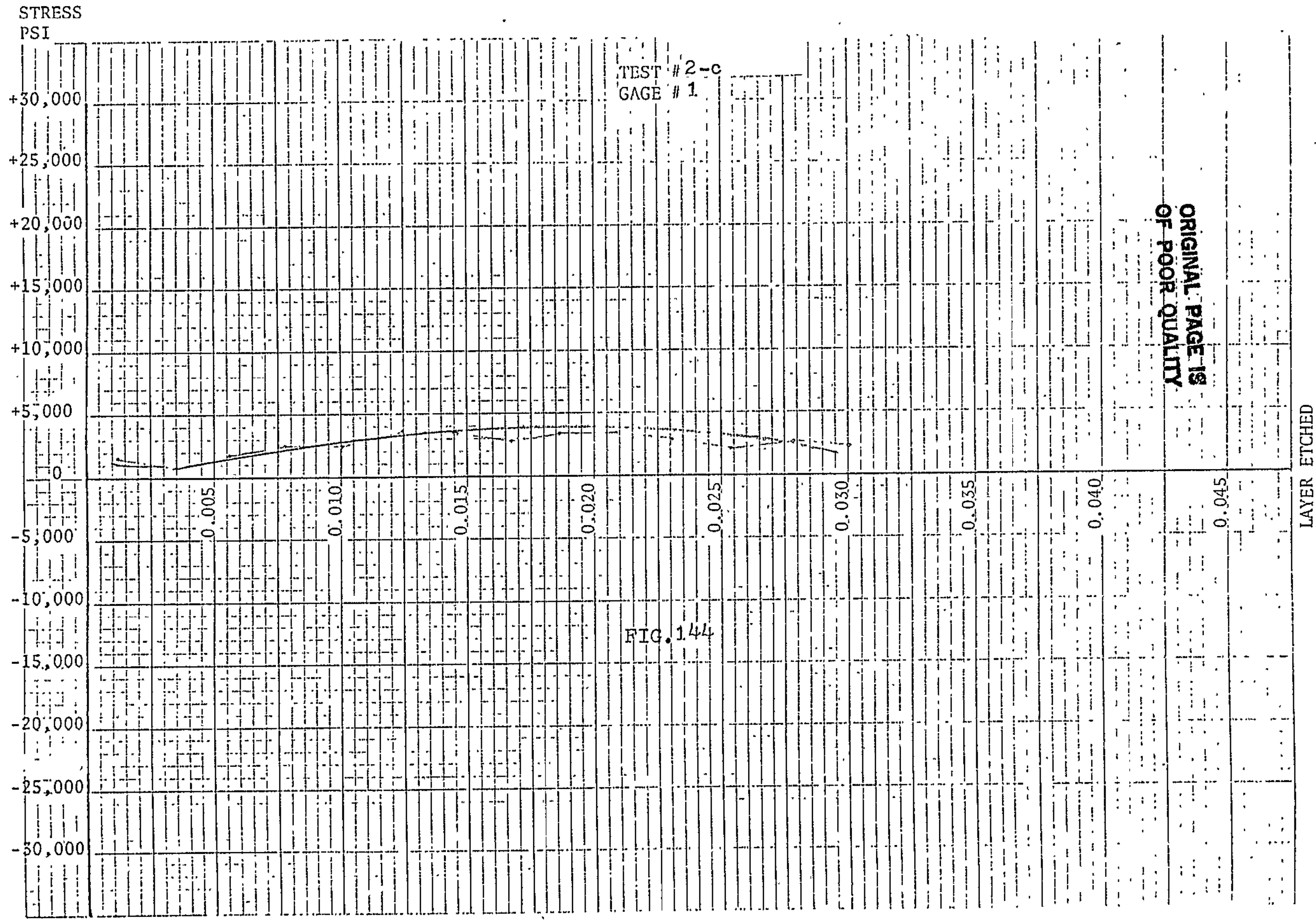

STRESS
PSI
TEST # 2-c
GAGE # 1
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 144

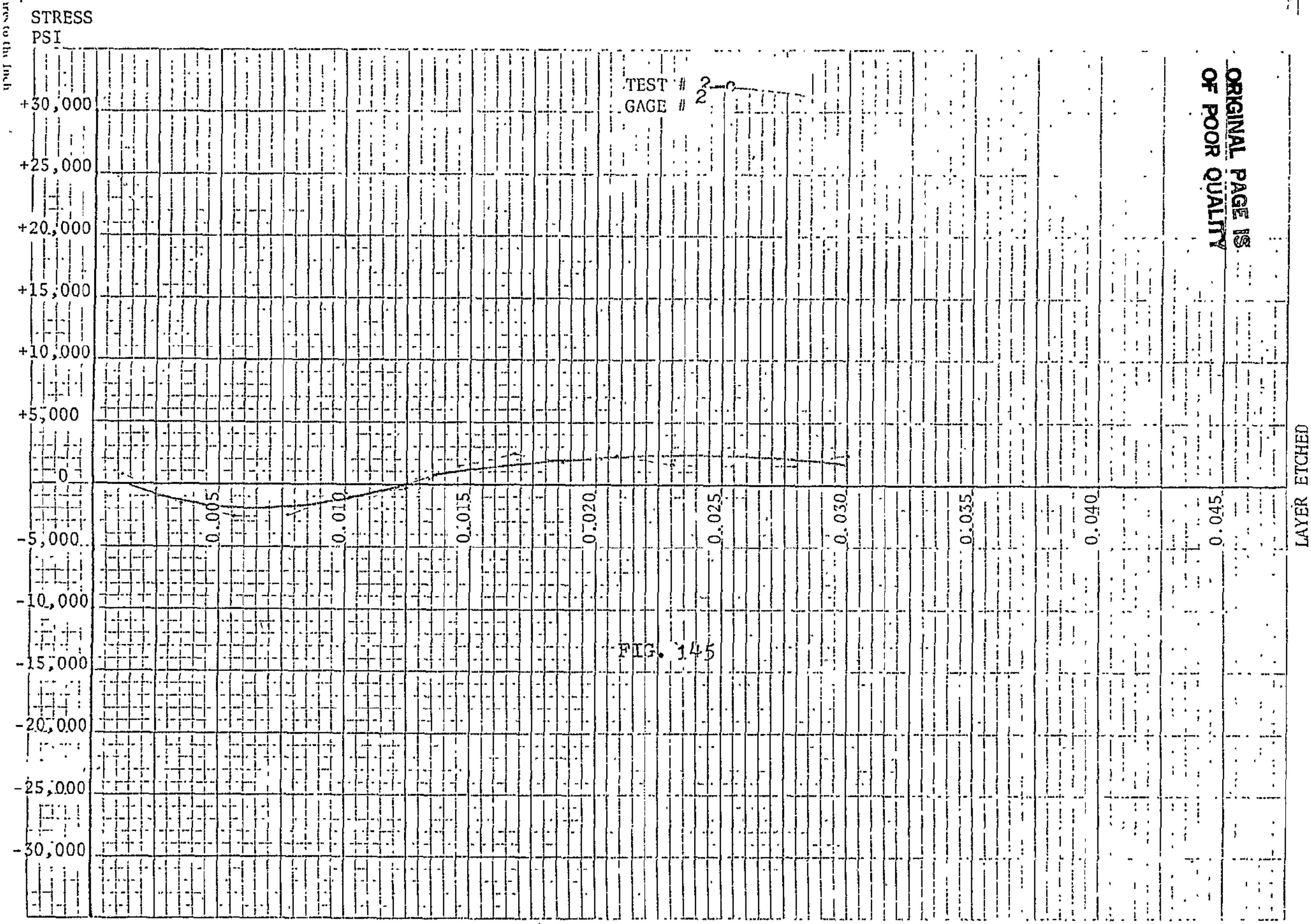
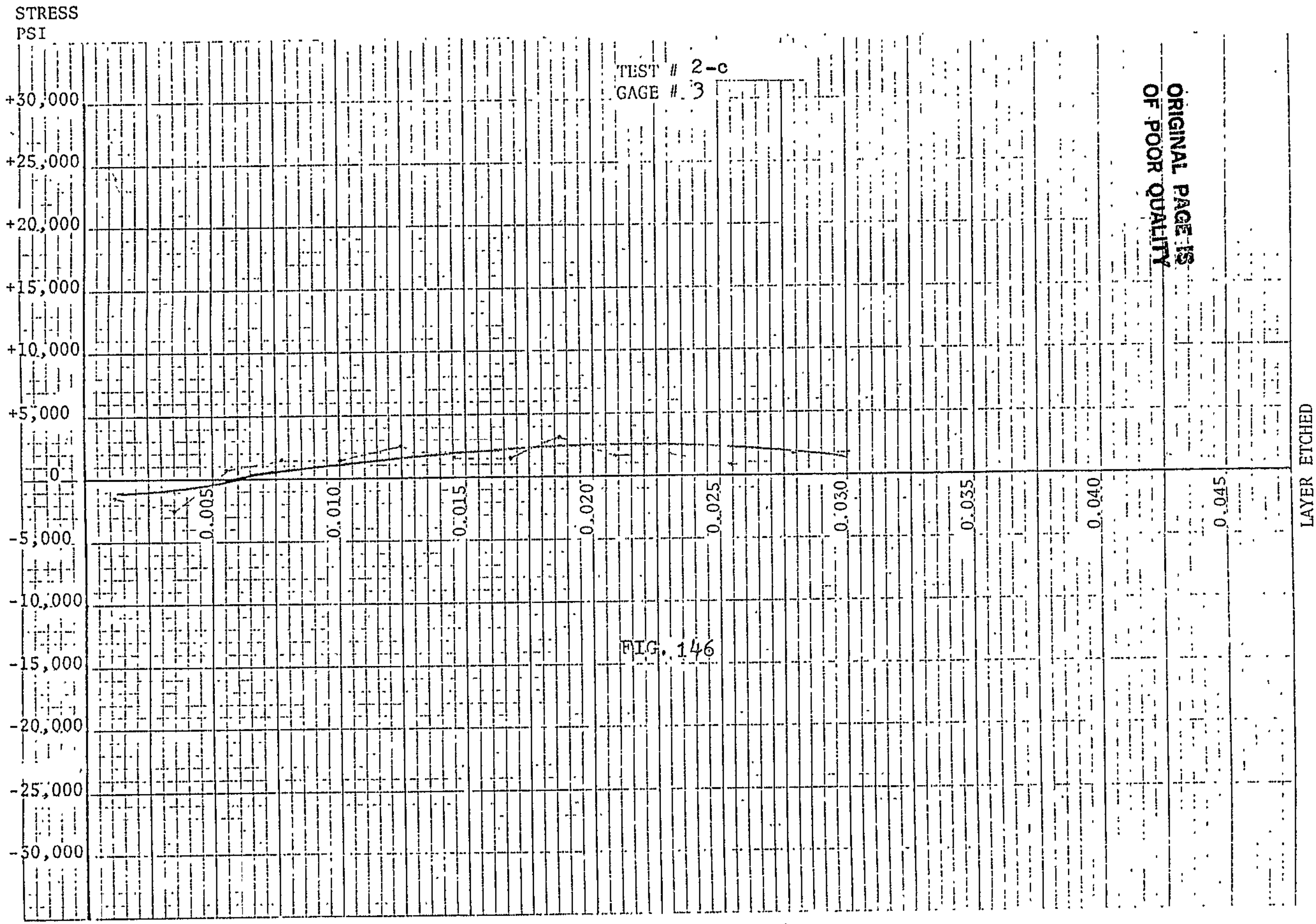

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
TEST # 2-C
GAGE # 2
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 145



STRESS
PSI
TEST # 2-c
GAGE # 3
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 146

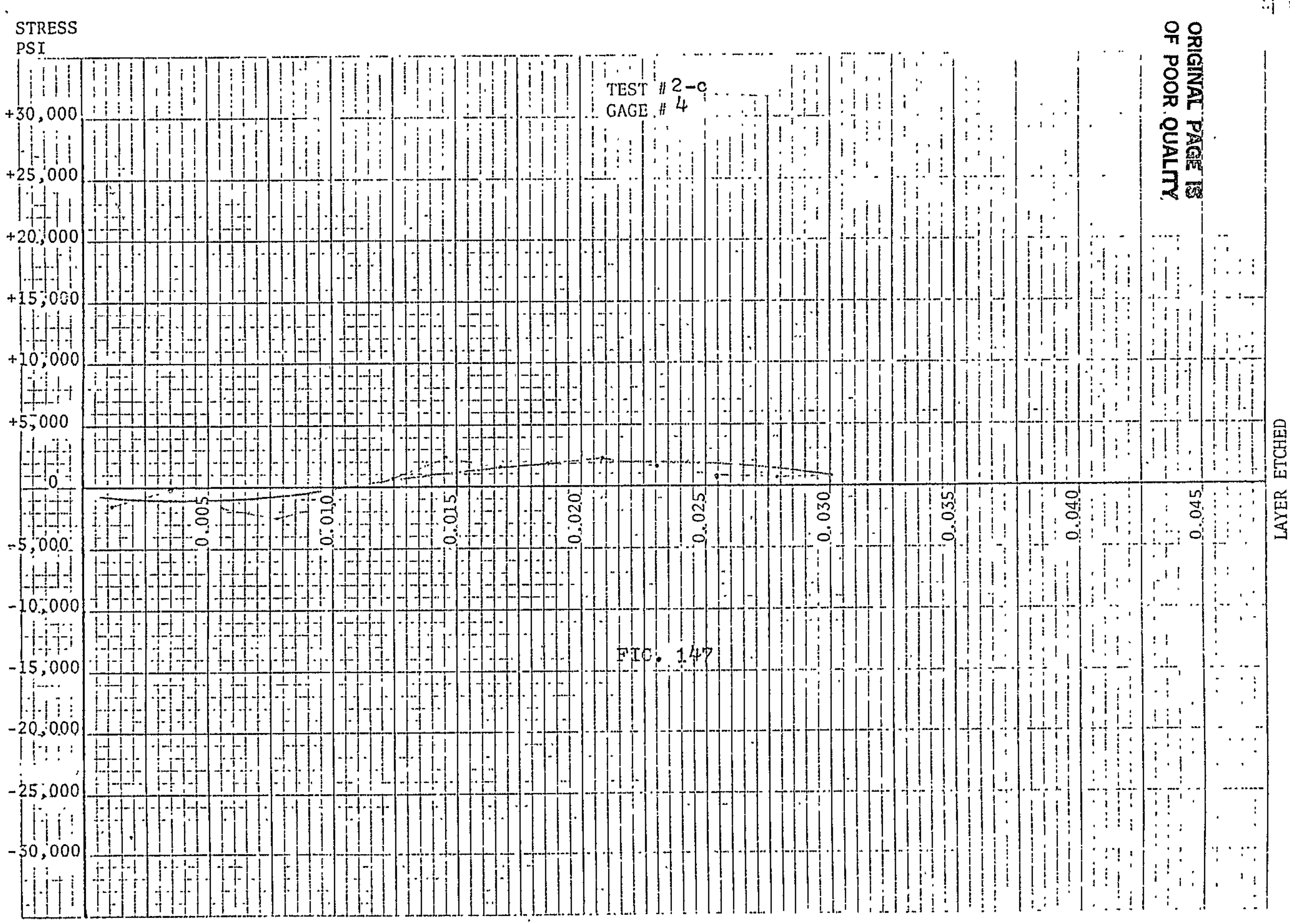


FIG. 147

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS OF POOR QUALITY

	GAGE #	1	2	3	4
AYER	1	1773.	3546.	3546.	-12413.
AYER	2	11289.	11309.	11309.	-13663.
AYER	3	10705.	7197.	8961.	-9080.
AYER	4	10086.	8424.	6803.	-8563.
AYER	5	6126.	7528.	3201.	-1897.
AYER	6	8549.	7515.	6441.	543.
AYER	7	5703.	6942.	4306.	4665.
AYER	8	5502.	4274.	1737.	6888.
AYER	9	6319.	8139.	2404.	12768.
AYER	10	1684.	1664.	-2983.	6099.
AYER	11	4584.	-2980.	-7067.	10096.
AYER	12	-8697.	-11226.	-11598.	19323.
AYER	13	-5562.	-5720.	-9264.	11459.
AYER	14	-6081.	-6237.	-8342.	14054.

TEST 3-a
FIG.148

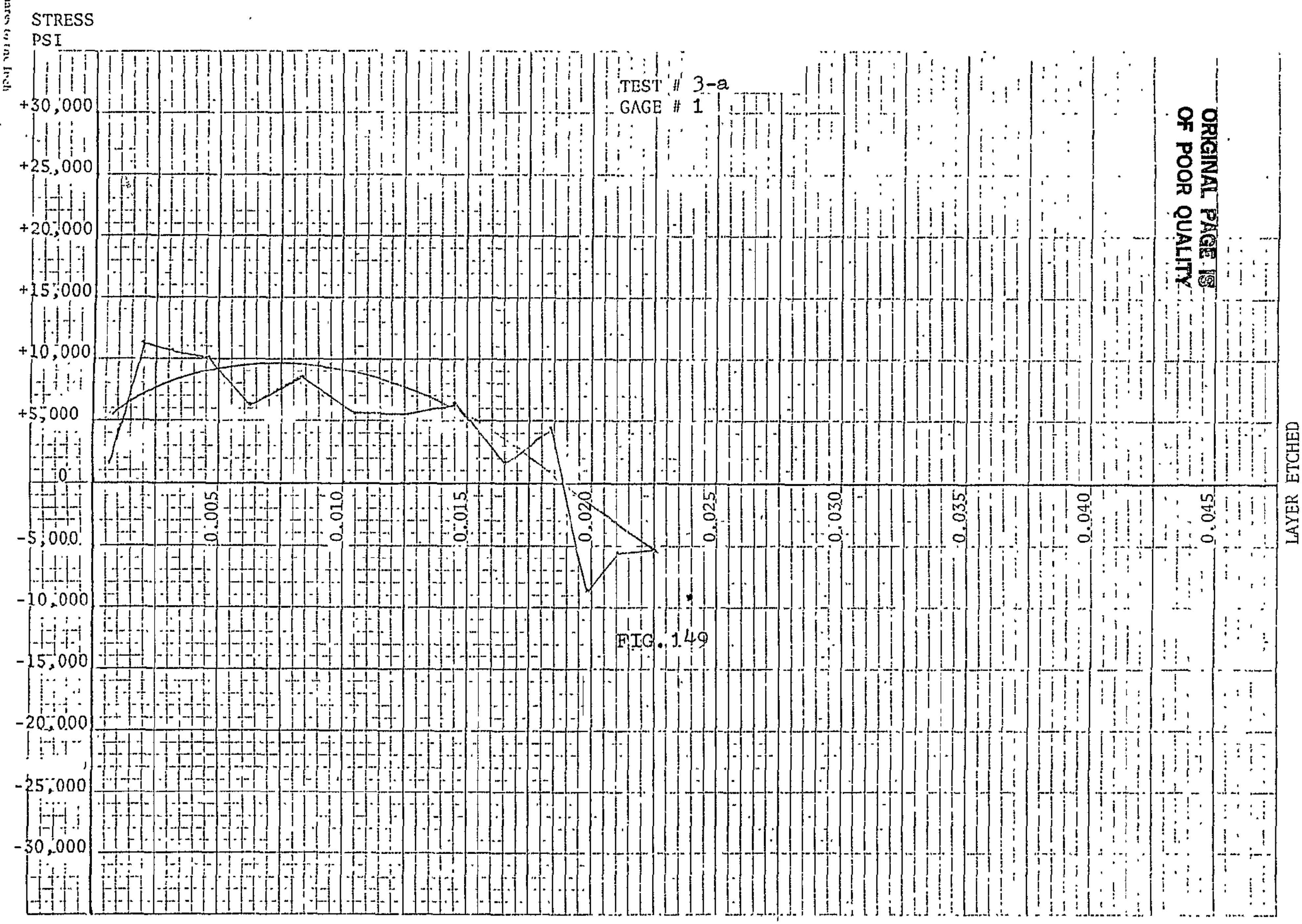

STRESS
PSI
TEST # 3-a
GAGE # 1
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 149

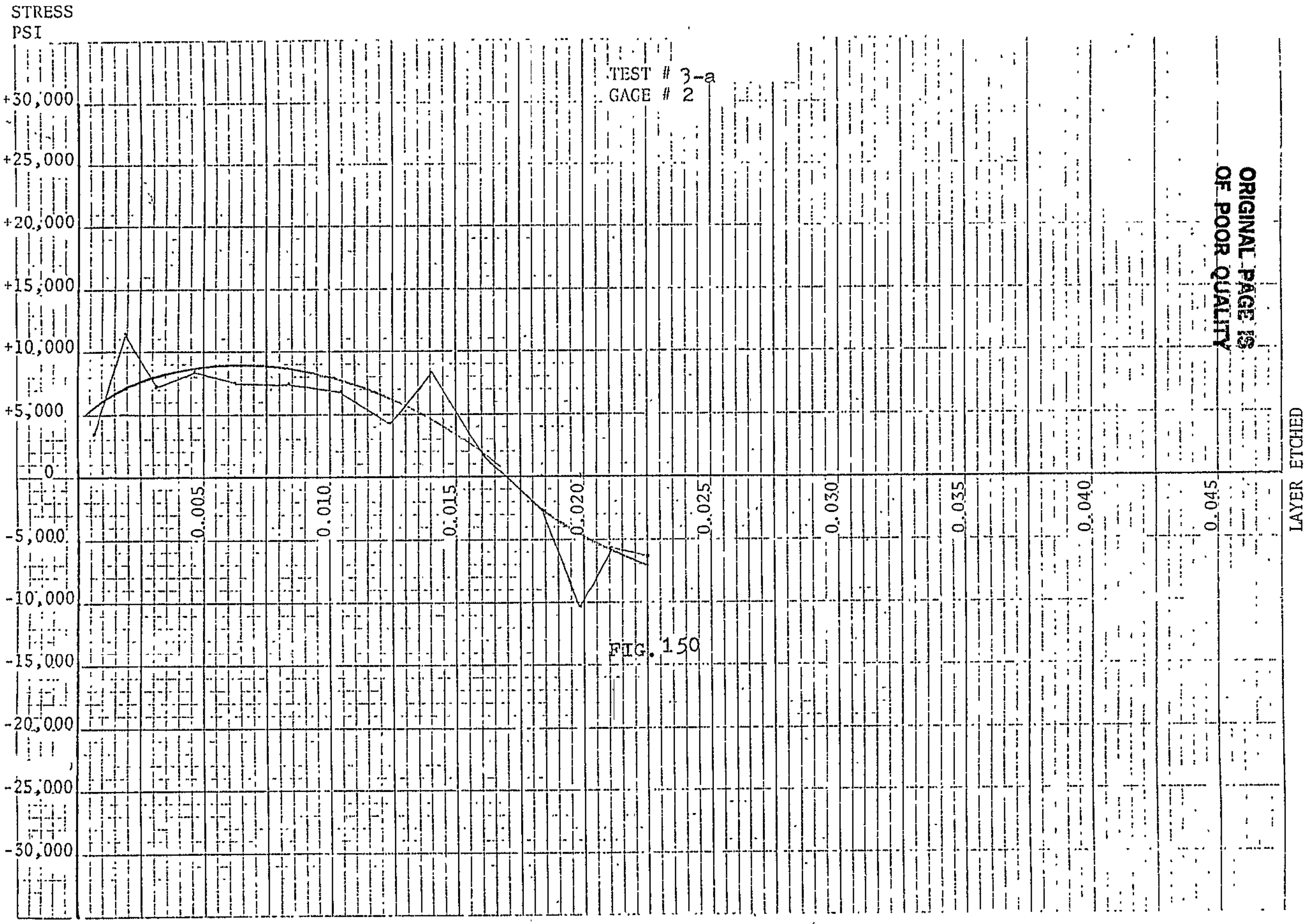

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
TEST # 3-a
GAGE # 2

FIG. 150

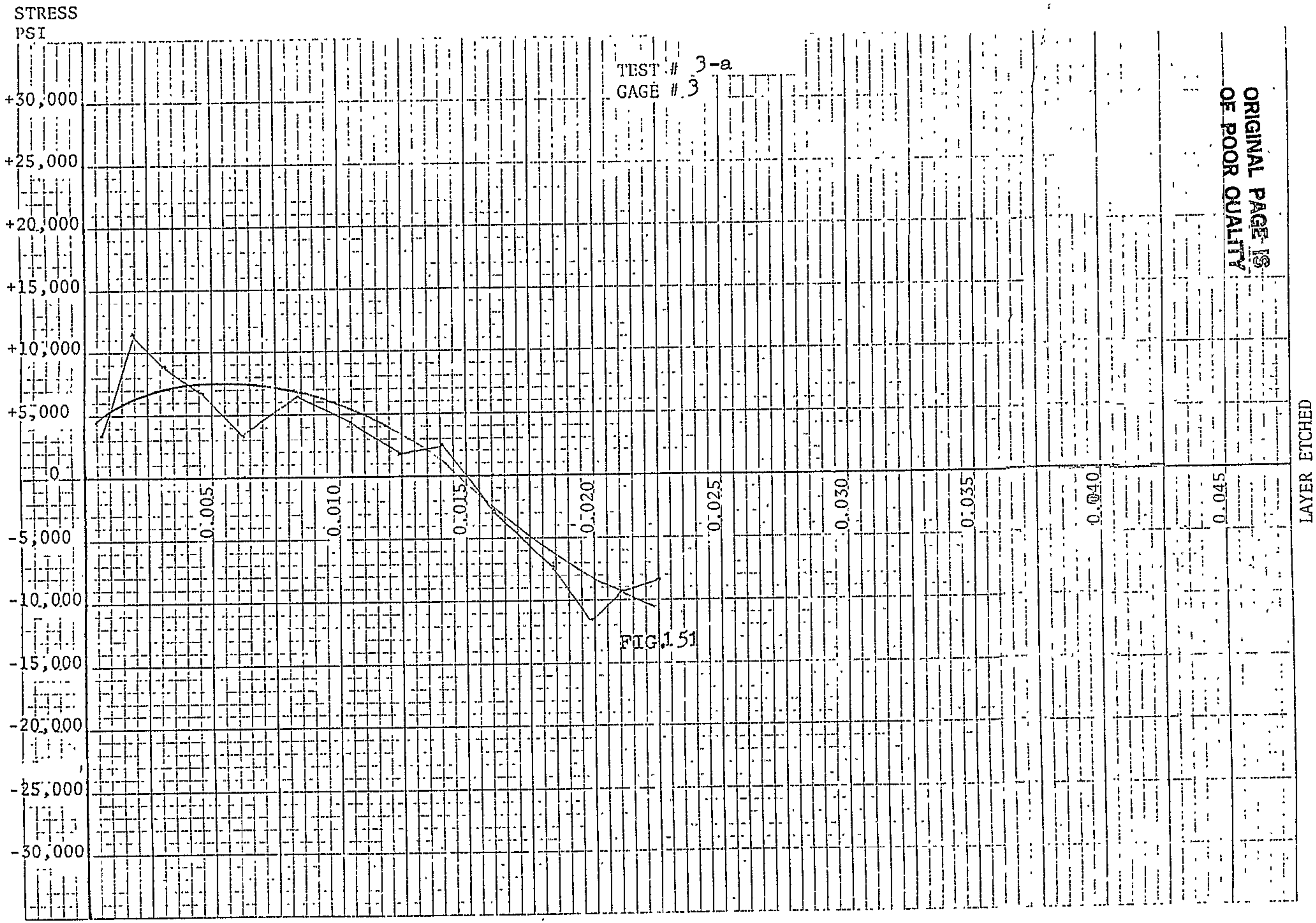

STRESS
PSI
TEST # 3-a
GAGE # 3
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG.1.51

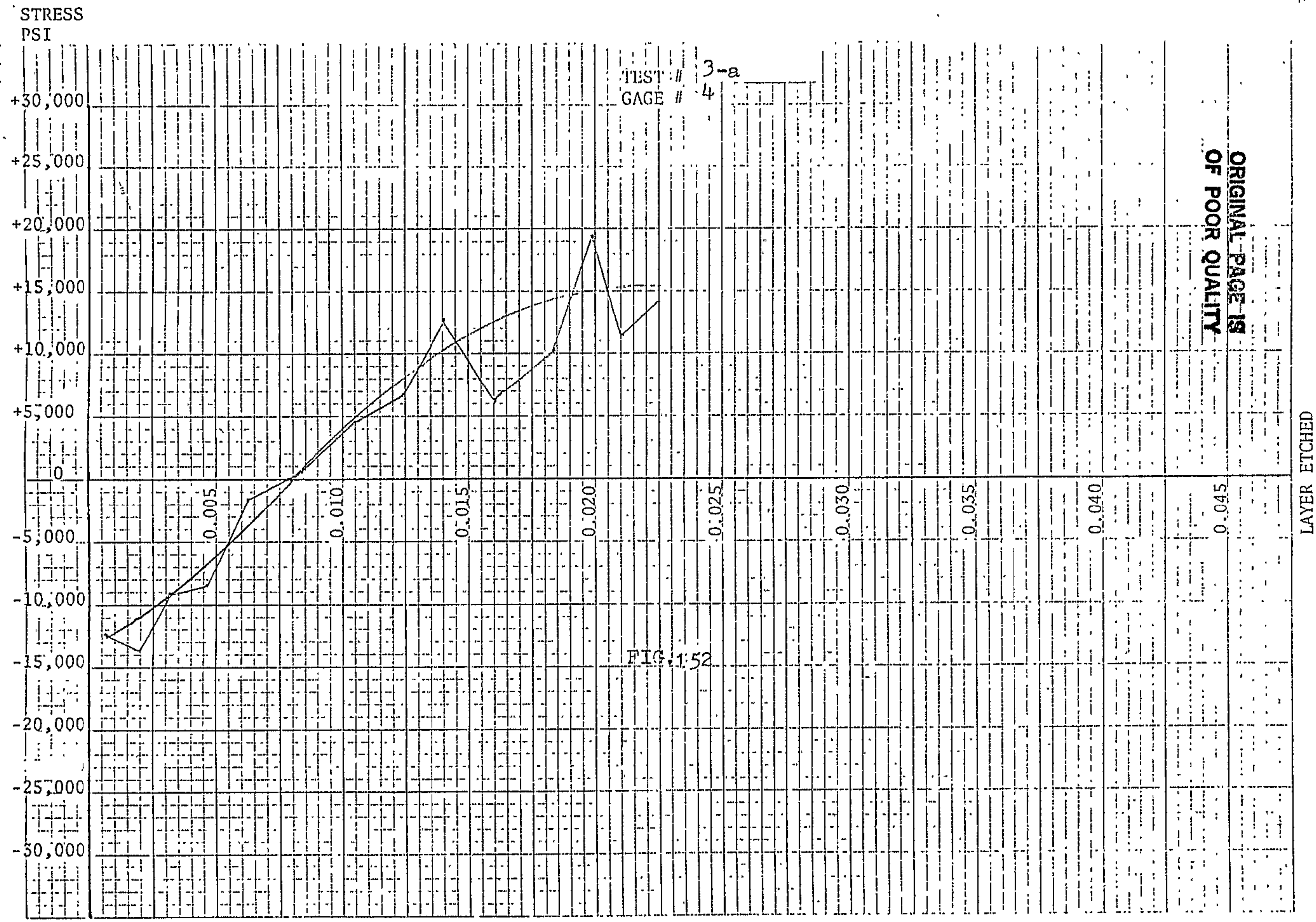
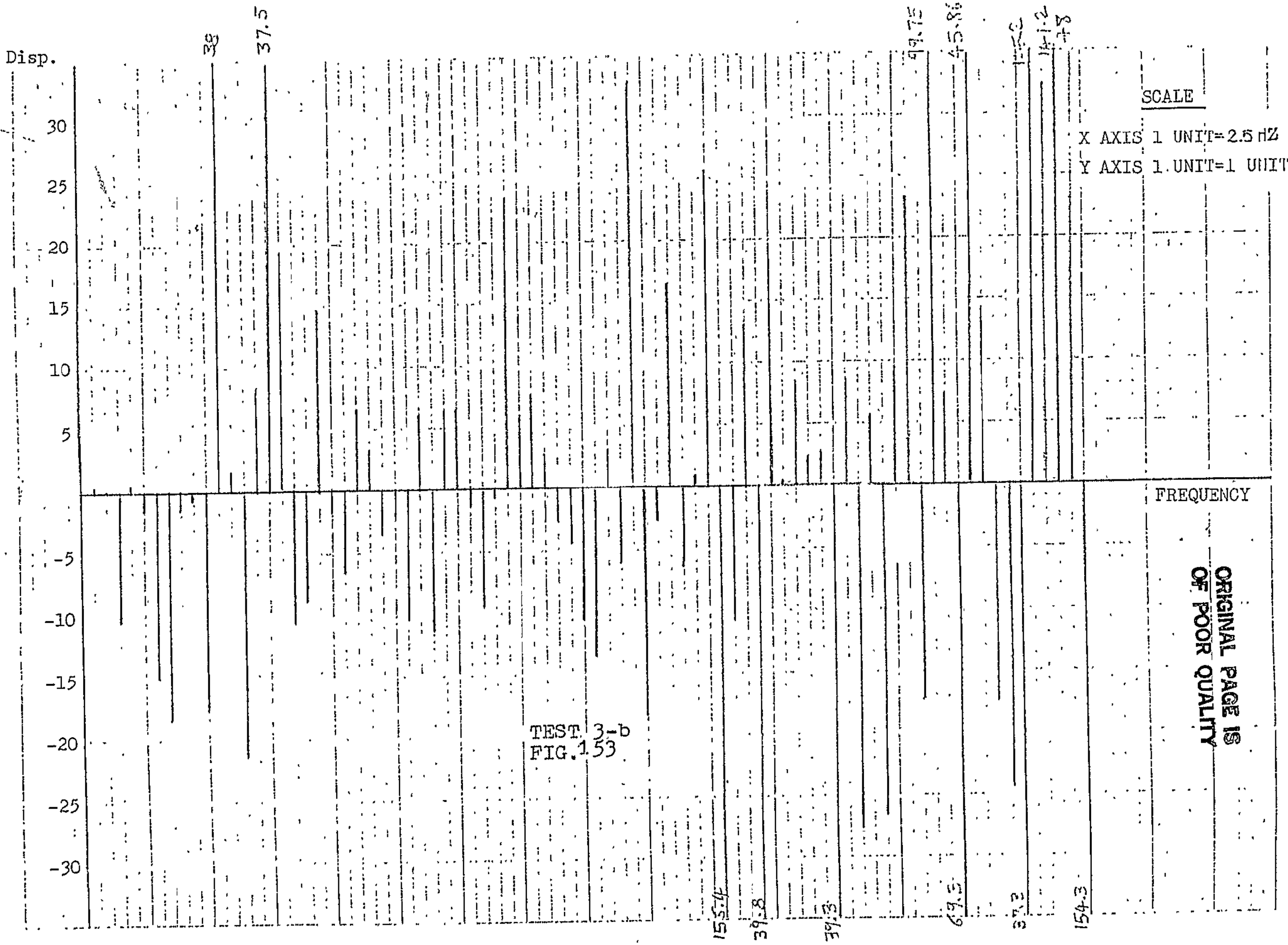

STRESS
PSI
TEST # 3-a
GAGE # 4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 152



TEST 3-b
FIG. 153

ORIGINAL PAGE IS
OF POOR QUALITY

	GAGE #	1	2	3	4
AYER	1	2479.	2479.	1239.	-3718.
AYER	2	2880.	1933.	1913.	-1953.
AYER	3	4363.	3277.	4324.	-2231.
AYER	4	4831.	4791.	4792.	-138.
AYER	5	5316.	3252.	5277.	-2161.
AYER	6	5851.	4673.	5813.	-176.
AYER	7	5272.	5174.	5233.	2236.
AYER	8	5097.	3857.	2774.	2151.
AYER	9	2993.	2877.	1721.	3492.
AYER	10	2905.	2789.	542.	3365.
AYER	11	4058.	3943.	-1717.	4538.
AYER	12	1909.	615.	-3043.	4824.
AYER	13	-1130.	-1263.	-1442.	3934.
AYER	14	-1330.	-2476.	-2654.	4320.

TEST 3-c
FIG. 154

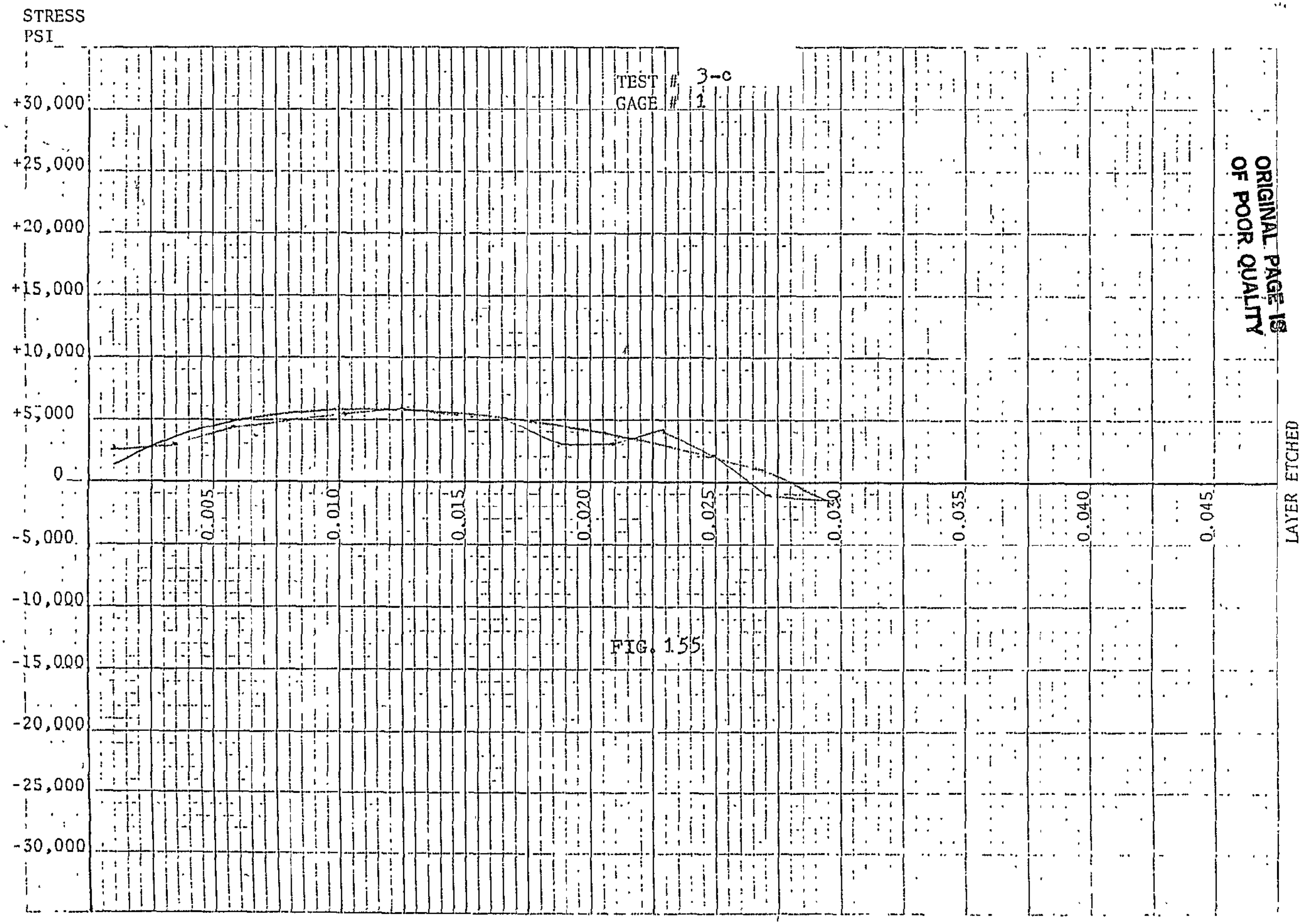
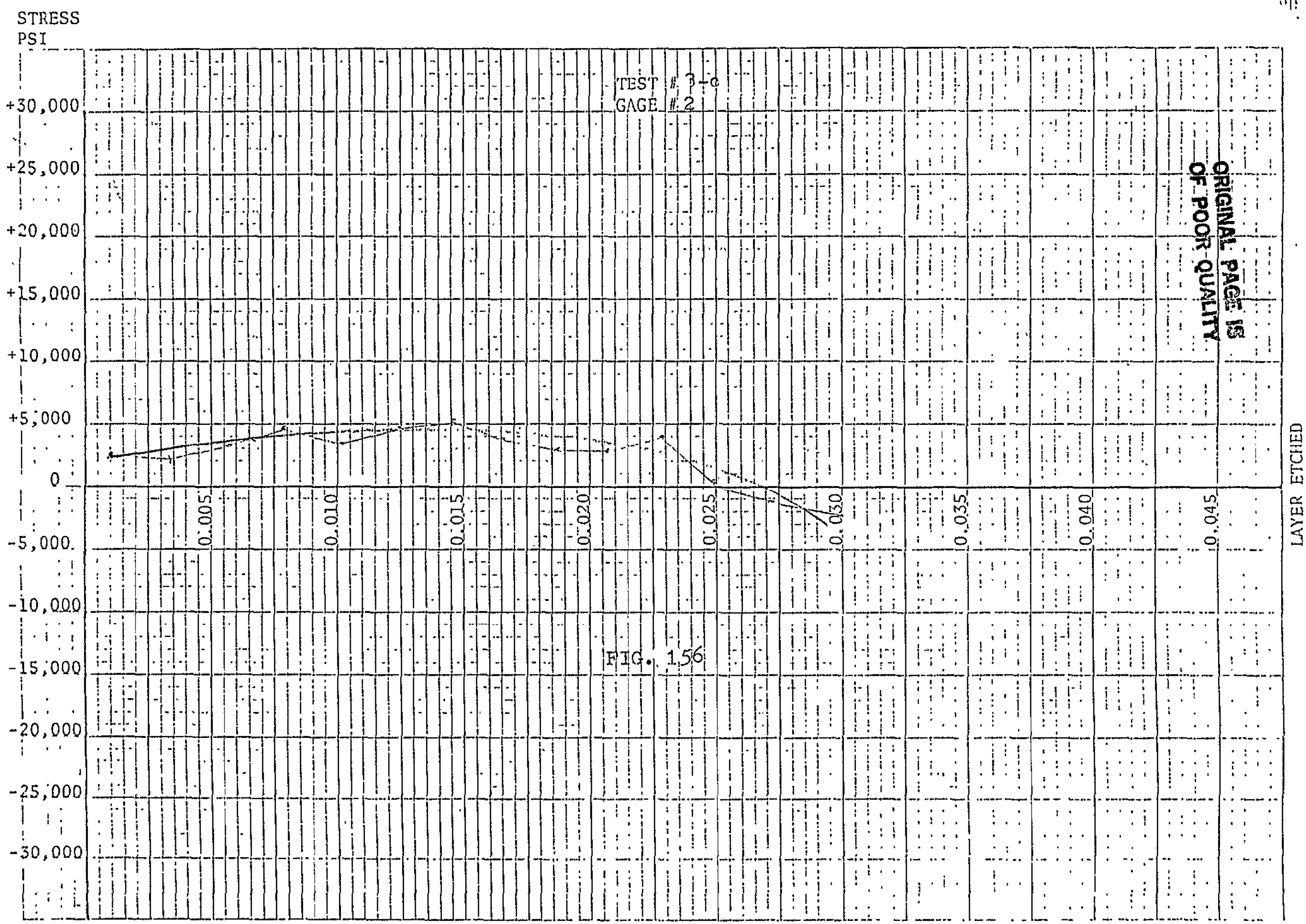

STRESS
PSI
TEST # 3-c
GAGE # 1
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 155



STRESS
PSI
TEST # 3-c
GAGE # 2
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 156

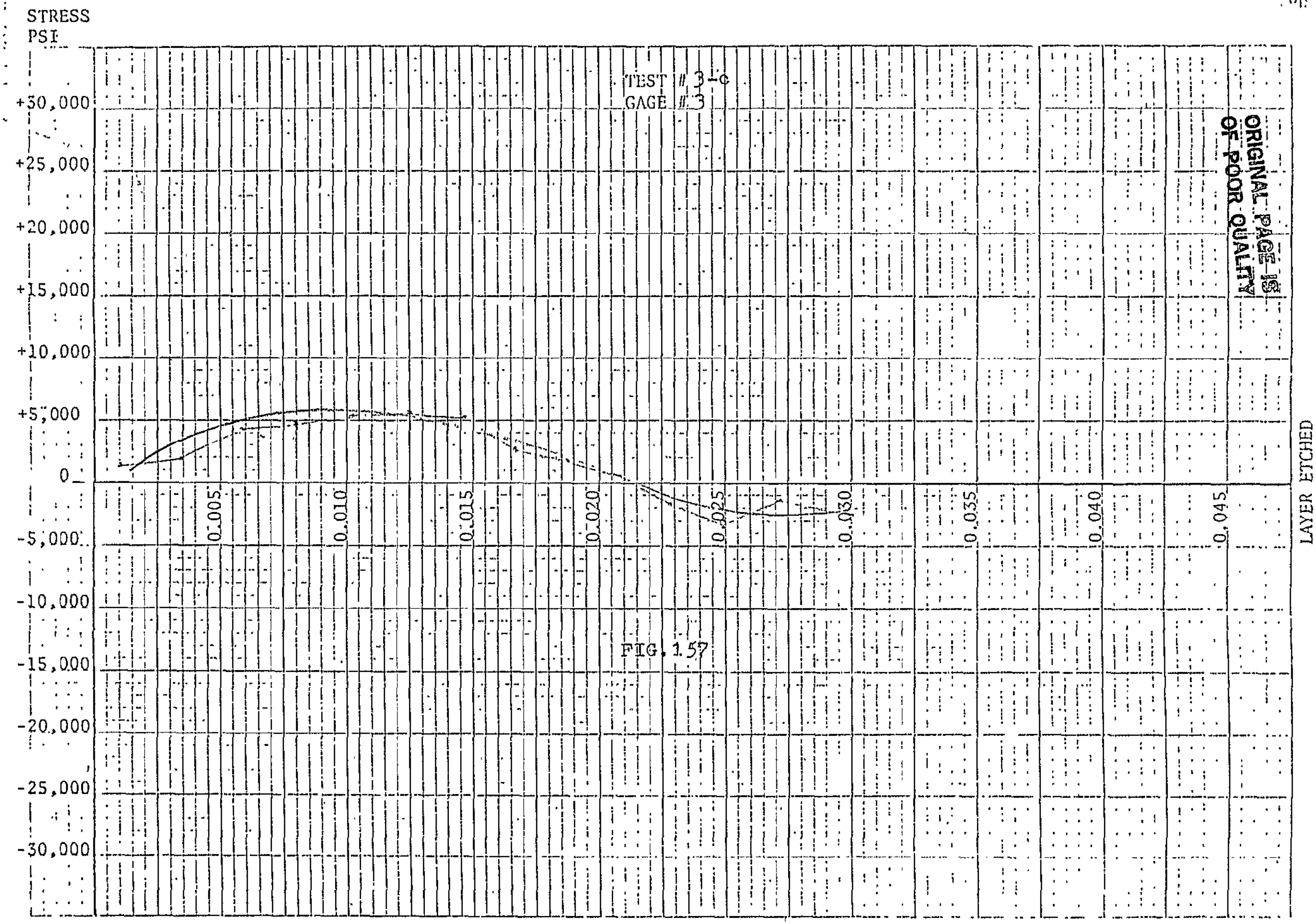


FIG. 157

ORIGINAL PAGE IS OF POOR QUALITY

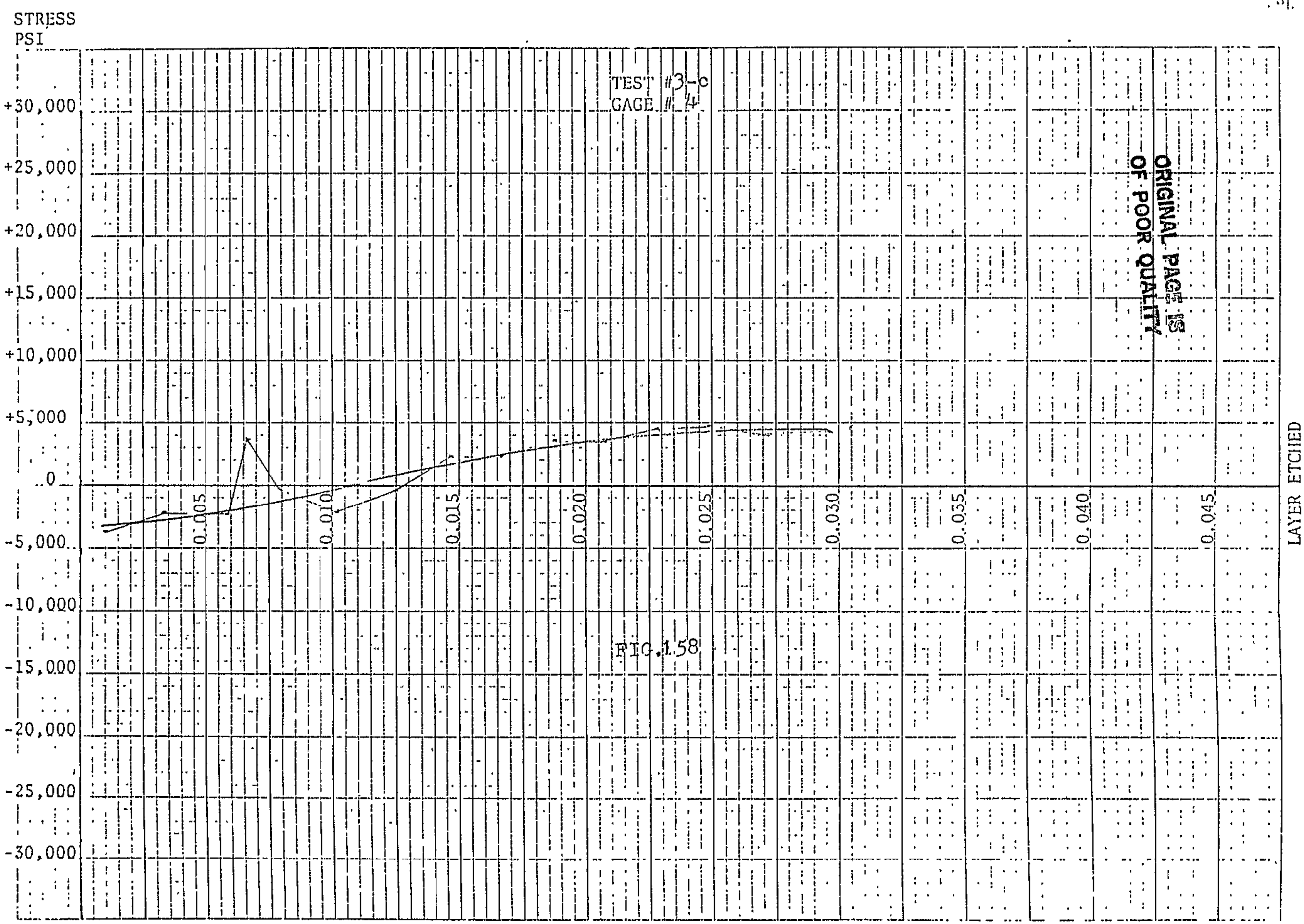

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST #3-c
GAGE # 4
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 158

	GAGE #	1	2	3	4
AYER	1	3362.	3362.	-6723.	-5603.
AYER	2	6189.	5167.	-5227.	-5207.
AYER	3	5996.	5976.	-4872.	-4852.
AYER	4	6685.	5384.	-5423.	-4122.
AYER	5	6178.	4204.	-1341.	633.
AYER	6	7820.	5647.	657.	1783.
AYER	7	6076.	4868.	3992.	4090.
AYER	8	5501.	4169.	5688.	6980.
AYER	9	4754.	2619.	5752.	5869.
AYER	10	2838.	-2279.	6827.	5958.
AYER	11	-2165.	-4503.	7233.	7328.
AYER	12	-4742.	-5072.	9139.	9233.
AYER	13	-5102.	-4264.	8539.	8633.
AYER	14	-4020.	-4326.	7479.	8734.

TEST 4-a
FIG. 159

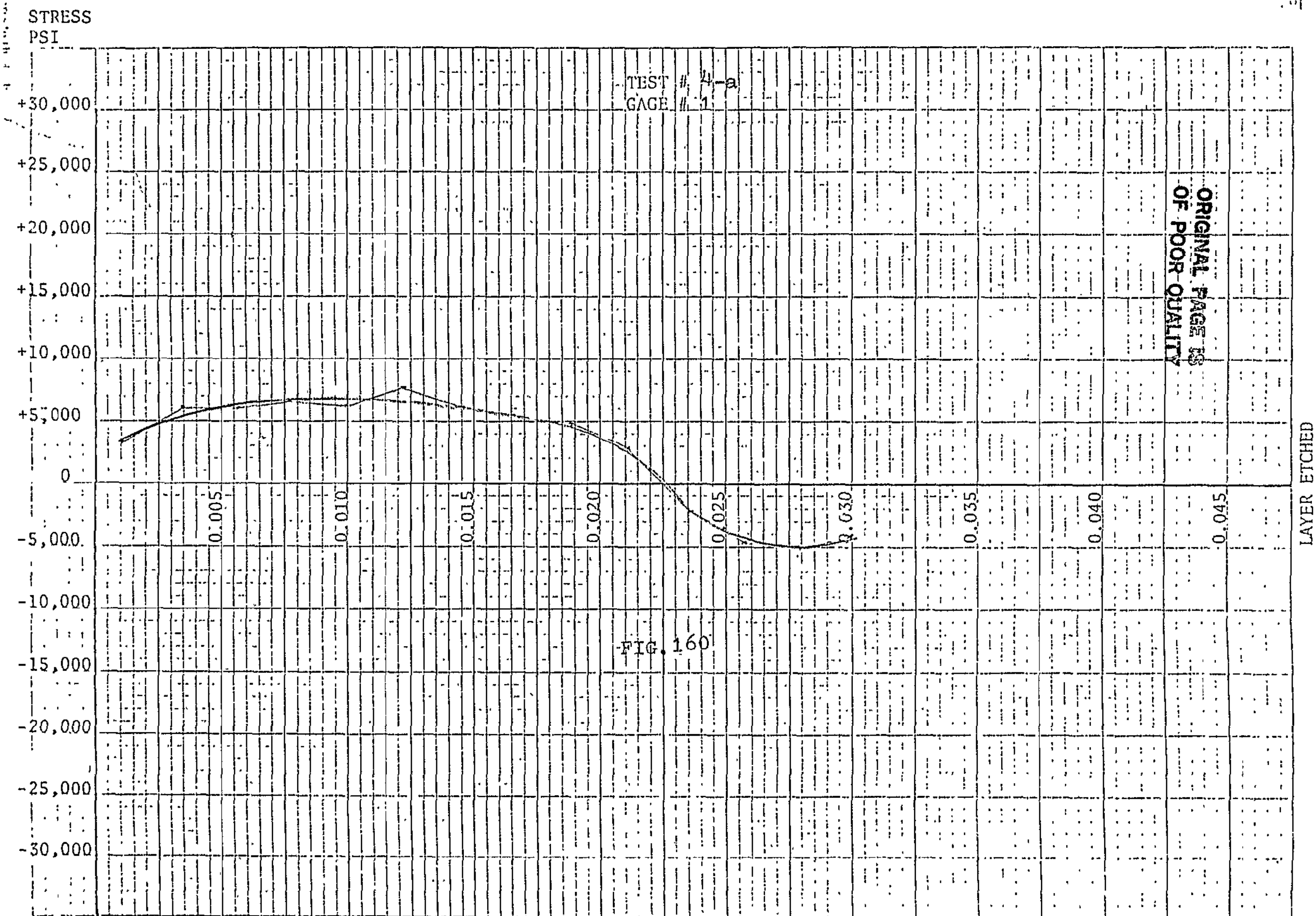

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 4-a
GAGE # 1
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 160

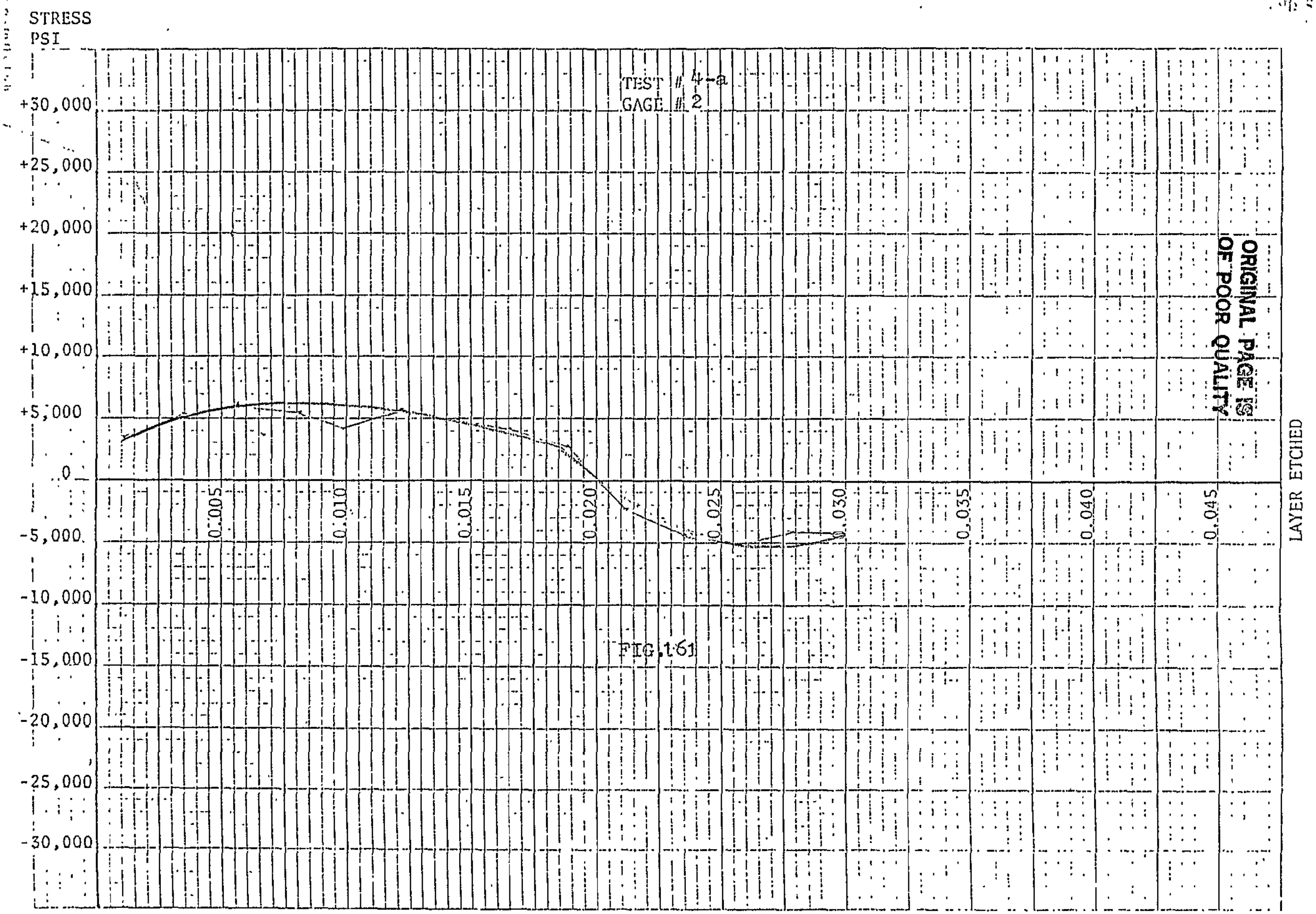


FIG. 161

ORIGINAL PAGE IS
OF POOR QUALITY

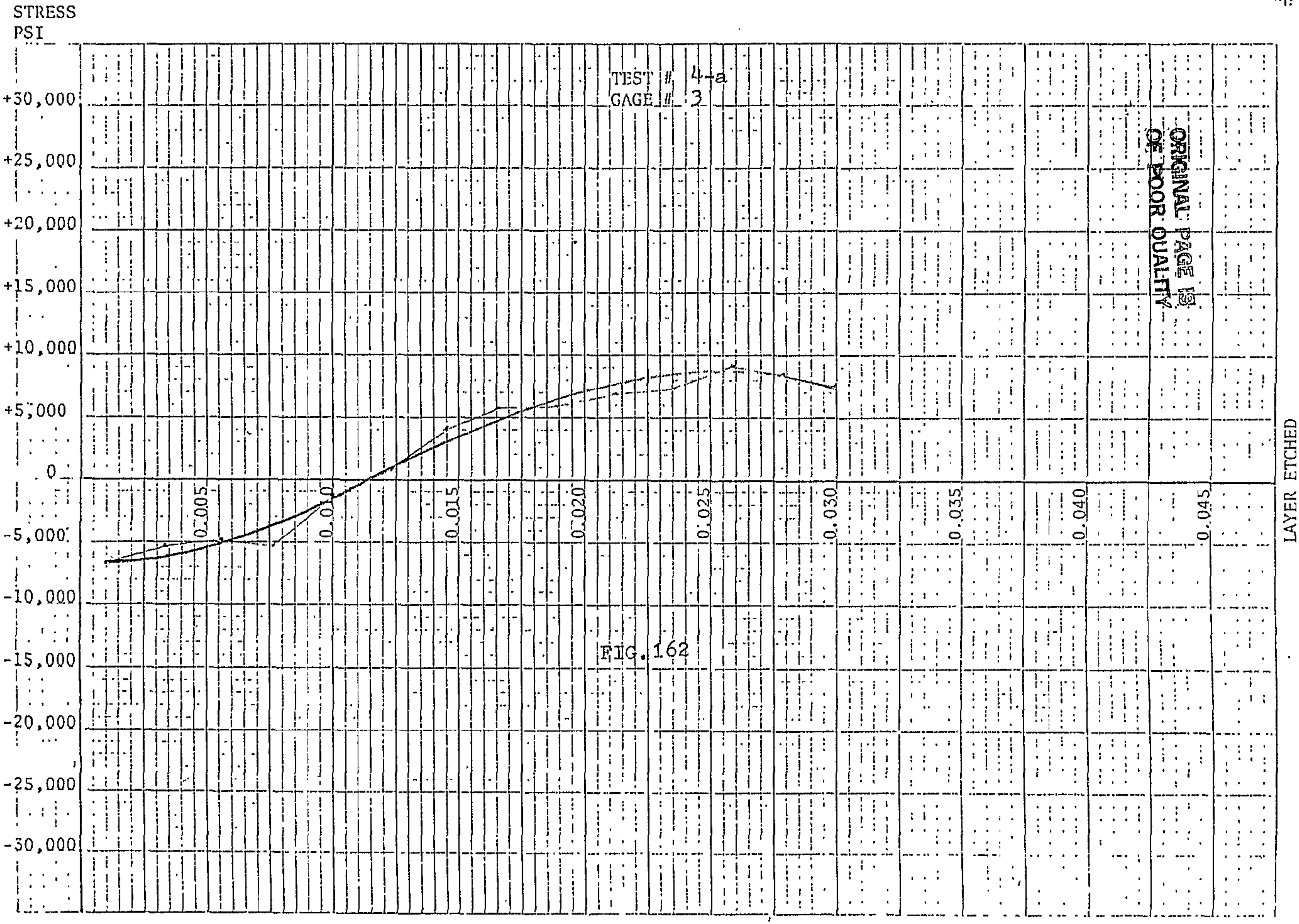

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 4-a
GAGE # 3
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 162

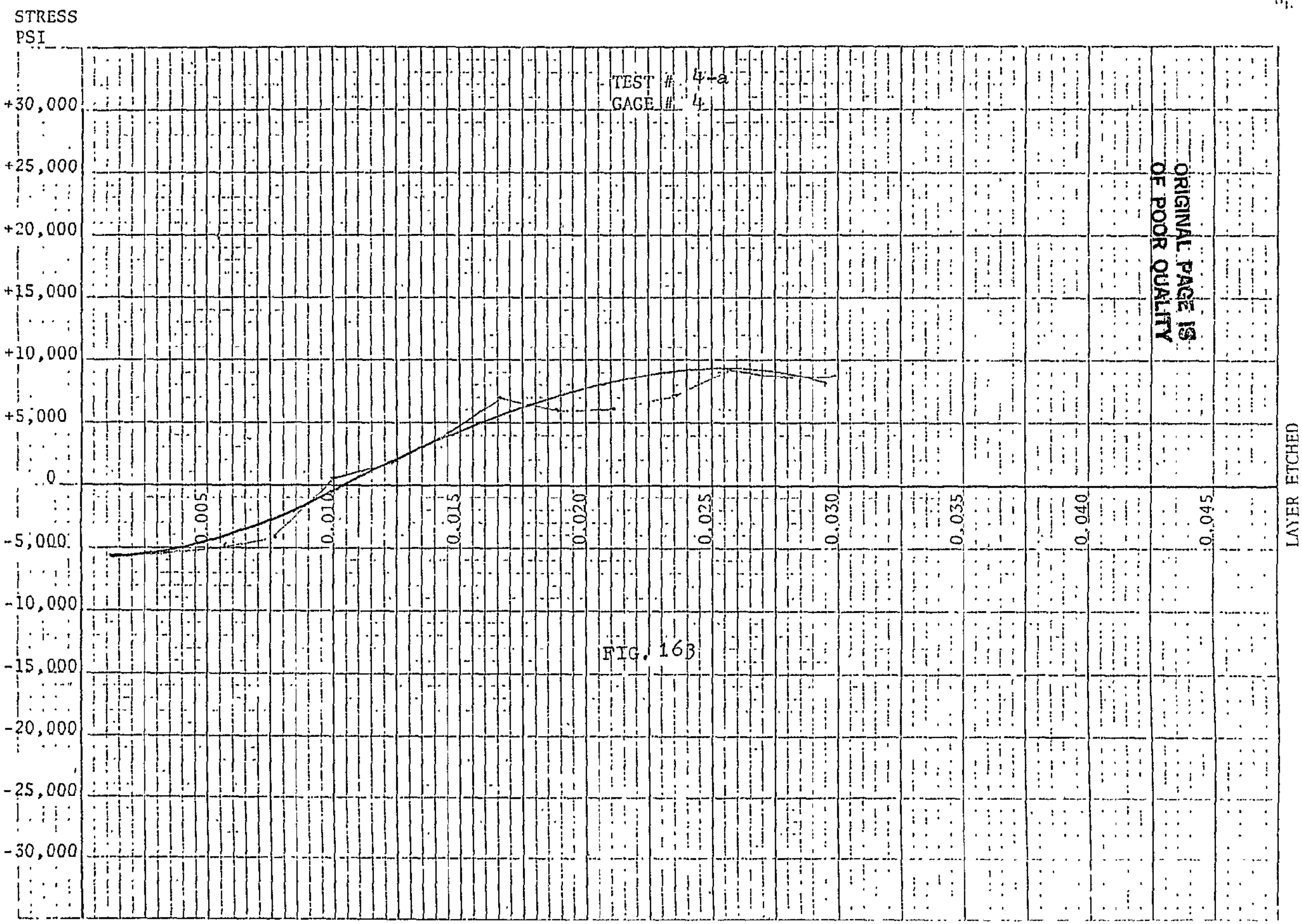
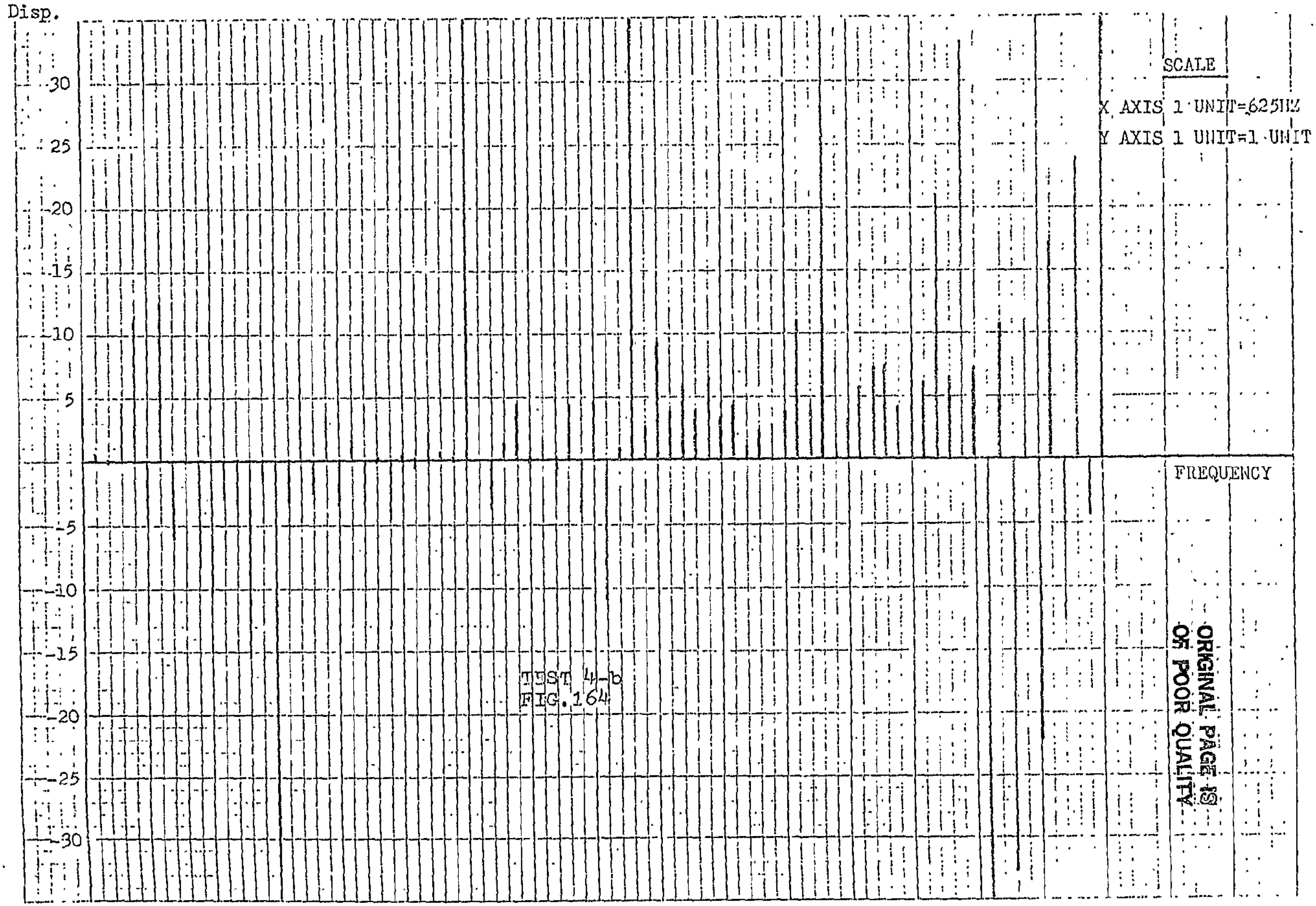

STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 4-a
GAGE # 4
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
ORIGINAL PAGE IS
OF POOR QUALITY

FIG. 163


Disp.
SCALE
X AXIS 1 UNIT=625HZ
Y AXIS 1 UNIT=1 UNIT
FREQUENCY
30
25
20
15
10
5
-5
-10
-15
-20
-25
-30
TEST 4-b
ORIGINAL PAGE IS OF POOR QUALITY
FIG. 164

	GAGE #	1	2	3	4
AYER	1	2061.	2061.	-2061.	-1030.
AYER	2	1159.	2279.	-2279.	-2259.
AYER	3	2514.	3761.	-1307.	-1287.
AYER	4	3282.	3322.	-99.	-79.
AYER	5	3632.	4829.	-2414.	-1236.
AYER	6	3675.	4887.	2169.	2208.
AYER	7	5099.	5177.	2316.	1149.
AYER	8	3227.	3305.	1861.	2838.
AYER	9	3521.	2561.	3096.	3135.
AYER	10	2530.	1555.	2108.	3179.
AYER	11	2869.	-645.	3633.	3691.
AYER	12	2895.	-1841.	3677.	4913.
AYER	13	1593.	-2584.	4276.	4353.
AYER	14	-423.	-2632.	3320.	4410.

TEST 4-c
FIG.165

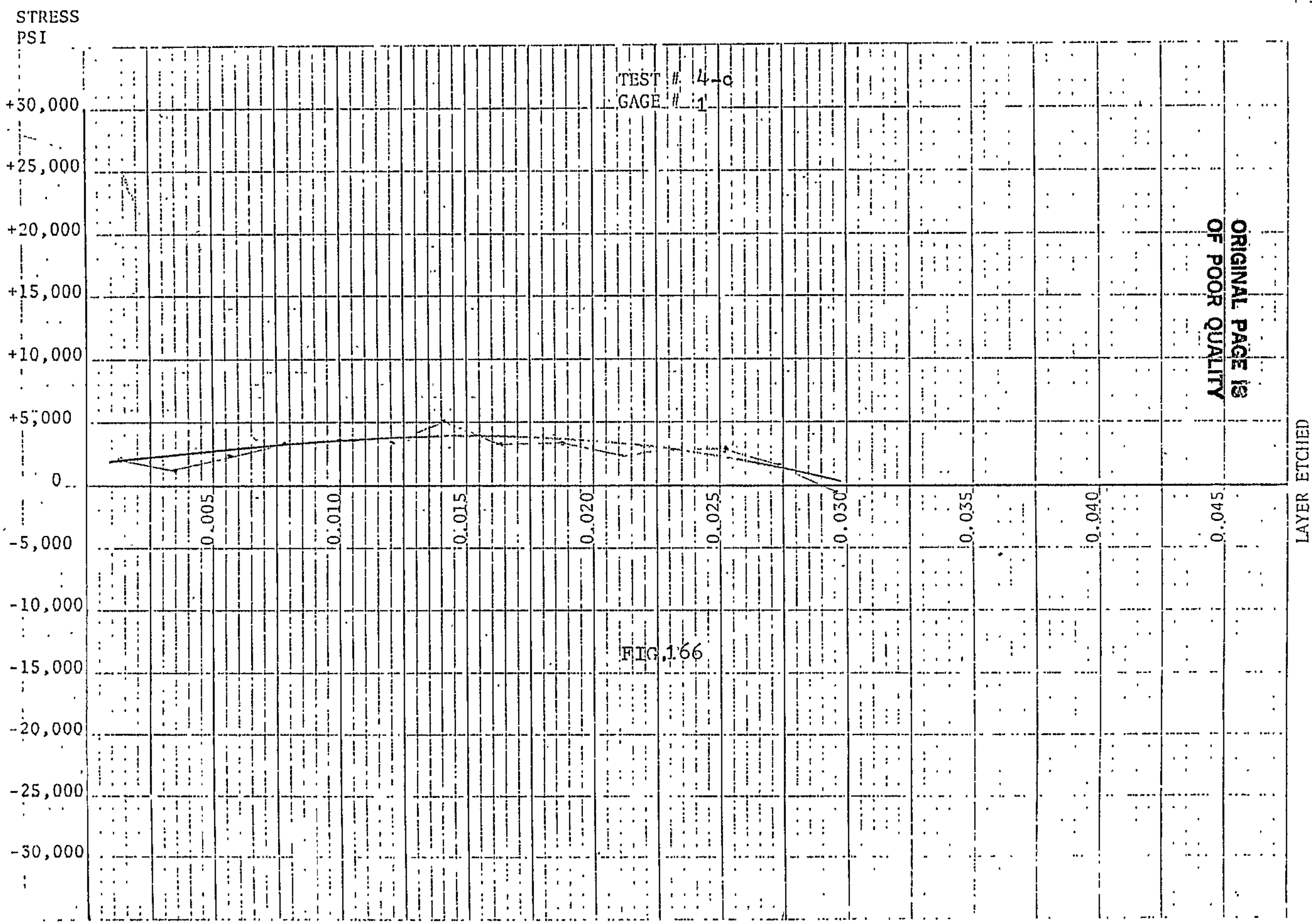

STRESS PSI
TEST # 4-c
GAGE # 1
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED
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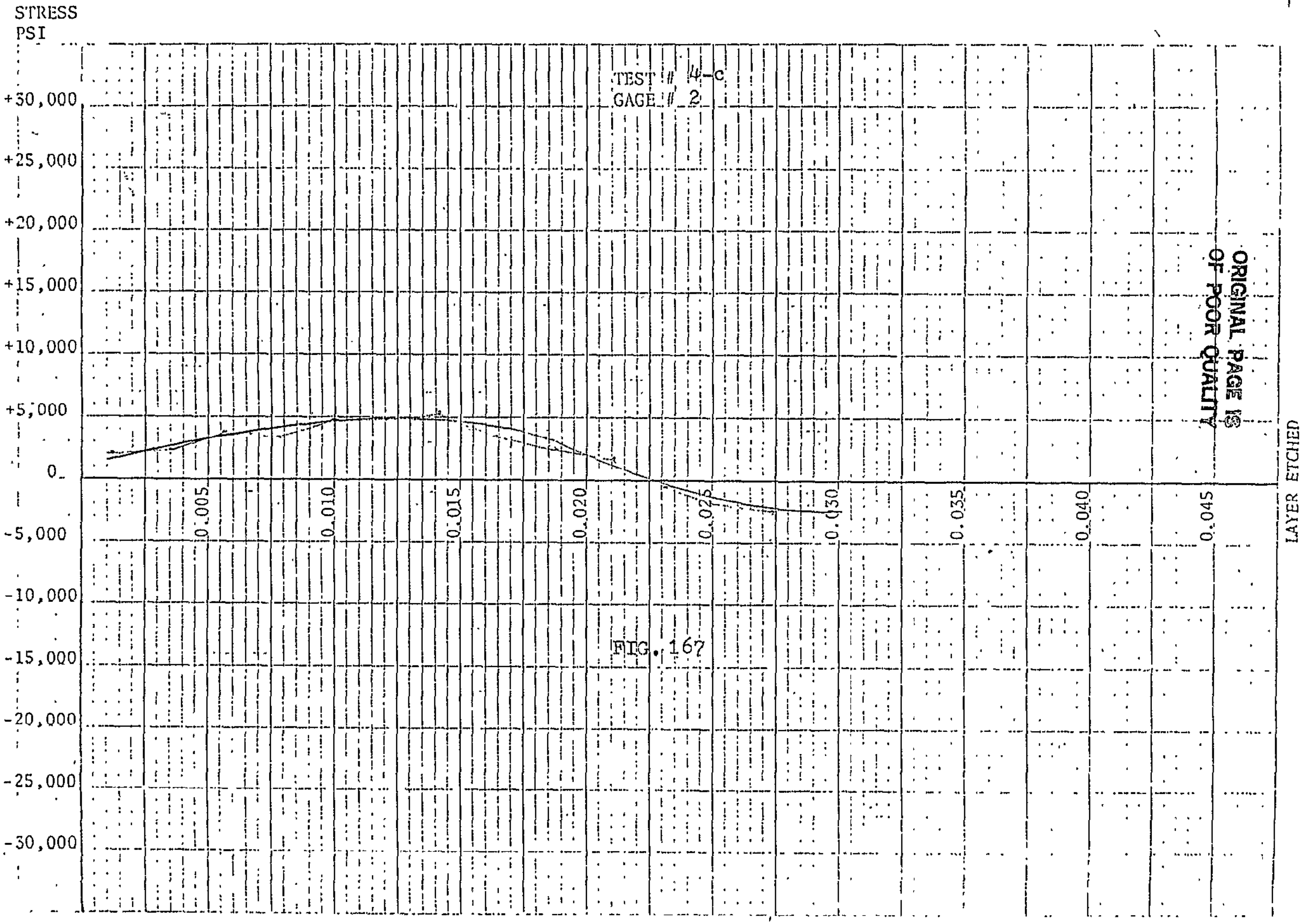
FIG. 166



STRESS
PSI
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
TEST # 4-c
GAGE # 2
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 167

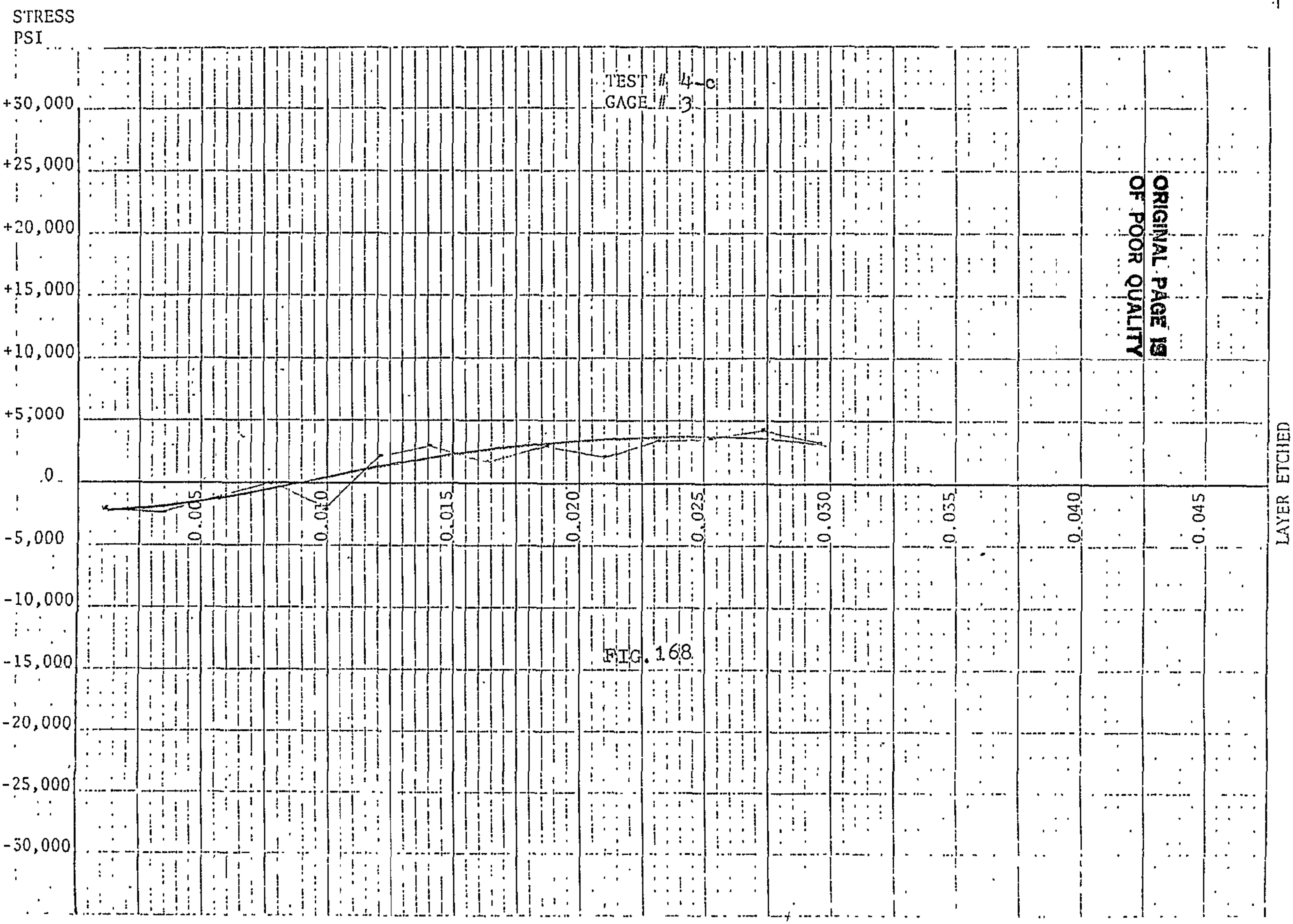


FIG. 168

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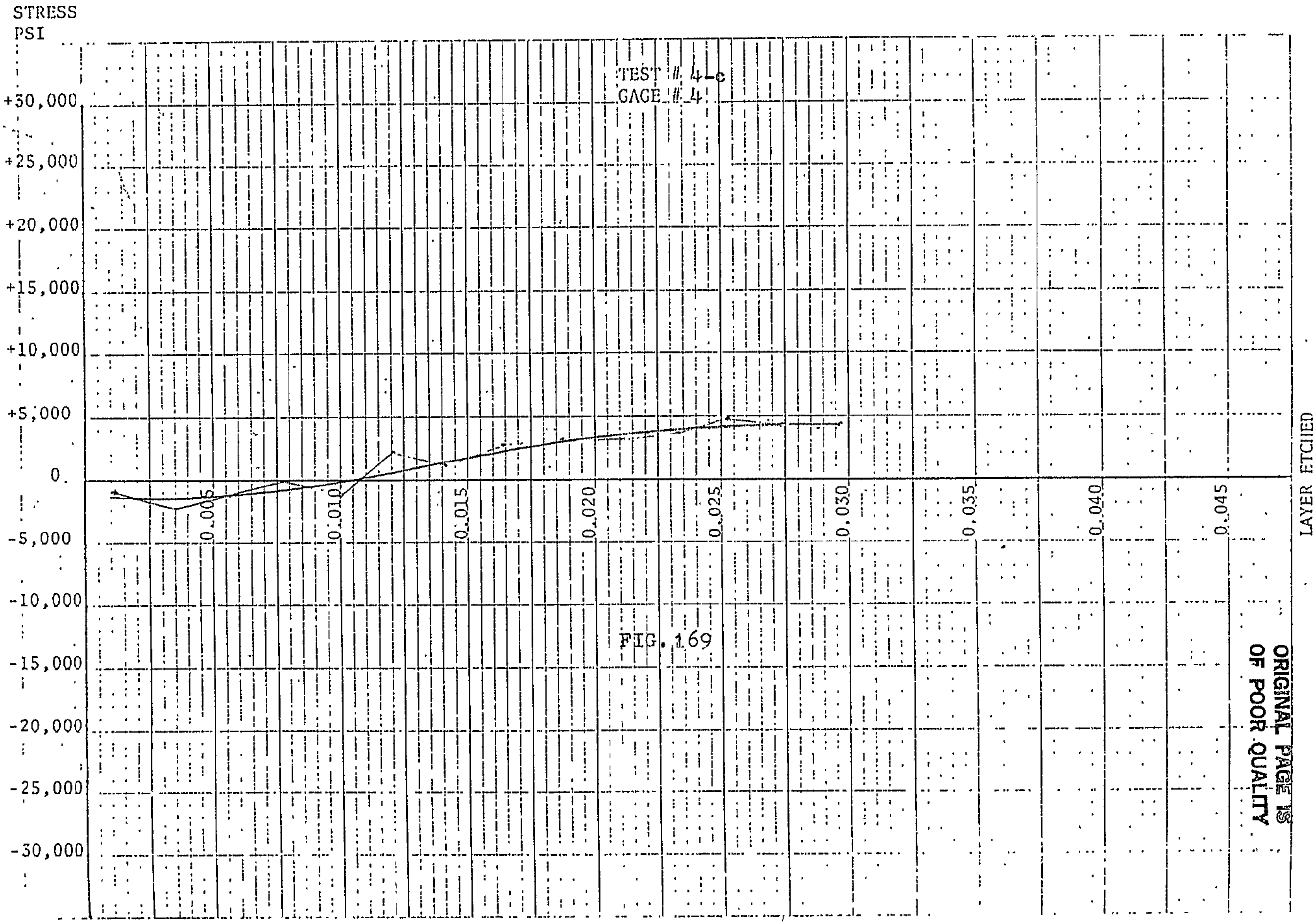

STRESS
PSI
TEST # 4-c
GAGE # 4
+30,000
+25,000
+20,000
+15,000
+10,000
+5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
LAYER ETCHED

FIG. 169

PART SIX

Previous experimental investigations proved that a mechanical vibration of a suitable frequency within 100 cps can be used to reduce the peaks of residual stresses at the weld zone for both structural steel and aluminum frames. The vibration period is limited to 15 minutes in order to eliminate any fatigue in the metal bars.

The earlier experiments with vibration techniques pointed up the need to examine temperatures at the weld point as they affect residual stresses and their distribution. It is believed that controlling sharp changes in temperature will modifiy or eliminate the harmful effects of residual stresses.

The basis for the calculations of heat flow originated in the work of Roberts(16) and Rosenthal(17). Various assumptions were necessary in the derivations of the mathematical formulae, including the possible radiation and convection losses(18).

The experimental work involved measuring the temperature along and across the weld and through the depth following the bead deposit. Chromel-alumel thermocouples with refrasil insulation were used for that purpose. The junction of each thermocouple was mounted in a hole drilled in the bar to be welded at specific locations, as given in the figures with the experimental results.

Sometimes the thermocouples were dipped into the molten metal to check the actual melting temperature.* Signals from the thermocouples were recorded using a pyrometer and a multi-channel switch. Equipment has been calibrated by the Omega manufacturers and rechecked locally on campus.

Results are presented as curves of temperature against time. The curves have a wide application for different speeds of moving heat source and for differing bar width. Results showed the max. temperature always located under the source of heat while it was moving across the metallic bar. Temperature increased through the bar thickness with the successive beads being deposited.

At the beginning of the weld and during the first pass, a steep temperature gradient was always encountered. But as the bars got hot the variation of the temperature narrowed. The multi bead deposition was carried out on both the A36 steel and the 6061T6 aluminum bars using the arc welding technique.

As the heat source crossed the metallic bar, the temperature dropped sharply from the weld zone along the bar, i.e., in a direction at right angles to the weld. This sharp drop was due to several reasons including the metal conductivity, the speed of weld, the bar proportions and the radiation and convection heat losses.

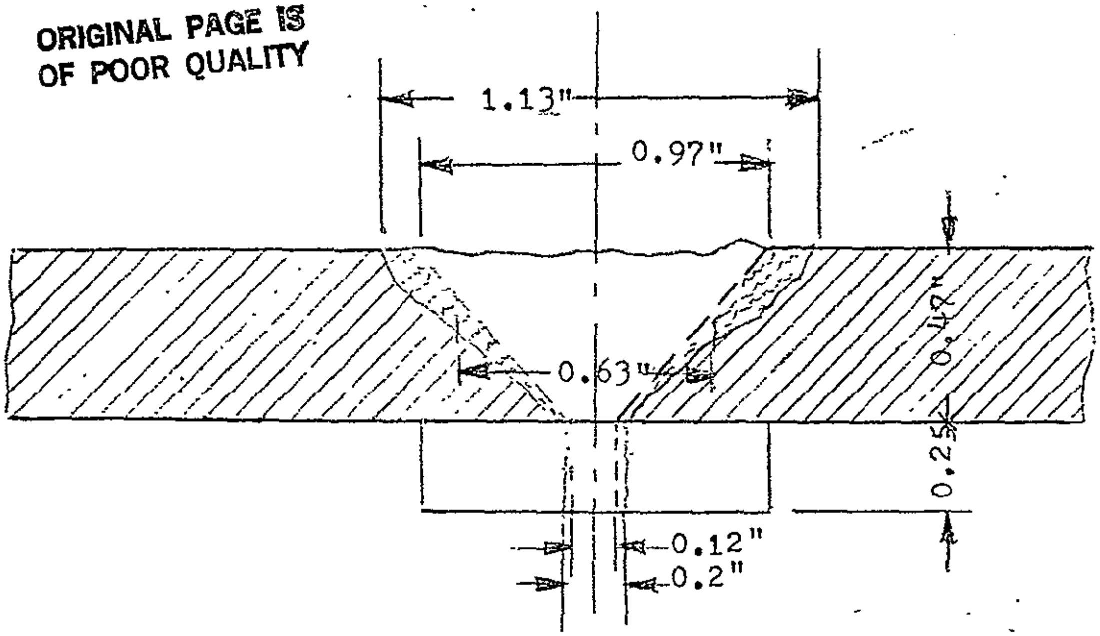
*A36 steel indicated a melting temperature of 2300°F
6061T6 aluminum indicated a melting temperature of 1100°F

Figures 172,173 show the variations in temperature in the direction of weld and that these variations narrow with the successive beads. This supports the idea of limiting the development of stresses if the metal is preheated. It also indicates that the larger the number of passes the better the temperature distribution and the less the danger of the internal stresses.

The same line of discussion is true for other tests where temperatures are measured along the bar , i.e., at right angles to the weld direction, the case that represents the most citical problem as far as the variation in temperatures and correspondingly the peaks of the generated residual stresses are concerned.

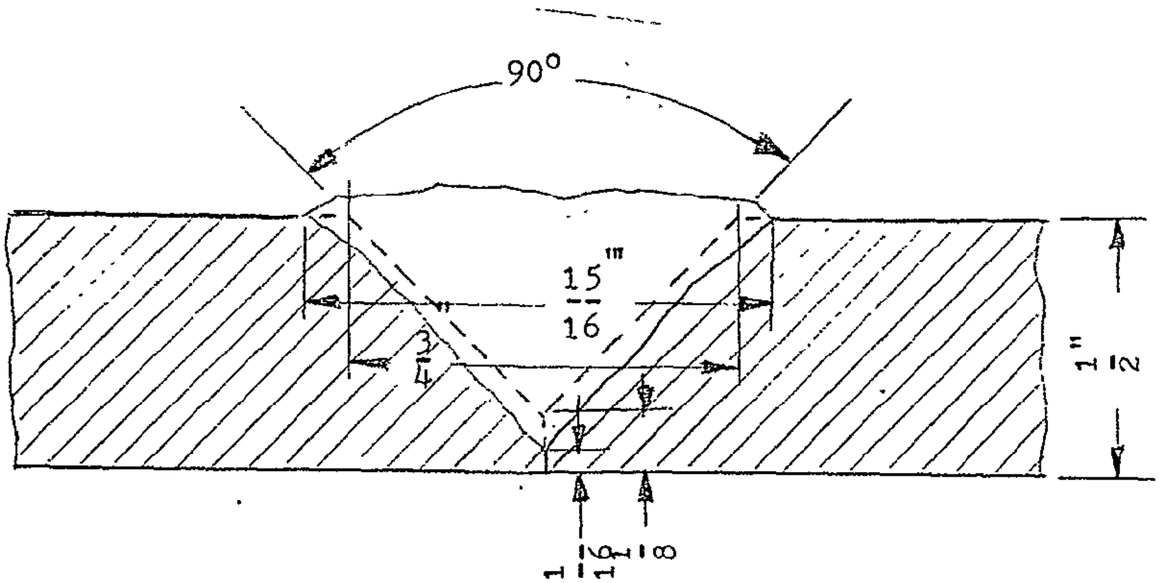
At present several tests are being carried out on both steel and aluminum bars of various thicknesses and widths. This is done in order to confirm the temperature distribution characteristics and to find out the effect of the bar proportions on the degrees of heat losses and the sudden differential temperature.

For future work, a study will be added to investigate the beneficial effects of stress-relief on the metallurgical structure of both the aluminum and steel and how can this be related to the fatigue strength of the metal. An investigation will be carried out on the possible reduction or control of the effects of peak temperatures at the weld zone by raising the temperature of the structure members around this zone using some type of induction heating thereby reducing the sudden differnetial of temperature in the surrounding metal.



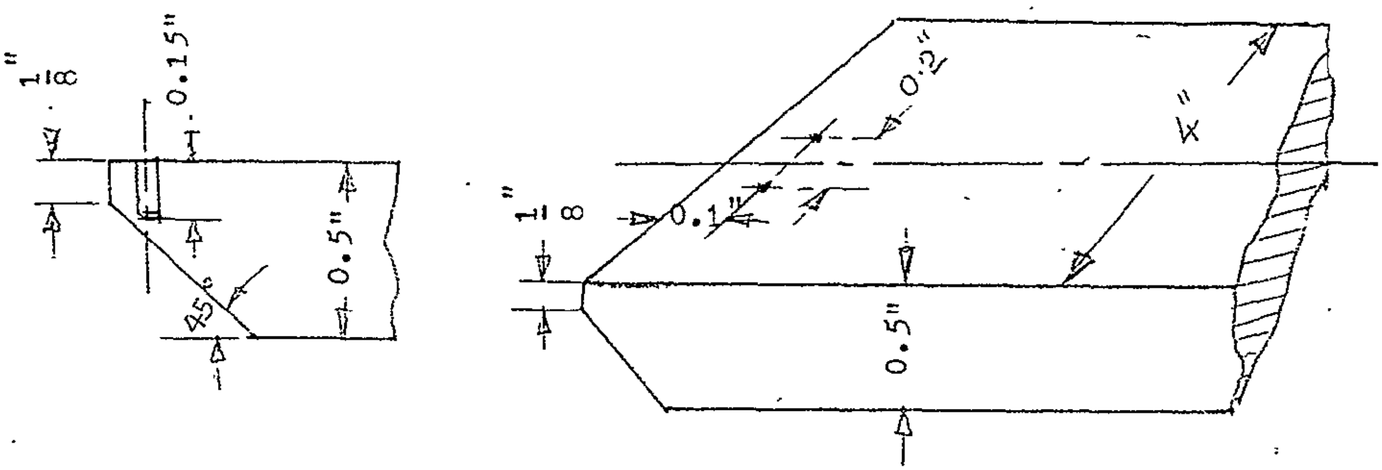
A36 Steel bars

FIG. 170



6061T6 - Aluminum Bars

FIG. 171



A36 Steel Bar 4" x 1/2"

FIG. 172

Gauge arrangement
Holes are drilled from the bottom side of the bar

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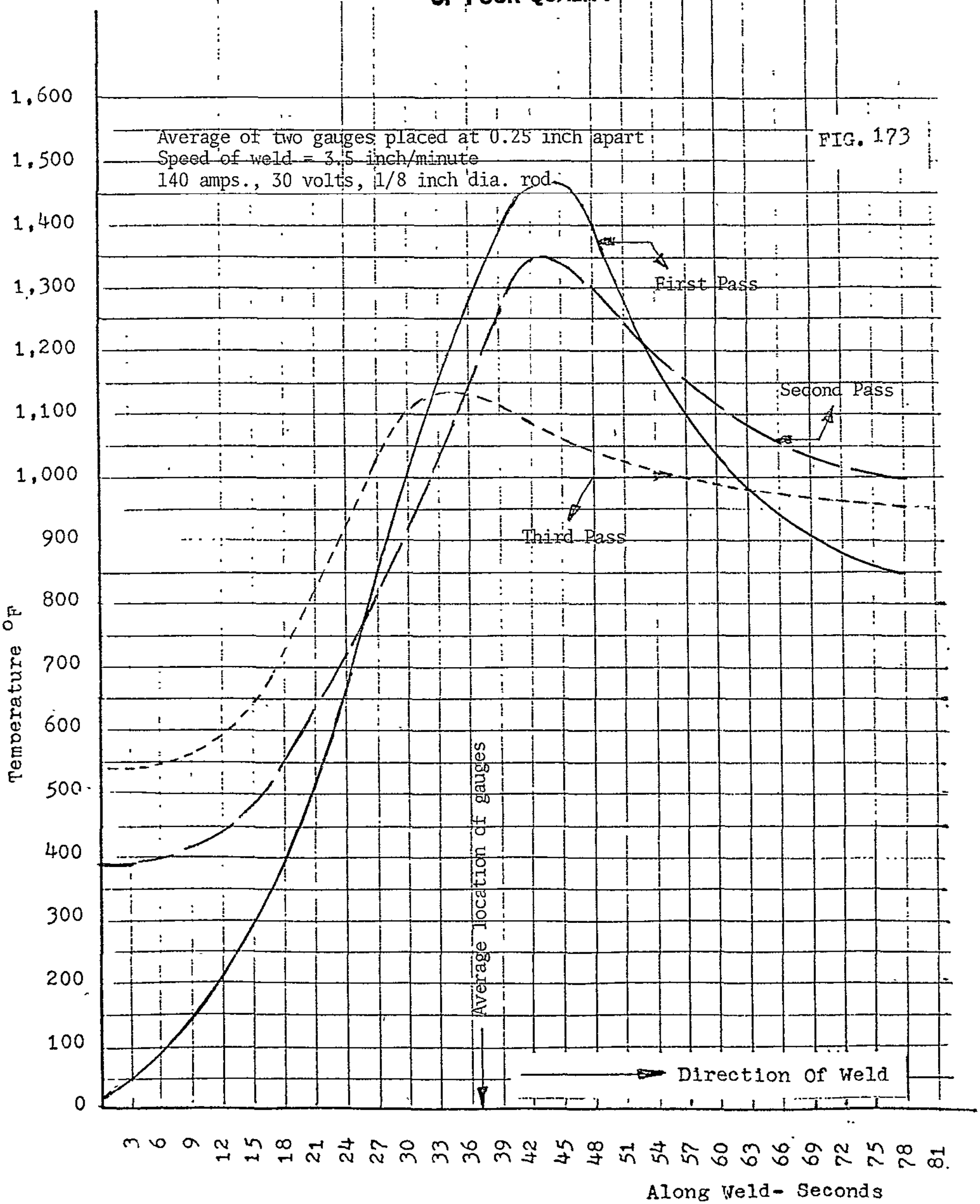
TABLE 24

GAUGE # 1			GAUGE # 2		
1st. Pass	2nd. Pass	3rd. Pass	1st. Pass	2nd. Pass	3rd. Pass
32	400	550	32	392	536 °F
78	400	550	68	392	520
200	450	550	212	438	572
380	560	730	392	572	752
680	730	955	692	752	932
1020	930	1100	1022	932	1112
1270	1120	1120	1282	1118	1115
1475	1335	1080	1472	1364	1076
1375	1300	1020	1382	1292	1030
1160	1170	1010	1152	1180	1020
1030	1090	1000	1036	1112	1004
935	1035	1000	932	1066	980
905	1020	960	890	1020	950
860	1000	950	852	990	950

NOTE: Readings are taken every 6 seconds


Average of two gauges placed at 0.25 inch apart
Speed of weld = 3.5 inch/minute
140 amps., 30 volts, 1/8 inch dia. rod
FIG. 173
First Pass
Second Pass
Third Pass
Average location of gauges
Direction Of Weld
Temperature °F
1,600
1,500
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
200
100
0
3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48 51 54 57 60 63 66 69 72 75 78 81
Along Weld- Seconds

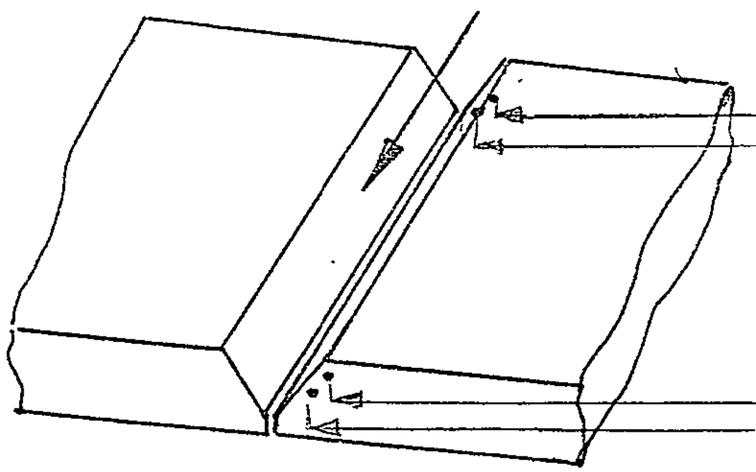
Arc Welding

Speed of weld = 3.5 inch/minute
Amp. 140, Volt 30, dia. of rod 1/8 inch

A36 Steel Bar 4" x $\frac{1}{2}$"

Gauge arrangement

Holes are drilled from the sides of the bar.



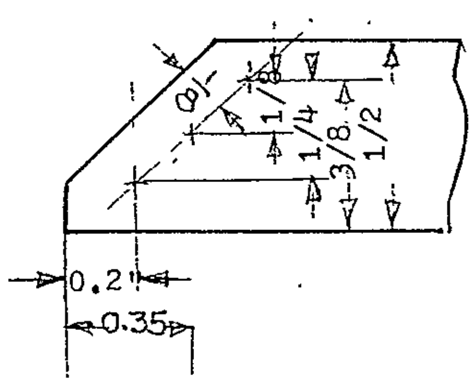


FIG.174

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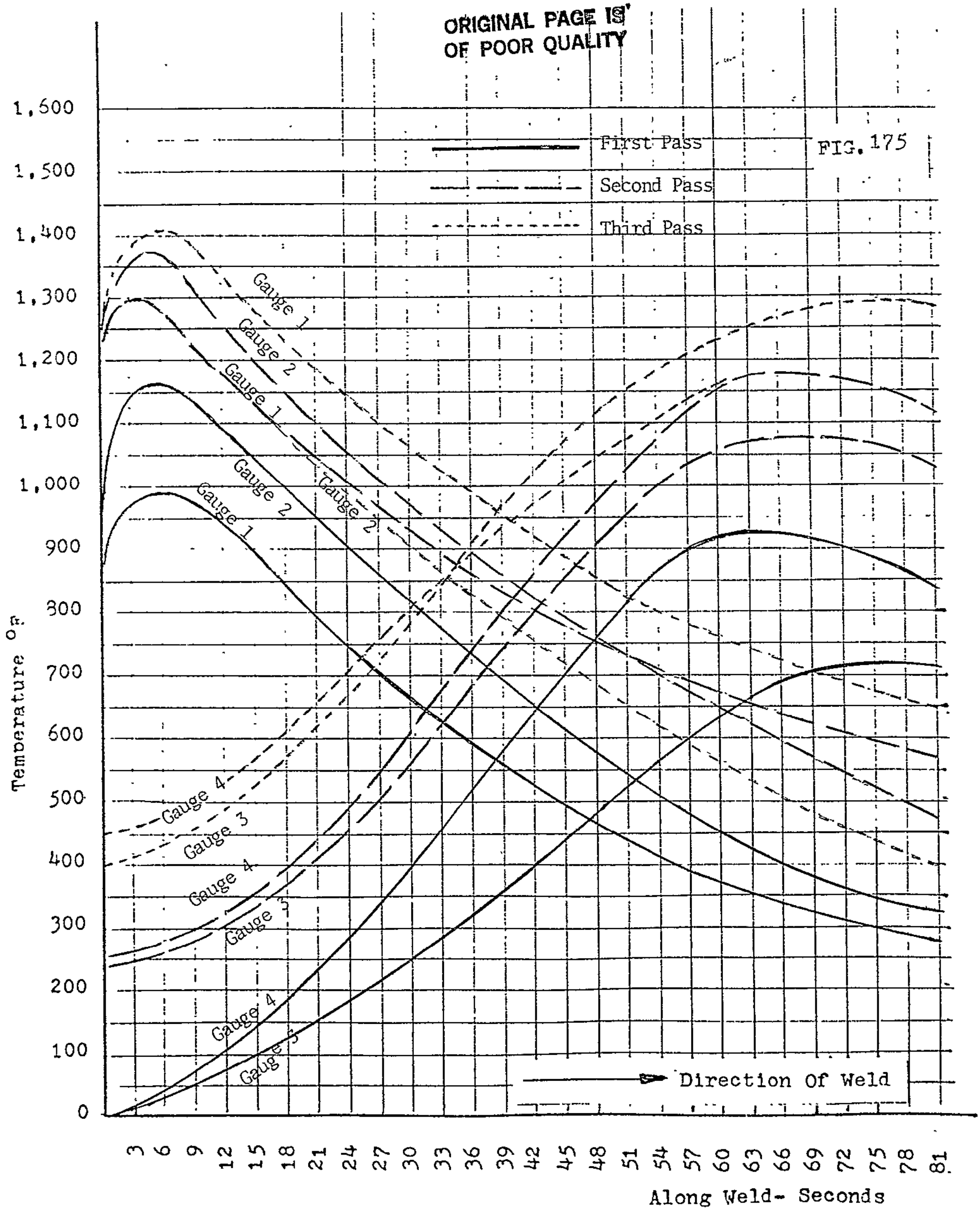
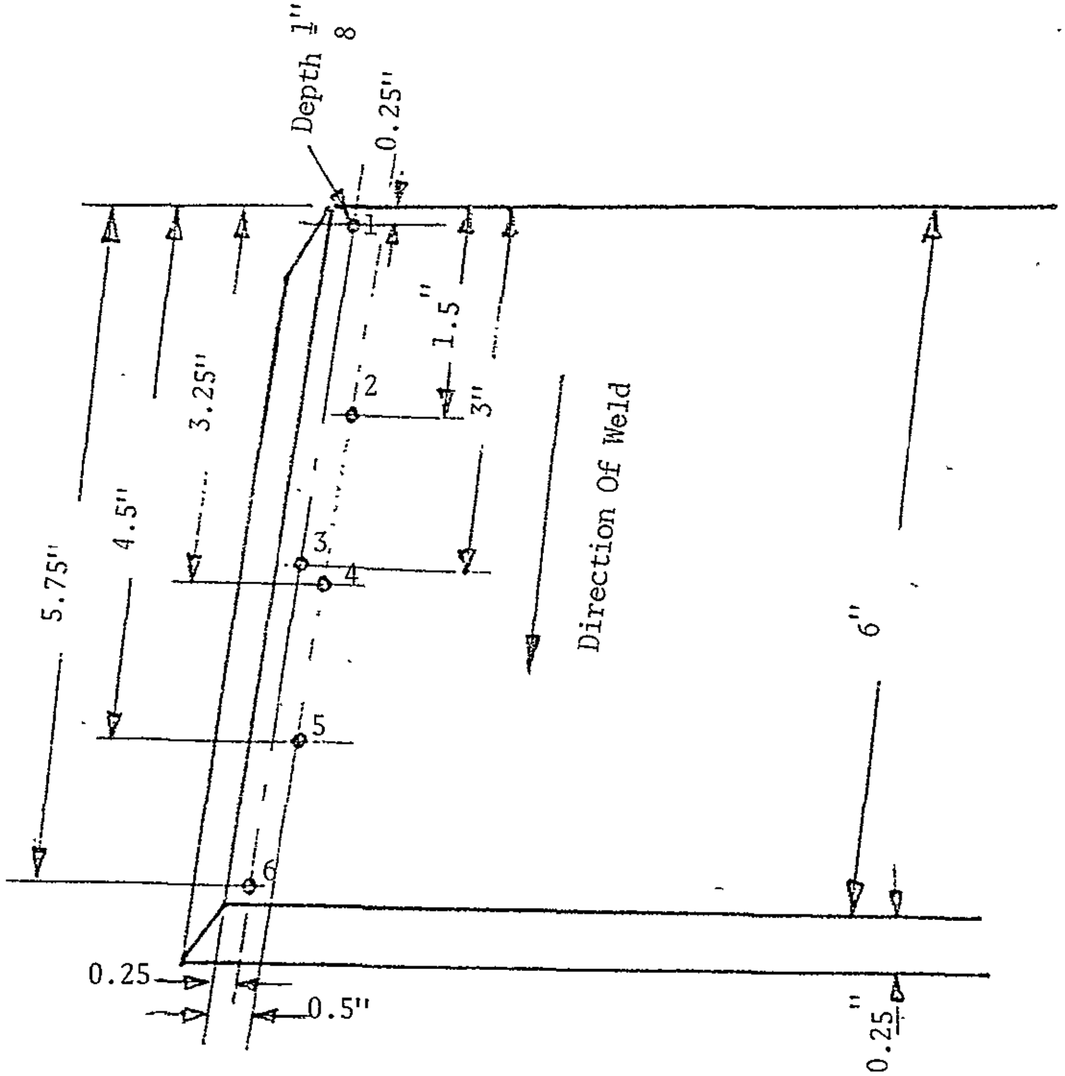
TABLE 25

GAUGE # 1			GAUGE # 2			GAUGE # 3			GAUGE # 4		
1st.P	2nd. P	3rd. P	1st. P	2nd. P	3rd. P	1st. P	2nd. P	3rd. P	1st. P	2nd. P	3rd. P
0	250	500	0	270	400	0	250	400	0	250	450
950	1280	1370									
			1150	1370	1270						
						50	270	450			
									100	320	520
900	1120	1270									
			1000	1150	1070						
						150	400	600			
									290	500	700
700	950	1090									
			800	960	900						
						270	610	825			
									500	720	880
540	815	995									
			630	810	730						
						430	830	1050			
									750	960	1030
430	710	820									
			490	690	600						
						600	1010	1190			
									900	1130	1135
340	630	770									
			380	580	490						
						685	1060	1250			
									880	1170	1170
280	555	650									
			310	470	400						
						700	1030	1260			

NOTE:- Readings are taken every 3 seconds


First Pass
Second Pass
Third Pass
FIG. 175
1,600
1,500
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
200
100
0
Temperature °F.
Gauge 1
Gauge 2
Gauge 1
Gauge 2
Gauge 2
Gauge 1
Gauge 4
Gauge 3
Gauge 4
Gauge 3
Gauge 4
Gauge 3
Direction Of Weld
3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48 51 54 57 60 63 66 69 72 75 78 81
Along Weld- Seconds

Steel Bar 6 inch x 1/4 inch



Arc Welding
Amp. 80, Volt 30, Dia. of rod 3/32"

Speed of weld=3.5 inch/minute

FIG. 176

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TABLE 26

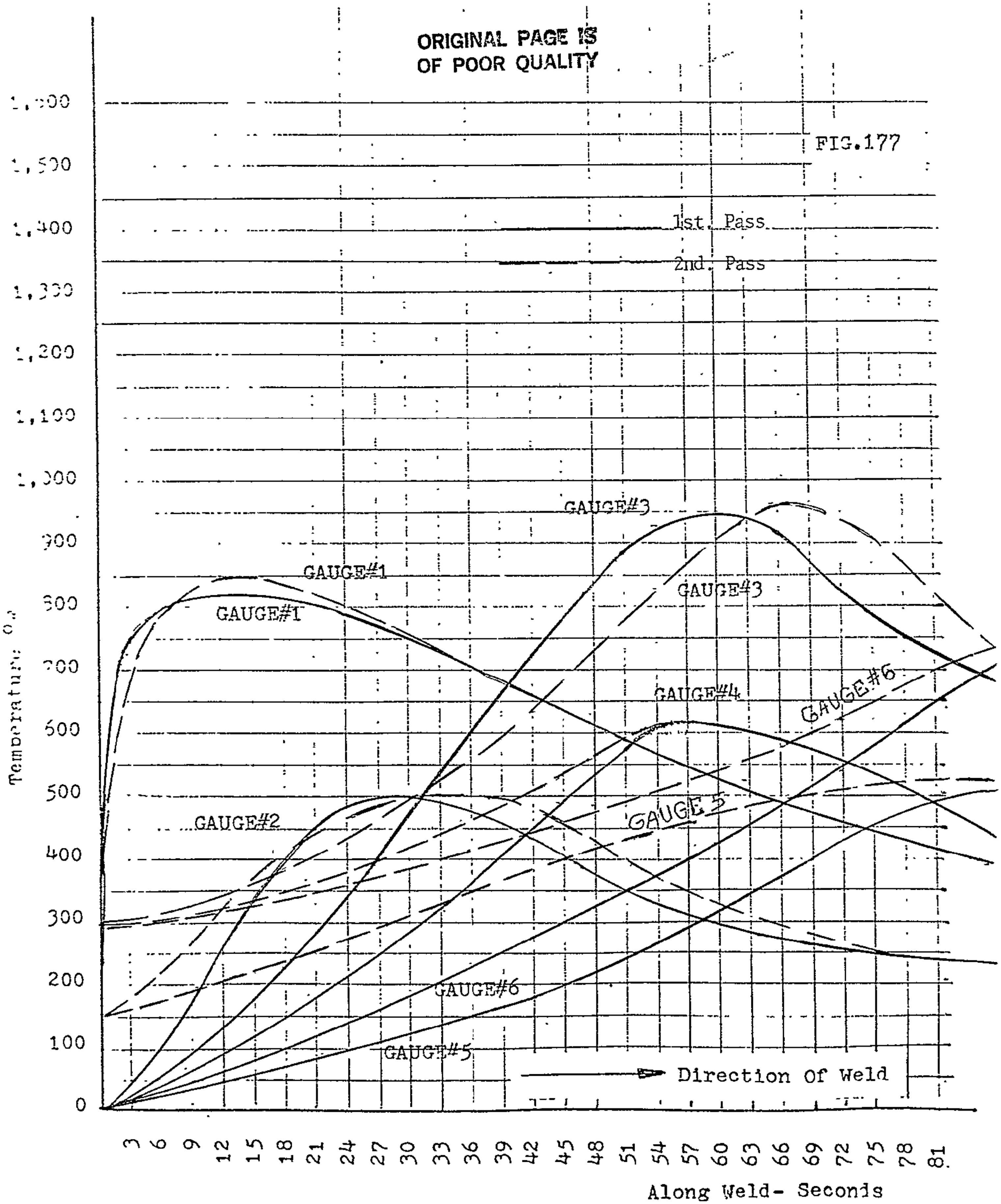
GAUGE # 1		GAUGE # 2		GAUGE # 3		GAUGF # 4		GAUGE # 5		GAUGE # 6	
1st. P	2nd. P	1st. P	2nd. P	1st. P	2nd. P	1st. P	2nd. P	1st. P	2nd. P	1st. P	2nd. P
0	370	0	150	0	300	0	300	0	155	0	300
770	630										
		50	175								
				50	320						
						70	310				
								40	195		
										70	320
820	850										
		350	275								
				225	380						
						175	370				
								80	255		
										150	360
750	780										
		500	420								
				475	500						
						310	450				
								130	325		
										230	415
680	680										
		450	490								
				730	630						
						490	530				
								200	400		
										320	480
590	590										
		350	390								
				925	825						
						600	600				
								300	460		
										425	540

TABLE 26 Cont.

530	530										
		280	300								
				920	960						
						580	580				
								400	500		
										530	620
450	450										
		250	250								
				750	870						
						500	495				
								500	525		
										680	715
395	390										
		220	215								
				620	670						
						420	420				
								530	500		
										790	795
350	345										
		195	200								
				520	570						
						350	355				
								425	425		
										835	835
300	305										
		170	170								
				430	440						
						300	300				
								320	320		
										700	700

Readings are taken every two seconds

FIG.177


1st. Pass
2nd. Pass
GAUGE#1
GAUGE#1
GAUGE#2
GAUGE#3
GAUGE#3
GAUGE#4
GAUGE 5
GAUGE#6
GAUGE#6
GAUGE#5
Direction Of Weld
Temperature °F
Along Weld- Seconds
0
100
200
300
400
500
600
700
800
900
1,000
1,100
1,200
1,300
1,400
1,500
1,600
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48
51
54
57
60
63
66
69
72
75
78
81

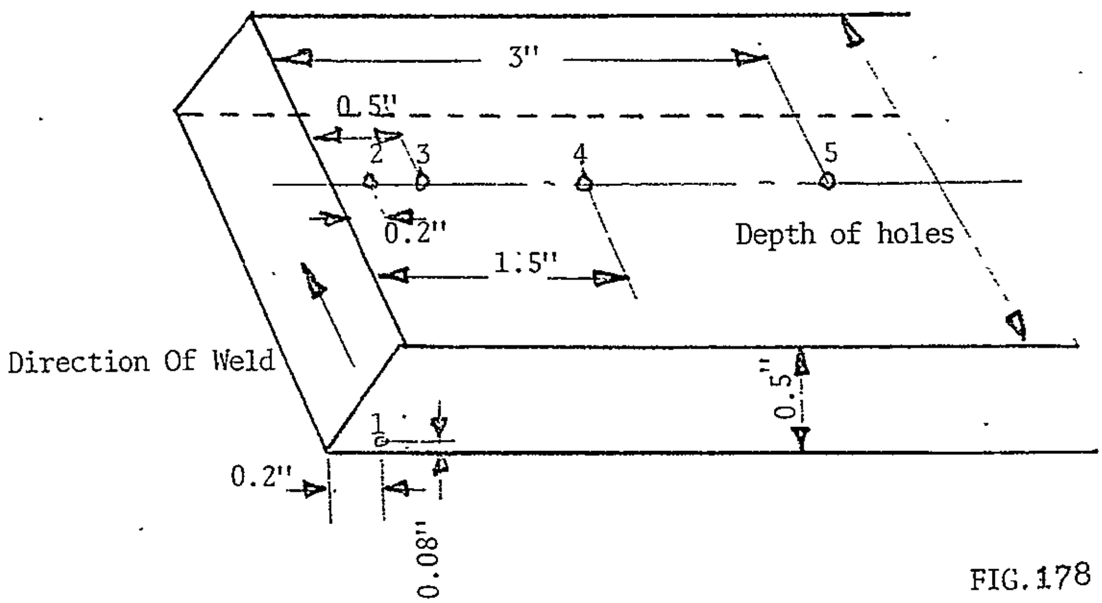


FIG. 178

A36 Steel Bar $4 \times \frac{1}{2}''$
Gauge arrangement
Holes along the axis of the bar

Arc weld
Amp. 160, Volt 25, Dia. of rod 1/8"
Speed of weld = 3.5 inch/min.

TABLE 27

Readings are taken every 2 seconds

GAUGE # 1			GAUGE # 2			GAUGE # 3			GAUGE # 4			GAUGE # 5		
1st.P	2nd.P	3rd.P	1st.P	2nd.P	3rd.P	1st.P	2nd.P	3rd.P	1st.P	2nd.P	3rd.P	1st.P	2nd.P	3rd.P
0	300	400	0	500	500	0	405	430	0	300	330	0	250	275
1450			40			25			20			20		
	1290			505			410			310			252	
		1100			508			450			350			280
1340			140			70			50			50		
	1260			540			435			350			270	
		1045			545			470			380			300
1050			300			180			120			90		
	1150			570			480			400			300	
		940			580			505			430			325
830			500			290			190			150		
	1040			630			525			430			350	
		850			630			550			475			350
740			690			430			280			200		
	925			690			570			485			395	
		770			675			600			500			400
635			830			540			355			245		
	825			755			630			530			425	
		700			705			645			540			440
555			920			595			395			260		
	730			800			650			550			445	
		650			720			650			550			450
505			905			600			395			255		
	665			780			650			540			440	
		600			700			640			520			430
460			825			560			365			240		
	600			730			625			500			410	
		550			660			600			475			400
430			720			510			340			220		
	545			660			570			450			380	
		500			610			555			430			365
415			630			450			310			200		
	500			605			540			415			350	
		480			570			530			400			330

TABLE 27 Cont.

400			560			405			280			190		
	460			560			515			380			310	
		445			545			500			360			300
400			505			380			270			180		
	440			530			490			335			295	
		435			520			475			325			280
395			455			355			270			180		
	425			500			480			315			280	

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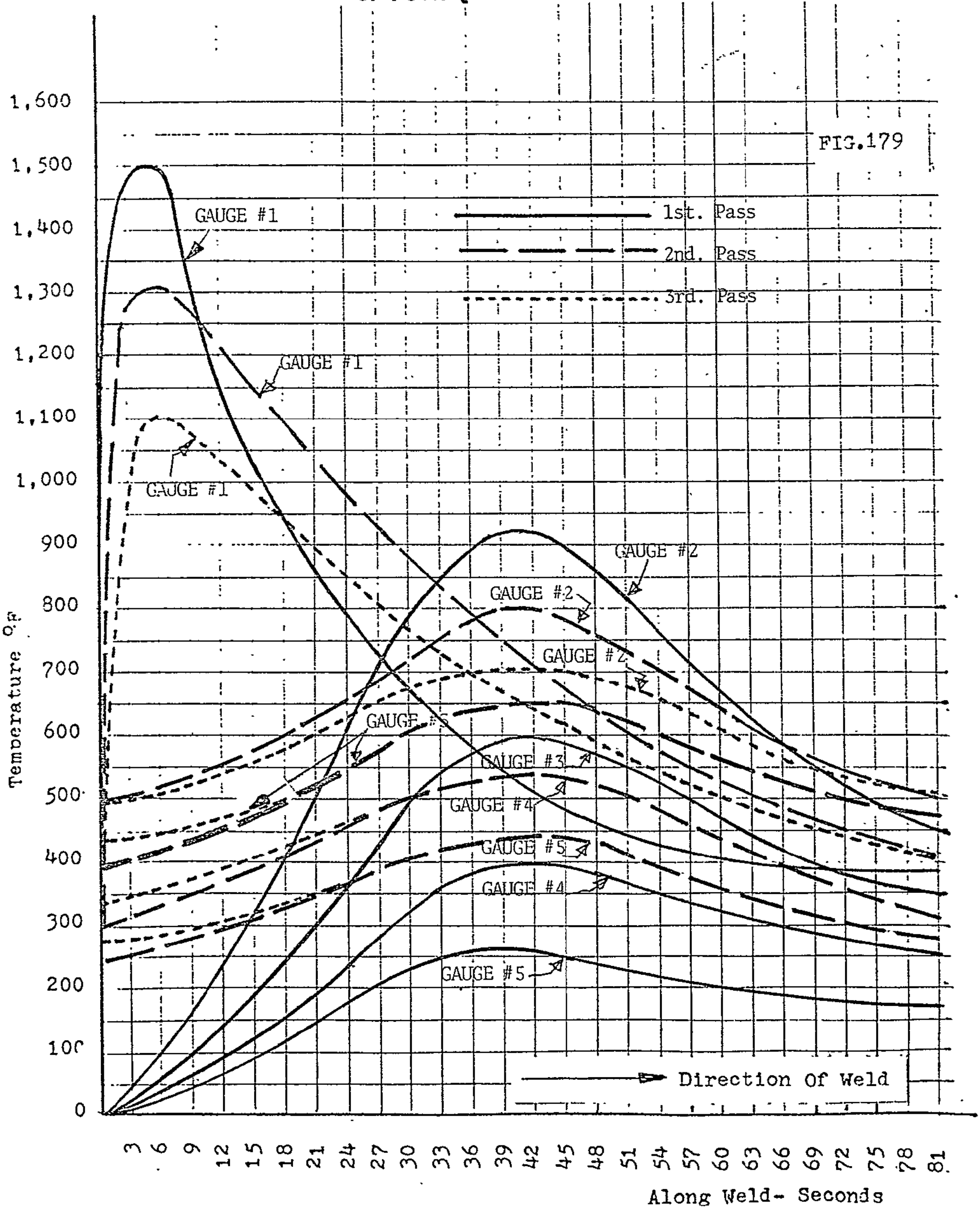

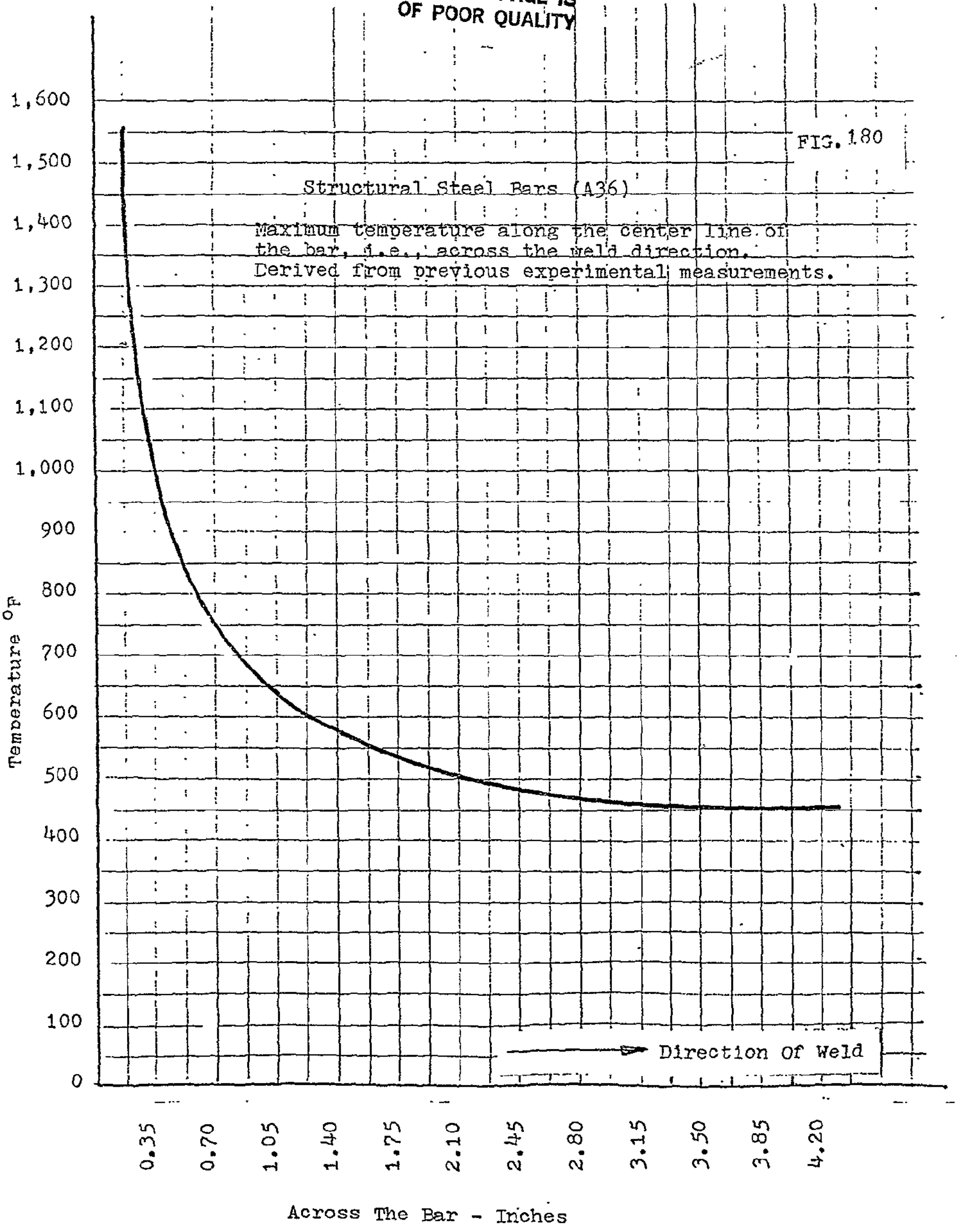
FIG. 180
Structural Steel Bars (A36)
Maximum temperature along the center line of the bar, i.e., across the weld direction. Derived from previous experimental measurements.
Temperature °F
1,600
1,500
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
200
100
0
Direction Of Weld
0.35
0.70
1.05
1.40
1.75
2.10
2.45
2.80
3.15
3.50
3.85
4.20
Across The Bar - Inches

6061T6 - Aluminum Bar 3" x ½"

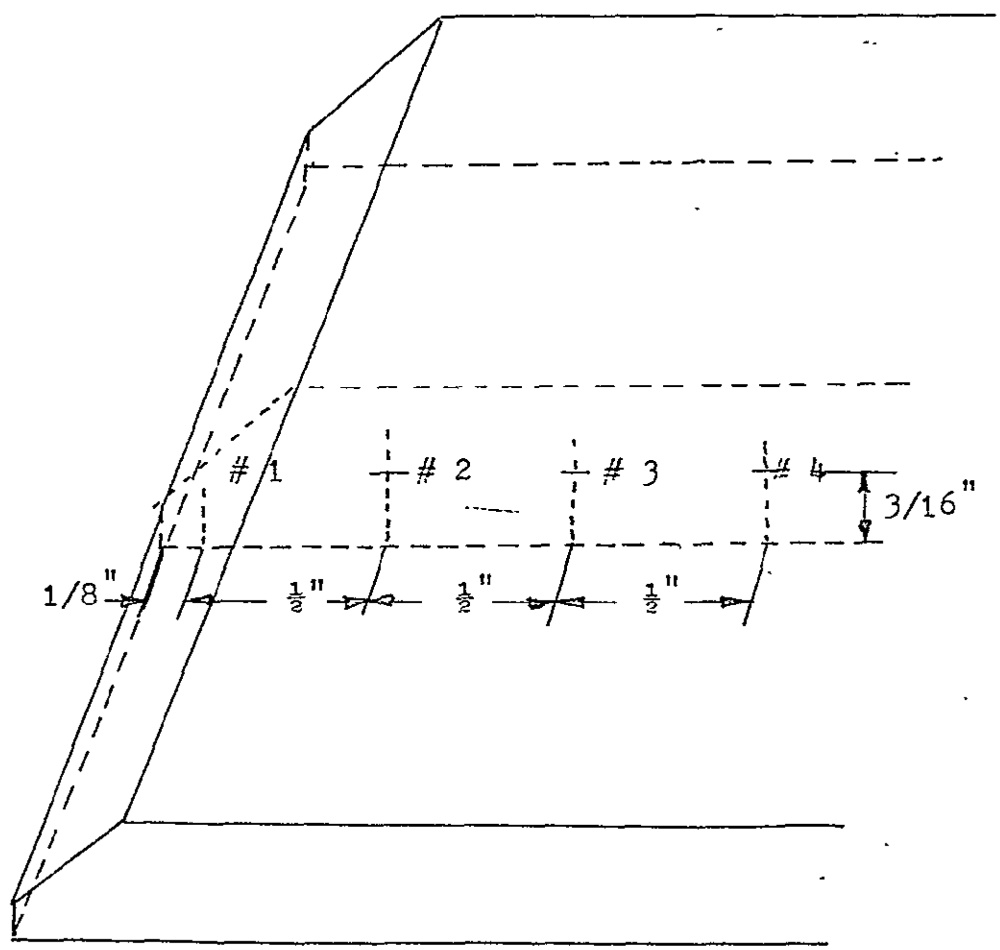

FIG.181

Readings Taken Every 3 Seconds . TABLE 28

GAUGE # 1				GAUGE # 2				GAUGE # 3				GAUGE # 4			
1st.P	2nd.P	3rd.P	4th.P	1st.P	2nd.P	3rd.P	4th.P	1st.P	2nd.P	3rd.P	4th.P	1st.P	2nd.P	3rd.P	4th.P
0	300	400	520	0	300	350	470	0	280	340	480	0	280	320	460
60	330	425	530												
				50	310	360	480								
								50	300	350	470				
												40	300	350	450
200	500	550	640												
				200	420	480	580								
								175	430	460	530				
												160	380	425	520
400	650	700	760												
				350	550	620	700								
								300	510	560	600				
												275	450	490	560
700	700	800	760												
				520	615	700	710								
								400	530	575	620				
												360	490	525	565
730	625	760	665												
				560	605	660	660								
								460	510	555	580				
												400	500	525	540
540	500	540	535												
				500	550	575	580								
								420	450	530	525				
												400	470	490	510

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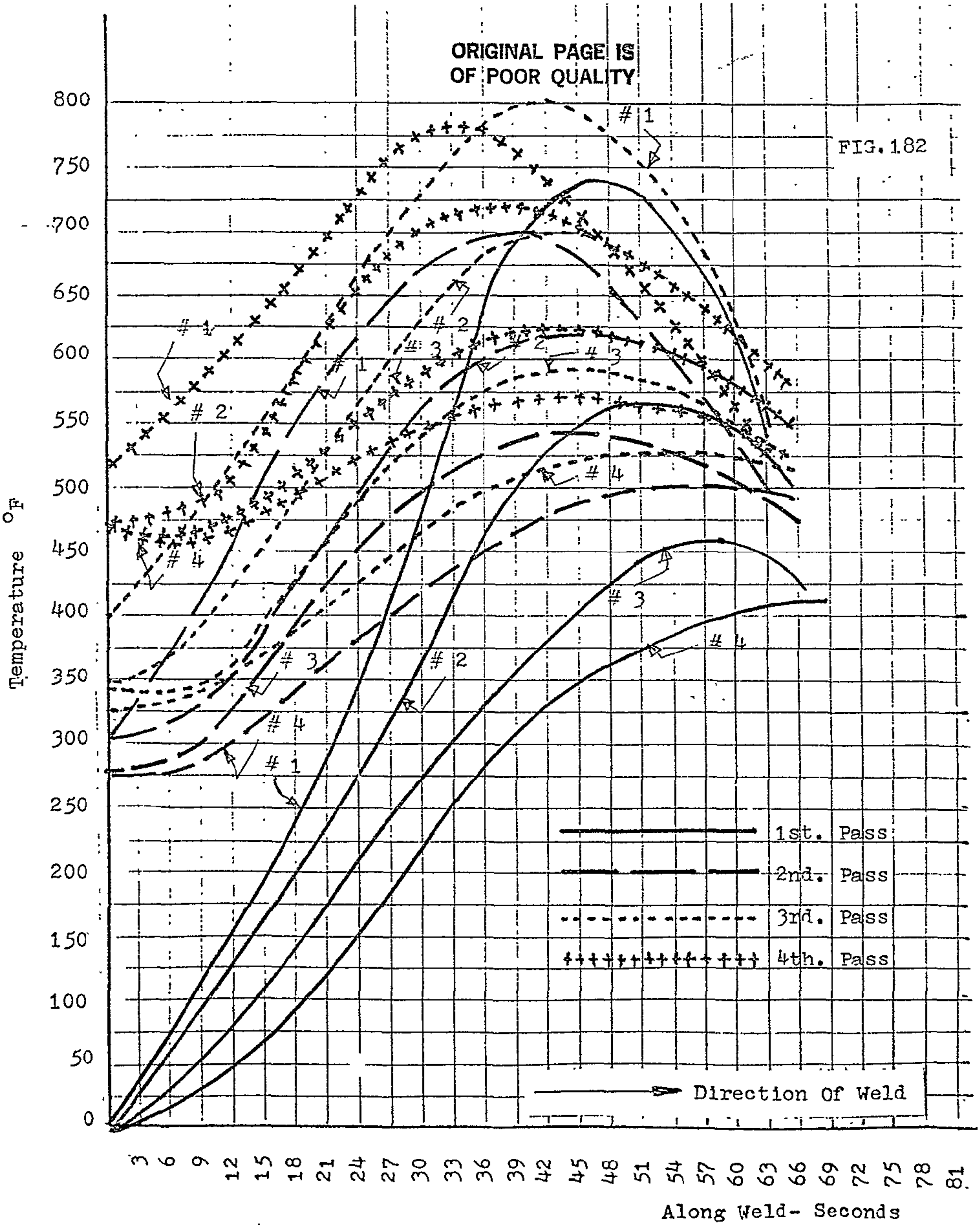


Aluminum Bar 3 x ½ inch

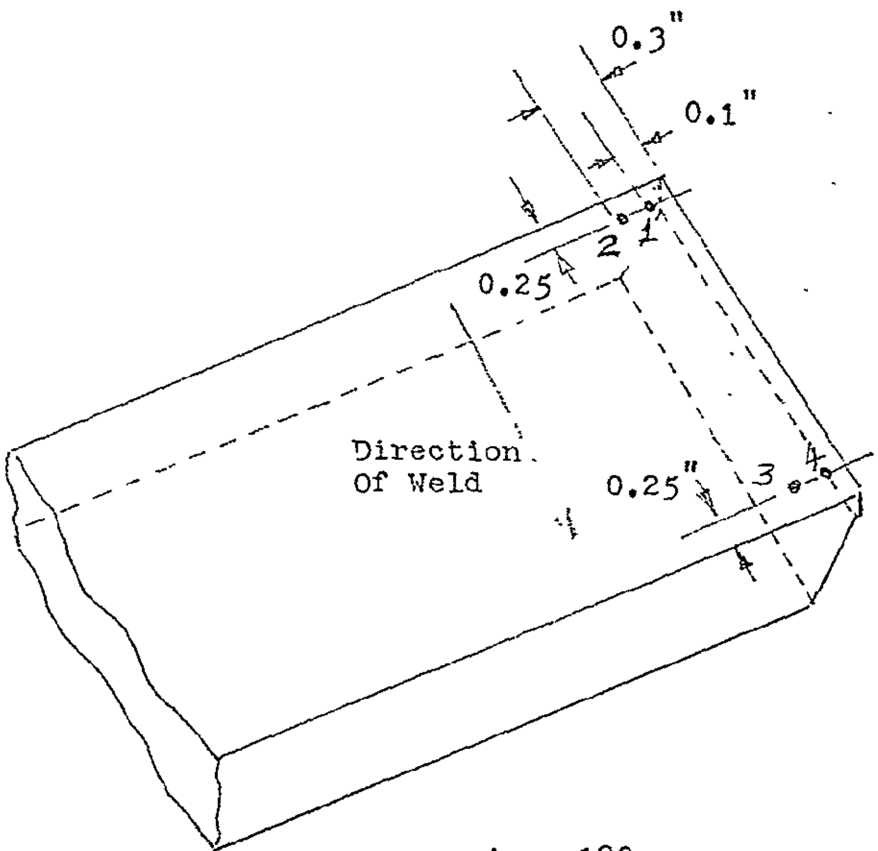
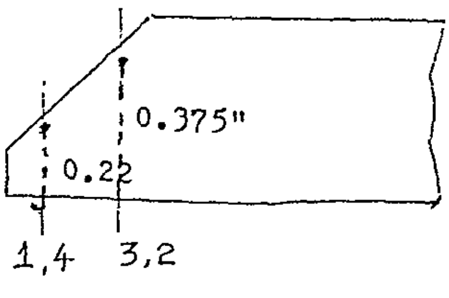


FIG.183

Amp. 120
Volt 32
Dia. of rod 1/8 inch(4043)
Speed of weld = 3½ inch/min.



Readings Taken Every 3 Seconds

TABLE 29

GAUGE # 1				GAUGE # 2				GAUGE # 3				GAUGE # 4			
1st.P	2nd.P	3rd.P	4th.P	1st.P	2nd.P	3rd.P	4th.P	1st.P	2nd.P	3rd.P	4th.P	1st.P	2nd.P	3rd.P	4th.P
0	400	450	585	0	350	430	530	0	355	400	525	0	330	380	505
680	435	555	655												
				370	520	500	650								
								25	355	370	475				
												75	355	365	485
680	600	690	745												
				615	515	625	665								
								100	425	400	550				
												165	410	450	610
580	555	690	680												
				580	465	680	750								
								220	550	510	725				
												300	500	595	820
510	475	630	600												
				455	420	655	675								
								375	785	725					
												485	630	800	
450	380	500	495												
				370	380	595	600								
								710							
												765	810		
340	300	375	375												
				315	350	500	500								

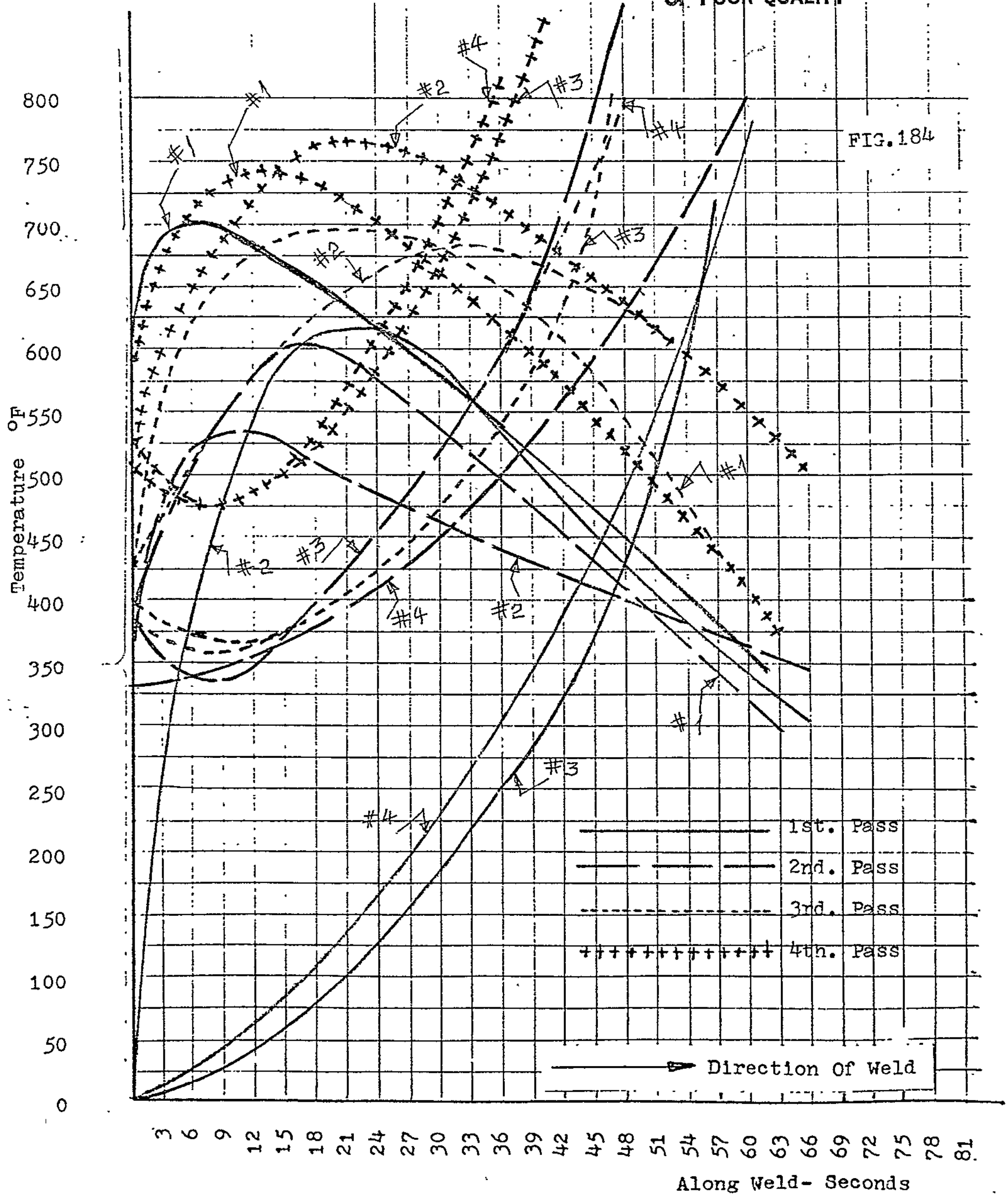


FIG. 184
Temperature °F
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48 51 54 57 60 63 66 69 72 75 78 81
Along Weld- Seconds
1st. Pass
2nd. Pass
3rd. Pass
4th. Pass
Direction Of Weld
#1
#2
#3
#4

SUMMARY OF CURRENT INVESTIGATIONS AND COMMENTS

During the current experimental investigations, it was observed that the thicker the bar and the more restrained the structure, the higher the magnitude of the trapped stresses [33,34]. Peak stresses of 25 to 30 x 10^3 psi appeared at the outer layers of the mild steel bars, and stresses of 8 to 10 x 10^3 psi appeared at a slight depth from the outer layers of the aluminum bars. Such a behavior is attributed to the higher thermal conductivity of the aluminum as compared to the steel.

Experimental analyses proved the effectiveness of the mechanical vibration technique on reducing and levelling the residual stresses generated by welding in both the steel and the aluminum. The vibration period was limited to 15 minutes at a frequency between 50 and 80 cps, in order to minimize any fatigue of the metal structure. Limited mechanical and metallurgical study of the resultant fatigue points to further experimental investigations.

Experimental studies with vibrations pointed out the need to examine the temperature at the weld and in the surrounding zone, and how the distribution of the temperature affects residual stresses.

It is believed that by controlling the sharp changes in the temperature around the weld it is possible to modify or eliminate the harmful effects of the residual stresses. Manual arc welds 3 to 8 inch long are made between pairs of steel or aluminum bars $\frac{1}{4}$ to $\frac{1}{2}$ inch thick. The bar edges are milled, straight with 45^o chamfer. This procedure represents the normal manual arc welding practice.

Examination of temperature distributions both along and across the weld direction, is ongoing. using chromel-alumel thermocouples with refrasil insulation. The junction of each thermocouple is mounted in a hole drilled in the bar at a specified location. Several thermocouples are used simultaneously during each test. Results showed that the maximum temperature is located under the source of heat and moves with it across the metallic bar.

A beneficial finding is that the temperature residue in the metal increases through the bar thickness as the successive beads are deposited. During the initial pass, a steep temperature gradient is encountered. As the bar heats the variation of the temperature narrows.

Reducing the current in arc welding causes slower melting and shallower penetration. A larger number of passes are needed to fill between the rods, helping to preheat the metal and reducing the contrast of temperature distribution. The resulting reduction of internal stresses minimizes damage to the metal bars.

FUTURE WORK PLAN

At present several tests are being carried out on both steel and aluminum bars of various thicknesses and widths. This is being done to confirm the temperature distribution characteristics and to determine the effect of bar proportions on the degree of heat loss and temperature differential. A theoretical study of the temperature distribution also is under way. The basis for the calculations of heat flow originated in the work of Roberts[16] and Rosenthal[17]. Various assumptions were necessary in the derivation of the mathematical formulae, including the possible radiation and convection losses[18].

Mechanical fatigue testing is continuing using the new MTS-810 type testing machine that has been added to our facilities. This testing will be supplemented with a metallurgical investigation of the grain structure to determine the internal effects of the vibration treatment.

A study is needed to analyse the beneficial effects of stress-relief on the metallurgical structure of both metals under investigation and how it can be related to the fatigue strength of the metal.

It was found that preheating steel to about 400°C produced a reduction in residual stresses of about fifty percent. The effectiveness of heat treatment following the welding fell off markedly at temperatures lower than 600°C[38,39]. Authors findings are based on mechanical tests rather than on actual measurements of residual stresses. Future investigation will examine the possible reduction or control of the effects of peak temperatures at the weld zone by preheating the bars around the zone using induction heating. The effect of combining such preheating with a limited vibration for about 15 minutes at a frequency of 50 to 80 cps, following the welding will also be studied. Mechanical and metallurgical investigation of the effects of differing vibration frequencies on the fatigue life of both steel and aluminum will reveal the optimum range for effectively reducing internal stresses.

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COMPUTER PROGRAMS

```
TYPE NWTST.FOR
            COMPLEX FILL
            INTEGER WORF(9)
            DIMENSION DHM(15),EO(15,10)
            WRITE(5,38)
      38    FORMAT(/,'ENTER H,L,N,G',/)
            READ(5,*)H,L,N,G
            WRITE(5,599)H
      599   FORMAT('**',F5.0)
            WRITE(5,39)
      39    FORMAT(/,'ENTER DATA',/)
            DO 200 I=1,L
            WRITE(5,201)I
      201   FORMAT(/,'LAYER',I2)
            READ(5,*)DHM(I),(EO(I,J),J=1,N)
      200   CONTINUE
            WRITE(5,466)
      466   FORMAT(//,'ENTER THE NAME FOR A NEW FILE FOR STORAGE')
            READ(5,112)WORF
      112   FORMAT(9A1)
            ENCODE(9,43,FILL)(WORF(I),I=1,9)
      43    FORMAT(9A1)
            OPEN(UNIT=20,FILE=FILL)
            WRITE(20,*)H,L,N,G,(DHM(I),I=1,L),((EO(I,J),J=1,N),I=1,L
)
      453   CLOSE(UNIT=20,FILE=FILL)
            END
```

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```
 TYPE LOOK.FOR
        COMPLEX FILE
        INTEGER WORK(9)
        DIMENSION EO(15,10),HM(15),DHM(15),HH(15)
        WRITE(5,1)
1       FORMAT(1H3,'ENTER THE DATA FILE NAME')
        READ(5,99) WORK
99      FORMAT(9A1)
        ENCODE(9,8,FILE)(WORK(I),I=1,9)
8       FORMAT(9A1)
        OPEN(UNIT=20,FILE=FILE)
89      READ(20,*,END=90) H,L,N,G,(DHM(I),I=1,L),((EO(I,J),J=1,
     1  N),I=1,L)
90      HHM=0.0
        DO 50 I=1,L
        HM(I)=HHM+DHM(I)
        HHM=HM(I)
        HH(I)=H-HM(I)
50      CONTINUE
888     CLOSE(UNIT=20,FILE=FILE)
        WRITE(5,21)H,N,L,G
21      FORMAT(//,5X,' BAR THICKNESS',F6.0,5X,'#
     1 OF GAGES',I3,5X,'# OF LAYERS',I3,5X,'GAGE SE
     1TTING',F8.2)
        WRITE(5,22)
22      FORMAT(//,5X,'AVERAGE THICKNESS',5X,'AVERAGE
     1  REMOVED',5X,'GAGE NUMBER      1      2      3
     1        4       5       6       7')
        DO 45 I1=1,L
        WRITE(5,26)HH(I1),DHM(I1),(EO(I1,J),J=1,N)
26      FORMAT(/,10X,F5.0,18X,F4.0,23X,10F8.0)
45      CONTINUE
        END
```

```
.TYPE MAKE
C       H  IS THE ORIGINAL THICKNESS (IN.)
C       HM IS THE DEPTH OF THE I LAYER REMOVED
C       DHM(I)  IS THE THICKNESS OF THE I LAYER REMOVED
C       EO(I,K)  IS THE CHANGE IN STRAIN IN THE OUTSIDE FIBER
C               I IS THE LAYER
C               K IS THE LOCATION
C       STRSS(I,K) IS THE TOTAL STRESS IN THE LAYER REMOVED
C               I IS THE LAYER
C               K IS THE STRAIN LOCATION
C       SSUM(I,K) IS THE SUM OF THE SUPERIMPOSED STRESS
C               I IS THE LAYER
C               K IS THE STRAIN LOCATION
C       SRES(I,K) IS THE RESIDUAL STRESS IN A LAYER
C               I IS THE LAYER
C               K IS THE LOCATION
C       L  IS THE NUMBER OF LAYERS
C       N  IS THE NUMBER OF STRAIN LOCATIONS
C       HHM IS AN INTERNAL COUNTING VARIABLE


        COMPLEX FILL
        INTEGER WORF(9)
        COMPLEX FILE
        DIMENSION HM(19),DHM(19),HN(19),DHN(19),EO(19,10),STRSS(
     119,10),SSUM(19,10),SRES(19,10),HH(19)
        WRITE(5,1)
1       FORMAT(1H3,' ENTER THE DATA FILE NAME')
        CALL OPEN(20,IER,FILE)
        IF(IER .EQ. 0)GO TO 87
        GO TO 89
87      WRITE(5,88)
88      FORMAT(/,' ERROR')
89      READ(20,*,END=495) H,L,N,G,(DHM(I),I=1,L),((EO(I
     1,J),J=1,N),I=1,L)
495     DO 15 J=1,L
        DO 10 K=1,N
10      SSUM(J,K)=0.0
15      CONTINUE
        HHM=0.0
        DO 50 I=1,L
        HM(I)=HHM+DHM(I)
        HN(I)=HM(I)
        DHN(I)=DHM(I)
        HHM=HM(I)
        HH(I)=H-HM(I)
50      CONTINUE
        CLOSE(UNIT=20,FILE=FILE)
        DO 500 I=1,L
        DO 700 K=1,N
        STRSS(I,K)=29.0*EO(I,K)*(-1.0)/(DHM(I)/(H-HM(I))-3.0*
     1DHM(I)*(H-HM(I)+DHM(I))/(H-HM(I))**2)
        DO 600 J=I+1,L
600     SSUM(J,K)=29.0*EO(I,K)*((H-HM(I))**2+3.0*(H-HM(I)
     1+DHM(I))*(H-2.0*HN(J)+DHN(J)+HM(I)))/((H-HM(I))**2-3.0*(H-
     1HM(I)+DHM(I))*(H-HM(I)))+SSUM(J,K)
700     SRES(I,K)=STRSS(I,K)-SSUM(I,K)
500     CONTINUE
        WRITE(5,21)H,N,L,G
21      FORMAT(//,5X,' BAR THICKNESS',F6.0.5X,'#
     1 OF GAGES',I3,5X,'# OF LAYERS',I3.5X 'GAGE SE
     1TTING',F8.2)
```

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```
22      FORMAT(//,5X,' AVERAGE THICKNESS',5X, AVERAGE RE
       1MOVED',5X,'GAGE NUMBER       1        2        3
       1    4 .     5        6        7 )
        DO 45 I1=1,L
        WRITE(5,26)HH(I1),DHM(I1),(EO(I1,J),J=1,N)
26      FORMAT(/,10X,F5.0,18X,F4.0,23X,10F8.0)
45      CONTINUE
        WRITE(5,66)
66      FORMAT(////,1H2,'        GAGE #      1       2       3

       1       5       6       7       8')
        DO 47 I1=1,L
        WRITE(5,34)I1,(SRES(I1,K),K=1,N)
34      FORMAT(/,' LAYER',3X,I2,3X,10F7.0)
47      CONTINUE
        TYPE 898
898     FORMAT(1H2)
        WRITE(5,466)
466     FORMAT(//,' ENTER THE NAME FOR A NEW FILE FOR
       1STORAGE')
        READ(5,112)WORF
112     FORMAT(9A1)
        ENCODE(9,43,FILL)(WORF(I),I=1,9)
43      FORMAT(9A1)
        OPEN(UNIT=20,FILE=FILL)
        WRITE(20,*)H,L,N,G,(DHM(I),I=1,L),((EO(I,J),J=1,
       1N),I=1,L),(HH(I),I=1,L),((SRES(I,J),J=1,N),I=1,L)
        CLOSE(UNIT=20,FILE=FILL)
        END
        SUBROUTINE OPEN(UNIT,IER,FILE)
        INTEGER UNIT
        INTEGER ERROR
        INTEGER WORK(9)
        COMPLEX FILE
        INTEGER COL
        DO 1 COL=1,9
        WORK(COL)='
1       CONTINUE
        COL=1
        READ(5,99)WORK
99      FORMAT(9A1)
        ENCODE(9,8,FILE)(WORK(I),I=1,9)
999     FORMAT(' ',2A5)
8       FORMAT(9A1)
        OPEN(UNIT=UNIT,FILE=FILE,ERR=9)
9       IER=1
10      RETURN
        END
```

```
 TYPE MAKA.FOR
C       H IS THE ORIGINAL THICKNESS(IN.)
C       HM IS THE DEPTH OF THE I LAYER REMOVED
C       DHM(I) IS THE THICKNESS OF THE I LAYER REMOVED
C       EO(I,K) IS THE CHANGE IN STRAIN IN THE OUTSIDE FIBER
C               I IS THE LAYER
C               K IS THE LOCATION
C       STRESS(I,K) IS THE TOTAL STRESS IN THE LAYER REMOVED


C                  I IS THE LAYER
C                   K IS THE STRAIN LOCATION
C       SSUM(I,K) IS THE SUM OF THE SUPERIMPOSED STRESS
C                  I IS THE LAYER
C                 K IS THE STRAIN LOCATION
C       SRES(I,K) IS THE RESIDUAL STRESS IN A LAYER
C                  I IS THE LAYER

C                   K IS THE LOCATION
C       L IS THE NUMBER OF LAYERS
C       N IS THE NUMBER OF STRAIN LOCATIONS
C       HHM IS AN INTERNAL COUNTING VARIABLE

        COMPLEX FILL
        INTEGER WORF(9)
        COMPLEX FILE
        DIMENSION HM(19),DHM(19),HN(19),DHN(19),EO(19,10),STRSS(
     119,10),SSUM(19,10),SRES(19,10),HH(19)
        WRITE(5,1)

1       FORMAT(1H3,' ENTER THE DATA FILE NAME')

        CALL OPEN(20,IER,FILE)

        IF(IER .EQ. 0)GO TO 87

        GO TO 89
87      WRITE(5,88)
88      FORMAT(/,' ERROR')
89      READ(20,*,END=495) H,L,N,G,(DHM(I),I=1,L),((EO(I
     1,J),J=1,N),I=1,L)
495     DO 15 J=1,L
        DO 10 K=1,N
10      SSUM(J,K)=0.0
15      CONTINUE
        HHM=0.0
        DO 50 I=1,L
        HM(I)=HHM+DHM(I)
        HN(I)=HM(I)
        DHN(I)=DHM(I)
        HHM=HM(I)
        HH(I)=H-HM(I)
50      CONTINUE
        CLOSE(UNIT=20,FILE=FILE)
        DO 500 I=1,L
        DO 700 K=1,N
```

```
      STRSS(I,K)=10.0*EO(I,K)*(-1.0)/(DHM(I)/(H-HM(I))-3.0*
     1DHM(I)*(H-HM(I)+DHM(I))/(H-HM(I))**2)
      DO 600 J=I+1,L
600   SSUM(J,K)=10.0*EO(I,K)*((H-HM(I))**2+3.0*(H-HM(I)
     1+DHM(I))*(H-2.0*HN(J)+DHN(J)+HM(I)))/((H-HM(I))**2-3.0*(H-
     1HM(I)+DHM(I))*(H-HM(I)))+SSUM(J,K)
700   SRES(I,K)=STRSS(I,K)-SSUM(I,K)
500   CONTINUE
      WRITE(5,21)H,N,L,G

21    FORMAT(//,5X,'BAR THICKNESS',F6.0,5X,'#
     1 OF GAGES',I3,5X,'# OF LAYERS',I3,5X,'GAGE SE
     1TTING',F8.2)
      WRITE(5,22)
22    FORMAT(//,5X,'AVERAGE THICKNESS',5X,'AVERAGE RE
     1MOVED',5X,'GAGE NUMBER      1       2       3
     1    4       5       6       7')
      DO 45 I1=1,L
      WRITE(5,26)HH(I1),DHM(I1),(EO(I1,J),J=1,N)
26    FORMAT(/,10X,F5.0,18X,F4.0,23X,10F8.0)
45    CONTINUE
      WRITE(5,66)
66    FORMAT(////,1H2,'        GAGE #      1       2       3
     1      4       5       6       7')
      DO 47 I1=1,L
      WRITE(5,34)I1,(SRES(I1,K),K=1,N)
34    FORMAT(/,'LAYER',3X,I2,3X,10F7.0)
47    CONTINUE
      TYPE 898
898   FORMAT(1H2)
      WRITE(5,466)
466   FORMAT(//,'ENTER THE NAME FOR A NEW FILE FOR
     1STORAGE')
      READ(5,112)WORF
112   FORMAT(9A1)
      ENCODE(9,43,FILL)(WORF(I),I=1,9)
43    FORMAT(9A1)
      OPEN(UNIT=20,FILE=FILL)
      WRITE(20,*)H,L,N,G,(DHN(I),I=1,L),((EO(I,J),J=1,
     1N),I=1,L),(HH(I),I=1,L),((SRES(I,J),J=1,N),I=1,L)
      CLOSE(UNIT=20,FILE=FILL)
      END
      SUBROUTINE OPEN(UNIT,IER,FILE)
      INTEGER UNIT
      INTEGER ERROR
      INTEGER WORK(9)
      COMPLEX FILE
      INTEGER COL
      DO 1 COL=1,9
      WORK(COL)=' '
1     CONTINUE
      COL=1
      READ(5,99)WORK
99    FORMAT(9A1)
      ENCODE(9,8,FILE)(WORK(I),I=1,9)
999   FORMAT(' ',2A5)
8     FORMAT(9A1)
      OPEN(UNIT=UNIT,FILE=FILE,ERR=9)
9     IER=1
10    RETURN
      END
```

Key To Computer Programs

WA1	Main program for frequency response analysis
WA2	Subroutine for transfer function (complex valued) and coherence function (Real). It makes complex variables out of real raw and smooth versions.
WA3	Subroutine for power spectral density functions (Raw version and smooth version by Parzen Lag).
WA4	Subroutine for cross spectral density function (Raw version and smooth version by Hanning).
WA5	Subroutine to check data and average X & Y (made equal to zero)
WA6	Subroutine used to make the input and output files (Opens, Reads and Closes the files containing data)
INTER	Intepolates X & Y data
FRFOUR	Finds Fourier Transfer. .SUBMIT FRFOUR Prints TRANS (Includes FOUR).
FRWA	Finds statistical transfer values(OUTPUT). SUBMIT FRWA Executes WA Series and the output includes: OUTPUT, FOR20.DAT, FOR30.DAT, FOR31.DAT and FOR32.DAT (No TRANS.)(M value is needed)
FRR	Finds both Fourier Transfer Values (TRANS) and the Statistical Transfer Values (OUTPUT) (M value is needed)

Possible Output Files

FOR20.DAT	Results of averages
FOR30.DAT	X power spectrum results
FOR31.DAT	Y power spectrum results
FOR32.DAT	Cross spectrum results(Complex)
FOR33	CK(I),QK(I)
FOR36	AR(I),BR(I)
FOR37	CKCX(I),QKCX(I) Raw
FOR38	CKCX(I),QKCX(I) Smooth
FOR55	CPK(I),QPK(I)

*File Name For Storage Of Results Must Be 9 Characters With .DAT Ext.

```
TYPE VA1.FOR
              PROGRAM VIBDAT
              COMMON GYX(100),GXYS(100)
              COMPLEX FILEX,HT,HS,GXY,GXYS
              DIMENSION X(999),Y(999),GKX(100),GKXS(100),GKY(100),

           1  GKYS(100),HT(100),HS(100);C(100),CS(100)
           1  ,D(100),RX(100)
           1  ,A(100),BB(100),CC(100),CD(100),CSS(100),DC(100)

      C       ENTER THE LAG NUMBER, M
              TYPE 5
      5       FORMAT(' M? ')
              READ(5,*)M
      C       OPENS READS, AND CLOSES THE FILE CONTAINING THE
      C       DATA FOR THE INPUT FUNCTION,X
              CALL NAME(FILEX)
              OPEN(UNIT=20,FILE=FILEX)
              READ(20,*)HX,NX,TR,(X(I),I=1,NX)
      40      CLOSE(UNIT=20,FILE=FILEX)
      C       CHECKS TO MAKE SURE M, AND N ARE POSITIVE AND EVEN
      C       CALCULATES CUTOFF FREQ BANDWIDTH, AND STANDARD ERROR
              CALL CHECK(NX,HX,M,F,B,E)
              WRITE(5,50)NX,HX,M,F,B,E
              WRITE(46,50)NX,HX,M,F,B,E
      50      FORMAT(5X,'NX=',I3,3X,'H=',F15.5,3X,'M=',
           1  I3,3X,'FC=',F15.5,3X,'BE=',F15.5,3X,'E=',F15.5)
      C       READ DATA FOR OUTPUT FUNCTION, Y
              CALL NAME(FILEX)
              OPEN(UNIT=20,FILE=FILEX)
              READ(20,*,END=75)HY,NY,TR,(Y(I),I=1,NY)
      75      CLOSE(UNIT=20,FILE=FILEX)
      C       CHECK Y DATA
              CALL CHECK(NY,HY,M,F,B,E)
              WRITE(5,51)NY
      51      FORMAT(' NY' ,I3)
      C       MAKE SURE THERE ARE SAME NO. OF X AND Y VALUES
              IF(NX .NE. NY) STOP 'NX NOT EQUAL TO NY'
      C       AVERAGE X AND Y MADE EQUAL TO ZERO
      C       RESULTS OF AVERAGING IN FILE FOR20.DAT
              CALL FORM(X,NX)
              CALL FORM(Y,NY)
              WRITE(20,29)
      29      FORMAT(3X,'X(I)',5X,'Y(I)',5X,'I')
              WRITE(20,31)(X(I),Y(I),I=1,NX)
      31      FORMAT(5X,I3,10X,2E10.5,F15.5)
      C       POWER SPECTRA FOUND FOR X AND Y
      C       RESULTS FOR X FUNCT.  FOR30.DAT
```

```
C          RESULTS FOR Y FUNCT.   FOR31.DAT
           CALL POWER(X,HX,NX,M,GKX,GKXS,D,RX)
           WRITE(30,*)(GKX(I),GKXS(I),I=1,M)
           CALL POWER(Y,HY,NY,M,GKY,GKYS,D,RX)
           WRITE(31,*)(GKY(I),GKYS(I),I=1,M)
C          COMPLEX VALUED CROSS-SPECTRAL DENSITYFOUND
C          RESULTS IN FILE FOR32.DAT
           CALL CROSS(X,Y,HX,M,NX,A,BB,CC,CD,CSS,DC)
           WRITE(32,*)(GXY(I),GXYS(I),I=1,M)
C          TRANSFER FUNCTION FOUND, COMPLEX VALUED
C          COHERENCE FUNCTION FOUND. REAL
           CALL TRANS(GKX,GKY,GKXS,GKYS,M,HT,HS,C,CS,
         1 A,BB,CC,CD)
C          FILE IS NAMED FOR STORAGE OF THE RESULTS
C          FILENAME MUST BE 9 CHARACTERS WITH .DAT EXT
           TYPE 105
           CALL NAME(FILEX)
           OPEN(UNIT=20,FILE=FILEX)
           WRITE(20,101)
101        FORMAT(5X'HT',5X,'HS(I)',5X,'C(I),',5X,'CS(I)',5X,'I'///)
           WRITE(20,*)(HT(I),HS(I),C(I),CS(I),I=1,M)
           CLOSE(UNIT=20,FILE=FILEX)
105        FORMAT('NAME OF FILE FOR TRANSFER DATA?')
           END
```

TYPE WA2.FOR

```
          SUBROUTINE TRANS(GKX,GKY,GKXS,GKYS,M,H,HS,C,CS,
     1    GKXC,CX,CXS,GKXSC)

C         THIS PROGRAM FINDS THE TRANSFER AND COHERENCE FUNCTION
C         COEFFICIENTS BETWEEN TWO SIGNALS.

          EXTERNAL ABS
          COMMON GXY(100),GXYS(100)
          COMPLEX GXY,GXYS,GKXC,GKYC,GKXSC,GKYSC,H,HS,CX,CXS
          REAL C,CS
          DIMENSION GKXC(M),GKXS(M),GKX(M),
     1    GKY(M),GKYS(M),H(M),HS(M),CX(M),CXS(M),C(M),CS(M)
     1    ,GKXSC(M)


C       FIND THE TRANSFER FUNCTION
        M=M+1

        DO 15 K=1,M

          IF(GKX(K).EQ.0)GKX(K)=.0001
          IF(GKXS(K).EQ.0)GKXS(K)=.0001
          IF(GKY(K).EQ.0)GKY(K)=.0001
          IF(GKYS(K).EQ.0)GKYS(K)=.0001
C       MAKE COMPLEX VARIABLES OUT OF REAL
        GKXC(K)=GKX(K)
        GKXSC(K)=GKXS(K)

C       THE 'RAW VERSION'
        H(K)=GXY(K)/GKXC(K)

C       THE 'SMOOTH VERSION'
        HS(K)=GXYS(K)/GKXSC(K)


C       THE COHERENCE FUNCTION

C         THE RAW VERSION
        CX(K)=GXY(K)*GXY(K)
        C(K)=CX(K)
        C(K)=C(K)/GKX(K)/GKY(K)
        C(K)=ABS(C(K))

C         THE SMOOTH VERSION
        CXS(K)=GXYS(K)*GXYS(K)
        CS(K)=CXS(K)
        CS(K)=CS(K)/GKXS(K)/GKYS(K)
        CS(K)=ABS(CS(K))

   15   CONTINUE

        RETURN
        END
C#############################################
```

```
TYPE WA3.FOR
      SUBROUTINE POWER(X,H,N,M,GK,GKS,DR,RXR)
      DIMENSION X(N),GK(M),GKS(M),RXR(M),DR(M)
        EXTERNAL COS
      DO 20 IR=1,M
      RXR(IR)=0.
      NX=N-IR
      DO 10 N1=1,NX
      RXR(IR)=RXR(IR)+X(N1)*X(N1+IR)
 10   CONTINUE
      RXR(IR)=RXR(IR)/NX
 20   CONTINUE
      R0=0.
      DO 30 N1=1,N
      R0=R0+X(N1)**2
 30   CONTINUE
      R0=R0/N
      MM=M-1
      QM=M
      MK=M+1
C       RAW VERSION
      DO 40 K=1,MK
      Q=K-1
      Q=Q/QM*3.1416
      GK(K)=0.
      DO 50 IR =1,MM
      R=IR
      GK(K)=GK(K)+RXR(IR)*COS(R*Q)
 50   CONTINUE
      GK(K)=2.*H*(R0+2.*GK(K)+(-1.**(K-1))*RXR(M))
 40   CONTINUE
      MM=M/2
      Q=M
C       SMOOTH BY PARZEN LAG FOR SMOOTH VERSION
      DO 60 IR=1,MM
      R=IR
        DR(IR)=1.-6.*((R/Q)**2-(R/Q)**3)
 60   CONTINUE
      DR(1)=1.
      DO 70 IR=MM+1,M
      R=IR
      DR(IR)=2.*((1.-R/Q)**3)
 70   CONTINUE
      DO 80 K=1,MK
      Q=K-1
      Q=Q/QM*3.1416
      GKS(K)=0.
      DO 90 IR=1,MM
      GKS(K)=GKS(K)+RXR(IR)*DR(IR)*COS(R*Q)
 90   CONTINUE
      GKS(K)=2.*H*(R0+2.*GKS(K))
 80   CONTINUE
      RETURN
      END
```

```
TYPE WA4.FOR

          subroutine cross(x,y,h,m,nx,br,ar,ryx,rxy,qk,ck)

          dimension x(nx),y(nx),ck(m),qk(m),
       1 RXY(M),RYX(M),AR(M),BR(M),QKCX(100),CKCX(100)
          common gxy(100),gxys(100)
          complex gxy,gxys,gkcx,qkcx,ckcx

          do 10 ir=0,m
          i=ir+1
          nr=nx-ir
          rxy(i)=0.
          ryx(i)=0.

          do 20 n=1,nr
          rxy(i)=rxy(i)+x(n)*y(n+ir)
          ryx(i)=ryx(i)+y(n)*x(n+ir)
   20     continue

          rxy(i)=rxy(i)/nr
          ryx(i)=ryx(i)/nr
          ar(i)=0.5*(rxy(i)+ryx(i))
          br(i)=0.5*(rxy(i)-ryx(i))

   10     continue

          do 15 k=0,m

          q=k
          qm=m
          q=q/qm*3.1416+.001
          kk=k+1

          ck(kk)=0.0
          qk(kk)=0.0

          do 25 ir=2,m
          r=ir-1
          ck(kk)=ck(kk)+2.*(ar(ir)*cos(q*r))
          qk(kk)=qk(kk)+br(ir)*sin(q*r)
   25     continue

          CK(KK)=2.*H*(AR(1)+CK(KK)+(-1.**K)*AR(M+1))
          qk(kk)=4.*h*qk(kk)

   15     continue

          mm=m+1
```

```
           do 30 i=1,mm

           qkcx(i)=(0,-1)
           ckcx(i)=ck(i)
           qkcx(i)=qkcx(i)*qk(i)
           gxy(i)=ckcx(i)+qkcx(i)
   30      continue

c          smoothing by hanning method
           ck(1)=(ck(1)+ck(2))/2.
           qk(1)=(qk(1)+qk(2))/2.
           do 37 j=2,m
           ck(j+1)=(ck(j)+ck(j+1))/2.
           QK(J+1)=(QK(J)+QK(J+1))/2.
   37      continue
           do 40 i=2,m
           ck(i)=(ck(i-1)+2.*ck(i)+ck(i+1))/4.
           qk(i)=(qk(i-1)+2.*qk(i)+qk(i+1))/4.
   40      continue

c          smooth version
           do 50 i=1,mm

           ckcx(i)=ck(i)
           qkcx(i)=(0,-1)
           qkcx(i)=qkcx(i)*qk(i)
           GXYS(I)=CKCX(I)+QKCX(I)

   50      continue

           return
           end
```

```
TYPE WA5.FOR
           SUBROUTINE FORM(X,N)
           DIMENSION X(N)
           SUM=0.
           SN=N
           DO 10 I=1,N
           SUM=SUM+X(I)
    10     CONTINUE
           SUM=SUM/SN
           DO 20 I=1,N
           X(I)=X(I)-SUM
    20     CONTINUE
           RETURN
           END
    C###############################################

           SUBROUTINE CHECK(N,H,M,FC,BE,E)
             EXTERNAL ABS,SQRT
             MM=ABS(M/2)
           MN=2*MM
             IF(MN .NE. M)PAUSE 'M NOT POSITIVE, EVEN'
           NQ=ABS(N/2)
           NC=2*NQ
             IF(NC .NE. N)PAUSE 'N NOT POSITIVE, EVEN'
             FC=.4/H
           QM=M
           BE=1./(QM*H)
           QN=N
           E=SQRT(QM/QN)
           RETURN
           END
    C ###############################################
```

```
TYPE WA6.FOR
        SUBROUTINE NAME(FILEX)
        COMPLEX FILEX
        INTEGER WORK(9)
        TYPE 30
 30     FORMAT('FILE NAME:DATA:')
        READ(5,99)(WORK(I),I=1,9)
 99     FORMAT(9A1)
        ENCODE(9,8,FILEX)(WORK(I),I=1,9)
 8      FORMAT(9A1)
        RETURN
        END
 C ####################################################
```

```
      PROGRAM FOUR
      DIMENSION X(999),Y(999),H(999),A(999)
      CALL ERXSET(10,0)
      READ(23,*,END=33) HP,NX,T,(X(I),I=1,NX)
33    READ(24,*,END=44) HP,NY,T,(Y(I),I=1,NY)
44    CALL FORM(X,NX)
      CALL FORM(Y,NX)
      CALL FOURTR(X,NX+4,-1,A)
      CALL FOURTR(Y,NX+4,-1,A)
      DO 50 I=1,NX
      IF(X(I).EQ.0.)X(I)=.001
      H(I)=Y(I)/X(I)
50    A(I)=I/T
      WRITE(41,11)
   11 FORMAT(4X,'A(I)',10X,'X(I)',10X,'Y(I)',10X,'H(I)'///)
      WRITE(41,*)(A(I),X(I),Y(I),H(I),I=1,NX)
10    FORMAT(10X,F10.3,5X,3E15.12)
      END
```

```
      PROGRAM INTER2
      DIMENSION Y(999),X(300)
      READ(23,*)A,J,C,(X(I),I=1,J)
      TYPE 5
5     FORMAT('  INPUT NUMBER OF INTERPOLATED VALUES')
      READ(5,*)N
      L=N*J
      A=A/N
      DO 10 I=1,N
      K=0
      DO 15 JJ=1,L,N
      K=K+1
      Y(JJ+I)=X(K)+I*(X(K+1)-X(K))/N
      Y(JJ)=X(K)
15    CONTINUE
10    CONTINUE
      WRITE(24,*)A,L,C,(Y(I),I=1,L)
      END
```

```
.TYPE FRFOUR.FOR
COPY FOR23.DAT=X.DAT
COPY FOR24.DAT=Y.DAT
EX FOUR.REL,WA5.REL,SYS:SPCLIB.REL
DELETE TRANS
RENAME TRANS=FOR41.DAT
PRINT TRANS
DEL FOR23.DAT,FOR24.DAT
DIR/L
DAYTIME
```

```
.TYPE FRWA.FOR
        COPY FOR23.DAT=X.DAT
        COPY FOR24.DAT=Y.DAT
        COPY FOR60.DAT=M.DAT
        EX WA11,WA2,WA3,WA4,WA5
        DEL FOR60.DAT,FOR23.DAT,FOR24.DAT
        PRINT FOR20.DAT,FOR30.DAT,FOR31.DAT,FOR32.DAT
        DEL OUTPUT
        RENAME OUTPUT=FOR46.DAT
        PRINT OUTPUT
        DEL FOR20.DAT,FOR30.DAT,FOR31.DAT,FOR32.DAT
        DIR/L
        DAYTIME
```

```
.TYPE FRR.FOR
COPY FOR23.DAT=X.DAT
COPY FOR24.DAT=Y.DAT
EX FOUR.REL,WA5.REL,SYS:SPCLIB.REL
DEL TRANS
RENAME TRANS=FOR41.DAT
PRINT TRANS
COPY FOR60.DAT=M.DAT
EX WA11,WA2,WA3,WA4,WA5
DEL FOR60.DAT,FOR23.DAT,FOR24.DAT
PRINT FOR20.DAT,FOR30.DAT,FOR31.DAT,FOR32.DAT
DEL OUTPUT
RENAME OUTPUT=FOR46.DAT
PRINT OUTPUT
DEL FOR20.DAT,FOR30.DAT,FOR31.DAT,FOR32.DAT
DIR/L
DAYTIME
```

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```
.TYPE UWAT
      PROGRAM V[illegible]
      COMMON GXY(100),GXYS(100)
      COMPLEX FILEX,HT,HS,GXY,GXYS
      DIMENSION X(999),Y(999),GNX(100),GNXS(100),GNY(100),
     1 GNYS(100),HT(100),HS(100),F(100),[illegible]
     1 ,H(100),RX(100)
     1 ,A(100),UR(100),EL(100),[illegible]
     ,CPN(100),OPN(100)
C     ENTER THE LOG NUMBER, M
      TYPE 5
5     FORMAT(' M? ')
      READ(5,*)M

C     OPENS READS, AND CLOSES THE FILE CONTAINING THE
C     DATA FOR THE INPUT FUNCTION, X
      CALL NAME(FILEX)
      OPEN(UNIT=20,FILE=FILEX)
      READ(20,*)IIX,NX,IR,(X(I),I=1,NX)
40    CLOSE(UNIT=20,FILE=FILEX)
C     CHECKS TO MAKE SURE M, AND N ARE POSITIVE AND EVEN
C     CALCULATES CUTOFF FREQ, BANDWIDTH AND STANDARD ERROR
      CALL CHECK(NX,IIX,M,F,B,E)
      WRITE(5,50)NX,IIX,M,F,B,E
50    FORMAT('     NX',I5,' IIX',F15.5,' M',I5,[illegible]
     1 ,' B',F15.5,' E',F15.5)
C     READ DATA FOR OUTPUT FUNCTION, Y
      CALL NAME(FILEY)
      OPEN(UNIT=20,FILE=FILEY)
      READ(20,*,END=75)IIY,NY,IR,(Y(I),I=1,NY)
75    CLOSE(UNIT=20,FILE=FILEY)
C     CHECK Y DATA
      CALL CHECK(NY,IIY,M,F,B,E)
      WRITE(5,51)NY
51    FORMAT(' NY',I5)
C     MAKE SURE THERE ARE SAME NO. OF X AND
C     Y VALUES
      IF(NX.NE.NY) STOP 'NX NOT EQUAL TO NY'
C     AVERAGE X AND Y MADE EQUAL TO ZERO
      CALL FORM(X,NX)
      CALL FORM(Y,NY)
      CALL POWER(X,IIX,NX,M,GNX,GNXS,[illegible])
      CALL POWER(Y,IIY,NY,M,GNY,GNYS,[illegible])
C     COMPLEX VALUED CROSS-SPECTRAL DENSITY FOUND
      CALL CROSS(X,Y,[illegible])
C     TRANSFER FUNCTION FOUND, COMPLEX VALUED
C     COHERENCE FUNCTION FOUND REAL
      CALL TRANS(GNX,GNY,GXY,GXYS,[illegible])
     1 A,UR,CC,[illegible])
      END
```

```
 TYPE WWA4.FOR

      SUBROUTINE CROSS(X,Y,H,M,NX,BR,AR,RYX,RXY,QK,CK
     1,CPK,QPK)

      DIMENSION X(NX),Y(NX),CK(M),QK(M),
     1 RXY(M),RYX(M),AR(M),BR(M),QKCX(100),CKCX(100)
     1 ,CPK(100),QPK(100)
      COMMON GXY(100),GXYS(100)
      COMPLEX GXY,GXYS,GKCX,QKCX,CKCX

      DO 10 IR=0,M
      I=IR+1
      NR=NX-IR
      RXY(I)=0.
      RYX(I)=0.

      DO 20 N=1,NR
      RXY(I)=RXY(I)+X(N)*Y(N+IR)
      RYX(I)=RYX(I)+Y(N)*X(N+IR)
20    CONTINUE

      RXY(I)=RXY(I)/NR
      RYX(I)=RYX(I)/NR
      AR(I)=0.5*(RXY(I)+RYX(I))
      BR(I)=0.5*(RXY(I)-RYX(I))

10    CONTINUE
      WRITE(36,*)(AR(I),BR(I),I=1,M+1)

      DO 15 K=0,M

      Q=K
      QM=M
      Q=Q/QM*3.1416+.001
      KK=K+1

      CK(KK)=0.0
      QK(KK)=0.0

      DO 25 IR=2,M
      R=IR-1
      CK(KK)=CK(KK)+2.*(AR(IR)*COS(Q*R))
      QK(KK)=QK(KK)+BR(IR)*SIN(Q*R)
      CPK(KK)=CK(KK)
      QPK(KK)=QK(KK)
25    CONTINUE

      CK(KK)=2.*H*(AR(1)+CK(KK)+(-1.**K)*AR(M+1))
      QK(KK)=4.*H*QK(KK)

15    CONTINUE

      MM=M+1
      WRITE(33,*)(CK(I),QK(I),I=1,MM)

      DO 30 I=1,MM
```

```
         QKCX(I)=(0,-1)
         CKCX(I)=CK(I)
         QKCX(I)=QKCX(I)*QK(I)
         GXY(I)=CKCX(I)+QKCX(I)
 30      CONTINUE
         WRITE(55,*)(CPK(KK),QPK(KK),KK,KK=1,MM)
         WRITE(37,*)(CKCX(I),QKCX(I),I=1,MM)
 C      SMOOTHING BY HANNING METHOD
         CK(1)=(CK(1)+CK(2))/2.
         QK(1)=(QK(1)+QK(2))/2.
         DO 37 J=2,M
         CK(J+1)=(CK(J)+CK(J+1))/2.
         QK(J+1)=(QK(J)+QK(J+1))/2.
 37      CONTINUE
         DO 40 I=2,M
         CK(I)=(CK(I-1)+2.*CK(I)+CK(I+1))/4.
         QK(I)=(QK(I-1)+2.*QK(I)+QK(I+1))/4.
 40      CONTINUE
 C      SMOOTH VERSION
         DO 50 I=1,MM
         CKCX(I)=CK(I)
         QKCX(I)=(0,-1)
         QKCX(I)=QKCX(I)*QK(I)
         GXYS(I)=CKCX(I)+QKCX(I)
 50      CONTINUE
         WRITE(38,*)(CKCX(I),QKCX(I),I=1,MM)
         RETURN
         END
```

```
TYPE WA11.FOR
              PROGRAM VIB222
              COMMON GXY(100),GXYS(100)
              COMPLEX FILEX,HT,HS,GXY,GXYS
              DIMENSION X(999),Y(999),GKX(100),GKXS(100),GKY(100),
         1    GKYS(100),HT(100),HS(100),C(100),CS(100)
         1    ,D(100),RX(100)
         1    ,A(100),BB(100),CC(100),CD(100),CSS(100),DC(100)
              READ(60,*)M
    C         OPENS READS, AND CLOSES THE FILE CONTAINING THE
    C         DATA FOR THE INPUT FUNCTION,X
              READ(23,*)HX,NX,TR,(X(I),I=1,NX)
    C         CHECKS TO MAKE SURE M, AND N ARE POSITIVE AND EVEN
    C         CALCULATES CUTOFF FREQ BANDWIDTH, AND STANDARD ERROR
              CALL CHECK(NX,HX,M,F,B,E)
              WRITE(46,50)NX,HX,M,F,B,E
    50        FORMAT(5X,'NX=',I3,3X,'H=',F15.5,3X,'M='
         1    I3,3X,'FC=',F15.5,3X,'BE=',F15.5,3X,'E=',F15.5)
    C         READ DATA FOR OUTRPUT FUNCTION, Y
              READ(24,*)HY,NY,TR,(Y(I),I=1,NY)
    C         CHECK Y DATA
              CALL CHECK(NY,HY,M,F,B,E)
    C         MAKE SURE THERE ARE SAME NO. OF X AND Y VALUES
              IF(NX .NE. NY)STOP 'NX NOT EQUAL TO NY'
    C         AVERAGE X AND Y MADE EQUAL TO ZERO
    C         RESULTS OF AVERAGING IN FILE FOR20.DAT
              CALL FORM(X,NX)
              CALL FORM(Y,NY)
              WRITE(20,29)
    29        FORMAT(3X,'X(I)',5X,'Y(I)',5X,'I')
              WRITE(20,31)(X(I),Y(I),I=1,NX)
    31        FORMAT(5X,I3,10X,2E10.5,F15.5)
    C         POWER SPECTRA FOUND FOR X AND Y
    C         RESULTS FOR X FUNCT. FOR30.DAT
    C         RESULTS FOR Y FUNCT. FOR31.DAT
              CALL POWER(X,HX,NX,M,GKX,GKXS,D,RX)
              WRITE(30,*)(GKX(I),GKXS(I),I=1,M)
              CALL POWER(Y,HY,NY,M,GKY,GKYS,D,RX)
              WRITE(31,*)(GKY(I),GKYS(I),I=1,M)
    C         COMPLEX VALUED CROSS-SPECTRAL DENSITY FOUND
    C                 RESULTS IN FILE FOR32.DAT
              CALL CROSS(X,Y,HX,M,NX,A,BB,CC,CD,CSS,DC)
              WRITE(32,*)(GXY(I),GXYS(I),I=1,M)
    C         TRANSFER FUNCTION FOUND. COMPLEX VALUED
    C         COHERENCE FUCTION FOUND. REAL
              CALL TRANS(GKX,GKY,GKXS,GKYS,M,HT,HS,C,CS,
         1    A,BB,CC,CD)
    C         FILE IS NAMED FOR STORAGE OF THE RESULTS
    C         FILENAME MUST BE 9 CHARACTERS WITH .DAT EXT
              WRITE(46,101)
    101       FORMAT(12X,'HT',22X,'HS(I)',18X,'C(I)',12X,'CS(I)'///)
              WRITE(46,102)(HT(I),HS(I),C(I),CS(I),I=1,M)
    102       FORMAT(2X,2F10.6,3X,2F10.6,3X,F10.6,5X,F10.6///)
              END
```

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Computer Program For The Measurement And Analysis Of Shock Load And Acceleration Response(1)

Theory

Definitions

f	Frequency
f_c	$1/2h$ = The cut off frequency
x & y	Variables - impulse & response wave values
$x(t)$	Record
$y(t)$	Record
h	The time interval between data values
k	The harmonic number
r	The lag number
m	The maximum lag number
n	The number of data samples (number of intervals)
ϵ	The normalized standard error desired for spectral calculations
A_q	The finite analogues of Fourier cosine coefficients
B_q	The finite analogues of Fourier cosine coefficients
R_r	The estimate of the true (autocorrelation function) value R_r at logr corresponding to the displacement rh
T_p	The period t
U_n or x_n	The data values
s_x	The sample standard deviation for $x(t)$
s_y	The sample standard deviation for $y(t)$
Be	The desired equivalent resolution band width for power spectra calculations
$\hat{C}_k$	Digital value of the co-spectrum estimate at harmonic k between $x(t)$ & $y(t)$
$\tilde{G}_k$	The "Raw" estimate of the power spectral density function at harmonic k, corresponding to the frequency $f=kf_c/m$.
$\hat{Q}_k$	Digital value of the quadspectrum estimate at harmonic k between $x(t)$ & $y(t)$
$G_x(f)$	Power spectral density function of $x(t)$
$\tilde{G}_x(f)$	Raw value of power spectrum $G_x(f)$
t	$=H_x, H_y$ Time intervals
$G_y(f)$	Power spectral density function of $y(t)$
T_r	Record length
Q	Index
D_r	Is Parzen Lag weighting function
ABS	Absolute value
C	Coherence function at each of the harmonic frequency k ($f=kf_c/m$)
$\wedge$	For smooth
$\sim$	For raw

$C_{xy}(f)$	The co-spectral density function
$Q_{xy}(f)$	The quadrature spectral density function
$\hat{G}_{k,x}$	Digital value of the power spectrum estimate at harmonic k for x(t)
$\hat{G}_{k,y}$	Digital value of the power spectrum estimate at harmonic k for y(t)
G_k	$(C_k, Q_k) = G_{xy}(kf_c/m)$
G_{kxs}	The smooth version of G_k
$G_{xy}(f)$	Cross spectral density function
$G_{xys}(f)$	Smooth version using Hanning method
$\Delta t = H_x$ or H_y	Time interval for x or y

<u>Digitizing Of Continuous Data</u>
i.e., converting continuous data into discrete numbers.

The procedure is first to define the points at which the data are observed (sampling).

If the time interval = Δt (secs.) between samples = h

$\therefore$ sampling rate = 1/h samples per second.

The useful data will be from 0 to 1/2h cps

The cutoff frequency $f_c = 1/2h$ ---------------- (1)
known as the Nyquist frequency

For any frequency f in the range $0 \leq f \leq f_c$, the higher frequencies which are aliased with f are:-

$(2f_c \pm f), (4f_c \pm f)$, -------, $(2nf_c \pm f)$ -------------- (2)

$(\cos 2\pi ft = \cos 2\pi(2nf_c \pm f).1/2f_c = \cos \pi f/f_c)$

Thus all data at frequencies $2nf_c \pm f$ have the same cosine function as data at frequency f when data are sampled at points $1/2f_c$ apart.

<u>To Deal With Aliasing Problem</u>
Choose h sufficiently small so that it is physically unreasonable for data to exist above the associated cutoff frequency f_c (example-assume that information below 500 cps is desired, as the case we are dealing with. This means that $1/2h \simeq 500$ or h=1 msec. would technically be sufficient).

In general, it is a good rule to select $f_c > 1\frac{1}{2}$ or 2 times greater than the maximum frequency of interest.

The second part of concern is quantization, i.e., the actual conversion of the observed values to numerical form.

If one assumes that the quantization errors follow a uniform probability distribution over one scale unit, then these errors will have a mean value p(x)=zero and a standard deviation of $\simeq 0.29$ scale unit. This is the rms value of the quantization error.

For most practical problems, quantization errors are negligible.

<u>Basic Statistical Calculations For A Single Record</u>
<u>Digitizing Of Data And Selection Of Sample Size</u>

Let $\{U_n\}$; n=1,2,---,N be the data values of a record U(t) found at the points $t_n = t_o + nh$.

These points are at distance h apart

$\therefore U_n = U(t_o + nh)$ ------------------------- (3)

Sample mean $= \bar{U} = \frac{1}{N}\sum_{n=1}^{N} U_n$ ------------------------ (4)

Sample standard deviation $= S = \left[\sum_{n=1}^{N}\frac{(x_n)^2}{N-1}\right]^{\frac{1}{2}}$ ------- (5)

And $\overline{x^2} = (\frac{N-1}{N}).s^2$

For independent data samples. The normalized standard error $= 1/\sqrt{N}$

Transformation Of Data To Zero Mean Value

This is done in order that subsequent formulas and calculations may be simplified.

Define a new time history record

$x(t) = U(t) - \bar{U}$

Then $x(t)$ has data values $\{x_n\}$ given by

$x_n = x(t_o+nh) = U_n - \bar{U}$ -------------------------- (6)

note that $\bar{x} = 0$

The reason for representing the original data values by $\{U_n\}$ instead of $\{x_n\}$ is to have the $\{x_n\}$ notation indicate a zero sample mean value.

Fourier Series Representation

If a transformed sample record $x(t)$ is periodic with a period of T_p and a fundamental frequency $f_1=1/T_p$, then $x(t)$ can be represented by the Fourier series:

$$x(t) = a_o/2 + \sum_{q=1}^{\infty}(a_q.\cos 2\pi qf_1t + b_q.\sin 2\pi qf_1t)$$

Where:

$$a_q = 2/T \cdot \int_0^T x(t).\cos 2\pi qf_1t.dt \qquad q= 0,1,2,---$$

$$b_q = 2/T \cdot \int_0^T x(t).\sin 2\pi qf_1t.dt \qquad q= 1,2,3,---$$

Assume a sample record $x(t)$ is of finite length $T_r=T_p$, the fundamental period of the data.

Also assume that the record is sampled at an even number of N equally spaced points a distance h apart, where h has been selected to produce a sufficiently high frequency cutoff $f_c=1/2h$.

Consider the initial point of the record to be zero and denote the transformed data values as before, by

$x_n = x(nh)$ -------------------------- (7)

One may calculate the finite version of a Fourier series which will pass through these N data values. For any point t in the interval $(0,T_p)$ one obtains:

$$x(t) = A_o + \sum_{q=1}^{N/2} A_q \cos(2\pi qt/T_p) + \sum_{q'=1}^{(N/2)-1} B_q \sin(2\pi qt/T_p) \quad \text{--} \qquad (8)$$

At the particular points $t=nh;\ n=1,2,---,N$
where $T_p = Nh$

$$x_n = x(nh) = A_o + \sum_{q=1}^{N/2} A_q \cos(2\pi qn/N) + \sum_{q'=1}^{(N/2)-1} B_q \sin(2\pi qn/N) \qquad (9)$$

The coefficients A_q & B_q are given by:

$$A_o = \frac{1}{N}\sum_{n=1}^{N} x_n = \bar{x} = 0$$

$$Aq = \frac{2}{N}\sum_{n=1}^{N} x_n \cos(2\pi qn/N) \quad q=1,2,---,(N/2)-1 \quad \text{----------} \qquad (10)$$

$$A_{N/2} = \frac{1}{N}\sum_{n=1}^{N} x_n . \cos \pi n$$

$$B_q = \frac{1}{N}\sum_{n=1}^{N} x_n . \sin(2\pi qn)/N$$

Note that $A_o=0$ since $x(t)$ is transformed data, Where: $\bar{x}$ is made equal to zero

Autocorrelation And Power Spectra Calculations

Basic formulas to calculate autocorrelation and power spectral density functions for single records from digitized data

Sampling interval

$h = \Delta t$ such that $h=1/2f_c$ ---------------- (11)
where $1/f_c$ is smallest "period" in record

For accurate correlation function measurements: Where the correlation function has frequencies near f_c, one should choose $h=1/4f_c$.

If the power spectra measurements are the prime consideration, one should choose $h=2/5f_c$.

Number of correlation lag values $m=1/B_e.h$ ------- (12)
or $B_e=1/m.h$ ----------------------------- (13)

Thus B_e will be small for a given h when m is large

The sample size: N is chosen such that $N=m/\epsilon^2$ ----- (14)

The associated minimum record length $T_r=N.h$ ------ (15)

The number of degrees of freedom for spectral calculations is:

$$n = 2B_e.T_r = 2N/m \quad \text{---------------------------} \qquad (16)$$

The Normalized Standard Error is given by $\epsilon = \sqrt{m/N}$ --- (17)

ϵ will be small for a given N when m is small

Autocorrelation Functions

For N data values $\{x_n\}$ from a transformed record $x(t)$ which is stationary with $\bar{x}=0$, the estimated autocorrelation function at the displacement rh is defined by

$$\hat{R}_r = \hat{R}_x(rh) = \frac{1}{N-r} \sum_{n=1}^{N-r} x_n . x_{n+r} \quad \text{---------------} \quad (18)$$

The Maximum Lag Number m determines the later equivalent frequency band-width resolution for the power spectral density function in the frequency interval $(0,f_c)$.

This equivalent band width is:

$$B_e = 2f_c/m = 1/(m.h) = 1/\tau_{max.} \quad \text{-------------} \quad (19)$$

It means B_e is twice the range found by dividing the frequency interval $(0,f_c)$ into m equally spaced parts (f_c/m apart).

(B_e divides the theoretical frequency interval $(-f_c,f_c)$ into m equally spaced parts). Thus from knowledge of f_c, one can choose m in advance so as to have a desired B_e.

Since the quantity m represents the maximum number of correlation lag values, the maximum displacement is:

$$\tau_{max.} = mh \quad \text{-------------------} \quad (20)$$

It is desirable to keep the maximum lag m less than 1/10 the sample size N. And it is required to smooth the "Raw" power spectral density function estimates.

The autocorrelation function may take on negative as well as positive values.

A normalized value for the autocorrelation function is obtained by dividing R_r by R_c where

$$\hat{R}_o = \hat{R}_x(0) = \frac{1}{N} \sum_{n=1}^{N} (x_n)^2 = \overline{x^2} \quad \text{-----------------} \quad (21)$$

When $\hat{R}_r$ is normalized, one obtains the quantity $\hat{R}_r/\hat{R}_o$ which theoretically will be between plus and minus one

$$-1 \leqslant \hat{R}_r/\hat{R}_o \leqslant 1 \quad \text{-----------------------} \quad (22)$$

Power Spectral Density Functions

For samples data from a transformed record $x(t)$ which is stationary with $\bar{x}=0$, a "Raw" estimate $\tilde{G}_x(f)$ of a true power spectral density function $G_x(f)$ is defined for an arbitrary f in the range $0 \leq f \leq f_c$ by:

$$\tilde{G}_x(f) = 2h\left[\hat{R}_0+2\sum_{r=1}^{m-1}\hat{R}_r.\cos(\pi rf/f_c) + \hat{R}_m.\cos(\pi mf/f_c)\right] \text{---} \quad (23)$$

The total mean square value of the record in the frequency range $0 \leq f \leq f_c$ is:

$$\int_0^{f_c}\tilde{G}_x(f).df = \hat{R}_0 = \hat{R}_x(0) \quad \text{--------------------------} \quad (24)$$

It is recommeded that the values of the function $\tilde{G}_x(f)$ be calculated only at the $m+1$ special discrete frequencies.

Where: $f=k.f_c/m \quad k=0,1,2,----,m$ --------------- (25)

This will provide $m/2$ independent spectral estimates since spectral estimates at points less than $2f_c/m$ apart will be correlated.

At these discrete frequency points:

$$\tilde{G}_k = \tilde{G}_x(k.f_c/m) = 2h\left[\hat{R}_0+2\sum_{r=1}^{m-1}\hat{R}_r.\cos(\pi rk/m)+(-1)^k.\hat{R}_m\right] \text{--} \quad (26)$$

Smoothing is necessary since the periodogram (Raw estimate) given by equation (18) is an inefficient estimate of the true spectral density. The variability of these estimates does not decrease with increased record length or sample size.

This leads to the requirement of smoothing the periodogram or equivalently, weighting the correlation function nonuniformly.

When the computation of frequency response and the associated coherence functions is the main goal, certain variations in the above formulas is appropriate

$$\left.\begin{aligned} D'_r &= 1 - 6(r/m)^2 + 6(r/m)^3 && r=0,1,2,-----,m/2 \\ &= 2(1 - (r/m))^3 && r=(m/2)+1,---,m \\ &= 0. && r > m \end{aligned}\right\} \text{---} \quad (27)$$

Note that $D'_0 = 1$ and $D'_m = 0$

The use of this Parzen Lag WF maintains the sample coherence function between its theoretical values of ± 1, as opposed to the Hanning window of equation (28) which allows a sample coherence function to vary over wider limits depending on the form of the power spectrum.

The final "Smooth" formula of the power spectral density estimate at harmonic k is

$$\hat{G}_k = \hat{G}_x(k.f_c/m) = 2h(\hat{R}_0+\sum_{r=1}^{m-1}D'_r.\hat{R}_r.\cos(\pi r.k/m)) \text{---} \quad (28)$$

where D'_r is given by equation (27)

Cross Correlation Functions

Choose a maximum lag number m which will give a desired equivalent frequency resolution $B_e = 1/mh$ as well as a desired number of degrees of freedom $2N/m$.

The autocorrelation functions and power spectral density functions are calculated for the transformed variables x(t) and y(t) in terms of the data values, x_n & y_n, separately according to the formulas listed previously.

The following are the formulas to calculate their joint cross-correlation functions and cross-spectral functions in terms of the trasformed data:

Estimates for the sample cross-correlation functions at lag numbers r=0,1,2,----,m are defined by:

$$\hat{R}_{xy}(rh) = \frac{1}{N - r} \sum_{n=1}^{N-r} x_n \cdot y_{n+r} \quad \text{---------------------} \quad (29)$$

$$\hat{R}_{yx}(rh) = \frac{1}{N - r} \sum_{n=1}^{N-r} y_n \cdot x_{n+r} \quad \text{---------------------} \quad (30)$$

(If N is $\gg$ m, it may be more convenient to divide by N instead of N-r in equations (30),(29) and (18).)

For later determination of the cross-spectral density function estimate

$\hat{G}_{xy}(f)$ between x(t) and y(t), calculate for r=0,1,2,----,m, the two quantities (even and odd parts of the cross-correlation function).

$$\hat{A}_r = \hat{A}_{xy}(rh) = \frac{1}{2}\left[\hat{R}_{xy}(rh) + \hat{R}_{yx}(rh)\right] \quad \text{-------------} \quad (31)$$

$$\hat{B}_r = \hat{B}_{xy}(rh) = \frac{1}{2}\left[\hat{R}_{xy}(rh) - \hat{R}_{yx}(rh)\right] \quad \text{-------------} \quad (32)$$

Cross Spectral Density Functions

It is a complex-valued quantity defined by:

$$G_{xy}(f) = C_{xy}(f) - jQ_{xy}(f) \quad \text{---------------------} \quad (33)$$

"Raw" estimates from sampled data for the co-spectral density function and the quadrature spectral density function may be found as follows:

The formulas are for one-sided spectra which are nonZero only for $f \geqslant 0$

At an arbitrary value of f in the range $0 \leqslant f \leqslant f_c$, "Raw" estimates for $\tilde{C}_{xy}(f)$ & $\tilde{Q}_{xy}(f)$ are

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$$\tilde{C}_{xy}(f) = 2h\left[\hat{A}_o+2\sum_{r=1}^{m-1}\hat{A}_r.\cos(\pi rf/f_c)+\hat{A}_m.\cos(\pi mf/f_c)\right] \quad (34)$$

$$\tilde{Q}_{xy}(f) = 2h\left[2\sum_{r=1}^{m-1}\hat{B}_r.\sin(\pi rf/f_c)+\hat{B}_m.\sin(\pi mf/f_c)\right] \quad (35)$$

Where $\hat{A}_r$ & $\hat{B}_r$ are given by equations (31) & (32). As before, these functions should be calculated only at the m+1 special discrete frequencies of harmonic.

At these discrete frequency points:

$$\tilde{C}_k = \tilde{C}_{xy}(kf_c/m) = 2h\left[\hat{A}_o+2\sum_{r=1}^{m-1}\hat{A}_r\cos(\pi rk/m)+(-1)^k.\hat{A}_m\right] \quad (36)$$

$$\tilde{Q}_k = \tilde{Q}_{xy}(kf_c/m) = 4h\sum_{r=1}^{m-1}\hat{B}_r.\sin(\pi rk/m) \quad (37)$$

"Smooth estimates for C_k & Q_k at harmonic k may now be calculated as in equation(27), by using the Hanning method. This yield:

$$\left.\begin{aligned}
\hat{C}_o &= 0.5\tilde{C}_o + 0.5\tilde{C}_1\\
\hat{Q}_o &= 0.5\tilde{Q}_o + 0.5\tilde{Q}_1\\
\hat{C}_k &= 0.25\tilde{C}_{k-1} + 0.5\tilde{C}_k + 0.25\tilde{C}_{k+1}\\
\hat{Q}_k &= 0.25\tilde{Q}_{k-1} + 0.5\tilde{Q}_k + 0.25\tilde{Q}_{k+1}\\
\hat{C}_m &= 0.5\tilde{C}_{m-1} + 0.5\tilde{C}_m\\
\hat{Q}_m &= 0.5\tilde{Q}_{m-1} + 0.5\tilde{Q}_m
\end{aligned}\right\} \quad (38)$$

At the m+1 discrete frequencies one obtains the smooth" cross-spectral density estimates

$$\hat{G}_{xy}(kf_c/m) = \hat{C}_k - j\hat{Q}_k$$

Frequency Response Functions

H(f) is a complex-valued function

$$H(f) = \left|H(f)\right| .e^{-j\phi(f)} \quad (39)$$

Where:-
$|H(f)|$ is the gain factor of the system
$\phi(f)$ is the phase factor of the system

If a stationary input x(t) produces an output y(t), the system gain factor

$$\left|\hat{H}(f)\right| = (\hat{G}_y(f)/\hat{G}_x(f))^{\frac{1}{2}} \quad (40)$$

Hence, at the discrete frequencies $f=kf_c/m$, the gain factor may be estimated digitally by

$$|\hat{H}_k| = |\hat{H}(kf_c/m)| = (\hat{G}_{k,y}/\hat{G}_{k,x})^{\frac{1}{2}} \quad \text{---------} \quad (41)$$

For either single input-single output problems where extraneous noise is present only at the output, or multiple input-single output problems where the inputs are uncorrelated, another more general method for estimating the system frequency response function (including both gain and phase factors) is given by:-

$$H(f) = \hat{G}_{xy}(f)/\hat{G}_x(f) \quad \text{--------------------} \quad (42)$$

It follows that:-

$$\text{And}\quad \left.\begin{aligned} |\hat{H}(f)| &= |\hat{G}_{xy}(f)| \;/\hat{G}_x(f) \\ \hat{\phi}(f) &= \hat{\theta}_{xy}(f) \end{aligned}\right\} \quad \text{------------------} \quad (43)$$

Therefore at the discrete frequencies $f=kf_c/m$ the gain factor and phase factor may be estimated digitally by:-

$$|\hat{H}_k| = (\hat{C}_k^2+\hat{Q}_k^2)^{\frac{1}{2}}/\hat{G}_{k,x} \quad \text{--------------------------} \quad (44)$$

$$\hat{\phi}_k = \tan^{-1}(\hat{Q}_k/\hat{C}_k) \quad \text{---------------------------} \quad (45)$$

Coherence Functions

The coherence function $\gamma_{xy}^2(f)$ between two stationary records $x(t)$ and $y(t)$ is defined by:-

$$\gamma_{xy}^2(f) = |G_{xy}(f)|^2/(G_x(f).G_y(f)) \quad \text{-------------} \quad (46)$$

The coherence function theoretically should satisfy

$$0 \leq \gamma_{xy}^2(f) \leq 1 \qquad \text{for all } f.$$

In terms of digital calculations, at the discrete frequencies $f=kf_c/m$ the coherence function is estimated by

$$\hat{\gamma}_k^2 = (\hat{C}_k^2 + \hat{Q}_k^2)/(\hat{G}_{k,x}.\hat{G}_{ky}) \quad \text{------------------} \quad (47)$$

The Transfer function is the mathematical description of the system. It can also be used to measure the relationship between any two signals. It can be defined as:-

$$\text{Transfer Function} = \frac{\text{Average cross power spectrum of input \&output}}{\text{Average power spectrum of input}}$$

This gives more reliable transfer function.

The coherence function can be used to check the validity of the transfer function, i.e., it can be used to measure the degree of causality between any two signals. A "0" value means no coherence between input and output of the system. A value of "1" means there is a complete coherence between them indicating that there is only one input and the system is linear.