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Stress-Strain Analysis of Silicon Ribbon

by

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INTRODUCTION

At the Mini-workshop on stresses and strains held at Mobil Solar on January 23-24, 1985, we reported on our numerical results for the in plane stresses and the dislocation fields in silicon ribbon. We stressed that we had obtained a number of convergent solutions which could be relied upon to provide insight into the physical phenomena involved. It was emphasized at the meeting that the approach to the calculation for the dislocation density was unique and is the FIRST such calculation ever done for any problem. In our model the internal structure (here the dislocation density) of the material itself changes due to the temperature field that is imposed and to the related stress field. The dislocation density changes from point to point and the result is a prediction of the dislocation density in the final ribbon. This appears to us to be a valuable aid to the improvement of quality of the ribbon and its ability to function as a solar cell. We have had no major difficulty with convergence when the dislocation density is kept fixed.

In the presentation it was honestly stated that we also had attempted a number of cases which did not converge. We had previously assumed that this lack of convergence modeled some physical phenomena and that the only open question was precisely what phenomena was involved. In short it did not bother us what phenomena it signaled. Fortunately other participants did not see that our divergence was not purely numerical in nature. This concern for the meaning of the divergence has encouraged us to perform that additional computations described below. There is no question that the changing dislocation density makes it more difficult to obtain convergence from a purely numerical modeling point of view. When a solution converges it usually does so beautifully. For example in most of the ribbon, the effective stress

changes by 1 Pa in 10^7 Pa from one iteration to the next after 40 iterations. Near the melt interface the changes are somewhat larger than 1 Pa but they are still very small.

RESULTS

Upon returning to Lexington from the Mini-workshop, we ran calculations on two thermal profiles closely related to the (old) EFG one. These calculations were done for a 3 cm by 5 cm ribbon just because our program was already set at that geometry.

The old EFG thermal profile was

$$T_4 = 437e^{-1.36x}\cos\pi x + 1157e^{-.066x} - 317e^{-.47}\sin\left(\frac{\pi x}{2} + \frac{\pi}{6}\right)$$

The two new ones to be considered are

$$T_5 = 437e^{-1.36}\cos\pi x + 1157e^{-.066x} - 158.5e^{-.47x}$$

and

$$T_6 = 437e^{-1.36x} + 1157e^{-.066x} - 158.5e^{-.47x}$$

These new profiles are shown in Fig. 1 and Fig. 2. Clearly the profile T_6 is very smooth and T_5 has a "bump" that occurs in the hot part of the ribbon.

The original (old) EFG profile has an additional annealing "bump" at larger x than the one shown in Fig. 1.

After 43 iterations absolutely beautifully convergent solution for both new profiles are obtained while the one for the (old) EFG profile (eg. T_4) does not converge. The dislocation density at the melt interface in these calculations was chosen as $0.001/cm^2$. The main results are shown in Figs. 3 and 4. The final dislocation density for profile T_6 is only $7.1/cm^2$ while it is $2375/cm^2$ for the thermal field T_5. These results illustrate the role of "wiggles" in the thermal profiles and their adverse effect on generating dislocations. Subsequently we have tried additional calculations for profile T_5 and a melt interface dislocation density of $0.0015/cm^2$. This case also converges beautifully and results in a final dislocation density (at y = .9 cm) of $3560/cm^2$ which is 1.5 times the value for the case when $No = .001/cm^2$.

We note in passing that there is divergence for profile T_5 and a melt interface density $No = 0.01/cm^2$.

The "effective stress" is shown in Fig. 5. It is clear that the mechanism which keeps the dislocations from getting out of hand in <u>these</u> calculations is that the stress falls below the "back stress" and hence the dislocation density does not further change with increasing x.

A detailed look at the results also shows that the dislocation density changes (almost) abruptly from $No = 0.001/cm^2$ at x = 0 to $N = 1.5/cm^2$ at x = .25 cm from the melt interface. Perhaps this value at x = .25 cm is a better physical parameter to relate to ones experiences.

For the case when the thermal profile is T_5 and the ribbon is 3 cm x 5 cm, the <u>elastic</u> stress σ_{yy} at the melt interface is $\sigma_{yy} = -.9607 \times 10^8$ Pa at y = 0.90 cm when the melt interface dislocation density is $No = 0.001/cm^2$, this same point has $\sigma_{yy} = -.8469 \times 10^8$ Pa. When the melt interface

dislocation density is No = 0.0015/cm^2, this same point has σ_{yy} = -.8462 x 10^8 Pa. The dislocation density at y = 0.9 cm and x = 2.375 cm is N = 3517/cm^2 for the case where No = 0.0015/cm^2. In all cases the σ_{yy} stresses in the plastic and elastic cases are already much closer to being the same by x = 0.25 cm. However the σ_{yy} stresses at x = 5 cm are actually larger in the plastic domain than when considered as being elastic. They are however smaller than at the melt interface.

In view of the magnitude of the dislocations generated (as shown in Fig. 3) and the corresponding extremely small plastic strains they represent, we do not see how much plastic deformation can be accomodated and still produce good solar cells. We therefore consider the case of a small dislocation density at the melt interface is really the one that is needed.

This investigator believes that his ability to return from the meeting and at once select a different profile that converges so well, reinforces the notion that he has a good understanding of what really causes the divergences to occur.

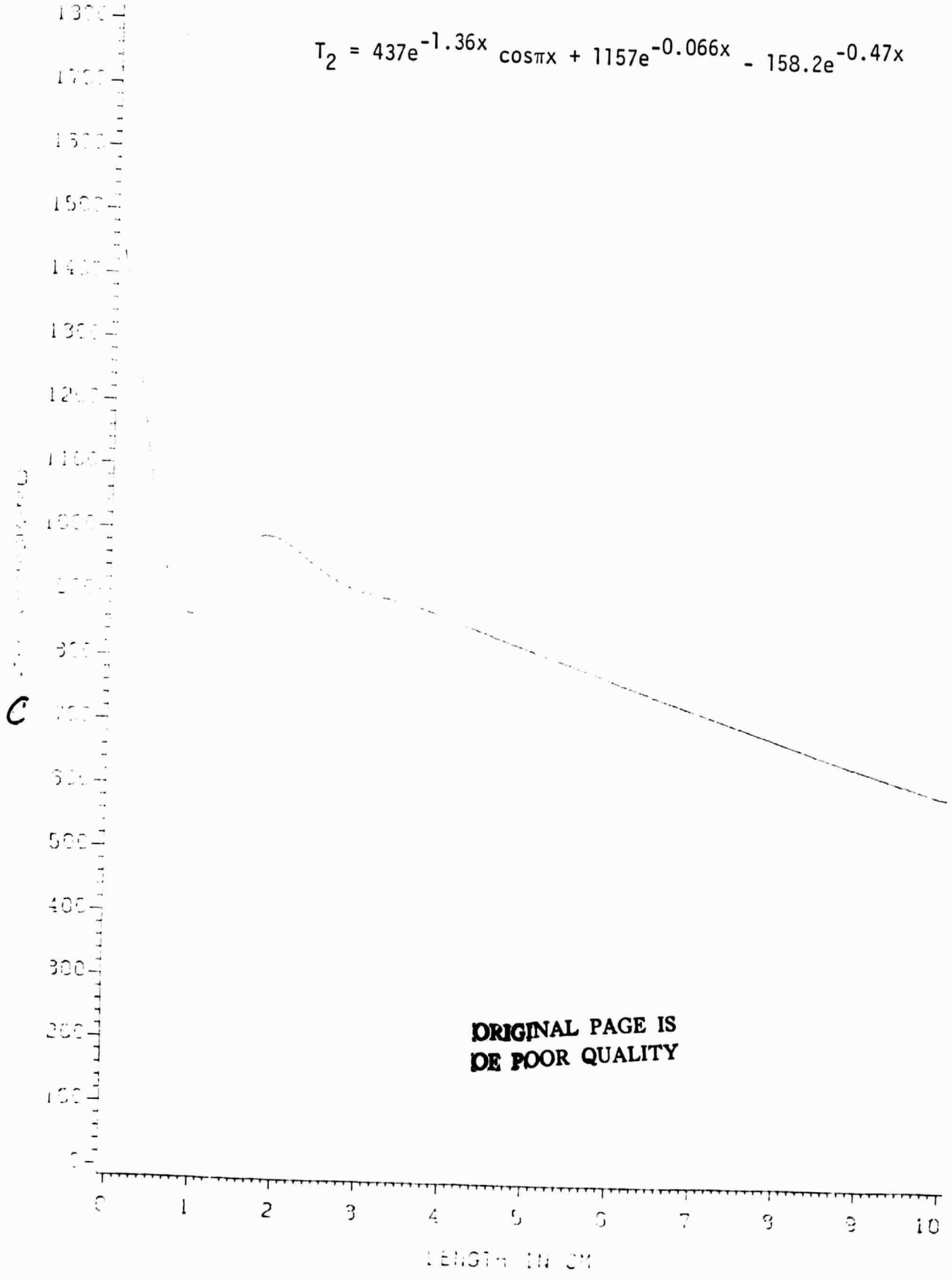
Fig. 6 shows the structure where a single crystal was used as the seed in an EFG furnace in 1974. One can note a short region of new ribbon single crystal and its subsequent break down into a polycrystal. This photo was first used in a paper by Leipold, Stirn, Fouterdyk and DeAngelis in the Eleventh IEEE Photovoltoris Specialists conference - 1975. It appears there but reproduces poorly hence is included herein.

CONCLUSIONS

In summary we believe that results such as those shown in Figs. 3 and 4 are of importance to this program for producing elastically good solar cells.

MODIFIED EFG TEMPERATURE PROFILE

$$T_2 = 437e^{-1.36x}\cos\pi x + 1157e^{-0.066x} - 158.2e^{-0.47x}$$



MODIFIED EFG TEMPERATURE PROFILE

$$T_1 = 437e^{-1.36x} + 1157e^{-0.066x} - 158.5e^{-0.47x}$$

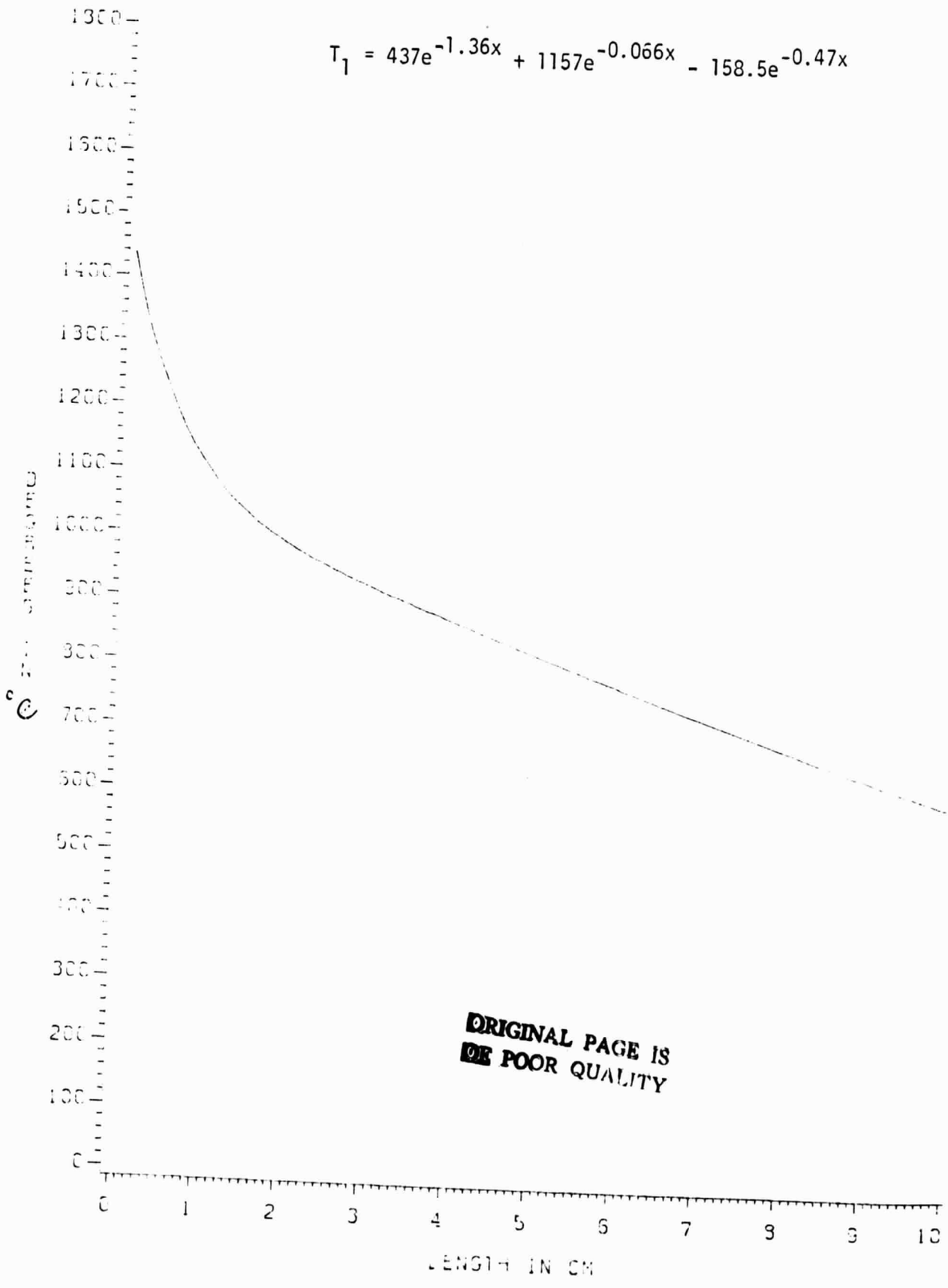


FIG 2

C = 1.5 cm
y = .75 cm

ORIGINAL PAGE IS
OF POOR QUALITY

43 iterations

Note

$T = 437\,e^{-1.36x} - 158.5\,e^{-0.47x} + 11.57\,e^{-0.066x}$

N/cm²

Computer Run V0033
26 January 1985

$N_0 = .001/cm^2$

$N = 7.8/cm^2$

FIG 3

Note:
Excellent Convergence
3 cm x 5 cm ribbon

0 2 4 6 8 10

1.0 2.0 3.0 4.0 5.0 x(cm)

C = 1.5

y = 0.9 cm

43 iterations

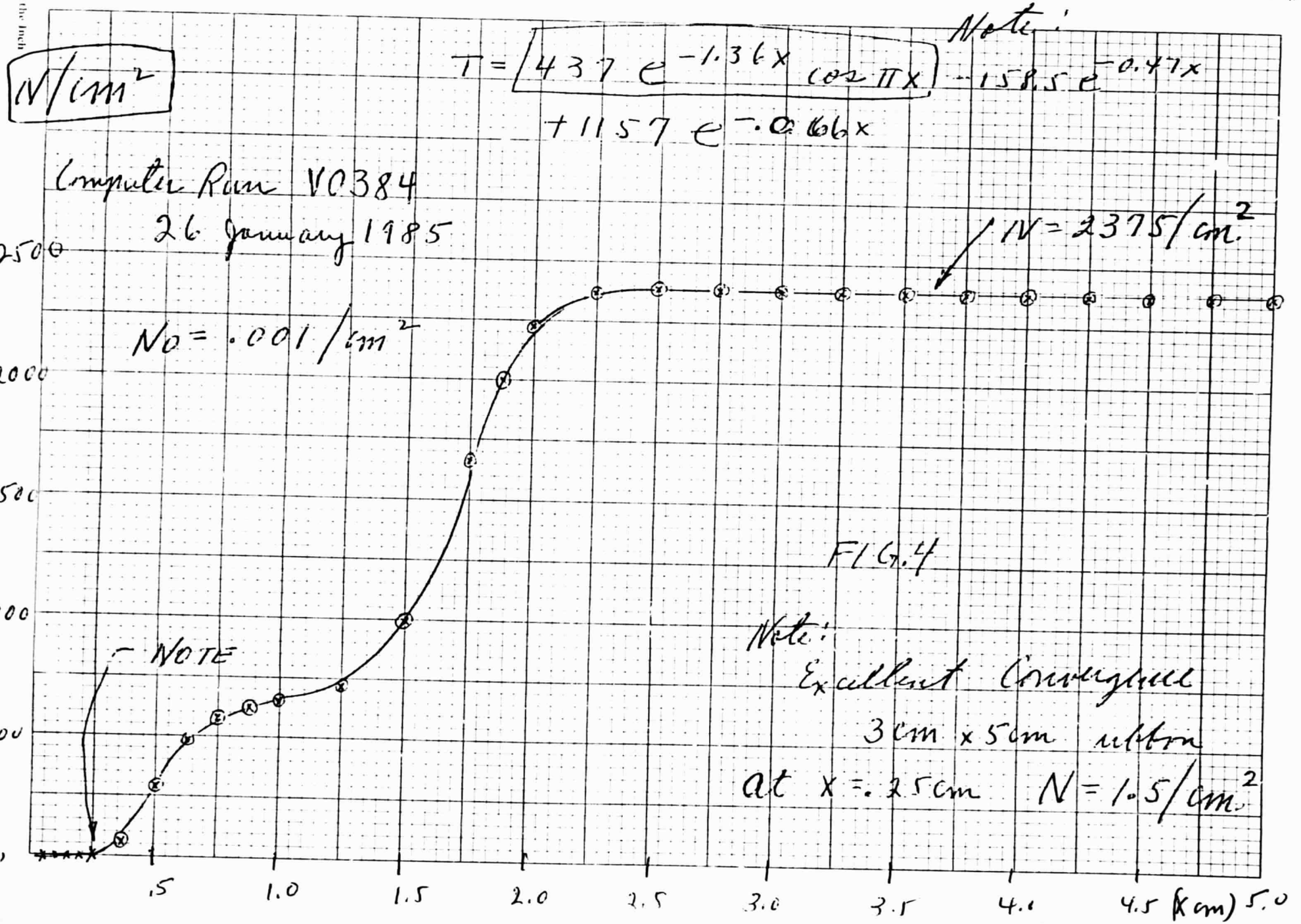


FIG. 4

Note:

Excellent Convergence

3 cm x 5 cm ribbon

at x = .25 cm N = 1.5/cm²

$C = 1.5$ cm
$y = .9$ cm

$$\bar{\tau} = 437 e^{-1.36x} \cos \pi x - 158.5 e^{-.47x} + 157 e^{-0.066x}$$

Effective Stress

$\bar{\tau}$ (MPa)

100
80
60
40
20
0

1.0
2.0
3.0
4.0
5.0

X (cm)

$y = .9$ cm

Fig 5

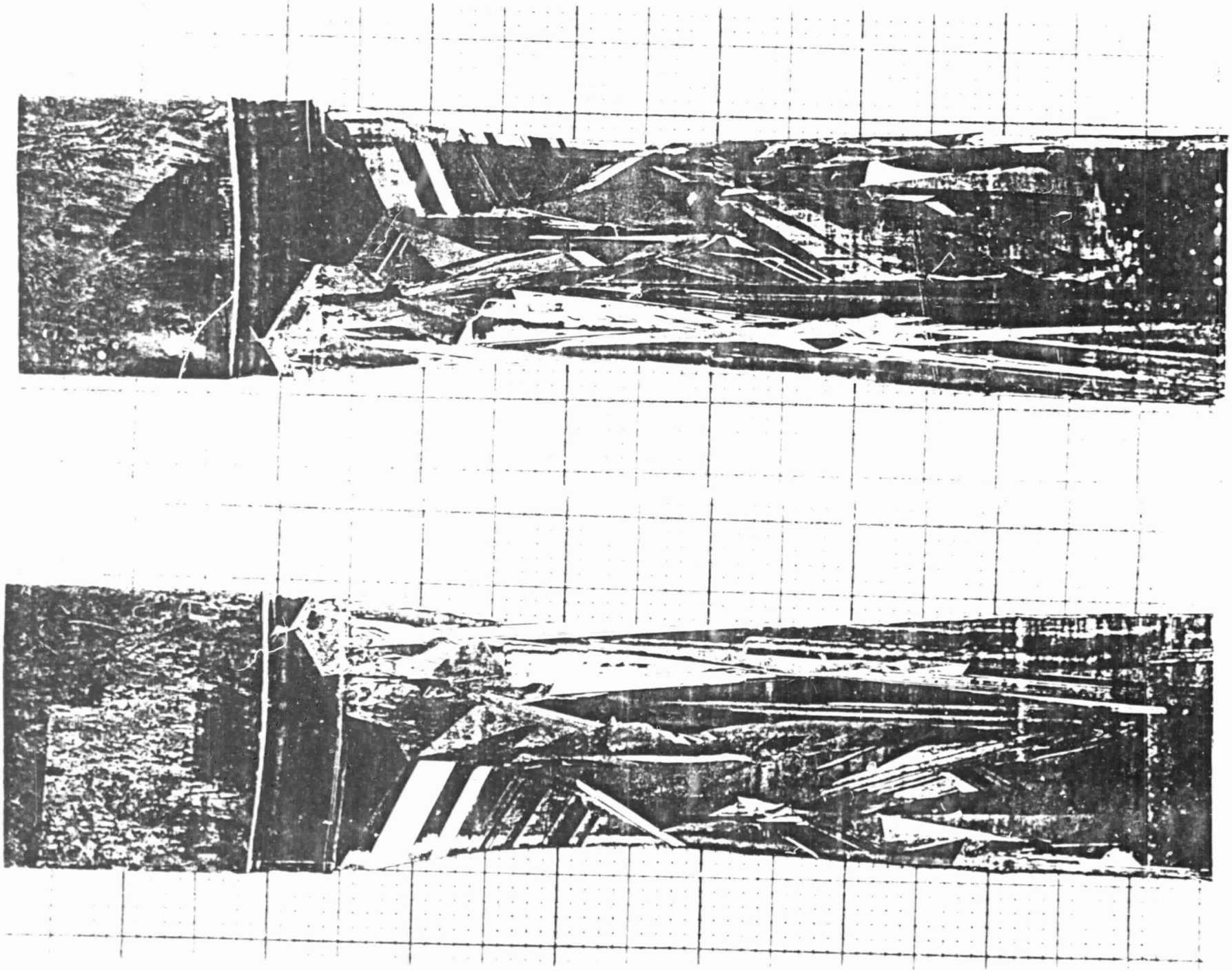


FIG. 6