The Stability of the Boundary Layer and the Spot
(the effects on its shape, rate of growth and internal structure)

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ABSTRACT

The similarity among turbulent spots observed in various transition experiments, and the rate in which they contaminate the surrounding laminar boundary layer is only cursory. The shape of the spot depends on the Reynolds number of the surrounding boundary layer and on the pressure gradient to which it and the surrounding laminar flow are exposed. The propagation speeds of the spot boundaries depend, in addition, on the location from which the spot originated and do not simply scale with the local free stream velocity. The understanding of the manner in which the turbulent spot destabilizes the surrounding, vortical fluid is a key to the understanding of the transition process. We therefore turned to detailed observations near the spot boundaries in

general and near the spanwise tip of the spot in particular.

Two, oblique wave packets of the Tollmien - Schlichting type, were observed beyond the tip of the spot. They passively trailed the spot when the surrounding boundary layer was marginally stable, but beyond the critical Re they amplified and broke down generating either new autonomous spots or coalescing with the "parent" spot and changing its shape and its rate of growth. When the boundary layer stability was enhanced by favorable pressure gradient the wave packets disappeared. Their absence is associated with the smaller rate of spread of the spot in a favorable pressure gradient.

Measurements of all three components of velocity in a turbulent spot are rare, particularly near the tip of the spot. A special hot-wire rake consisting of 8 "V" arrays was built in order to measure the spanwise and streamwise components of velocity simultaneously over a sizable fraction of the span of the spot. The data reveals the existence of a strong spanwise component of velocity which increases monotonically with increasing distance from the plane of symmetry and attains its maximum value near the tip. This perturbation velocity resembles a wave which follows the leading interface of the spot and looks like a single vortex near the tip. It also changes direction near the tip from having the dominant vorticity component parallel to the leading interface to a dominant, yet diffused vertical vorticity. A typical dimension of this vortex is comparable to 20% of the span of the spot at the location measured. This observation does not support the notion which is based on observations in a nascent spot that a spot may consist of an orderly formation of "Λ" vortices whose number is proportional to the size of the spot. No such vortices were observed near the tip of a fully aged (or developed) spot when they were analyzed by similar techniques.

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ACKNOWLEDGEMENTS

M. Zilberman

R. E. Kaplan

J. Haritonidis

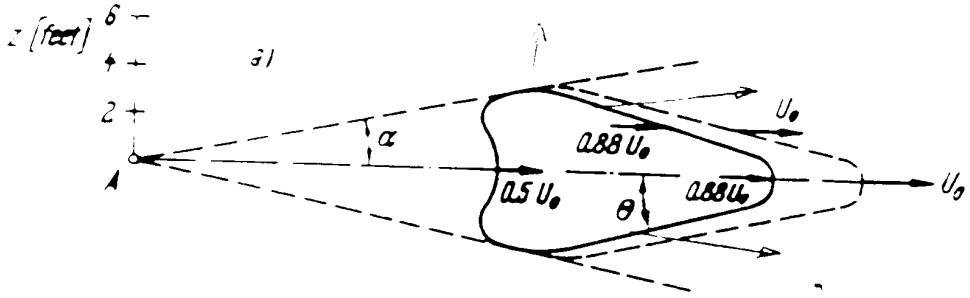
A. Glezer

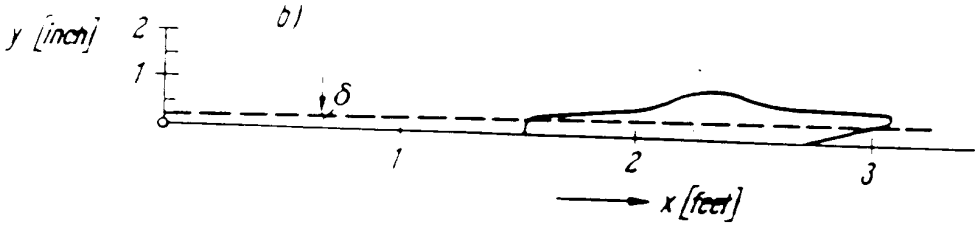
Y. Katz

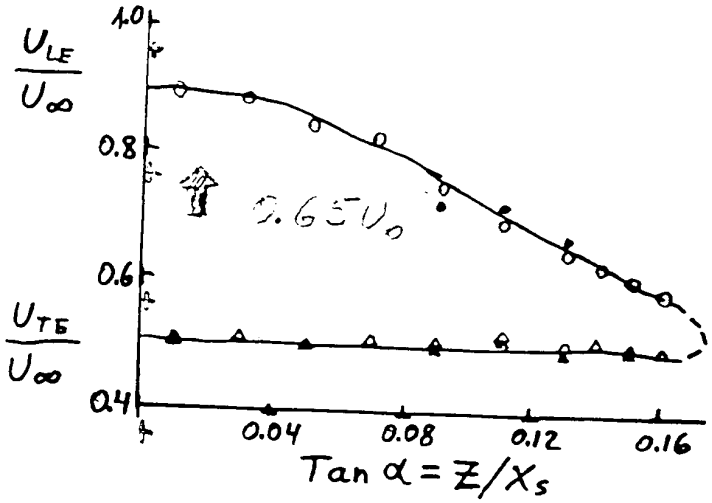
A. Seifert

The work was supported for many years by AFOSR

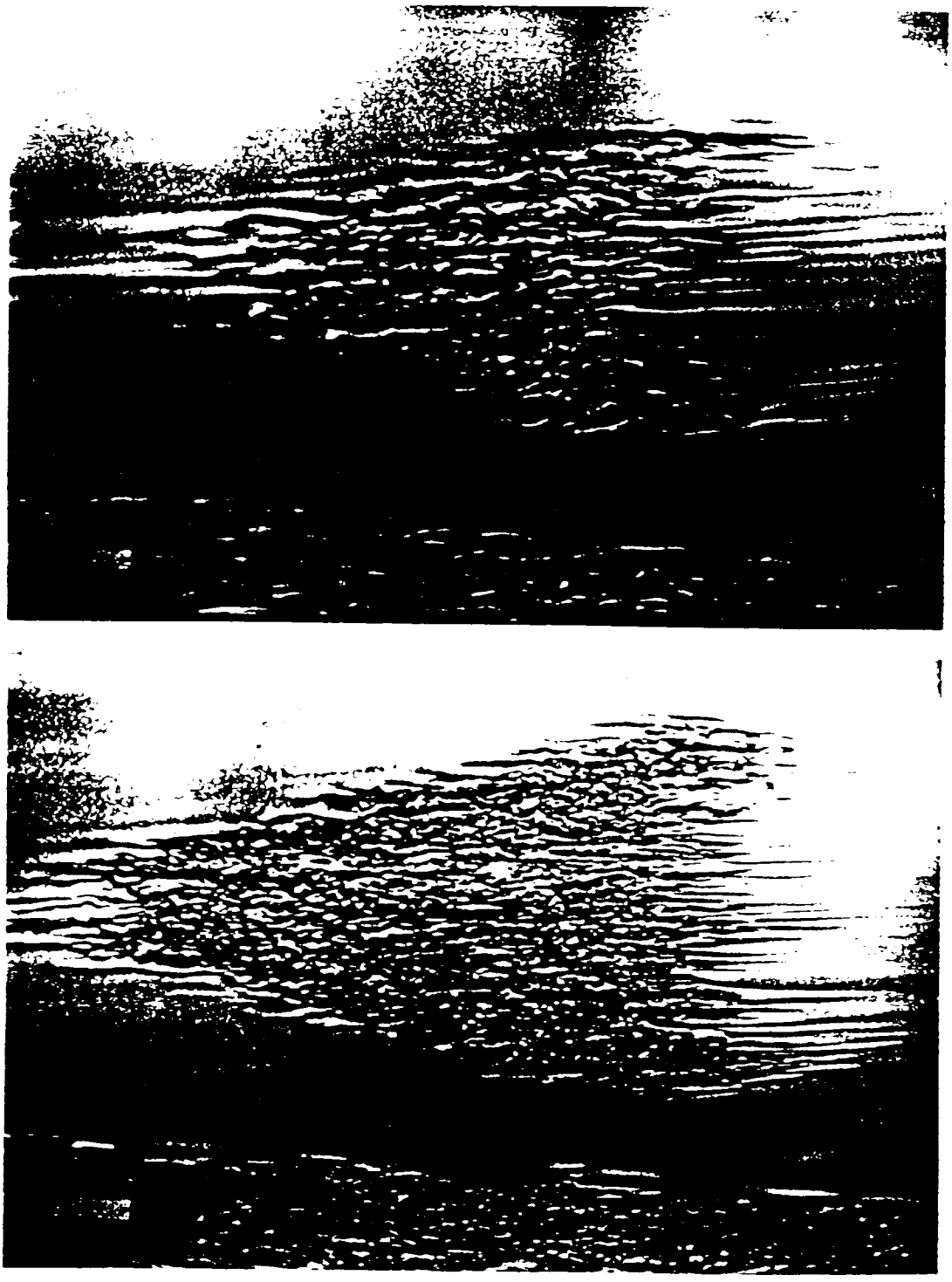
1
2


z [feet]
6
4
2
a)
A
α
0.88 U₀
0.5 U₀
θ
0.88 U₀
U₀
U₀


y [inch]
2
1
b)
δ
1
2
3
x [feet]

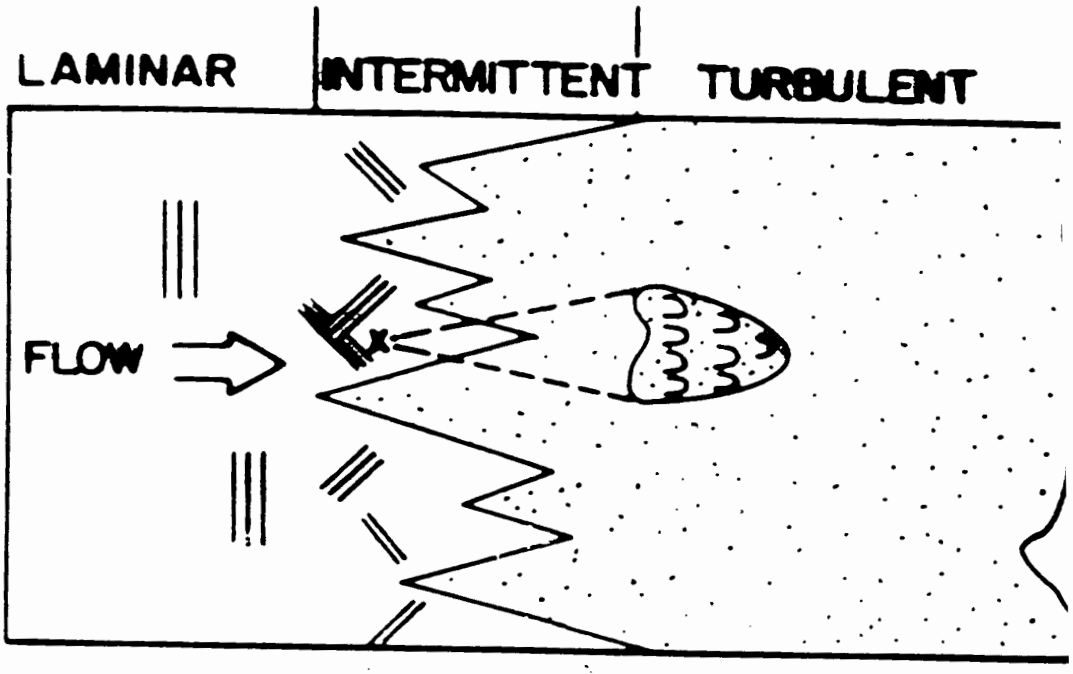

1.0
U_LE / U_∞
0.8
0.65 U₀
0.6
U_TE / U_∞
0.4
0.04
0.08
0.12
0.16
Tan α = Z/X_s

WSF 1976



Cantwell Coles & Dimotakis 1978

Figure 6. Aluminum visualization of sublayer streaks for turbulent spots in water. (a) Low Reynolds number; U_∞ = 12 cm/sec. (b) Higher Reynolds number; U_∞ = 23 cm/sec. Note region of transverse contamination from channel bottom.

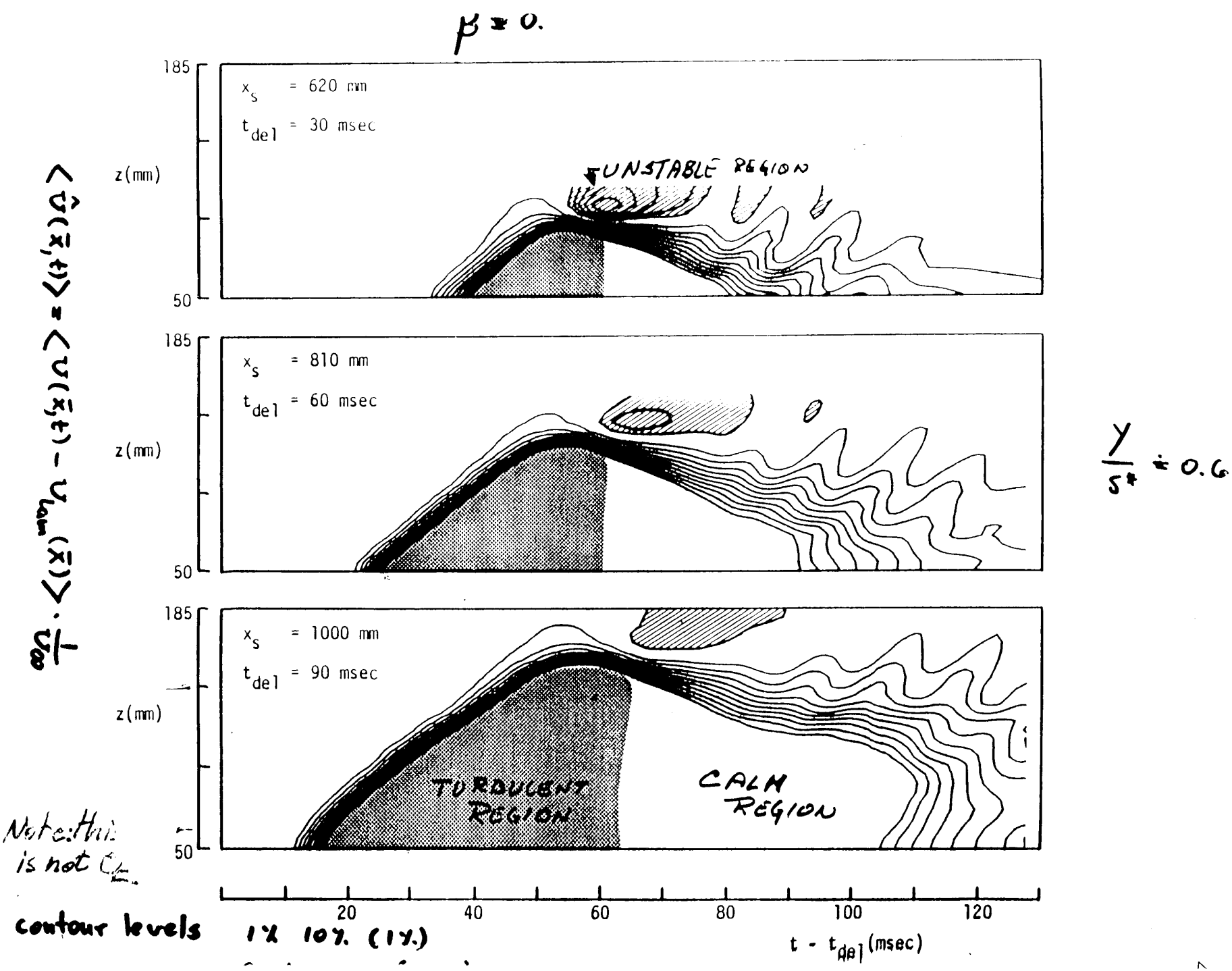


1. The spot represents the final recognizable stage in the transition process.

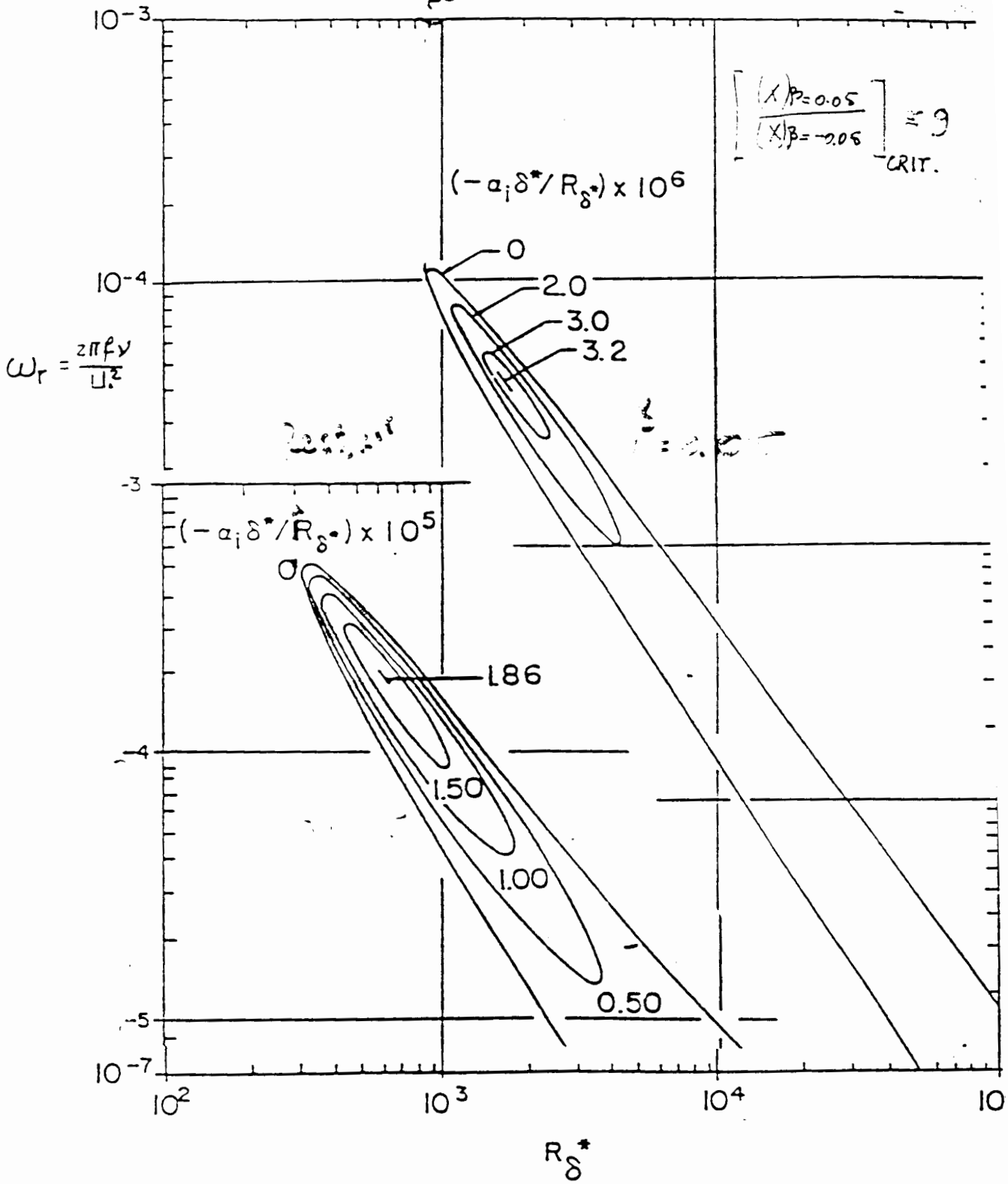
2. It provides a linkage to linear stability.

3. It generates large coherent structures in a fully turbulent boundary layer.

4. It has a higher internal degree of order than the turbulent boundary layer.

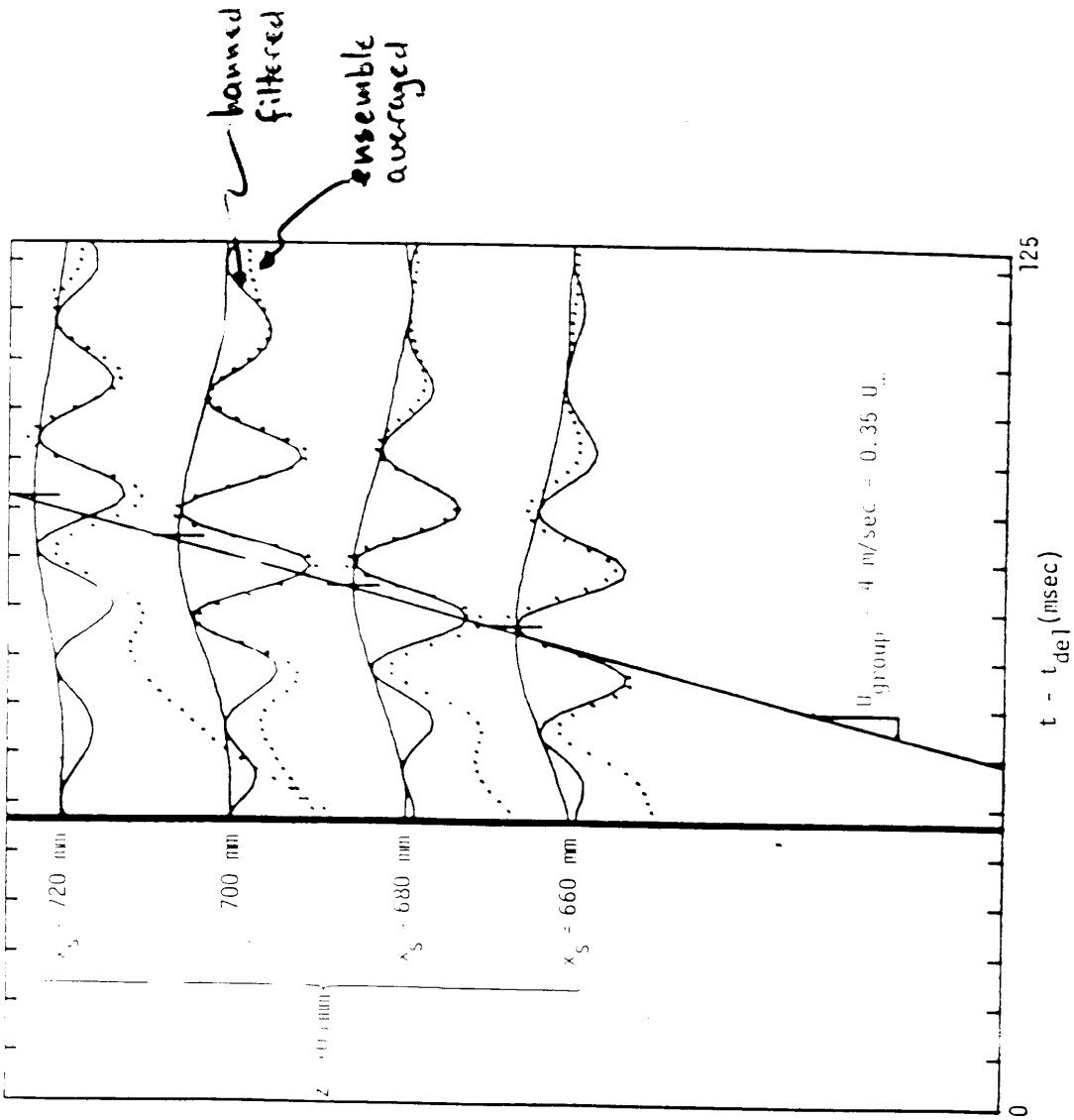


$\beta \doteq 0.$
x_s = 620 mm
t_{del} = 30 msec
UNSTABLE REGION
x_s = 810 mm
t_{del} = 60 msec
x_s = 1000 mm
t_{del} = 90 msec
TURBULENT REGION
CALM REGION
z(mm)
185
50
20
40
60
80
100
120
$t - t_{del}$ (msec)
$\langle \hat{U}(\bar{x},t) \rangle = \langle U(\bar{x},t) - U_{lam}(\bar{x}) \rangle \cdot \frac{1}{U_\infty}$
$\frac{y}{s^*} \doteq 0.6$
Note: this is not C_L
contour levels 1% 10% (1%)



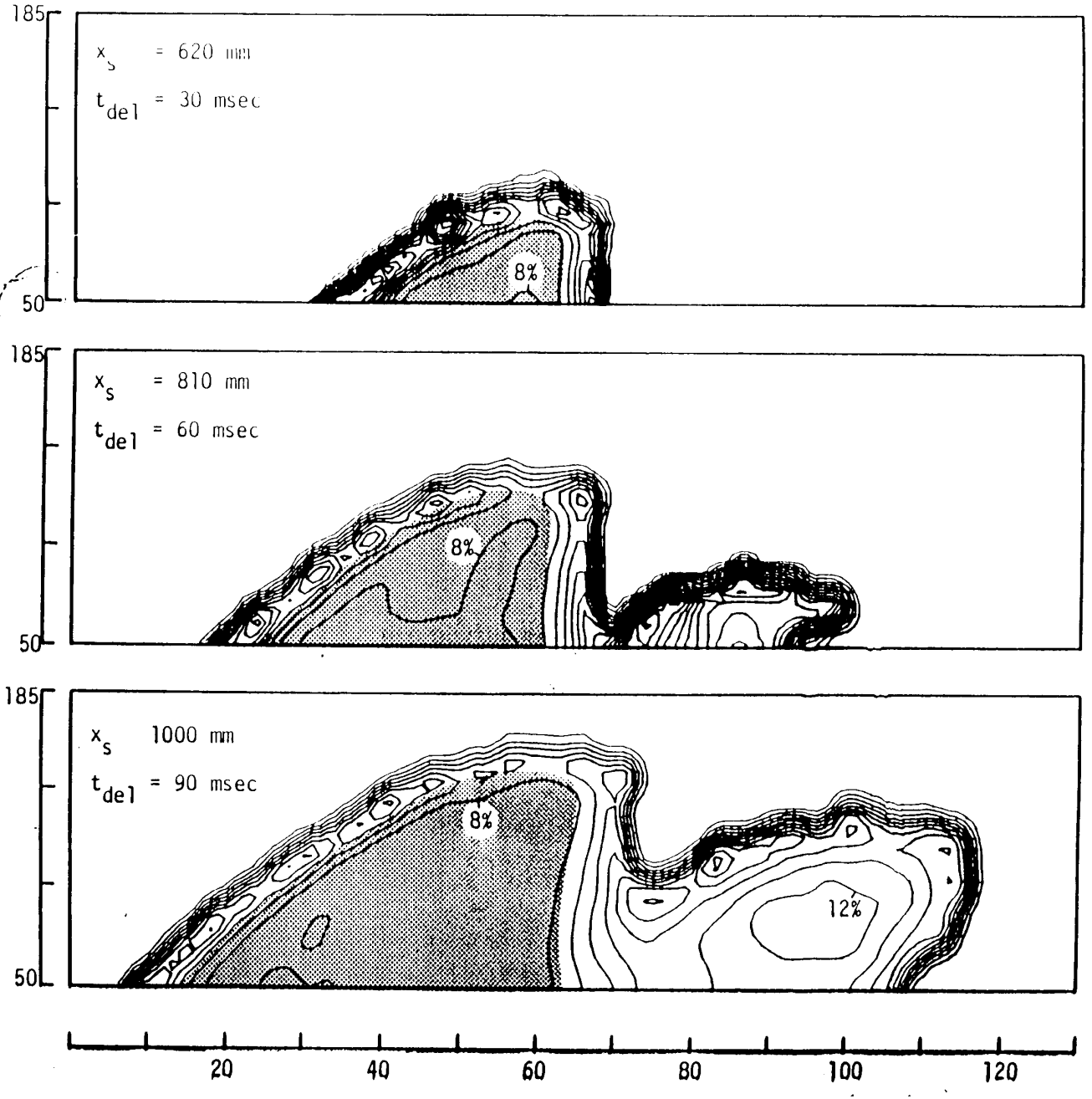
WAZZAN OKAMURA & SMITH (1968)

Figure 9. - Curves of constant spatial amplification rates ($\beta = 0.05$) (top β = Bottom



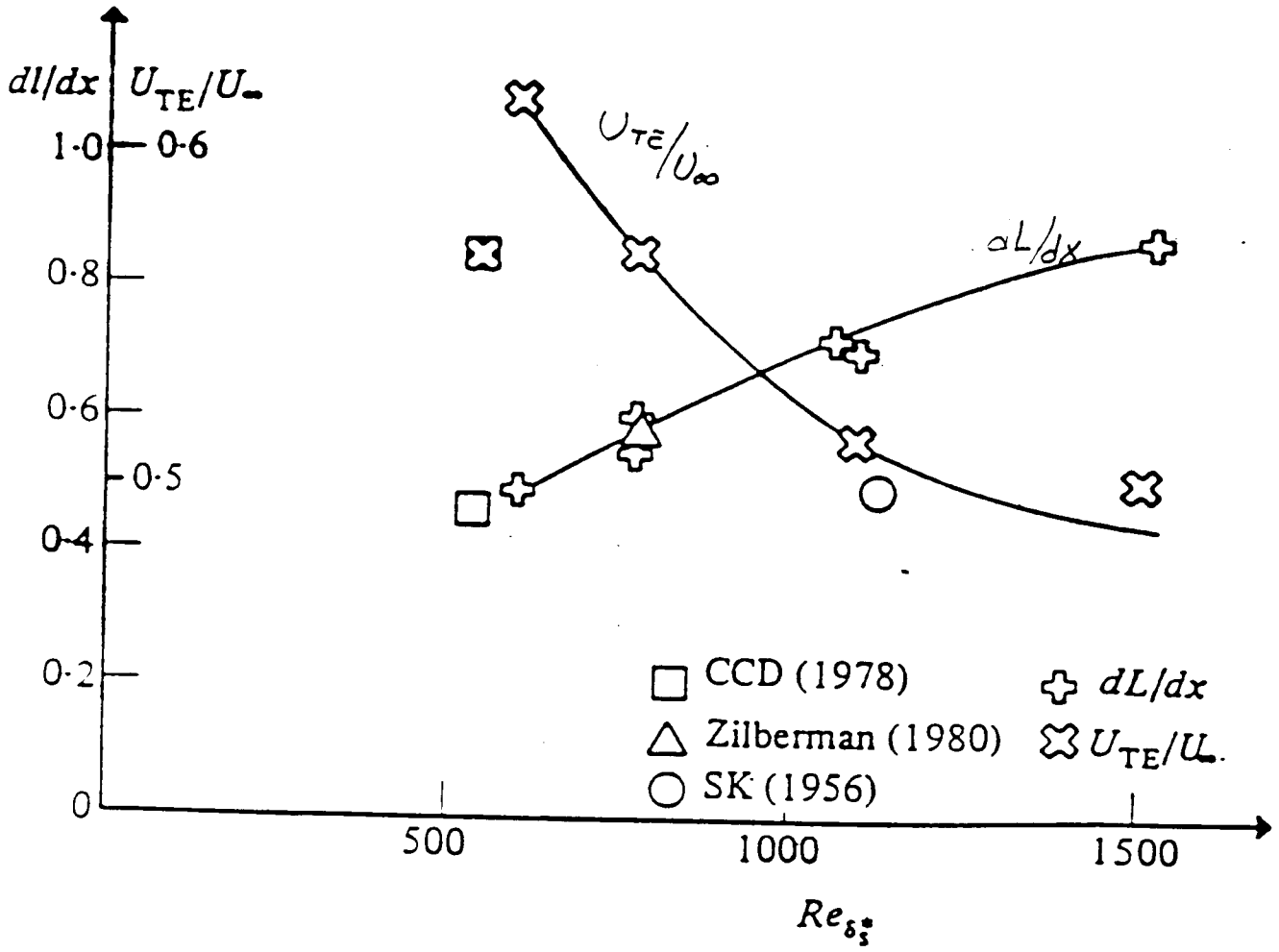
Chamber & Thoma 1995.

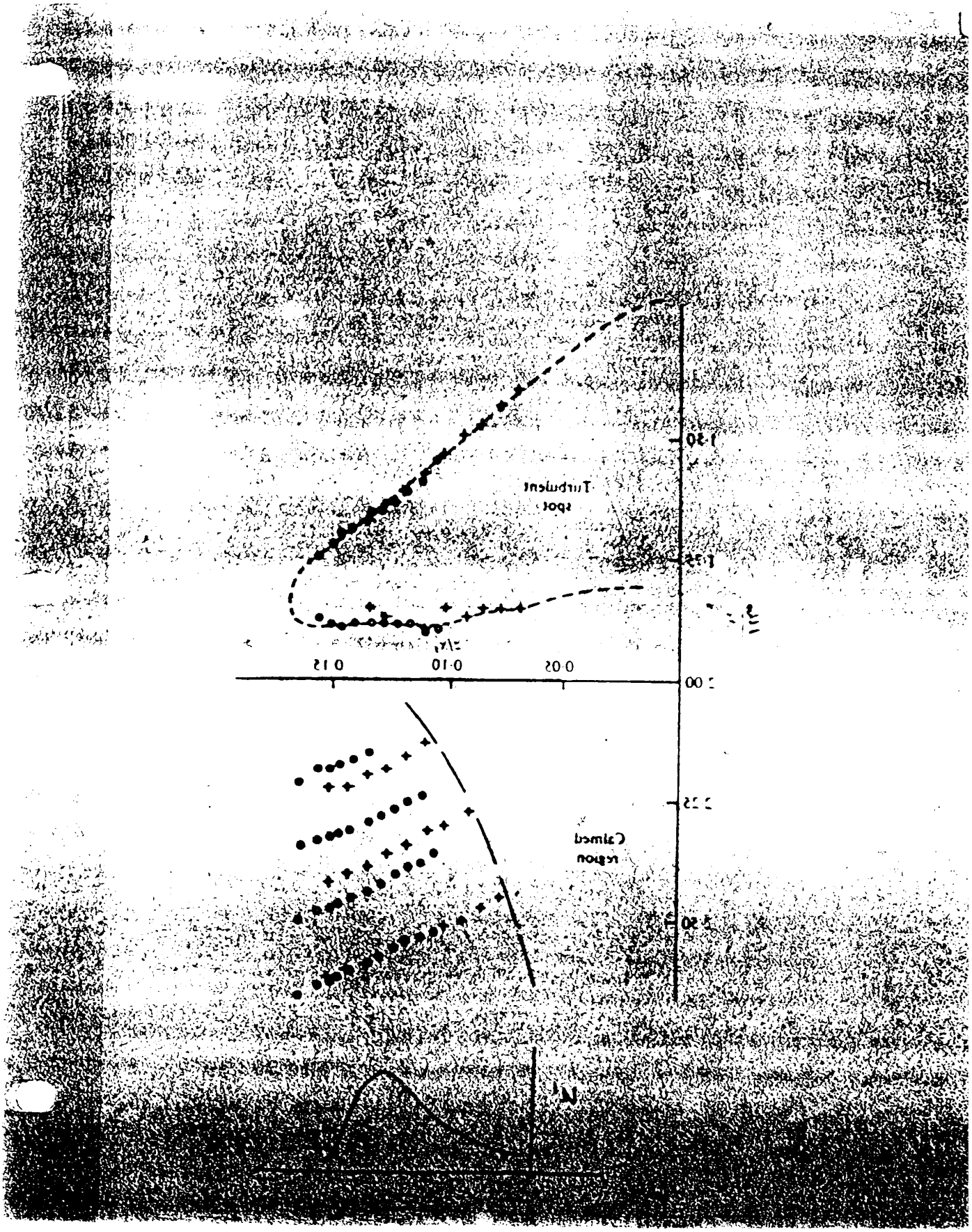
$\langle u_c'^2(\bar{x},t)\rangle = \frac{1}{b(\bar{x},t)} \langle G(\bar{x},t)\cdot u_t'^2 \rangle$ $\beta = 0.0$

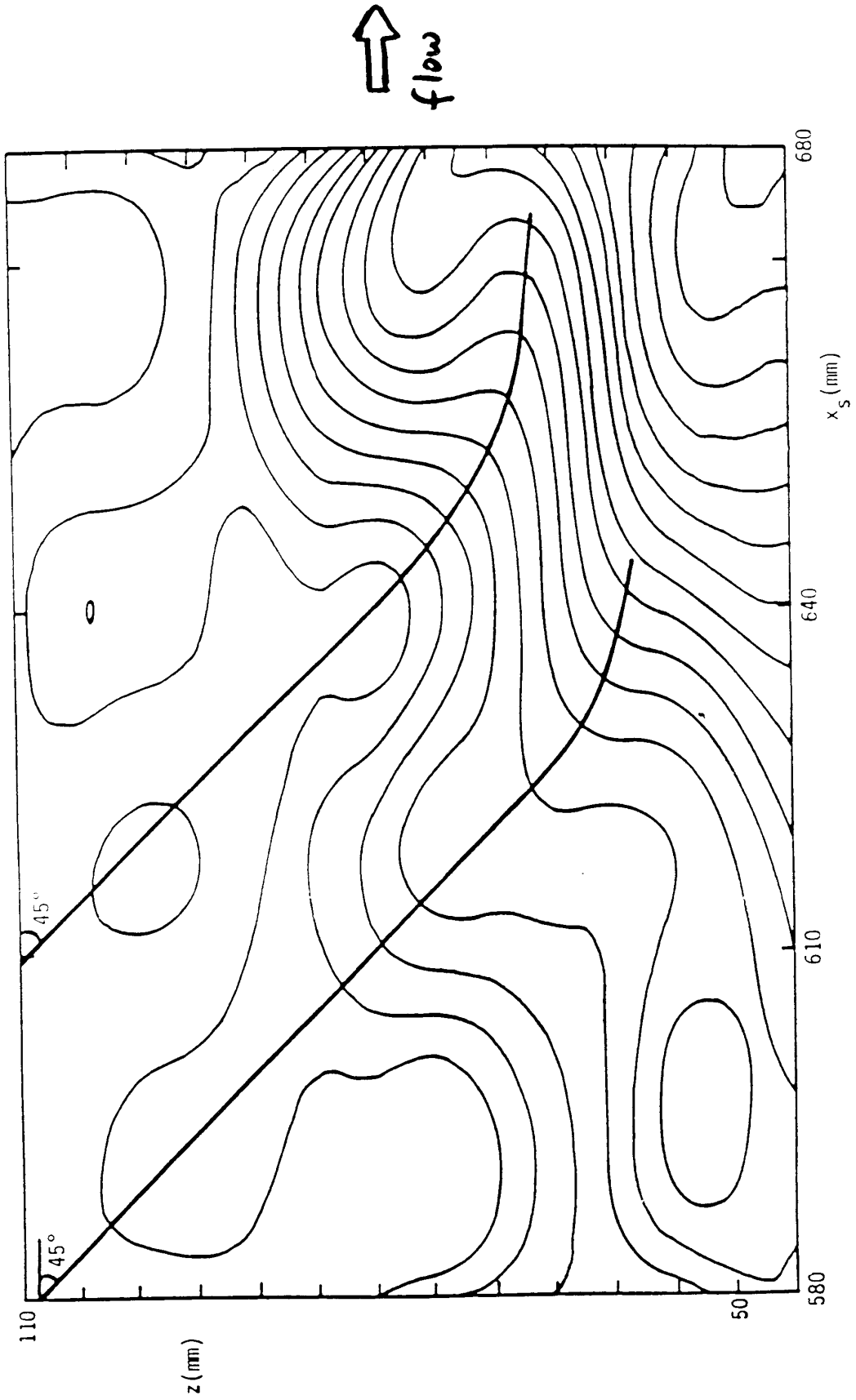


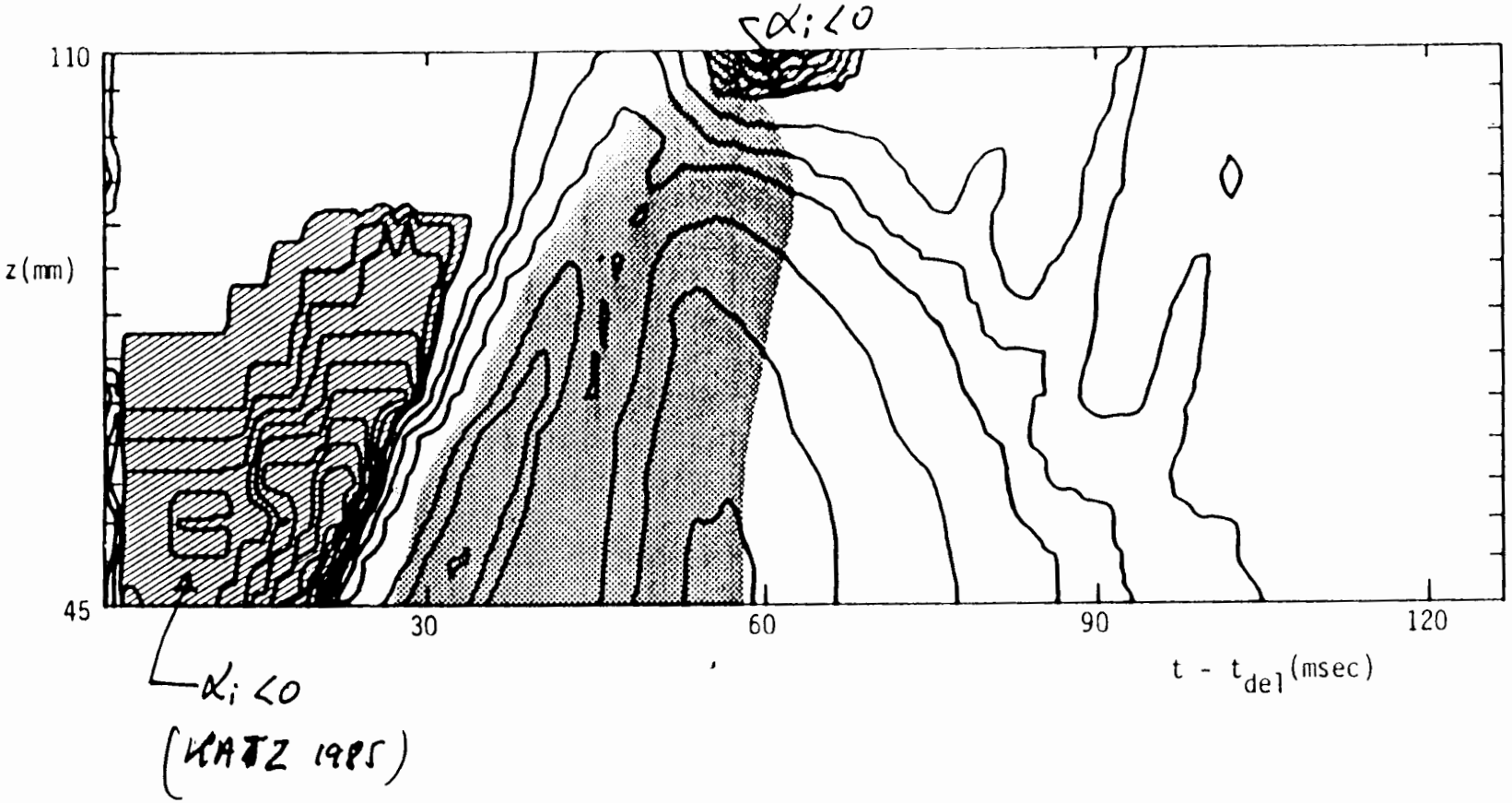
Note origin

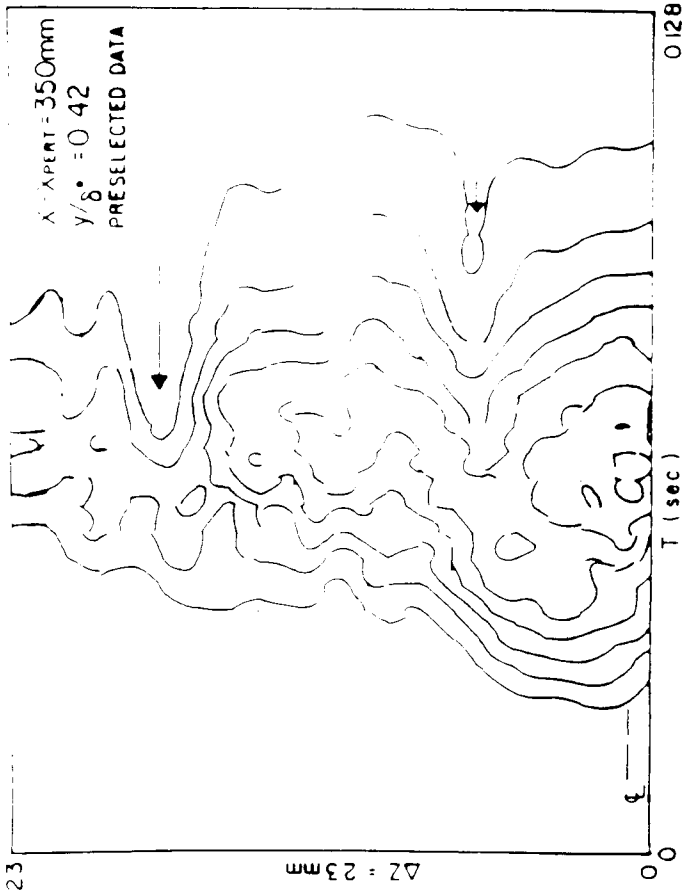
$\frac{y}{s^*} = 0.6$

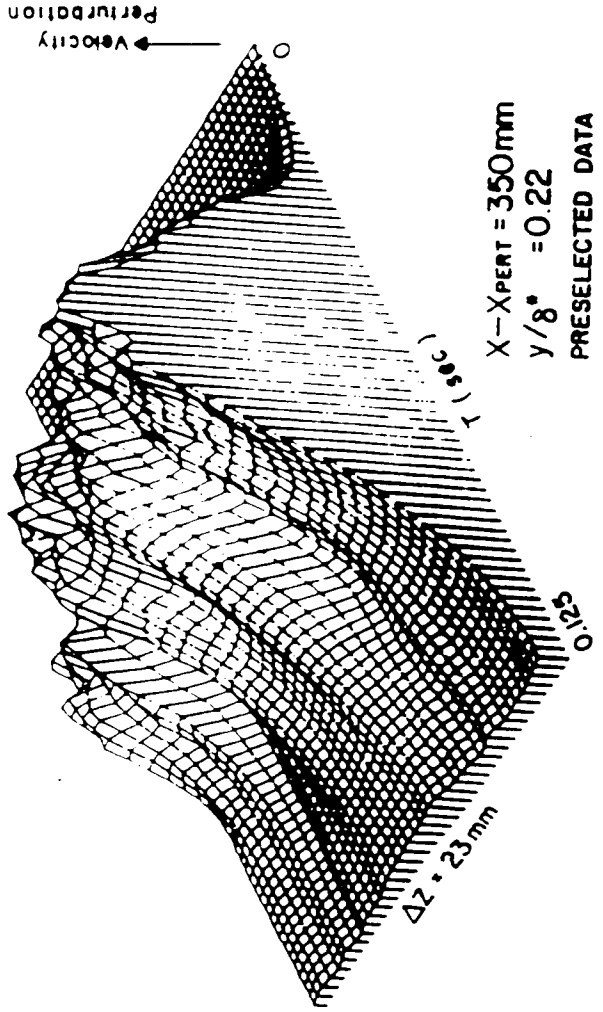

dl/dx
U_TE/U_∞
1·0
0·6
0·8
0·6
0·5
0·4
0·2
0
500
1000
1500
Re_δ*
U_TE/U_∞
dL/dx
CCD (1978)
Zilberman (1980)
SK (1956)
dL/dx
U_TE/U_∞

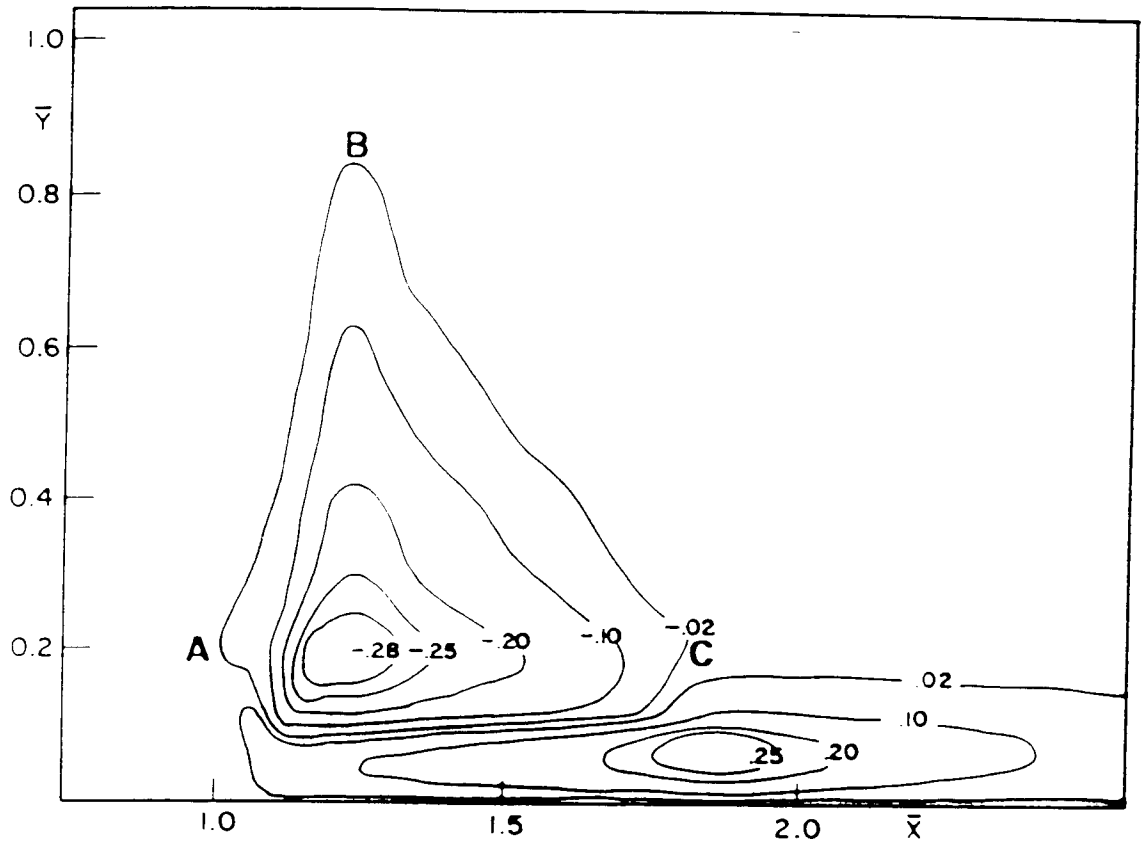

Turbulent
spot
Calmed
region

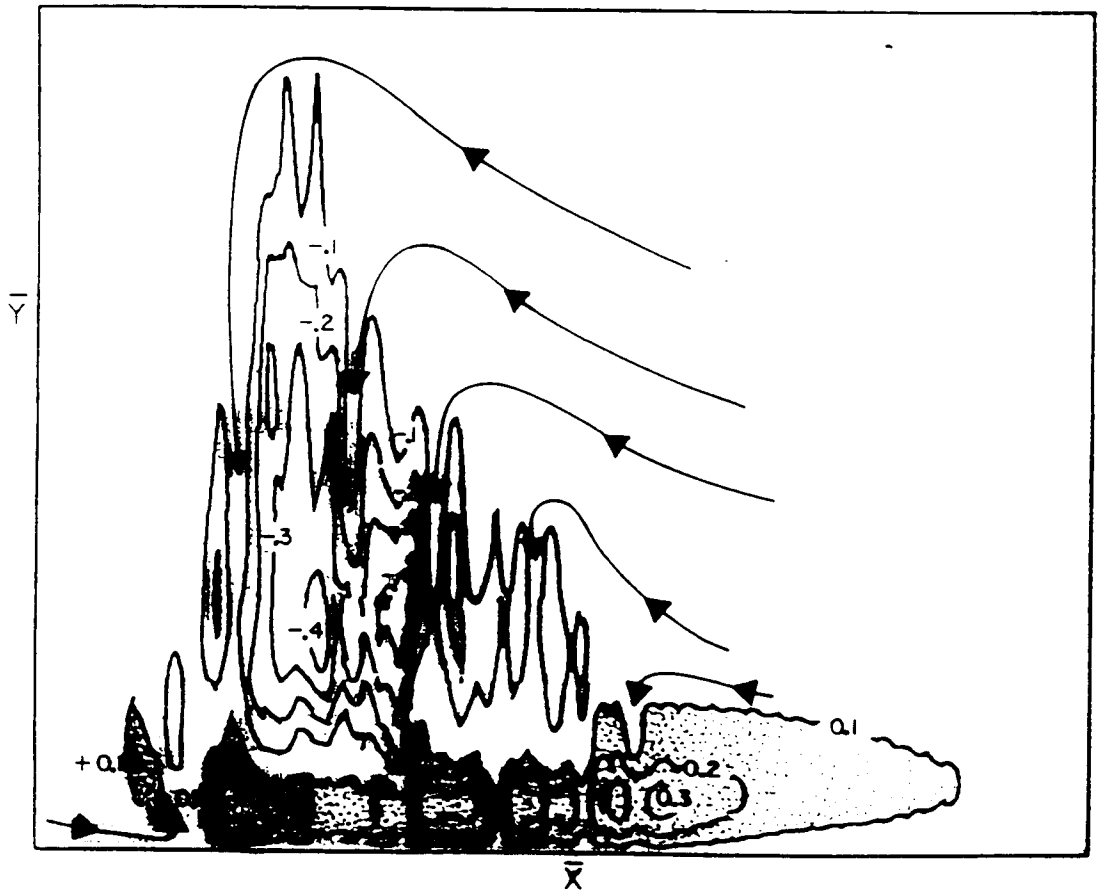

flow
680
640
610
580
x_s (mm)
110
50
z (mm)
45°
45°


α_i < 0
110
z (mm)
45
30
60
90
120
t - t_del (msec)
α_i < 0
(KATZ 1985)


X-XPERT=350mm
y/δ* =0 42
PRESELECTED DATA
0128
T (sec)
0
0
ΔZ = 23mm
23


Velocity
Perturbation
0
X-XPERT = 350mm
y/δ* =0.22
PRESELECTED DATA
T (sec)
0.125
ΔZ = 23mm


1.0
$\bar{Y}$
0.8
0.6
0.4
0.2
B
A
C
-.28 -.25
-.20
-.10
-.02
.02
.10
.25
.20
1.0
1.5
2.0
$\bar{X}$


$\bar{Y}$
-.1
-.2
-.3
-.4
0.1
0.2
0.3
$\bar{X}$

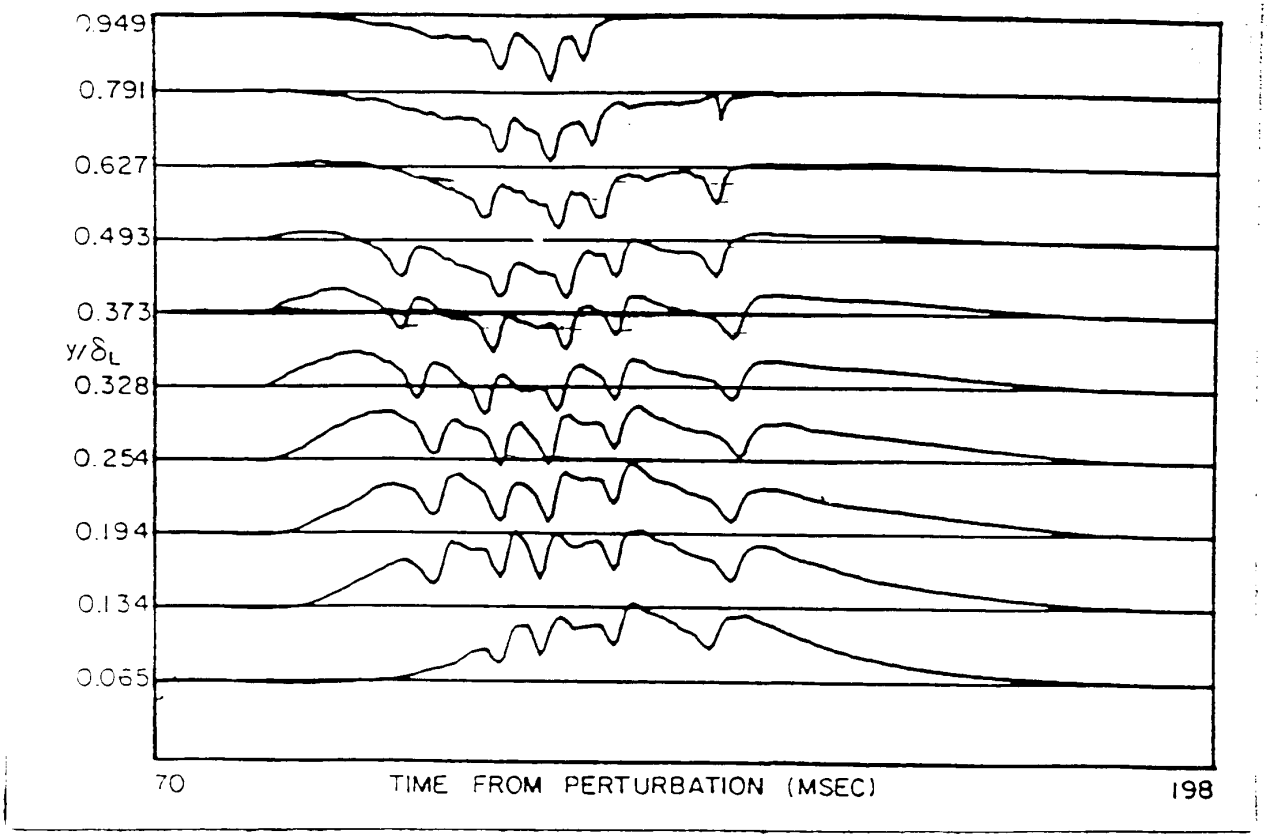

0.949
0.791
0.627
0.493
0.373
y/δL
0.328
0.254
0.194
0.134
0.065
70
TIME FROM PERTURBATION (MSEC)
198

FIG. 6 b

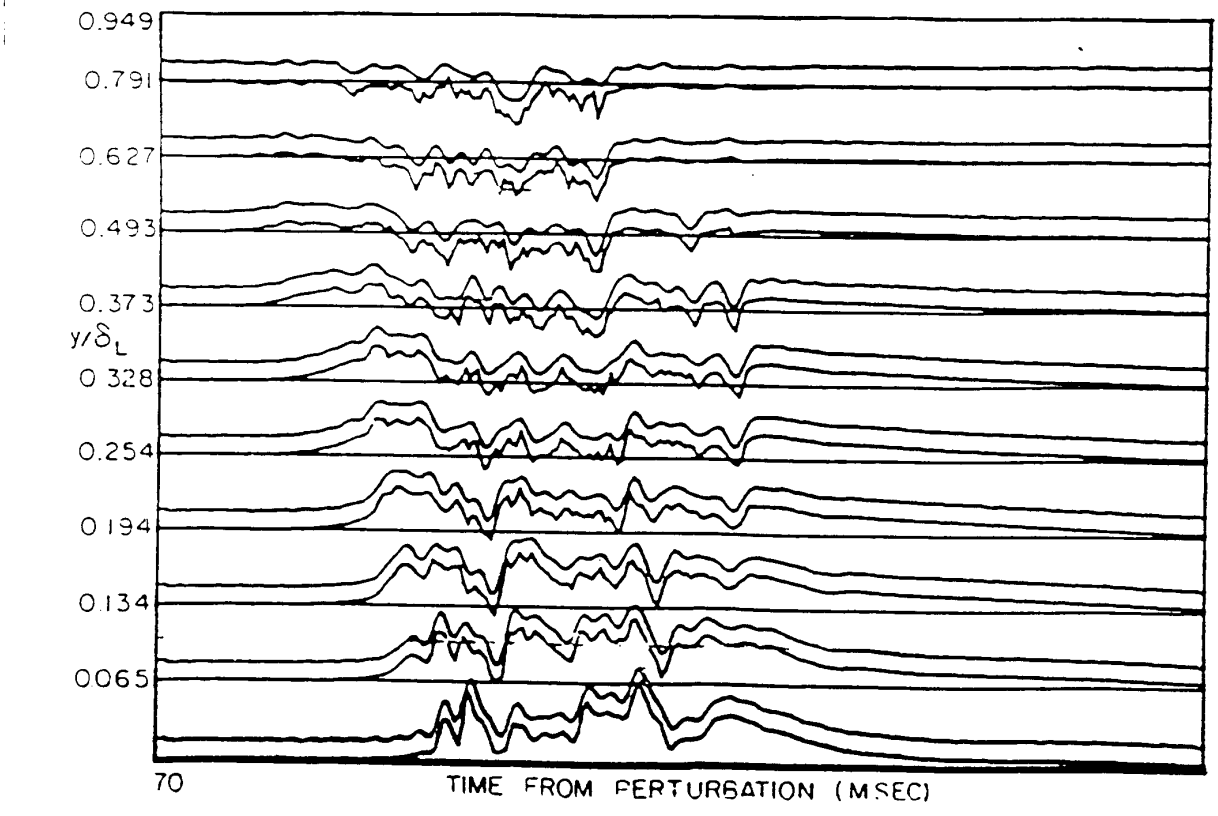

0.949
0.791
0.627
0.493
0.373
y/δL
0 328
0.254
0 194
0.134
0065
70
TIME FROM PERTURBATION (MSEC)

FIG 6 a

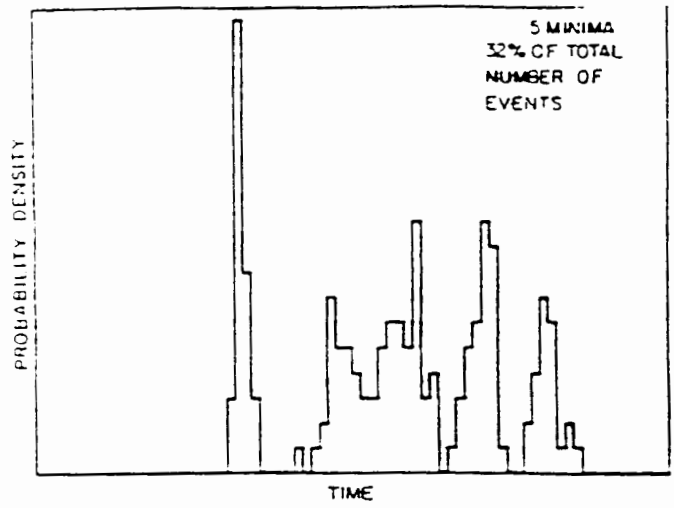


FIG. 7: HISTOGRAMS SHOWING THE PREFERRED TIME OF ARRIVAL OF EDDIES IN THE MOST PROBABLE SPOT AT A GIVEN LOCATION.

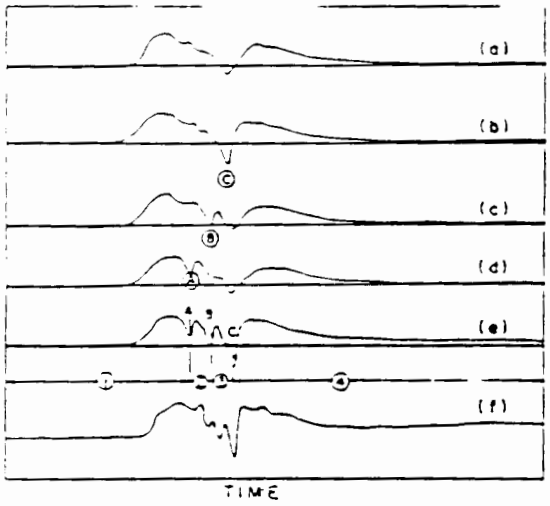


FIG. 8: A SCHEMATIC DIAGRAM SHOWING THE EDUCTION TECHNIQUE

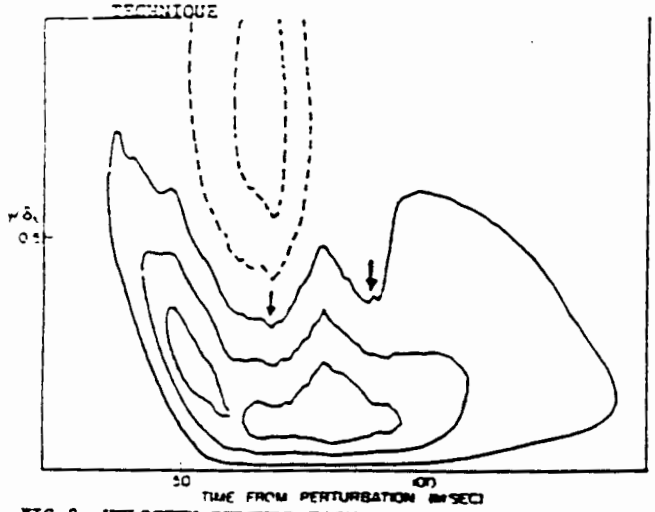


FIG.9: VELOCITY PERTURBATION CONTOURS RESULTING FROM A PASSAGE OF A SPOT a)simple ensemble average

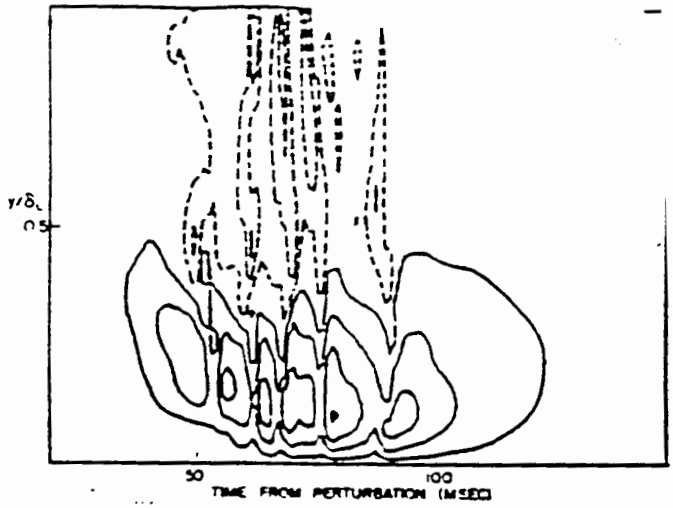


FIG. 9: b) the most probable realization

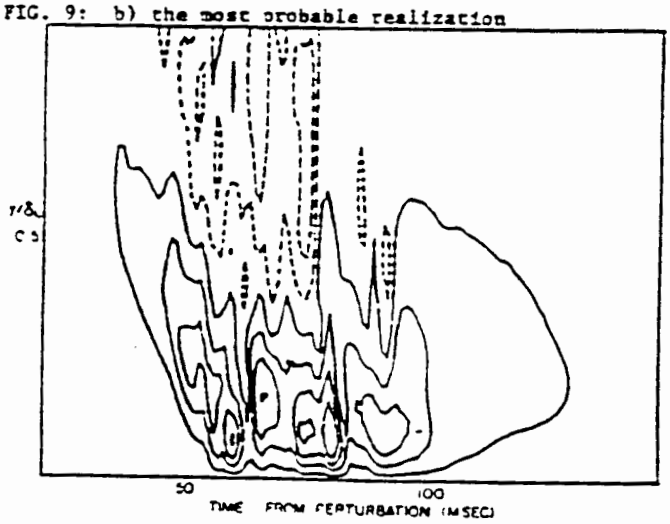


FIG. 9: c) a single realization

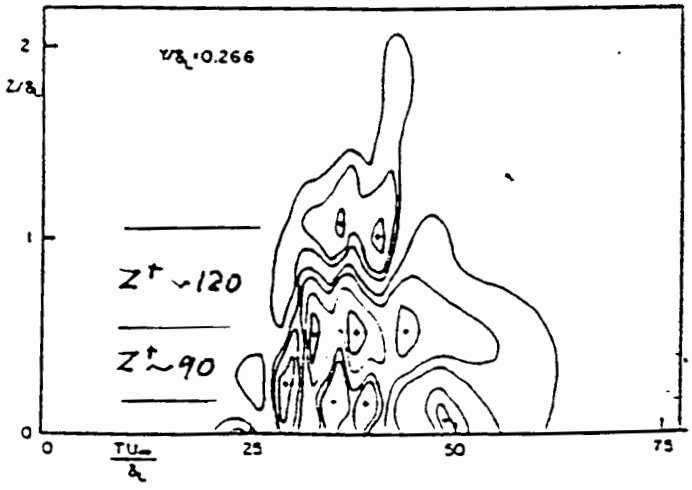
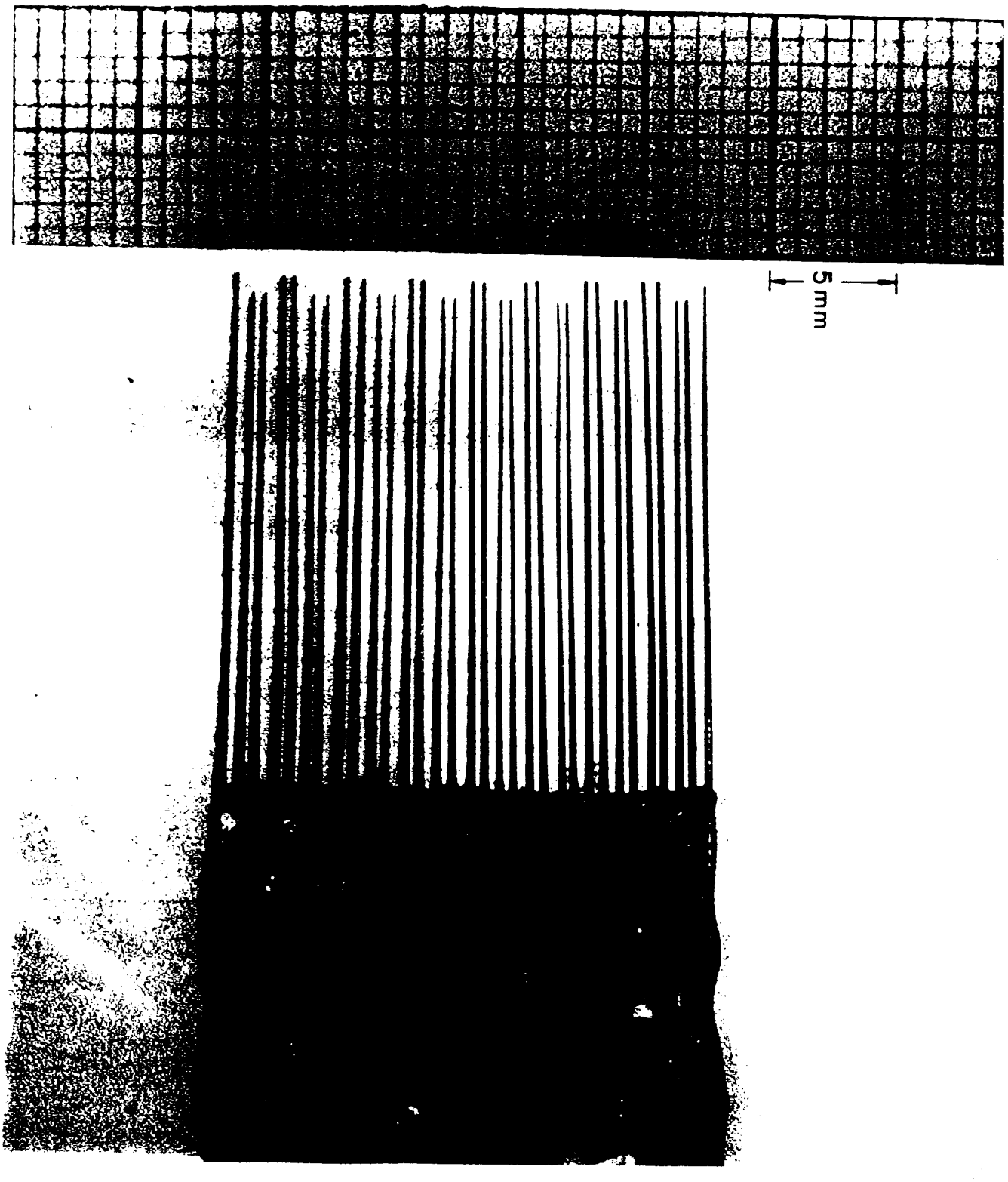


FIG. 10: PLAN VIEW OF A SPOT.

MOST PROBABLE REALIZATION


5 mm

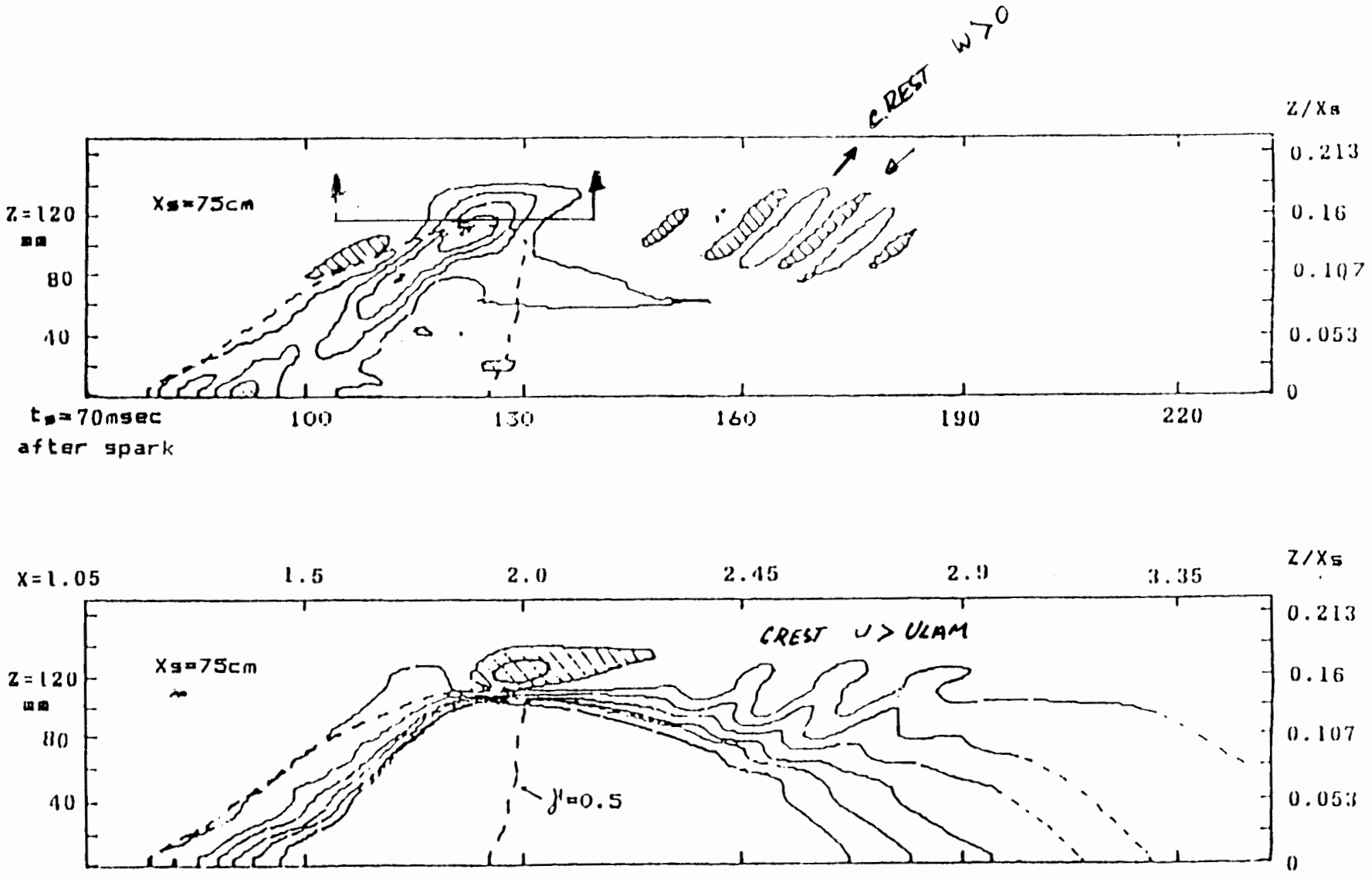


Fig. 4.2.4 comparison between Educed U pertubation (lower fig.) and Educed W (upper fig.) at Xs=75cm.

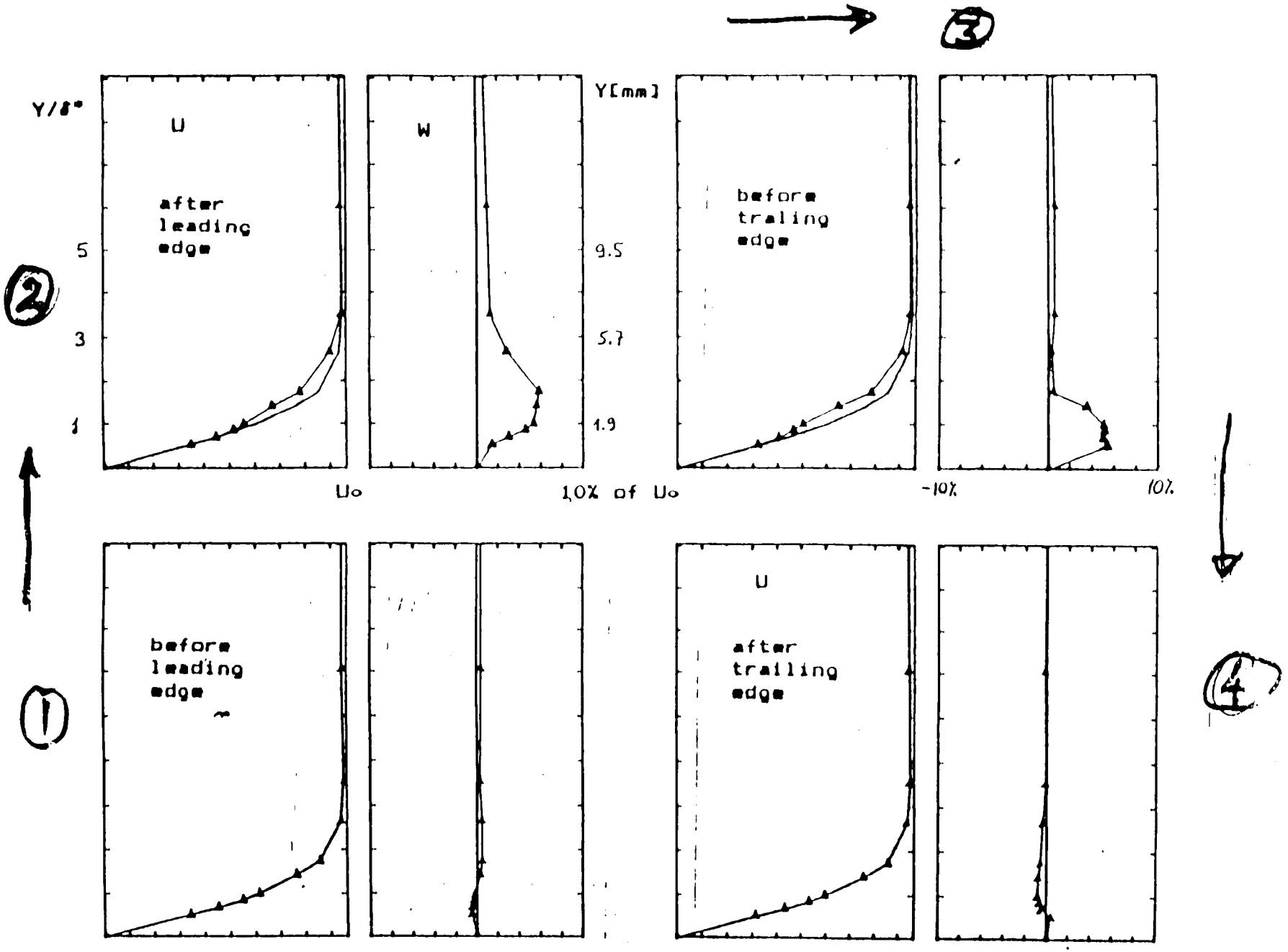
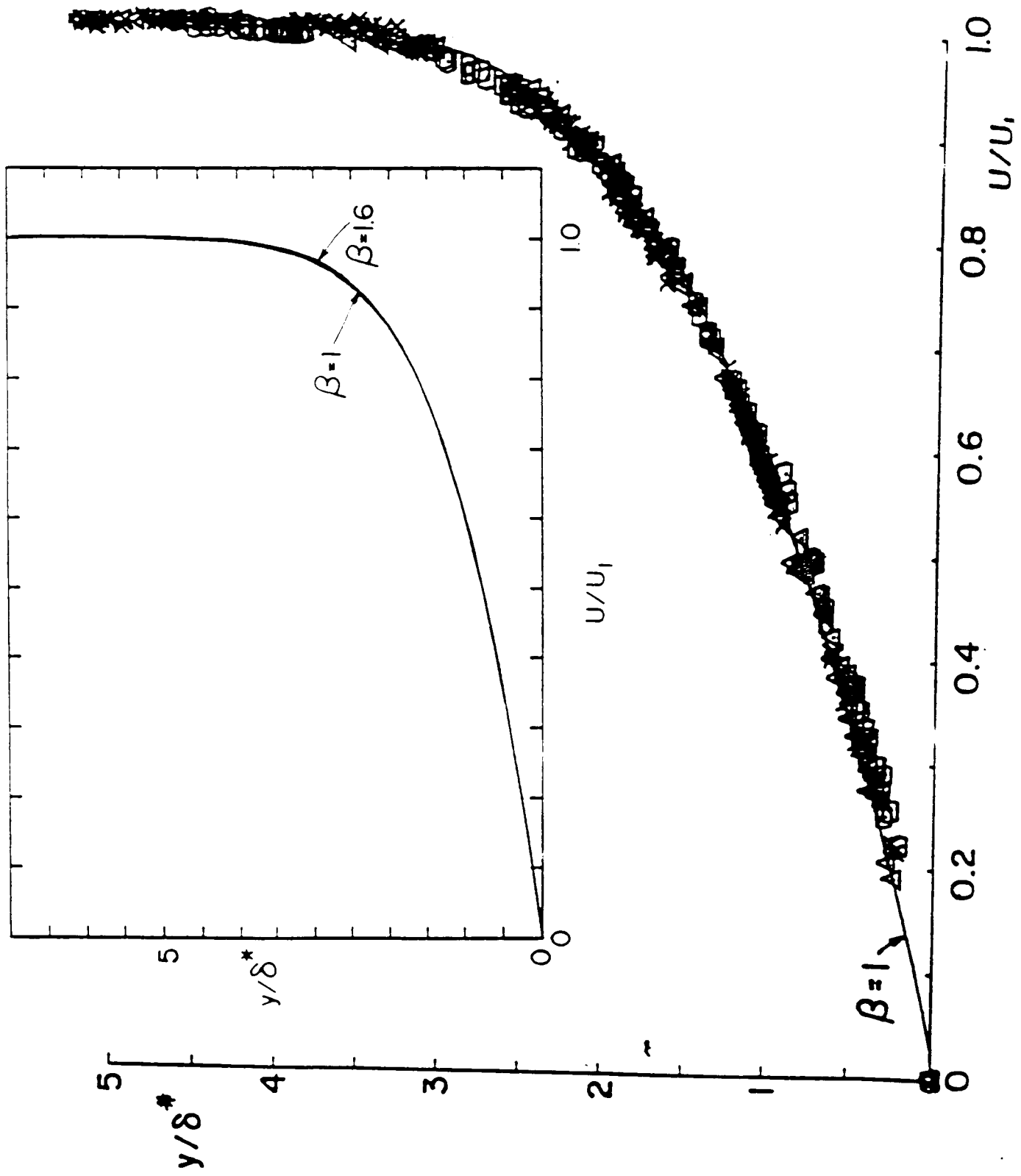
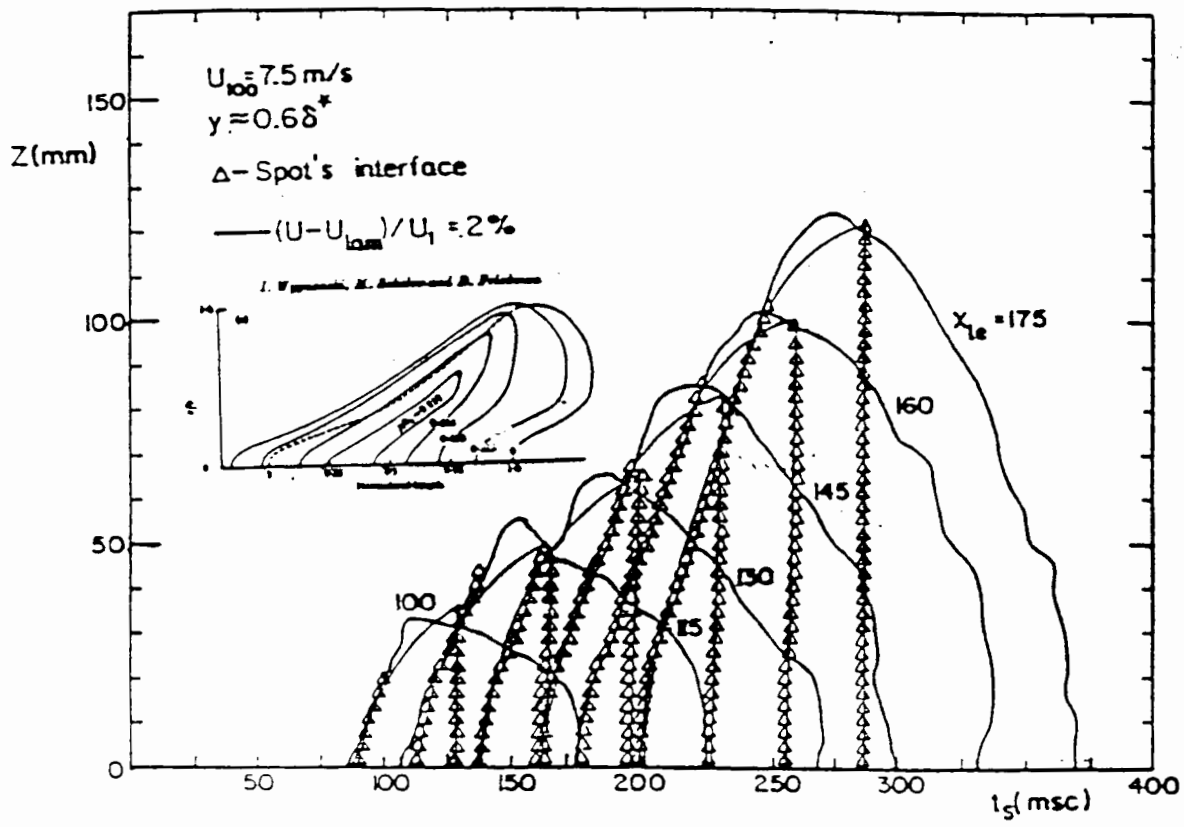
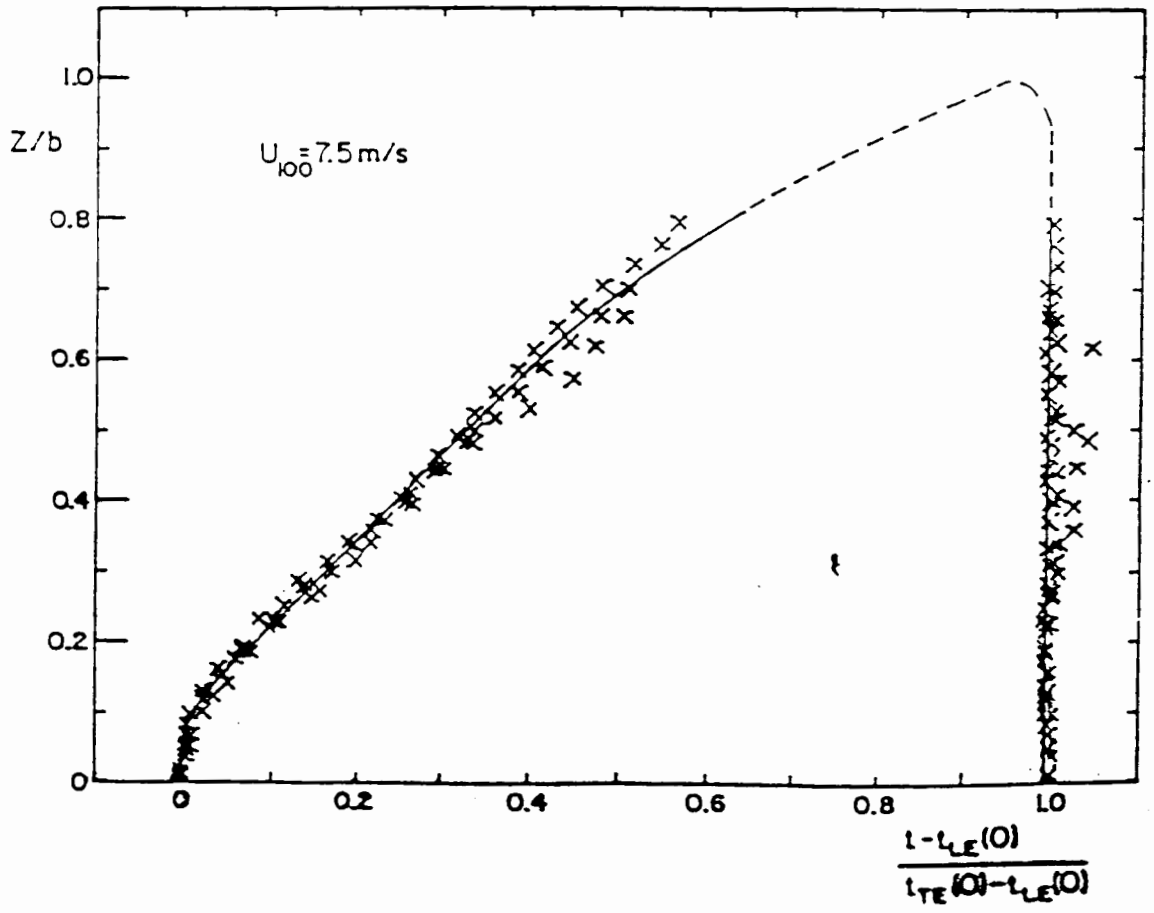


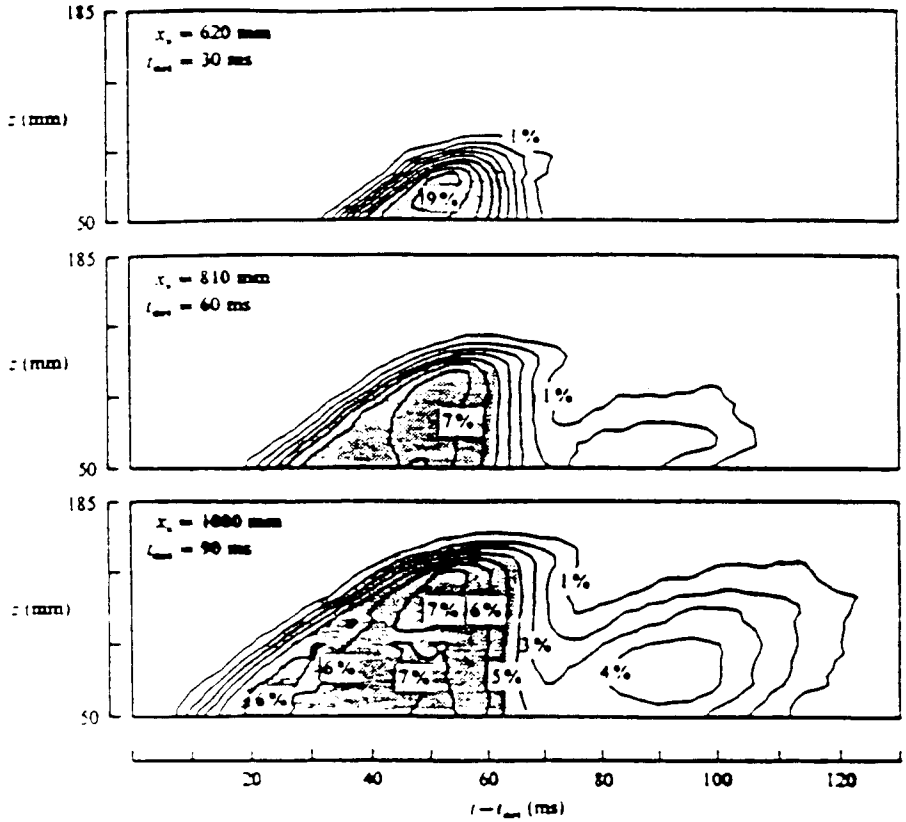
Fig. 6.7.5 Instantenous streamwise and spanwise velocity profiles on turbule laminar interface, in compare with laminar profiles. $Z/X_s=0.149$, for different times afetr spark. $\delta^* = 1.9$ mm



y/δ*
U/U₁
β=1
β=1.6
0
0.2
0.4
0.6
0.8
1.0
1
2
3
4
5

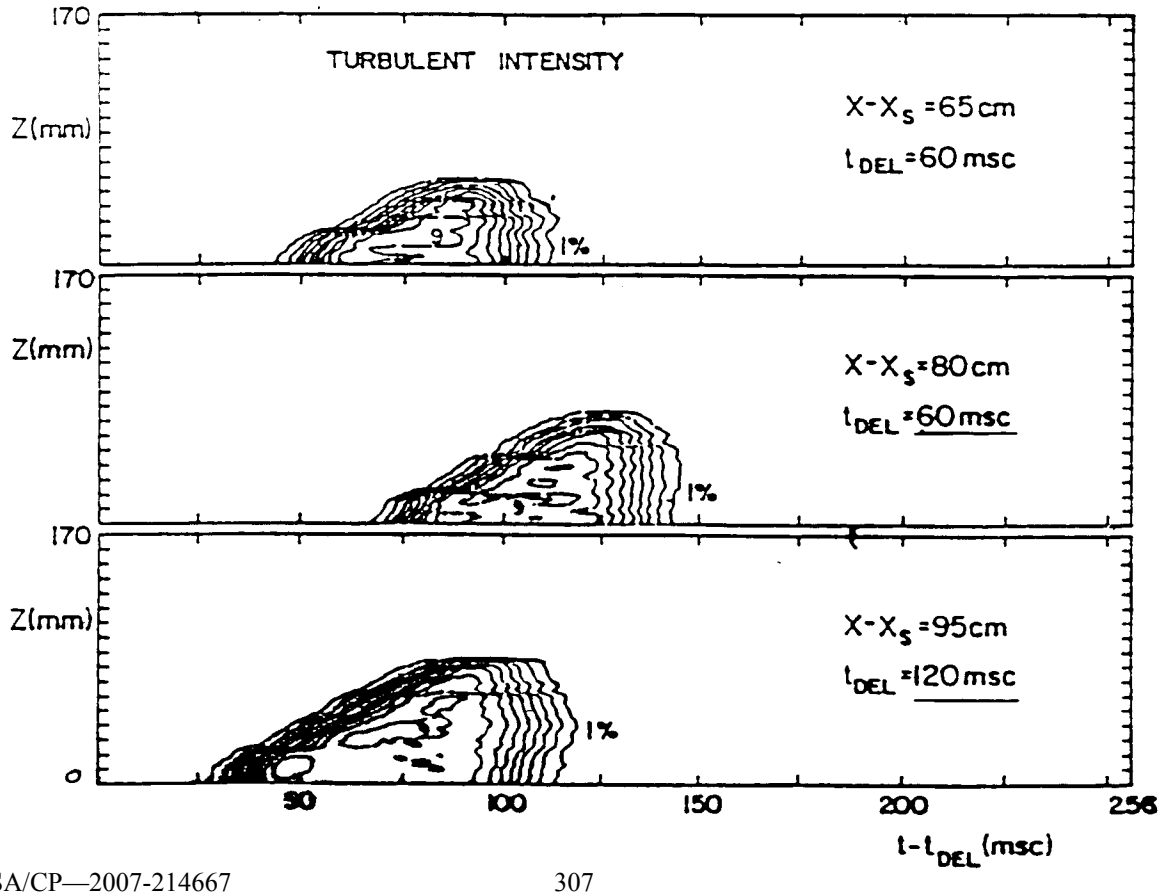

U_{100}=7.5 m/s
y ≈0.6δ*
Δ– Spot's interface
——(U–U_{100m})/U_1 =.2%
Z(mm)
150
100
50
0
50
100
150
200
250
300
400
t_5(msc)
X_{te}=175
160
145
130
115
100


Z/b
U_{100}=7.5 m/s
1.0
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1.0
$\frac{t-t_{LE}(0)}{t_{TE}(0)-t_{LE}(0)}$

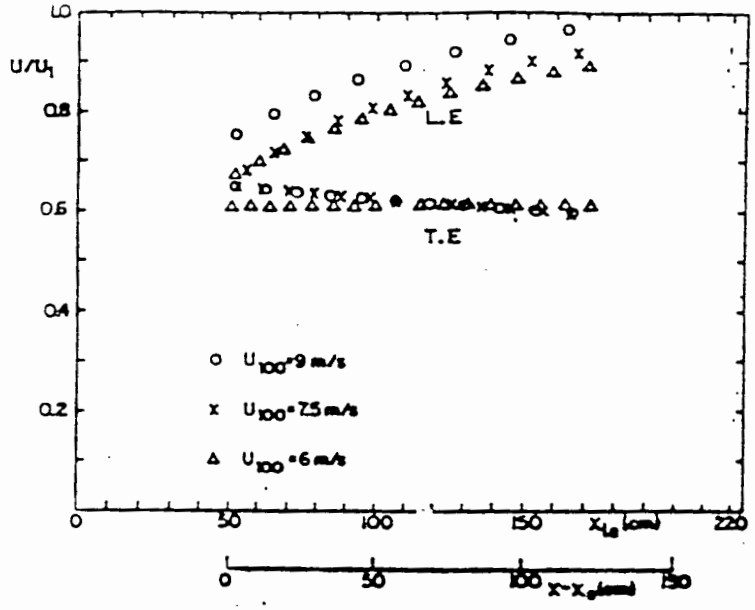


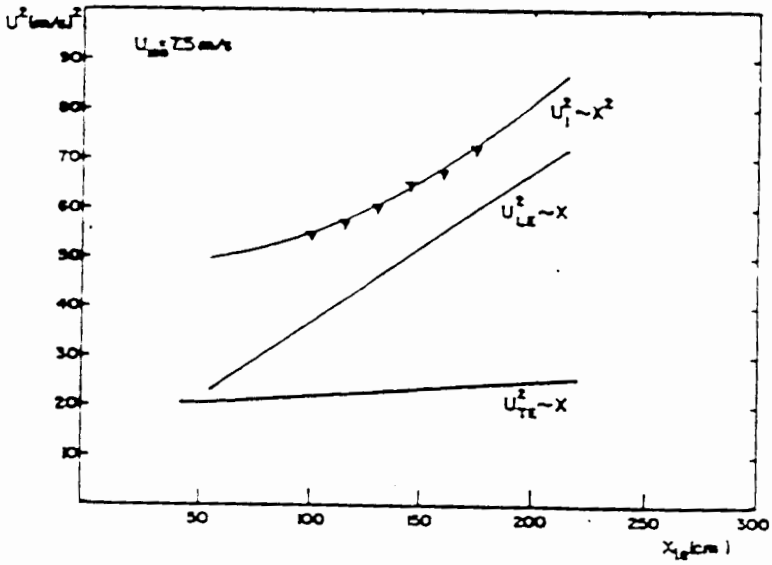
$\beta = 0$

FIGURE 6. Spanwise distribution of 'true' r.m.s. contours at the same locations as shown in figure 3. Contour levels are 1%–10% at intervals of 1%. The shaded area indicates $\gamma > 50\%$.

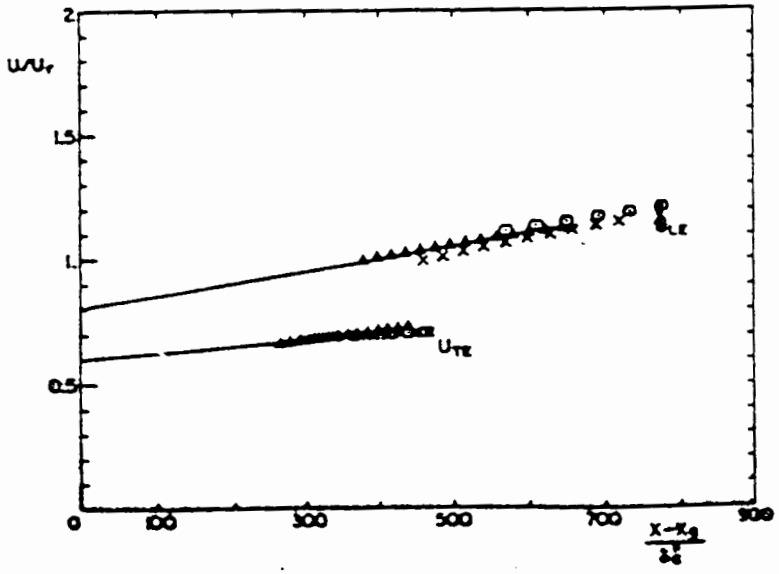


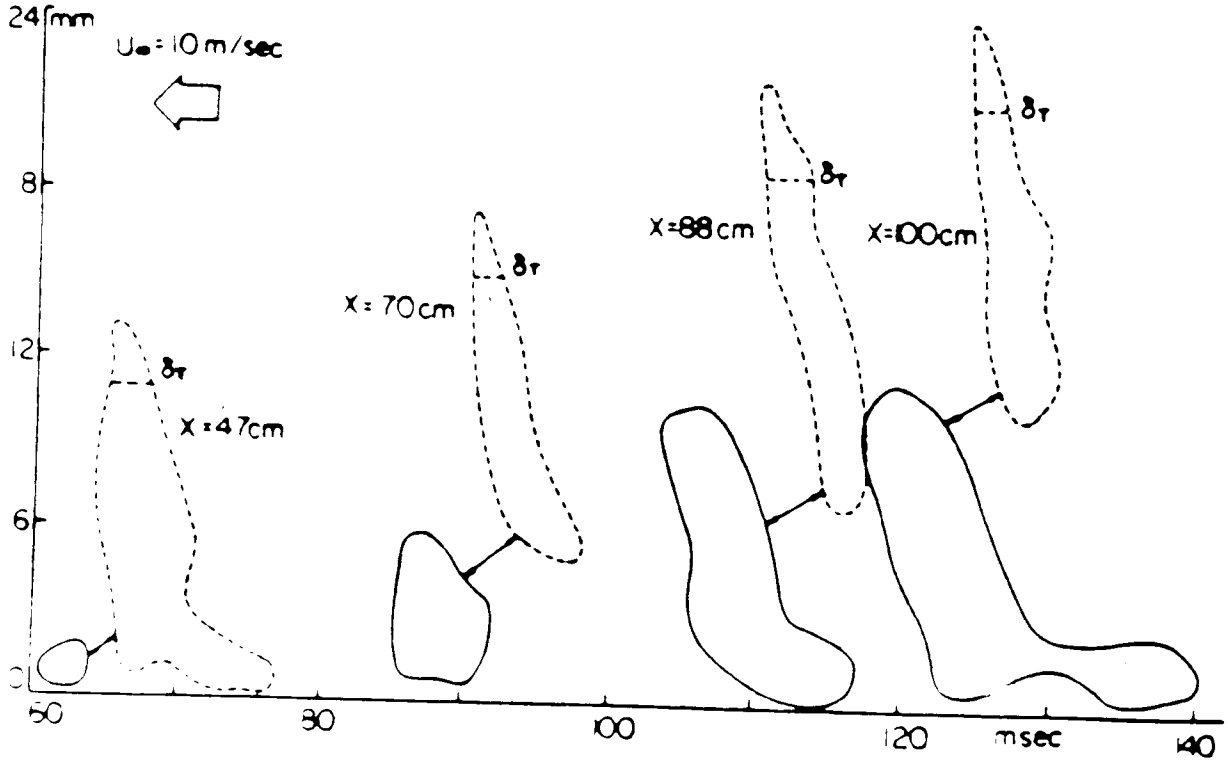
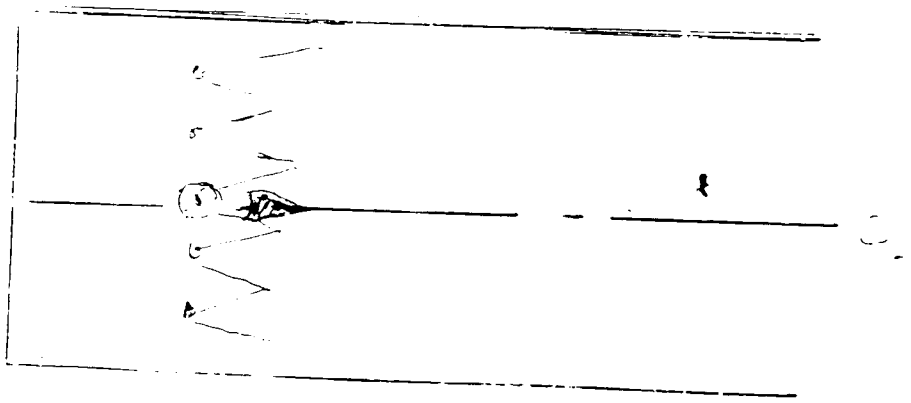
$\beta = 1.0$





$$\frac{U_{INT.}}{U_r} = \frac{\rho}{\ } \left[\int \beta_j \, R_{e\delta^*_r j} \, \frac{X-}{\ } \right.$$




24 mm
U_∞ = 10 m/sec
8
12
6
0
δ_T
X = 47cm
X = 70cm
X=88cm
X=100cm
50
80
100
120
msec
140