N90-17652

Main Results of CAST-10 Airfoil Tested in T2 Cryogenic Wind Tunnel

A. Blanchard, A. Seraudie, and J. F. Breil
ONERA/CERT
DERAT
Toulouse-France

INTRODUCTION

The aims of the cooperation NASA/DFVLR/ONERA

* Examine Re, M, and Transition effects on a very sensitive airfoil, systematically tested previously.

* Evaluation of the airfoil characteristic prediction
  - comparison experimental/theoretical results
  - comparison adaptive walls/conventional wind tunnel results

* Mutual help for T2 , 0.3m TCT , TWB (Braunschweig)
  - Gives us more experience for airfoil tests under cryogenic operation (second cryogenic airfoil tests)
  - lots of experience with adaptive wall techniques

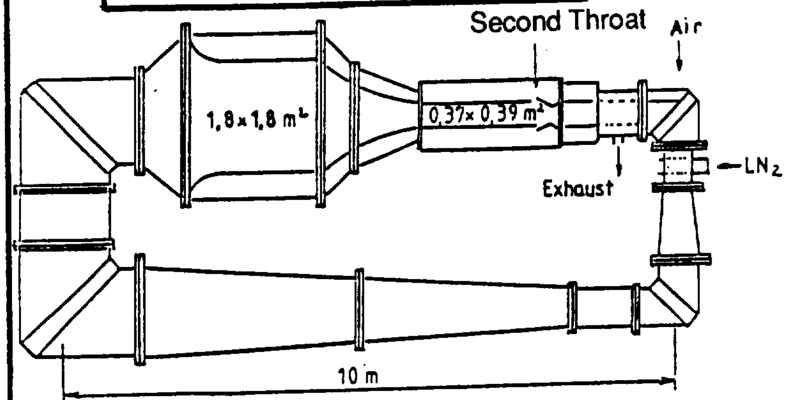
2 Series of Tests in T2

-1st in November 1984
-2nd in April 1985

Model

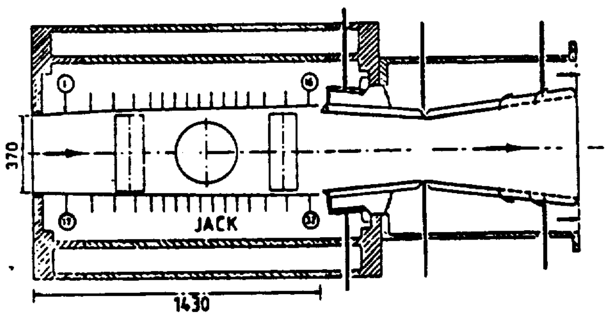
* Designed by Dornier
* Manufactured by ONERA
* Chord= 180mm , Width= 560mm
* 103 pressure tapes (L.E. Ø 0.1mm)
  21 thermocouples (15 in the skin region)

T2 Wind Tunnel

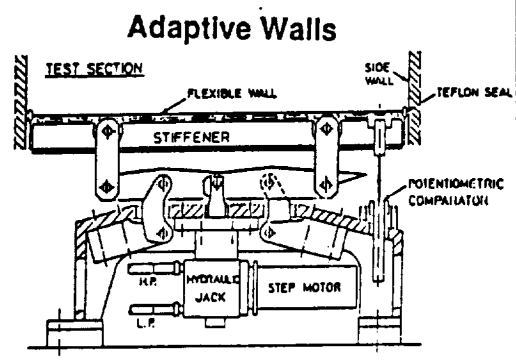


* Transonic
* Pressurized
* Cryogenic
* Adaptive walls

- Air induction
- LN2 injection
- Internal insulation



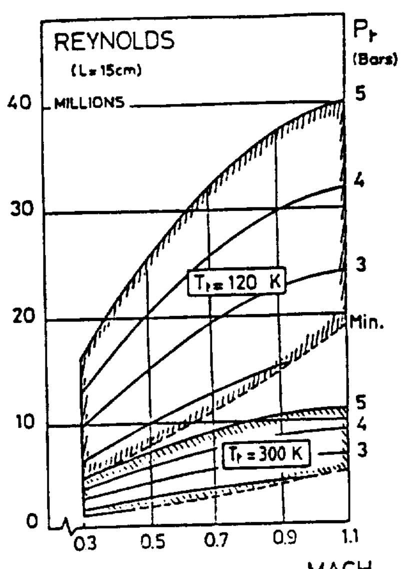
WALL DISPLACEMENT MECHANISM



- Control by computer
- Runs = 30s to 60s
- Model precooling
  - outside
  - in the test section

$$\frac{\sqrt{\overline{p'^2}}}{q} = 0.004$$

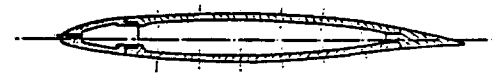
Tu = 0.1 %

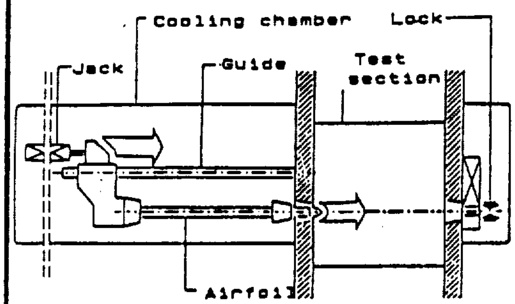


Operational envelope

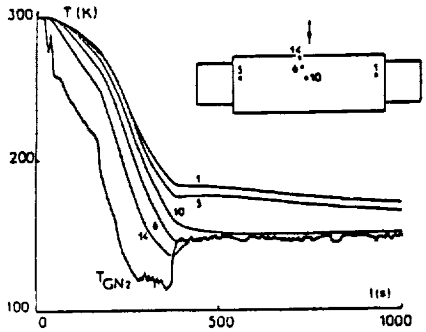
$0.6 < Mo < 0.9$
$1.6 < Pt < 3$ bars
$110K < Tt < T.amb$
$100mm < Chord < 200mm$
$Rc < 30.10^6$

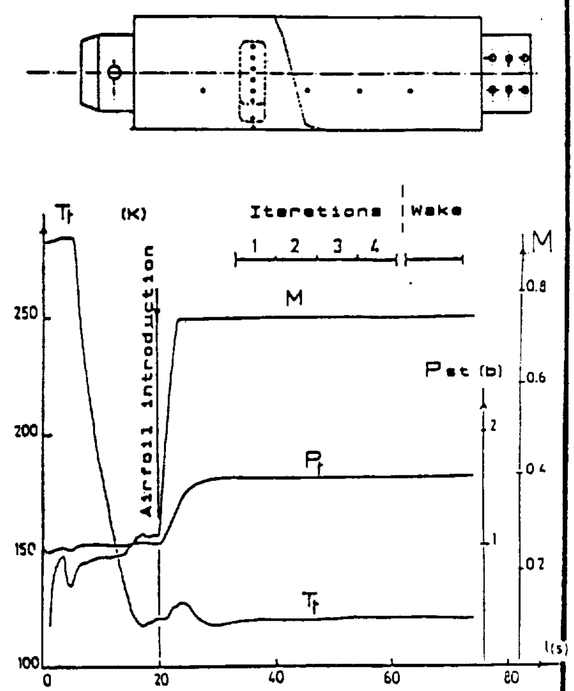
T2 Run





Model Precooling





RUN

* A part of the model is hollow

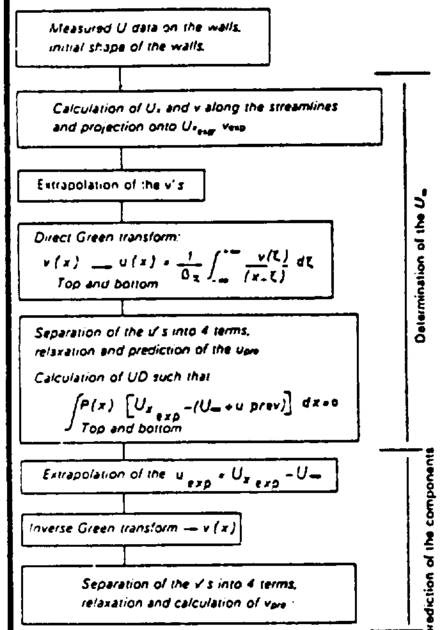
* [- Model is cooled outside before the run
- Start of the run at low Mach number (0.3)
low pressure (1.1 b)
selected temperature
- Introduction of the model in the test section
(T model = T flow)
- Increase of (M,Pt) at the required level

* [- Wall adaptation, measurements on the walls and
on the model
- Other measurements (Wake)

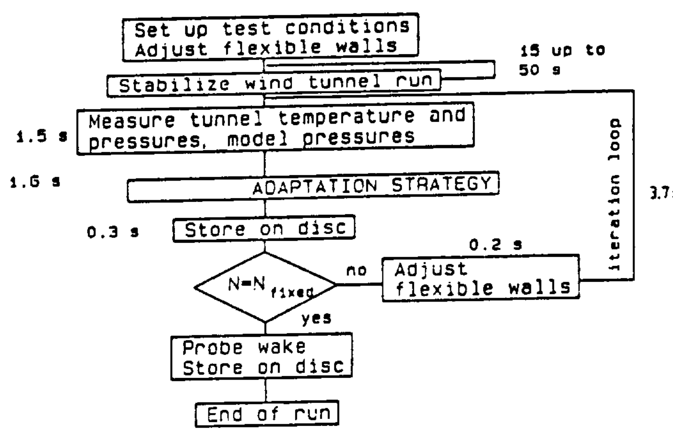
* [- End of the run (one configuration has been tested)

2-D Adaptation

2-D Adaptation Strategy



Adaptation Flowchart



* Regulation by computer. (M,P,T) independent

Measurements ⟶ Pt , Tt , Pwalls , Zwalls , Pmodel, ...

Mo

theoretically $\Delta\alpha$, ΔM =0 ⟵ Adaptation

* Principle rather simple

  internal field- measured (walls) } iterations until they are
  external field-calculated(Green) } equal on the control surf.

  Accuracy of the method

  u,v extrapolation ⟶ $\pm\infty$

  u,v streamline projection on a straight line

  Stategy rather complicated to obtain rapidly the convergence

  - Mo calculation (field around the model)
  - separation in 4 elementary terms
  - relaxation coefficients

  Convergence criterion: until no variations (Pwalls,Zwalls, Pmodel)

* Convergence in 3 or 4 iterations in a run (each one $\approx$ 5s)

* Residual errors $\Delta M \approx 0.002$, $\Delta\alpha \approx \pm 0.02°$

Measurement Accuracy

* **Model : good quality (shape, surface roughness,...)**
  (very important for Natural Transition,
  some problems at High Reynolds Number)

* **Steady flow accuracy**

P_t =3 bars T_t =120 K M = 0.8 C_L = 0.5	**Instrumentation** • Calibration	**Control** • Computer process • Mechanical limits	**Aerodynamic Field** •Adaptive walls	 • Gradients
Pressure	0.001 bar	0.004 bar		
Temperature	0.3 K	0.4 K		< 0.5 K (wall: 10 K)
Mach number	0.002	0.001	0.002	
Angle of attack	0.02°		0.02°	

Control / Adaptive walls : $\Delta M = 0.005$
Model temperature $T_w/T_{aw} = 1.015$

Flexible wall shape : $\Delta y = + 0.1$ mm

* **Flow quality** (important for Natural Transition)
  - **Pressure fluctuations** (low levels)
  - **Velocity fluctuations** (due to pressure fluctuations)
  - **Temperature fluctuations** (seem reasonable)
  - **Uniformity in the test section** (good enough)
  - **Purity of the fluid** (moisture is the most important problem for flow quality in a cryogenic wind tunnel)

* **Side wall boundary layers**
  seems a real problem ($\Delta\alpha$ = 0.1 to 0.2°)

CAST 10 Tests in T2

1st series of tests — * Natural Transition — T.N.

	0.69 < M < 0.77
α (+3° to -2°)	lot of values

$Rc = 4 . 10^6$

$6 .10^6 < Rc < 30 .10^6$:

- M=0.7 α=+1°
- M=0.73 α=-0.25°
- M=0.76 α=+0.25°
- M=0.765 α=+0.25°
- +some scatter points

Nb of runs = 160

2nd series of tests — * Tripped Transition — T.D.

h=0.045mm Xt/C = 5%

	0.7 < M < 0.765
α (+4° to -2°)	lot of values

$Rc = 4 . 10^6$

$6 .10^6 < Rc < 27. 10^6$:

- M=0.7 α = +1°
- M=0.73 α = -0.25°
- M=0.76 α = +0.25°
- M=0.76 α = +1°
- M=0.765 α = -2°
- M=0.765 α = +2°

Nb of runs = 90

* Half Tripped Transition — T.1/2D.

(lower surface)

	0.73 < M < 0.78
α (+2° to -2°)	some values

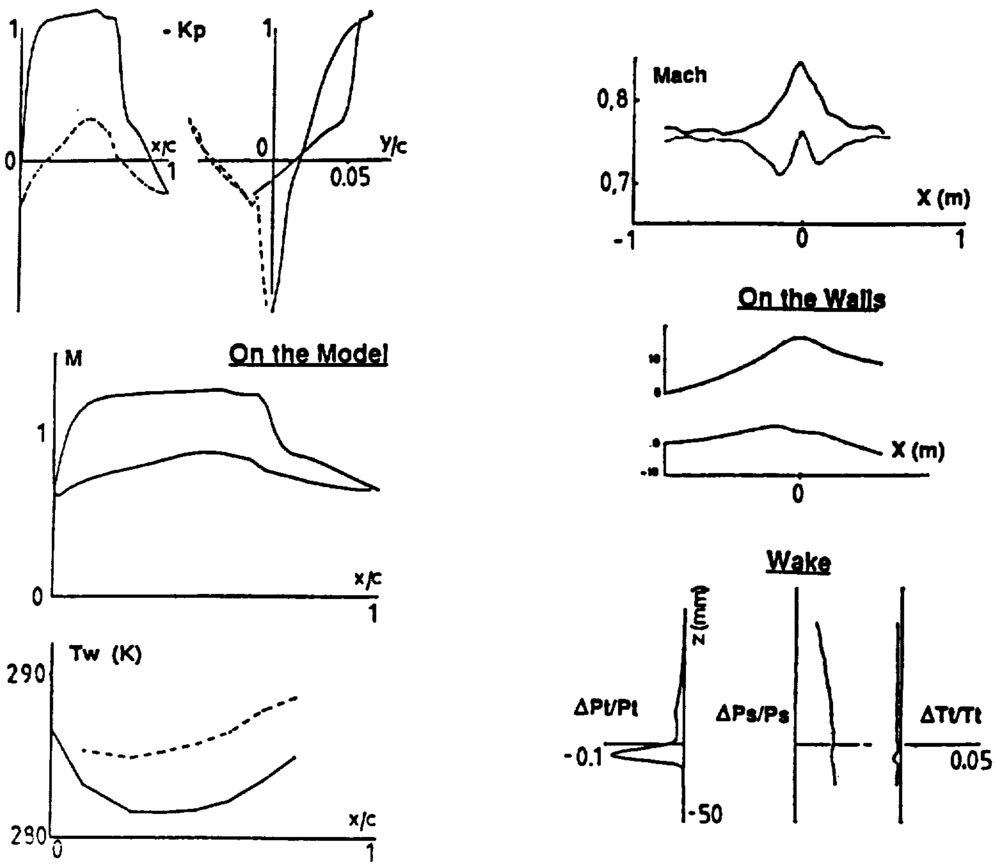
$Rc = 4 . 10^6$

$6 .10^6 < Rc < 14. 10^6$:

- M=0.73 α = -0.25°
- M=0.76 α = +0.25°

Nb of runs = 45

Measurements at each run



+ Oil Visualisation ---> 2-D of the flow
(Shock, Transition, Bubble, Separation,...) locations .

* Tunnel ---> $\boxed{Pt, Tt}$
* M walls ---> Infinite conditions $\boxed{Mo}$
  Z walls ---> Streamline convergence
  (C_L not exploited here)
* Kp ---> $\boxed{C_L}$ $(C_D)_{pressure}$
* M model ---> Shock location, B.L./Shock wave interaction
  lam. Bubble , T.E. separation , L.E. peak , ...
* Tw ---> Equilibrium
  (B.L. information not exploited here)
* Wake ---> $\boxed{C_D}$ (Pt Ps and Tt probes, 400 pts in a wake)
  B.L./Shock wave interaction

Transition Detection in a Transonic Cryogenic Tunnel

Measure

	Surface	Lines	Points
T = 300K … 100K	-Oil visualisation - Infrared -(small CO_2 icing)	- Pt longitudinal probing	-Skin friction gauges - Thermocouples

used for CAST 10 tests

not exploited

Identification

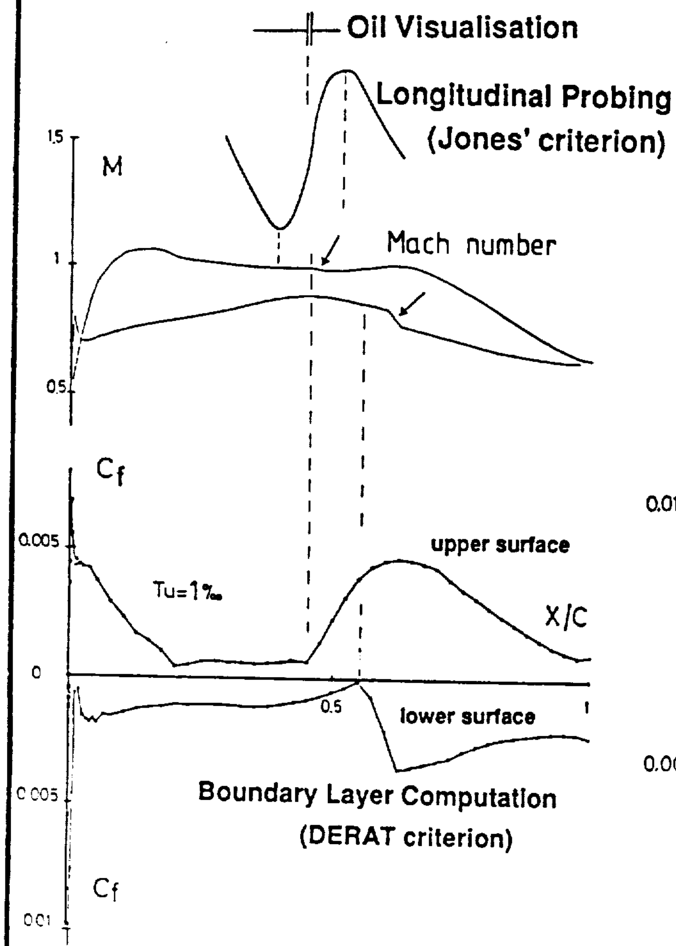
On Mach number on the airfoil	Laminar bubble separation	"Bump" if Mlocal=1	Lam. or Turb. B.L./Shock wave interaction
On Wake shape			

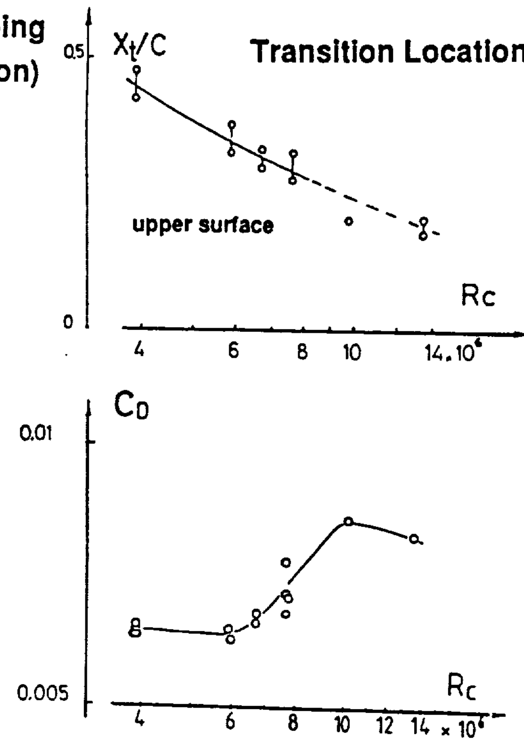
Estimation

- Aerodynamic coefficients $C_D(Re)$, $C_L(Re)$
- T.N. / T.D. comparisons
- Experiment / calculation comparisons

Reynolds Number Effects

α =-0.25°
M = 0.73



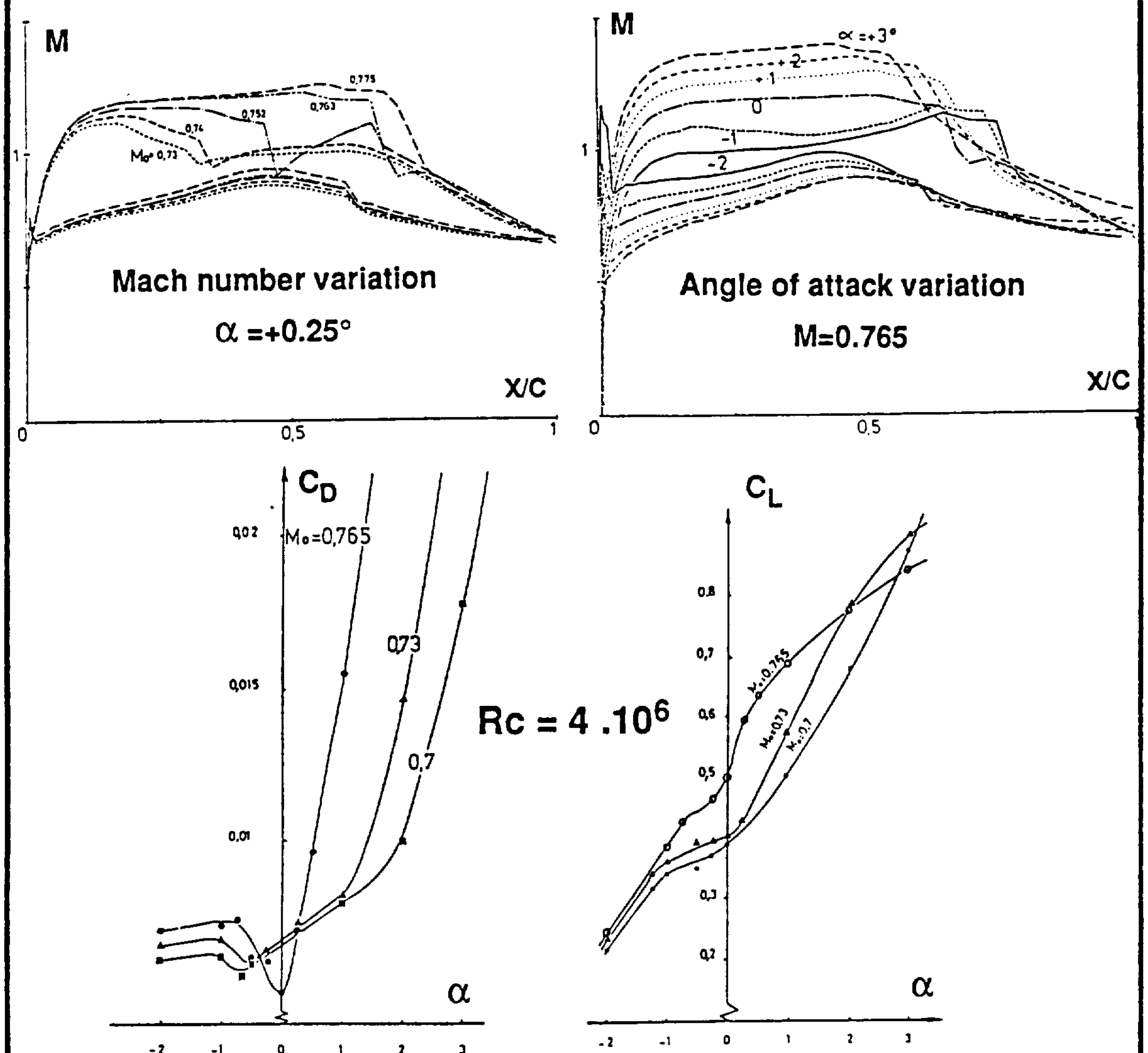


* Good correlation of the estimated transition locations
  from :
  - oil visualisation
  - longitudinal probing
  - local Mach number distortion
  - computation

* The transition location moves with the Reynolds number
  - regularly on the upper surface
  - suddenly on the lower surface (60%--->L.E. for Rc=7.10^6)

* These transition displacements explain the C_D(Re) evolutions
  - direct Re effect : (Re↗) ---> (C_D↘)
  - indirect Re effect : (Re↗) ---> (Xt/C↘) ---> (C_D↗)

Natural Transition



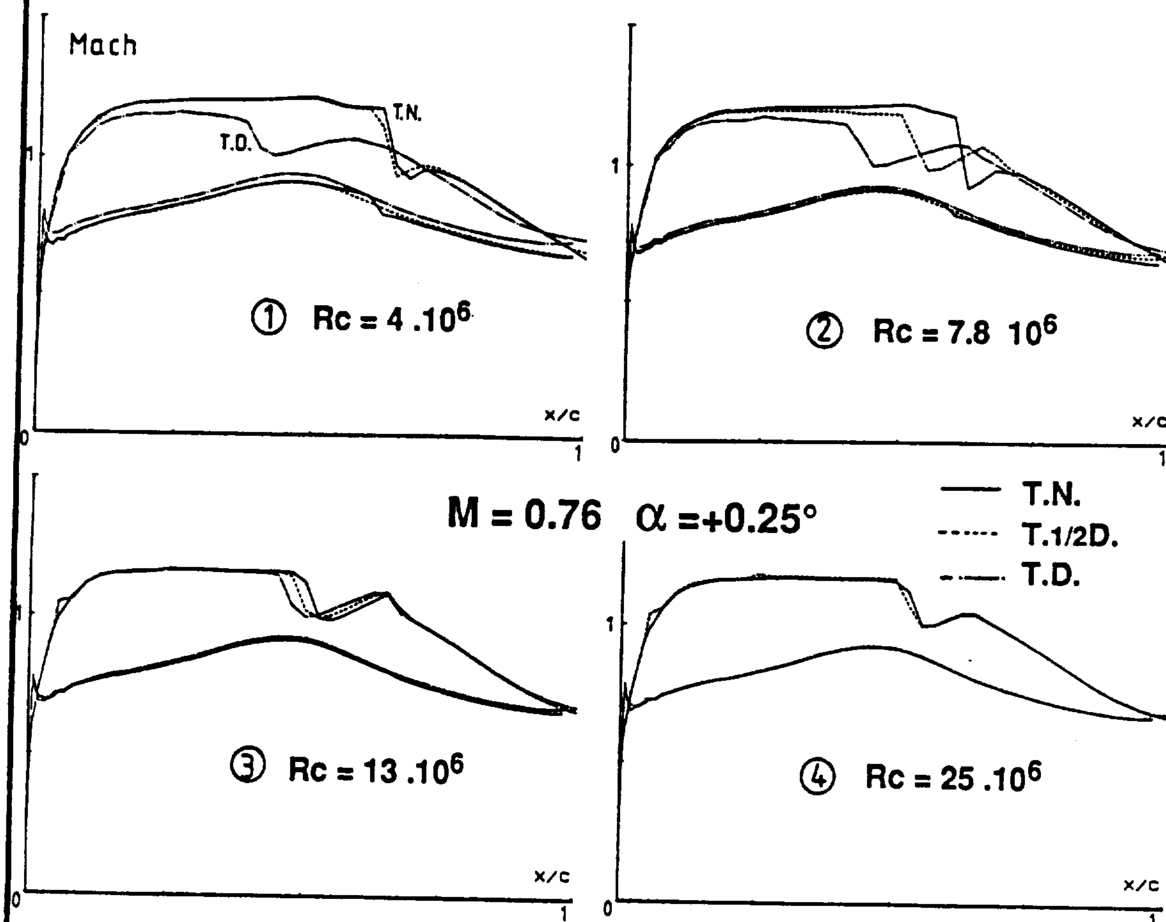
*Unusual $C_L(\alpha)$ and $C_D(\alpha)$ evolutions at $Rc=4\ .10^6$
due to transition displacements

	upper surface	lower surface
α<-1°	lam.	Peak at the L.E.
α=0°	(turb.)	
α> 0°	lam.	60%

(must be examined for each Mo)

* + Classical effects of shock wave, and T.E. separation

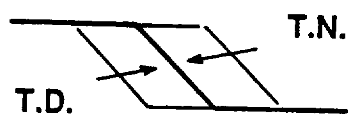
T.N / T.1/2D. / T.D. Comparison



* At low Re : very different

* T.1/2D. $\boxed{\text{upper surface = T.N.} \\ \text{lower surface = T.D.}}$? —— $\boxed{\text{NO}}$ upper/lower S. coupling

* Shock wave location



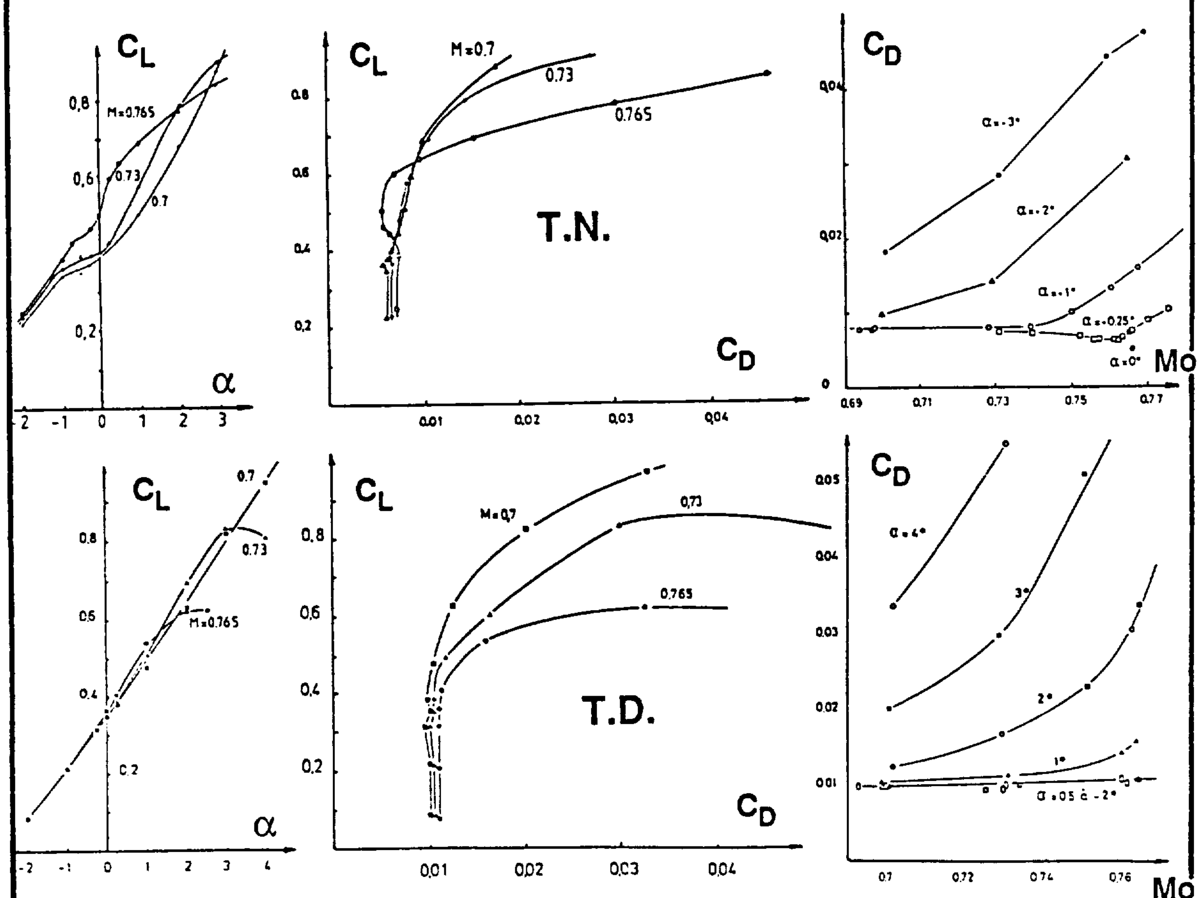
with Re

* Transition T.N. L.E.| <—— Xt/C with Re

* At high Re : T.N. = T.D.

CAST 10 Airfoil Characteristics

Rc= 4 .10^6



* Very different results with boundary layer conditions

* Smoother curves in T.D.

* The divergence Mach number is not very affected but, C_D levels are different

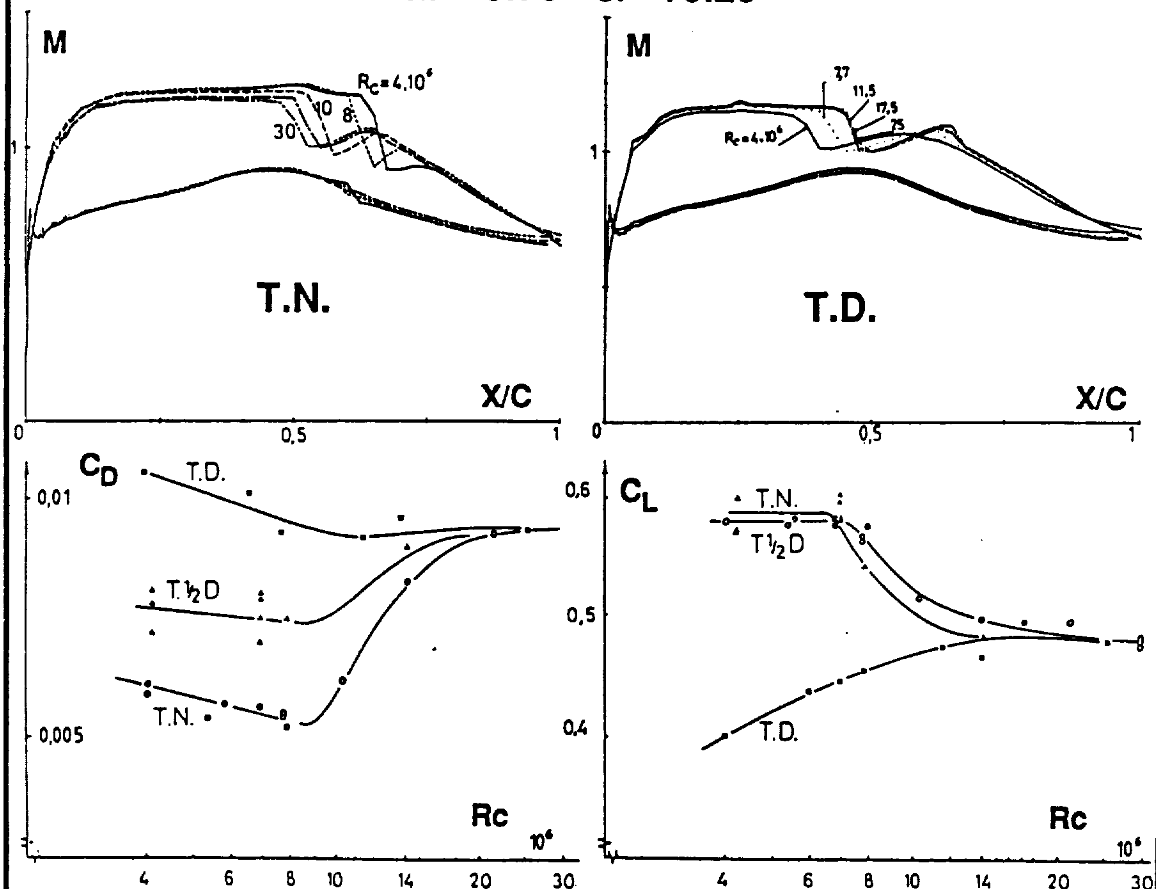
* $(C_L)_{max}$ is higher in T.N.

* Typical $C_L(C_D)$ laminar airfoil shape (M=0.765)

* (C_L/C_D) ratio higher in T.N.

Aerodynamic Coefficient Evolutions with the Reynolds Number

M = 0.76 α =+0.25°

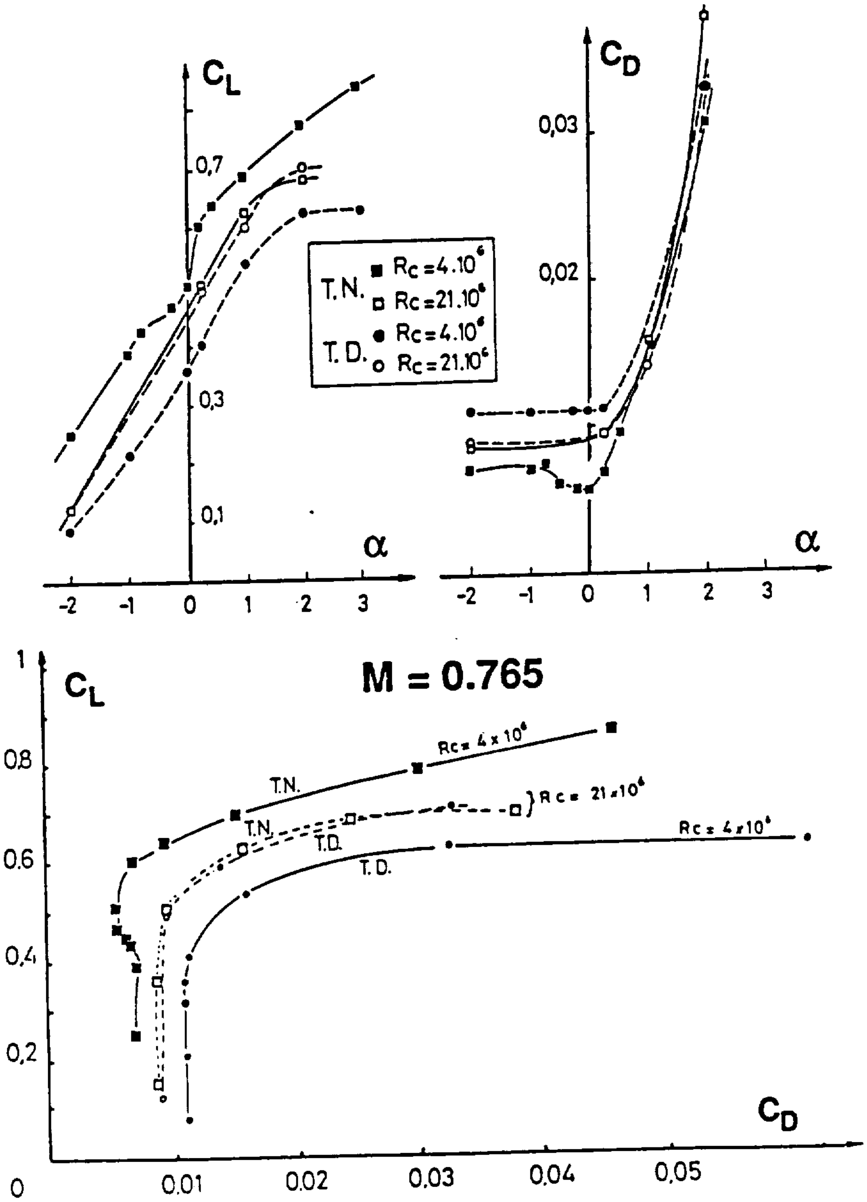


* **Comparison of (T.N. / T.1/2D. / T.D.)**
  - precises the transition motion in T.N. ,
  - precises the CD and CL evolutions ,
  - partly dissociates what is due to upper and lower surfaces
  - gives confidence in the results

* **The CAST 10 airfoil is still laminar at Rc= 8 .10^6 this must be considered as a success for T2 performances**

* **At Rc$\geq$ 20 .10^6 , transition is near the L.E.**

Airfoil Performances



* High airfoil performances in laminar flow

* Inverse evolutions with the Reynolds number in T.N. and T.D

* Same results at Rc= 20 .10^6

Conclusions

- Good model quality (necessary for T.N. measurements)

* T2 tests

- General characteristics of the CAST 10 airfoil
  (M , α , Rc , Free/Fixed transition)

- Fundamental studies on Reynolds number effects
  - The T.N. and T.D. evolutions are very different
  - Comprehension of phenomenon in T.N.
  - Interest of the laminar airfoil

- Analysis of some special points
  - Tw / Taw effects
  - Thermal equilibrium
  - Estimation of the transition location under cryogenic operation
  - Cross control for Rc (P,T)

- Good T2 cryogenic operation
  - Adaptive wall functioning = T.amb.
  - Laminar studies : O.K. for $Rc \leqslant 8 .10^6$
    pbs at higher Reynolds Number
  - Improvements must be done
    for moisture elimination
    for side wall boundary layer effects

* Comparison with prediction methods

---> ONERA results (J. Thibert)

* Comparison with others tunnel results

---> (J. Thibert) and (workshop)

TEST DATA ANALYSIS
AND
THEORY - EXPERIMENT COMPARISONS

J. J. THIBERT
TRANSPORT AIRCRAFT DIVISION
AERODYNAMICS DEPARTMENT
ONERA (FRANCE)

ONERA / DFVLR / NASA COOPERATION

ON CRYOGENIC AND ADAPTIVE WALLS

TECHNOLOGIES FOR AIRFOIL TESTING

- OBJECTIVES

EXPERIMENTAL TEST ON THE CAST 10 AIRFOIL IN THE ONERA T2 TUNNEL IN ORDER TO PROVIDE DATA AT FLIGHT EQUIVALENT REYNOLDS NUMBER ON A SUPERCRITICAL AIRFOIL

COMPARISON OF DATA ON THE SAME MODEL IN SEVERAL WIND TUNNELS

CAST 10 AIRFOIL WORKSHOP
SUMMARY OF THE PRESENTATION

T2 TEST ANALYSIS

T2 - TCT DATA COMPARISONS

COMPUTER CODES DESCRIPTION

THEORY - EXPERIMENT COMPARISONS

CONCLUSION

T2 TEST ANALYSIS

-- TRANSITION EFFECT

$M = 0.765 \quad Re = 4 \times 10^6$

-- REYNOLDS NUMBER EFFECT

$M = 0.765 \quad \alpha = 0.25$

-- TRANSITION EFFECT

$M = 0.765 \quad Re = 20 \times 10^6$

-- MACH NUMBER EFFECT

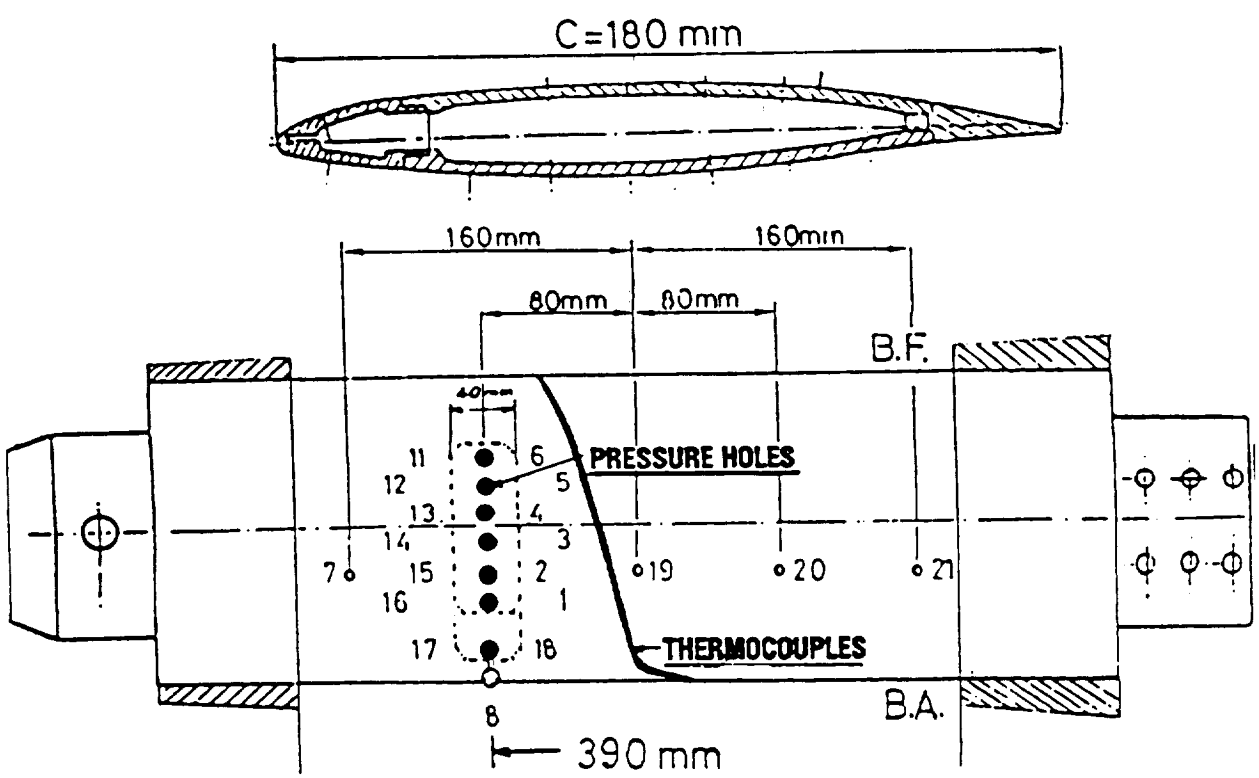
fixed transition

$Re = 25 \times 10^6 \quad \alpha = 0.25$

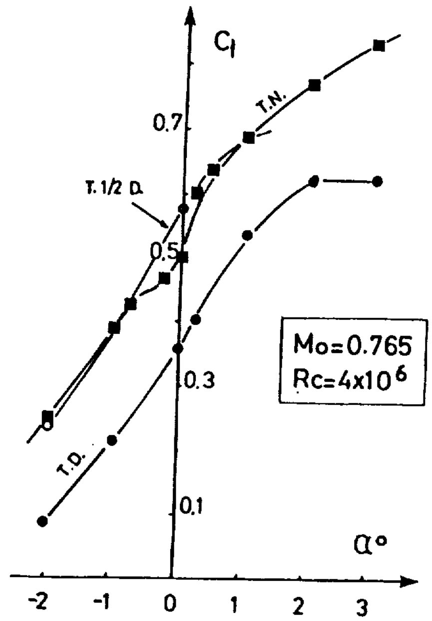
-- REYNOLDS NUMBER EFFECT

$M = 0.73 \quad \alpha = 0.25$

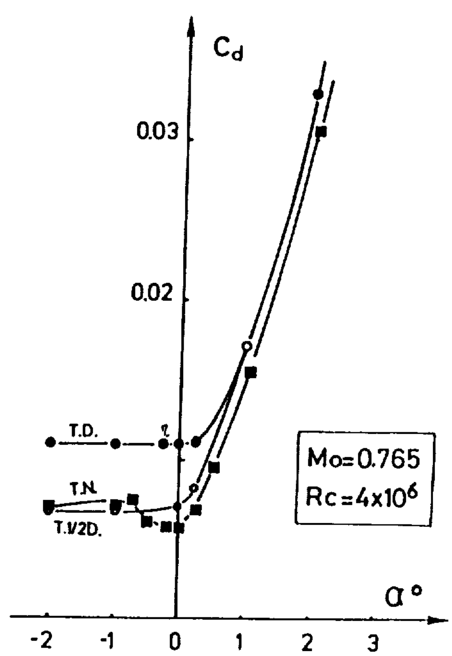
CAST 10 AIRFOIL MODEL



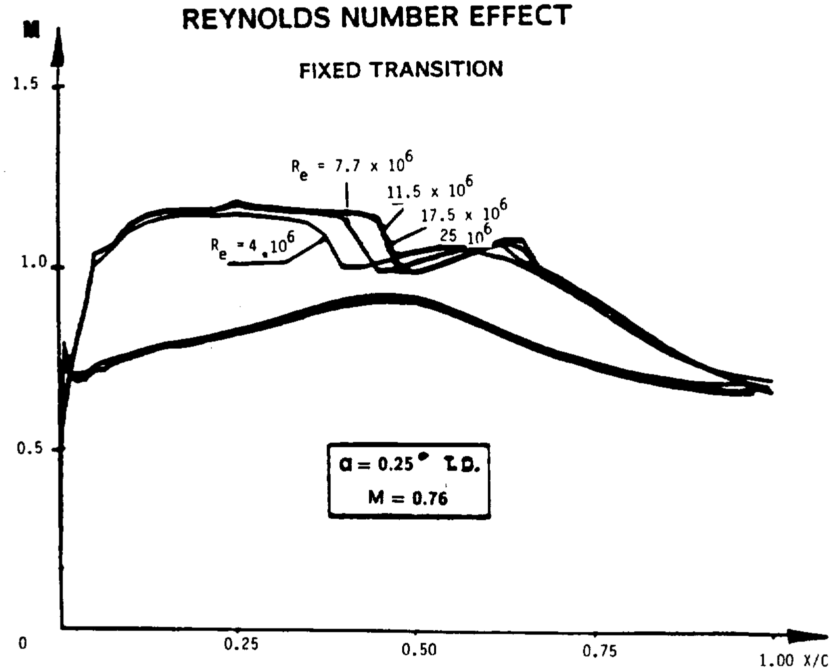
TRANSITION EFFECT



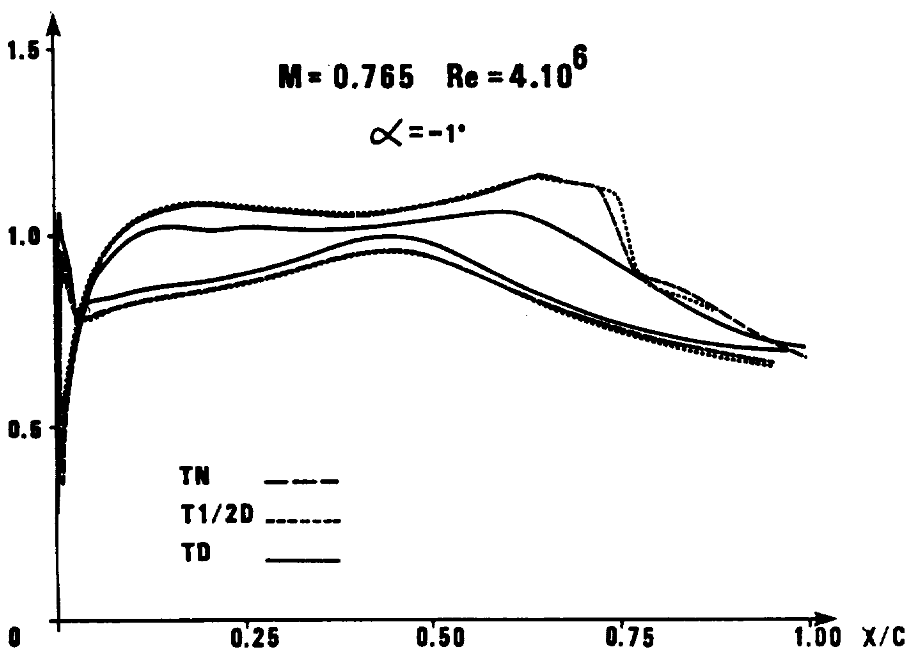
TRANSITION EFFECT

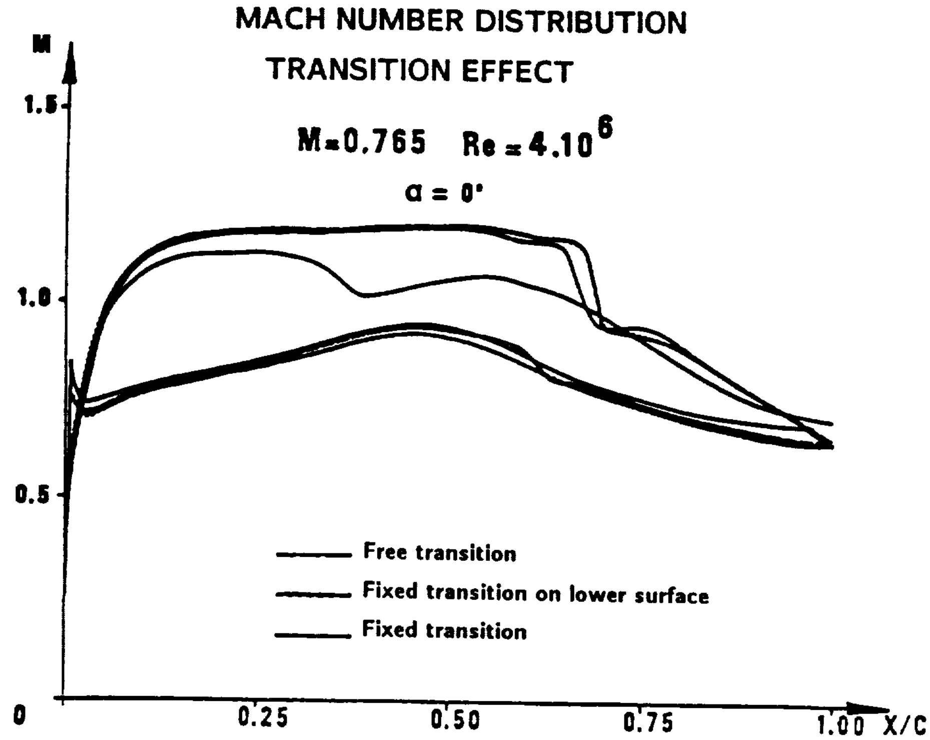


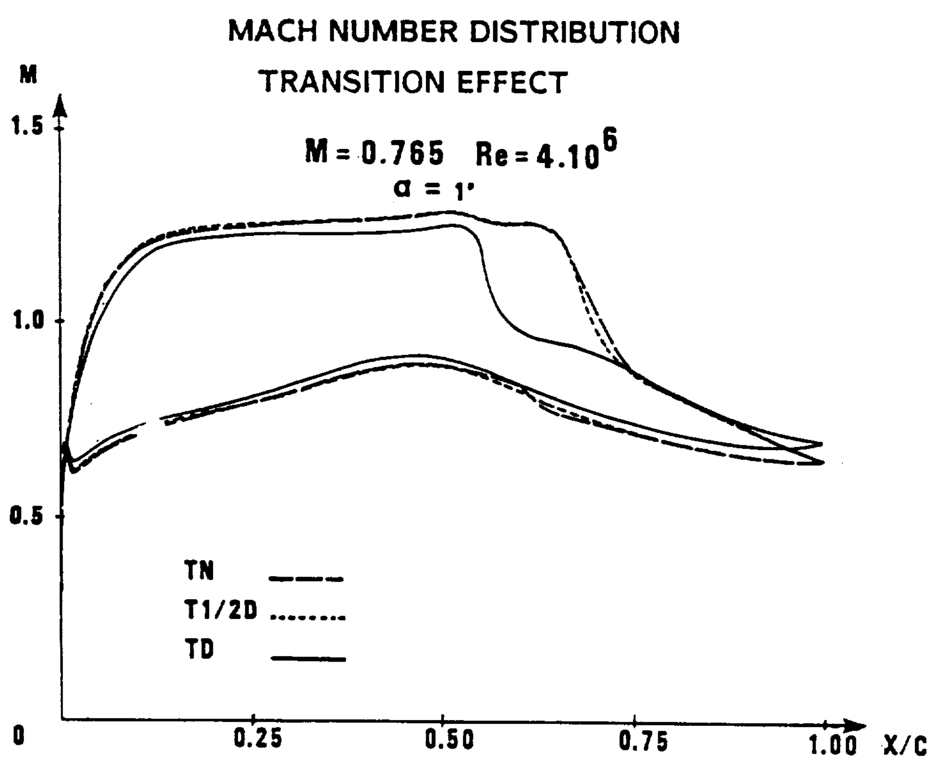
MACH NUMBER DISTRIBUTION
REYNOLDS NUMBER EFFECT



MACH NUMBER DISTRIBUTION
TRANSITION EFFECT

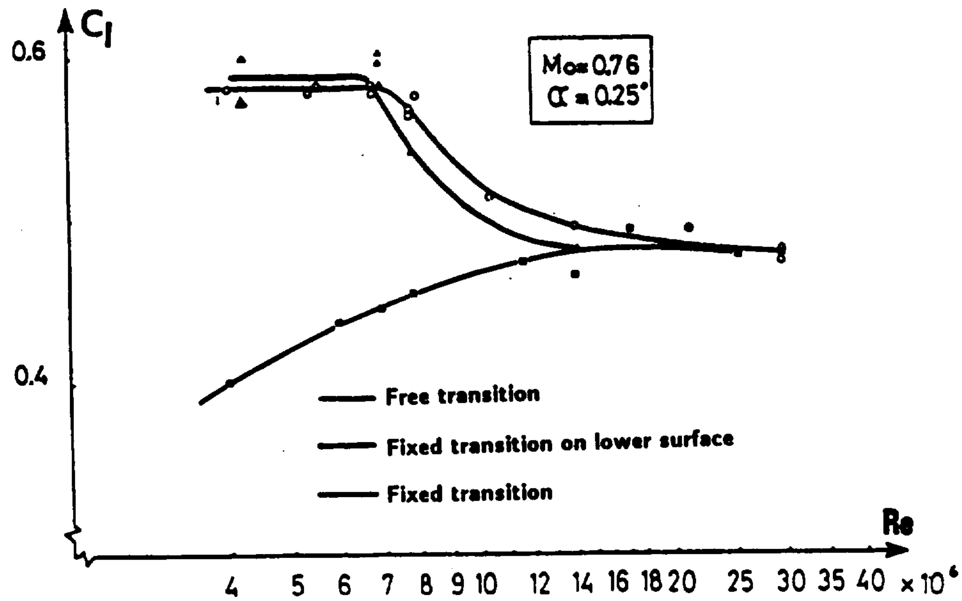



MACH NUMBER DISTRIBUTION
TRANSITION EFFECT
M=0.765 Re=4.10^6
α = 0°
M
1.5
1.0
0.5
0
0.25
0.50
0.75
1.00
X/C
Free transition
Fixed transition on lower surface
Fixed transition


MACH NUMBER DISTRIBUTION
TRANSITION EFFECT
M = 0.765 Re = 4.10^6
α = 1°
M
1.5
1.0
0.5
0
0.25
0.50
0.75
1.00
X/C
TN
T1/2D
TD

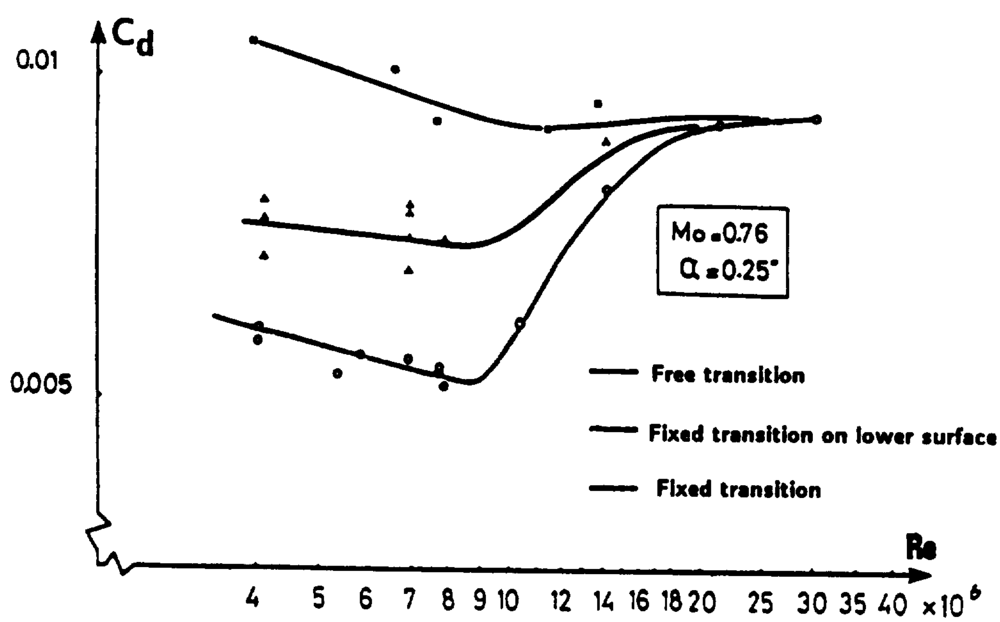
T2 TESTS

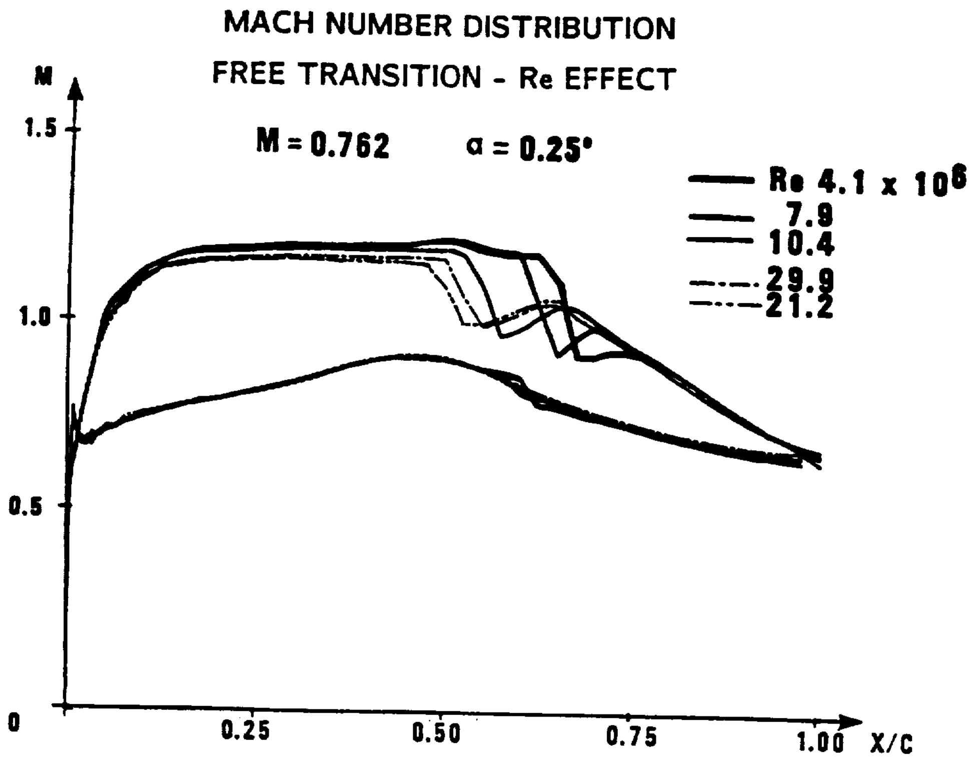
EVOLUTION OF THE LIFT COEFFICIENT WITH THE REYNOLDS NUMBER

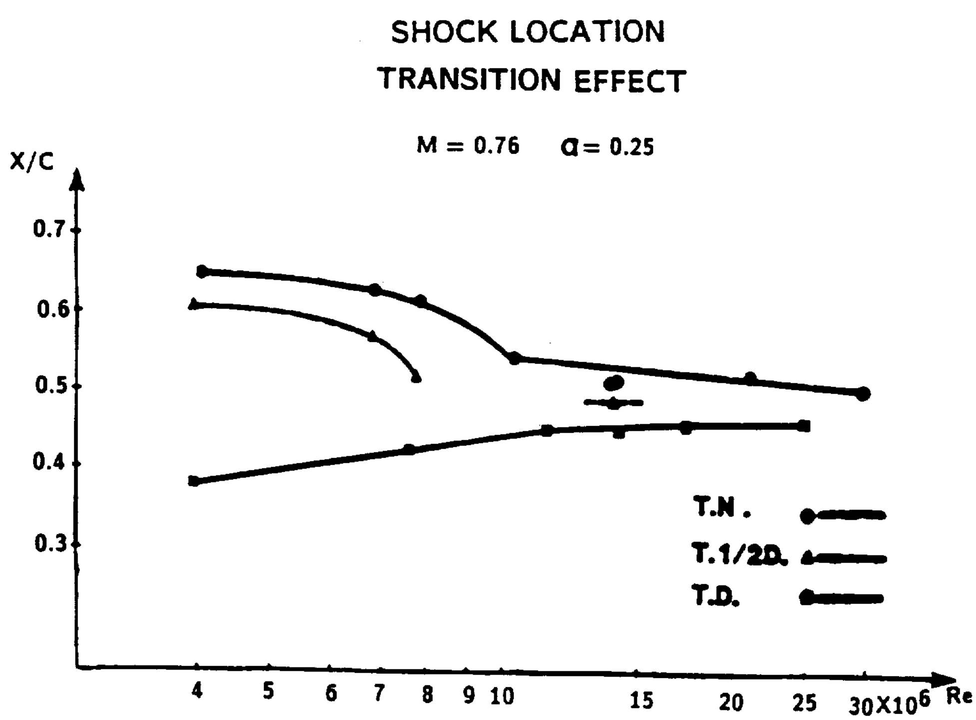


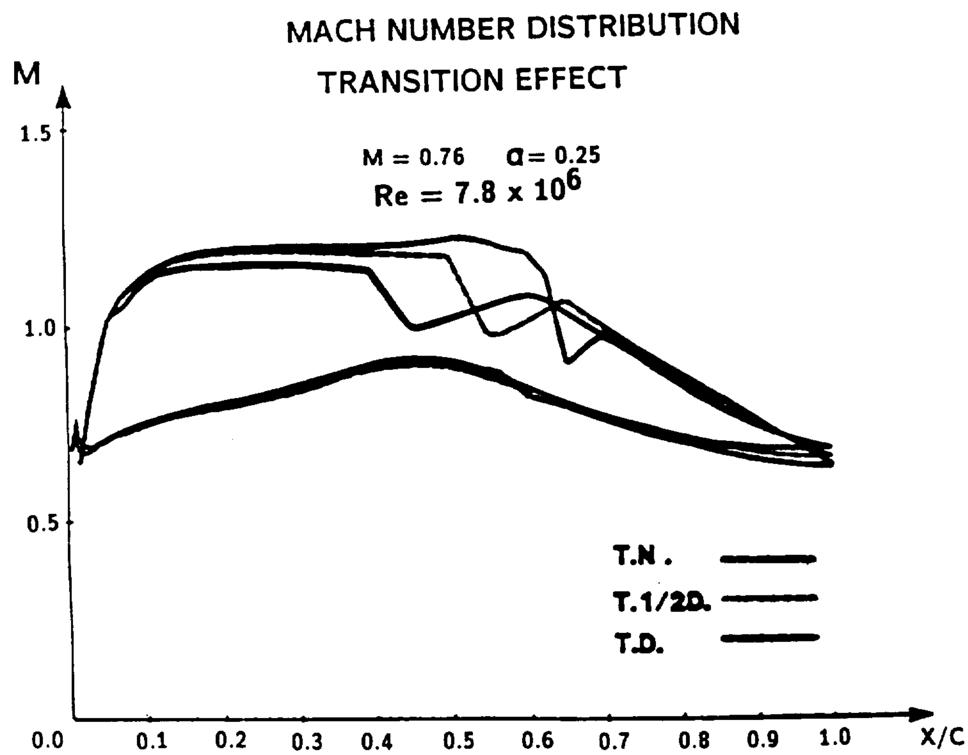
T2 TESTS

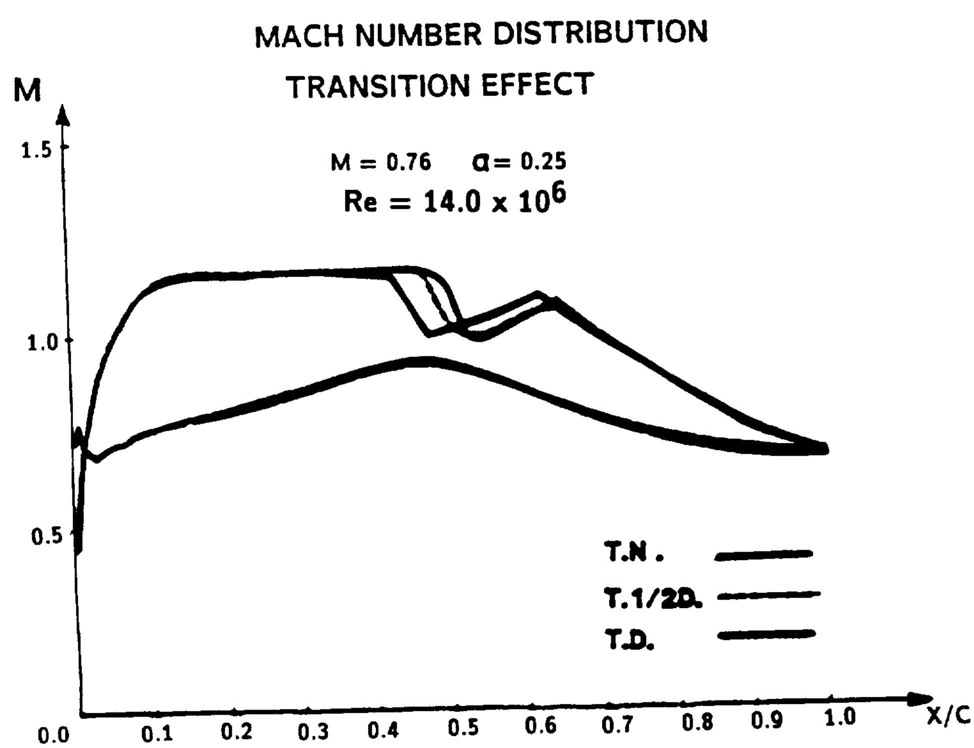
EVOLUTION OF THE DRAG WITH THE REYNOLDS NUMBER



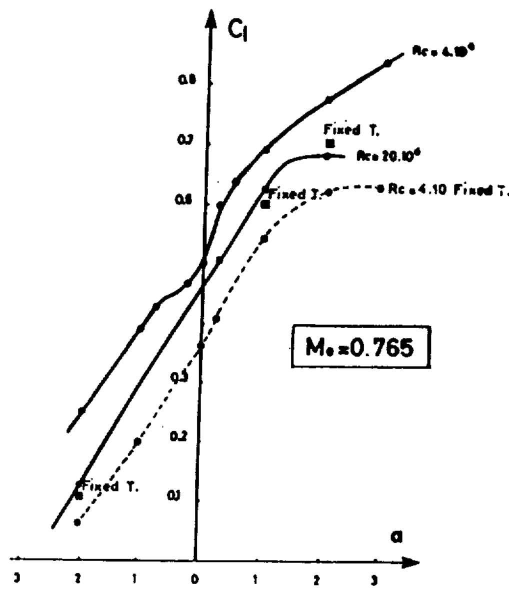

MACH NUMBER DISTRIBUTION
FREE TRANSITION - Re EFFECT
M = 0.762 α = 0.25°
M
1.5
1.0
0.5
0
0.25
0.50
0.75
1.00
X/C
Re 4.1 x 10⁶
7.9
10.4
29.9
21.2


SHOCK LOCATION
TRANSITION EFFECT
M = 0.76 α = 0.25
X/C
0.7
0.6
0.5
0.4
0.3
4
5
6
7
8
9
10
15
20
25
30X10⁶
Re
T.N.
T.1/2D.
T.D.

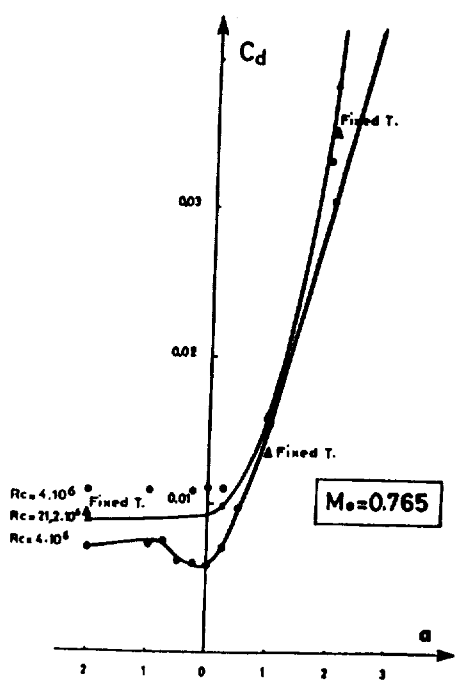

MACH NUMBER DISTRIBUTION
TRANSITION EFFECT
M
1.5
1.0
0.5
M = 0.76 α= 0.25
Re = 7.8 x 10^6
T.N .
T.1/2D.
T.D.
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
X/C


MACH NUMBER DISTRIBUTION
TRANSITION EFFECT
M
1.5
1.0
0.5
M = 0.76 α= 0.25
Re = 14.0 x 10^6
T.N .
T.1/2D.
T.D.
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
X/C

REYNOLDS NUMBER EFFECT
M = 0.765
FREE TRANSITION

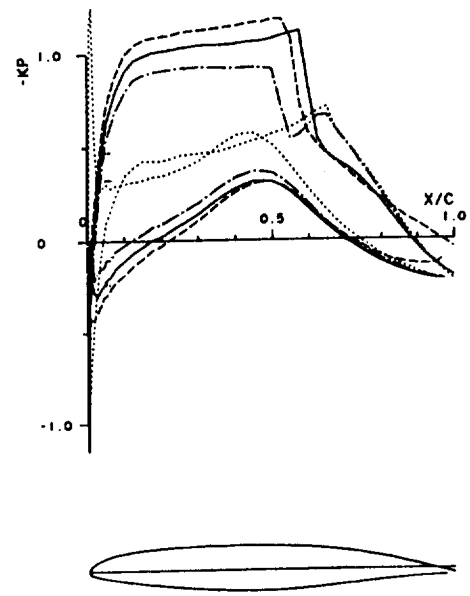


REYNOLDS NUMBER EFFECT
M = 0.765
FREE TRANSITION



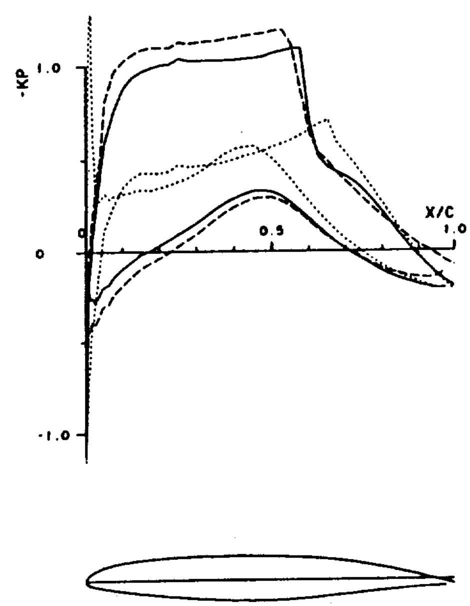
T2 T.N. M=0.765 RE=21.106

NUM.	MACH	ALPHA	RE	CZ	CX	CM
121	.764	-2.00	21.3	.110	.00870	-.07500
77	.762	.25	21.2	.497	.00930	-.07500
101	.762	1.00	21.2	.620	.01480	-.08100
116	.769	2.00	21.3	.675	.04050	-.07600



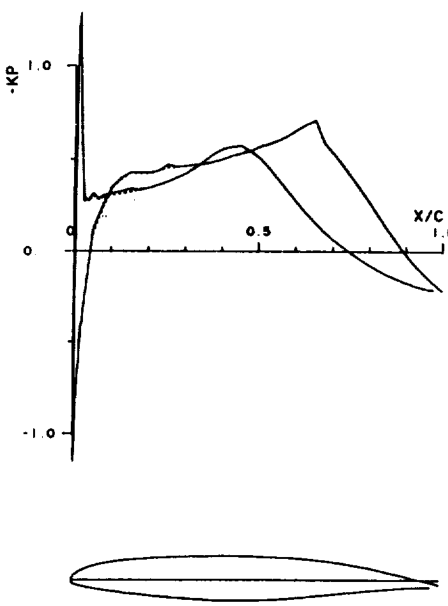
T2 T.D. M=0.765 RE=21.106

NUM.	MACH	ALPHA	RE	CZ	CX	CM
315	.765	-2.00	20.9	.108	.00910	-.07500
311	.764	1.00	21.2	.597	.01360	-.07800
320	.767	2.00	21.0	.692	.03500	-.07600



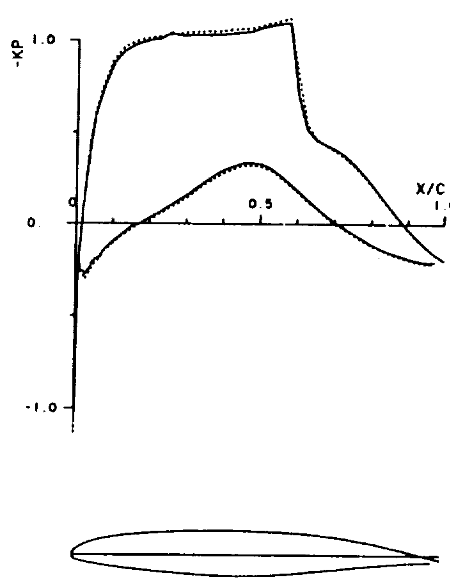
T2 T.N.-T.D. M=.765 RE=21.106 AL=-2

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
TD	315	.765	-2.00	20.9	.108	.00910	-.07500
T.N.	121	.764	-2.00	21.3	.110	.00870	-.07500



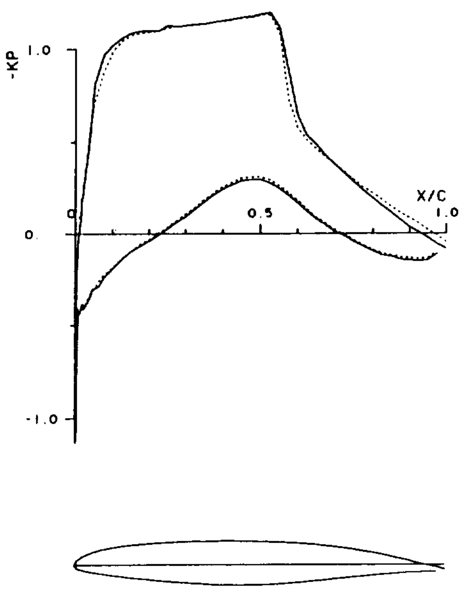
T2 T.N.-T.D. M=.765 RE=21.106 AL=+1

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
TD	311	.764	1.00	21.2	.597	.01360	-.07800
T.N.	101	.762	1.00	21.2	.620	.01480	-.08100



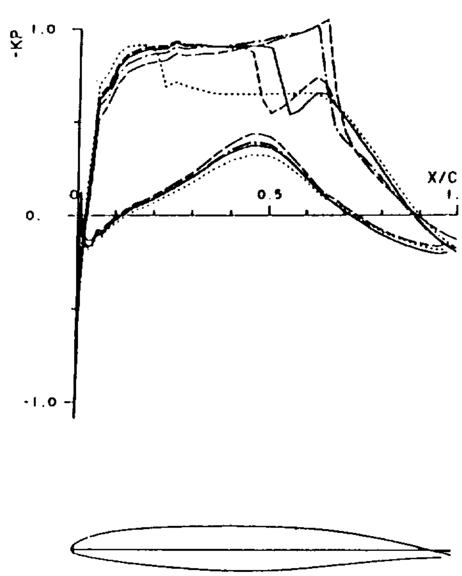
T2 T.N.-T.D. M=.765 RE=21.106 AL=+2

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
TD	320	.767	2.00	21.0	.692	.03500	-.07600
....T.N......	116	.769	2.00	21.3	.675	.04050	-.07600



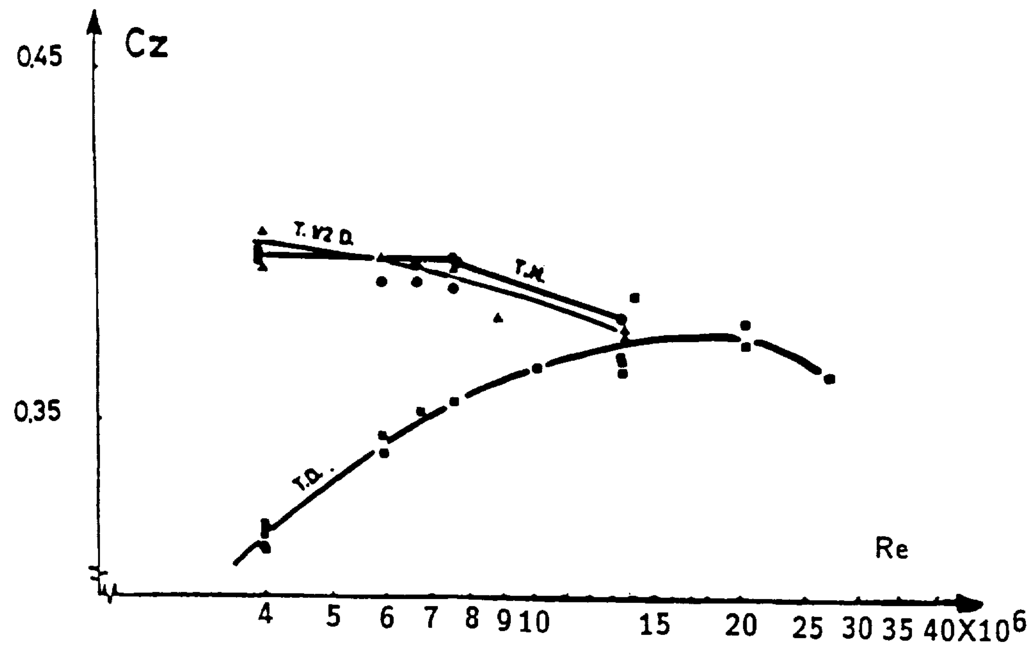
T2 EFFECT MACH EN T.D. RE=25.106 AL=0.25

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
....	336	.729	.25	24.5	.450	.00870	-.06700
------	296	.760	.25	25.2	.478	.00940	-.07000
———	332	.766	.25	25.0	.485	.00970	-.07200
—·—·—	333	.777	.25	25.3	.508	.01130	-.08100
—— ——	335	.790	.25	25.7	.478	.01660	-.08200



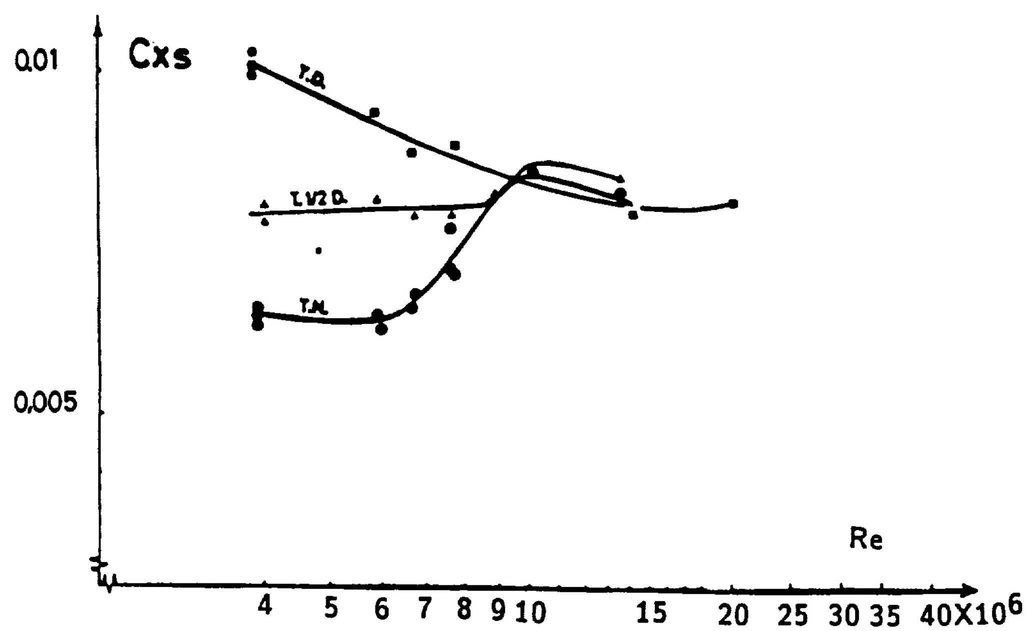
LIFT EVOLUTION WITH REYNOLDS NUMBER

$M_o = 0.73 \quad \alpha = -0.25$

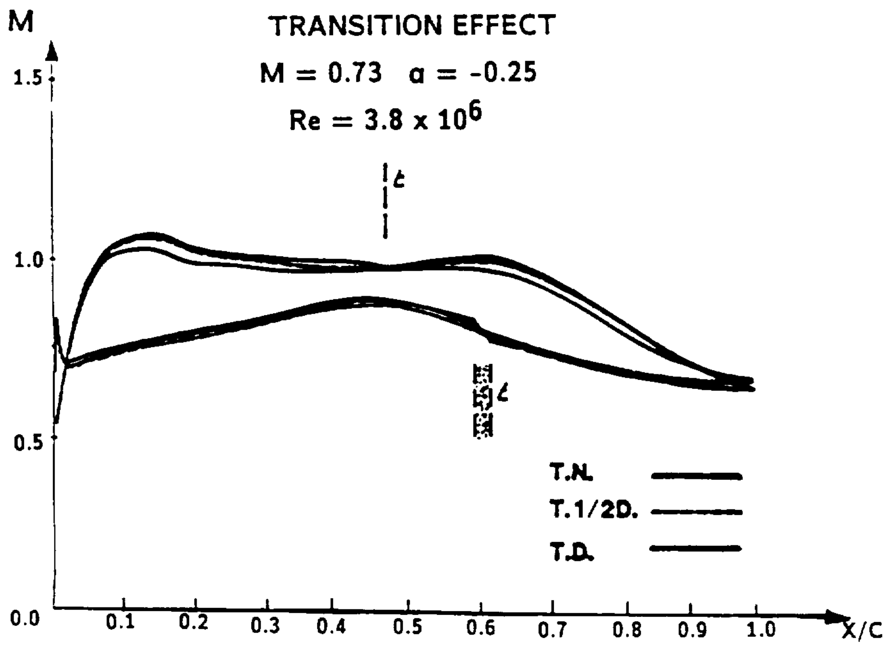


DRAG EVOLUTION WITH REYNOLDS NUMBER

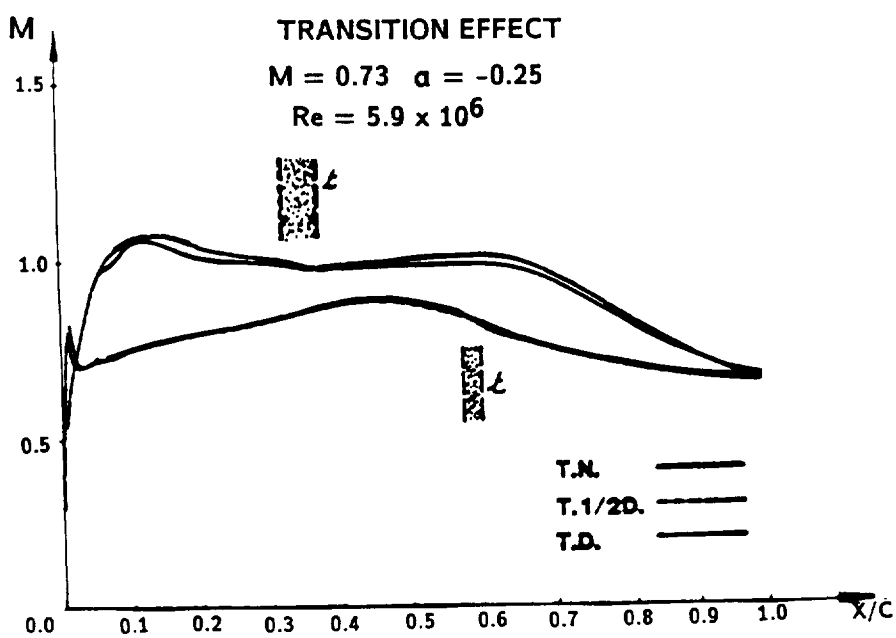
$M_o = 0.73 \quad \alpha = -0.25$

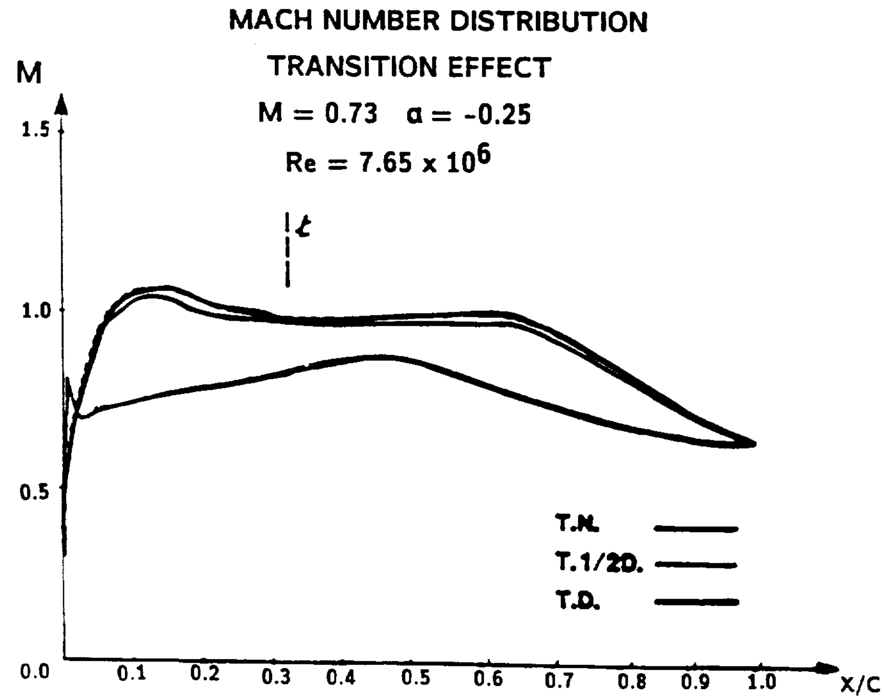


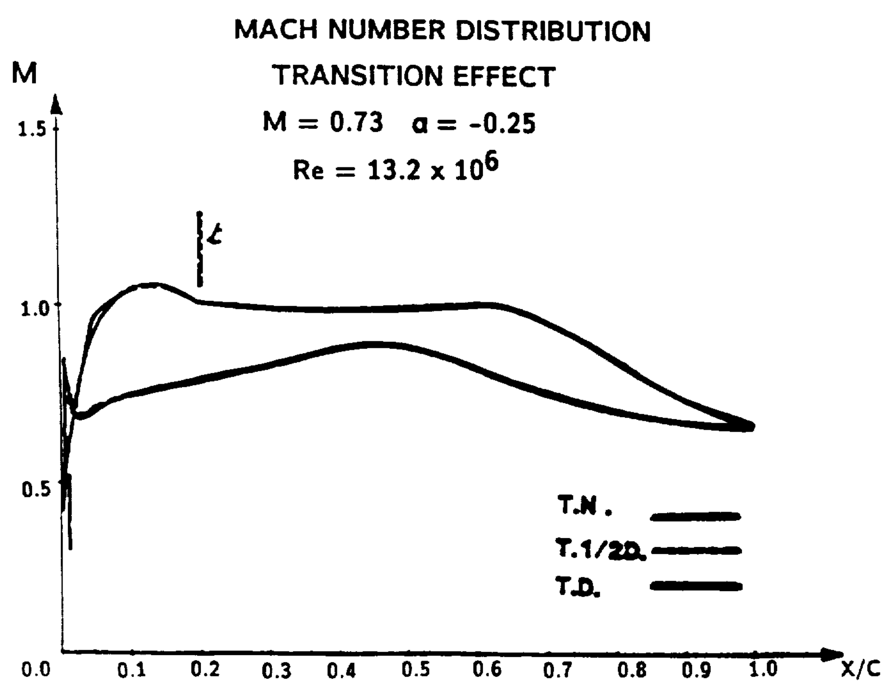
MACH NUMBER DISTRIBUTION
TRANSITION EFFECT
$M = 0.73 \quad \alpha = -0.25$
$Re = 3.8 \times 10^6$



MACH NUMBER DISTRIBUTION
TRANSITION EFFECT
$M = 0.73 \quad \alpha = -0.25$
$Re = 5.9 \times 10^6$




MACH NUMBER DISTRIBUTION
TRANSITION EFFECT
M = 0.73 α = -0.25
Re = 7.65 x 10^6
M
1.5
1.0
0.5
0.0
t
T.N.
T.1/2D.
T.D.
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
X/C


MACH NUMBER DISTRIBUTION
TRANSITION EFFECT
M = 0.73 α = -0.25
Re = 13.2 x 10^6
M
1.5
1.0
0.5
0.0
t
T.N .
T.1/2D.
T.D.
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
X/C

T2 - TCT DATA COMPARISON

- $M = 0.765$ $Re = 4 \times 10^6$

  fixed and free transition

  Total forces

  Pressure

- REYNOLDS NUMBER EFFECT

  $M = 0.76$ $\alpha = -0.25°$

CAST 10 MODEL
AND WIND TUNNEL CHARACTERISTICS

— MODEL

CRYOGENIC TECHNOLOGY

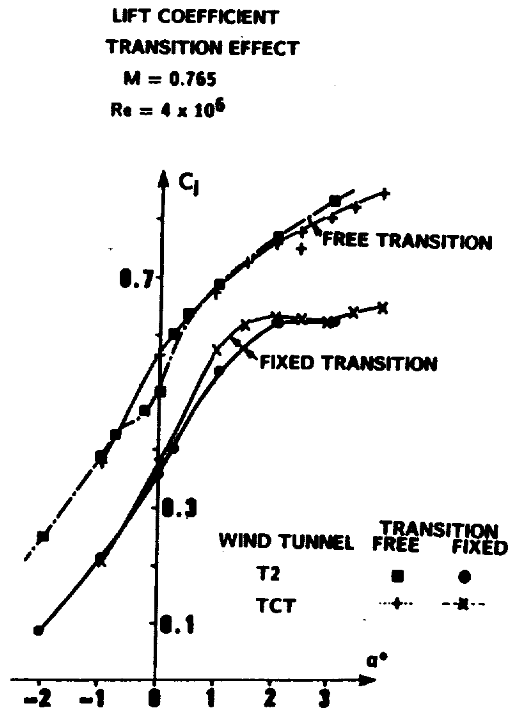
CHORD : 180 mm

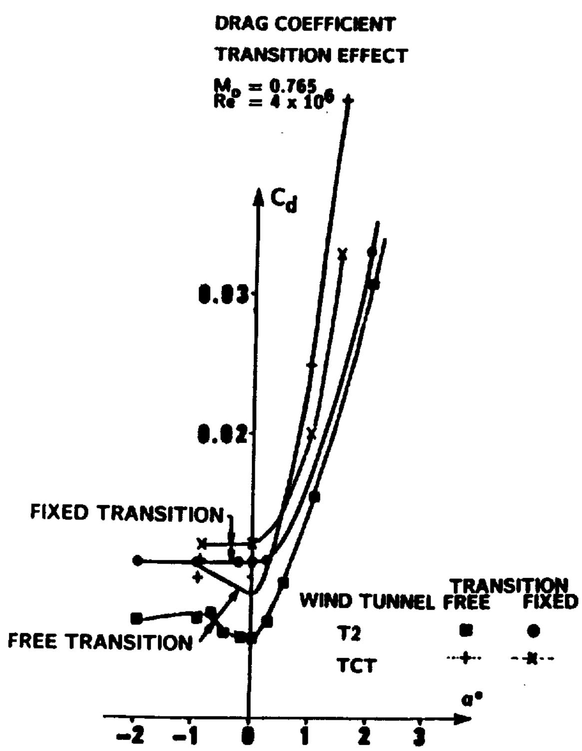
POSSIBILITY OF MOUNTING IN THE T2, TWB, TCT TUNNELS

EQUIPMENT : 103 PRESSURE HOLES (Ø 0.1 mm AND 0.3 mm)
19 THERMOCOUPLES

— WIND TUNNEL CHARACTERISTICS

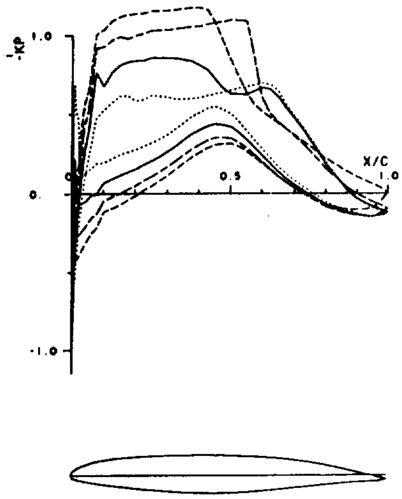
TUNNEL	WALLS	TEST SECTION	$Re \times 10^{-6}$
T2	ADAPTIVE	$0.4 \times 0.4\ m^2$	4 - 30
TWB	SLOTTED	$0.34 \times 0.6\ m^2$	4 - 12
TCT	ADAPTIVE	$0.2 \times 0.6\ m^2$	4 - 45


LIFT COEFFICIENT
TRANSITION EFFECT
M = 0.765
Re = 4 x 10^6
C_l
0.7
0.3
0.1
FREE TRANSITION
FIXED TRANSITION
WIND TUNNEL
TRANSITION
FREE
FIXED
T2
TCT
α°
−2
−1
0
1
2
3


DRAG COEFFICIENT
TRANSITION EFFECT
M_o = 0.765
Re = 4 x 10^6
C_d
0.03
0.02
FIXED TRANSITION
FREE TRANSITION
WIND TUNNEL
TRANSITION
FREE
FIXED
T2
TCT
α°
−2
−1
0
1
2
3

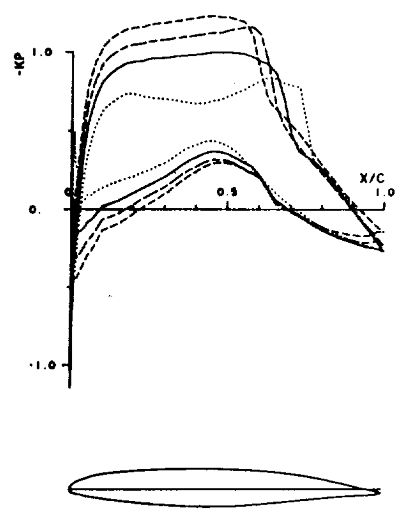
TCT T.D. M=0.765 RE=4.106

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
....	438	.771	-.99	4.0	.206	.01193	-.05952
————	439	.766	-.01	4.0	.378	.01197	-.05732
— — — -.	440	.767	.98	4.0	.570	.02048	-.06661
- - - - - -	442	.767	2.00	4.0	.634	.04551	-.06087



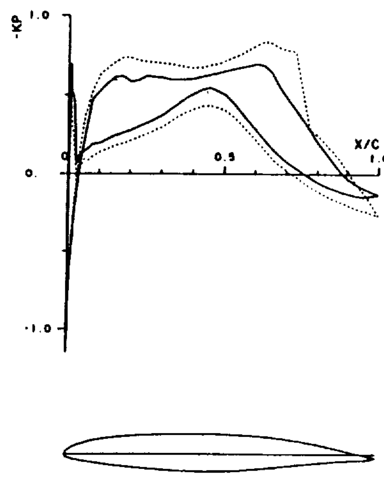
TCT T.N. M=0.765 RE=4.106

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
....	31269	.764	-1.02	4.0	.377	.01042	-.09748
————	31270	.765	-.02	4.0	.565	.00920	-.09796
— — — -.	31272	.766	.95	4.0	.675	.02453	-.09748
- - - - - -	31275	.770	1.98	4.0	.761	.05011	-.09787



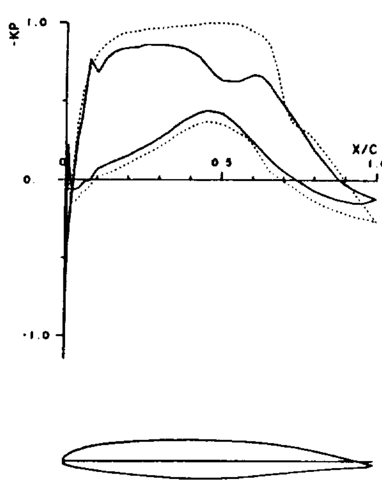
TCT T.N.-T.D. M=.765 RE=4.106 AL=-1.

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
T.D.	438	.771	-.99	4.0	.206	.01193	-.05952
T.N.	31269	.764	-1.02	4.0	.377	.01042	-.09748



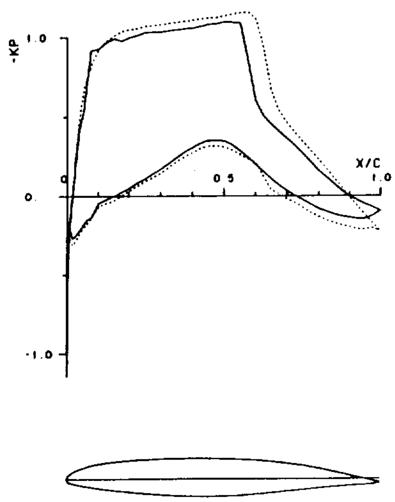
TCT T.N.-T.D. M=.765 RE=4.106 AL= 0.

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
T.D.	439	.766	-.01	4.0	.378	.01197	-.05732
T.N.	31270	.765	-.02	4.0	.565	.00920	-.09796



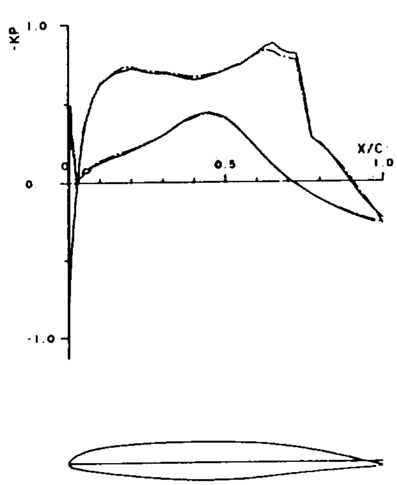
TCT T.N.-T.D. M=.765 RE=4.106 AL=+1.

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
TD	440	.767	.98	4.0	.570	.02048	-.06661
T.N.	31272	.766	.95	4.0	.675	.02453	-.09748



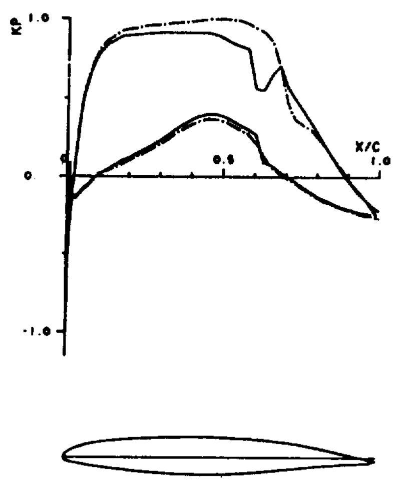
T2-TCT T.N. . M=.765 RE=4.106 AL=-1.

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
T2	24	.766	-1.00	4.1	.380	.00730	-.09800
TCT	31269	.764	-1.02	4.0	.377	.01042	-.09748



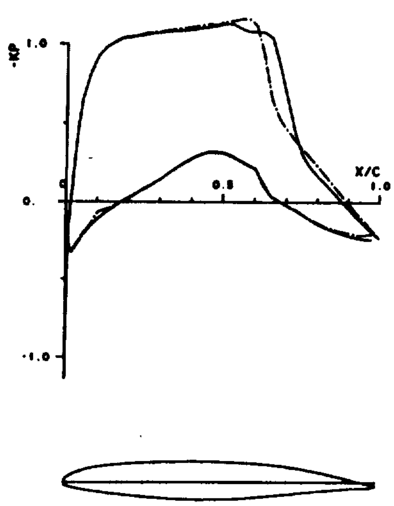
T2-TCT T.N. . M=.765 RE=4.106 AL= 0.

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
T2	19	.764	.00	4.0	.493	.00000	-.08400
TCT	31270	.765	-.02	4.0	.565	.00920	-.09796



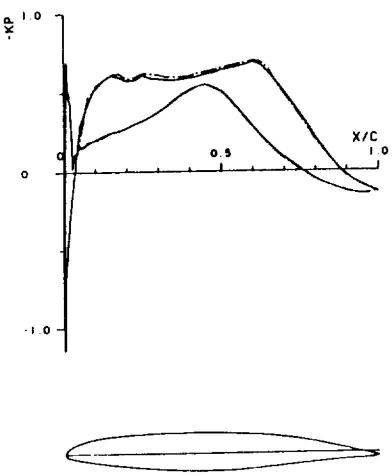
T2-TCT T.N. . M=.765 RE=4.106 AL=+1.

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
T2	29	.766	1.00	4.1	.691	.01570	-.10300
TCT	31272	.766	.95	4.0	.675	.02453	-.09748



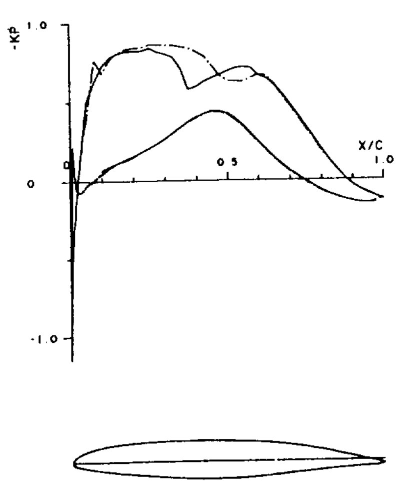
T2-TCT T.D. M=.765 RE=4.106 AL=-1.0

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
T2	270	.765	-1.00	40.0	.199	.01080	-.05800
TCT	438	.771	-.99	4.0	.206	.01193	-.05952



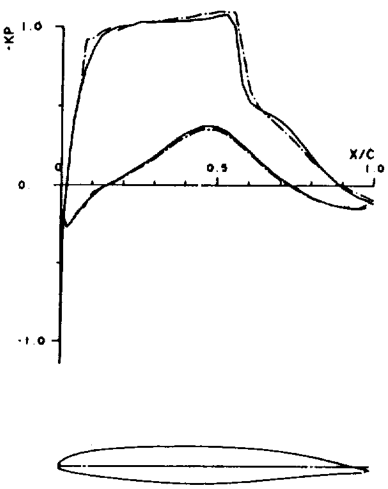
T2-TCT T.D. M=.765 RE=4.106 AL= 0.0

	NUM	MACH	ALPHA	RE	CZ	CX	CM
T2	251	.762	.00	4.0	.359	.01090	-.05600
TCT	439	.766	-.01	4.0	.378	.01197	-.05732

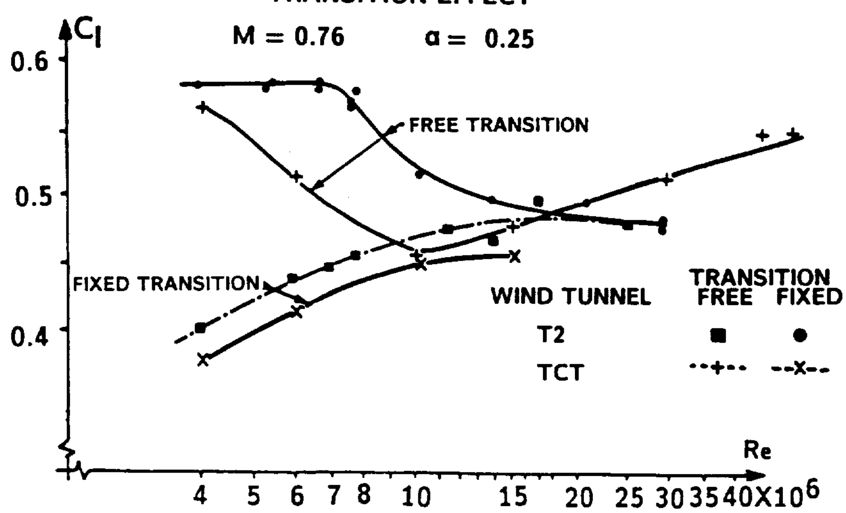


T2-TCT T.D. M=.765 RE=4.106 AL=+1.C

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
T2	246	.765	1.00	4.1	.542	.01580	-.06300
TCT	440	.767	.98	4.0	.570	.02048	-.06661

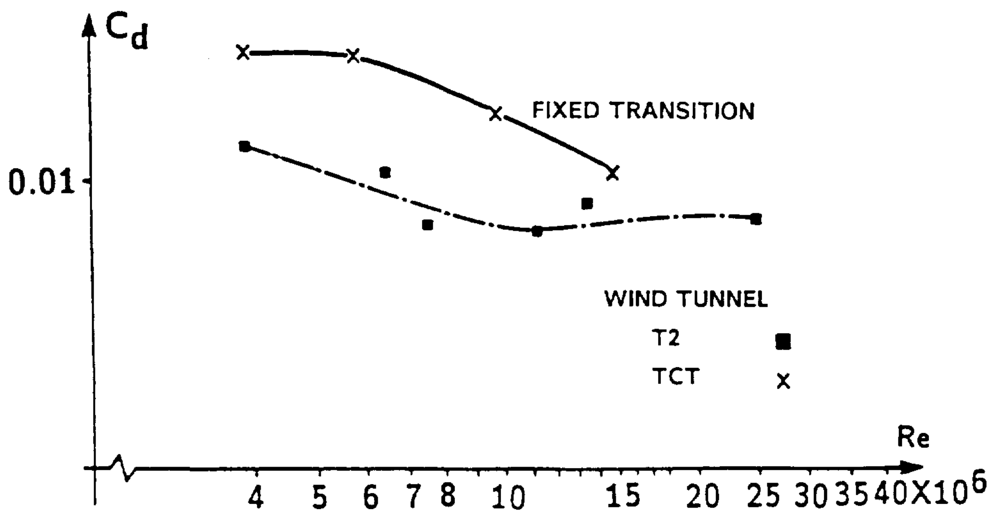


EVOLUTION OF THE LIFT COEFFICIENT
WITH THE REYNOLDS NUMBER
TRANSITION EFFECT



EVOLUTION OF THE DRAG
WITH THE REYNOLDS NUMBER

$M = 0.76 \qquad \alpha = 0.25$



COMPUTER CODES DESCRIPTION

. POTENTIAL CODES
(finite difference)

- AP 27

Inviscid flow : Garabedian and Korn method (nonconservative)
Boundary layer : Michel method
Weak coupling
No wake computation

- VISC 05

Inviscid flow : Chattot method
Boundary layer / Strong coupling {Le Balleur method
Wake computation
Nonconservative or conservative options
C type mesh

. NAVIER STOKES CODE
(Veuillot-Cambier)

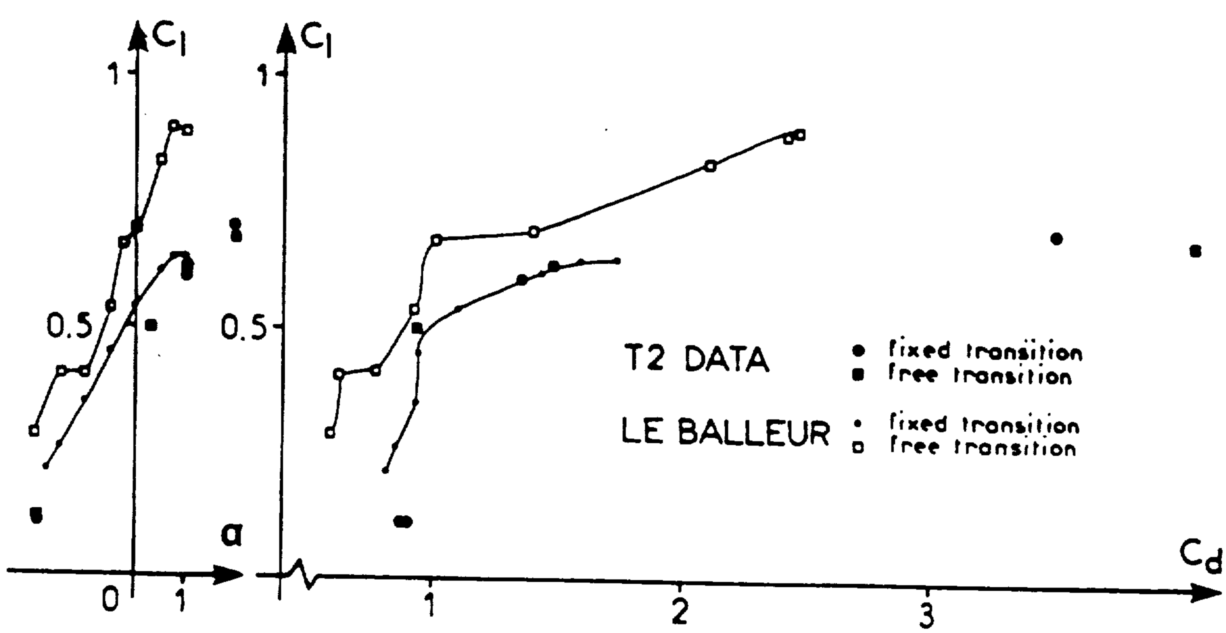
Compressible N.S equation with constant total enthalpy 3-possible turbulence models (Michel, Baldwin-Lomax, K-ε)
Explicit finite difference scheme
Local time step
Multigrid acceleration technique
Far field boundary conditions treatment using characteristics relations
C type mesh

THEORY - EXPERIMENT COMPARISONS

- M = 0.765 Re = 21x10[6]
  Total forces
  Pressure: free transition Cl~0.5
  Side wall B.L. effect simulation
- M = 0.765 Re = 25x10[6]
  Pressure: fixed transition Cl~0.5
- Mach number effect Re = 25x10[6]
  fixed transition
  Pressure
  Total forces
- M = 0.73 Cl ~ 0.35
  fixed transition
- Reynolds number effect
  M = 0.73 α = -0.25°
  Total forces

THEORY EXPERIMENT COMPARISON

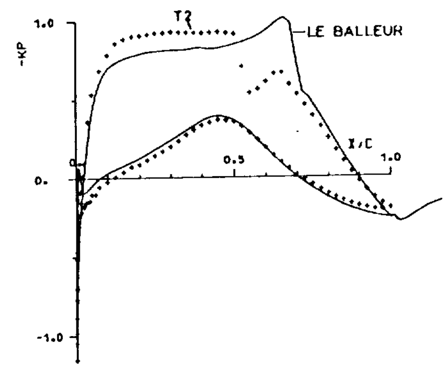
M = 0.765 Re = 21 x 10^6



THEORY-EXPERIMENT COMPARISON

FREE TRANSITION

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
———	65	.765	-.64	21.0	.501	.00870	-.10711
• •	77	.762	.25	21.2	.497	.00930	-.07500

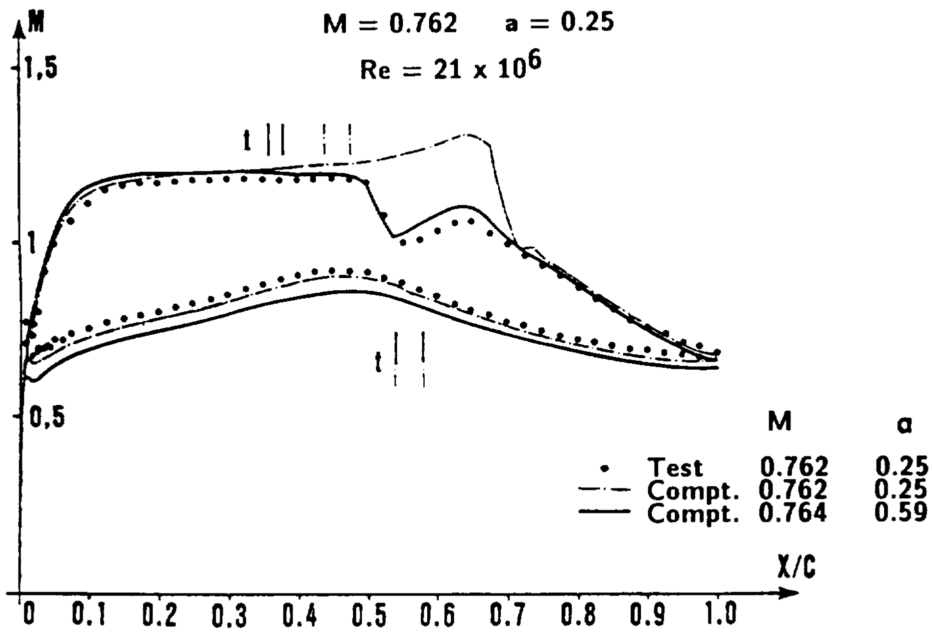


TEST - THEORY COMPARISON

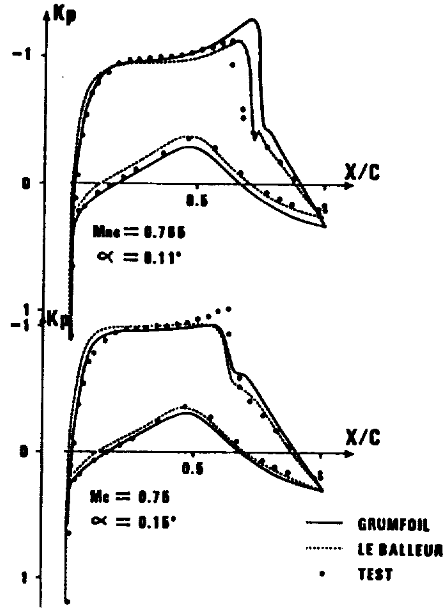
FREE TRANSITION

M = 0.762 a = 0.25

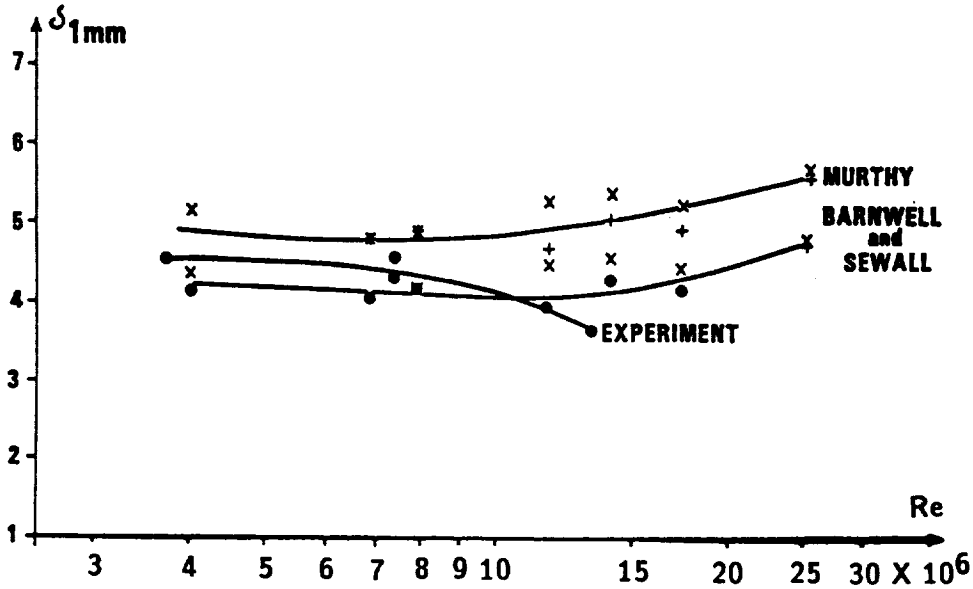
Re = 21 x 10^6



COMPUTER CODE COMPARISONS
Re = 15 x 10^6



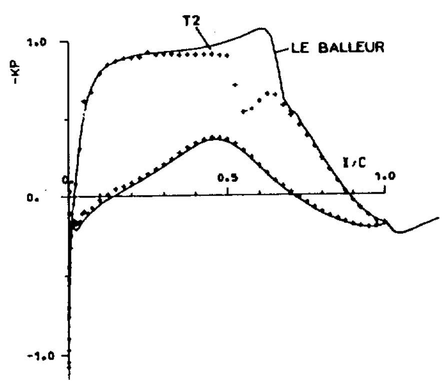
LATERAL WALL B.L.EFFECT
FIXED TRANSITION



THEORY - EXPERIMENT COMPARISON

FIXED TRANSITION

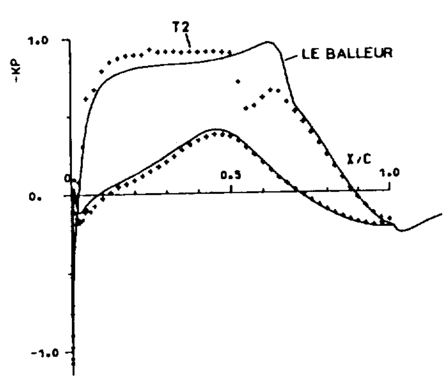
	NUM.	MACH	ALPHA	RE	CZ	CX	CM
———	1	.765	.25	25.0	.581	.0129	-.09774
+ +	332	.766	.25	25.0	.485	.00970	-.07200



THEORY-EXPERIMENT COMPARISON

FIXED TRANSITION

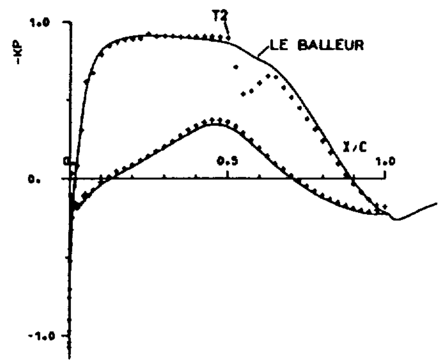
	NUM.	MACH	ALPHA	RE	CZ	CX	CM
———	21	.766	-.35	25.0	.484	.00990	-.09392
+ +	332	.766	.26	25.0	.485	.00970	-.07200



THEORY - EXPERIMENT COMPARISON

FIXED TRANSITION

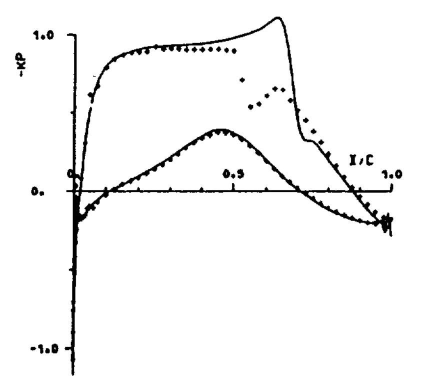
	NUM.	MACH	ALPHA	RE	CZ	CX	CM
———	61	.748	.00	24.7	.542	.00000	-.08766
• •	332	.766	.25	25.0	.485	.00970	-.07200



N.S. CALCULATIONS

FIXED TRANSITION

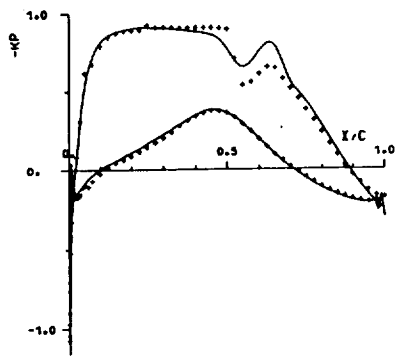
	NUM.	MACH	ALPHA	RE	CZ	CX	CM
———	102	.765	.25	25.0	.548	.01381	.00000
• •	332	.766	.25	25.0	.485	.00970	-.07200



N.S. CALCULATIONS

FIXED TRANSITION

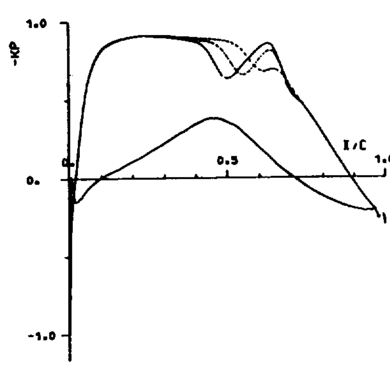
	NUM.	MACH	ALPHA	RE	CZ	CX	CM
———	105	.750	.00	25.0	.498	.00987	.00000
• •	332	.766	.25	25.0	.485	.00970	-.07200



N.S. CALCULATIONS

MACH NUMBER EFFECT

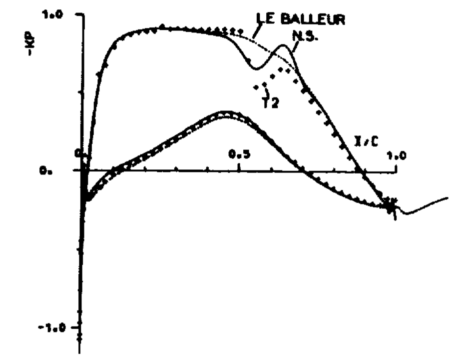
	NUM.	MACH	ALPHA	RE	CZ	CX
———	103	.748	.00	25.0	.493	.00989
········	105	.750	.00	25.0	.498	.00987
········	104	.752	.00	25.0	.504	.00986



THEORY - EXPERIMENT COMPARISON

FIXED TRANSITION

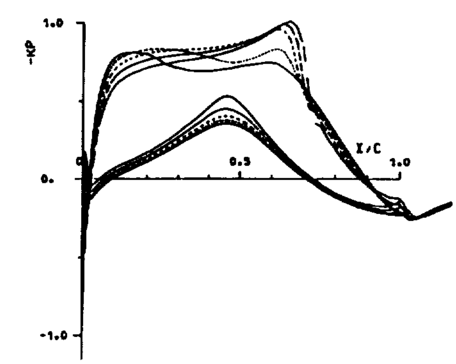
	NUM.	MACH	ALPHA	RE	CZ	CX	CM
———	105	.750	.00	25.0	.498	.00987	.00000
········	61	.748	.00	24.7	.542	.00800	-.08765
• •	332	.766	.25	25.0	.485	.00970	-.07200



"LE BALLEUR" CALCULATIONS

FIXED TRANSITION

	NUM.	MACH	ALPHA	RE	CZ	CX	CM
———	41	.730	-.35	24.3	.453	.00780	-.08340
········	42	.750	-.35	24.7	.473	.00800	-.08723
- - - - -	21	.766	-.35	25.0	.484	.00990	-.09392
— — —	43	.777	-.35	25.2	.445	.01190	-.09125
— —	44	.790	-.35	25.4	.394	.01440	-.08752

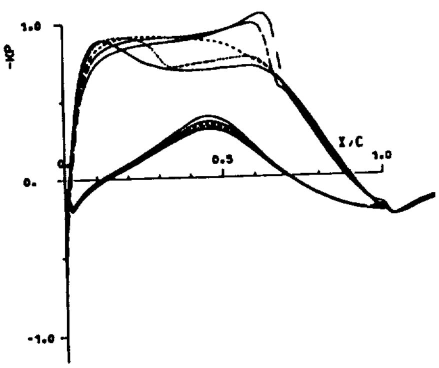


"LE BALLEUR" CALCULATIONS

FIXED TRANSITION

(corrected Mach numbers)

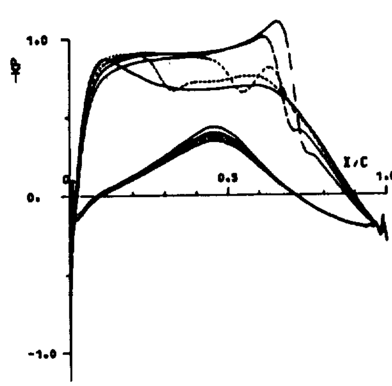
NUM.	MACH	ALPHA	RE	CZ	CX	CM
67	.711	.00	24.0	.499	.00760	-.08154
68	.732	.00	24.4	.517	.00780	-.08379
61	.748	.00	24.7	.542	.00800	-.08765
69	.759	.00	24.9	.552	.00970	-.09453
70	.772	.00	25.1	.530	.01270	-.09727



N.S. CALCULATIONS

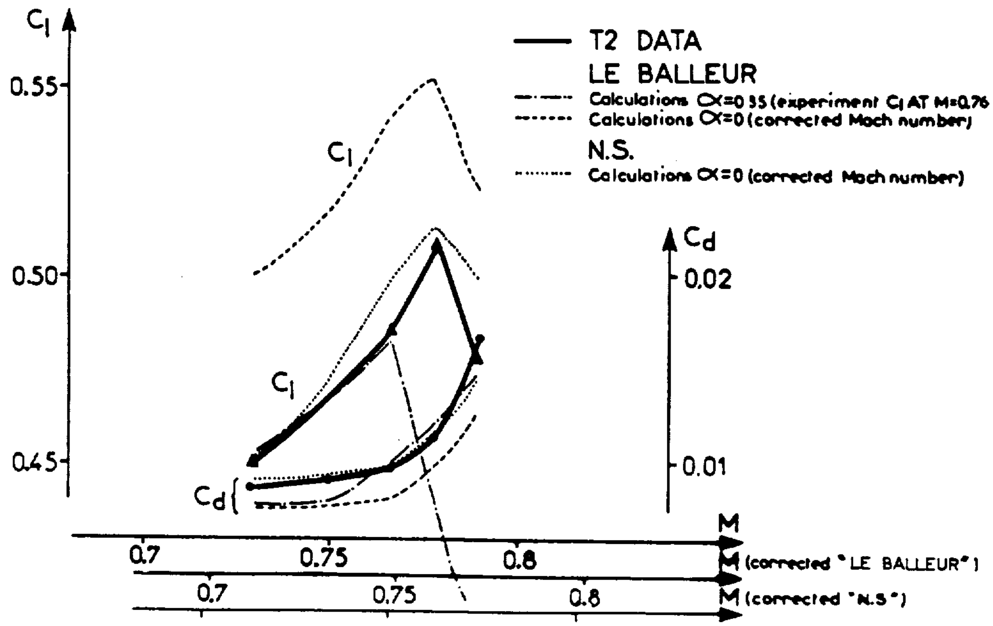
(corrected Mach numbers)

NUM.	MACH	ALPHA	RE	CZ	CX
109	.713	.00	25.0	.452	.00908
108	.734	.00	25.0	.473	.00943
105	.750	.00	25.0	.498	.00987
107	.761	.00	25.0	.513	.01116
106	.774	.00	25.0	.499	.01461



THEORY EXPERIMENT COMPARISON

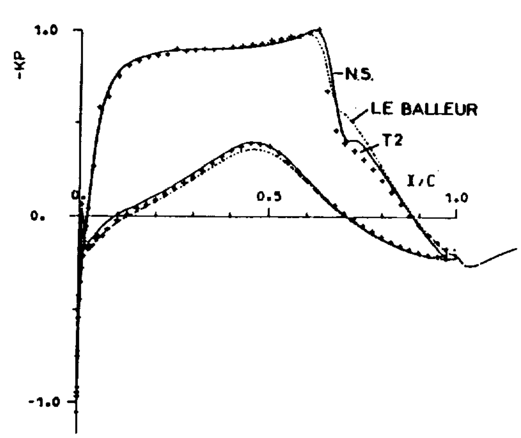
FIXED TRANSITION



THEORY-EXPERIMENT COMPARISON

FIXED TRANSITION

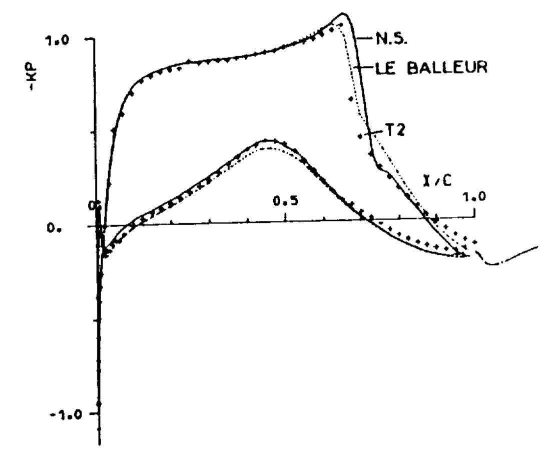
	NUM.	MACH	ALPHA	RE	CZ	CX	CM
———	107	.761	.00	25.0	.513	.01115	.00000
········	69	.759	.00	24.9	.552	.00970	-.09453
+ +	333	.777	.25	25.3	.508	.01130	-.08100



THEORY-EXPERIMENT COMPARISON

FIXED TRANSITION

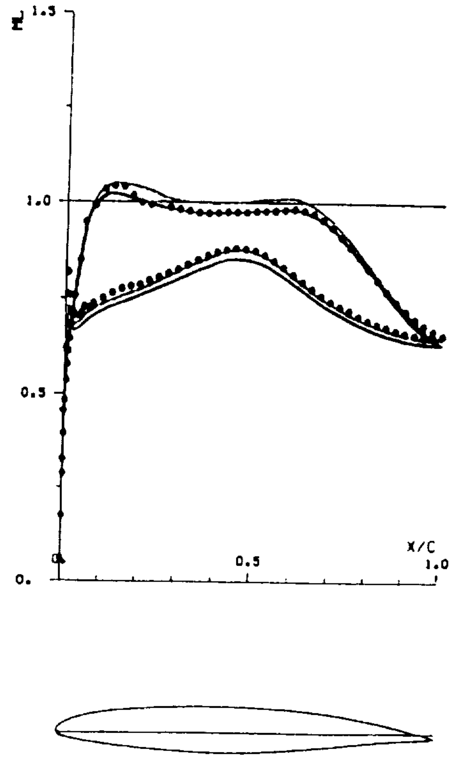
	NUM.	MACH	ALPHA	RE	CZ	CX	CM
	106	.774	.00	25.0	.499	.01461	.00000
	70	.772	.00	25.1	.530	.01270	-.09727
	335	.790	.25	25.7	.478	.01660	-.08200



THEORY - EXPERIMENT COMPARISON
LE BALLEUR'S METHOD
FIXED TRANSITION

** REC.C.FORT ESSAI M=0.73 I=-0.25 **

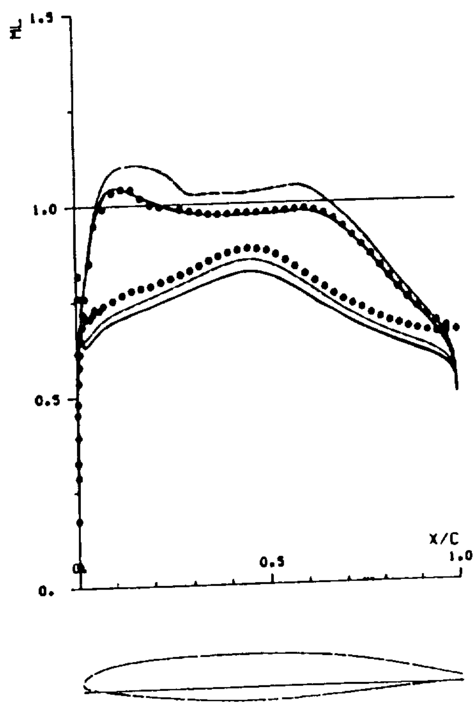
	NUM.	MACH	ALPHA	RE	CZ	CX	CM
• •	273	.727	-.25	7.6	.350	.00890	-.06400
———	1	.727	-.25	7.6	.409	.01167	-.07148
═══	2	.715	-.25	7.5	.411	.01138	-.07233



THEORY - EXPERIMENT COMPARISON
WEAK COUPLING METHOD

** REC.C.FAIBLE ESSAI M=.73 I=-.25 **

NUM.	MACH	ALPHA	RE	CZ	CX	CM
273	.727	-.25	7.6	.350	.00890	-.06400
1	.727	-.25	7.6	.529	.00987	-.09253
2	.705	-.25	7.6	.498	.00953	-.08754



CONCLUSIONS

1) T2 DATA

. CAST 10 AIRFOIL VERY SENSITIVE TO :
- TRANSITION LOCATION
- MACH NUMBER
- REYNOLDS NUMBER

. T2 DATA VERY WELL DOCUMENTED AT LOW AND MEDIUM REYNOLDS NUMBERS

. T2 DATA SHOWS LARGE EXTENT OF LAMINAR FLOW UP TO Re 10

. TRANSITION LOCATION DISPLACEMENTS CONTROL
- Cl, CD EVOLUTIONS VERSUS ANGLE OF ATTACK
- Cl, CD EVOLUTIONS VERSUS Re NUMBER

2) T2 - TCT DATA COMPARISONS

. TCT DATA SHOW LESS LAMINAR FLOW THAN T2 AT THE SAME Re NUMBER

. FIXED TRANSITION DATA SEEMS TO CORRELATE CORRECTLY

. MORE COMPARISONS ARE NEEDED AT HIGH Re NUMBER

3) TEST - THEORY COMPARISONS

. CORRELATIONS ARE POOR USING THE SAME MACH NUMBER

. SIDEWALL B-L CORRECTIONS IMPROVE COMPARISONS

. NS COMPUTATIONS (WITH CORRECTED MACH NUMBERS) GIVE GOOD CORRELATIONS FOR :
- Cl, CD VERSUS MACH NUMBER
- PRESSURE VERSUS MACH NUMBER