

50376  
1988  
109-2

N° d'ordre : 763



50376  
1988  
109-2

T H E S E

présentée à

L'UNIVERSITE DES SCIENCES ET TECHNIQUES DE  
LILLE FLANDRES ARTOIS

pour obtenir

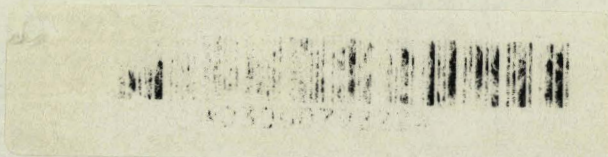
le grade de Docteur ès Sciences Physiques (Mécanique)

par

Alain MERLEN

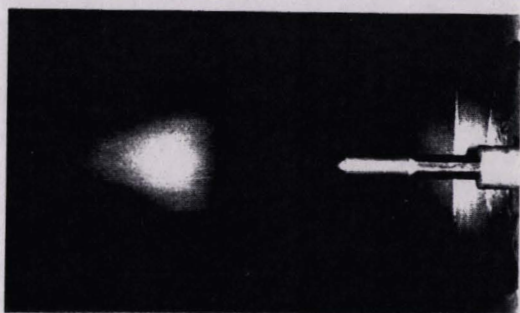
SIMILITUDE PHYSIQUE ET MODELISATION  
PAR EXPLOSION EQUIVALENTE DES PHENOMENES  
AERODYNAMIQUES DE BALISTIQUE INTERMEDIAIRE

F I G U R E S



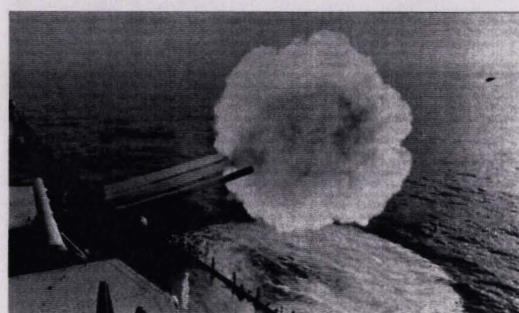
Jury : Président : M. GUIRAUD, Professeur, Université de Paris VI.  
Rapporteurs : M. BOIS, Professeur, Université de Lille I.  
M. DYMENT, Professeur, Université de Lille I.  
Membres : M. ZEYTOUNIAN, Professeur, Université de Lille I.  
M. DI NICOLA, Ingénieur en Chef Armement, Chef du Groupe 6, DRET.  
M. PERRIER, Chef du Dépt. Aérodynamique, AMD-BA.  
M. VIVIAND, Directeur Scientifique Adjoint de l'Aérodynamique,  
ONERA.

Soutenue le 27 avril 1988



1

**Pose photographique en chambre noire  
Visualisation des lueurs de bouche**



2

**Photographie instantanée  
du projectile**

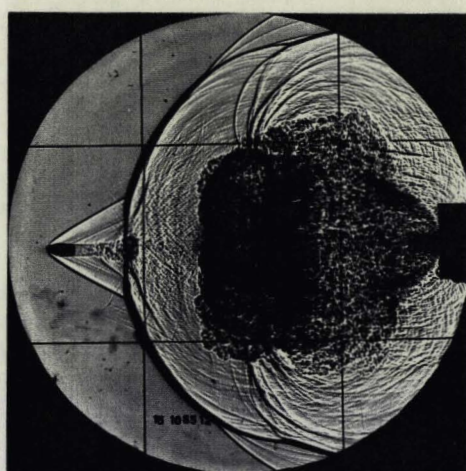


Photos 2&3 tirées  
de PROCEEDINGS  
U.S.Naval Institute

J. ALAN ELLIOTT, PH.D. SW. U.S.

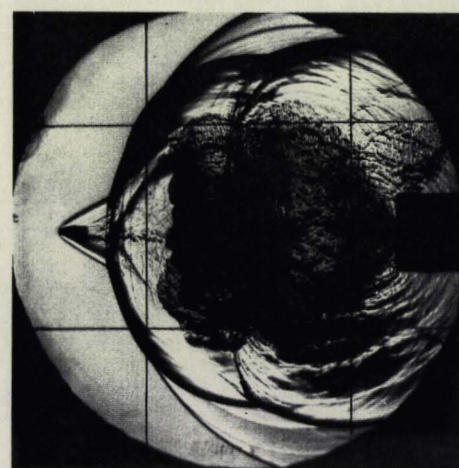
3

**Photographie instantanée des réflexions d'ondes sur l'eau**



4

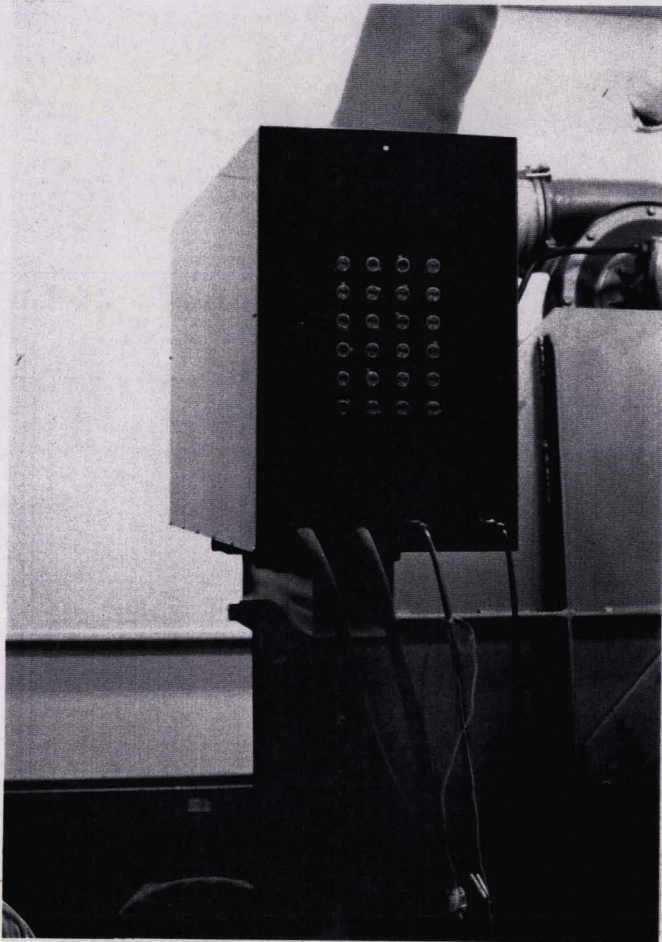
**Ombroscopie instantanée**



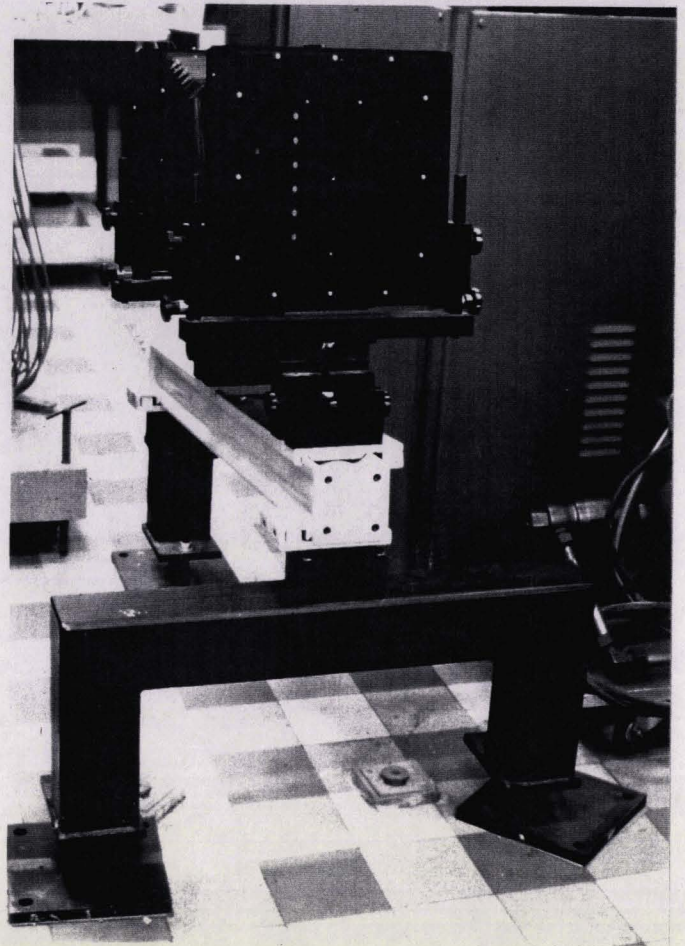
5

**Strioscopie instantanée**

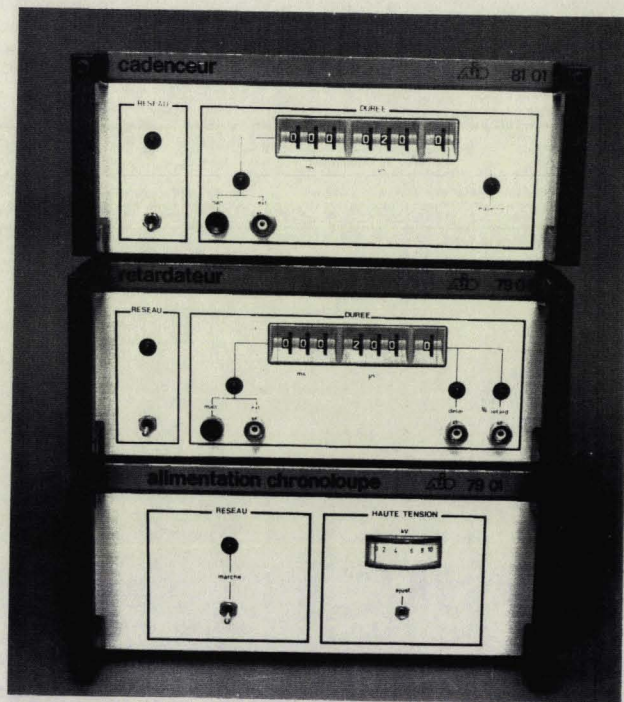
**Visualisations de tirs d'armes par différentes techniques**



Batterie d'éclateurs



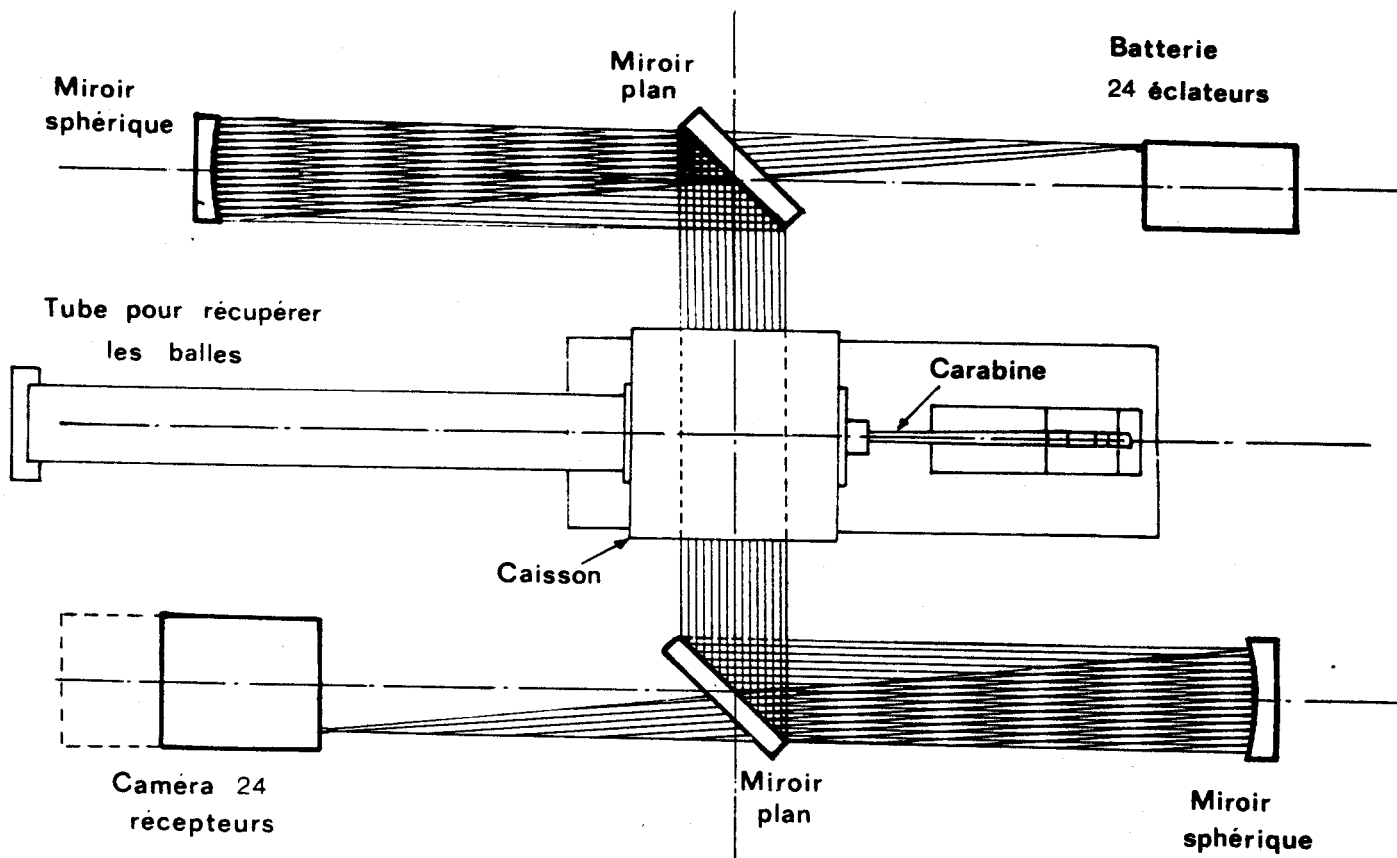
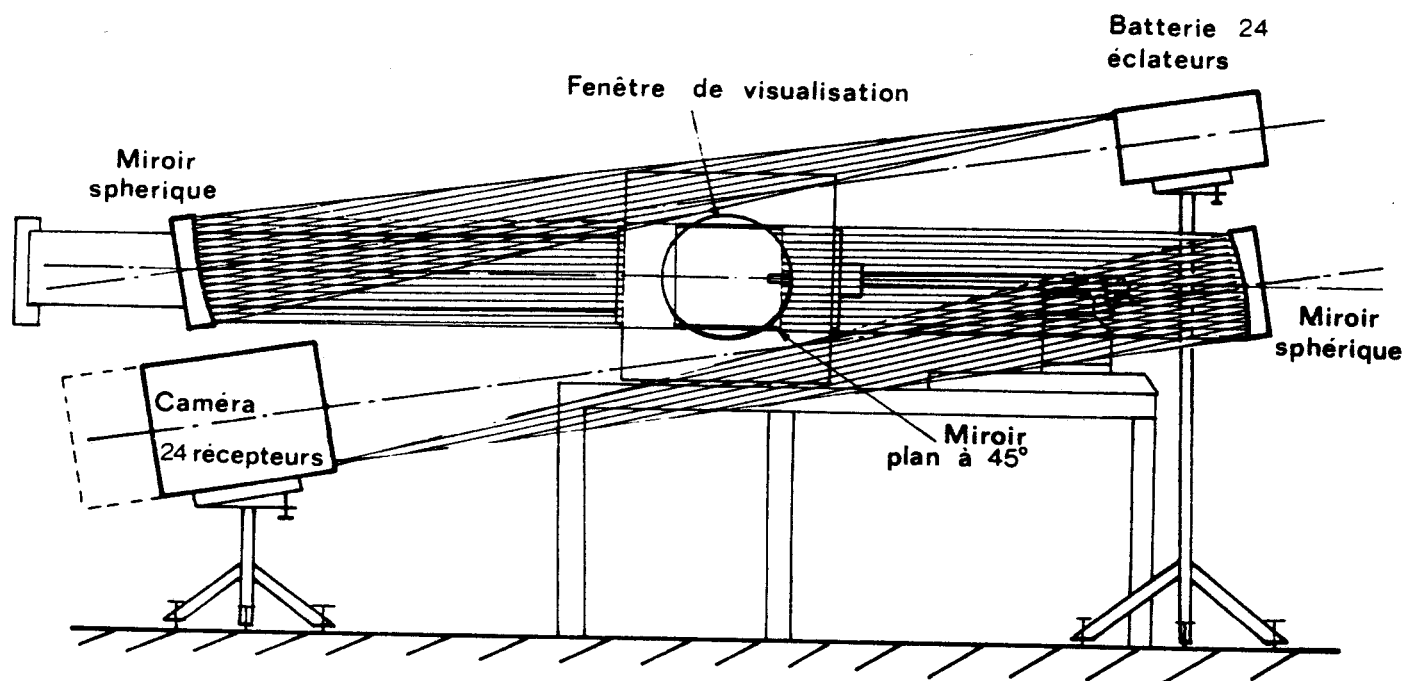
Récepteur



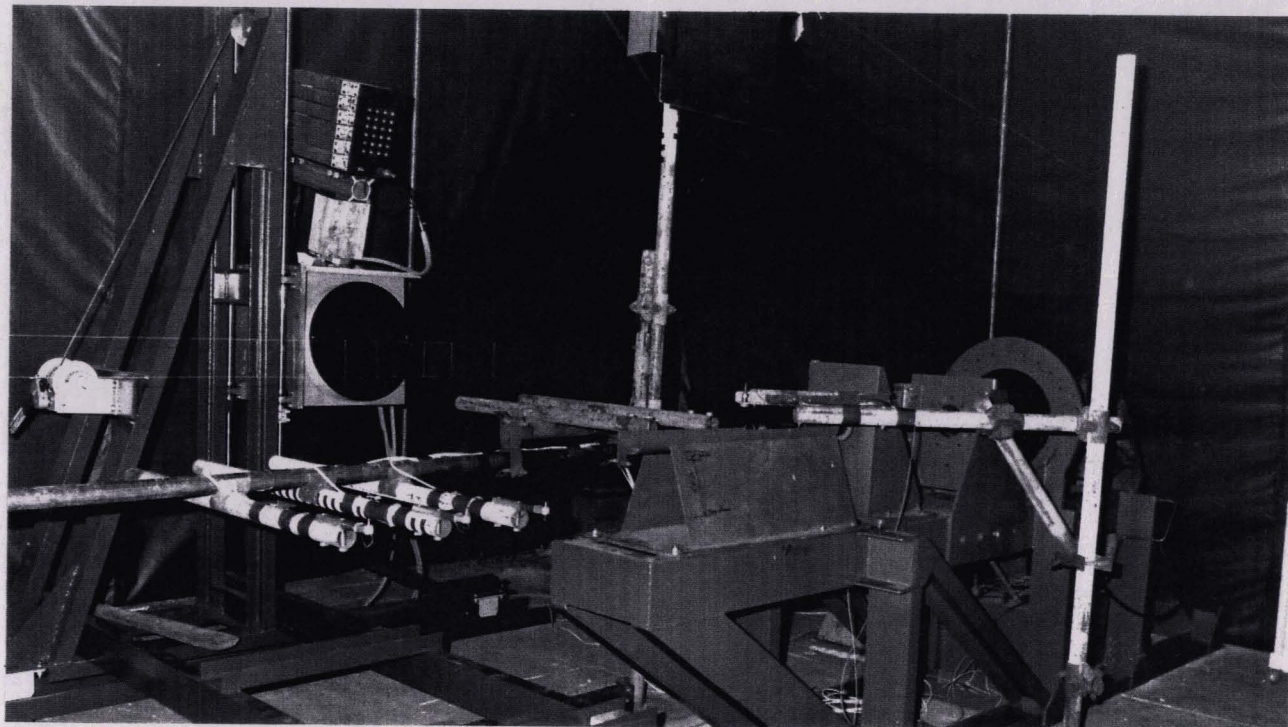
Boitiers de commande

Dispositif chronoloupes

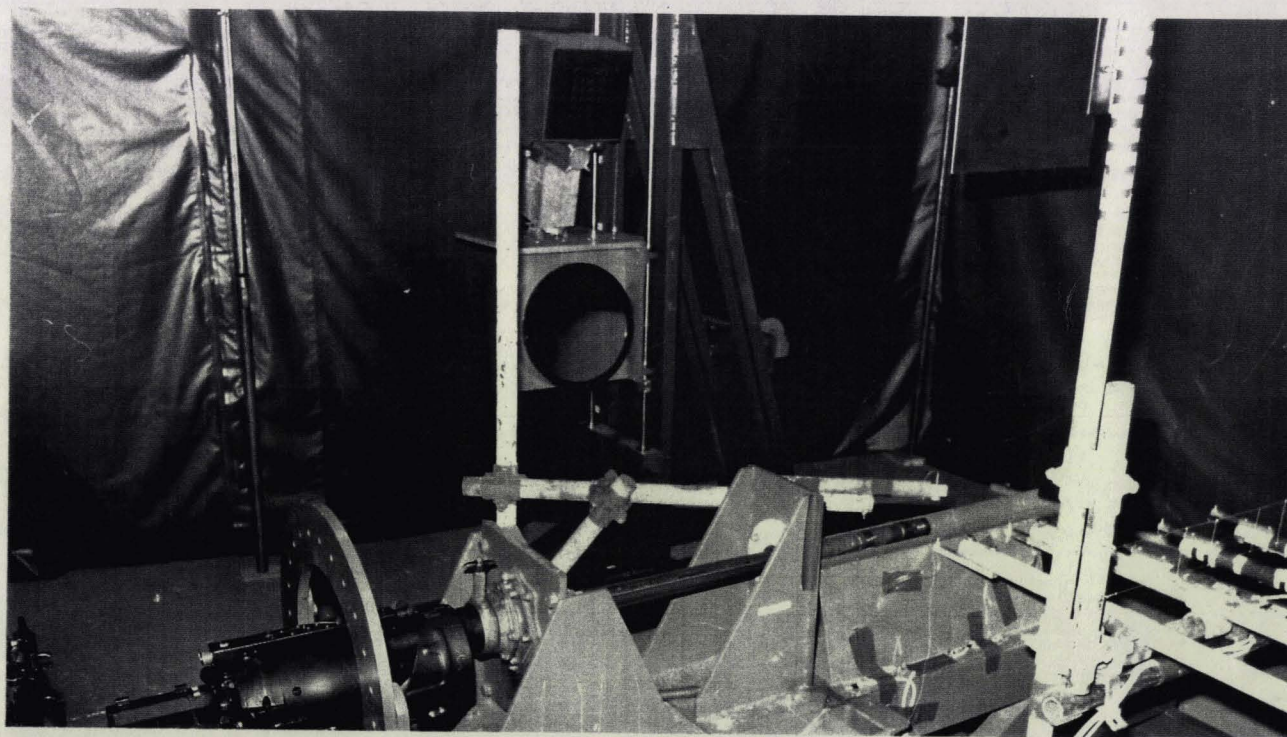




Visualisations ultra-rapides

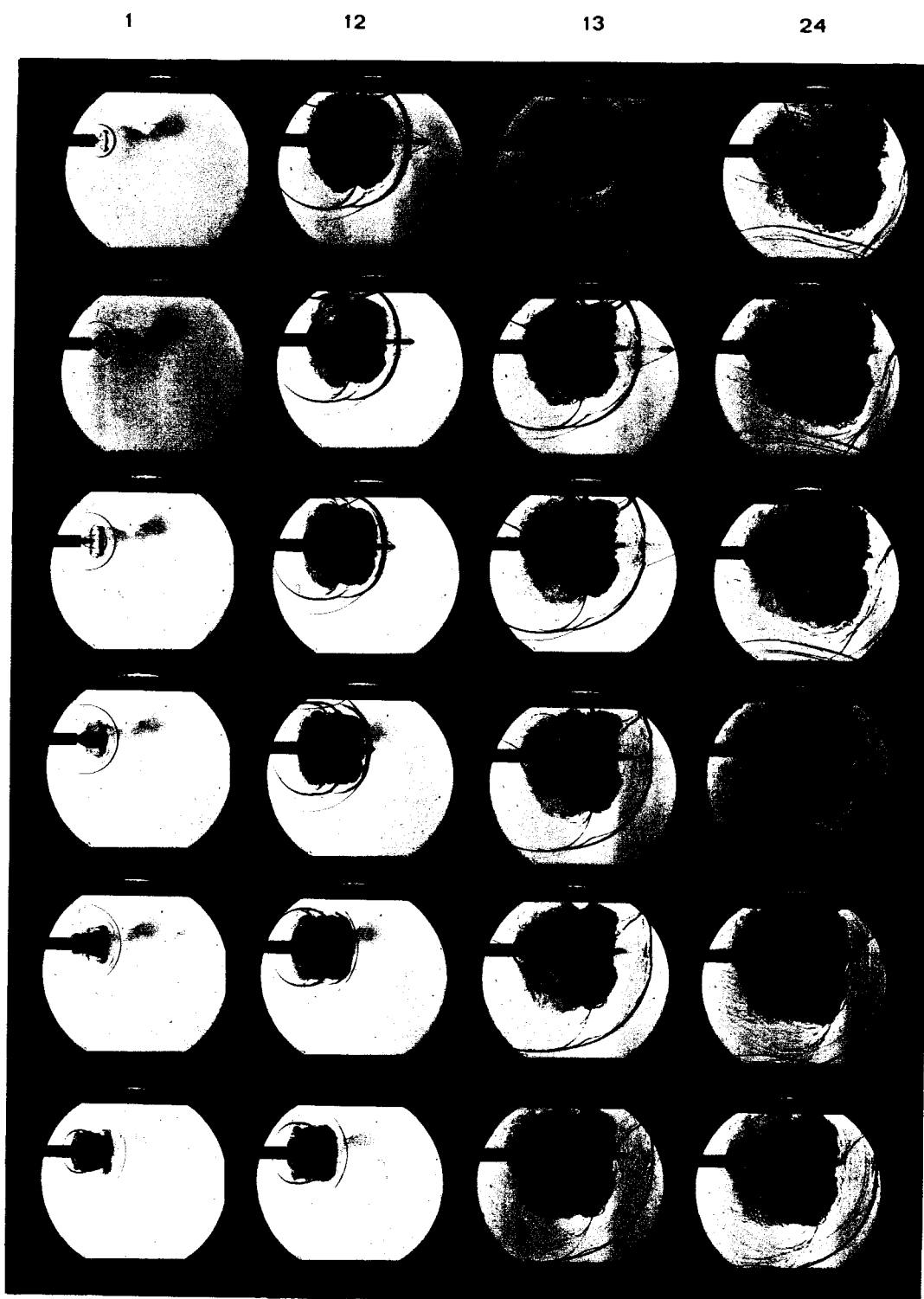


**côté éclateurs**



**côté récepteur**

**Vue de l'installation d'essai  
miroirs en vis-à-vis**



6  
 $\Delta t = 20 \mu s$

7

18  
 $V_p \approx 940 \text{ m/s}$

19

**Plaque photographique**

**Tir d'une carabine de calibre 5.56**

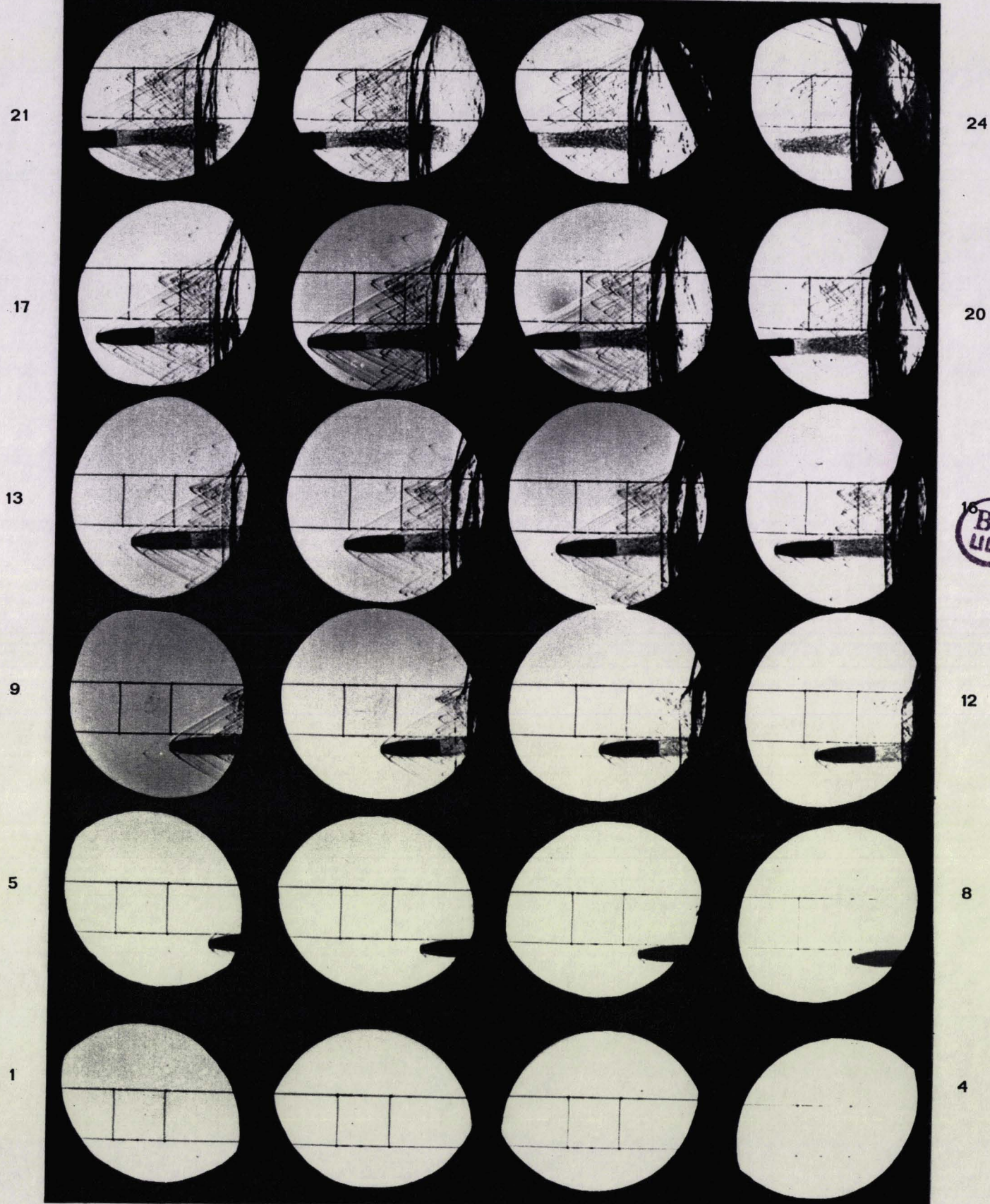
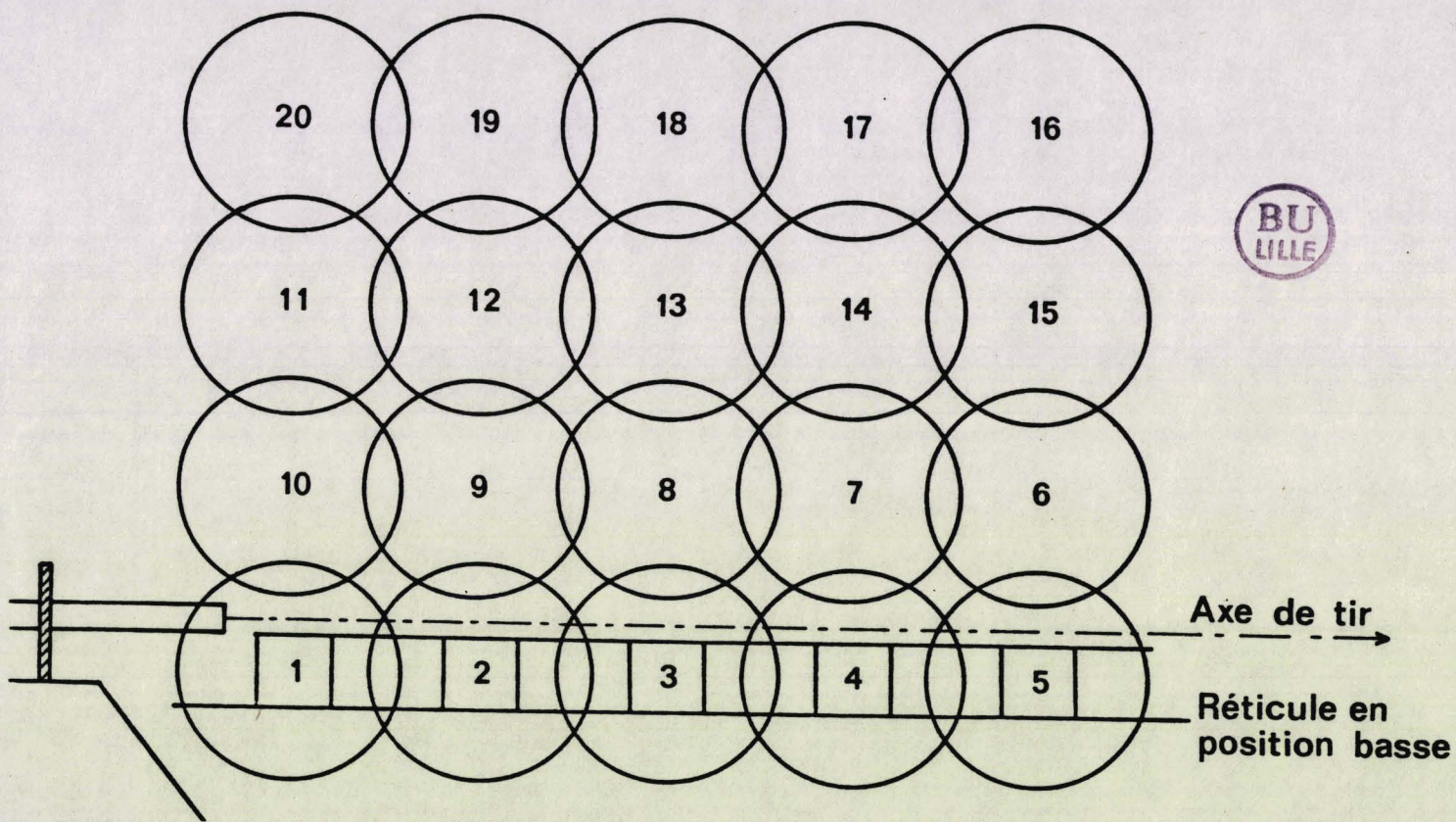


Image d'une fenêtre de visualisation  
Tir d'un canon de 30 mm

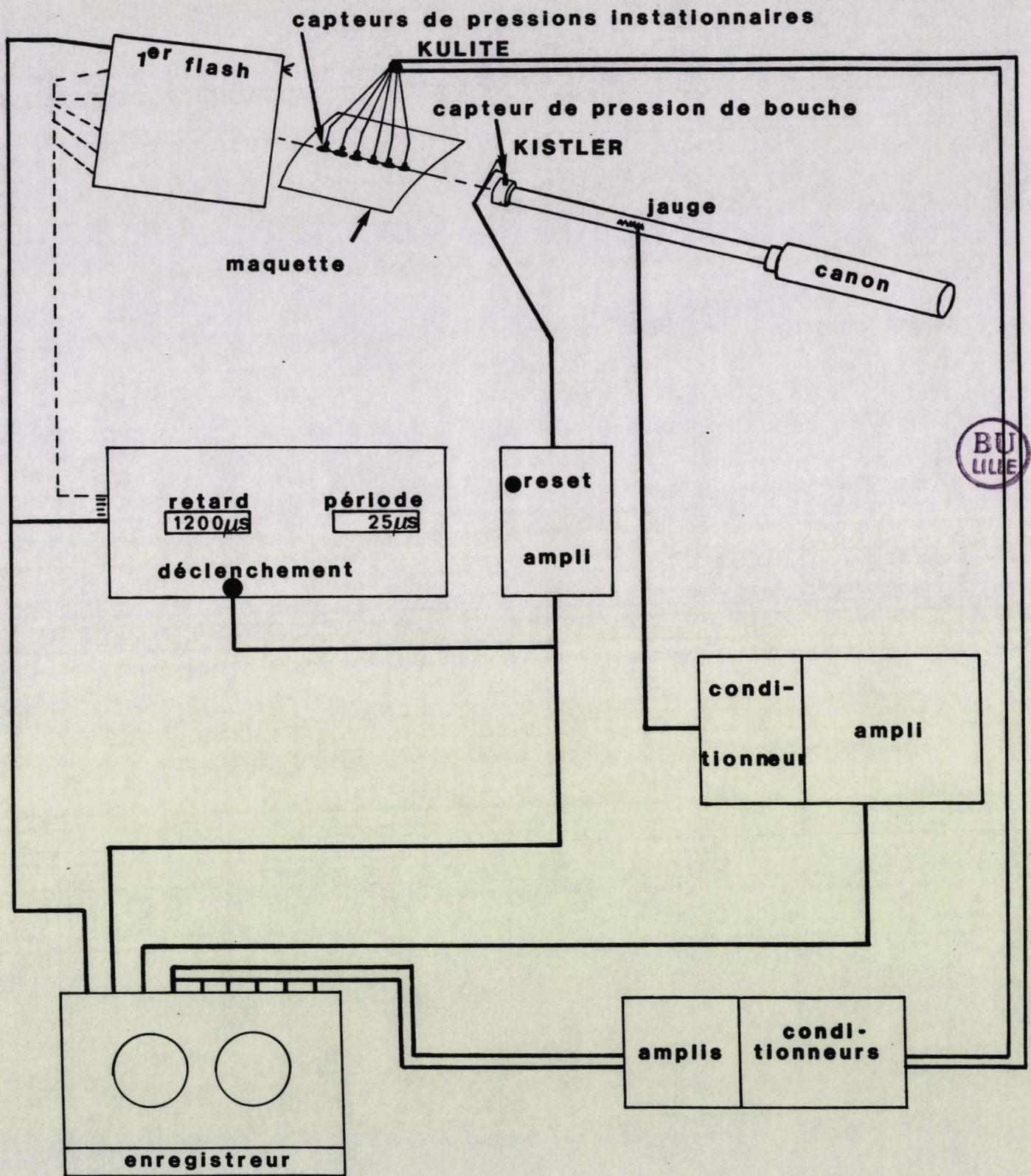
$$\Delta t = 25 \mu s$$

Echelle 1/10



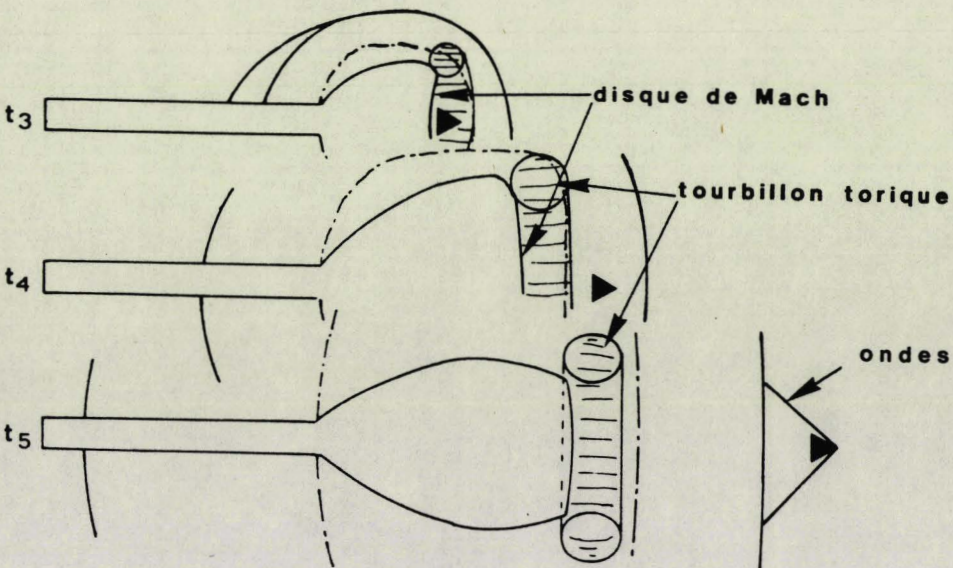
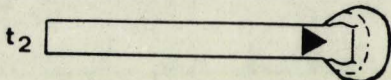
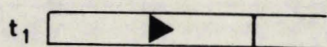
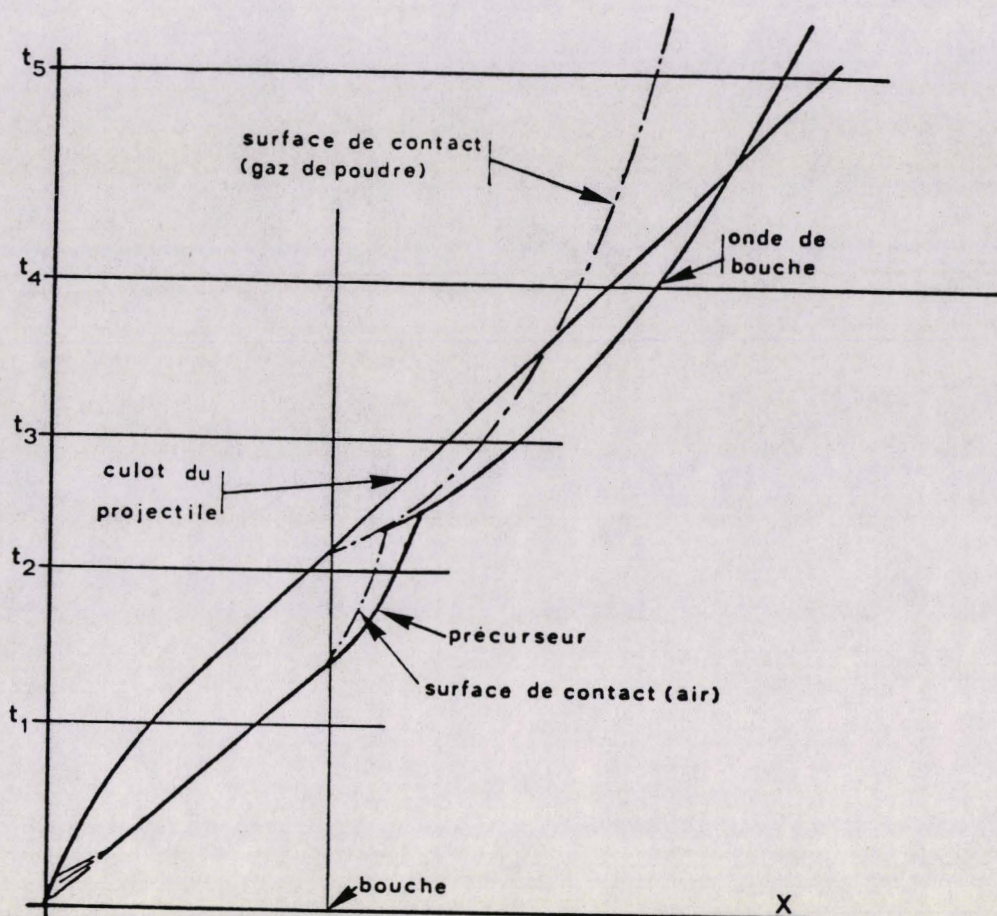
Champ optique autour d'un canon de 30 mm



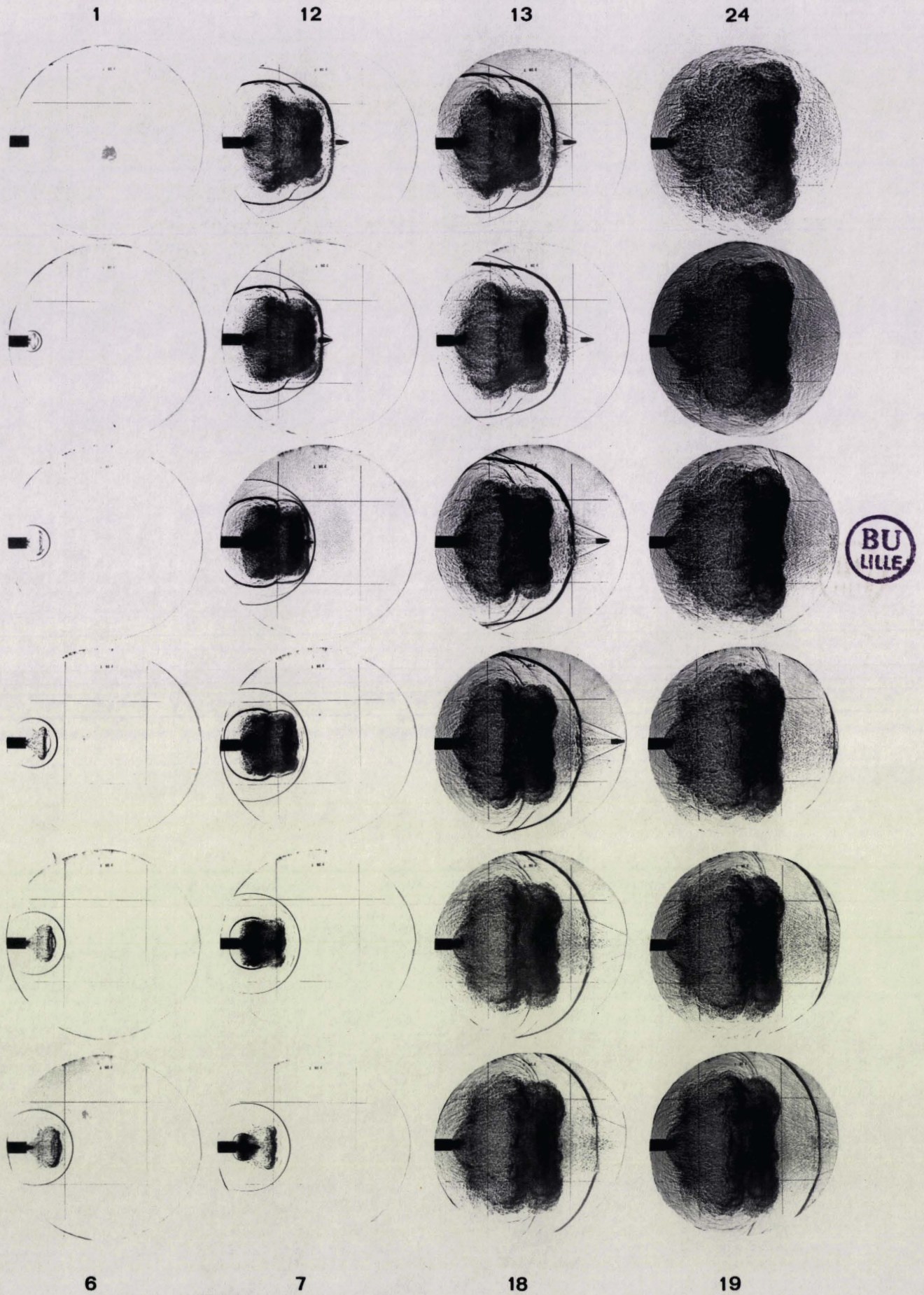


Chaîne de mesure

Fig. 9



Développement schématique du système d'ondes

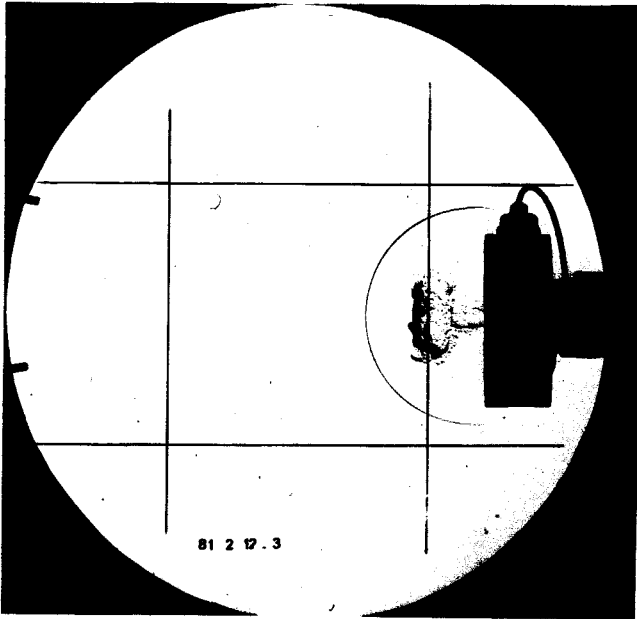


Tir en atmosphère infinie  
 $\Delta t = 20 \mu s$

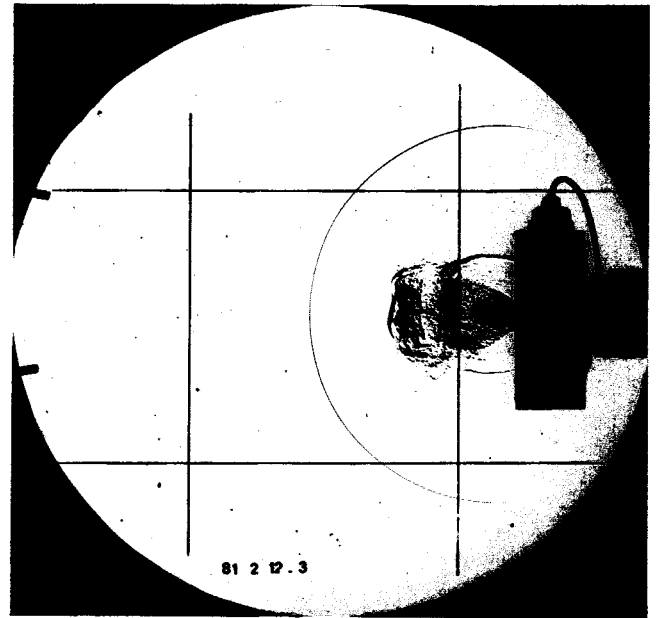
$t = 0$  au débouchage du canon

$\bar{P} = 1 \text{ bar}$

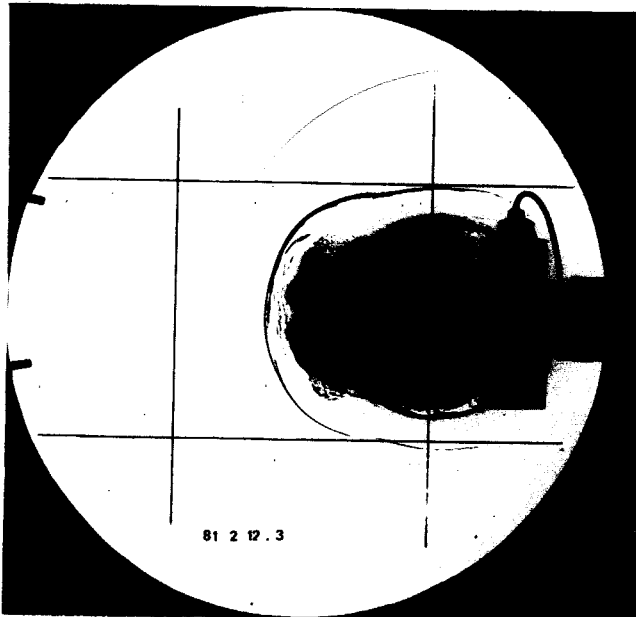
$\bar{T} = 288^\circ\text{K}$



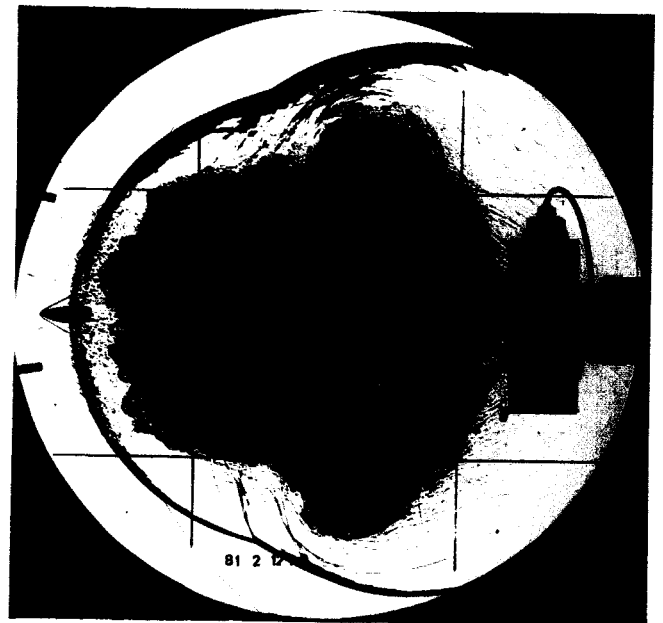
1<sup>er</sup> précurseur  $t = -140 \mu\text{s}$



2<sup>ème</sup> précurseur  $t = 0 \mu\text{s}$

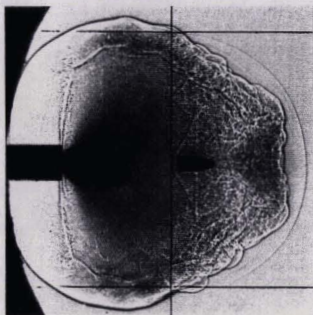


Formation de l'onde de bouche  
 $t = 60 \mu\text{s}$

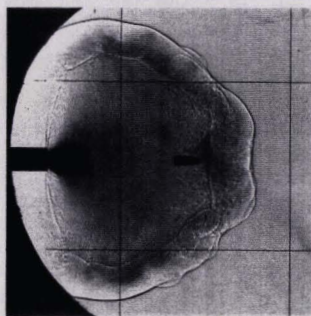


Onde de bouche et projectile  
 $t = 160 \mu\text{s}$

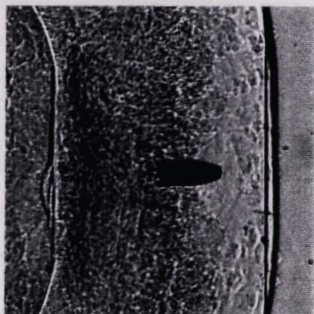
Déroulement du phénomène  
Bloc aux pressions  $D = 5.56 \text{ mm}$



Onde au culot  
du projectile

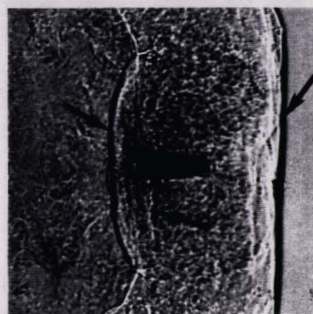


Interaction  
projectile-disque de Mach



Projectile subsonique  
dans les gaz

disque de  
Mach



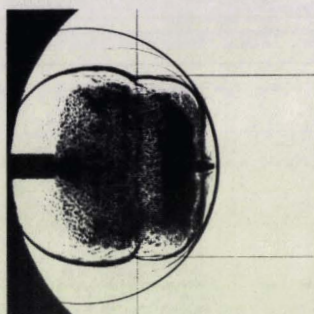
onde de  
bouche

onde liée  
au projectile

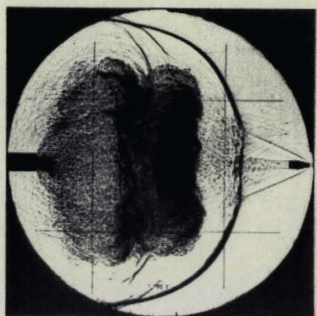
Projectile transonique  
dans les gaz



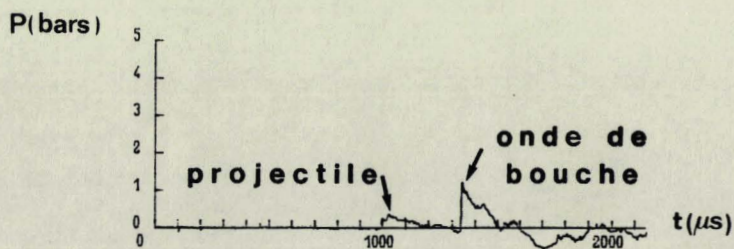
Traversée de l'onde  
de bouche



Traversée de l'onde  
de bouche en formation

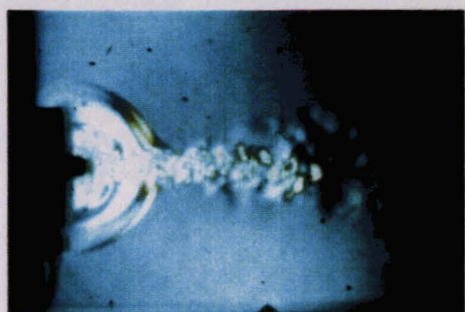


Projectile devant  
l'onde de bouche

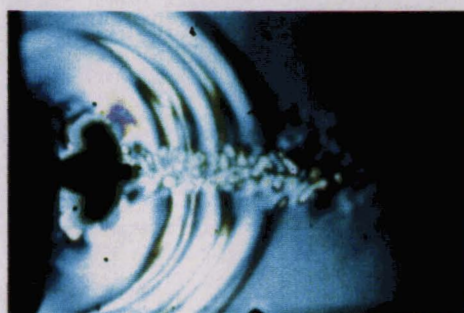


Signal de pression

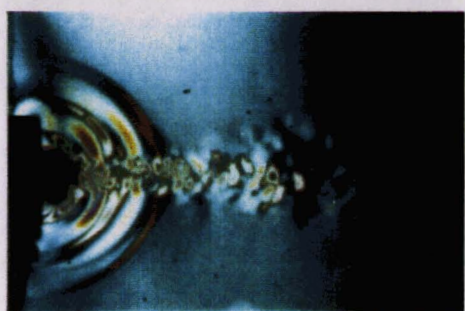
Interactions du projectile avec l'écoulement



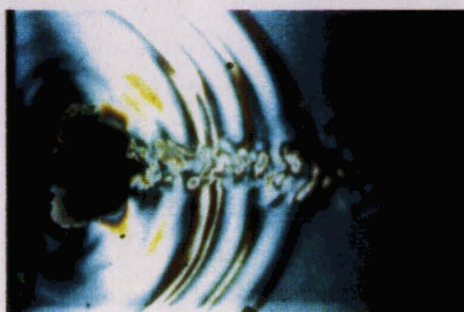
1



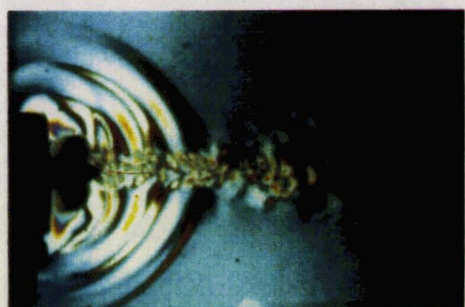
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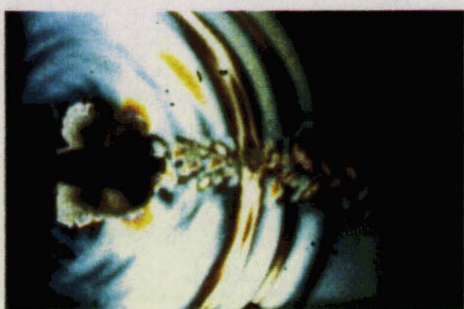
2



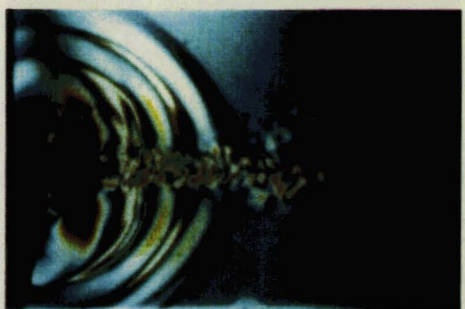
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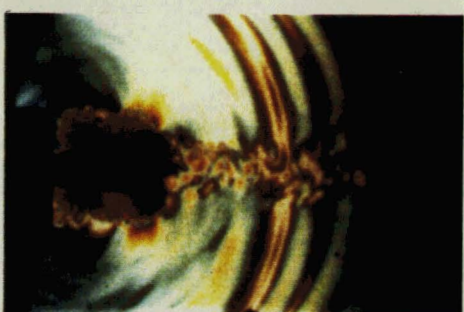
3



7



4



8

Tir d'un pistolet à gaz carbonique dans l'air

$\Delta t = 28.6 \mu s$

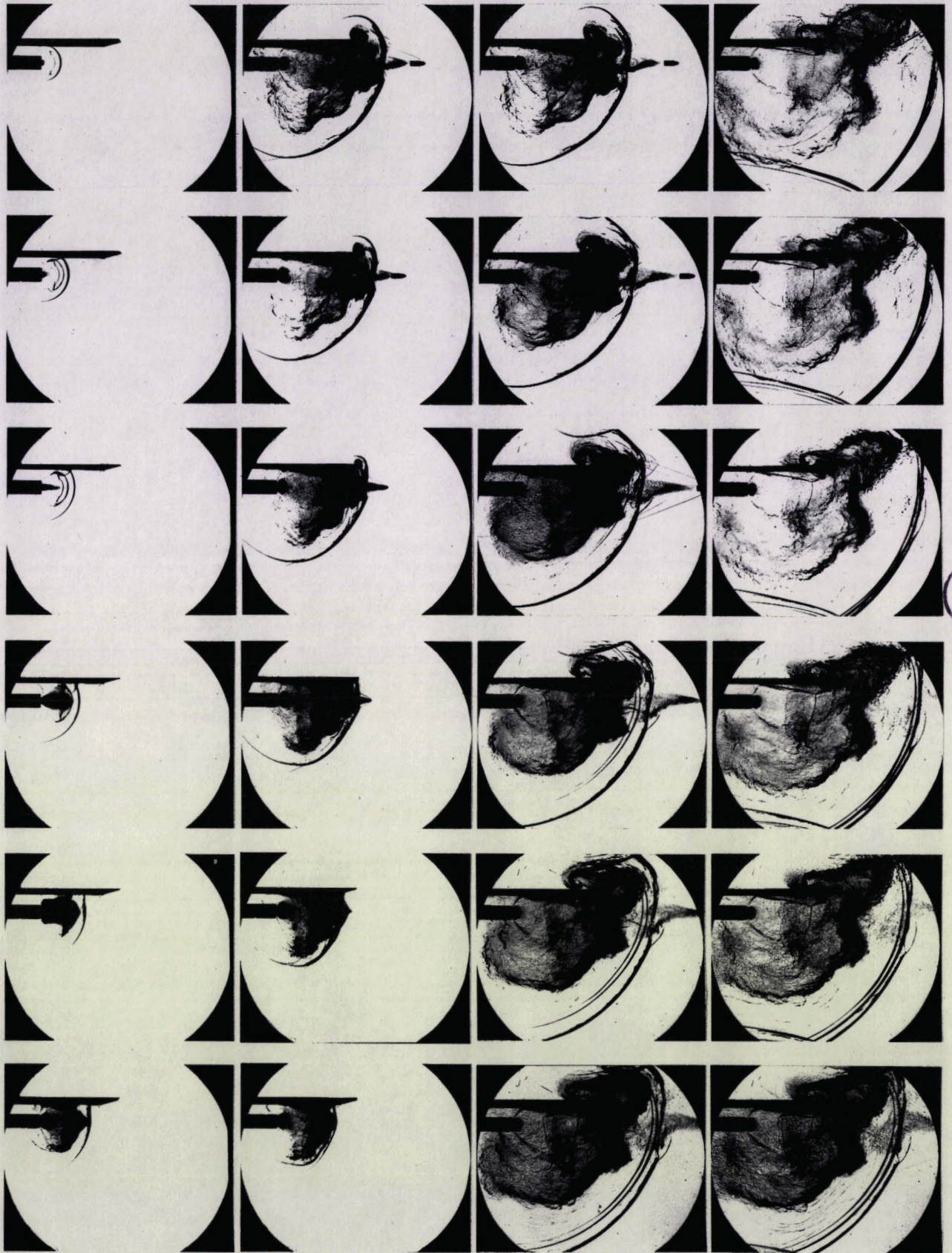
Interférogrammes ultra-rapides

1

12

13

24



BU  
LILLE

6

$\bar{V} = 198 \text{ m/s}$

7

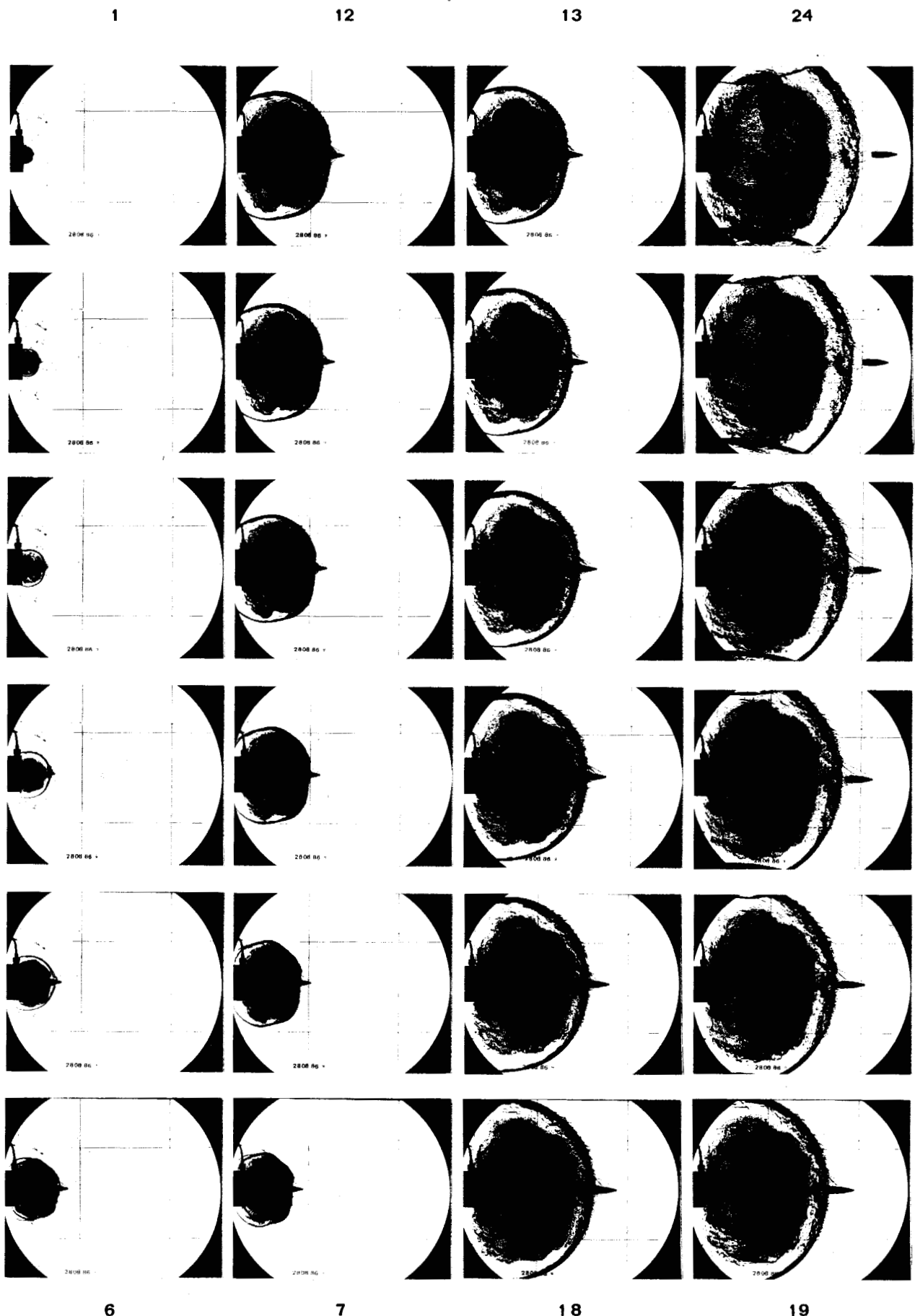
$V_p \approx 940 \text{ m/s}$

18

$\Delta t = 20 \mu\text{s}$

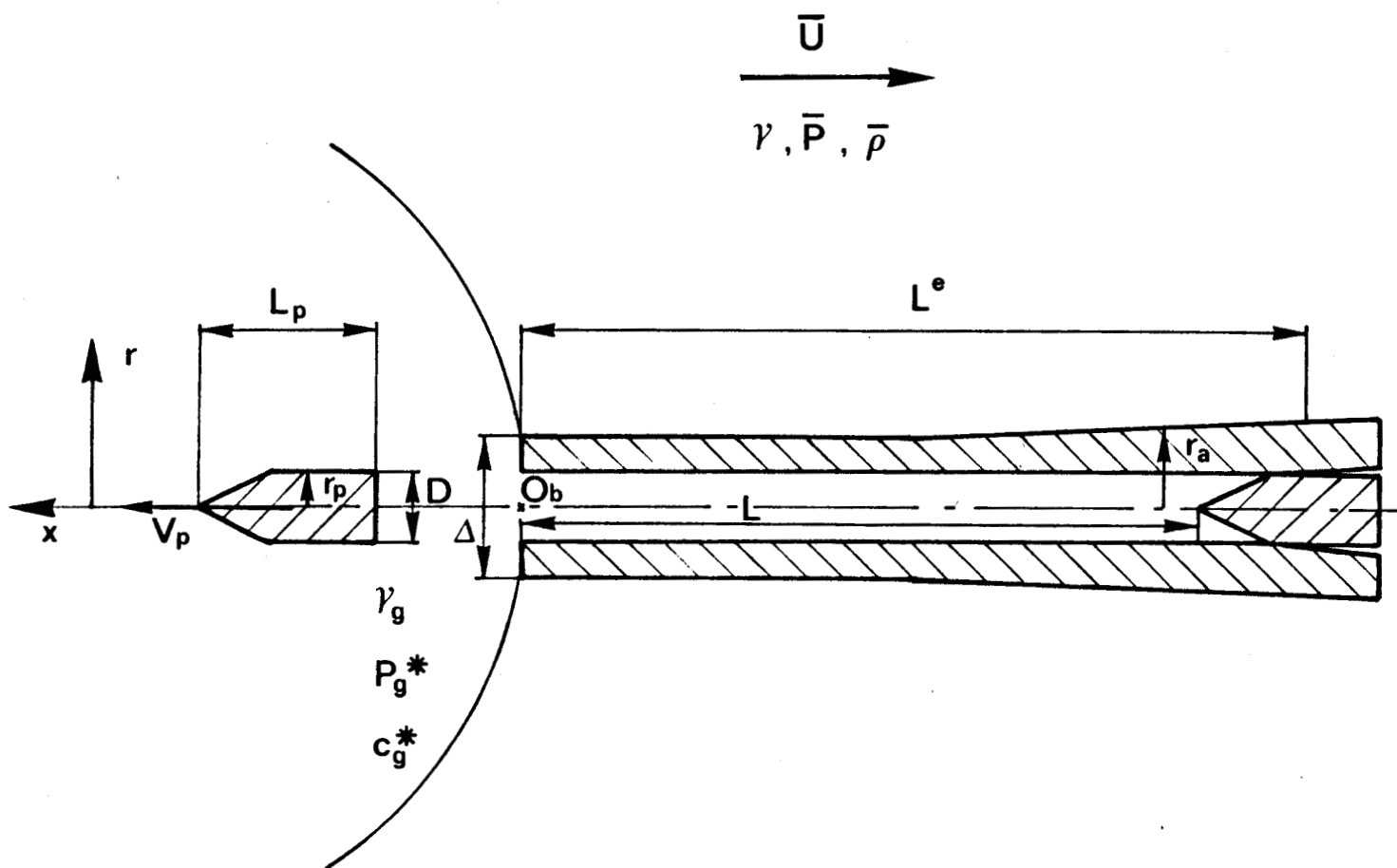
19

Tir en présence d'un obstacle

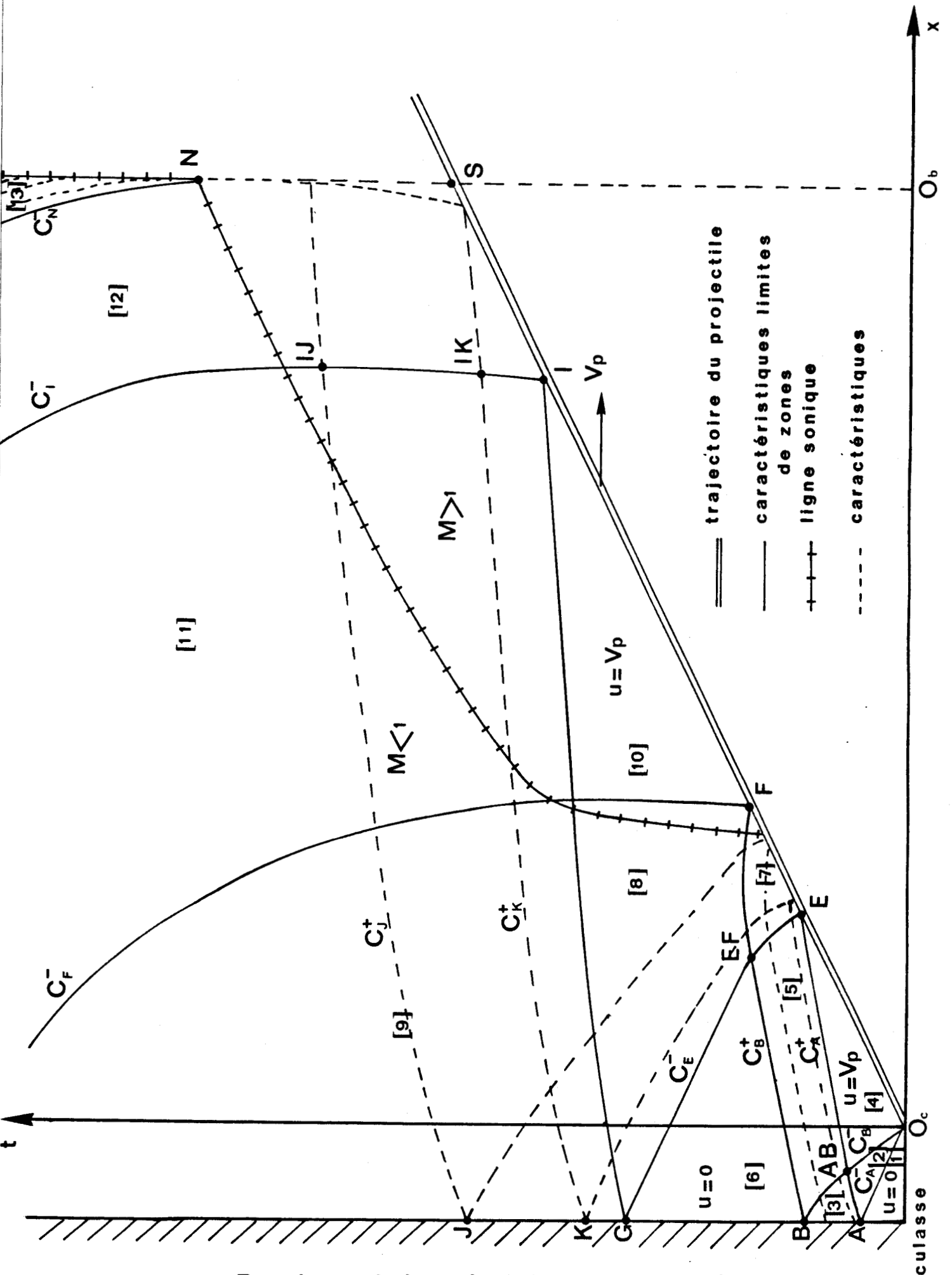


Tir idéal : fusil de 7.62 mm.  
 $\Delta t = 20 \mu s$



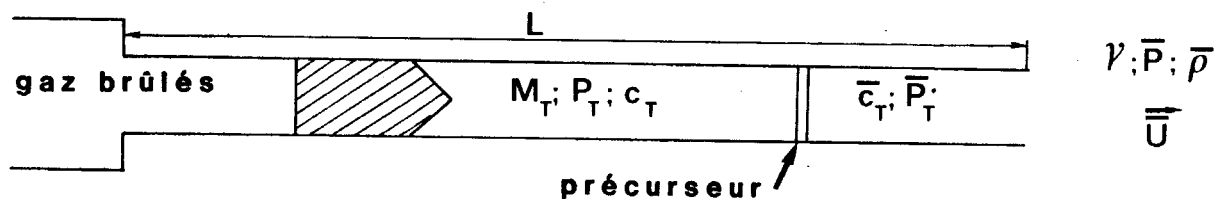


Paramètres physiques pour le tir idéal

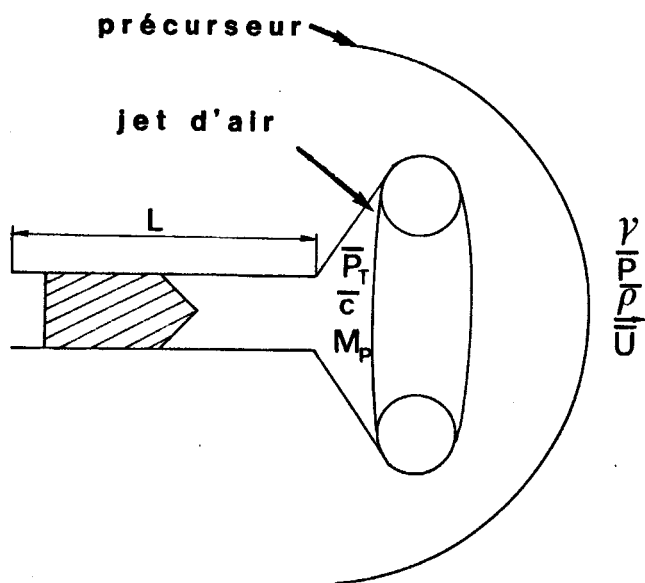
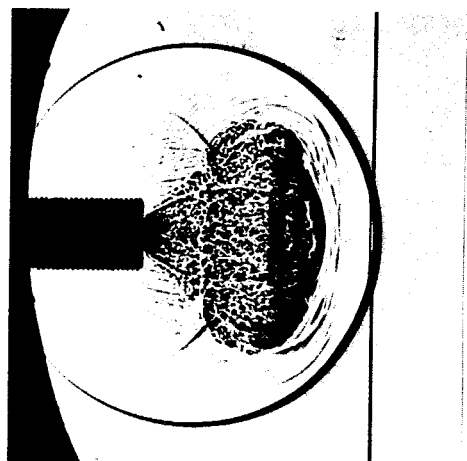


Ecoulement dans le tube pour une mise en vitesse instantannée du projectile

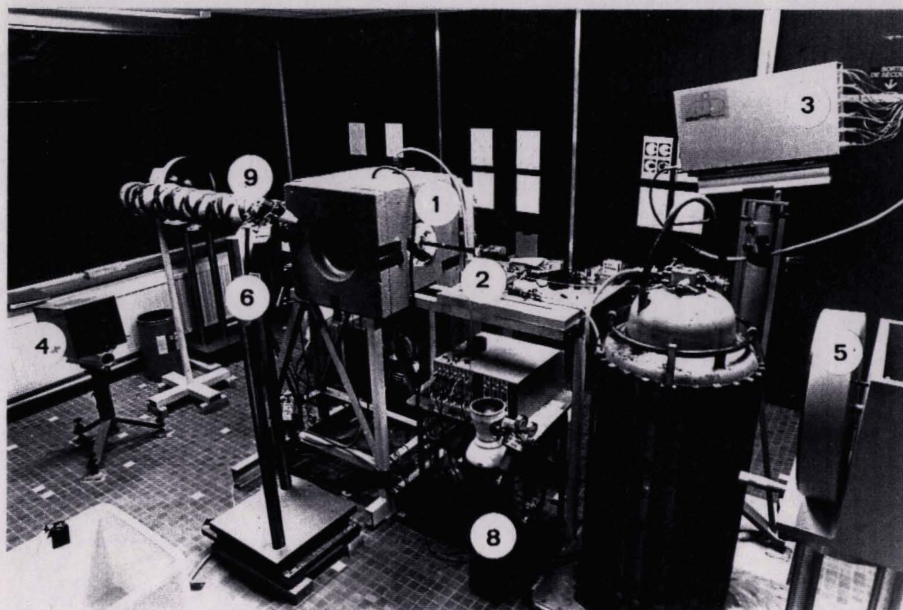




**Définition des paramètres physiques pour la phase de formation**

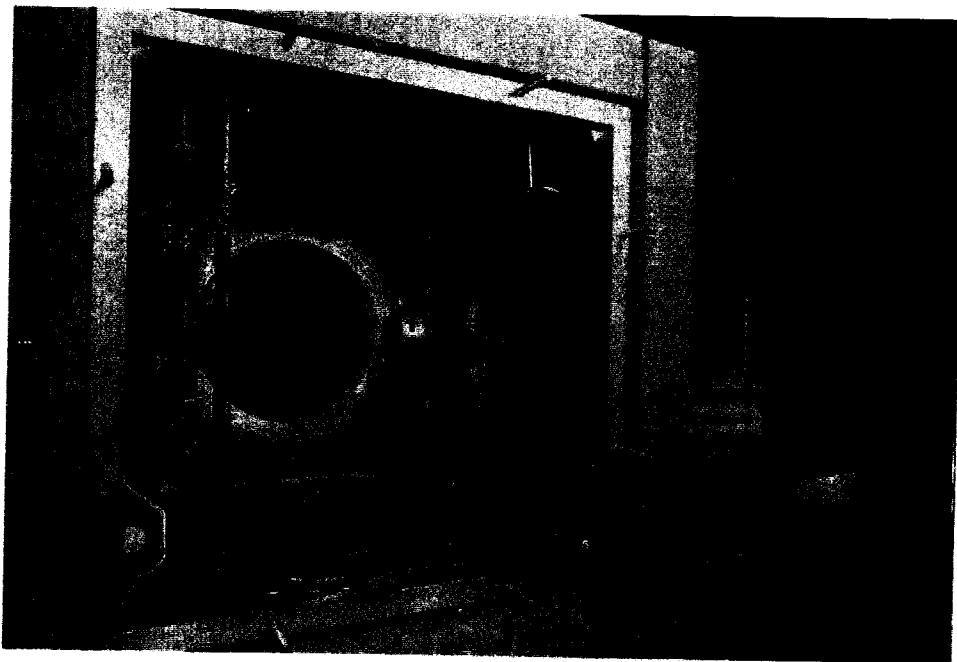


**Paramètres caractéristiques de la phase de formation**



- 1 Caisson
- 2 Carabine 222 Remington
- 3 Eclateurs chronoloupe
- 4 Récepteur chronoloupe
- 5 Miroirs sphériques
- 6 Miroirs plans
- 7 Réservoir d'azote liquide
- 8 Bouteille d'oxygène
- 9 Séchage des hublots

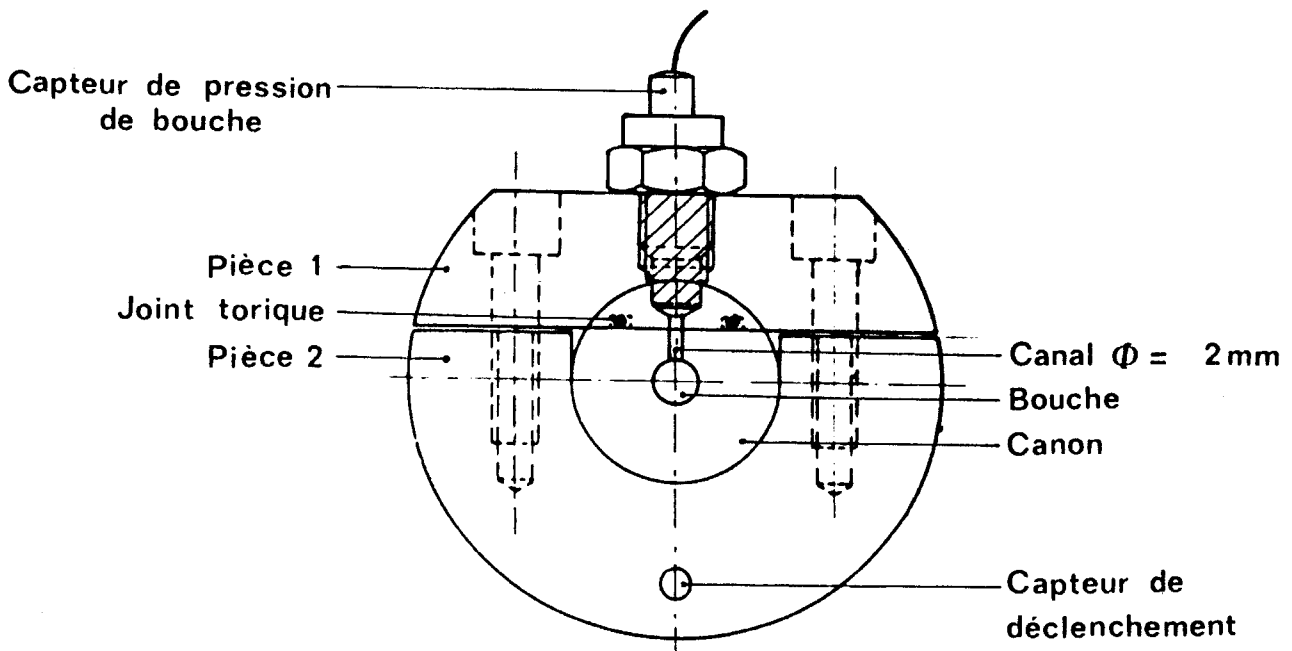
**Installation d'essais**



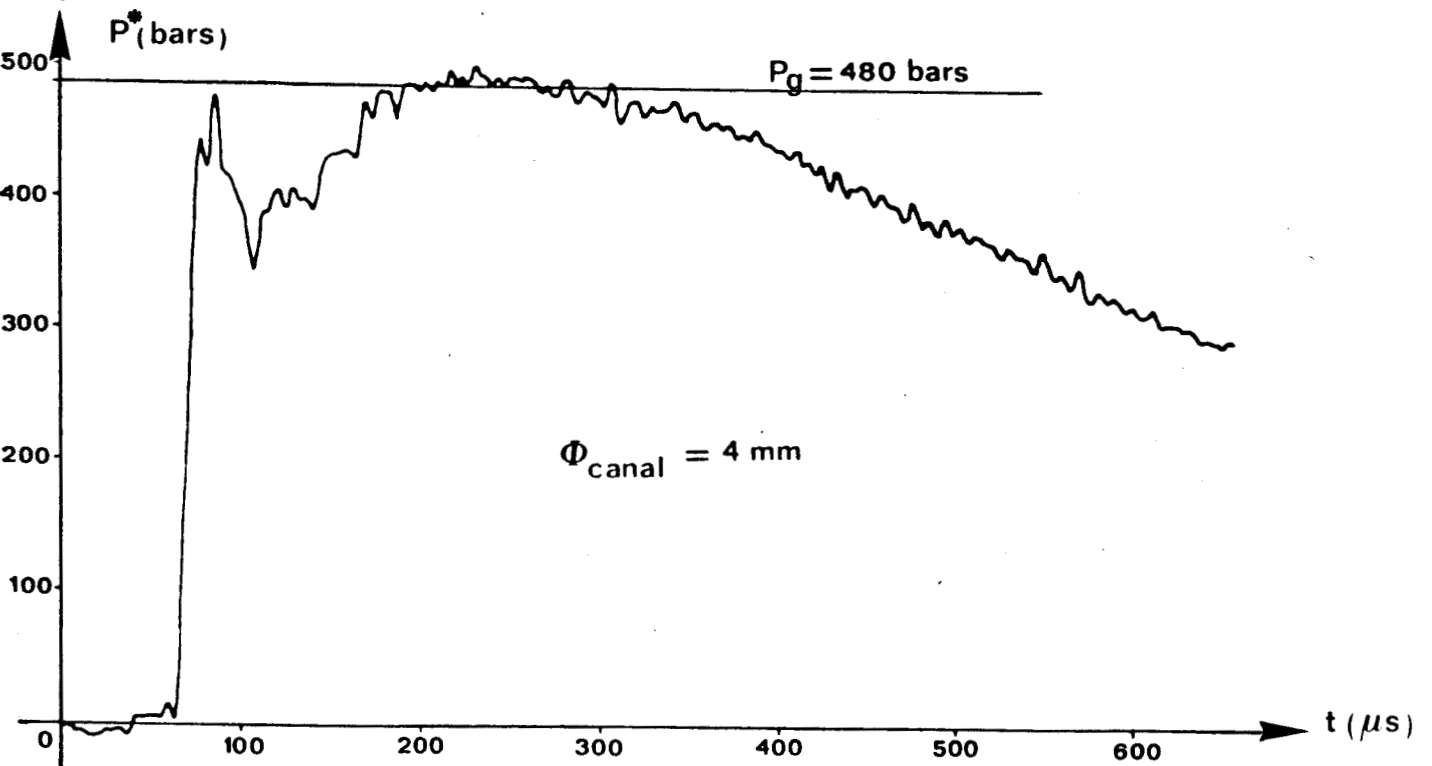
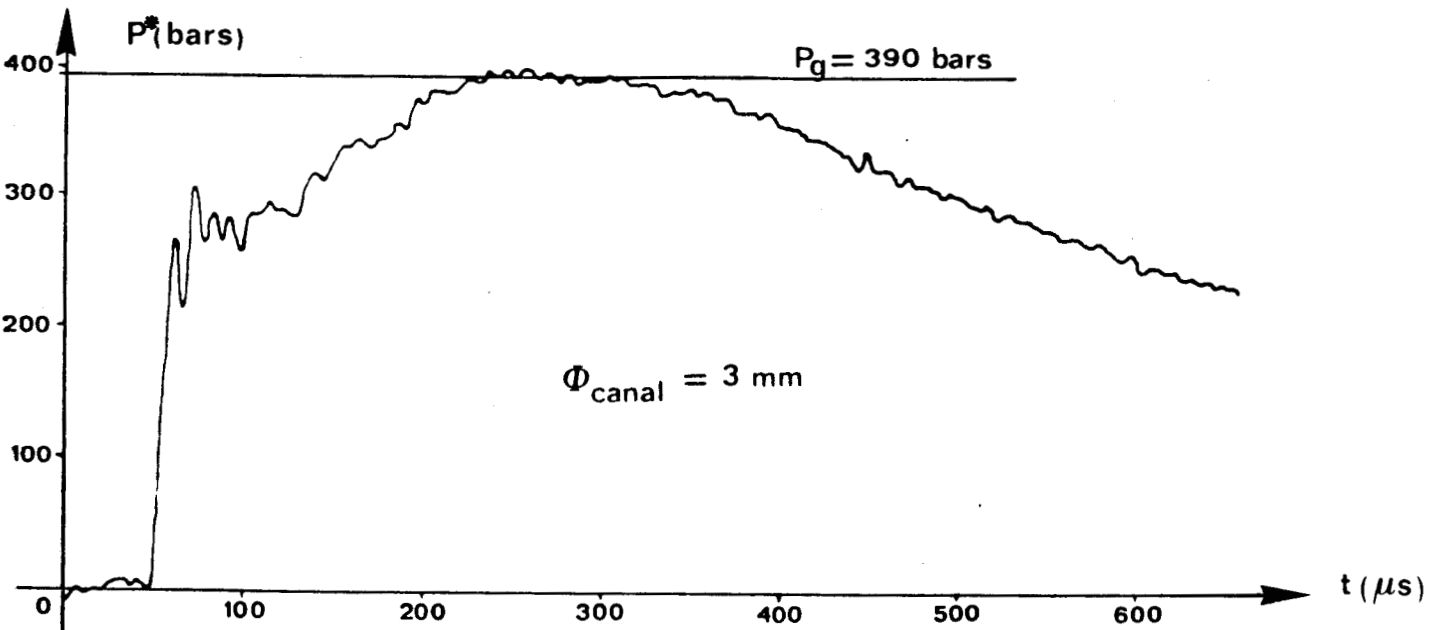
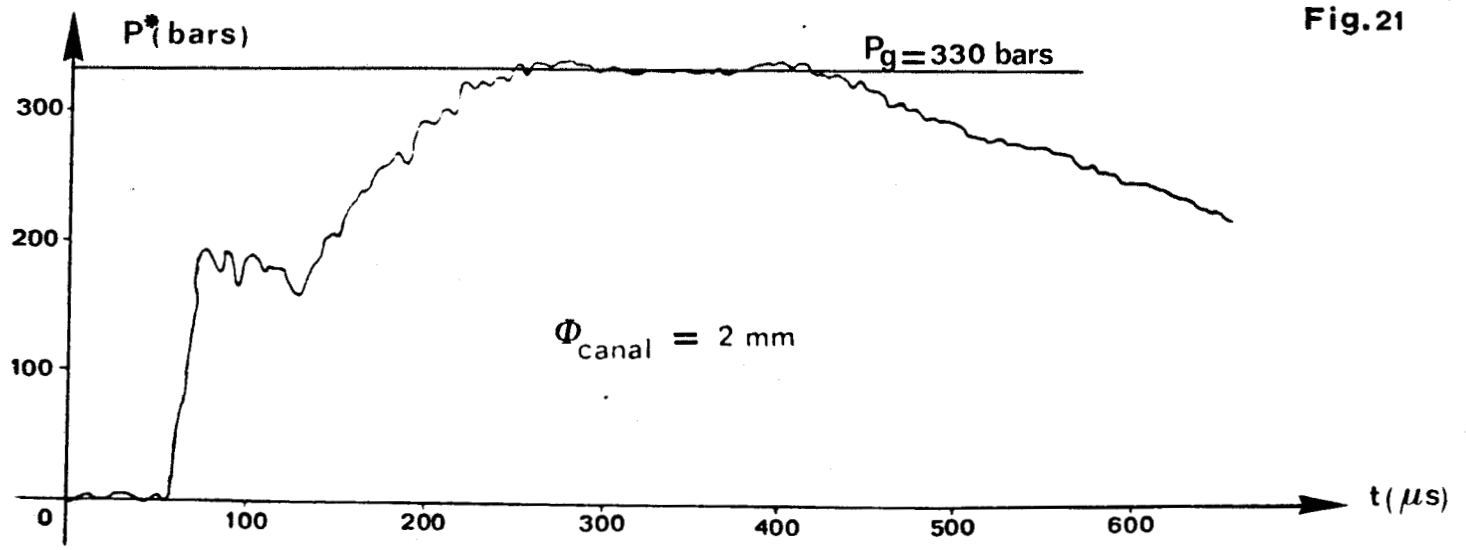
1 Capteur de bouche

2 Arrivée d'azote

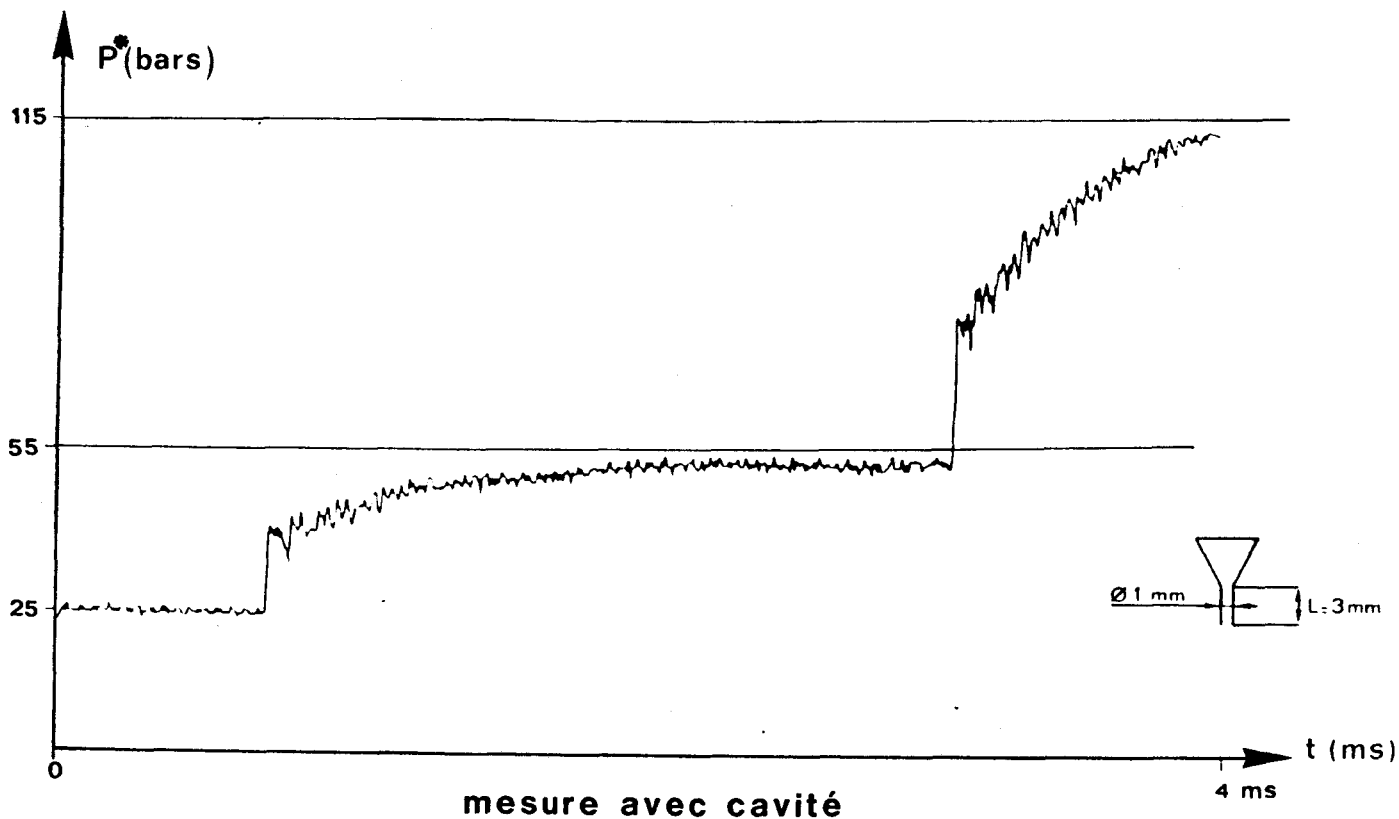
3 Arrivée d'oxygène



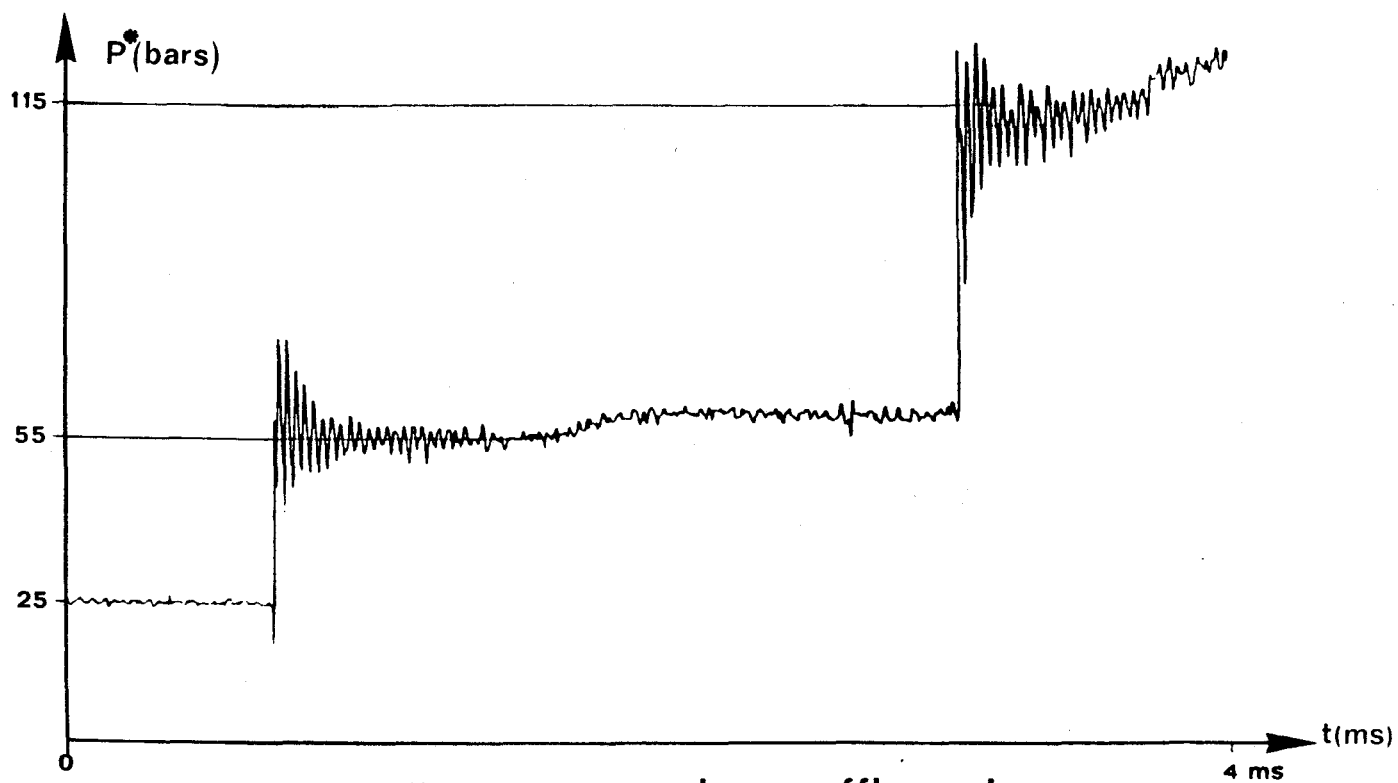
Capteur de pression de bouche



Influence du diamètre de la cavité sur la mesure de pression pour la carabine ( capteur à membrane )



mesure avec cavité

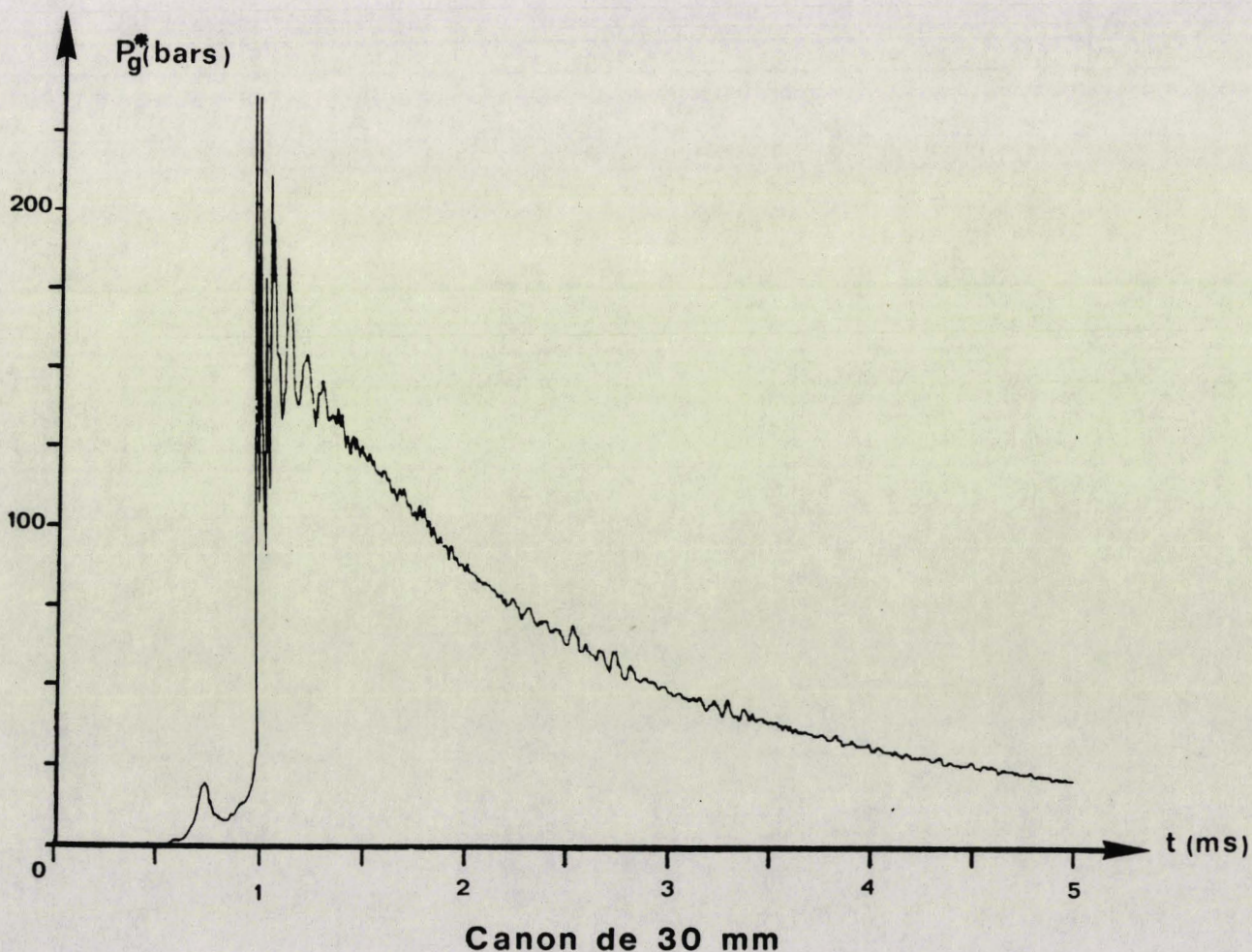
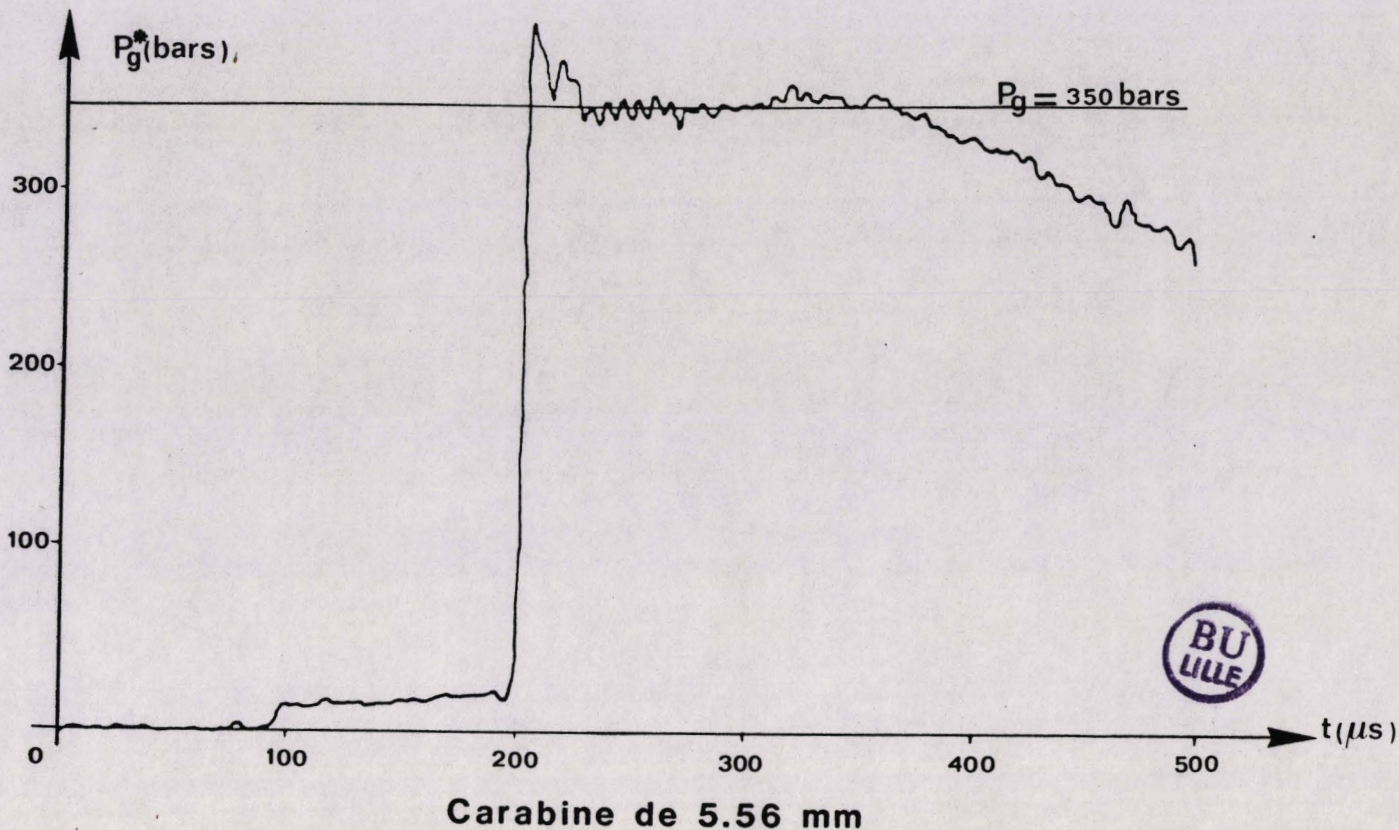


mesure en membrane affleurante

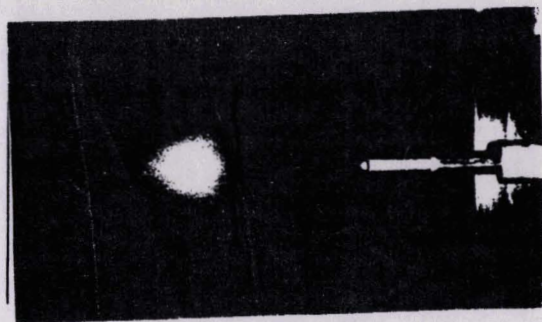
capteur piézo-électrique

Vérification de l'influence de la cavité  
( essais au tube à choc du CERT )



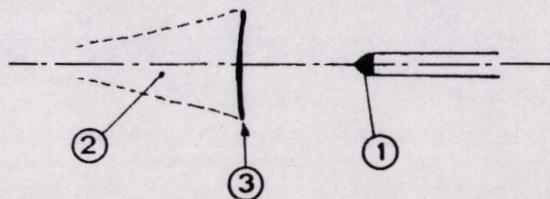


Mesures de pression de bouche avec le capteur piézo-électrique monté en membrane affleurante

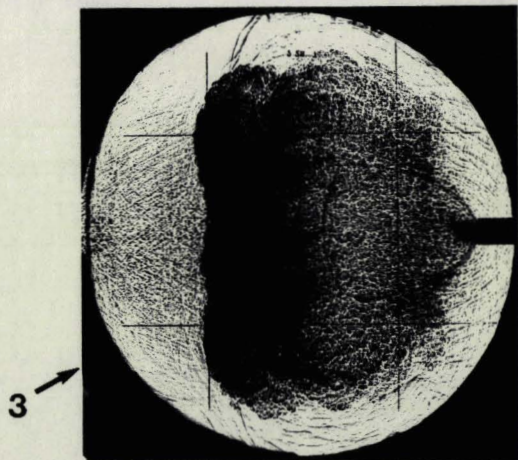


- ① lueur primaire
- ② lueur secondaire
- ③ position du disque de Mach

carabine seule

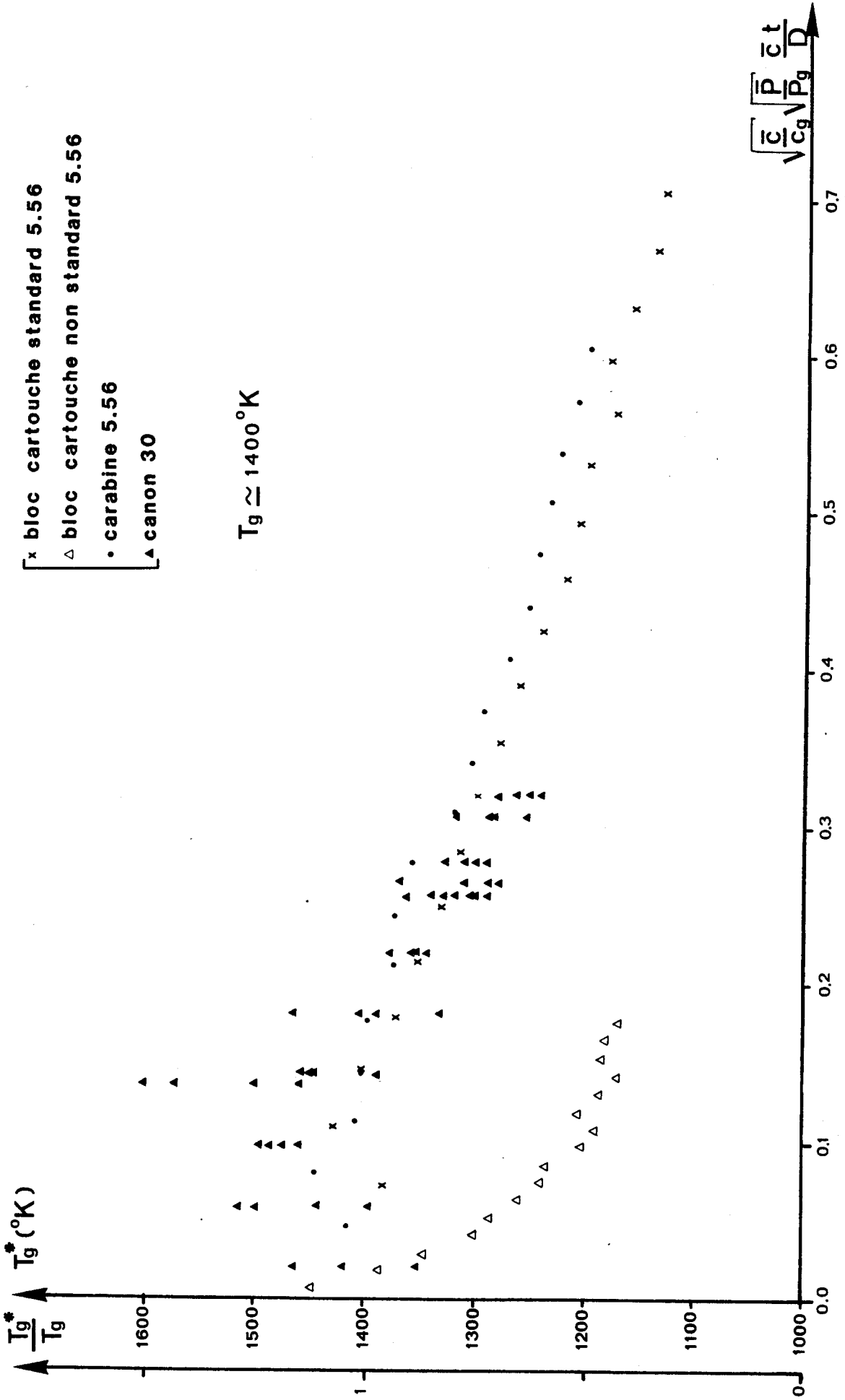


Lueurs de bouche  $X_D/D = 13.49$

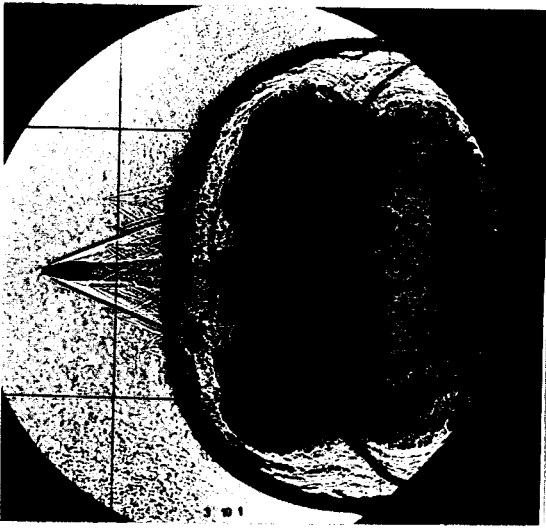


Ombroscopie  $X_D/D = 13.49$

Mesure de  $P_g$  par visualisation



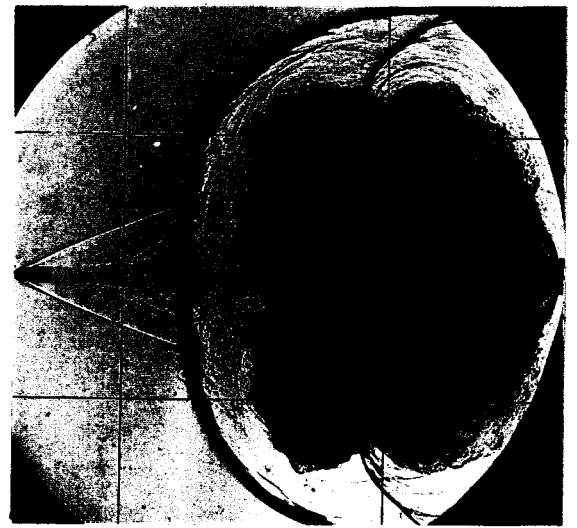
Evolution de la température de bouche en fonction du temps adimensionné



$\bar{P} = 1 \text{ bar}$

$M_p = 3.38$

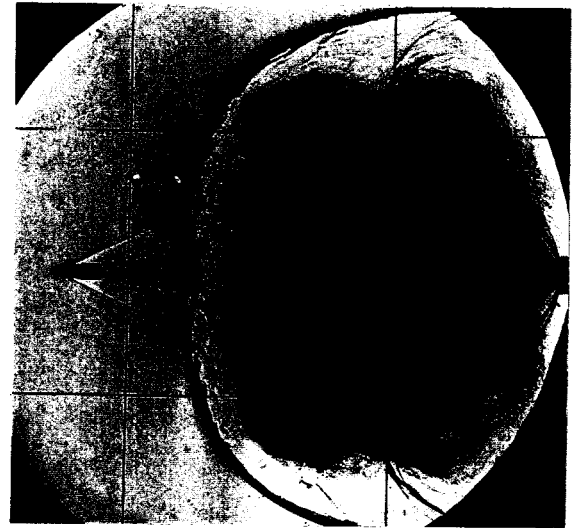
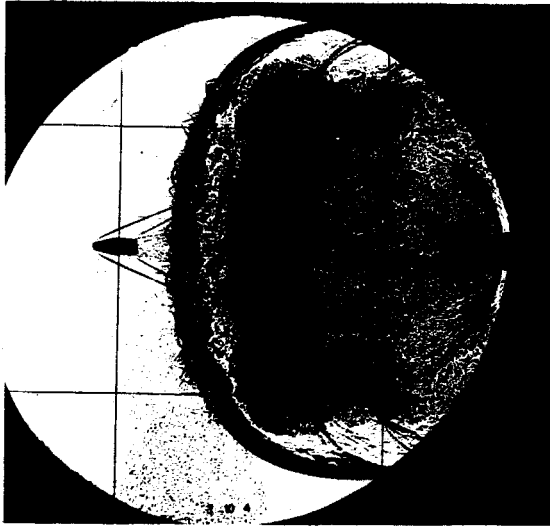
$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 3.39 ; \frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 1.2 \cdot 10^{-3}$$



$\bar{P} = 0.6 \text{ bar}$

$M_p = 3.38$

$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 3.62 ; \frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 1.3 \cdot 10^{-3}$$

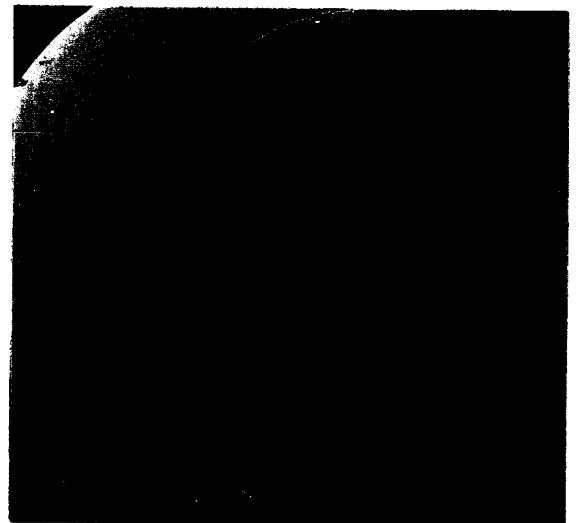
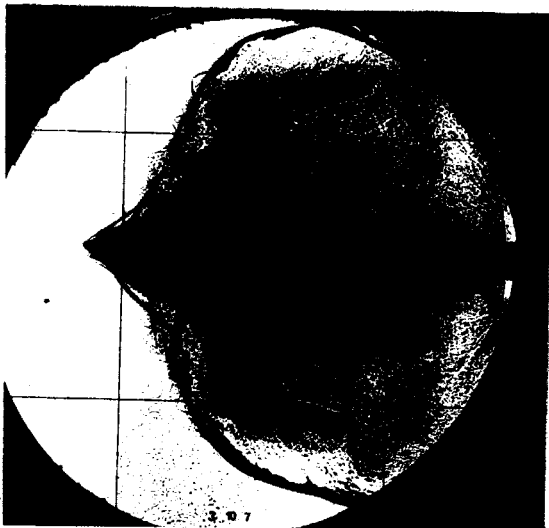


$\bar{P} = 0.2 \text{ bar}$

$M_p = 3.38$

$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 2.63 ; \frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 0.7 \cdot 10^{-3}$$

$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 2.8 ; \frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 0.8 \cdot 10^{-3}$$



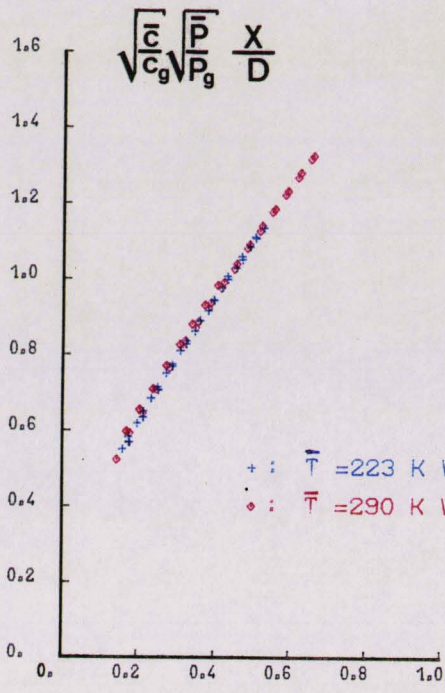
$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 1.52 ; \frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 0.2 \cdot 10^{-3}$$

$\bar{T} = 223 \text{ K} \quad V_p = 1015 \text{ m/s}$

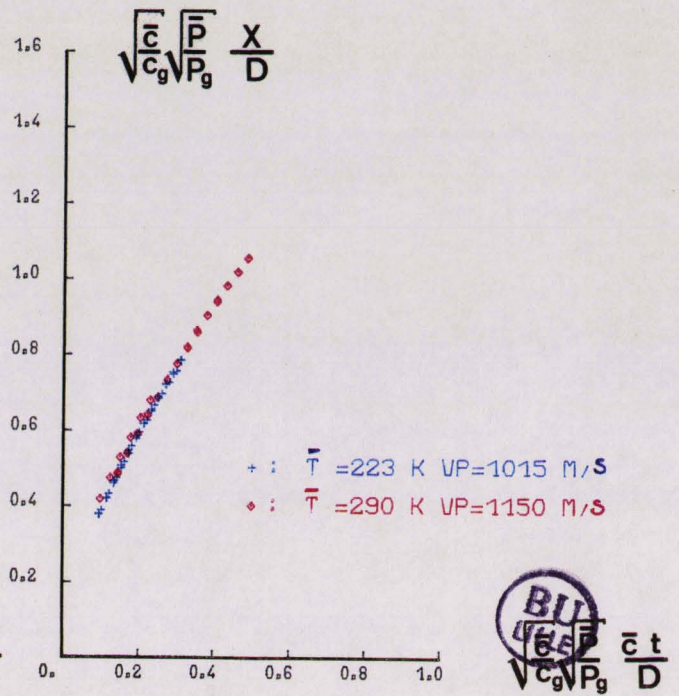
$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 1.62 ; \frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 0.3 \cdot 10^{-3}$$

$\bar{T} = 290 \text{ K} \quad V_p = 1150 \text{ m/s}$

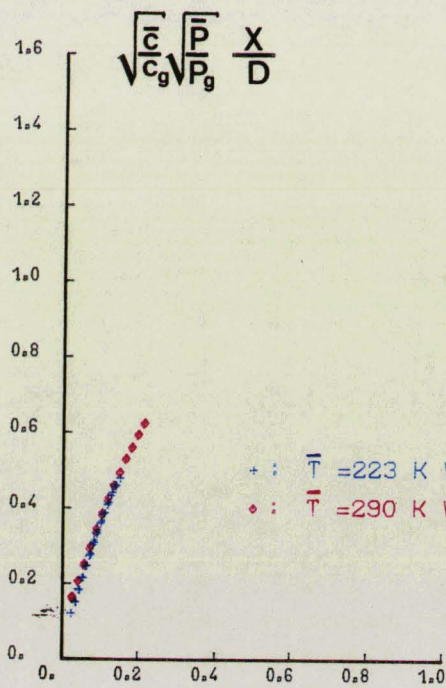
Invariance de la forme de l'onde pour une variation de  $\frac{\bar{T}}{T_g}$



$\bar{P} = 1 \text{ bar}$



$\bar{P} = 0.6 \text{ bar}$



$\bar{P} = 0.2 \text{ bar}$

$M_p \approx 3.38$

$\bar{\gamma} = 1.4$

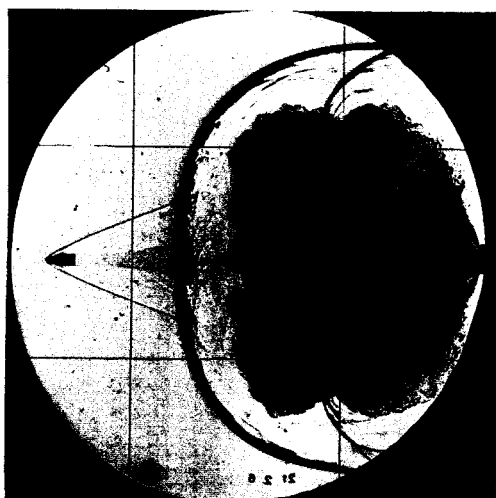
$\gamma_g = 1.25$

$M_g = 1$

$\bar{M} = 0$

$T_g \approx 1400^\circ\text{K}$

Effet de  $\frac{\bar{T}}{T_g}$

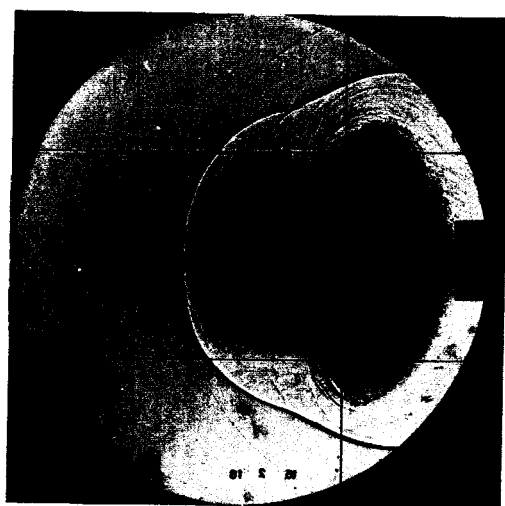


$M_p = 3.38$

$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 2.44$$

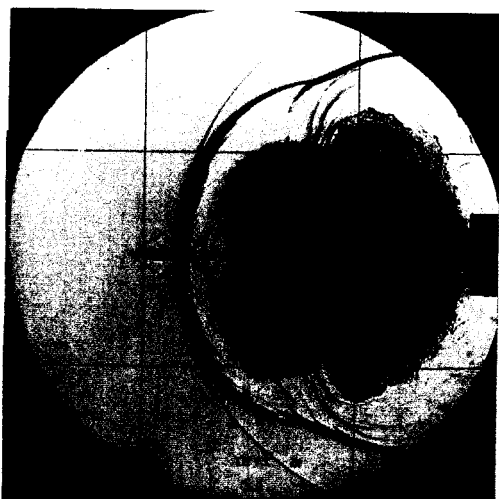
$$\frac{\bar{c}}{c_g} \frac{\bar{P}_I}{P_g} = 1.3 \cdot 10^{-3}$$

$$\bar{P} = \bar{P}_I$$

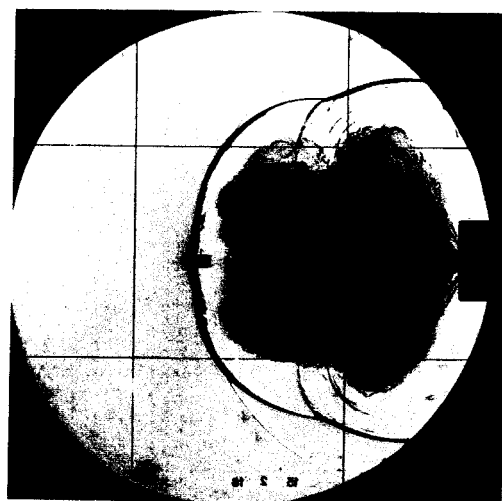


$M_p = 2.26$

Influence de  $M_p$  sur la forme d'onde

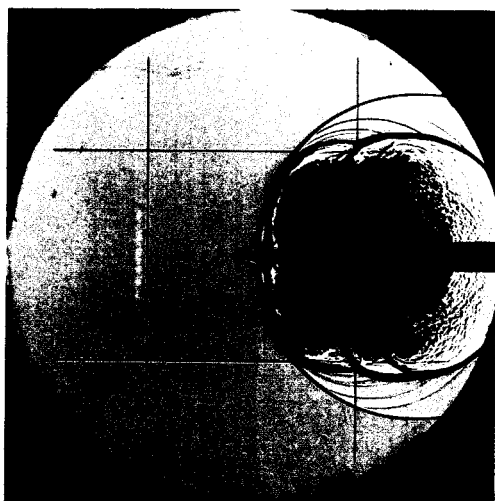


$M_p = 2.40$

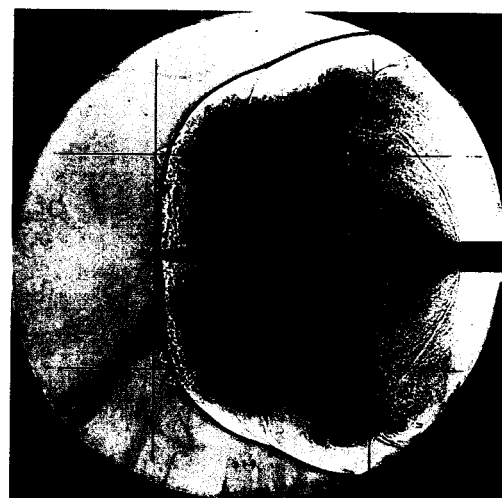


$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 2.7 ; \frac{\bar{c}}{c_g} \frac{\bar{P}_I}{P_g} = 1.6 \cdot 10^{-3}$$

$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 2.42 ; \frac{\bar{c}}{c_g} \frac{\bar{P}_I}{P_g} = 1.3 \cdot 10^{-3}$$



$M_p = 2.97$



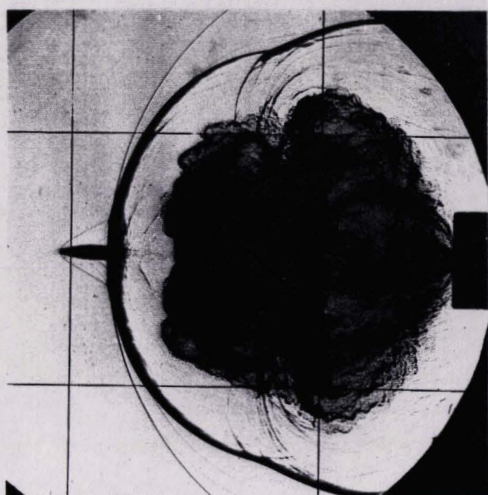
$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 5.64 ; \frac{\bar{c}}{c_g} \frac{\bar{P}_I}{P_g} = 1.3 \cdot 10^{-3}$$

$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 1.62 ; \frac{\bar{c}}{c_g} \frac{\bar{P}_I}{P_g} = 0.3 \cdot 10^{-3}$$

Influences combinées de  $\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D}$  et de  $\frac{\bar{c}}{c_g} \frac{\bar{P}_I}{P_g}$

$P_g = 274 \text{ bars}$

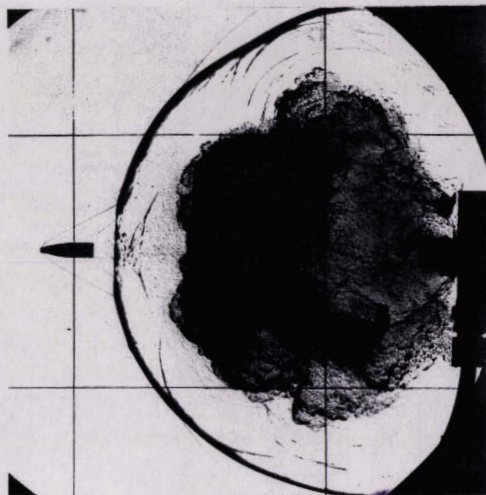
$\bar{P} = 1 \text{ bar}$



$\bar{P} = 1 \text{ bar}$

$\bar{P}_T = 0.6 \text{ bar}$

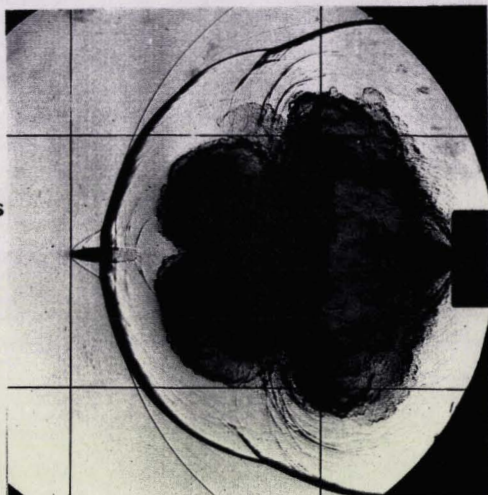
$P_g = 2.74 \text{ bars}$



BU  
LILLE

$P_g = 253 \text{ bars}$

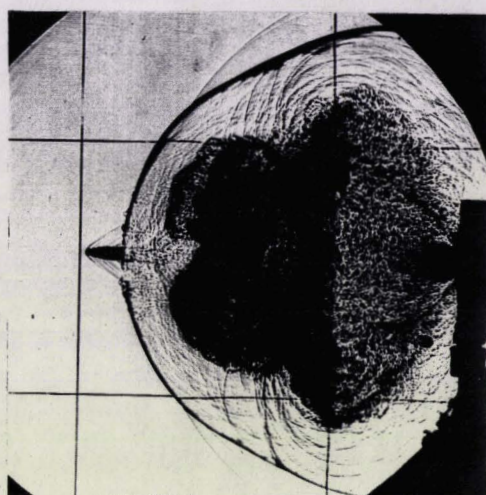
$\bar{P} = 0.93 \text{ bar}$



$\bar{P} = 0.92 \text{ bar}$

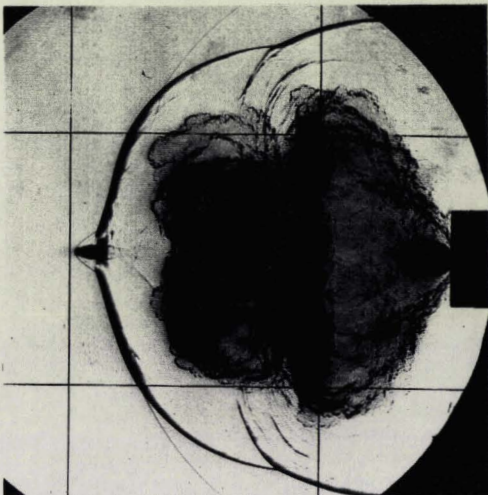
$\bar{P}_T = 0.55 \text{ bar}$

$P_g = 253 \text{ bars}$



$P_g = 228 \text{ bars}$

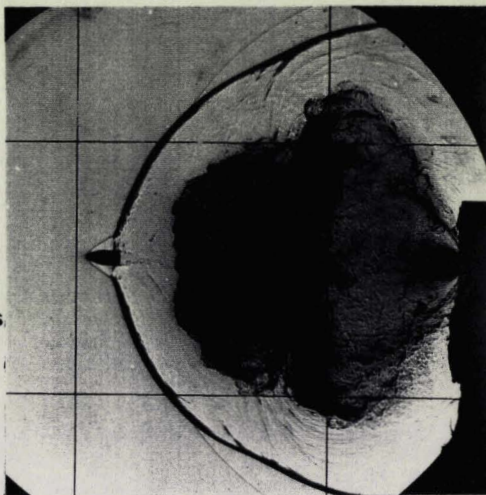
$\bar{P} = 0.82 \text{ bar}$



$\bar{P} = 0.83 \text{ bar}$

$\bar{P}_T = 0.5 \text{ bar}$

$P_g = 228 \text{ bars}$

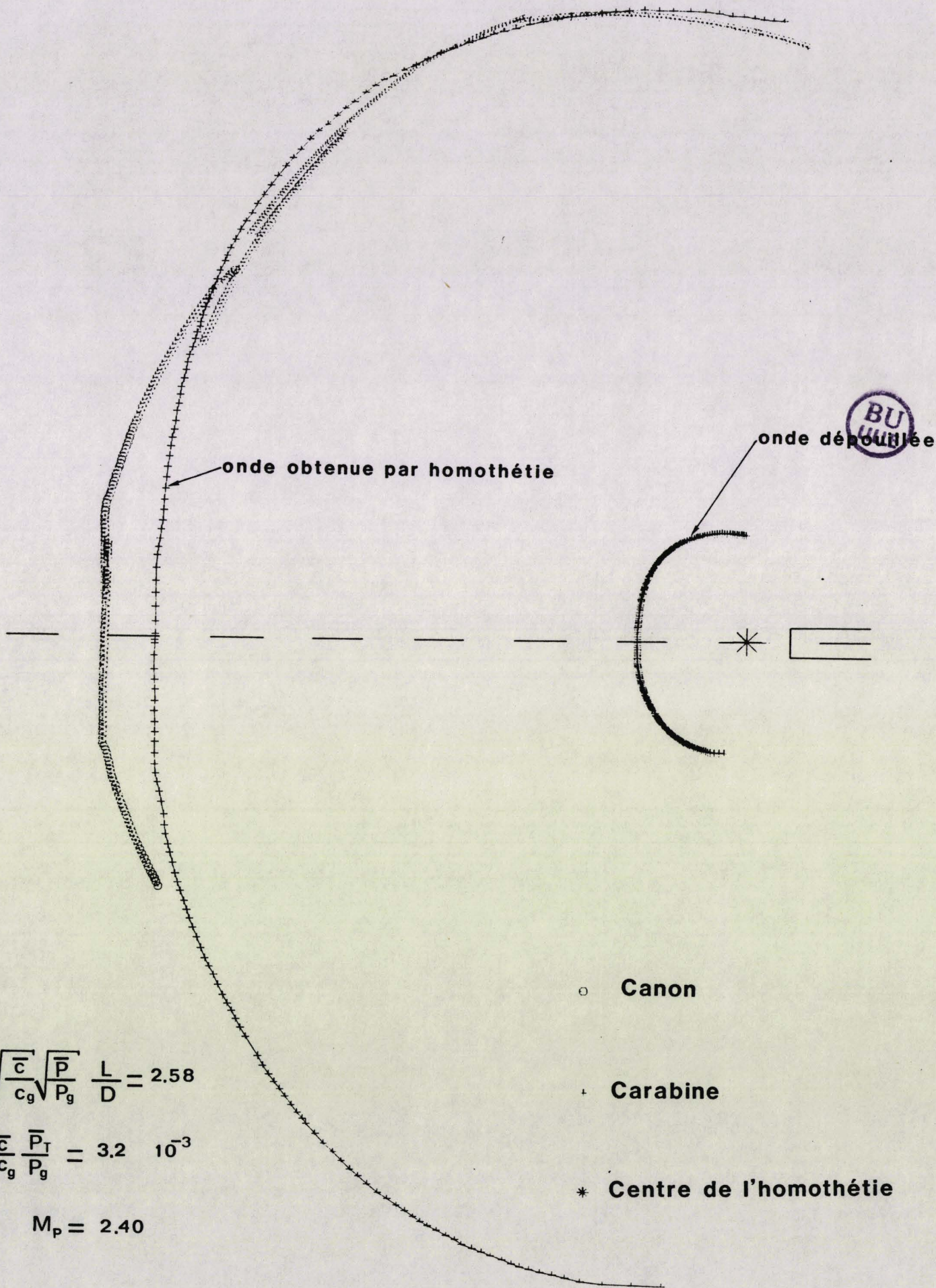


$$\frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 1.6 \cdot 10^{-3} ; \bar{P} = \bar{P}_T$$

$M_p = 2.4$

$$\frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 1 \cdot 10^{-3} ; \bar{P} \neq \bar{P}_T$$

Réalisation de la similitude sur la forme de l'onde



onde obtenue par homothétie

onde dépouillée



- Canon
- + Carabine
- \* Centre de l'homothétie

$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 2.58$$

$$\frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 3.2 \cdot 10^{-3}$$

$$M_p = 2.40$$

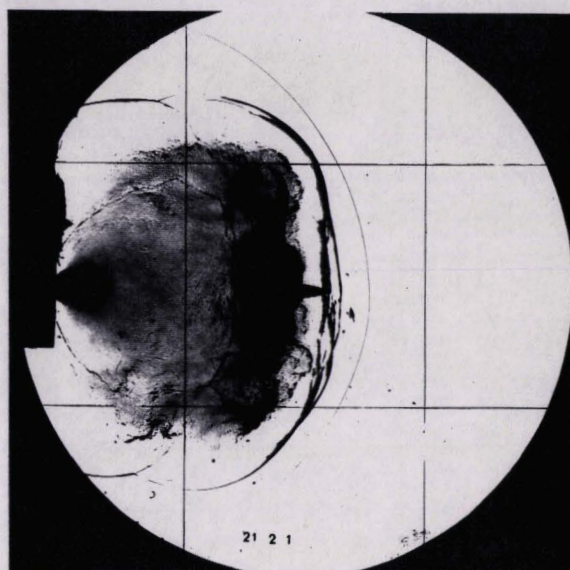
Comparaison canon-carabine Forme de l'onde





canon de 30 mm

$$\frac{\sqrt{\bar{c}} \sqrt{\bar{P}}}{\sqrt{c_g} \sqrt{P_g}} \frac{\bar{c} t}{D} = 0.16$$

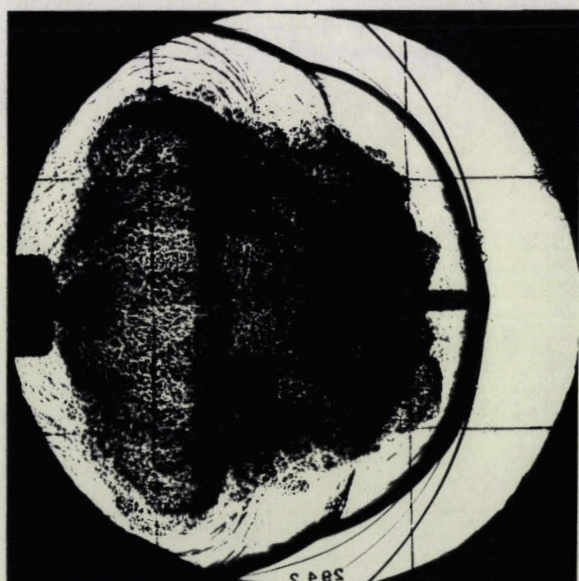


carabine avec opercule de 5.56 mm



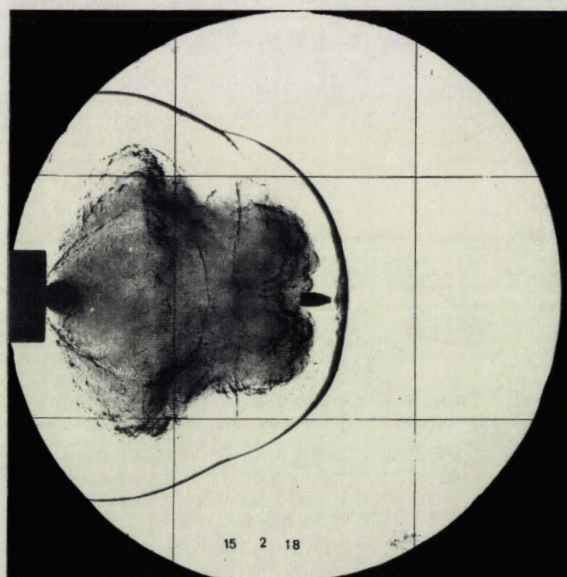
$$M_p = 2.4 \quad \frac{\sqrt{\bar{c}} \sqrt{\bar{P}}}{\sqrt{c_g} \sqrt{P_g}} \frac{L}{D} = 2.58 ; \frac{\bar{c} \bar{P}_T}{c_g P_g} = 3.2 \cdot 10^{-3}$$

Comparaison canon de 30 mm - carabine de 5.56 mm



fusil de 7.62 mm

$$\frac{\sqrt{\bar{c}} \sqrt{\bar{P}}}{\sqrt{c_g} \sqrt{P_g}} \frac{\bar{c} t}{D} = 0.3$$



carabine sans opercule de 5.56 mm

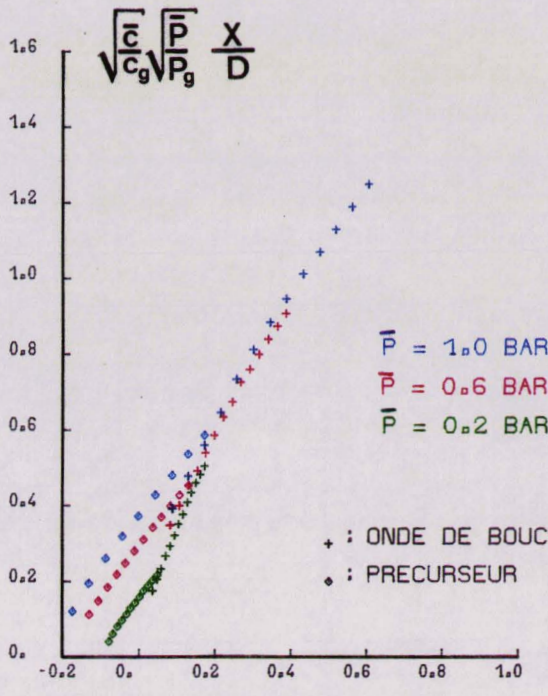
$$\frac{\sqrt{\bar{c}} \sqrt{\bar{P}}}{\sqrt{c_g} \sqrt{P_g}} \frac{L}{D} = 3.26 ; \frac{\bar{c} \bar{P}_T}{c_g P_g} = 1.5 \cdot 10^{-3}$$

$$M_p = 2.3$$

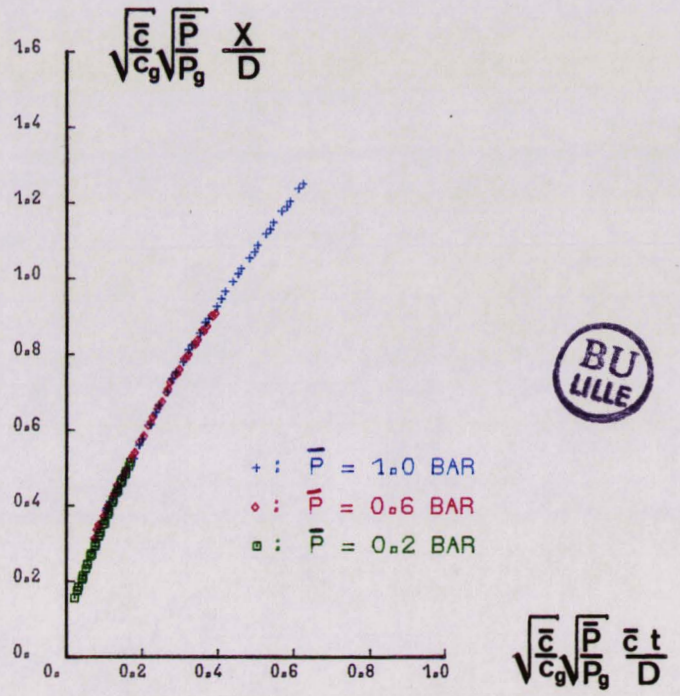
$$\frac{\sqrt{\bar{c}} \sqrt{\bar{P}}}{\sqrt{c_g} \sqrt{P_g}} \frac{L}{D} = 3.85 ; \frac{\bar{c} \bar{P}_T}{c_g P_g} = 1.3 \cdot 10^{-3}$$

Comparaison fusil de 7.62 mm - carabine de 5.56 mm

Similitude sur la forme de l'onde de bouche  
armes de différents calibres

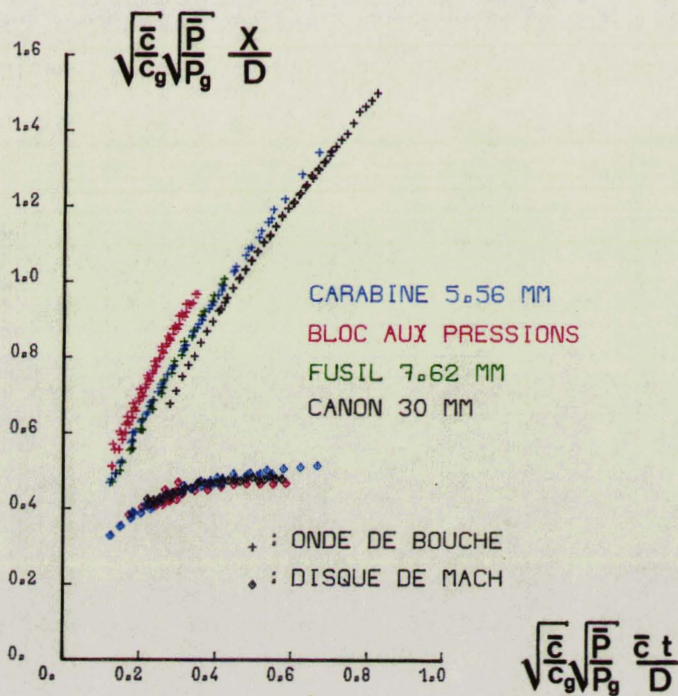


1. essais bruts

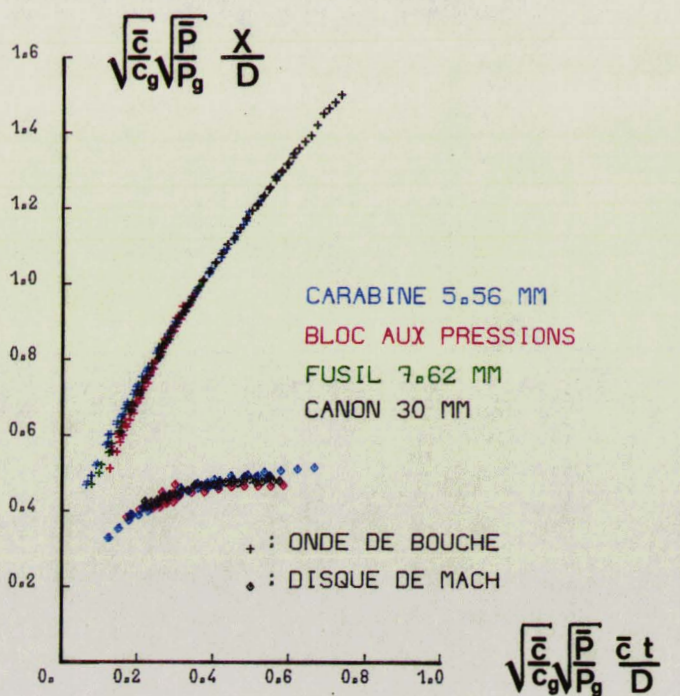


2. essais recalés

Tirs à pressions  $\bar{P}$  différentes



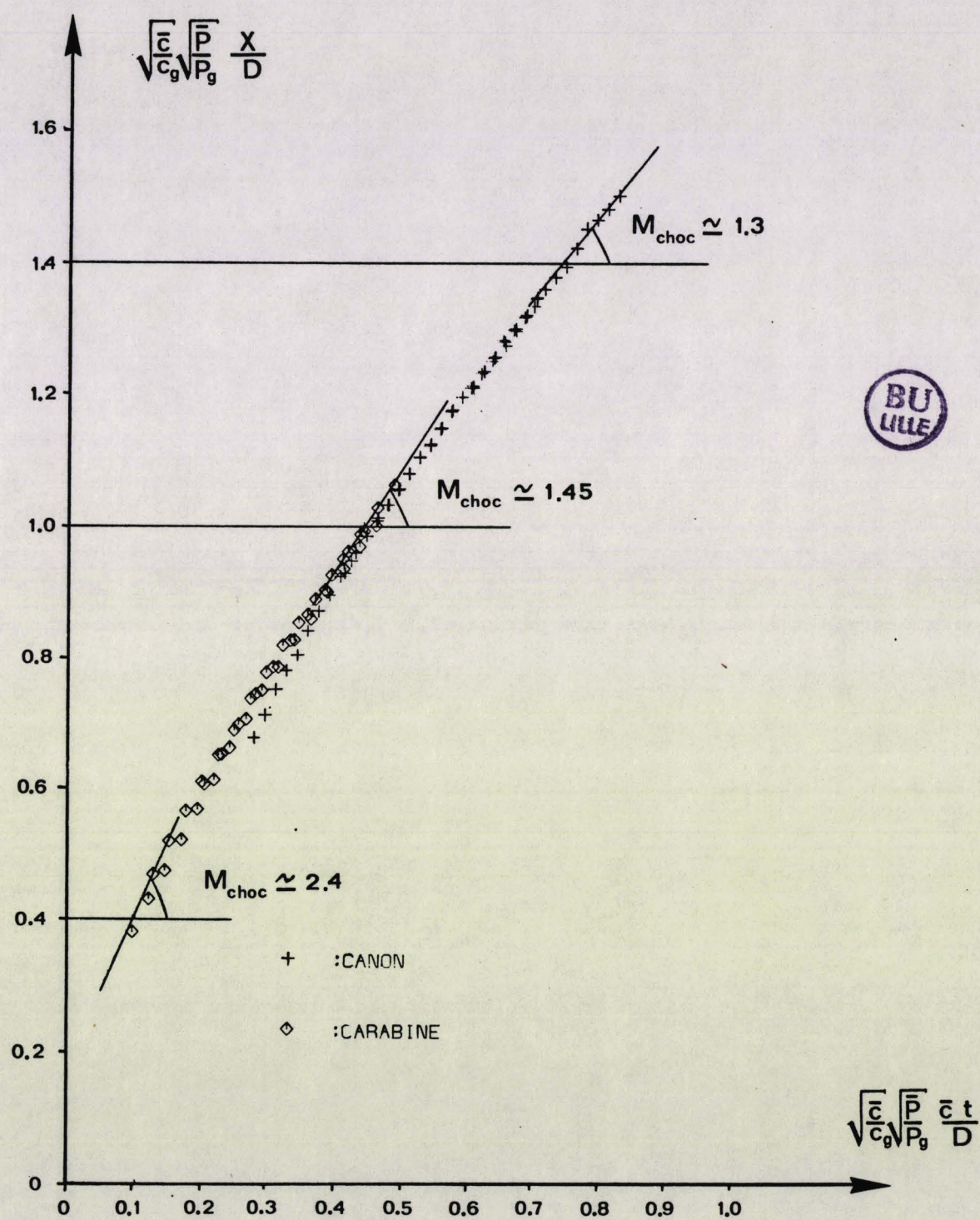
3. essais bruts



4. essais recalés

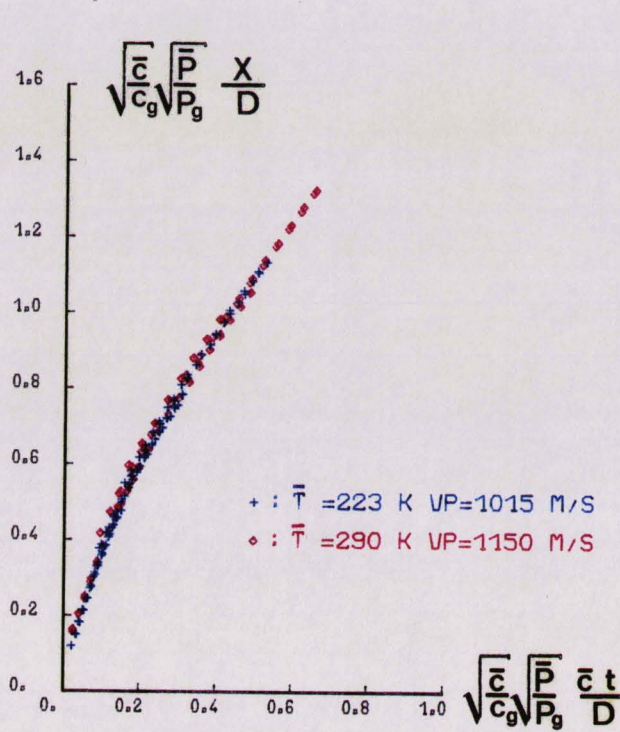
Tirs d'armes de calibres différents

Progression de l'onde de bouche sur l'axe de tir en atmosphère infinie

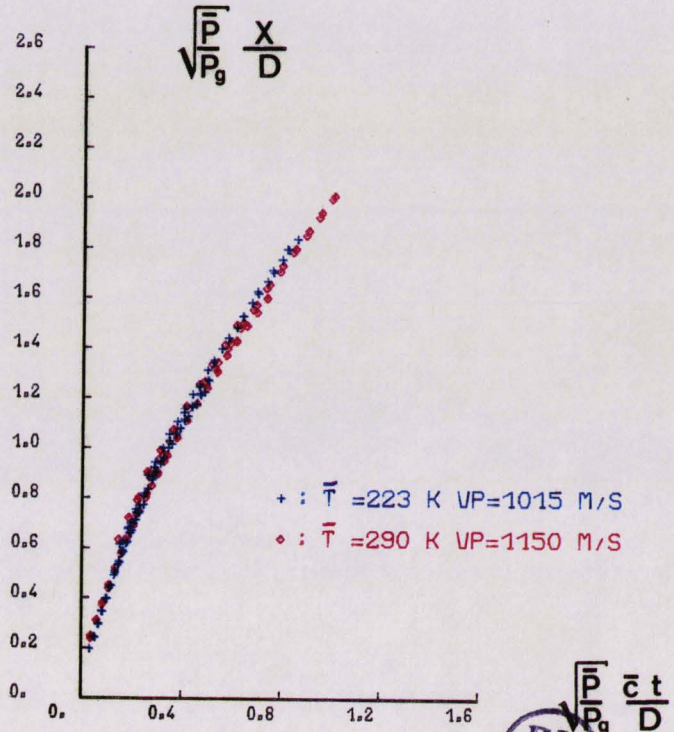


Comparaison canon-carabine

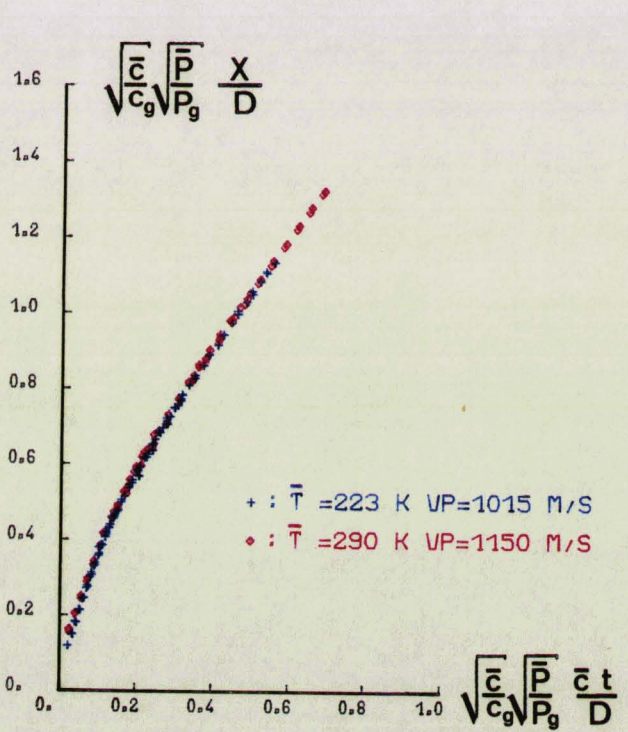
Progression sur l'axe



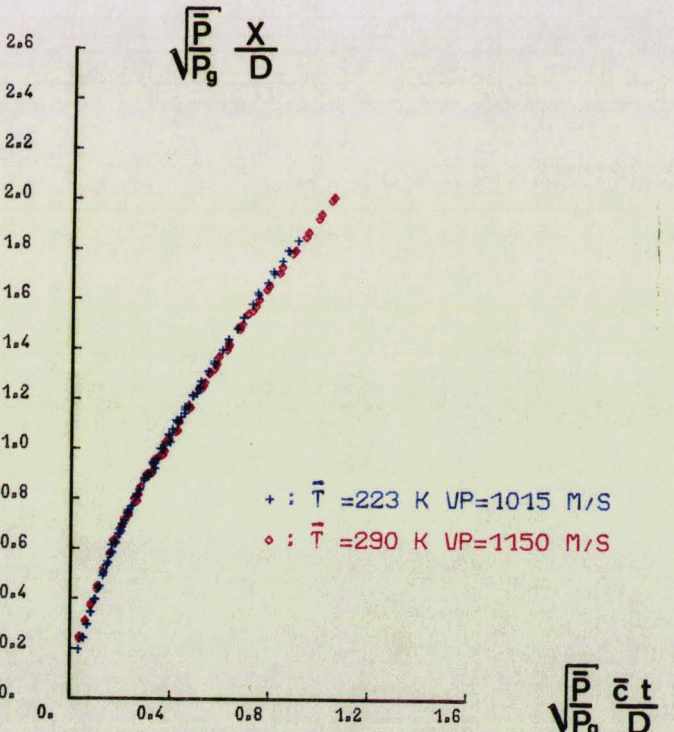
1. Essais bruts



2. Essais bruts

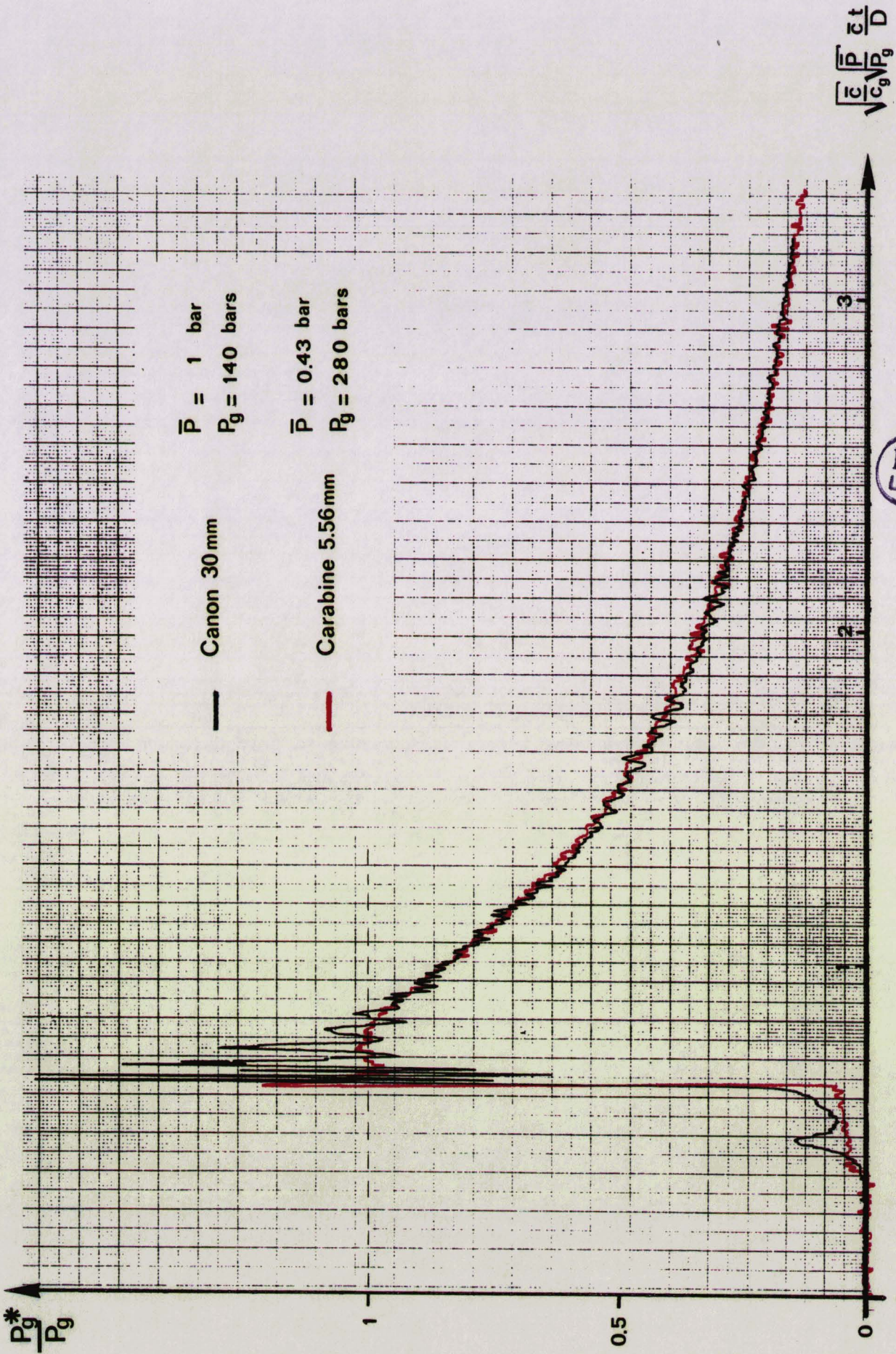


3. Essais recalés



4. Essais recalés

Effet du choix des grandeurs primaires sur la représentation de la progression de l'onde de bouche pour deux valeurs de  $\bar{T}$

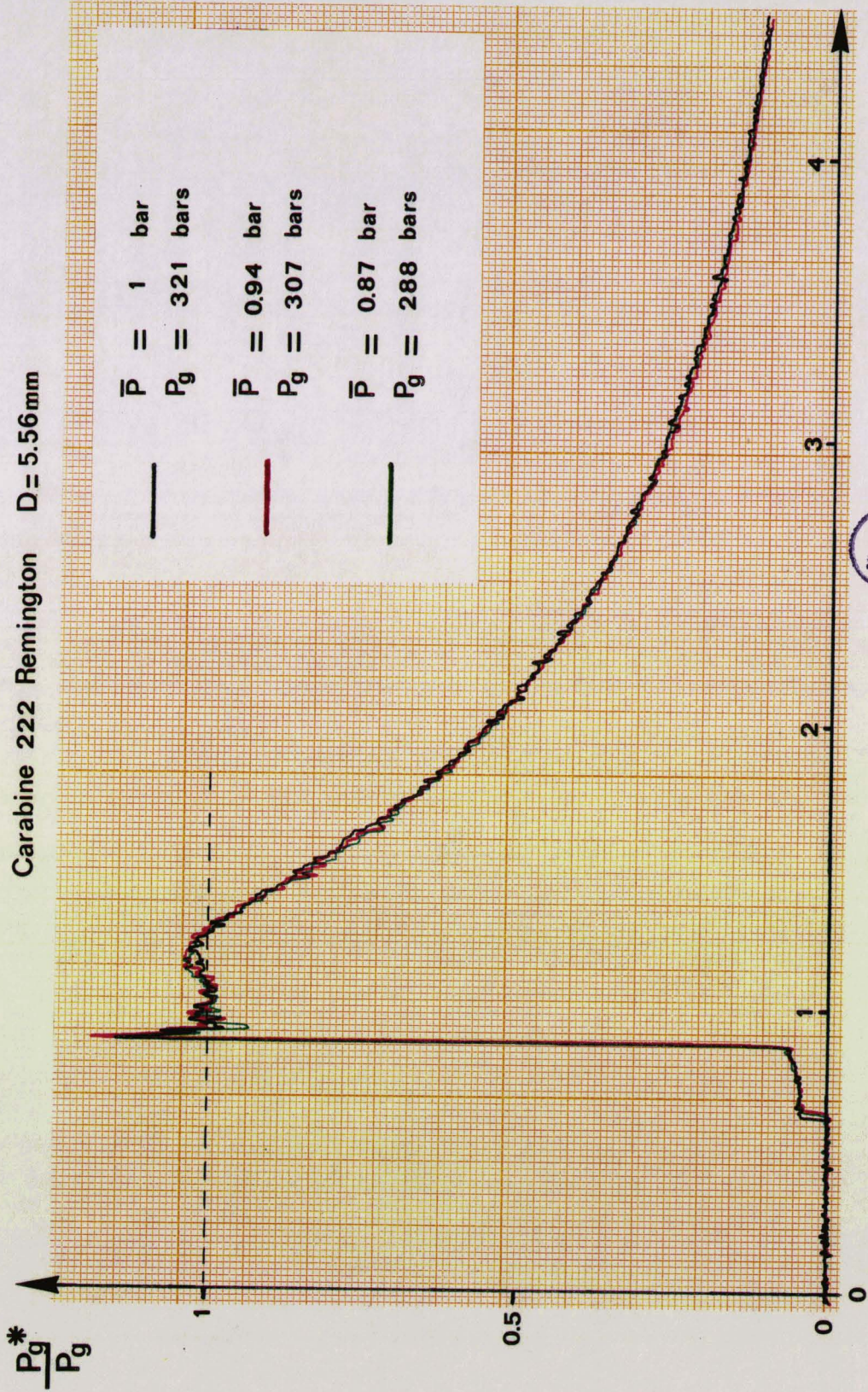


$M_p = 2.40$

$\sqrt{c_g} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 2.58$

Comparaison canon-carabine  $\frac{P_g^*}{P_g}$

Carabine 222 Remington D = 5.56 mm



$$\sqrt{\frac{\bar{c}_g \sqrt{\bar{P}}}{P_g}} \frac{t}{D}$$



$M_p = 2.93$

$$\sqrt{\frac{\bar{c}_g \sqrt{\bar{P}}}{P_g}} \frac{L}{D} = 3.66$$

Comparaison de différents chargements de la carabine  $\frac{P_g^*}{P_g}$

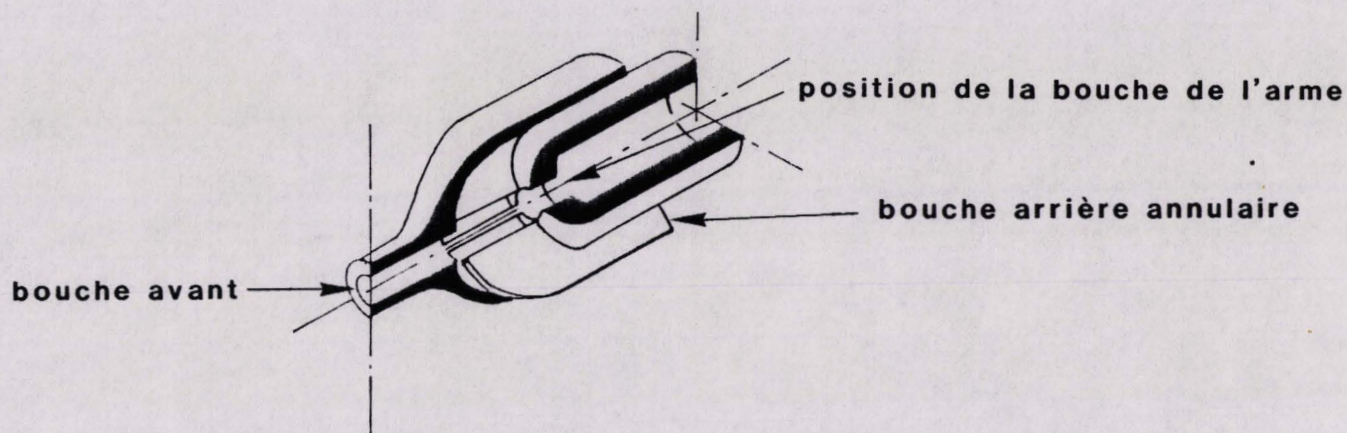
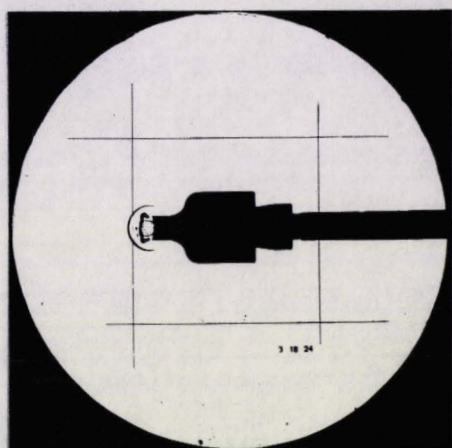
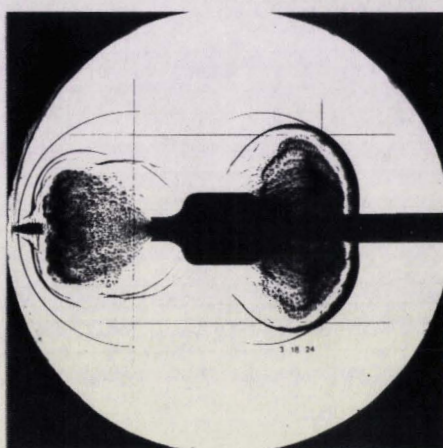


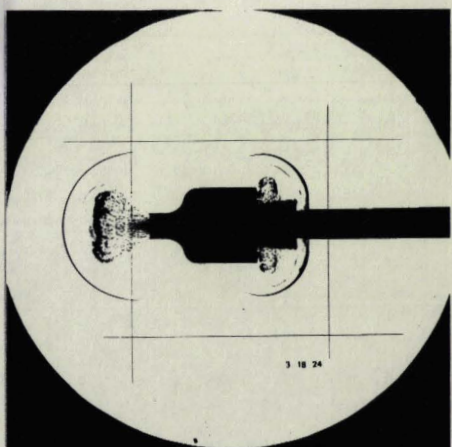
Schéma du décompresseur tulipe



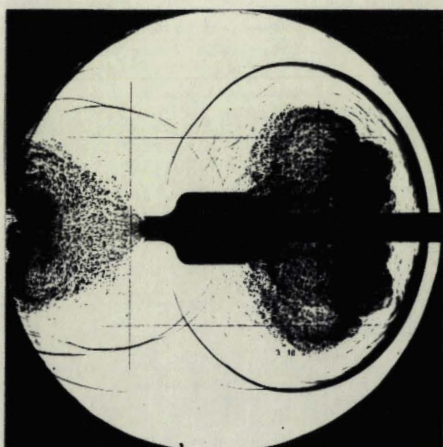
1



3

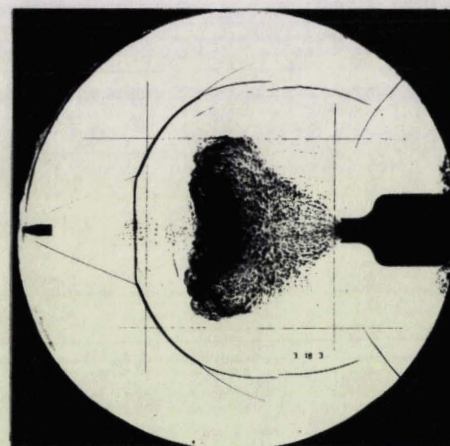


2



4

visualisation des deux ondes de bouche  
 $\Delta t = 68 \mu s$

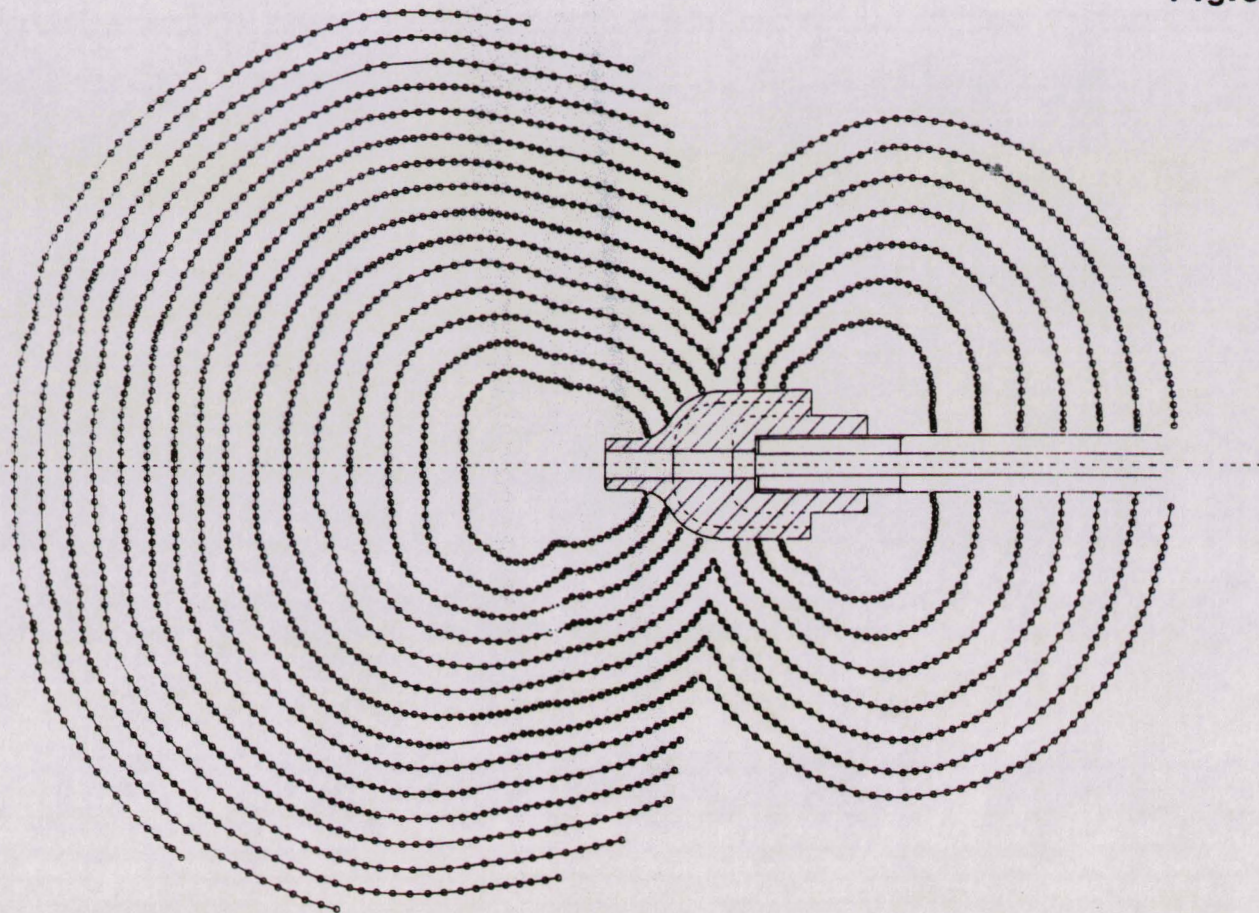


onde vers l'avant

Carabine de 5.56 mm munie d'un décompresseur tulipe

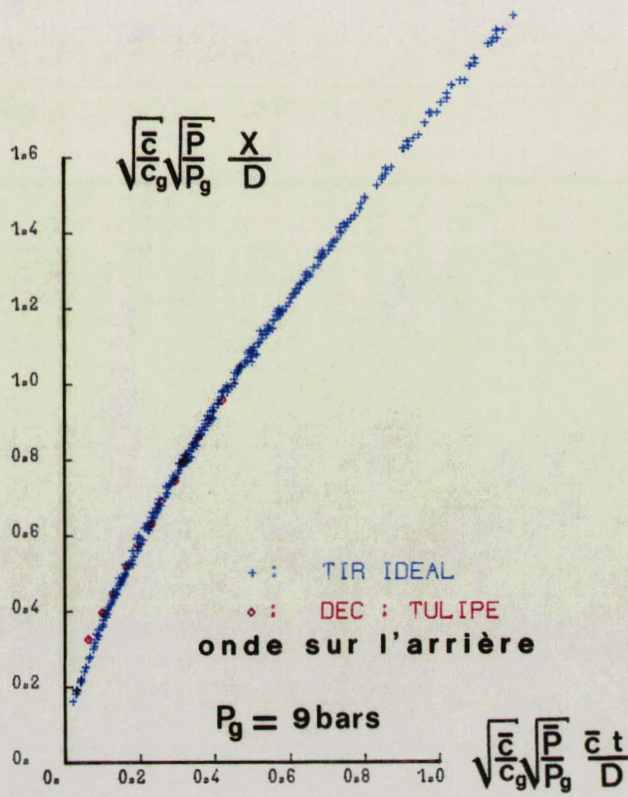
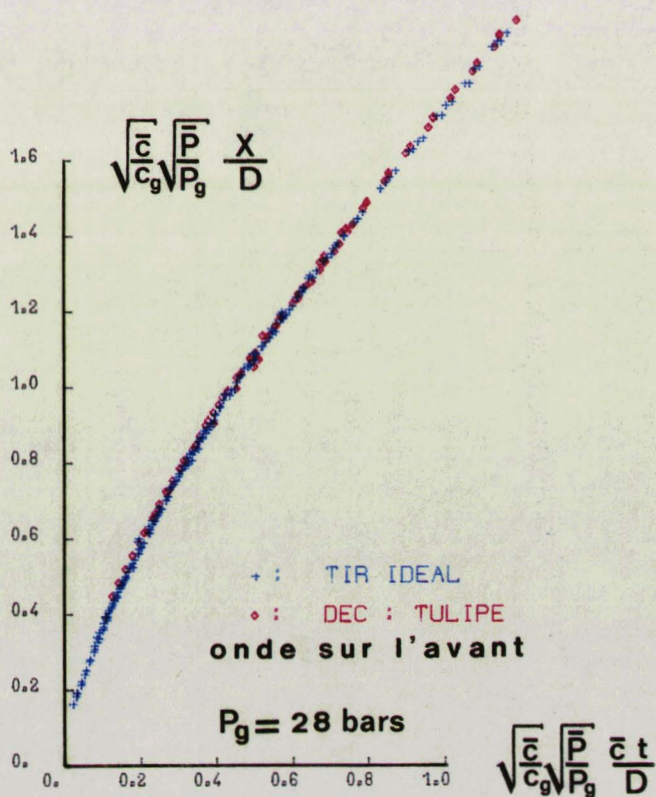
Obstacle lié à la bouche exemple du décompresseur tulipe





Reconstitution de l'onde de bouche à des instants différents  $\Delta t = 17 \mu s$

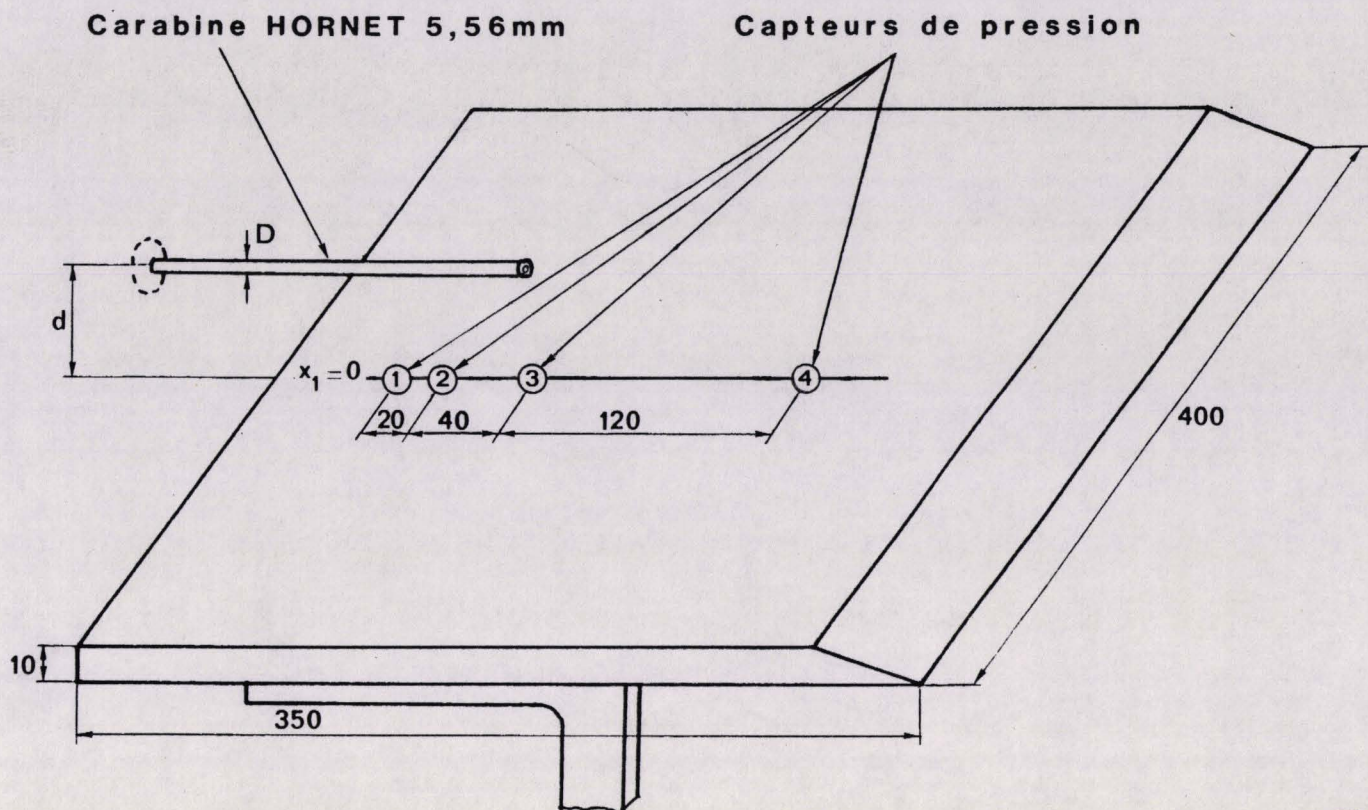
DECOMPRESSEUR "TULIPE"



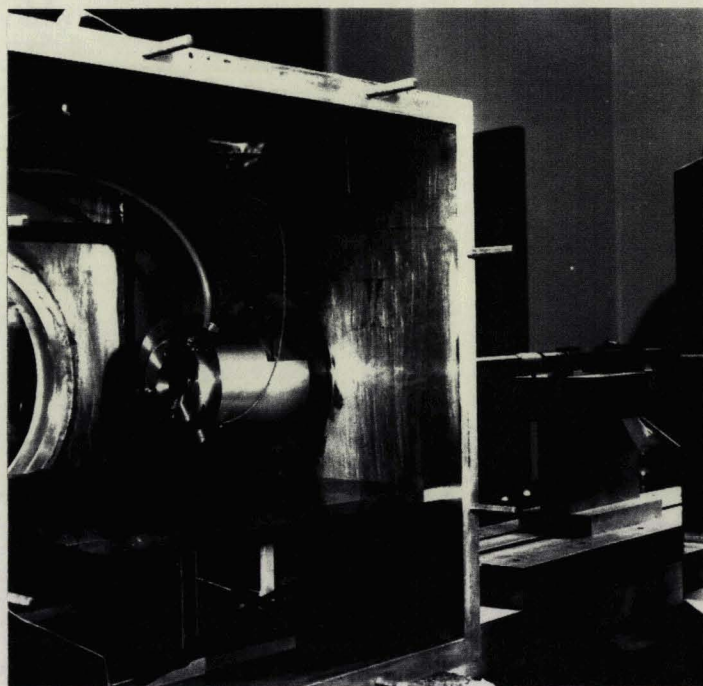
Progression sur l'axe de tir

Comparaison entre le décompresseur "tulipe" et les armes sans décompresseur





Maquette plaque avec rapport H/D variable

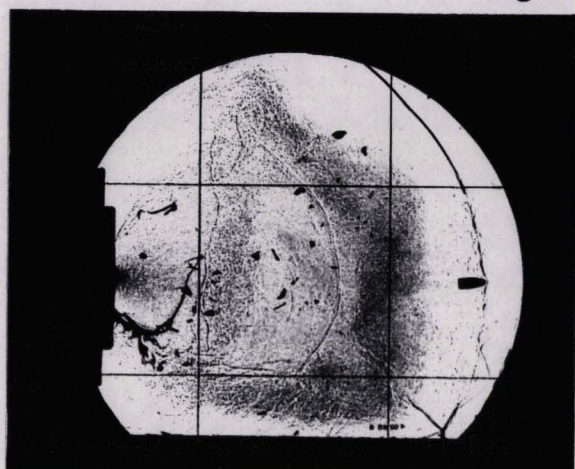
 $d/D = 5$  $d/D = 15$ 

Installation dans le caisson



1

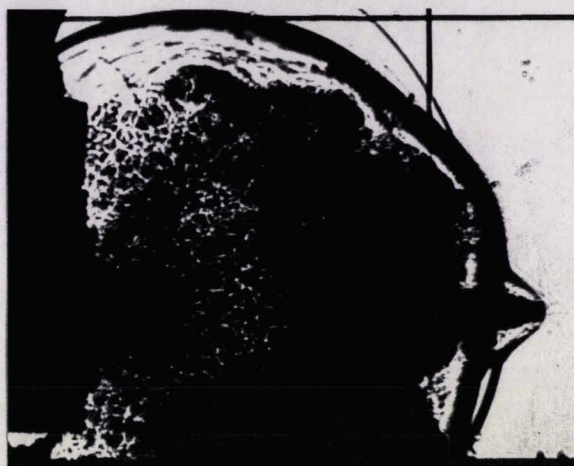
$$\sqrt{\frac{\bar{c}}{c_g} \frac{\bar{P}}{P_g}} \frac{L}{D} = 5.3$$



2

$$\sqrt{\frac{\bar{c}}{c_g} \frac{\bar{P}}{P_g}} \frac{L}{D} = 1.76$$

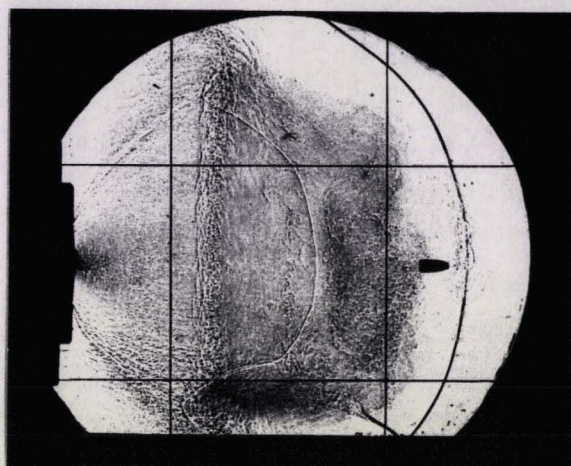
Tir idéal (1,2)



3

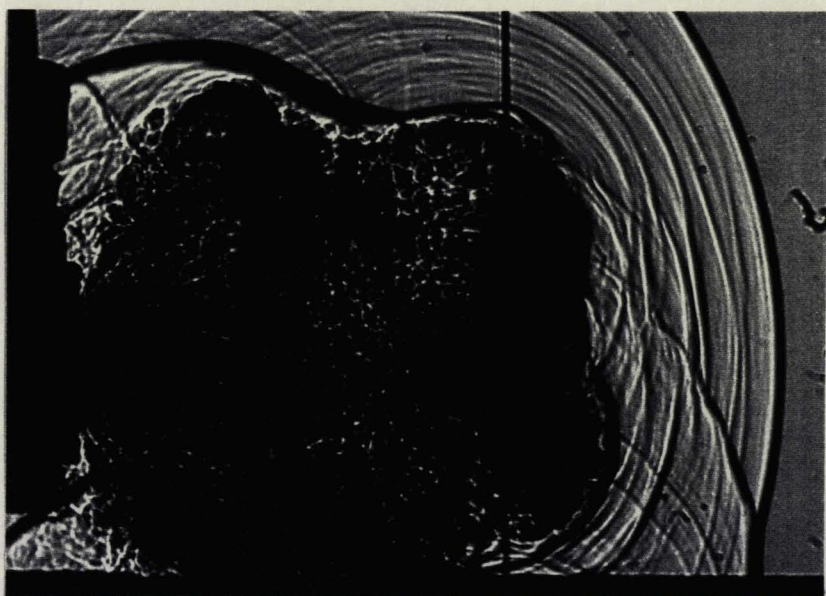
$$\sqrt{\frac{\bar{c}}{c_g} \frac{\bar{P}}{P_g}} \frac{L}{D} = 5.3$$

$$\frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 0.3 \cdot 10^{-3}$$



4

$$\sqrt{\frac{\bar{c}}{c_g} \frac{\bar{P}}{P_g}} \frac{L}{D} = 1.76$$



5

$$\sqrt{\frac{\bar{c}}{c_g} \frac{\bar{P}}{P_g}} \frac{L}{D} = 5.3$$

$$\frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 2.9 \cdot 10^{-3}$$

Tir non idéal (3,4,5)

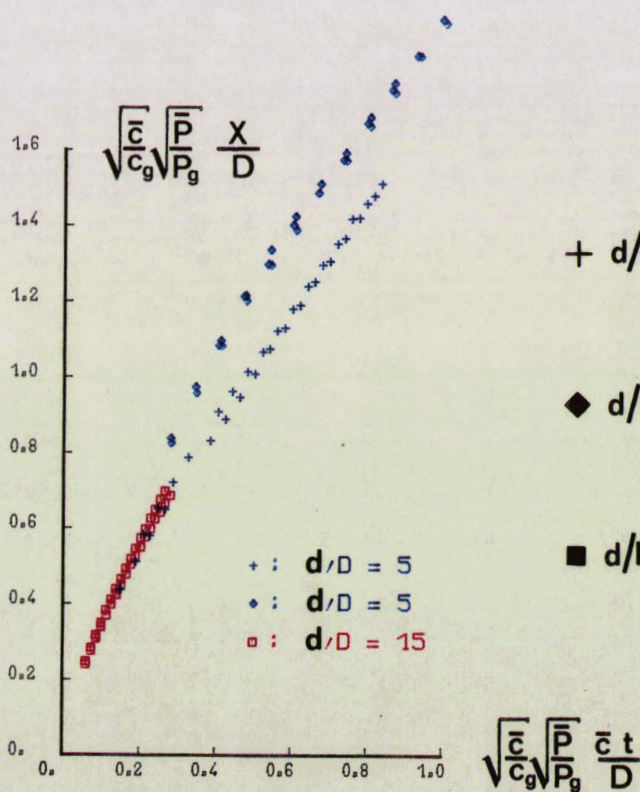
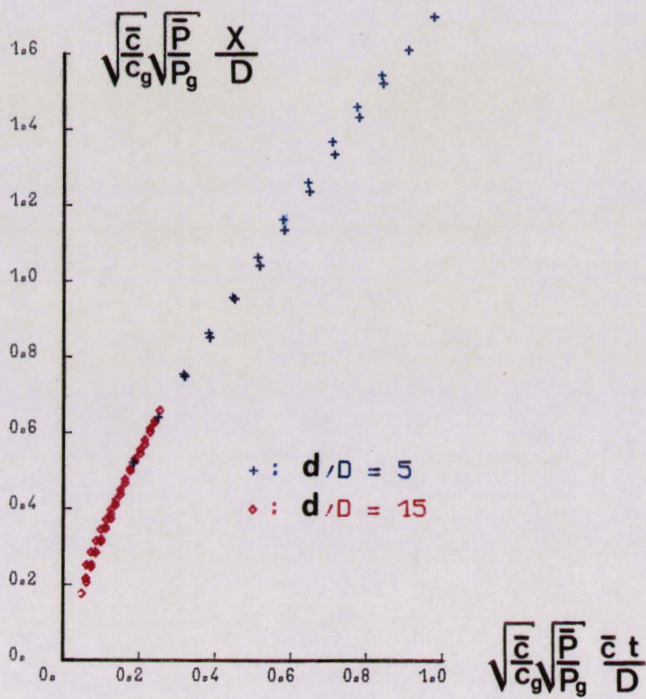
$$M_p = 2.4$$

$$\sqrt{\frac{\bar{c}}{c_g} \frac{\bar{P}}{P_g}} \frac{X}{D} \approx 0.3$$

$$\sqrt{\frac{\bar{c}}{c_g} \frac{\bar{P}}{P_g}} \frac{\bar{c} t}{D} \approx 0.19$$

$$\delta = 0.26$$

Influence du non respect de la similitude géométrique  
au voisinage immédiat de la bouche



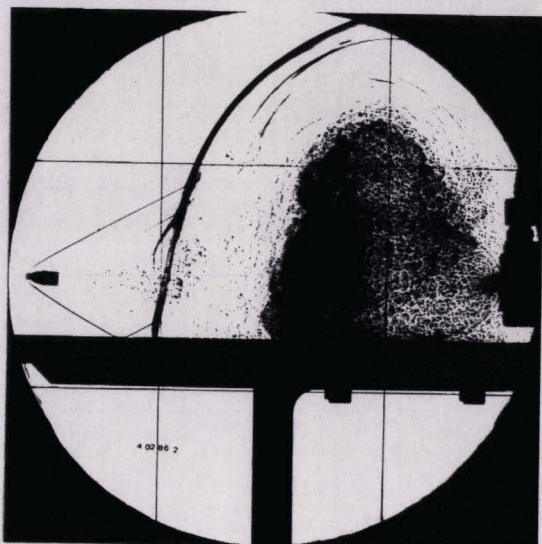
+  $d/D = 5$  ;  $\frac{\sqrt{\bar{c}} \sqrt{\bar{P}}}{\sqrt{c_g} \sqrt{P_g}} \frac{L}{D} = 5.3$  ;  $\frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 2.47 \cdot 10^{-3}$

◊  $d/D = 5$  ;  $\frac{\sqrt{\bar{c}} \sqrt{\bar{P}}}{\sqrt{c_g} \sqrt{P_g}} \frac{L}{D} = 5.3$  ;  $\frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 2.66 \cdot 10^{-4}$

◻  $d/D = 15$  ;  $\frac{\sqrt{\bar{c}} \sqrt{\bar{P}}}{\sqrt{c_g} \sqrt{P_g}} \frac{L}{D} = 1.76$  ;  $\frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 2.66 \cdot 10^{-4}$

**Propagation de l'onde de bouche sur l'axe de tir**

**Tirs en présence d'une plaque infinie**



tir idéal

tir non idéal

$$M_p = 2.4 ; \frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 0.3 \cdot 10^{-3}$$

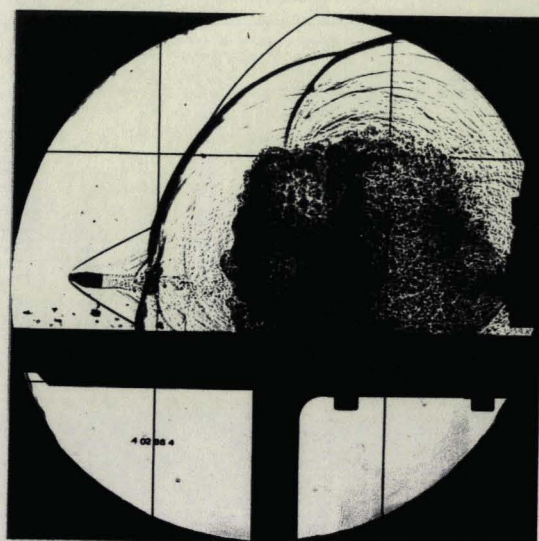
$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 5.3$$



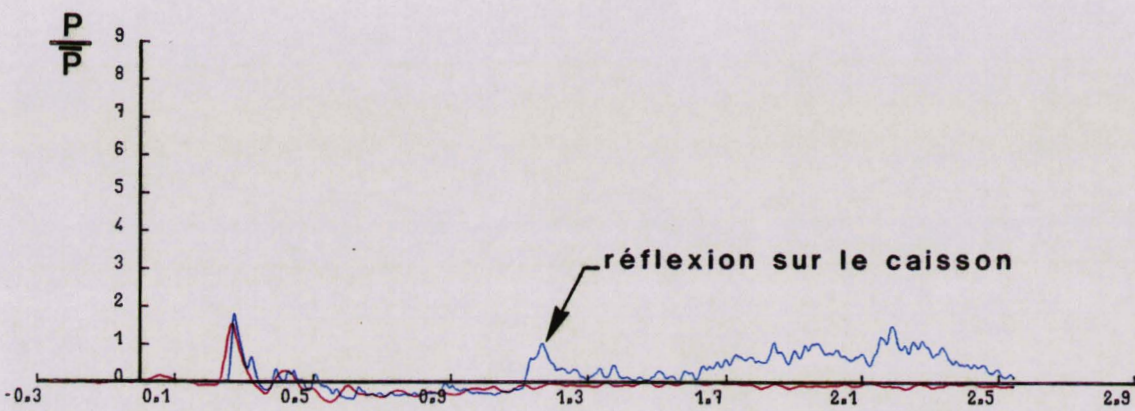
tir non idéal

$$M_p = 2.4 ; \frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 2.9 \cdot 10^{-3}$$

$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 5.3$$

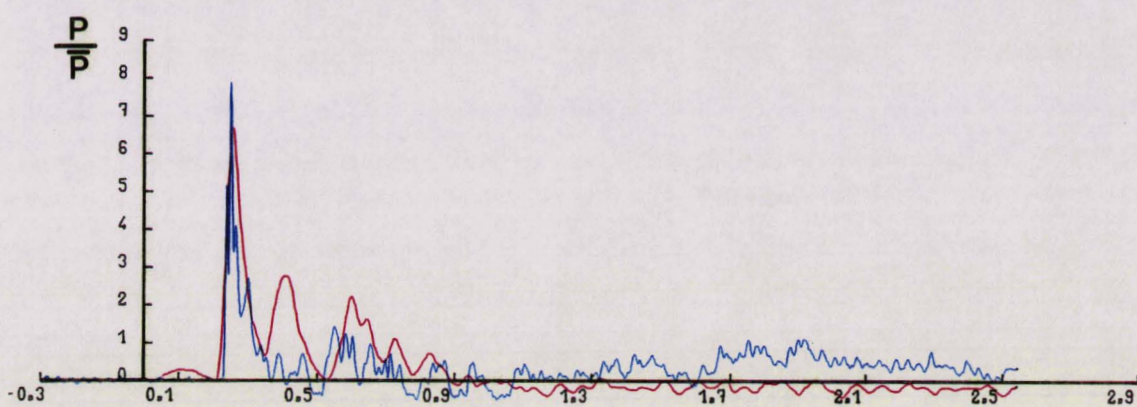


Forme de l'onde pour  $\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{X}{D} \approx 1.4$



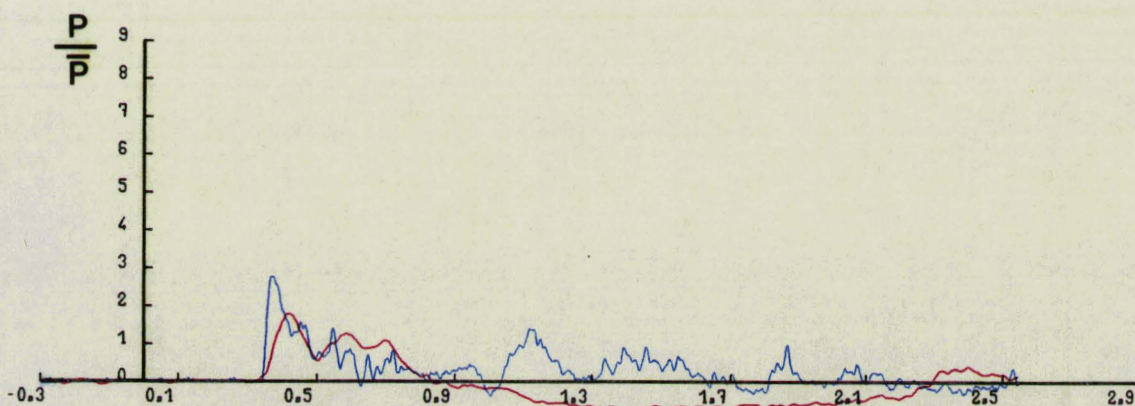
$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{\bar{c} t}{D}$$

Position 1 ;  $\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{X}{D} = 0.$



$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{\bar{c} t}{D}$$

Position 2 ;  $\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{X}{D} = 0.2$



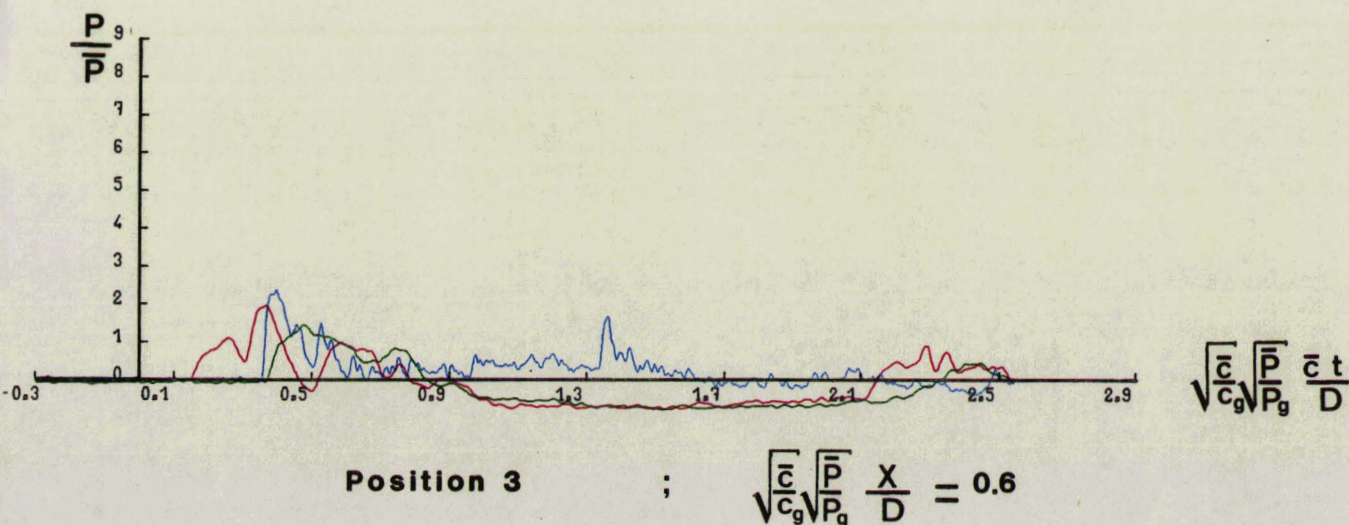
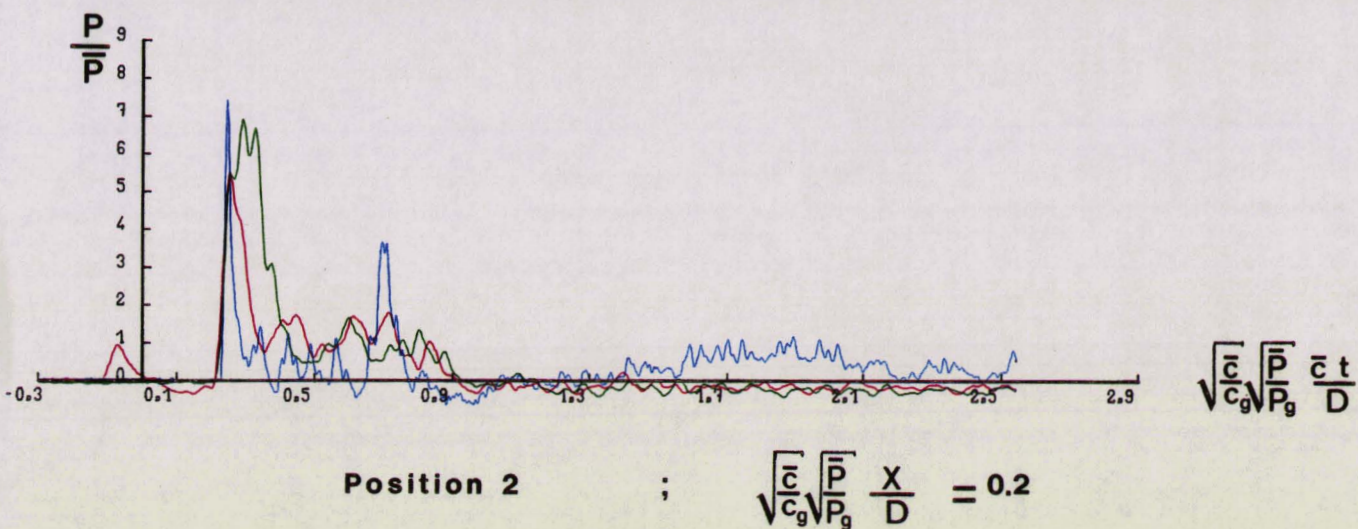
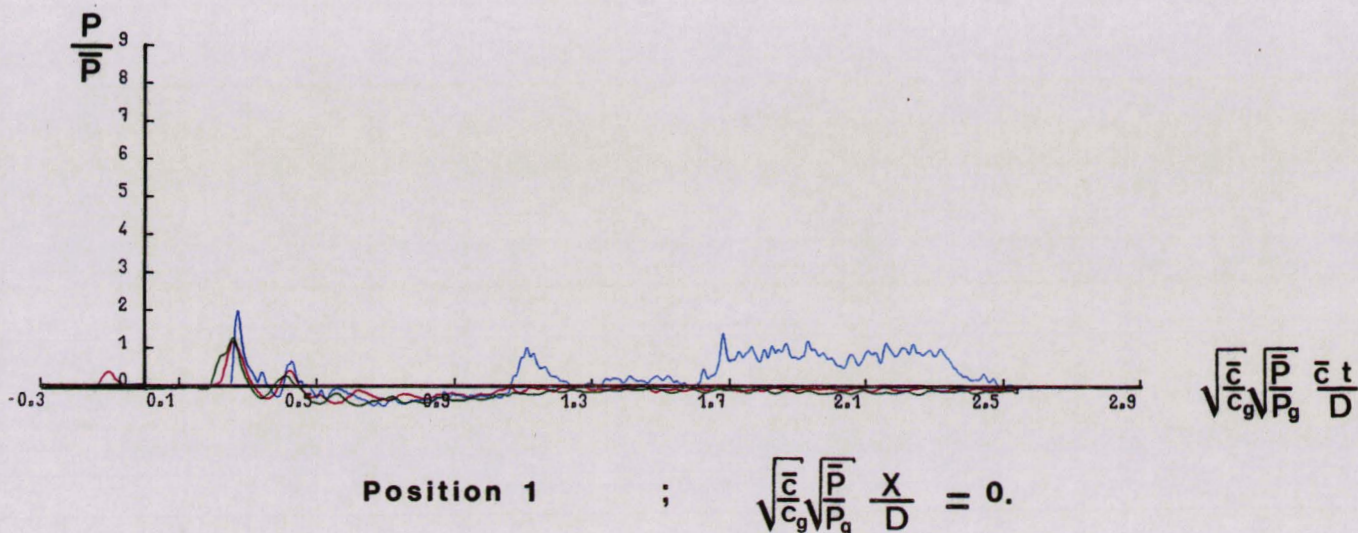
$$\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{\bar{c} t}{D}$$

Position 3 ;  $\sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{X}{D} = 0.6$

— configuration 1  $d/D = 5$

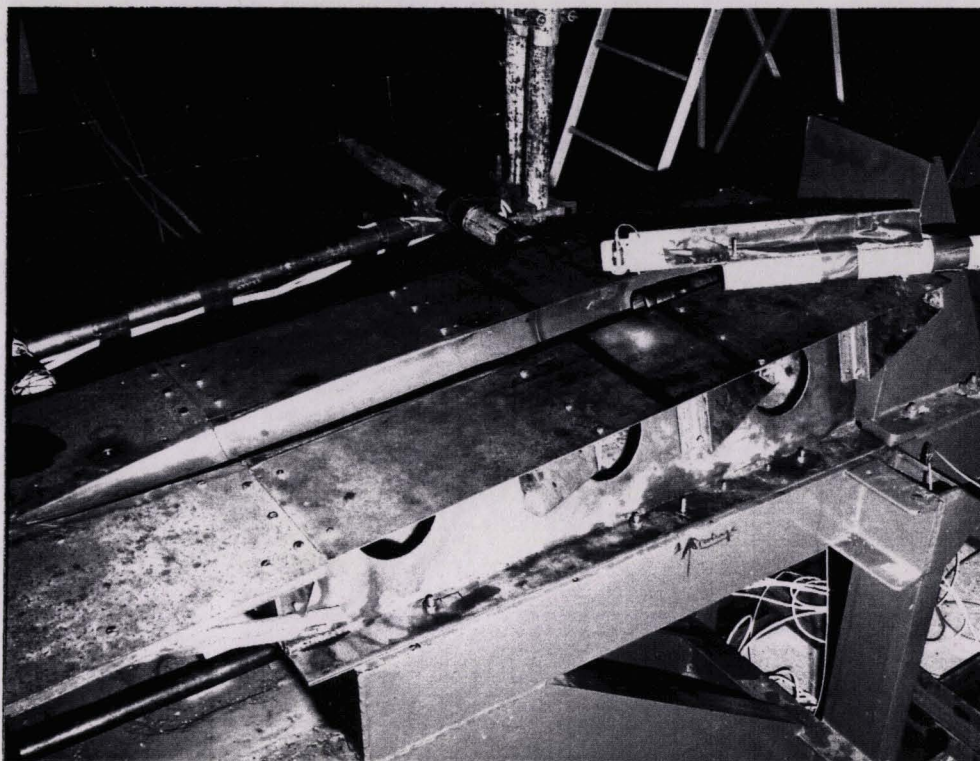
— configuration 2  $d/D = 15$

Pressions instationnaires sur la plaque plane  
Tir idéal

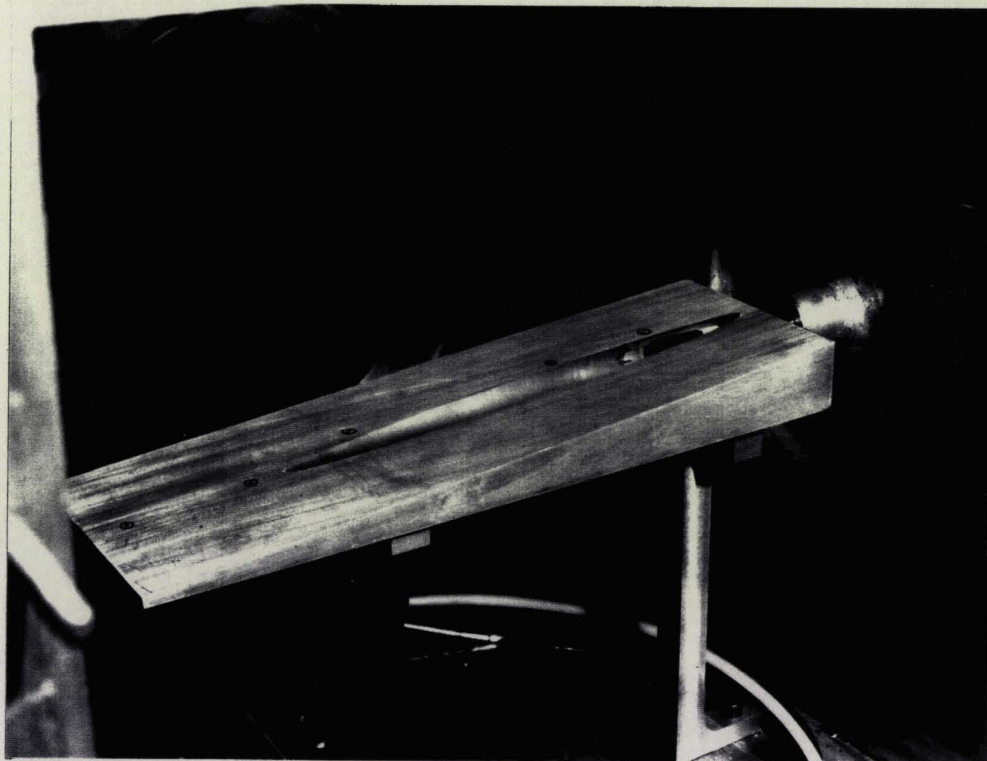


configuration 1 $\left\{ \begin{array}{l} \frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 0.3 \cdot 10^{-3} \quad \sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 5.3 \\ \frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 2.9 \cdot 10^{-3} \quad \sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 5.3 \end{array} \right.$	configuration 2 $\left\{ \begin{array}{l} \frac{\bar{c}}{c_g} \frac{\bar{P}_T}{P_g} = 0.310^{-3} \\ \sqrt{\frac{\bar{c}}{c_g}} \sqrt{\frac{\bar{P}}{P_g}} \frac{L}{D} = 1.76 \end{array} \right.$
---	---

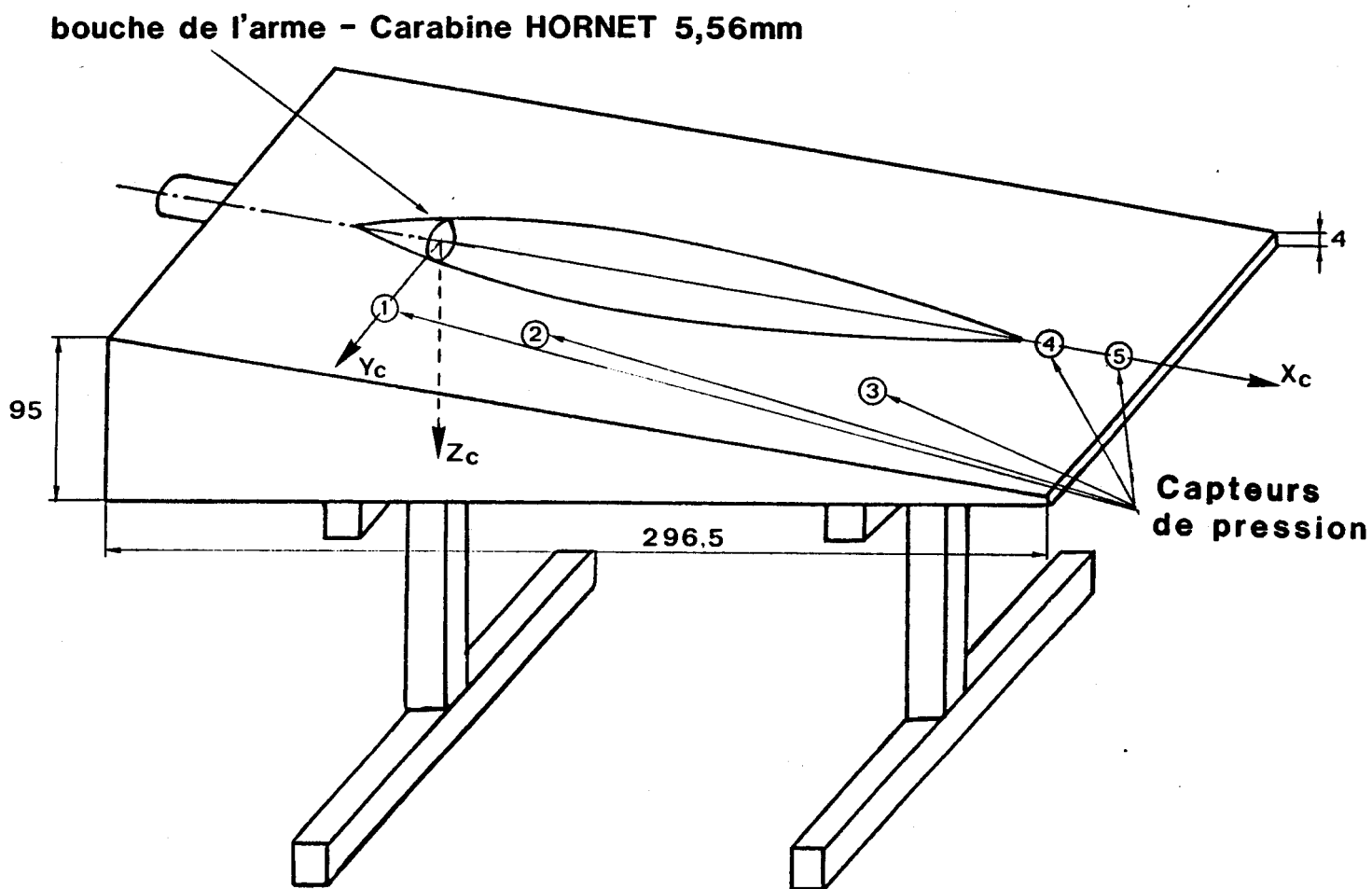
**Pressions instationnaires sur la plaque plane**  
**Tir non idéal**  $M_p = 2.4$



Installation de tir canon de 30mm



Installation dans le caisson



### Capteurs:

$$C_1: \quad \frac{X_c}{D} = 0.66 \quad ; \quad \frac{Y_c}{D} = 2.33 \quad ; \quad \frac{Z_c}{D} = 0.9$$

$$C_2: \quad \frac{X_c}{D} = 7.66 \quad ; \quad \frac{Y_c}{D} = 2.33 \quad ; \quad \frac{Z_c}{D} = 0.23$$

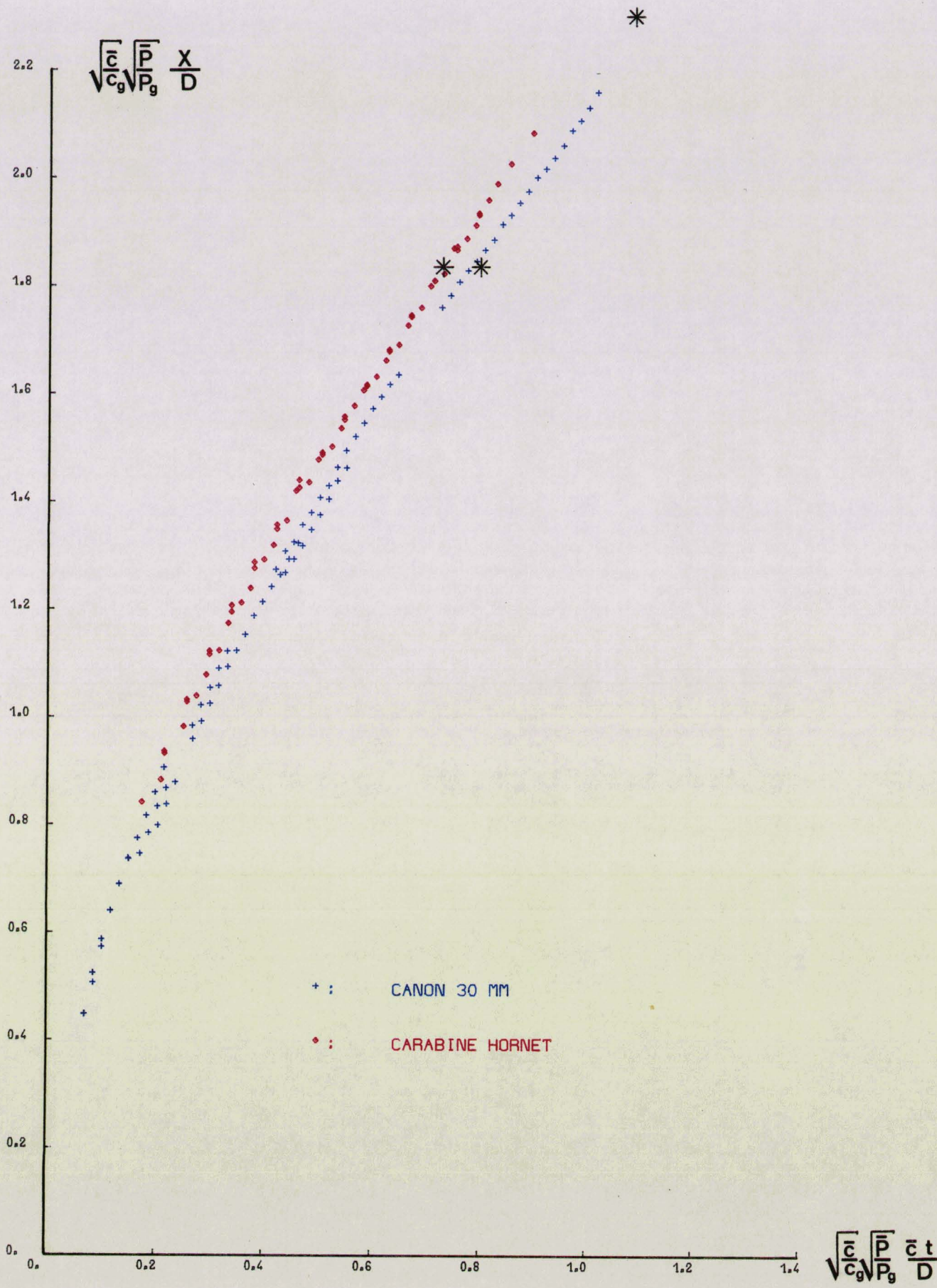
$$C_3: \quad \frac{X_c}{D} = 24.33 \quad ; \quad \frac{Y_c}{D} = 2.33 \quad ; \quad \frac{Z_c}{D} = 1.14$$

$$C_4: \quad \frac{X_c}{D} = 32.66 \quad ; \quad \frac{Y_c}{D} = 0. \quad ; \quad \frac{Z_c}{D} = 1.94$$

$$C_5: \quad \frac{X_c}{D} = 41. \quad ; \quad \frac{Y_c}{D} = 0. \quad ; \quad \frac{Z_c}{D} = 2.6$$

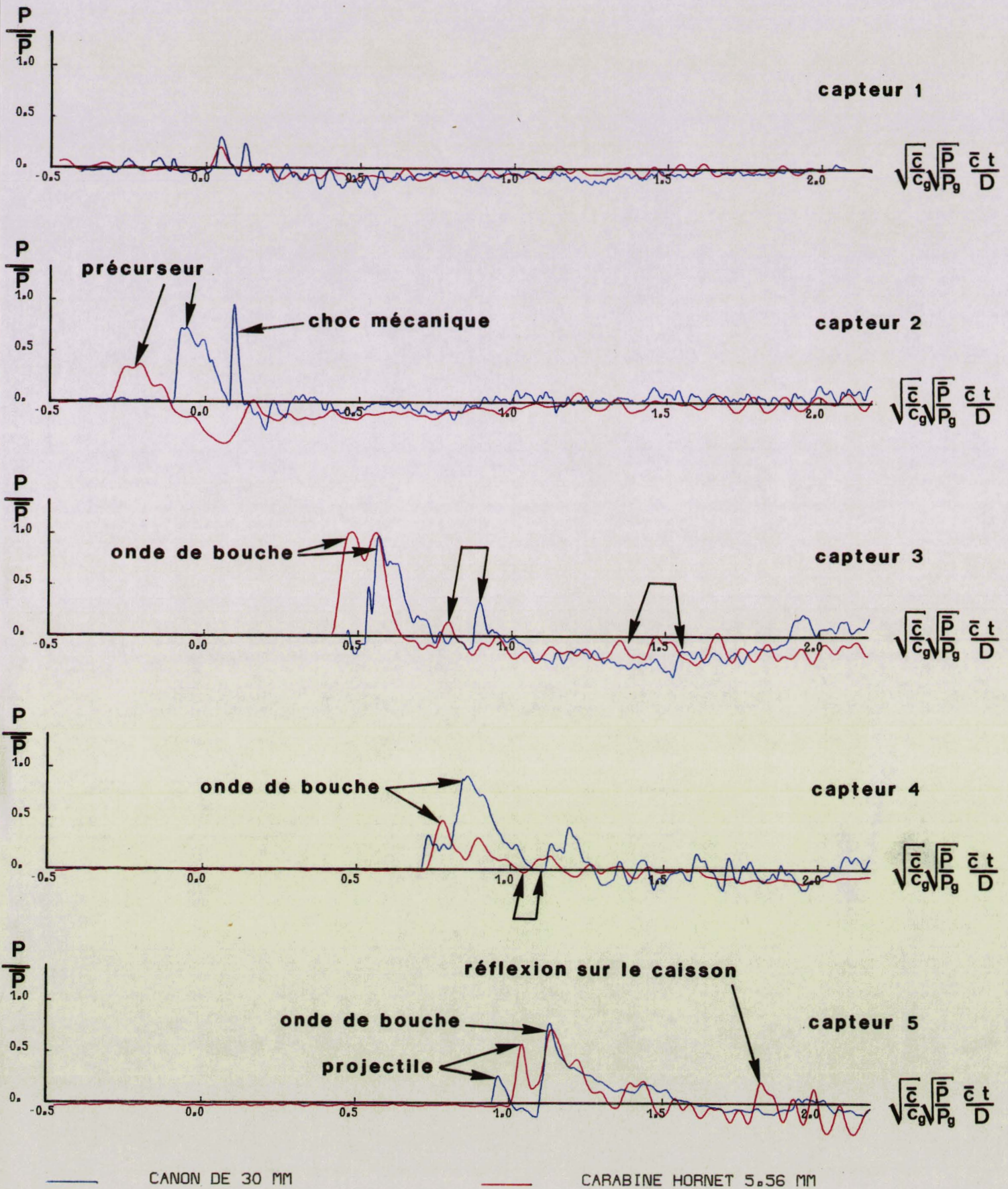
Tir dans une goulotte inclinée  
Schéma d'implantation des capteurs





Progression sur l'axe de tir

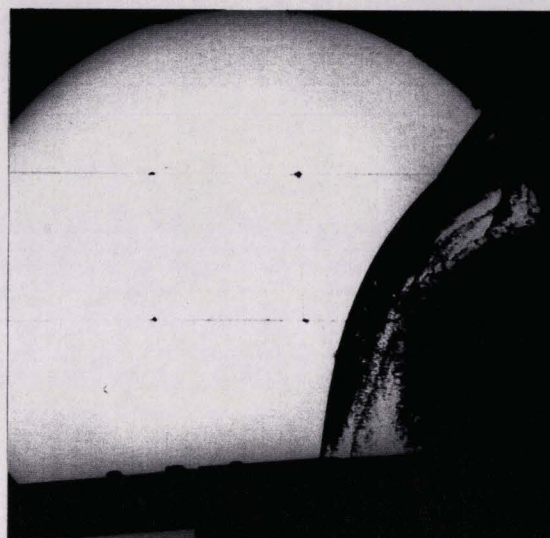
Comparaison canon-carabine en présence d'un obstacle



Courbes de pression . Comparaison canon-carabine

carabine

canon



$$\sqrt{\frac{\bar{c}}{c_9}} \sqrt{\frac{\bar{P}}{P_9}} \frac{\bar{c} t}{D} \simeq 0.4$$

$$\sqrt{\frac{\bar{c}}{c_9}} \sqrt{\frac{\bar{P}}{P_9}} \frac{\bar{c} t}{D} \simeq 0.5$$

Arrivée de l'onde sur le capteur 3

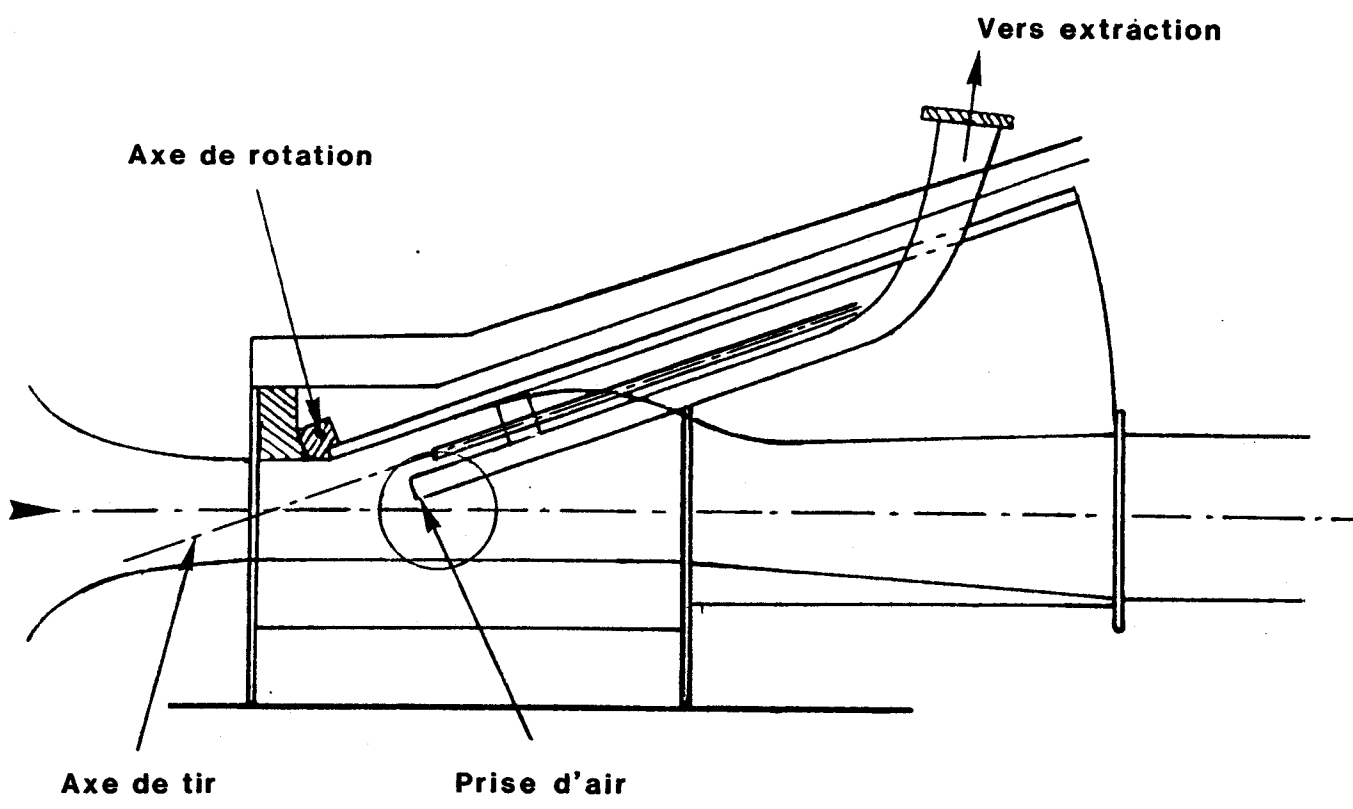
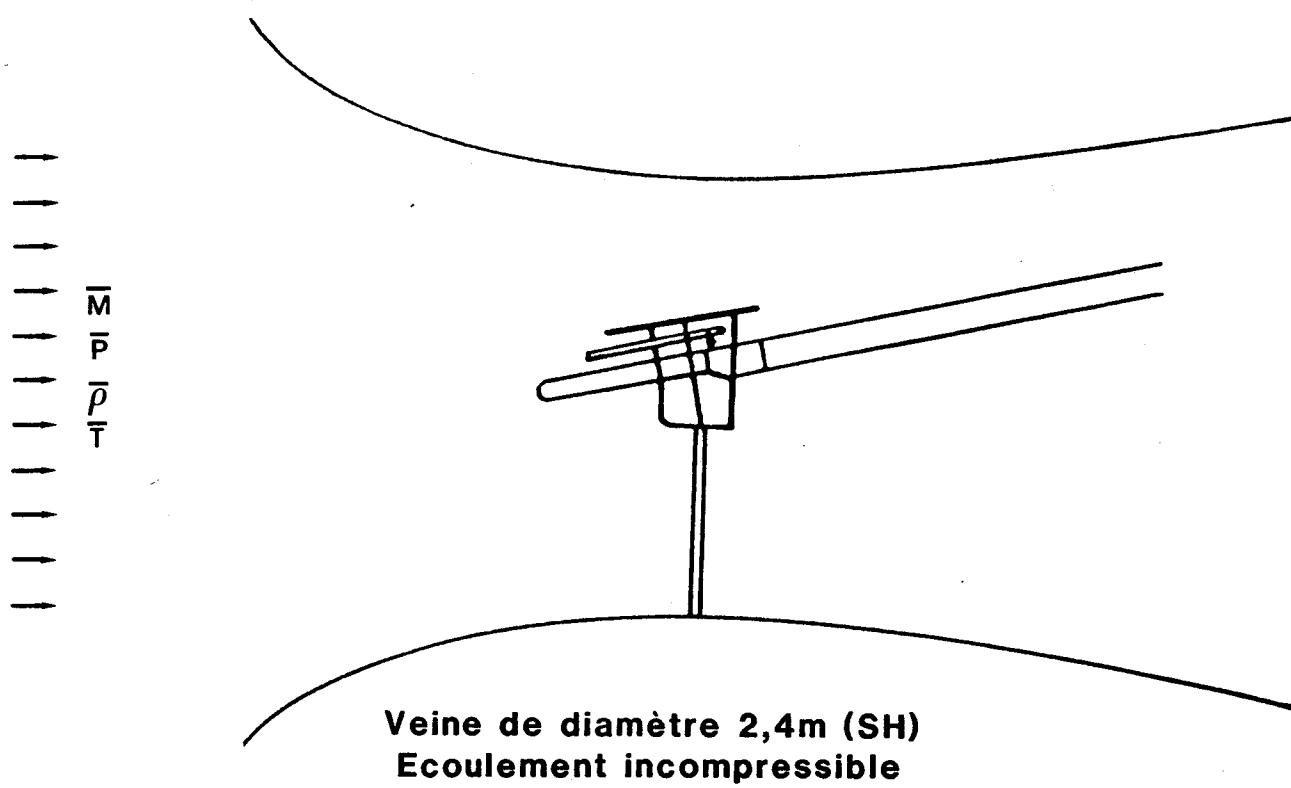


$$\sqrt{\frac{\bar{c}}{c_9}} \sqrt{\frac{\bar{P}}{P_9}} \frac{\bar{c} t}{D} \simeq 0.72$$

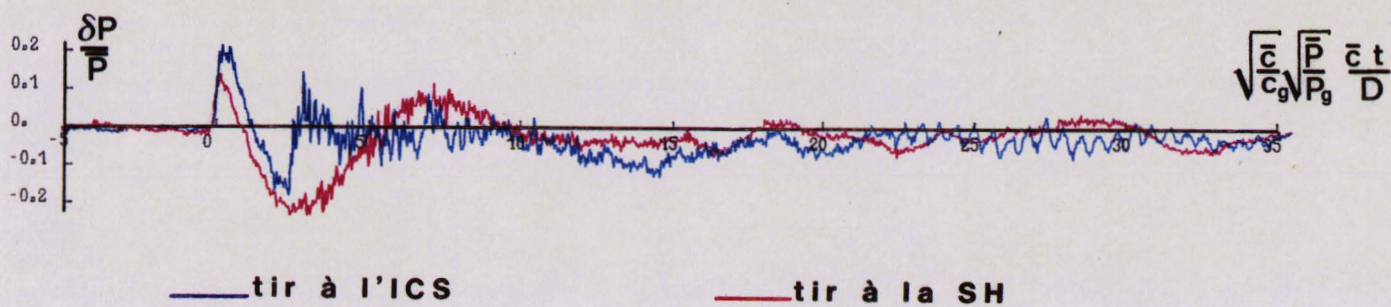
$$\sqrt{\frac{\bar{c}}{c_9}} \sqrt{\frac{\bar{P}}{P_9}} \frac{\bar{c} t}{D} \simeq 0.79$$

Arrivée de l'onde sur le capteur 4

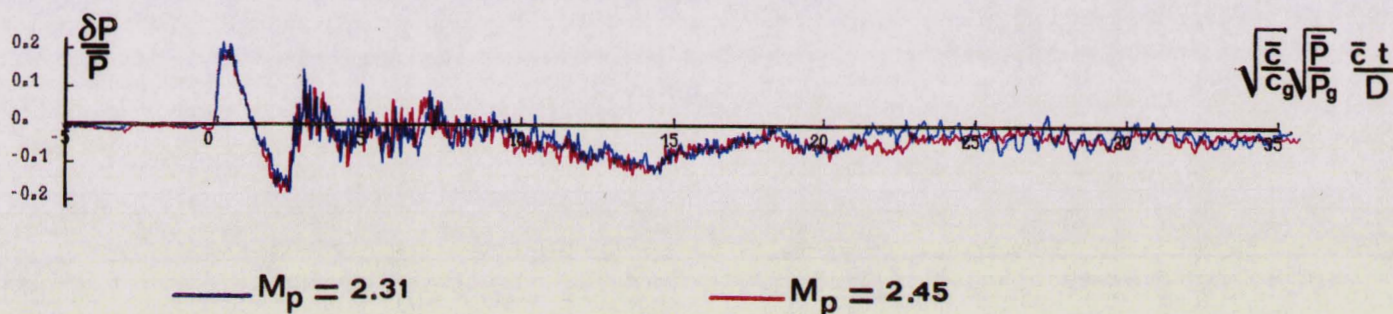
Similitude entre un canon et une carabine  
Visualisations



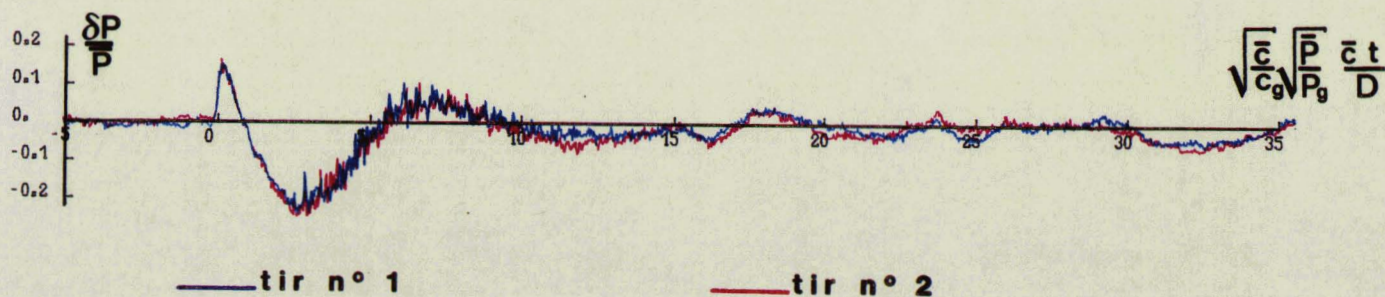
Veine de section 200×150mm (ICS)  
Schéma de montage d'une entrée d'air en soufflerie



**Effet du confinement**

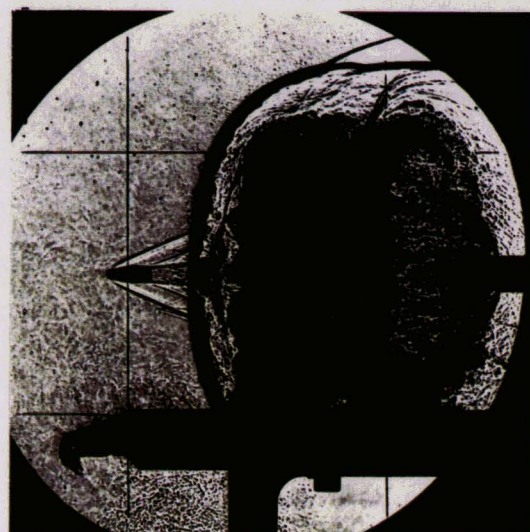
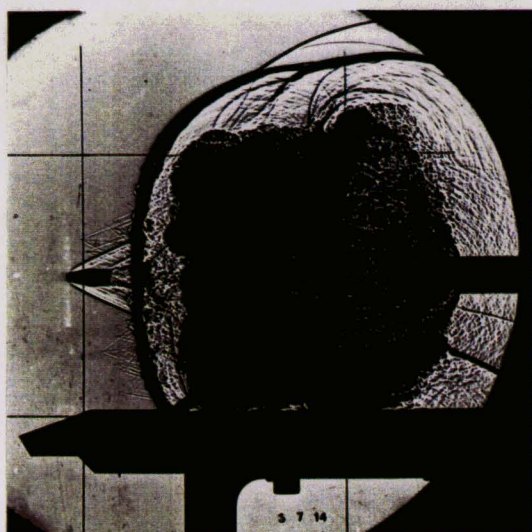


**Effet de  $M_p$**



**Répétitivité**

**Interaction tir-entrée d'air**



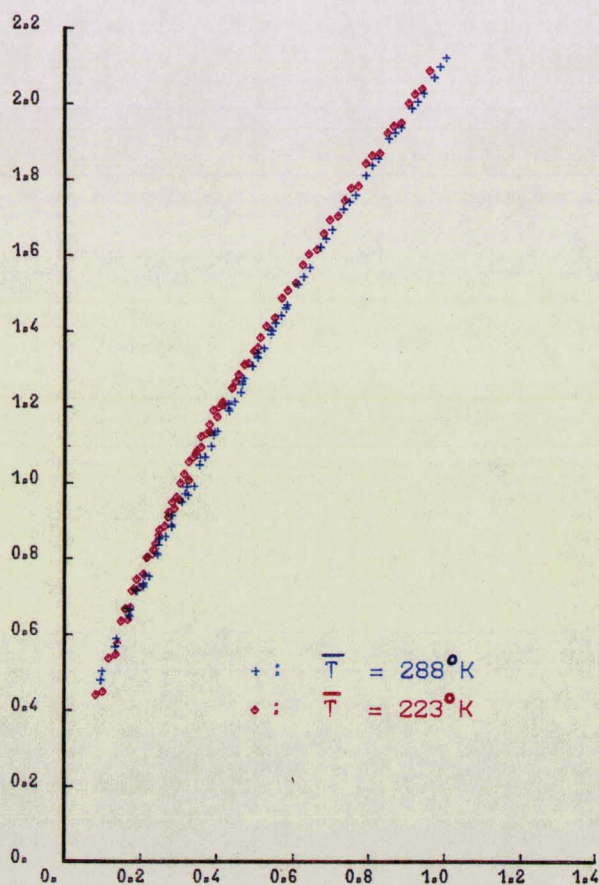
$\bar{T} = 288^\circ\text{K}$

$\bar{P} = 1 \text{ bar}$

$d = 10 D$

$\bar{T} = 223^\circ\text{K}$

$$\frac{\sqrt{\bar{c}} \sqrt{\bar{P}}}{\sqrt{c_g} \sqrt{P_g}} \frac{X}{D}$$



$$\frac{\sqrt{\bar{c}} \sqrt{\bar{P}}}{\sqrt{c_g} \sqrt{P_g}} \frac{\bar{c} t}{D}$$

Effet de  $\bar{T}$  sur un tir en présence d'un obstacle

( plaque plane infinie )



$t = 50 \mu s$



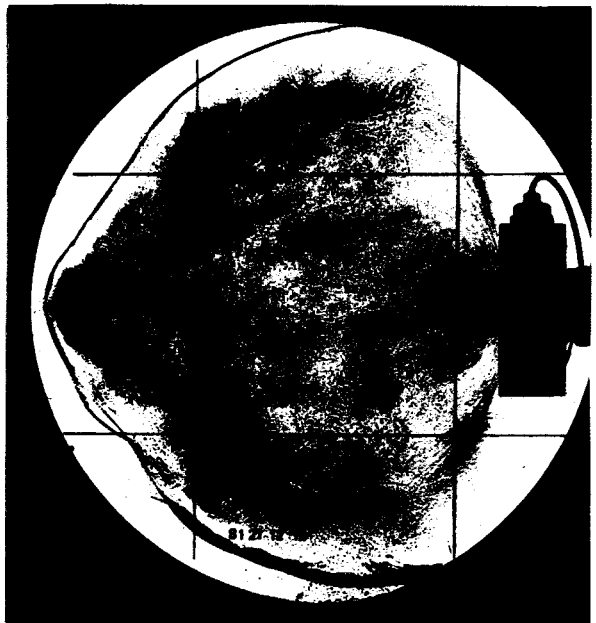
$t = 70 \mu s$

$\bar{P} = 0.2 \text{ bar}$

$\bar{T} = 223 \text{ K}$

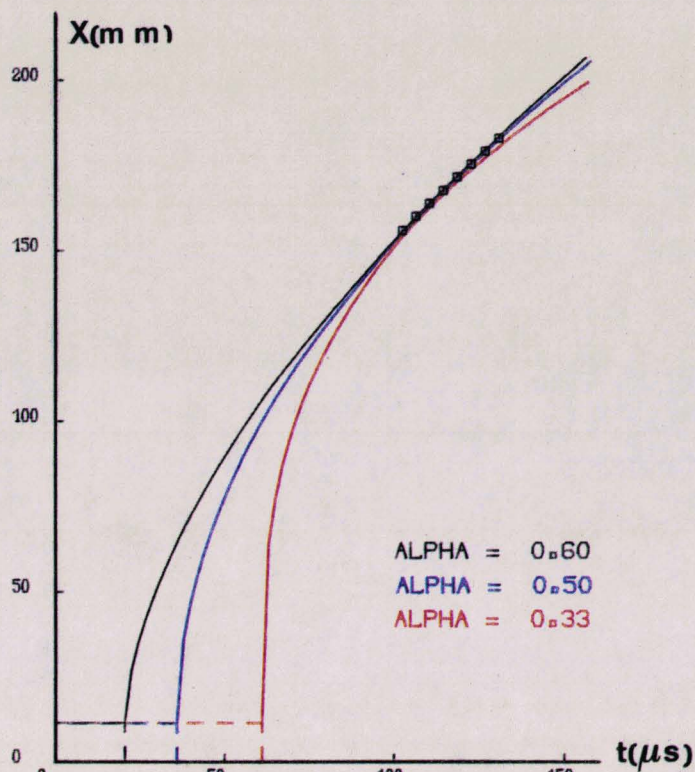


$t = 90 \mu s$

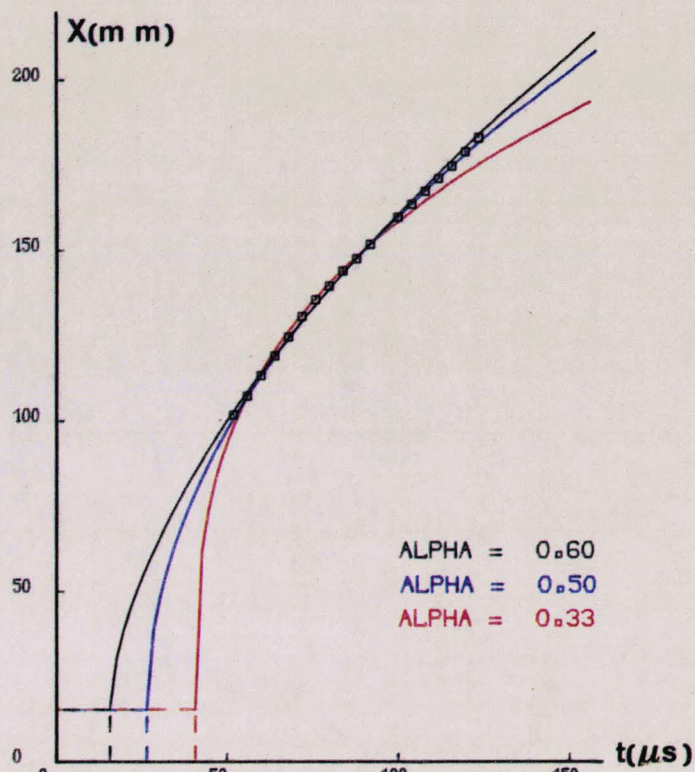


$t = 114 \mu s$

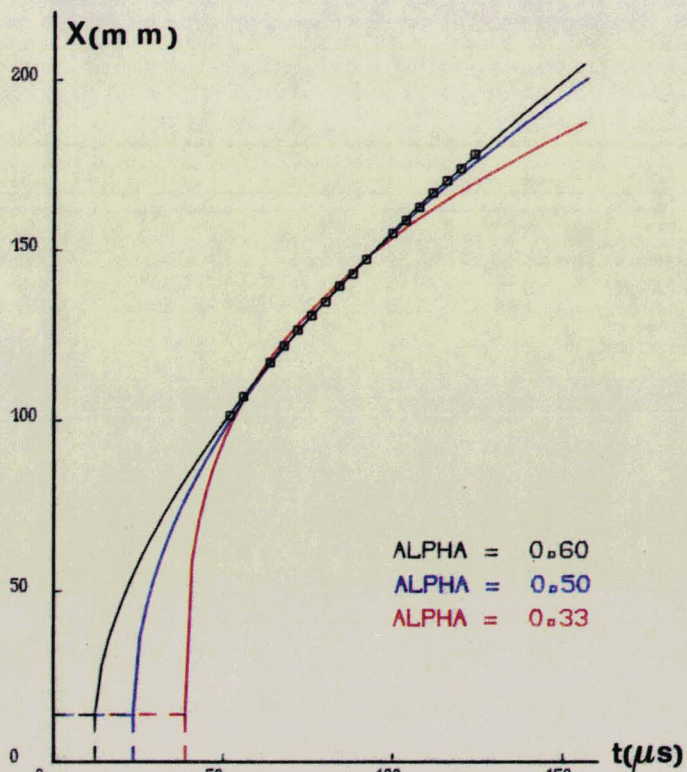
Forme de l'onde



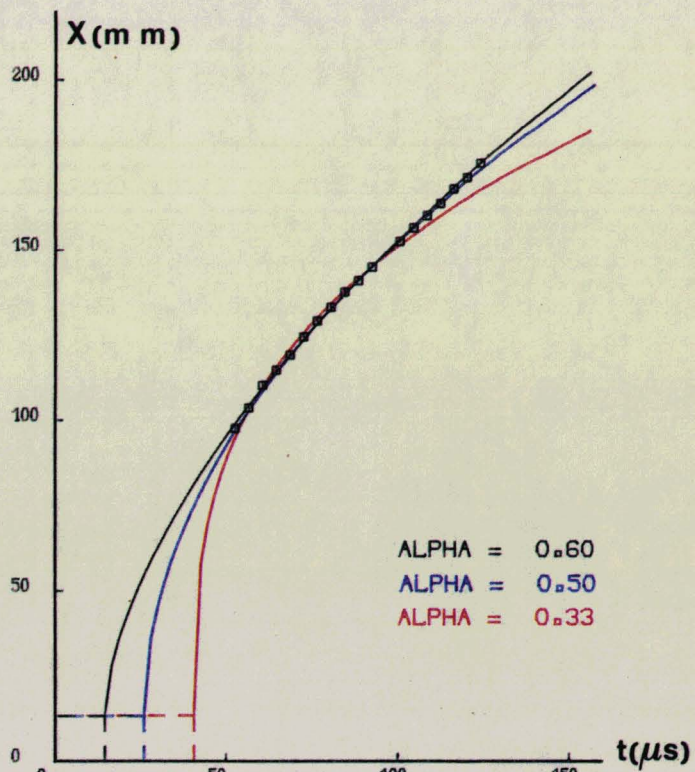
Essai 1



Essai 2



Essai 3

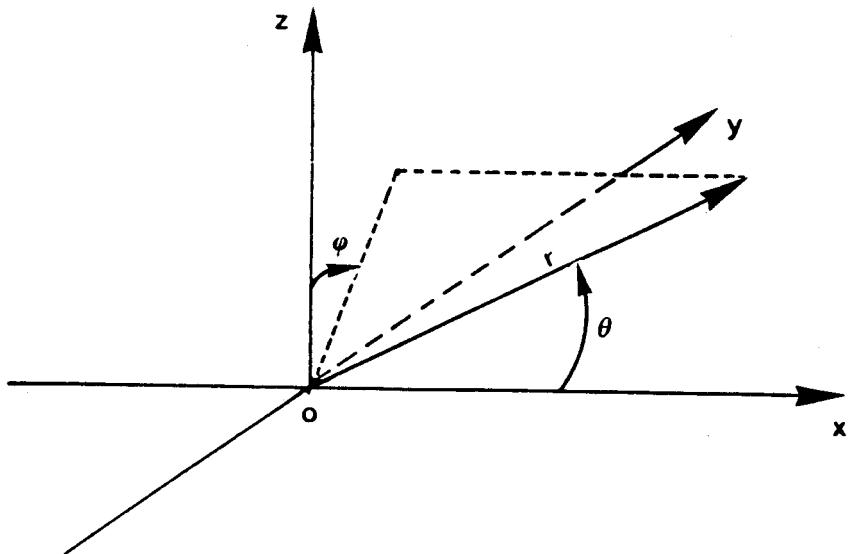


Essai 4

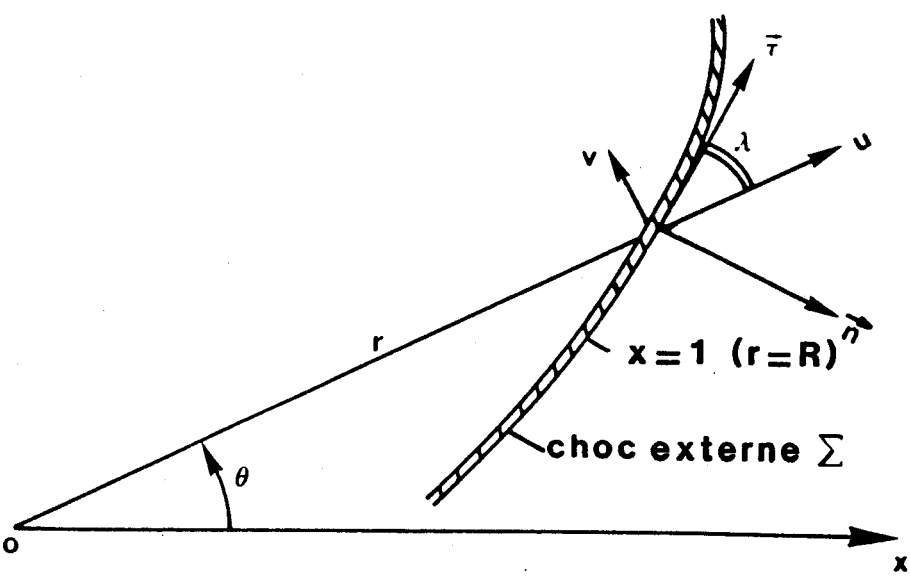
Comparaison tir-modèle

(Essais à  $\bar{P} = 0.2$  bar)

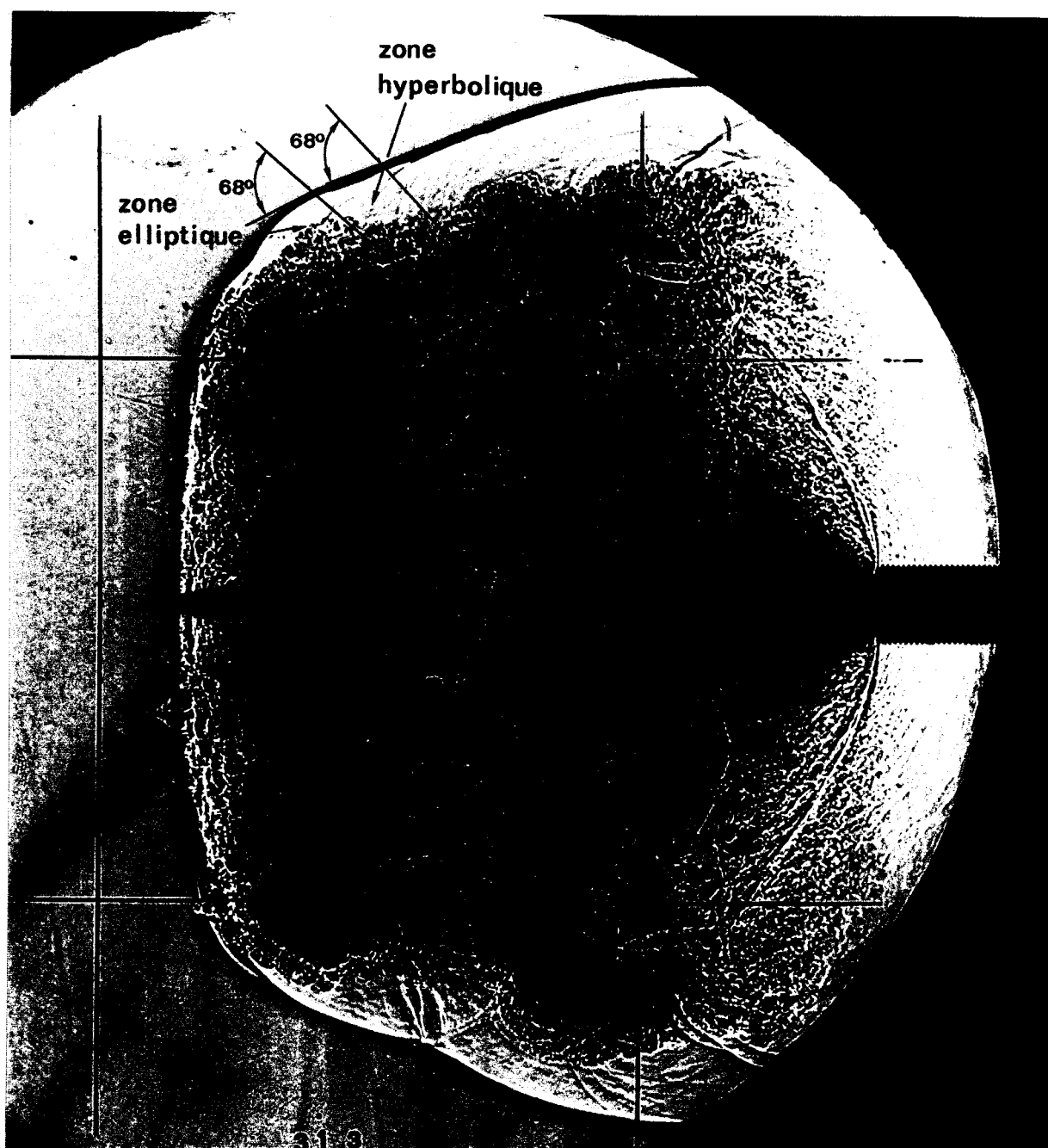




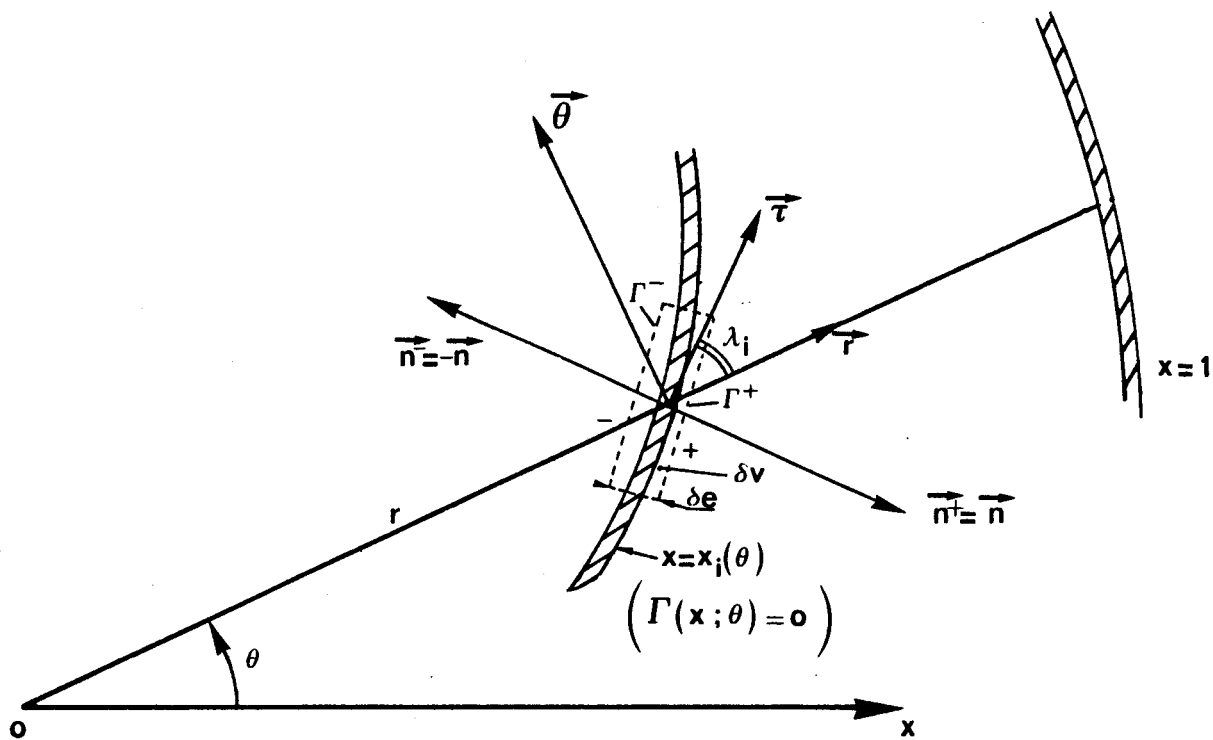
Repère



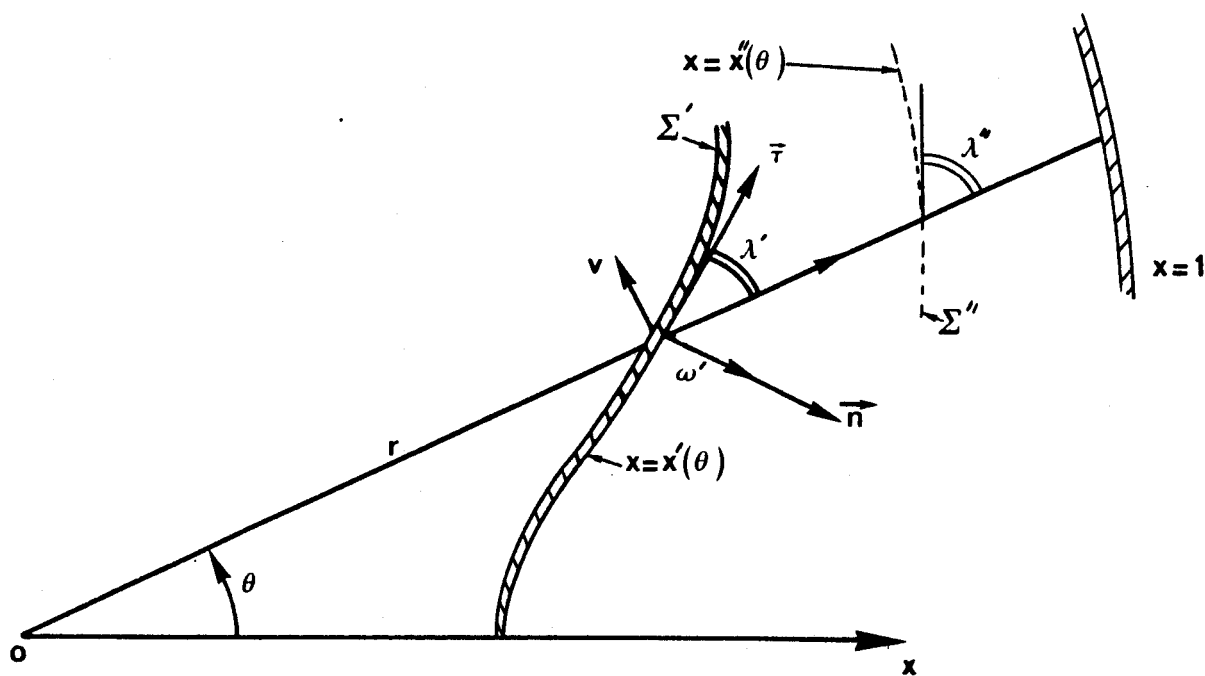
Notations sur le choc externe



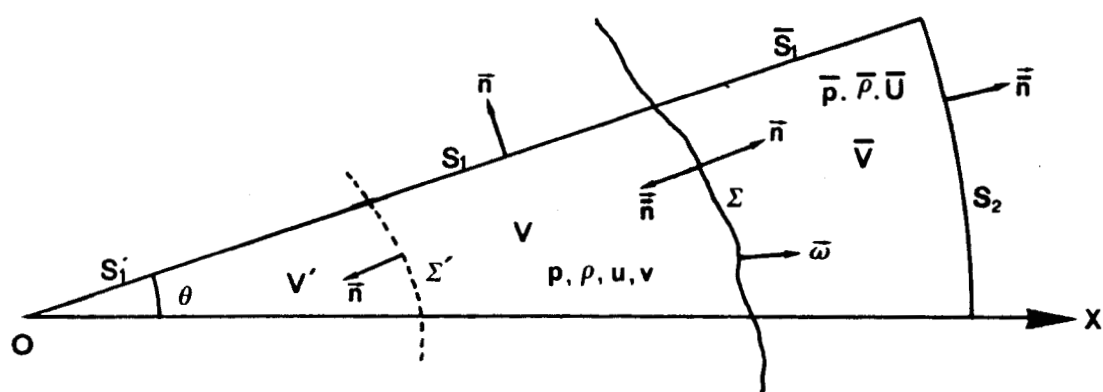
**Visualisation ultra rapide d'une onde de choc  
anisotrope créée par un tir d'arme**



Notations sur les chocs internes



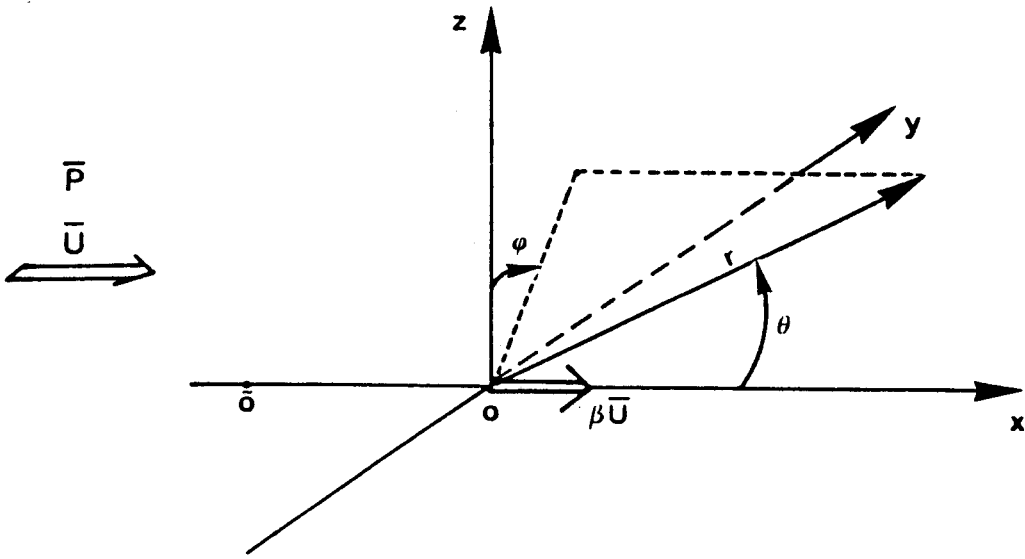
Notations sur la frontière du vide



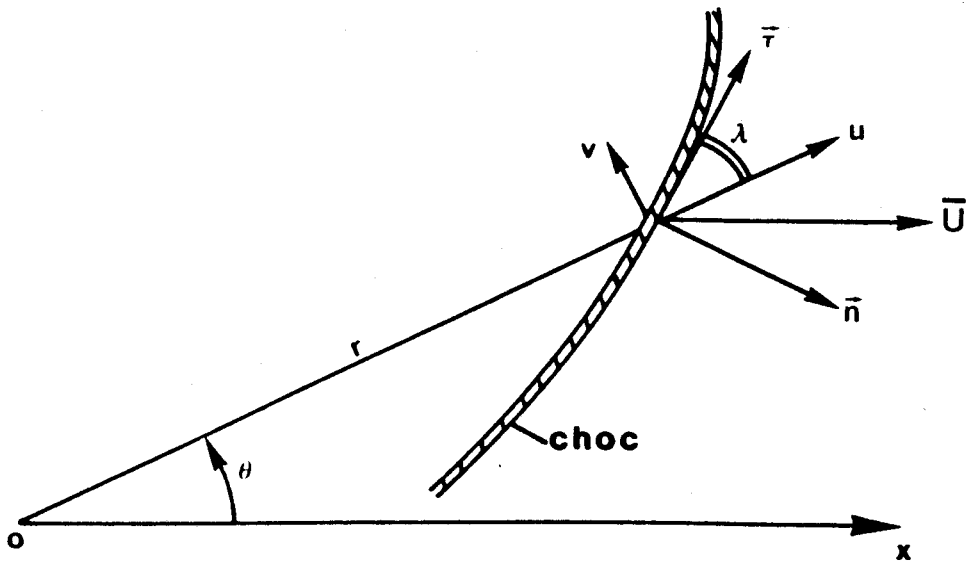
$\Sigma$  représente le choc

$\Sigma'$  la limite éventuelle du vide

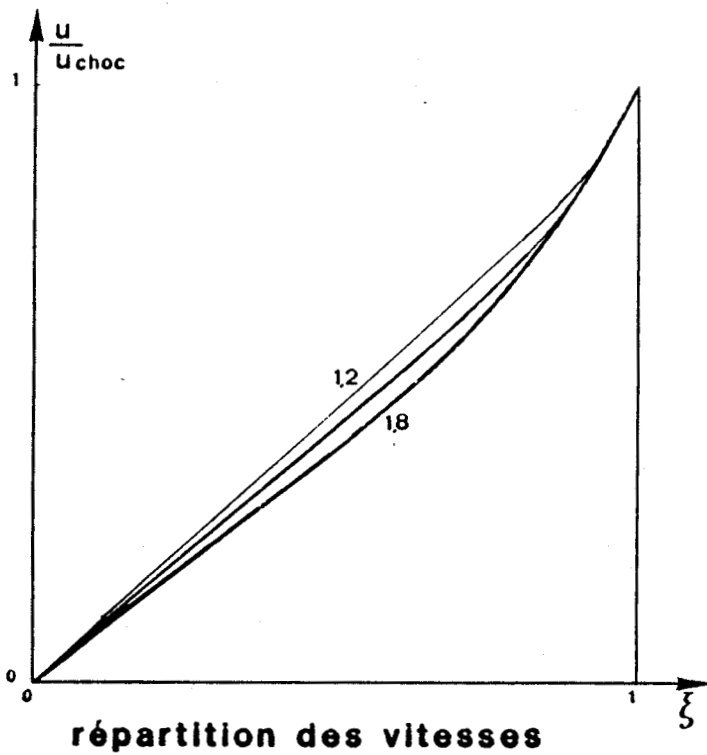
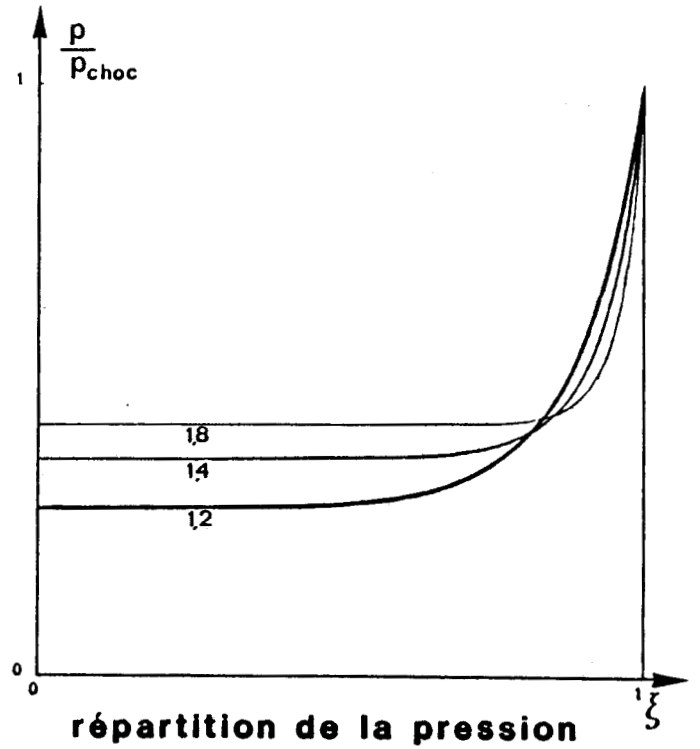
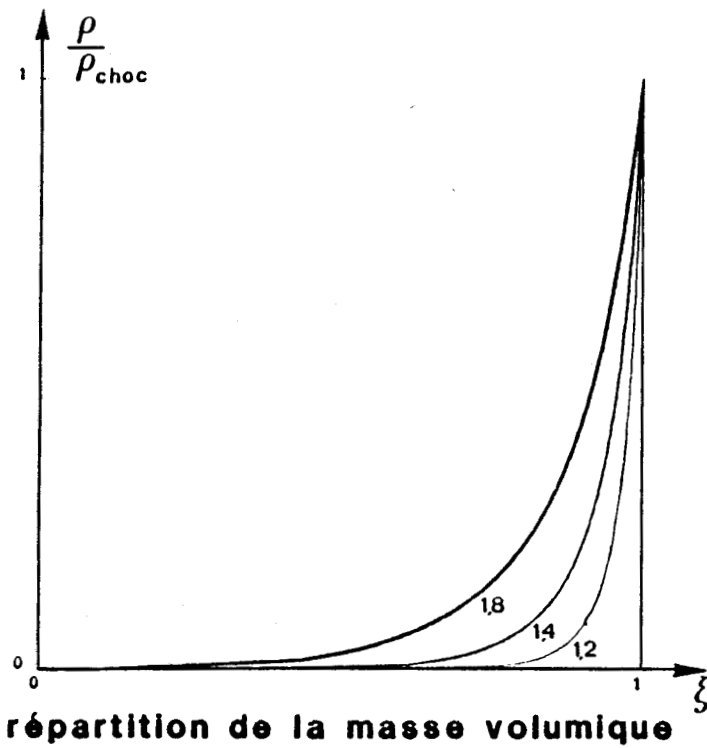
Domaine d'intégration pour l'équation de l'énergie



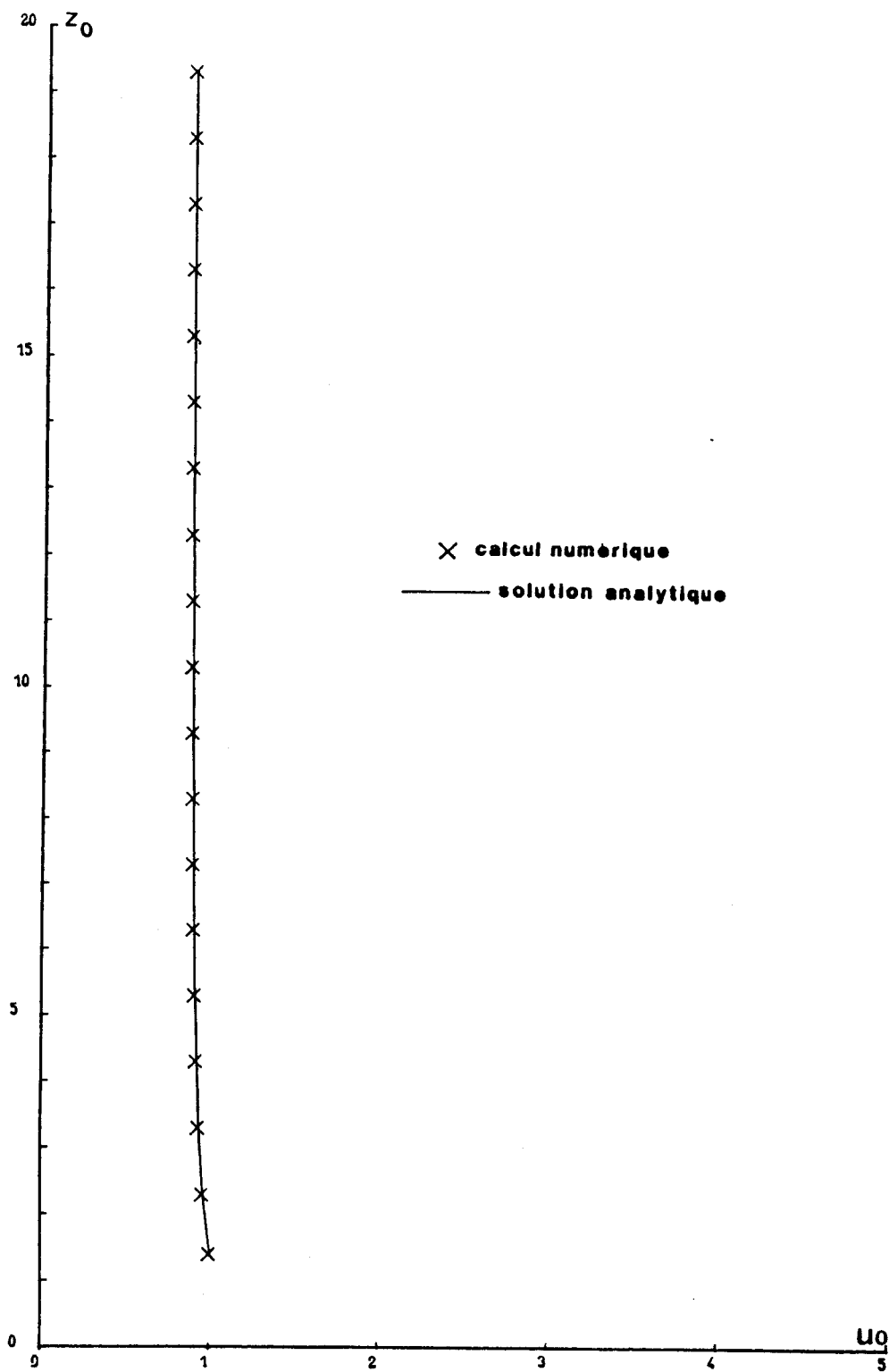
Repère



Notations sur le choc



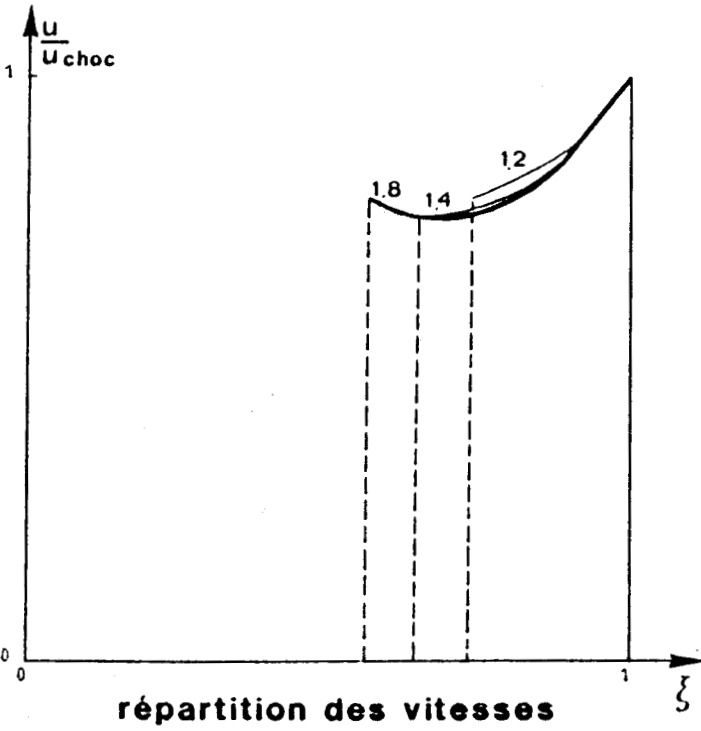
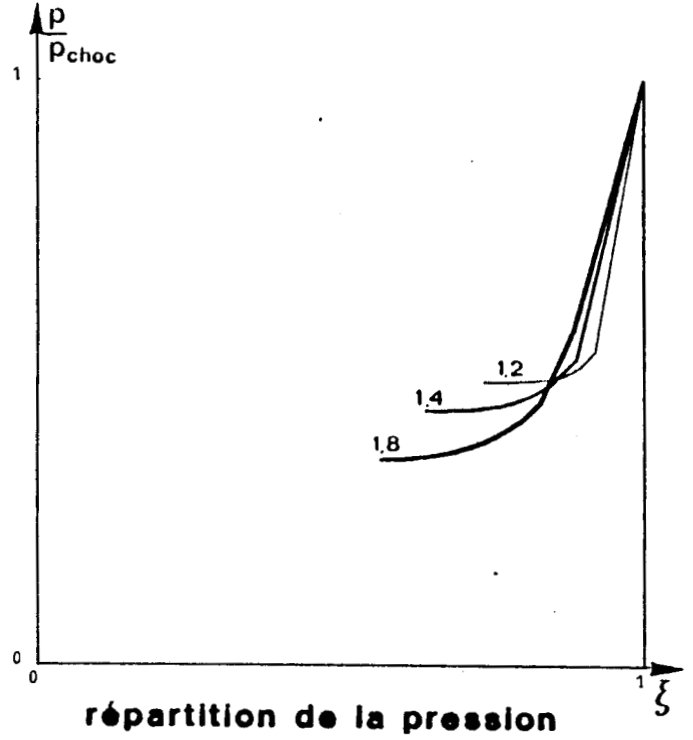
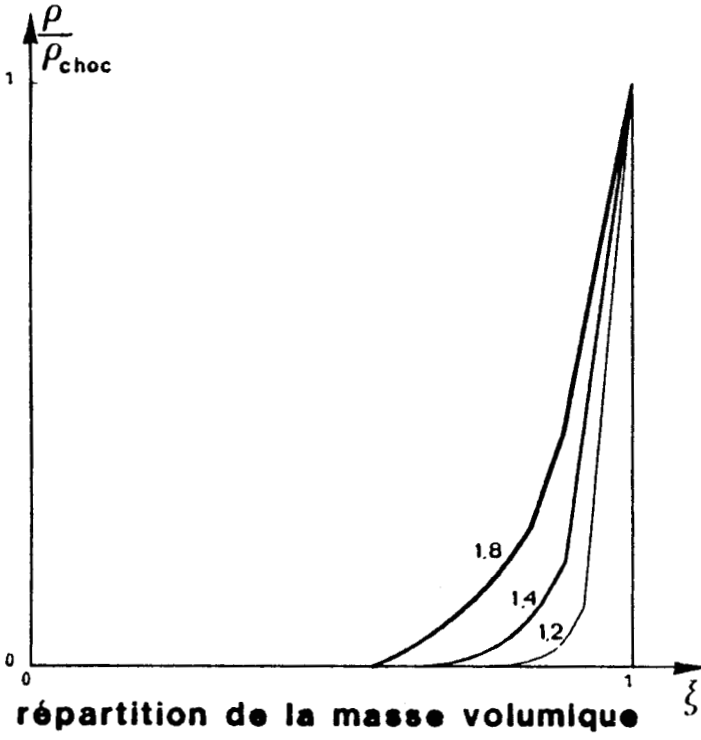
- $\gamma = 1.2$
- $\gamma = 1.4$
- $\gamma = 1.8$



Intégration de  $\frac{dz_0}{du_0} = G_1(u_0, z_0)$

Comparaison solution analytique-calcul numérique

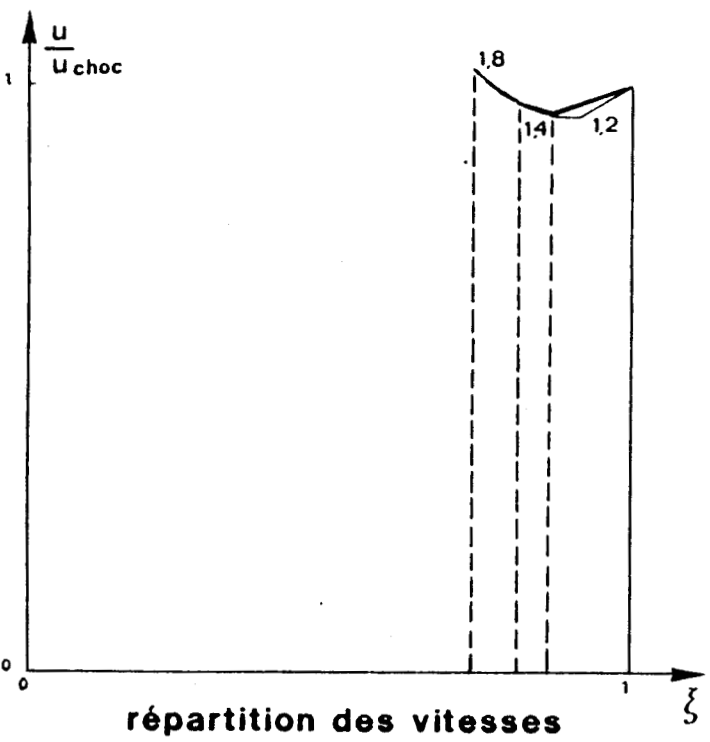
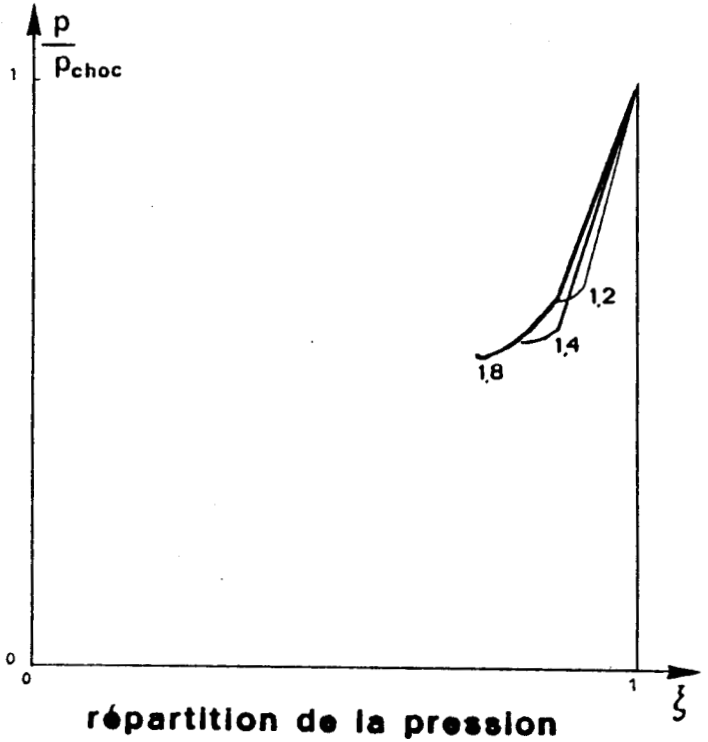
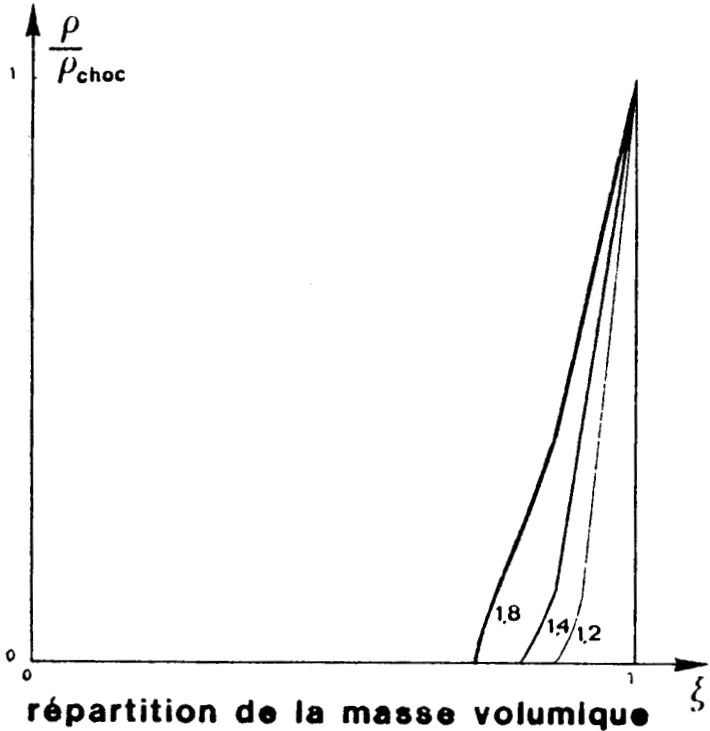
$$\gamma = 1.4 \quad \alpha = 0$$



- $\gamma = 1,2$
- $\gamma = 1,4$
- $\gamma = 1,8$

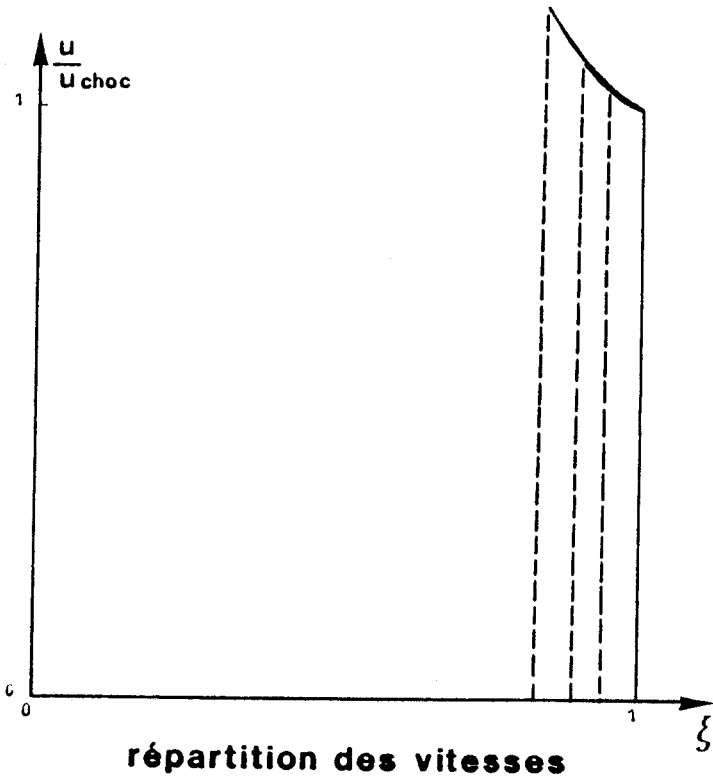
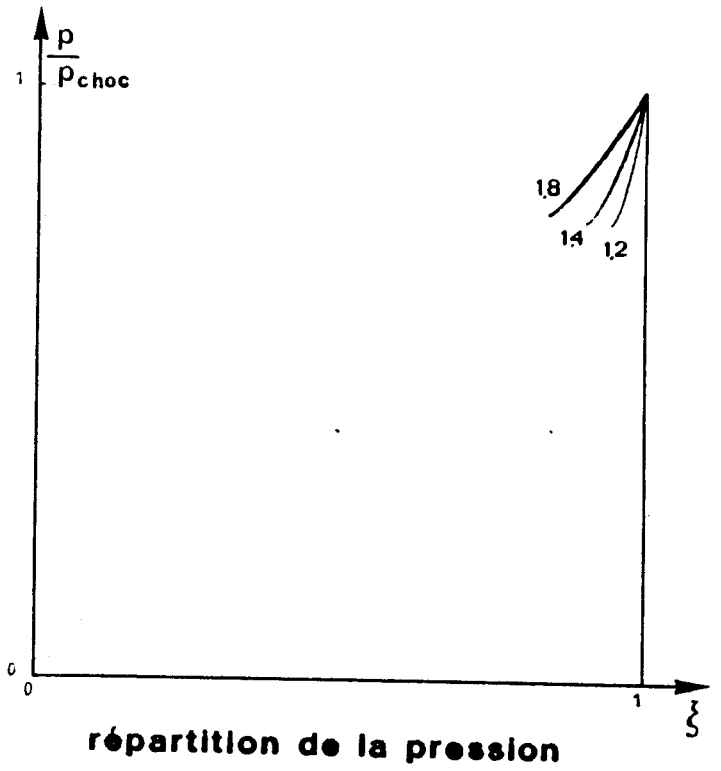
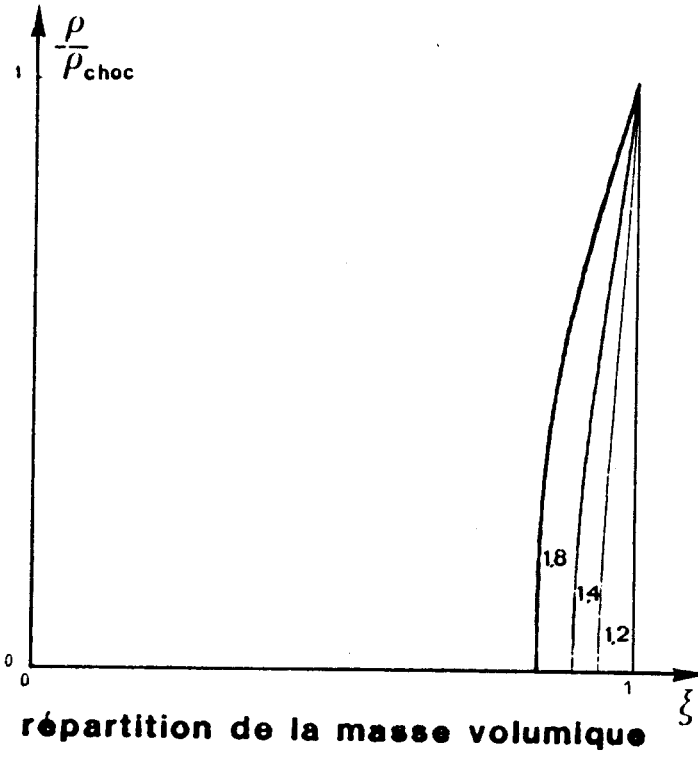
Résultats numériques à l'ordre 0 : ( $\alpha = 0,1$ )





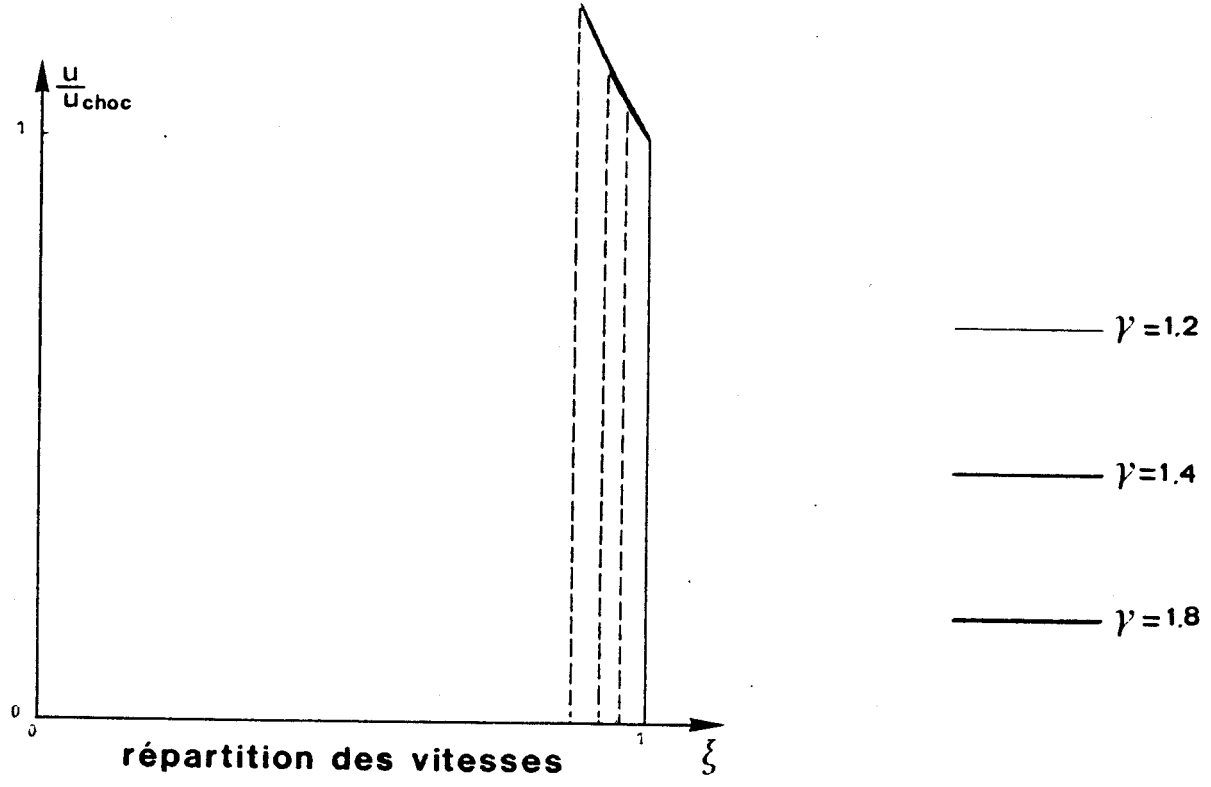
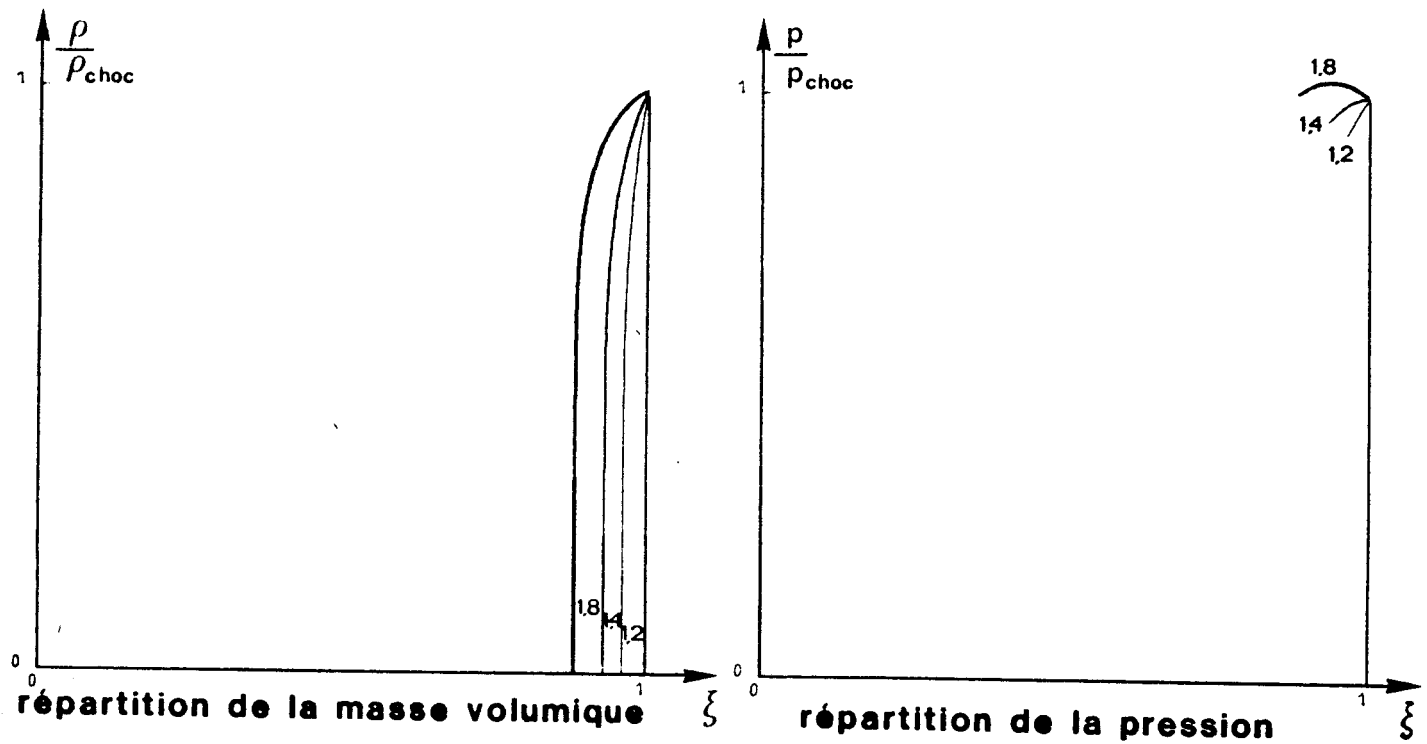
- $\gamma = 1,2$
- $\gamma = 1,4$
- $\gamma = 1,8$

Résultats numériques à l'ordre 0 : ( $\alpha = 0,35$ )

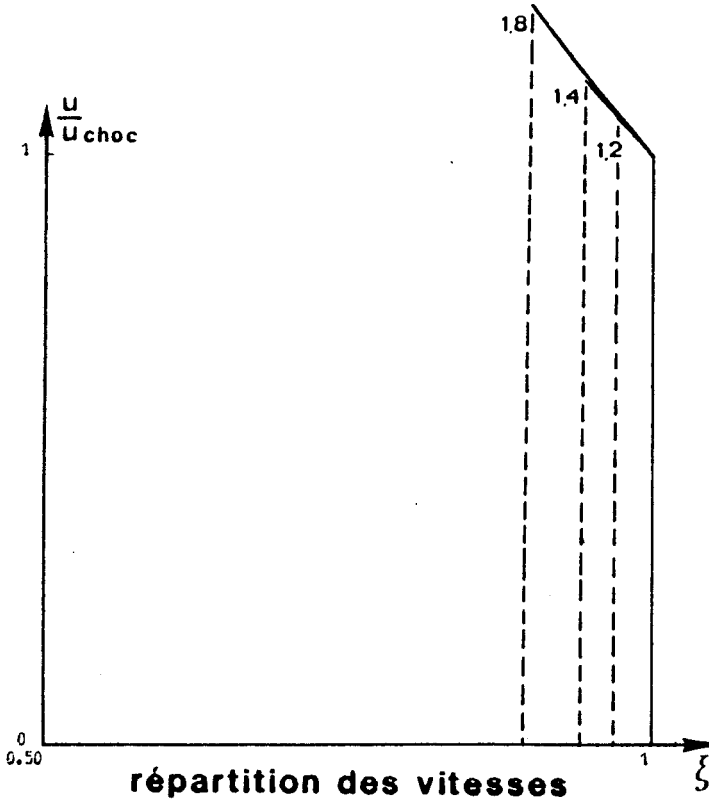
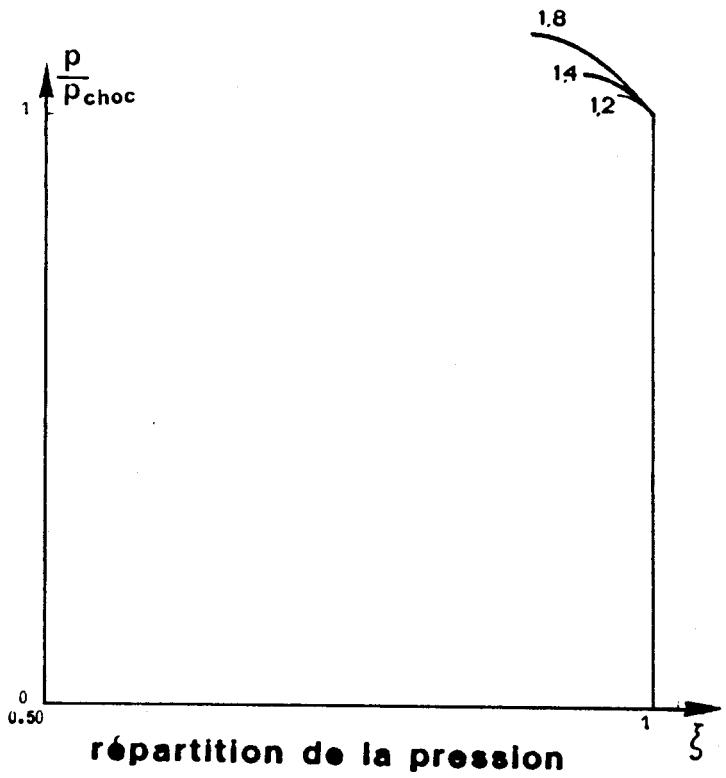
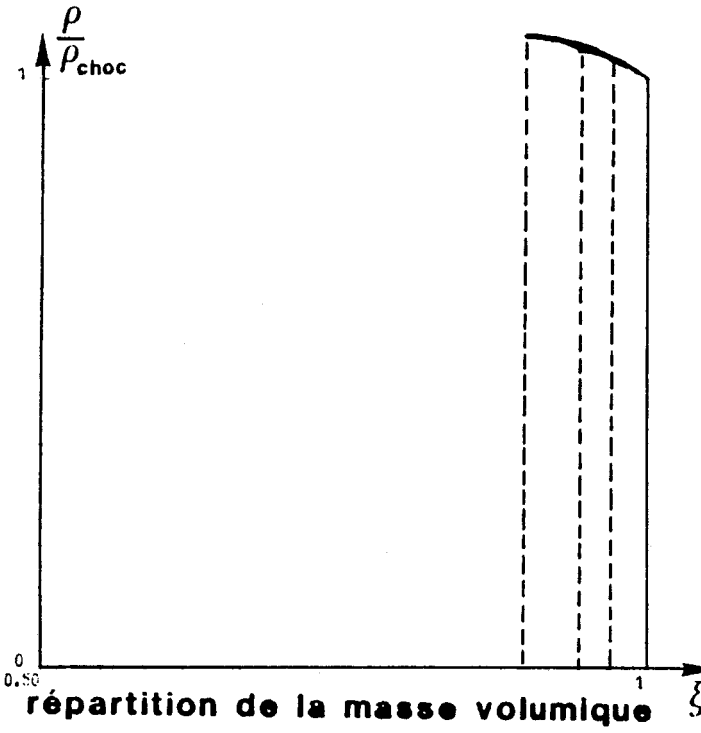


- $\gamma = 1,2$
- $\gamma = 1,4$
- $\gamma = 1,8$

Résultats numériques à l'ordre 0 : ( $\alpha = 1$ )

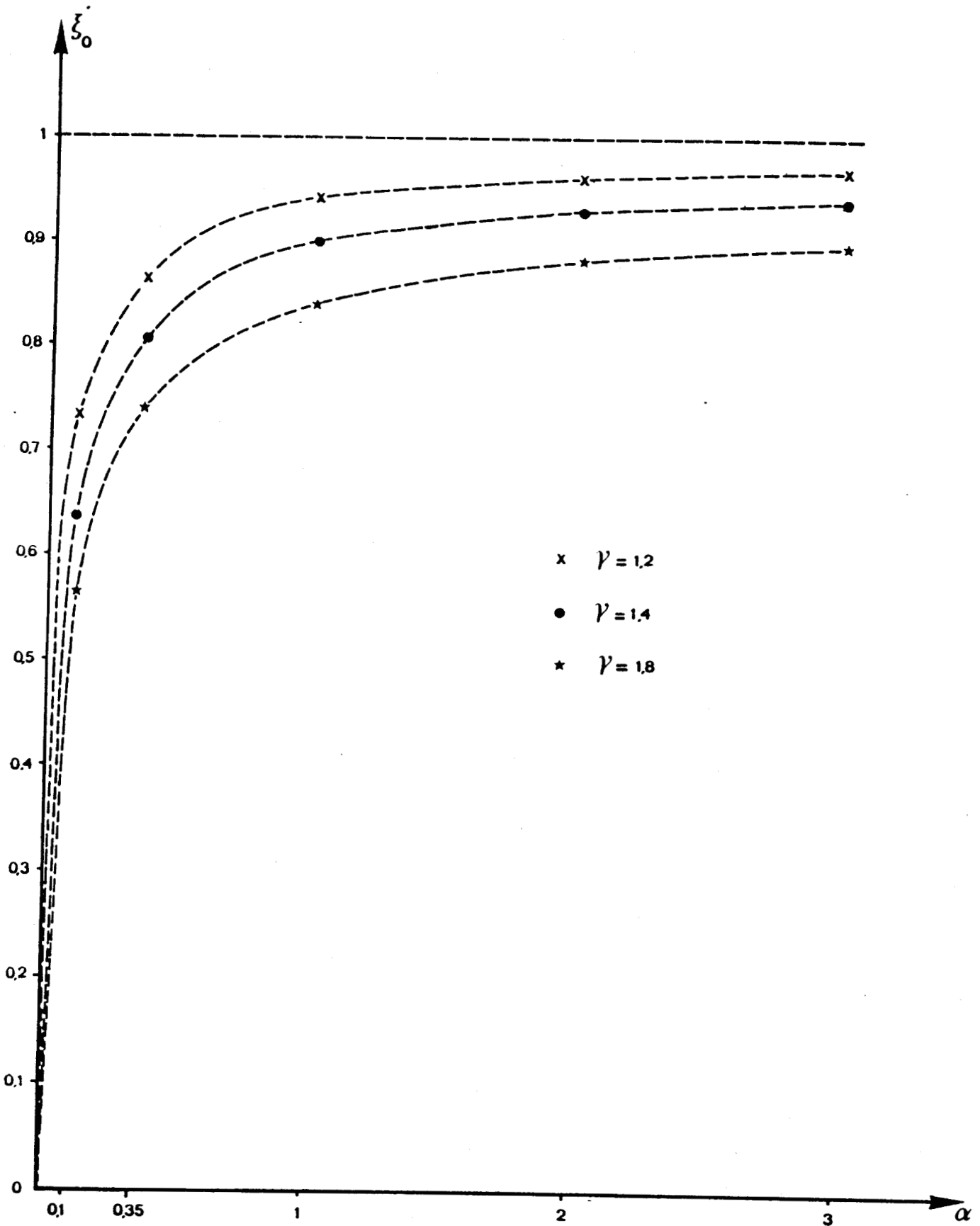


Résultats numériques à l'ordre 0 : ( $\alpha = 2$ )

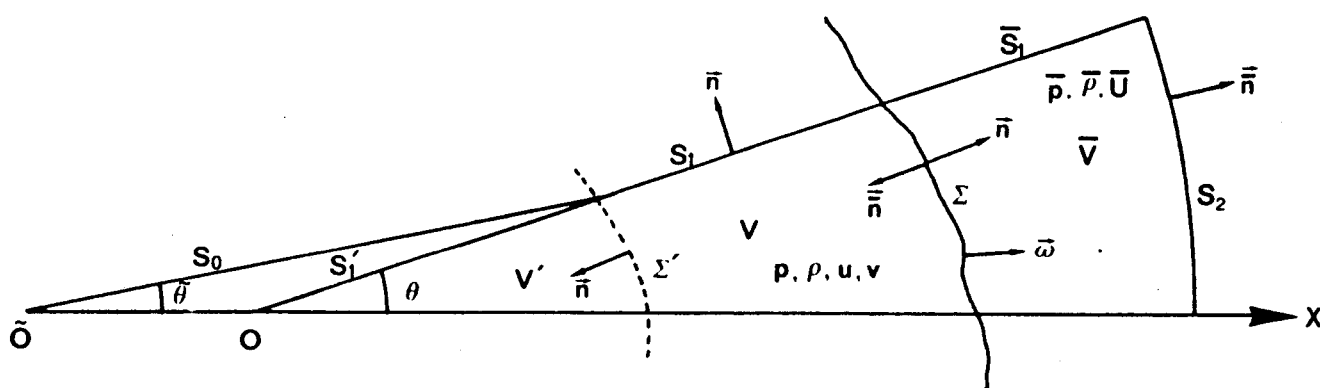


- $\gamma = 1,2$
- $\gamma = 1,4$
- $\gamma = 1,8$

Résultats numériques à l'ordre 0 : ( $\alpha = 3$ )



$\xi_0'$  en fonction de  $\alpha$

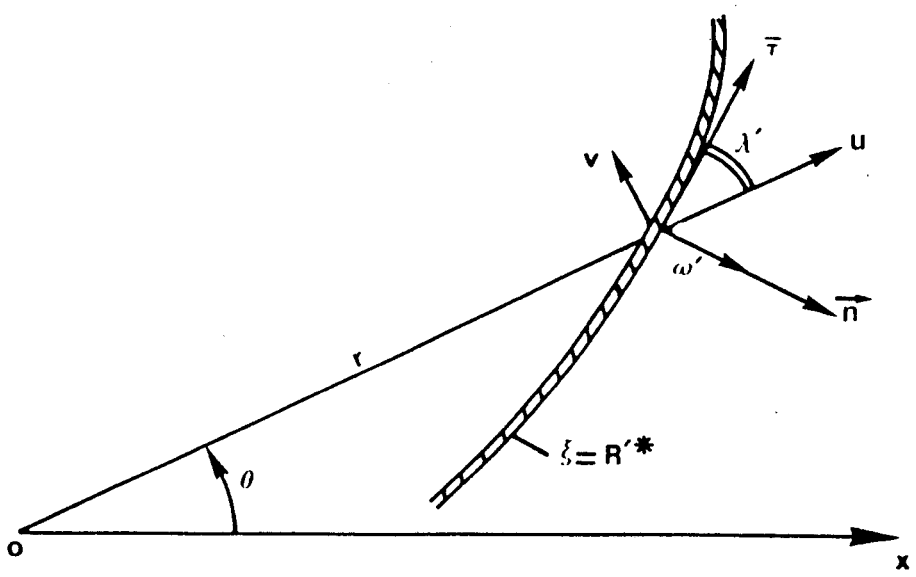


$\Sigma$  représente le choc

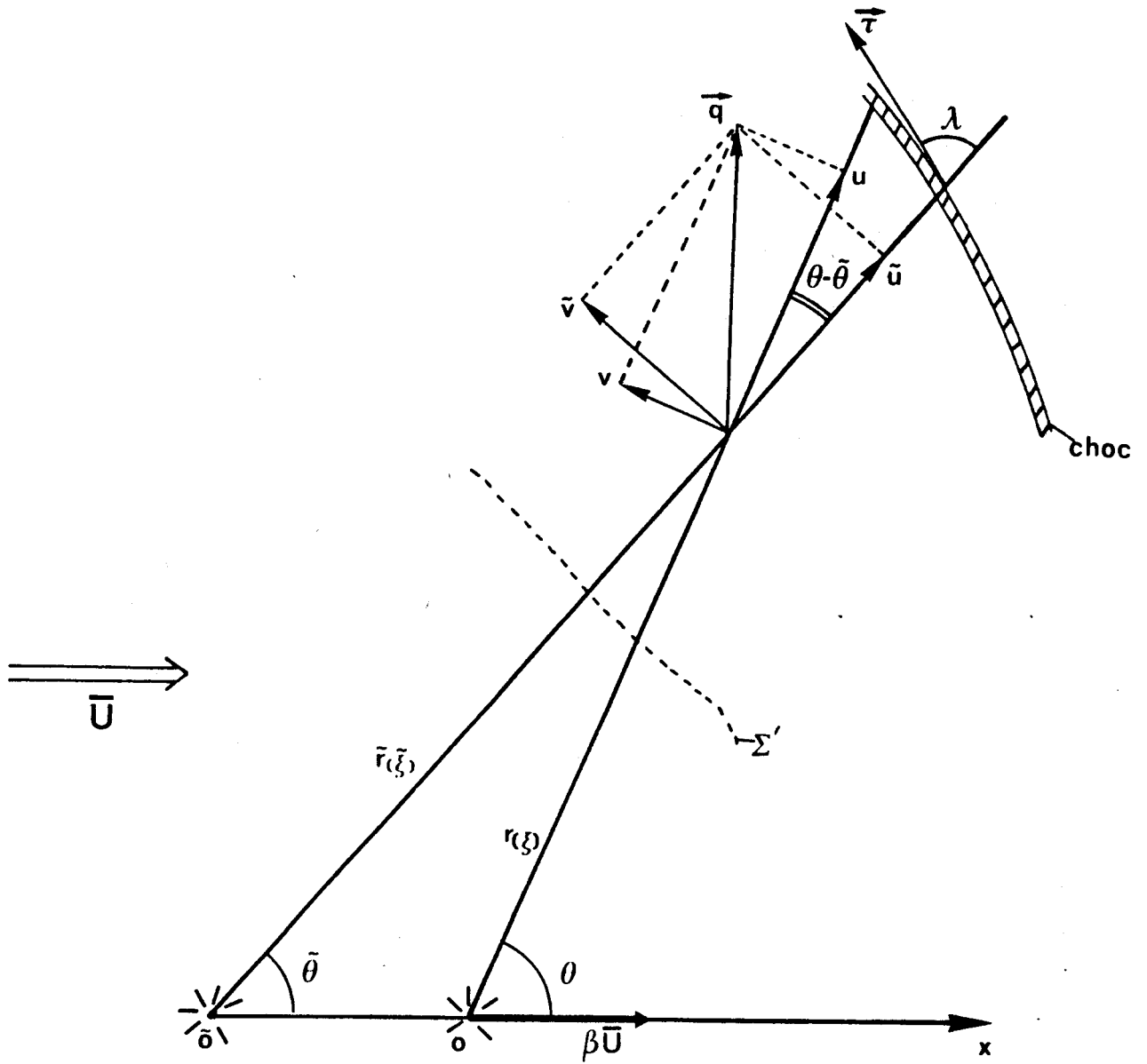
$\Sigma'$  la limite éventuelle du vide

$V_0$  est le volume limité par  $S_0$  et  $\Sigma'$

**Domaine d'intégration pour l'équation de l'énergie**



Notations sur la limite du vide

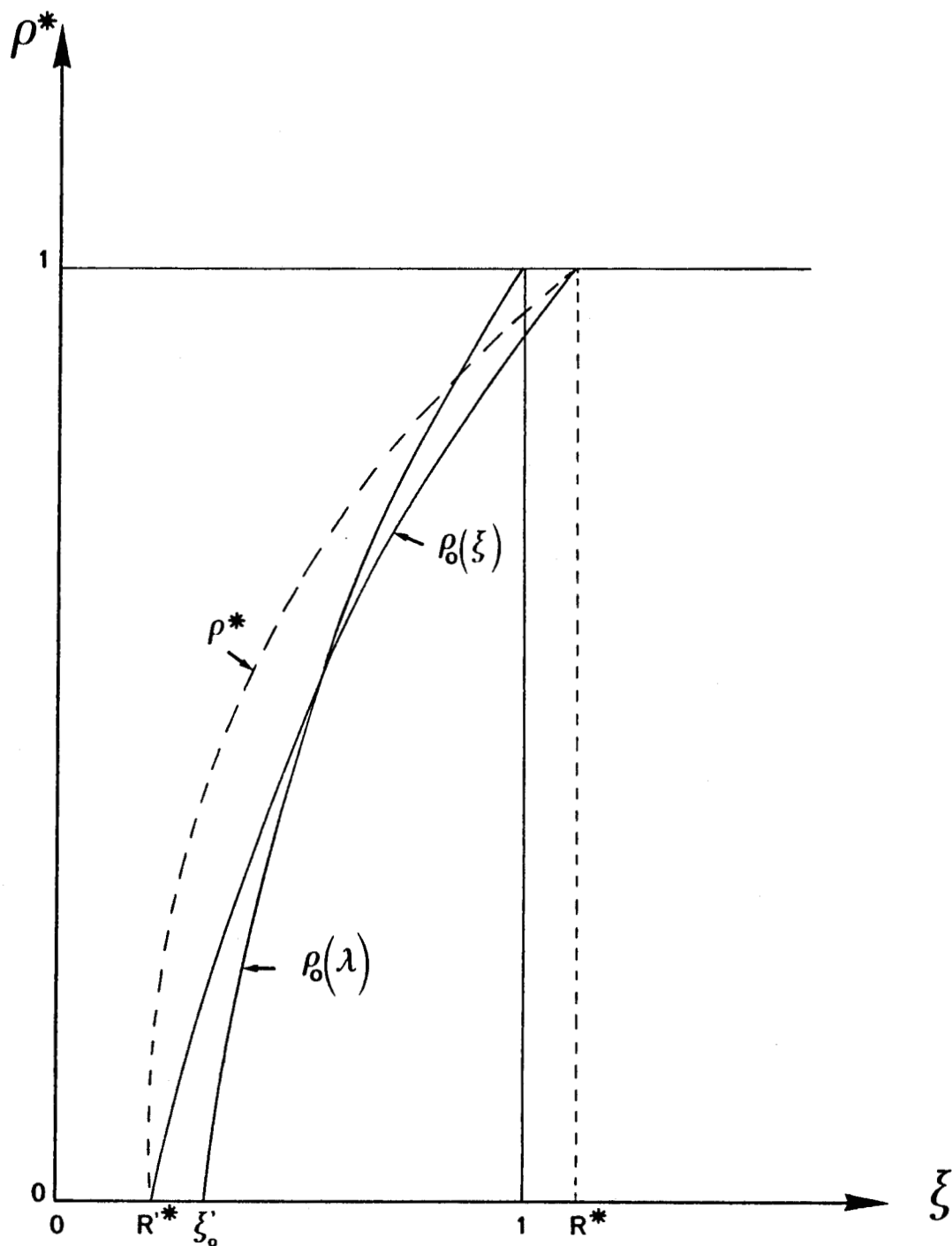


**REPERES**

- NOTATIONS:**
- (O) repère mobile centré en O de vitesse  $\beta\bar{U}$   
coordonnées  $r, \theta$
  - ( $\tilde{O}$ ) repère fixe centré en  $\tilde{O}$  lieu de l'explosion  
coordonnées  $\tilde{r}, \tilde{\theta}$

**Comparaison repère fixe - repère mobile**



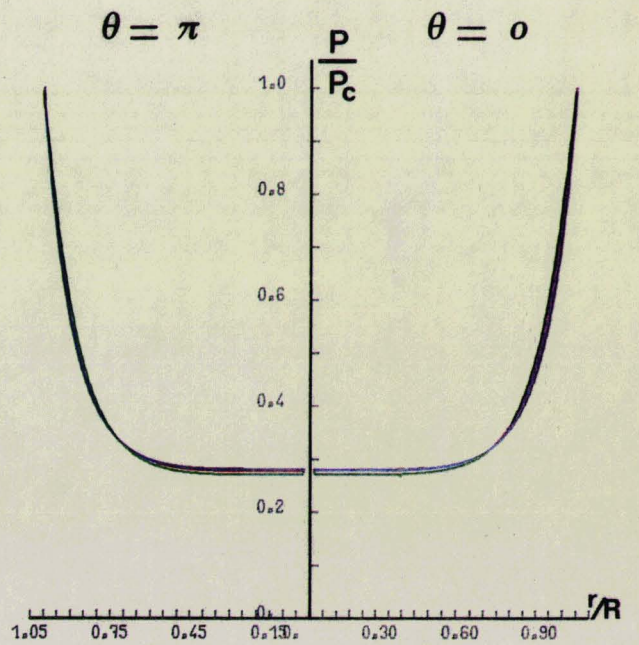
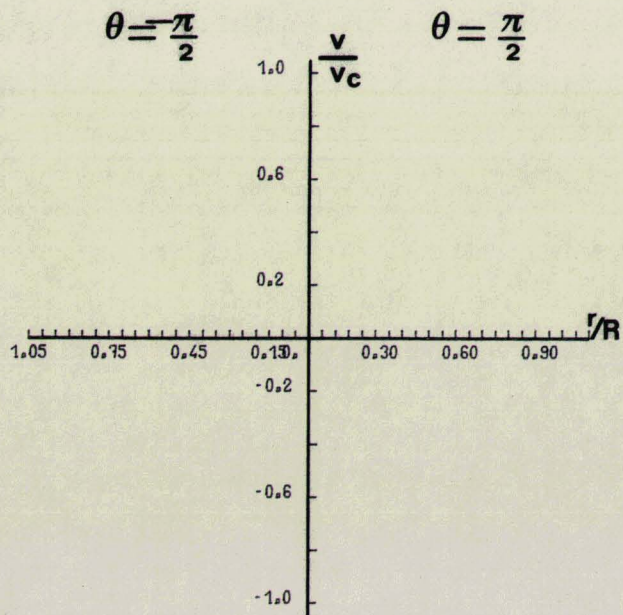
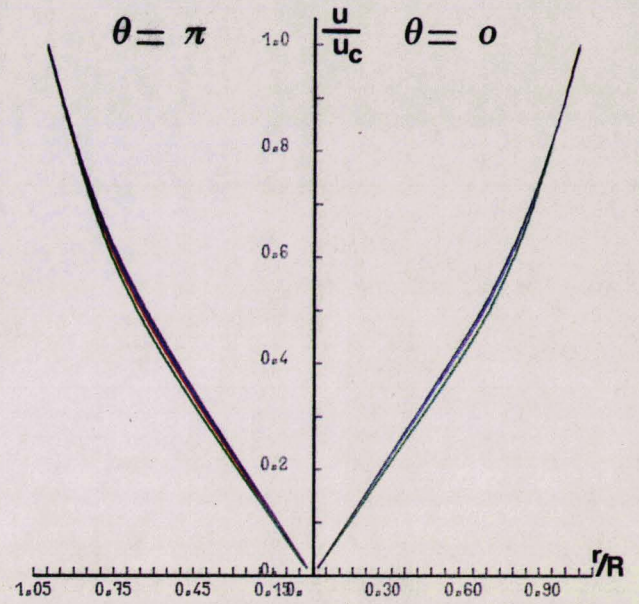
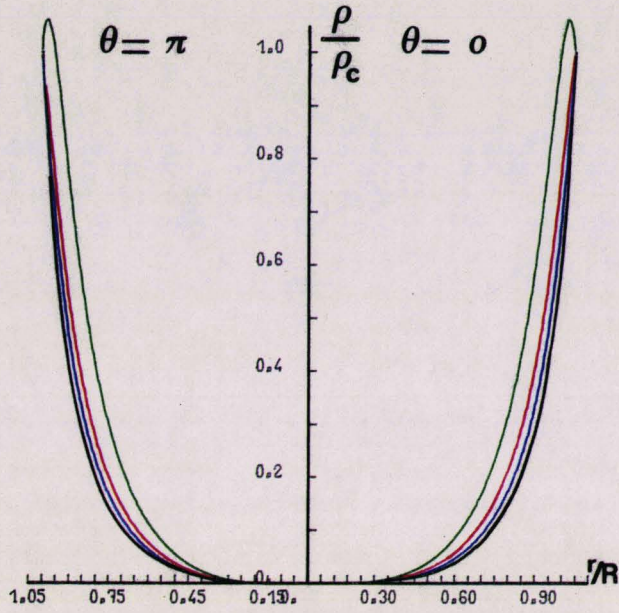


$$R^* = 1 + \eta \xi_1 \cos \theta + \eta^2 [\xi_{20} + \xi_{21} \cos 2\theta]$$

$$R^* = \xi'_0 + \eta^2 [\xi'_{20} + \xi'_{21} \cos 2\theta]$$

**Dilatation de la solution d'ordre 0 au cours du temps**

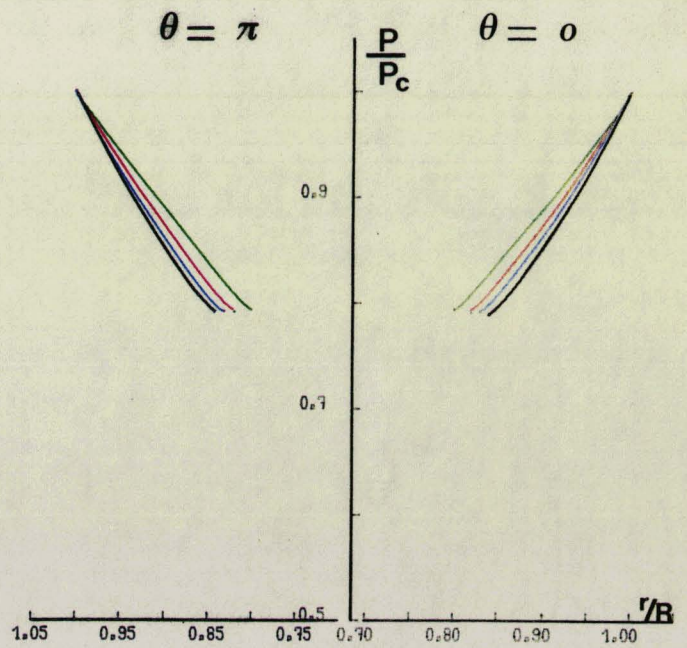
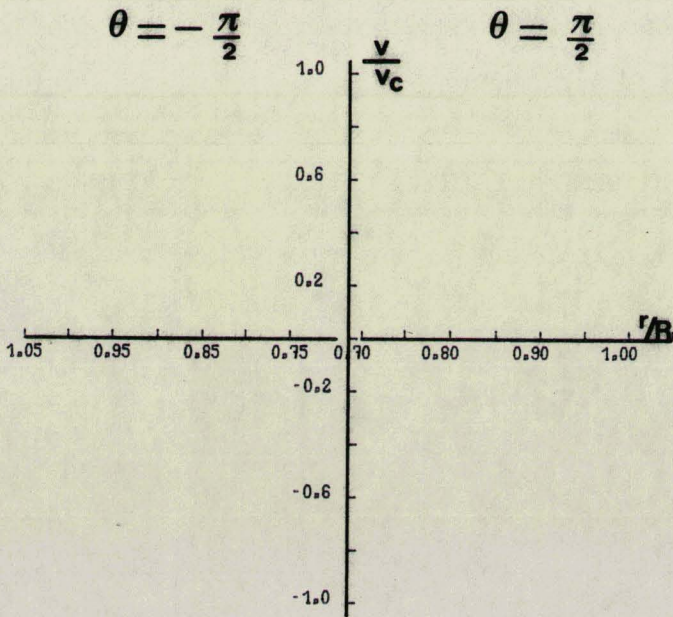
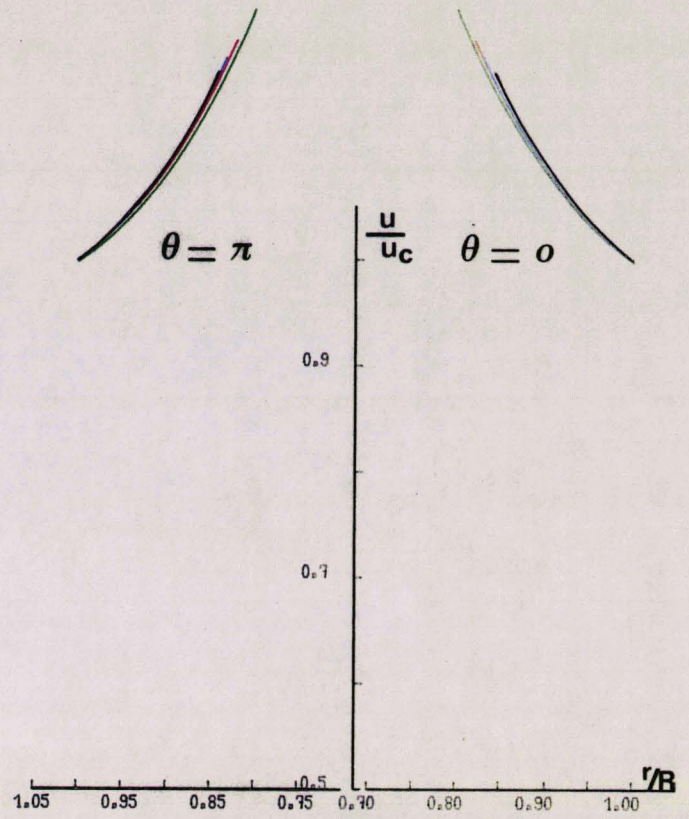
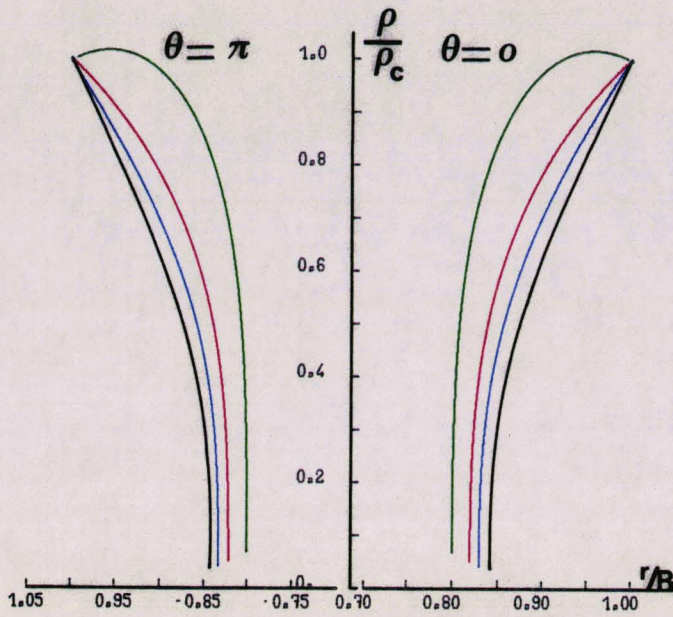
- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$
- $M_c = 2.5$



$\gamma = 1.8$        $\alpha = 0$

Répartitions vues dans le repère mobile

- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$
- $M_c = 2.5$



$\gamma = 1.8$

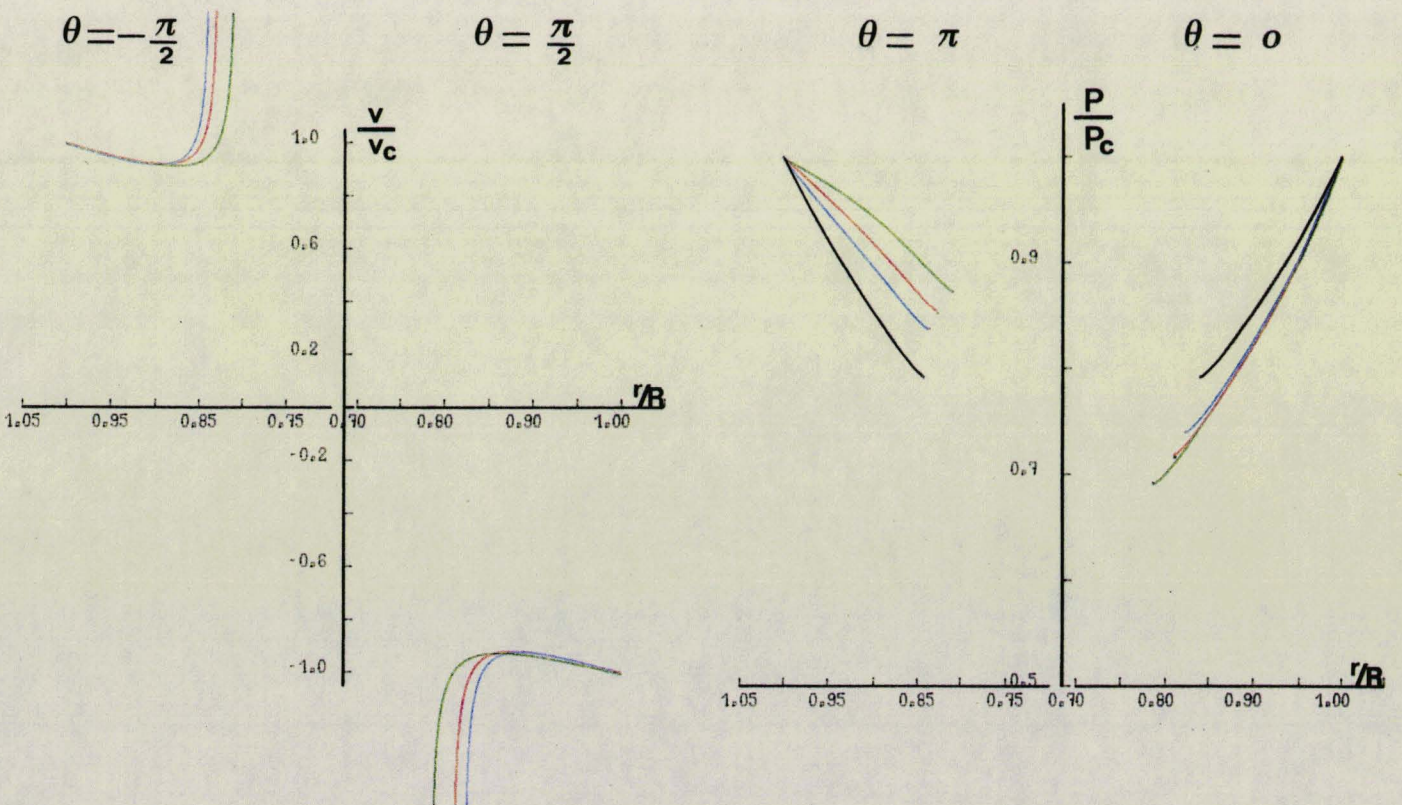
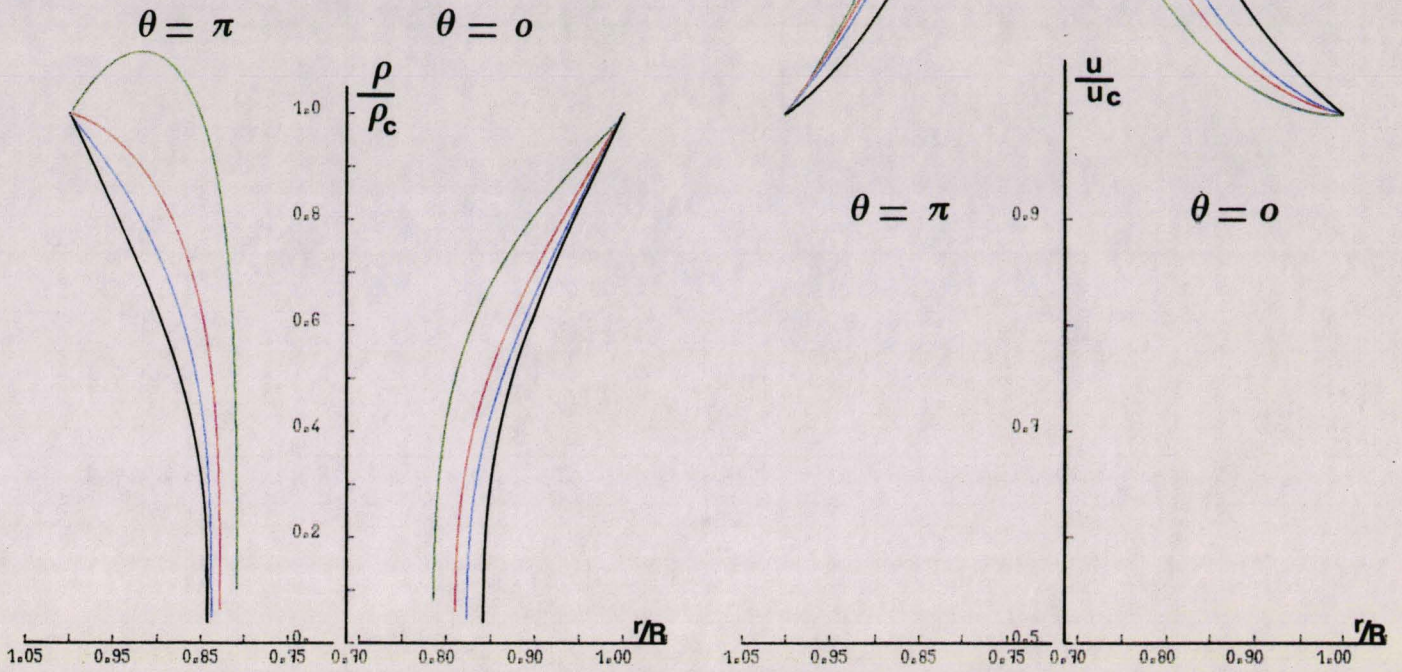
$\alpha = 1$

$\bar{M} = 0.$

Répartitions vues dans le repère mobile

Fig.74

- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$
- $M_c = 2.5$



$\gamma = 1.8$

$\alpha = 1$

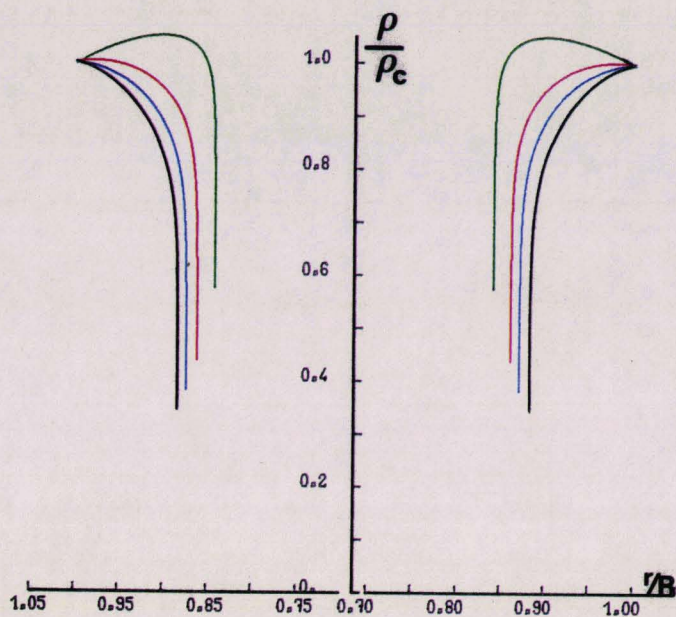
$\bar{M} = 0.8$

Répartitions vues dans le repère mobile

- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$
- $M_c = 2.5$

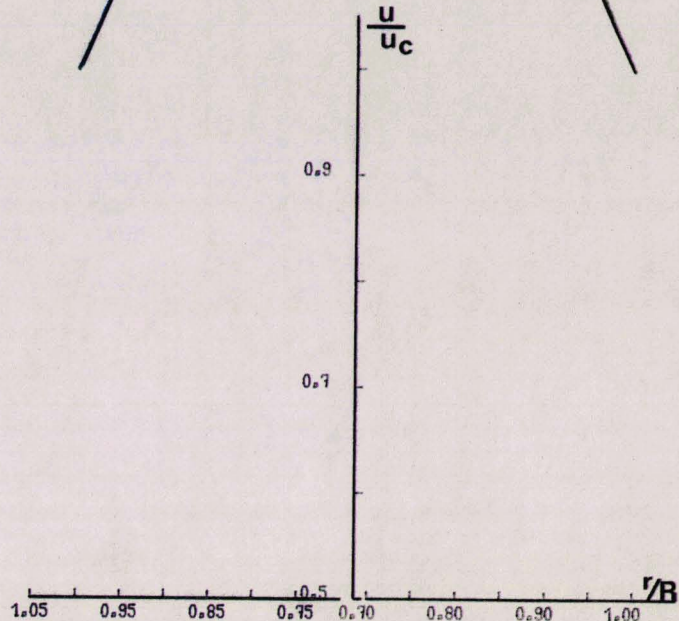
$\theta = \pi$

$\theta = 0$



$\theta = \pi$

$\theta = 0$

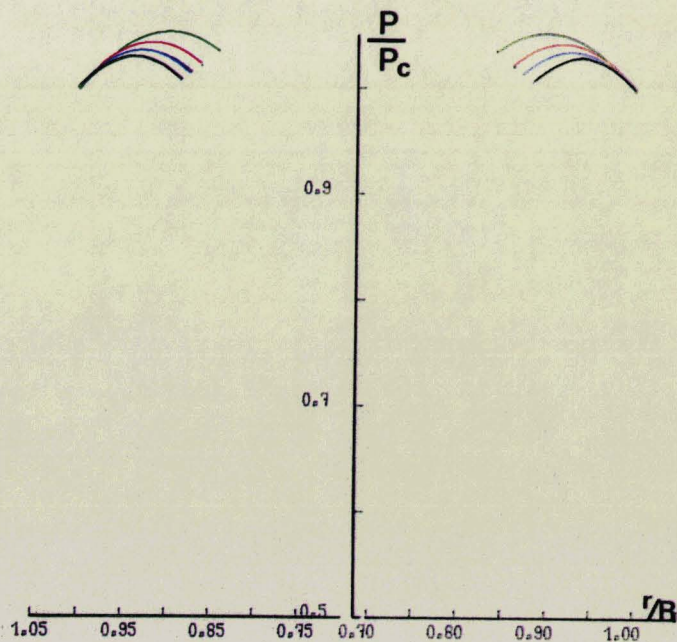
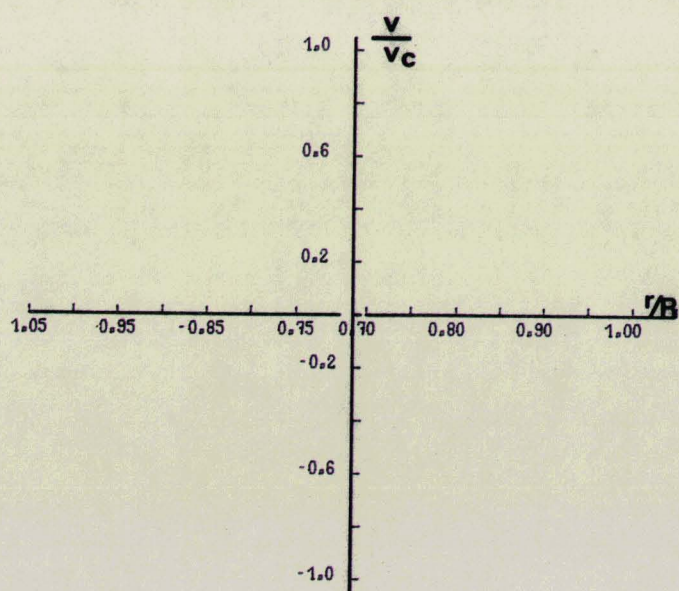


$\theta = -\frac{\pi}{2}$

$\theta = \frac{\pi}{2}$

$\theta = \pi$

$\theta = 0$



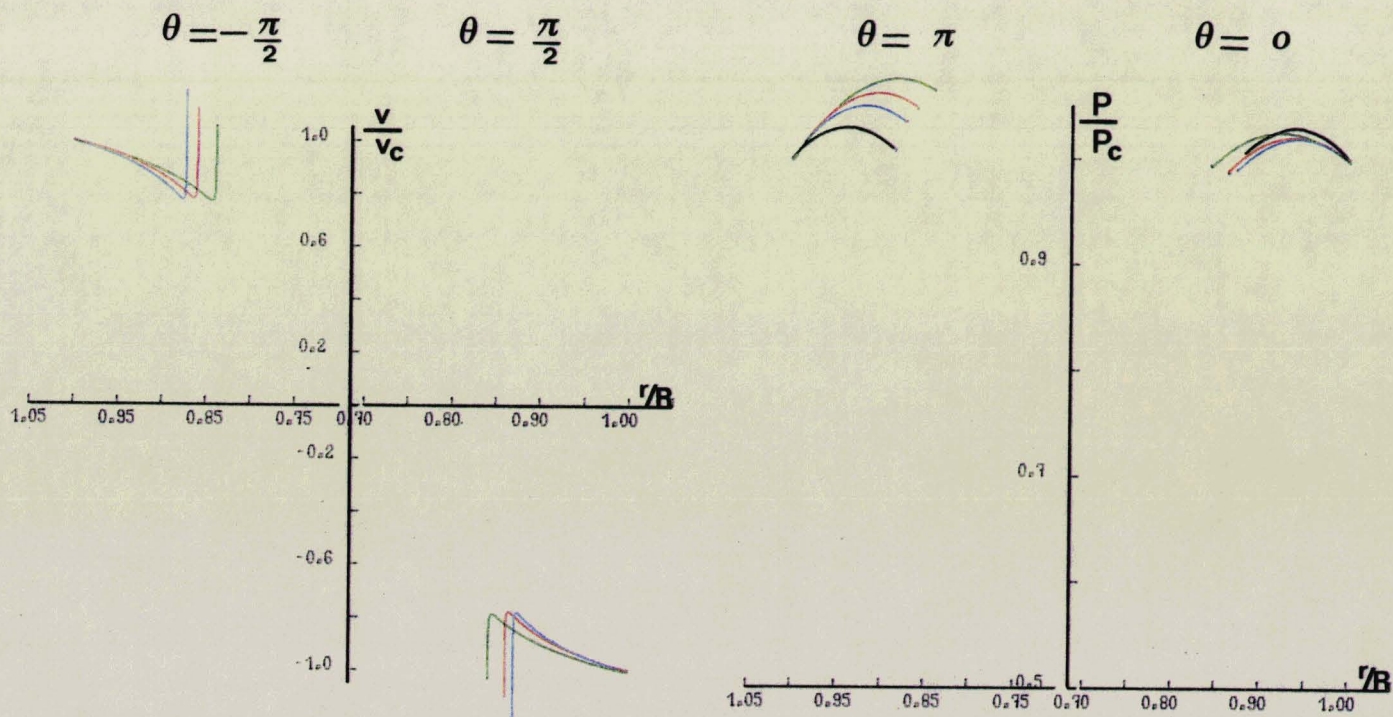
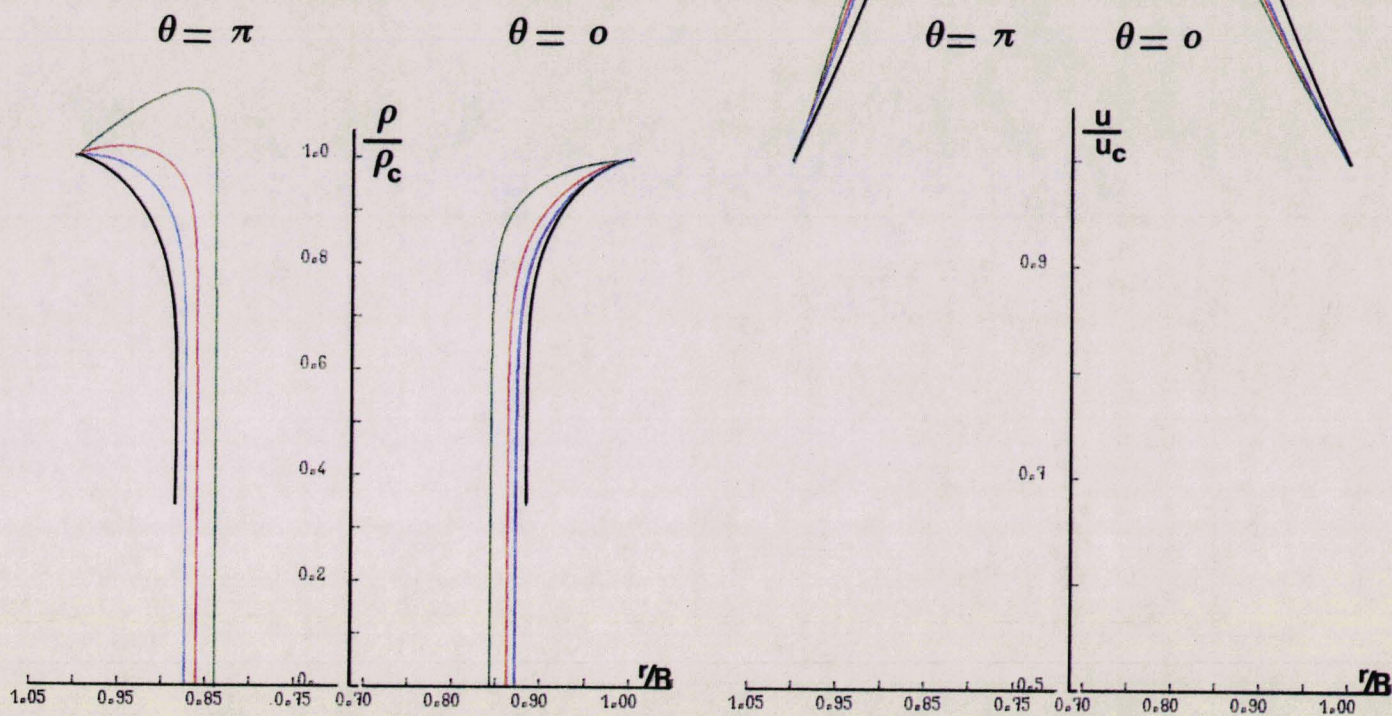
$\gamma = 1.8$

$\alpha = 2$

$\bar{M} = 0.$

Répartitions vues dans le repère mobile

- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$
- $M_c = 2.5$



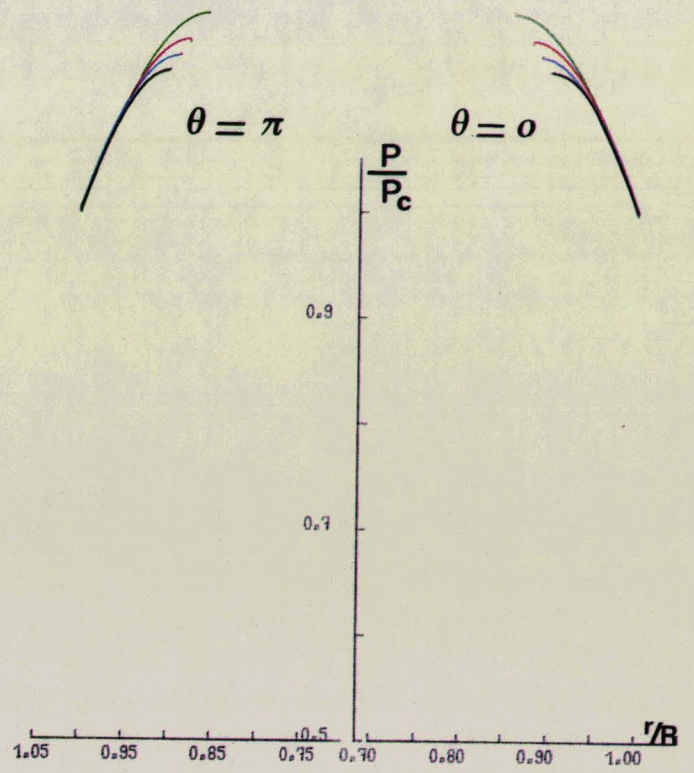
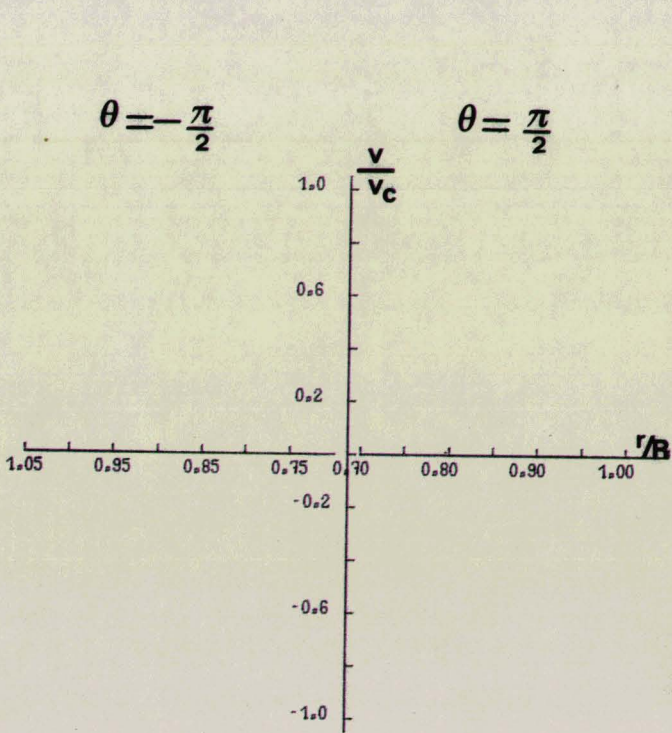
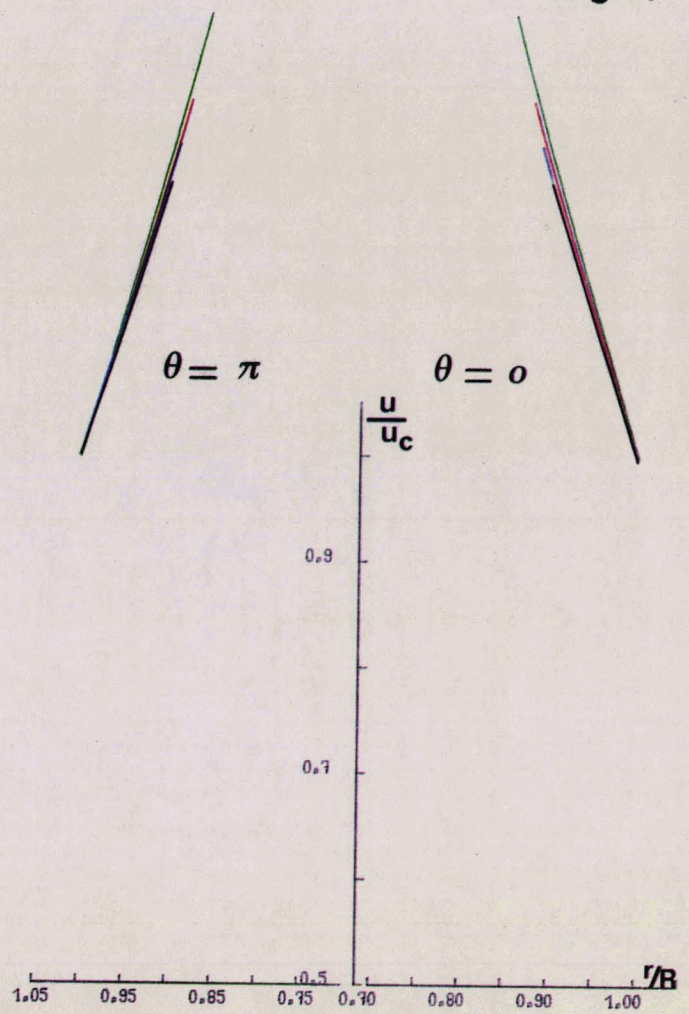
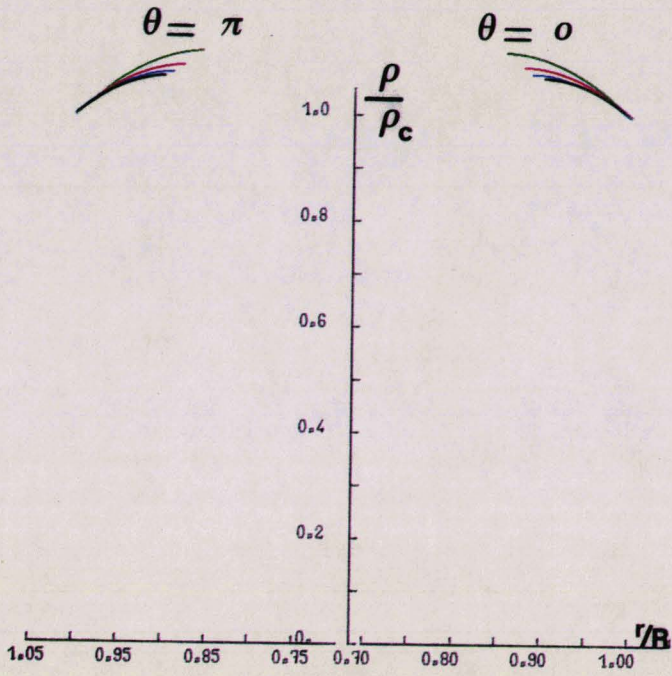
$\gamma = 1.8$

$\alpha = 2$

$\bar{M} = 0.8$

Répartitions vues dans le repère mobile

- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$
- $M_c = 2.5$



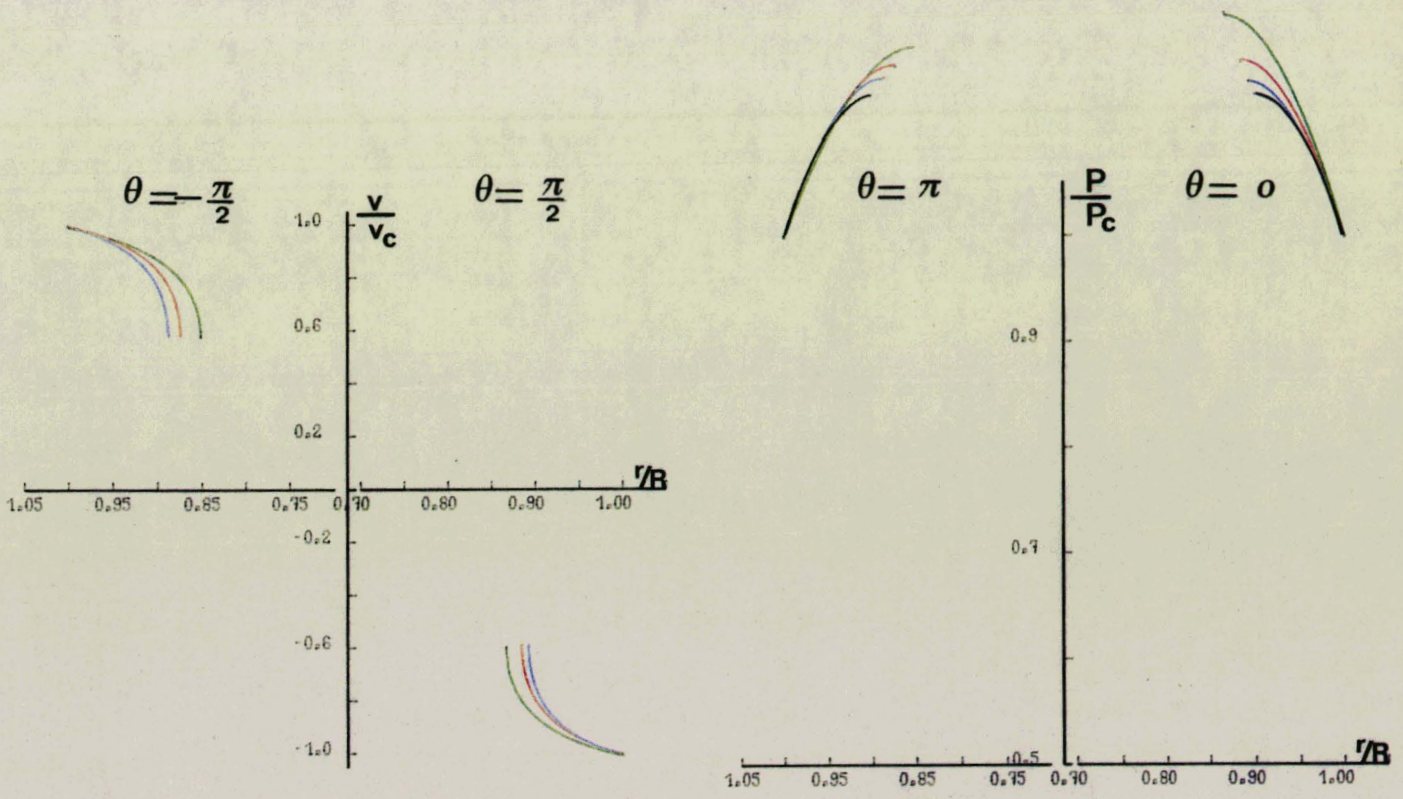
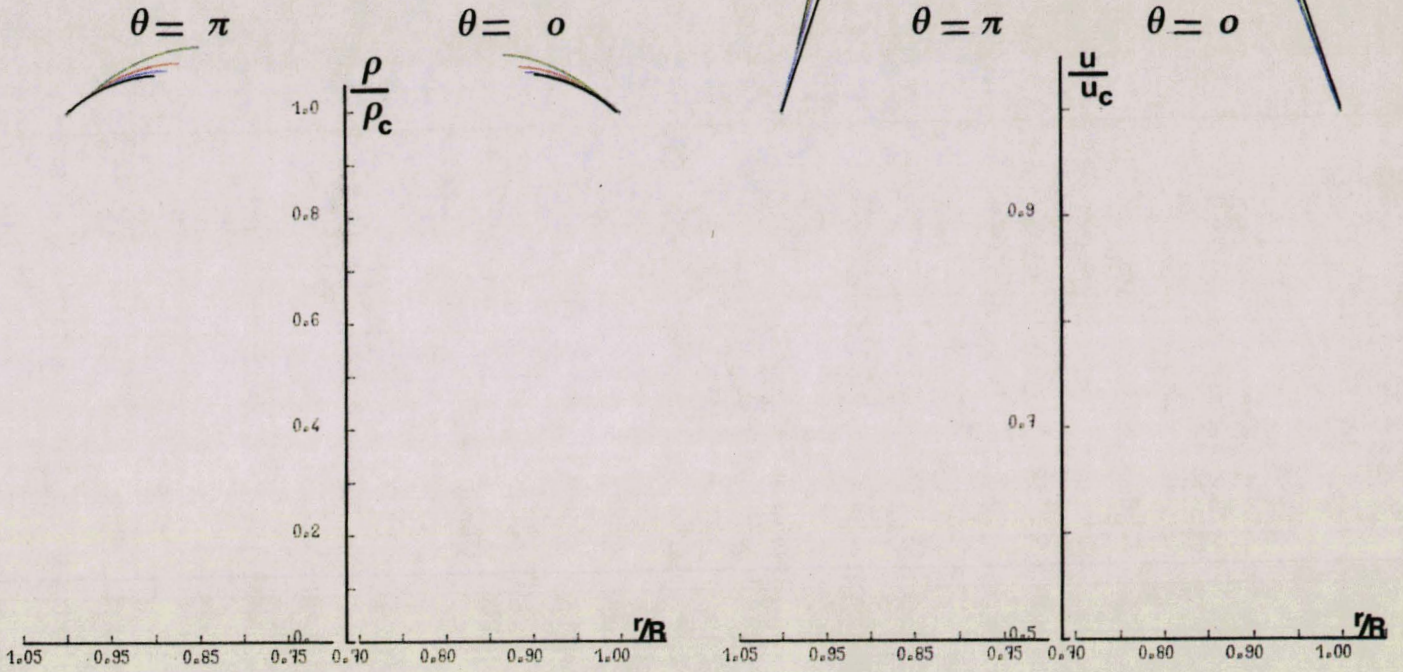
$\gamma = 1.8$

$\alpha = 3$

$\bar{M} = 0.$

Répartitions vues dans le repère mobile

- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$
- $M_c = 2.5$



$\gamma = 1.8$

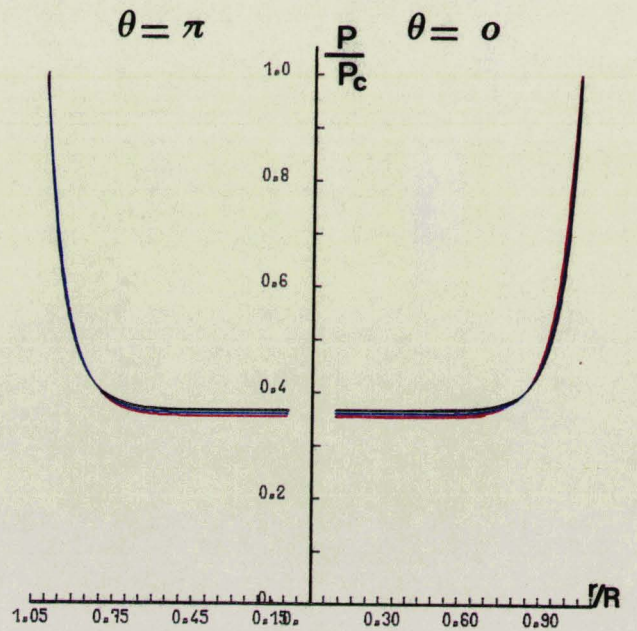
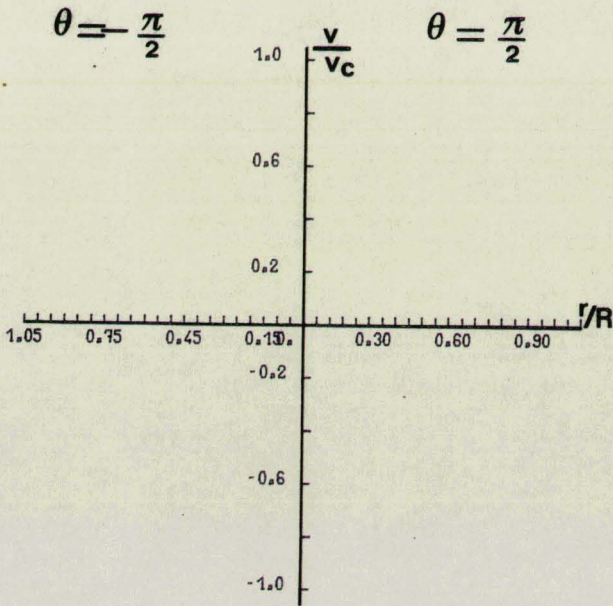
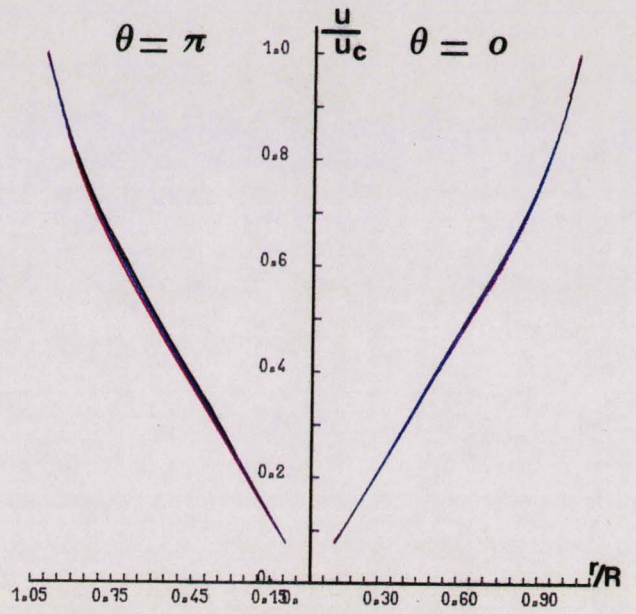
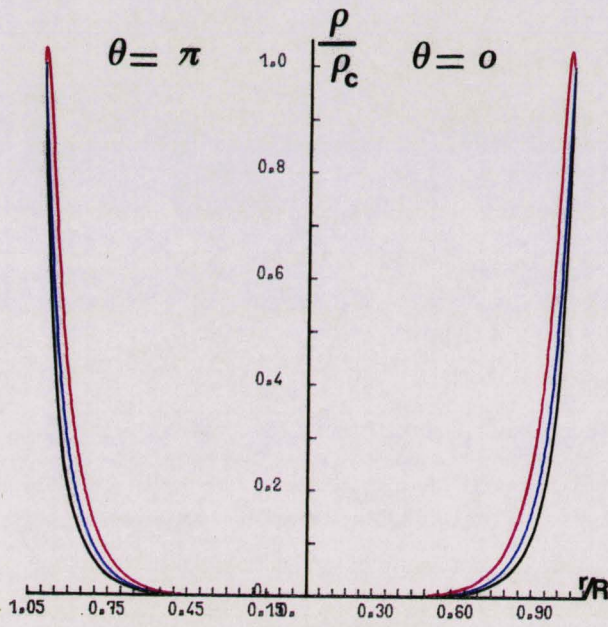
$\alpha = 3$

$\bar{M} = 0.8$

Répartitions vues dans le repère mobile



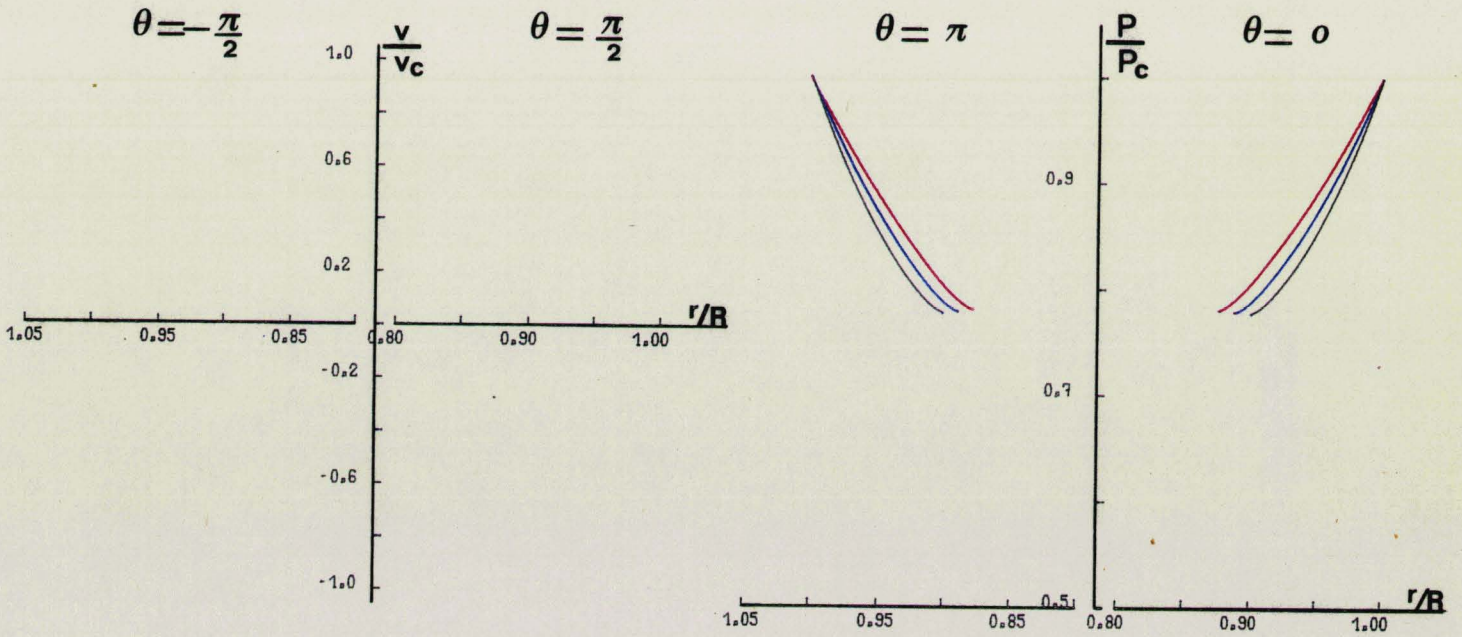
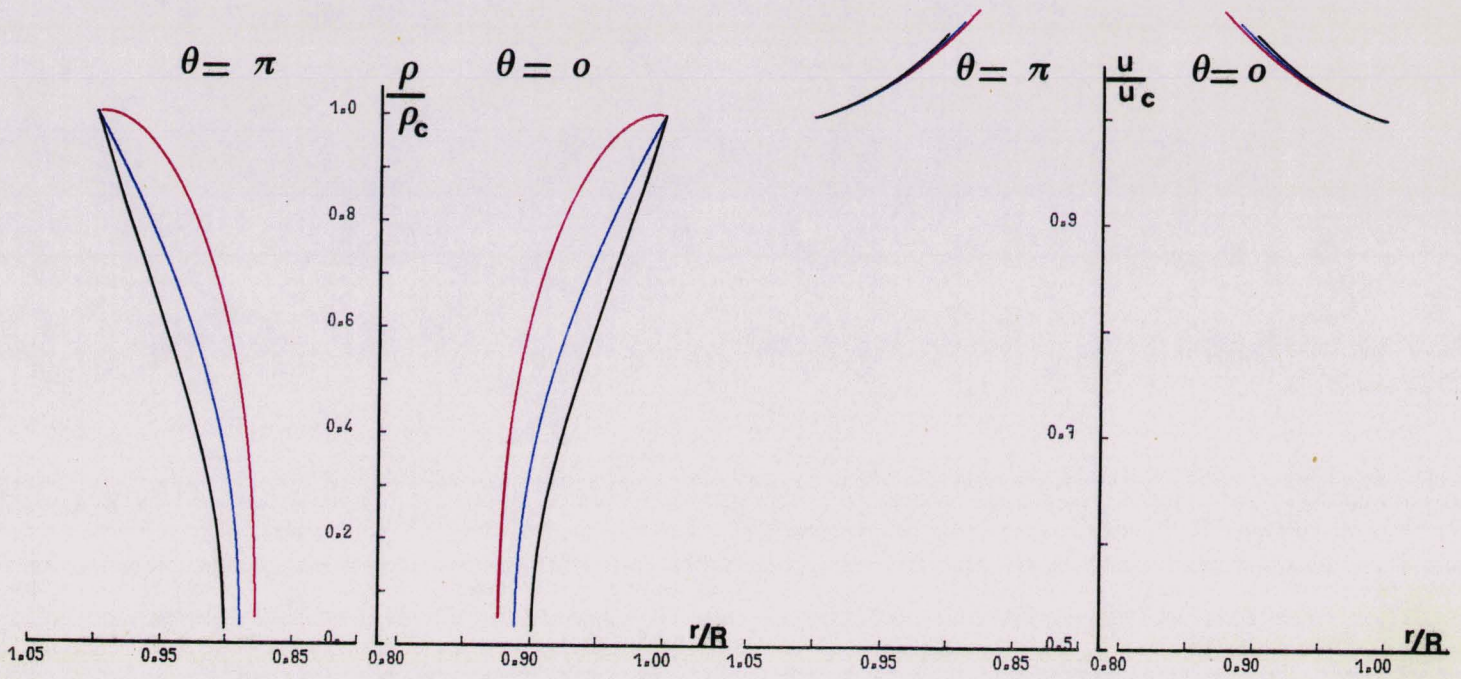
- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$



$\gamma = 1.4$        $\alpha = 0$

Répartitions vues dans le repère mobile

- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$

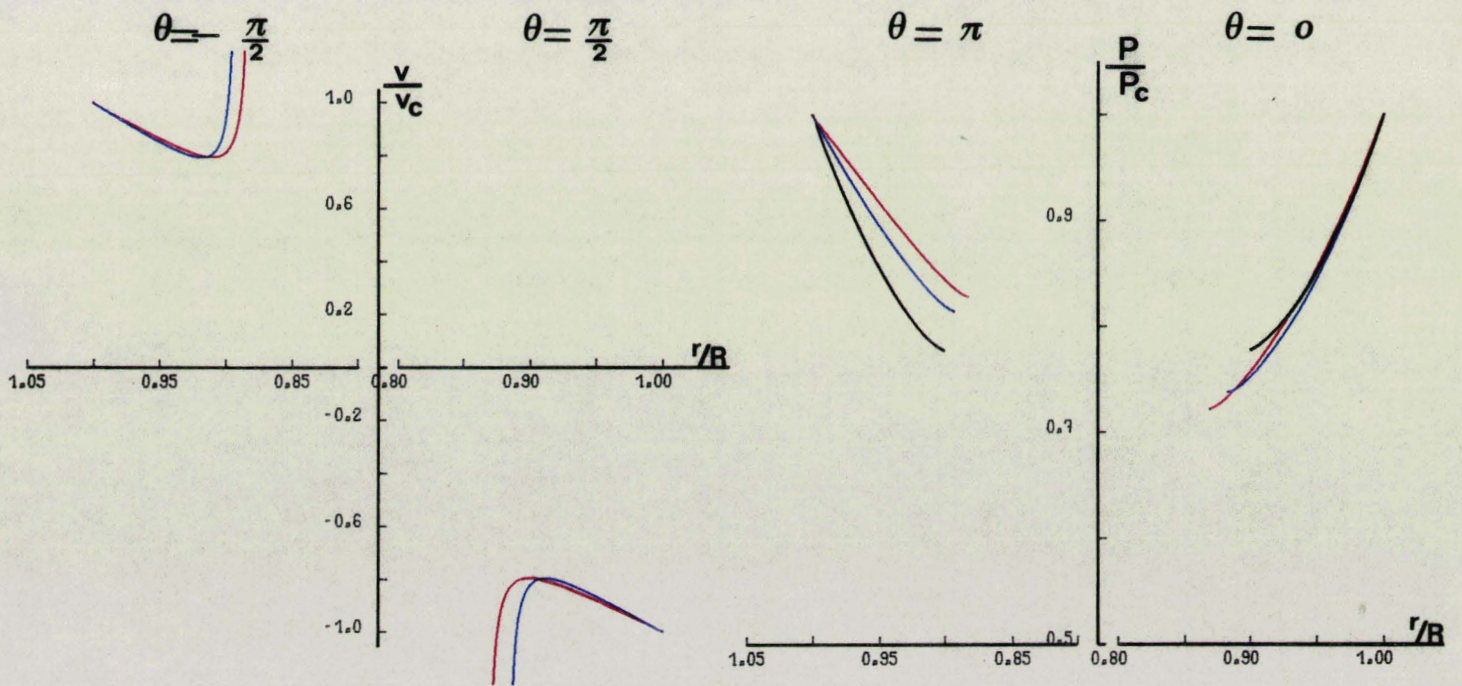
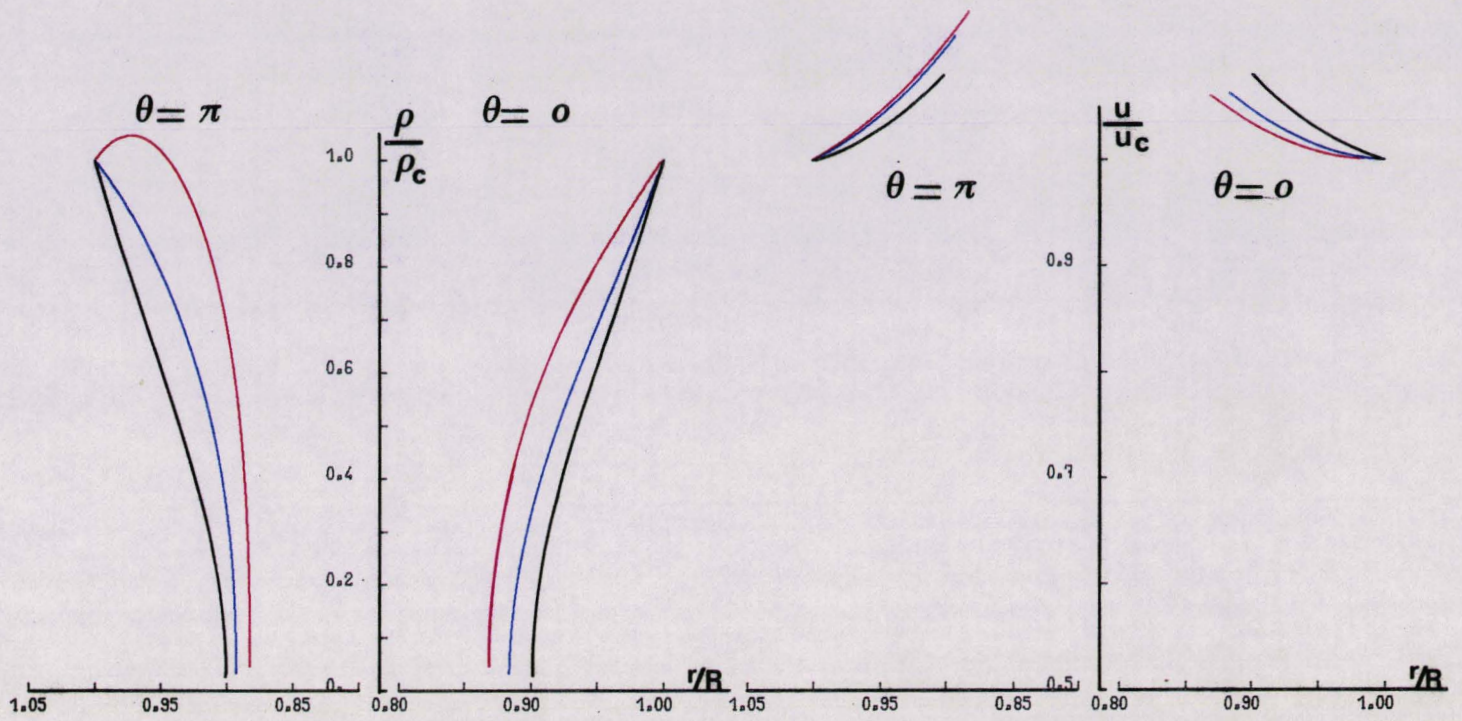


$\gamma = 1.4$        $\alpha = 1$        $\bar{M} = 0.$

Répartitions vues dans le repère mobile

Fig. 81

- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$



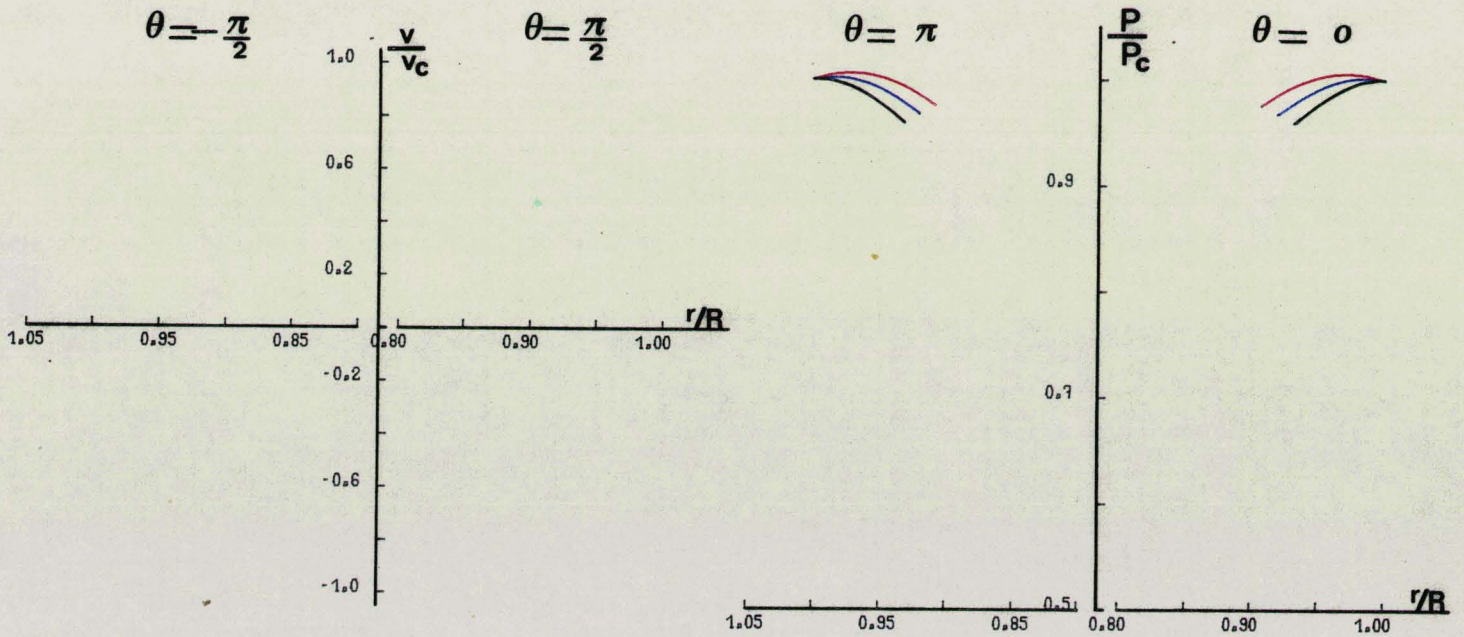
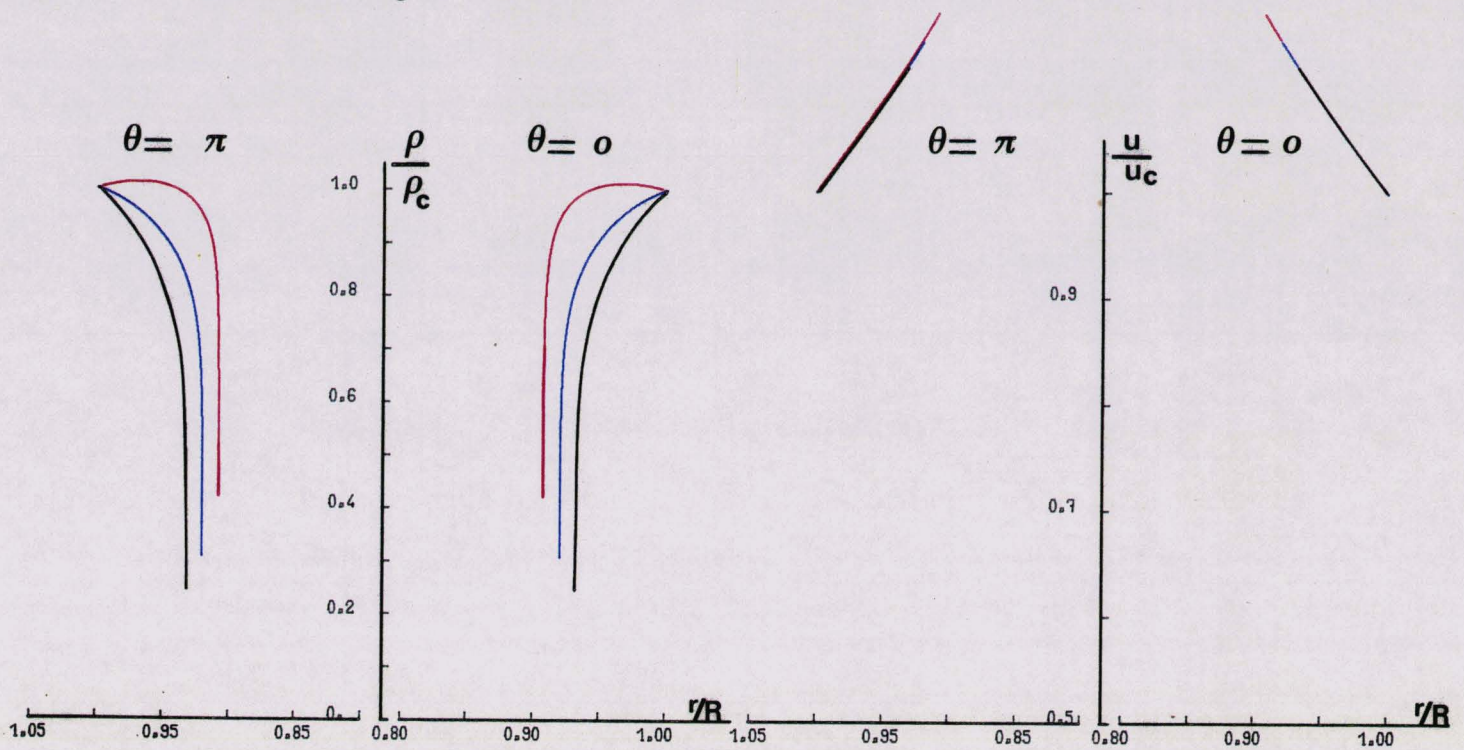
$\gamma = 1.4$

$\alpha = 1$

$\bar{M} = 0.8$

Répartitions vues dans le repère mobile

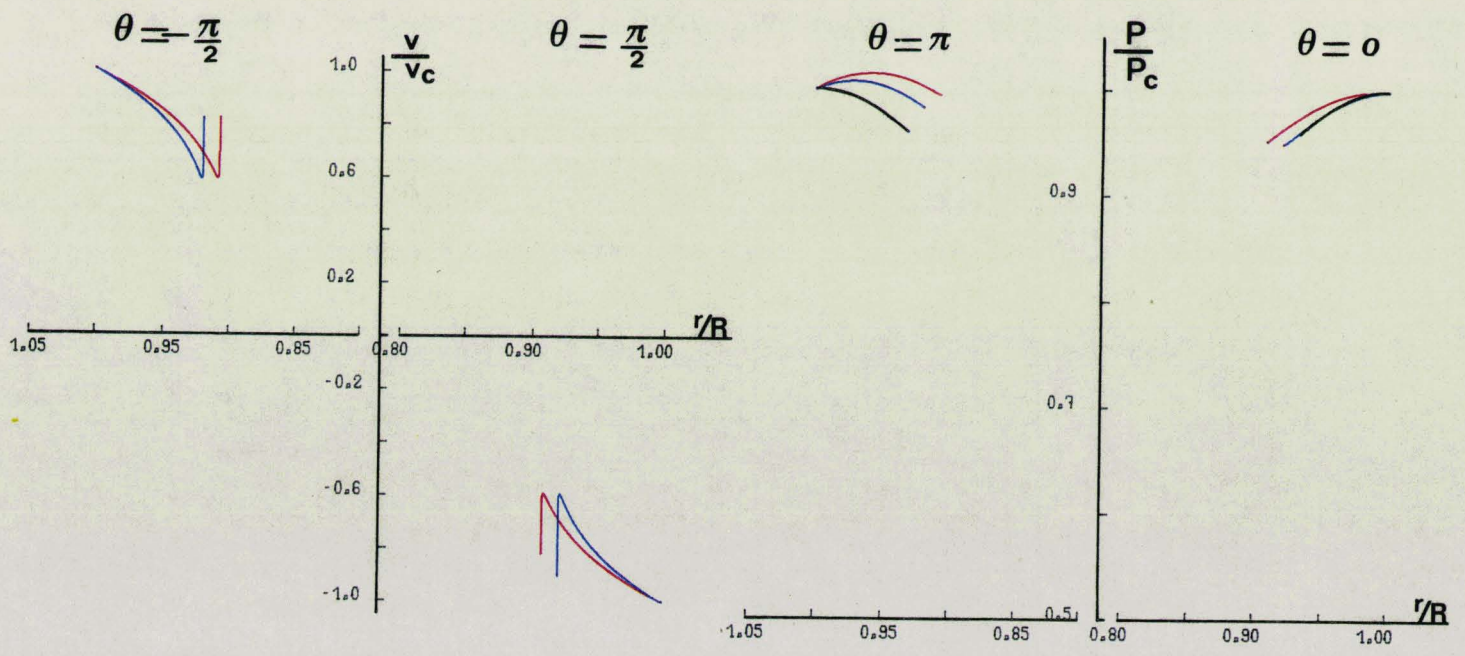
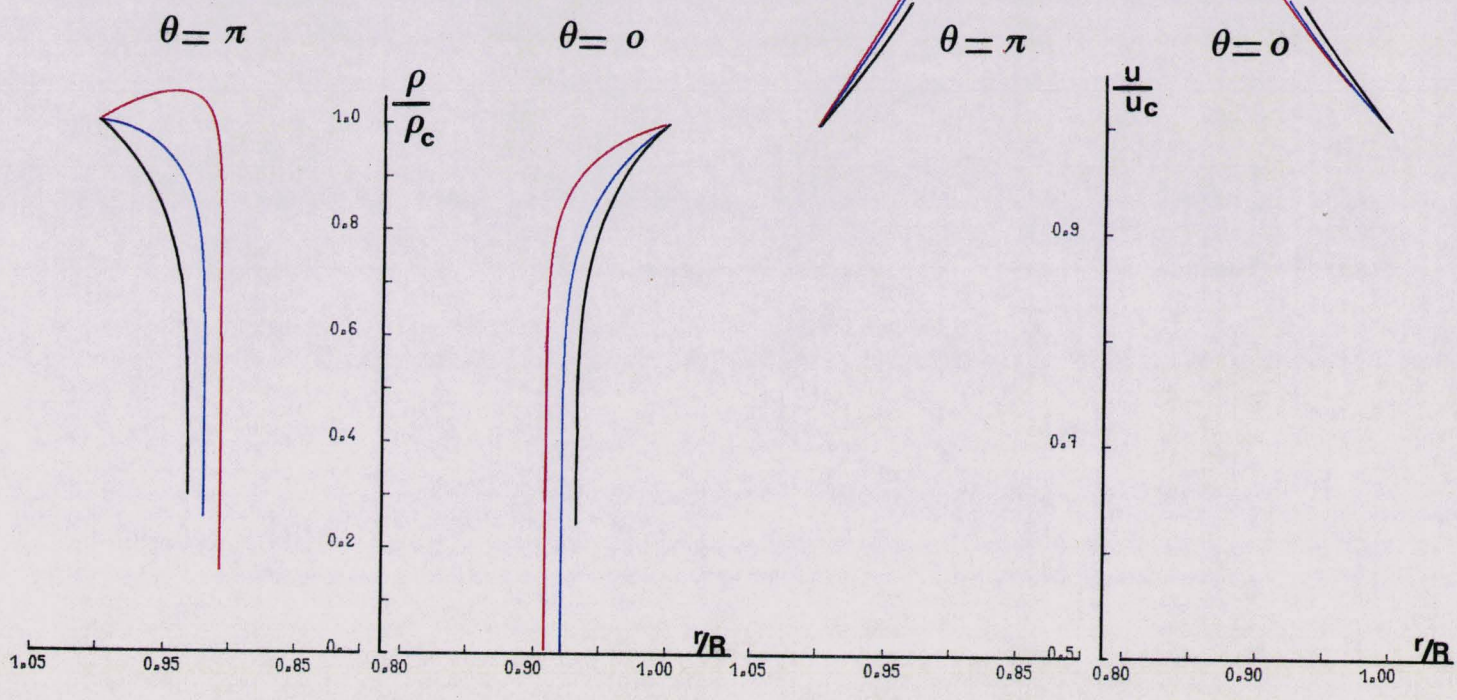
- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$



$\gamma = 14$        $\alpha = 2$        $\bar{M} = 0.$

Répartitions vues dans le repère mobile

- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$



$\gamma = 1.4$

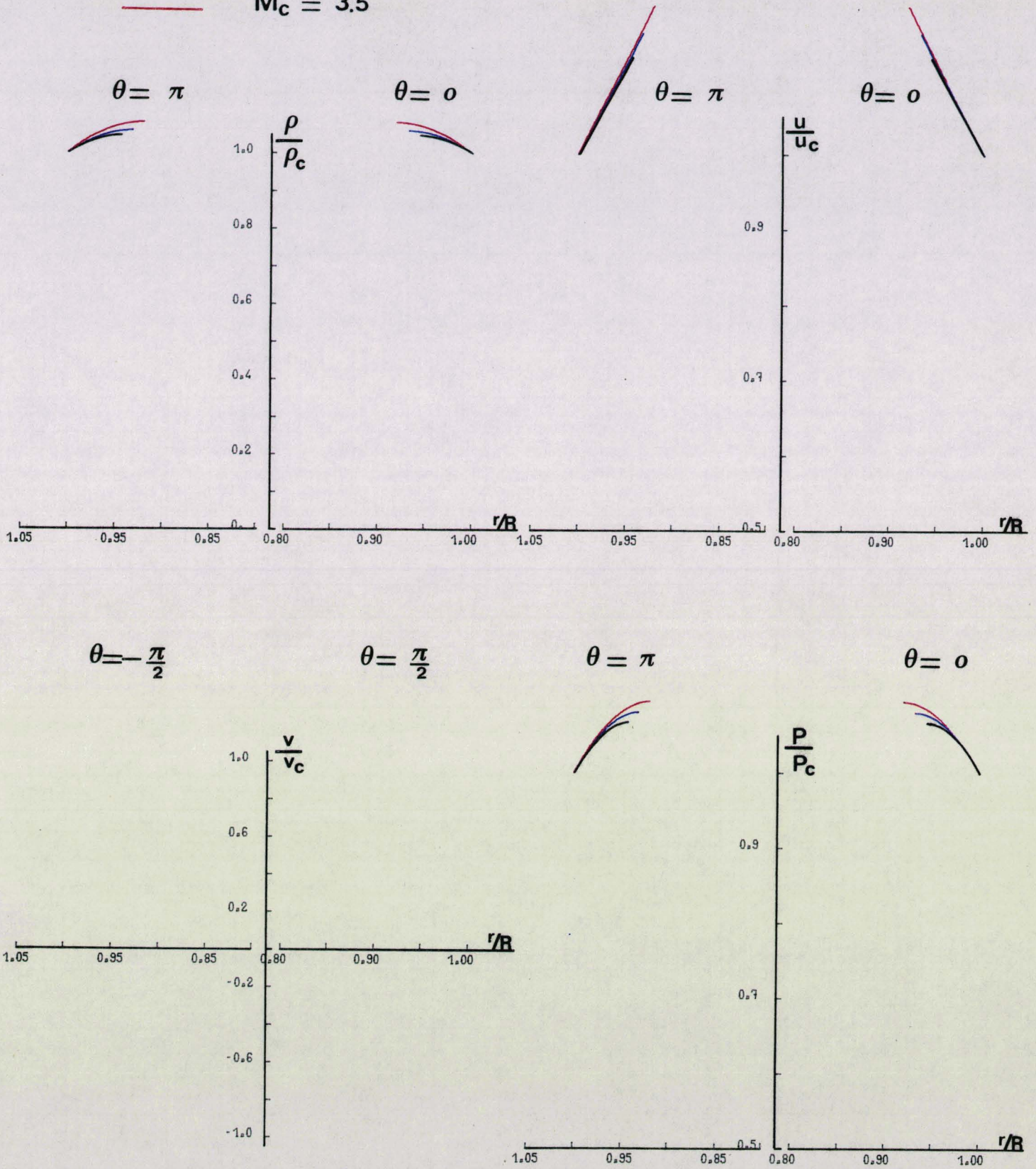
$\alpha = 2$

$\bar{M} = 0.8$

Répartitions vues dans le repère mobile

Fig. 84

- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$



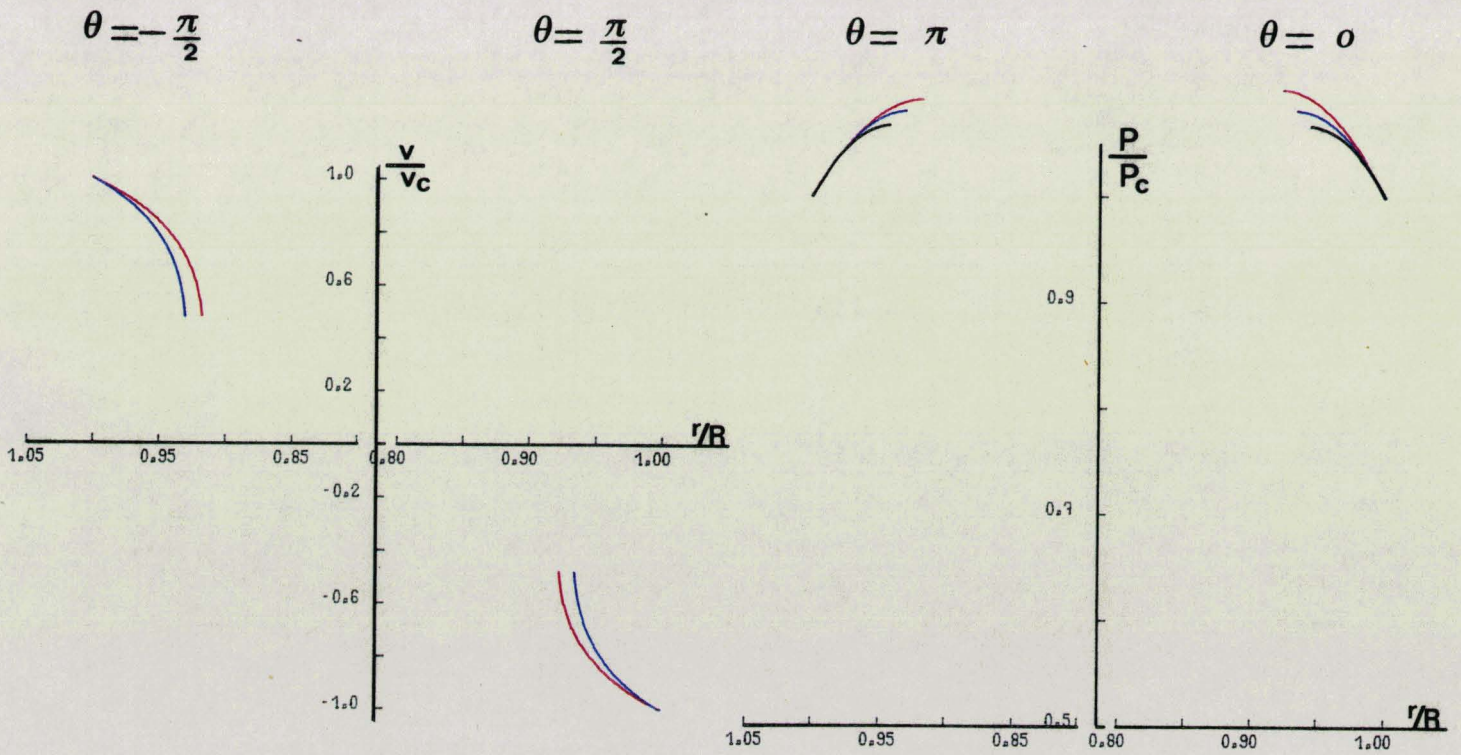
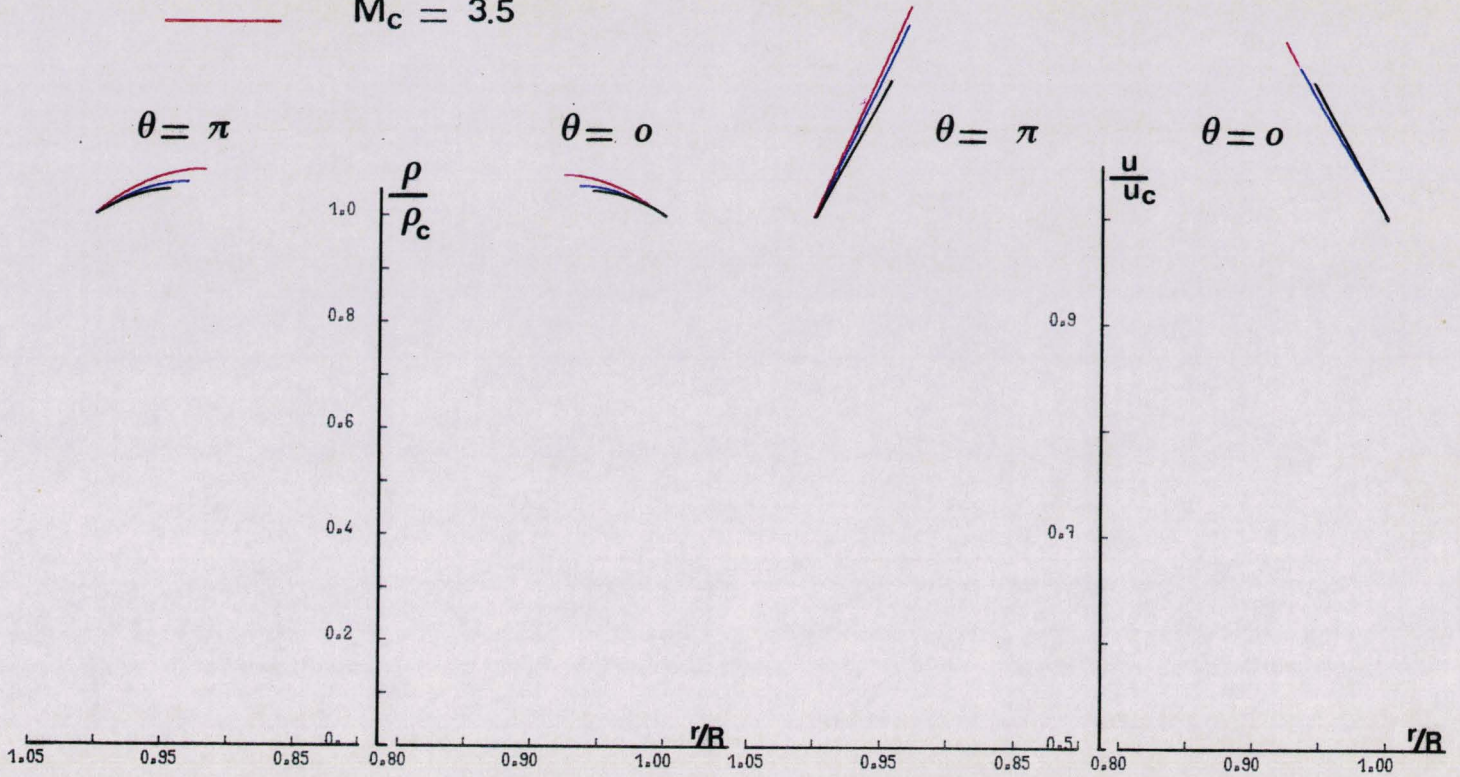
$\gamma = 1.4$

$\alpha = 3$

$\bar{M} = 0.$

Répartitions vues dans le repère mobile

- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$



$\gamma = 1.4$

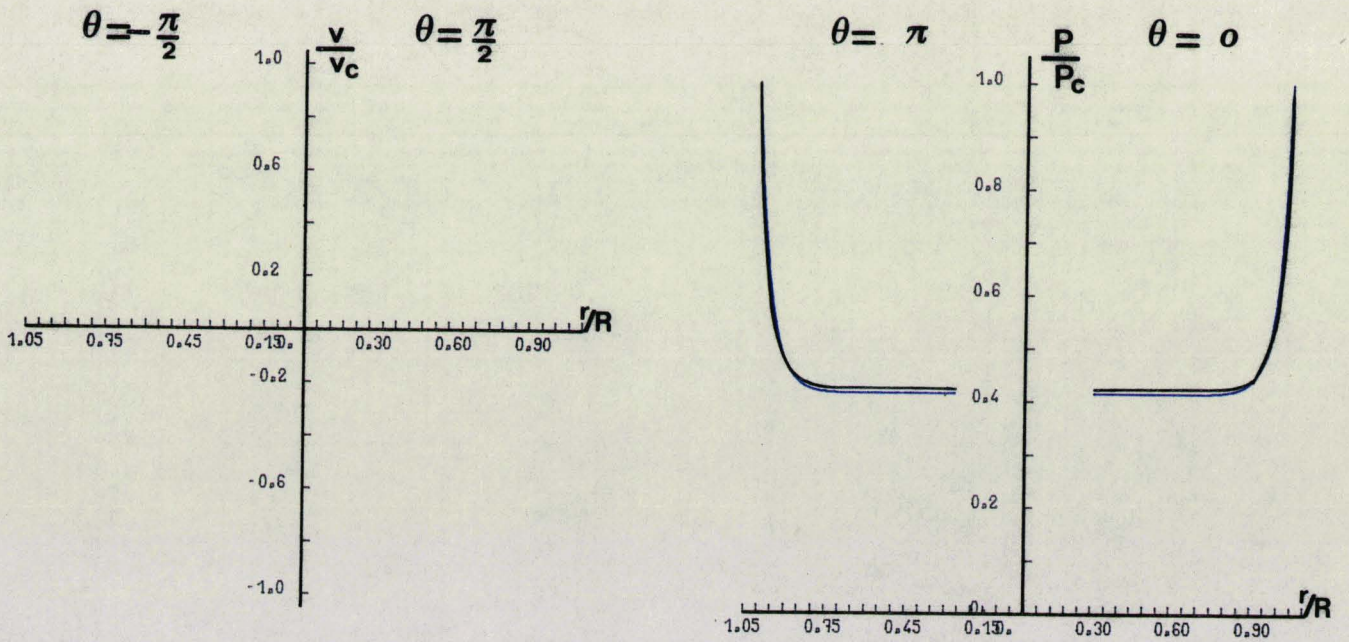
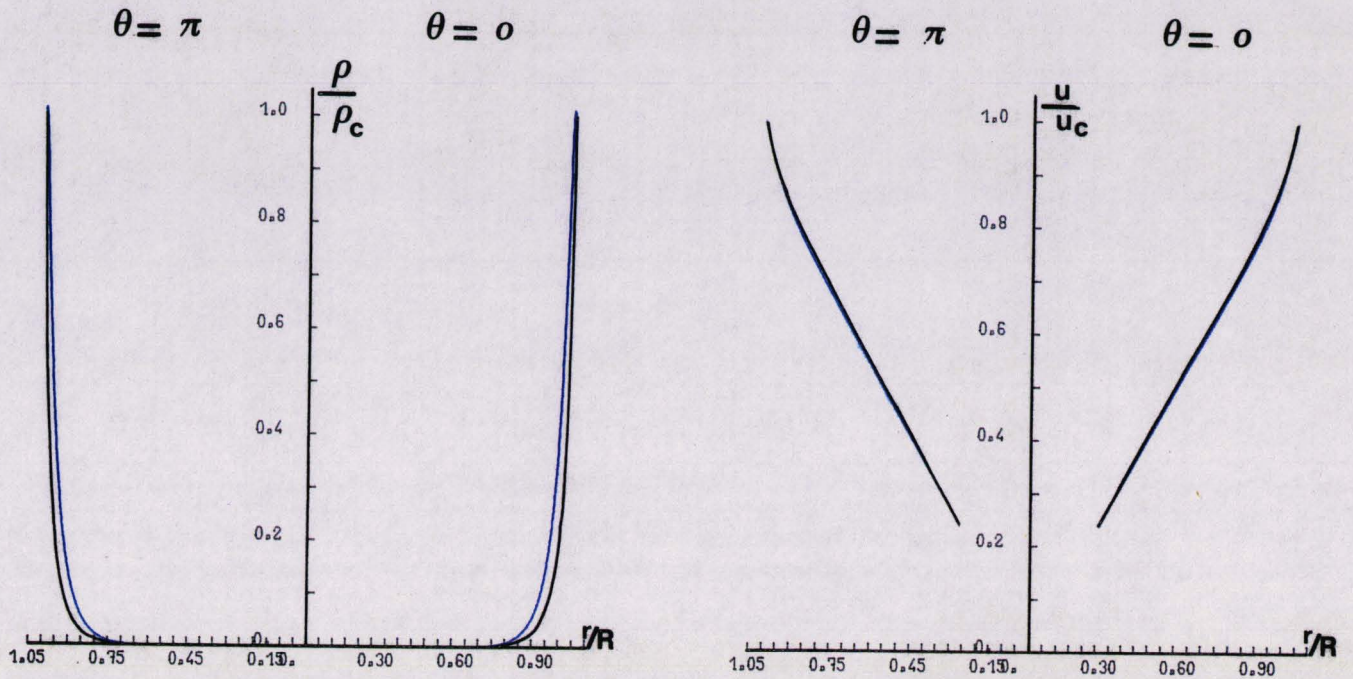
$\alpha = 3$

$\bar{M} = 0.8$

Répartitions vues dans le repère mobile

—  $M_c = \infty$

—  $M_c = 5.$

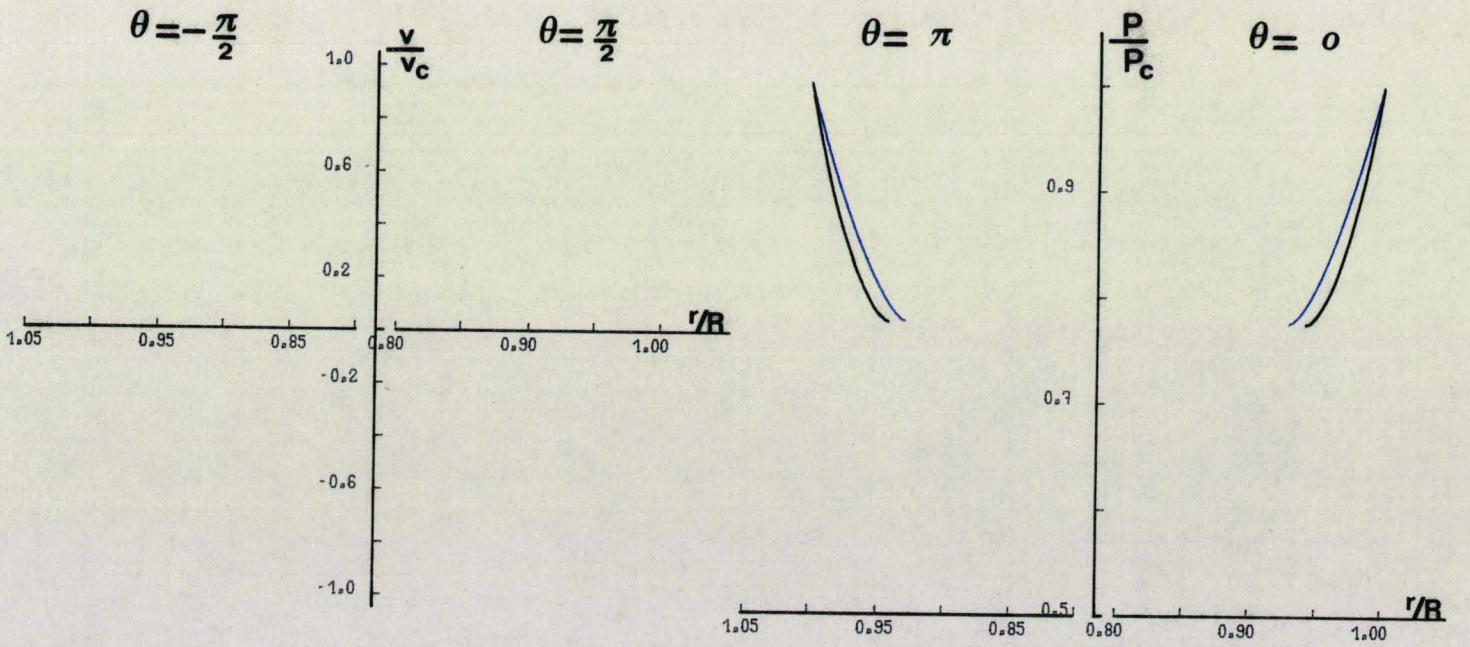
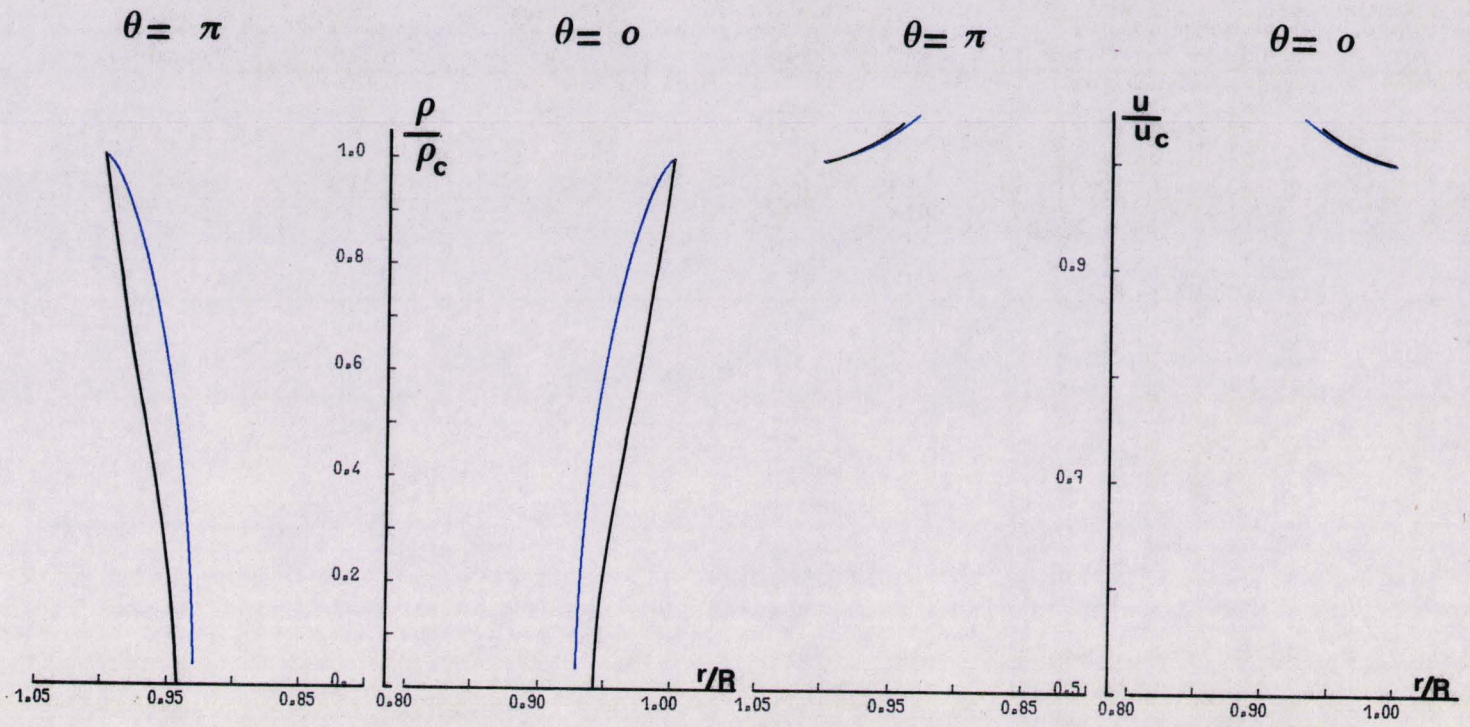


$\gamma = 12 \quad \alpha = 0$

Répartitions vues dans le repère mobile



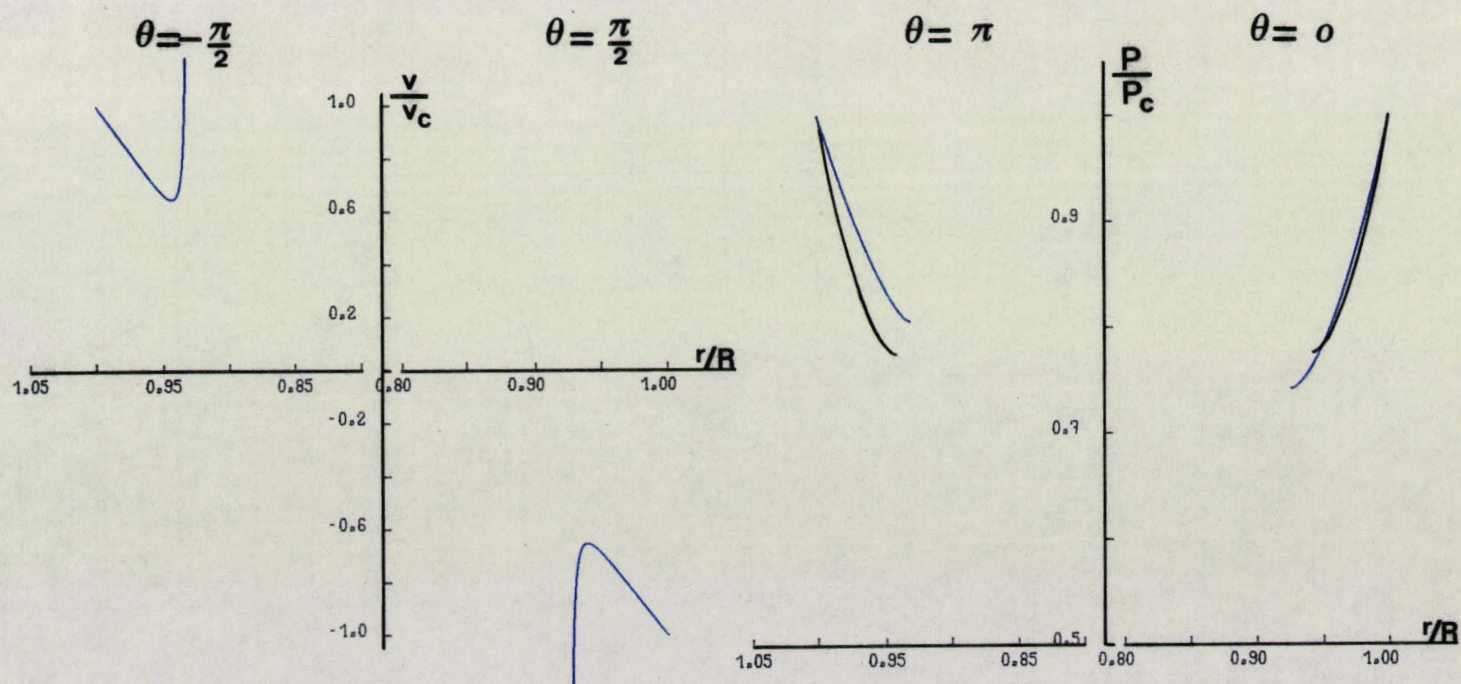
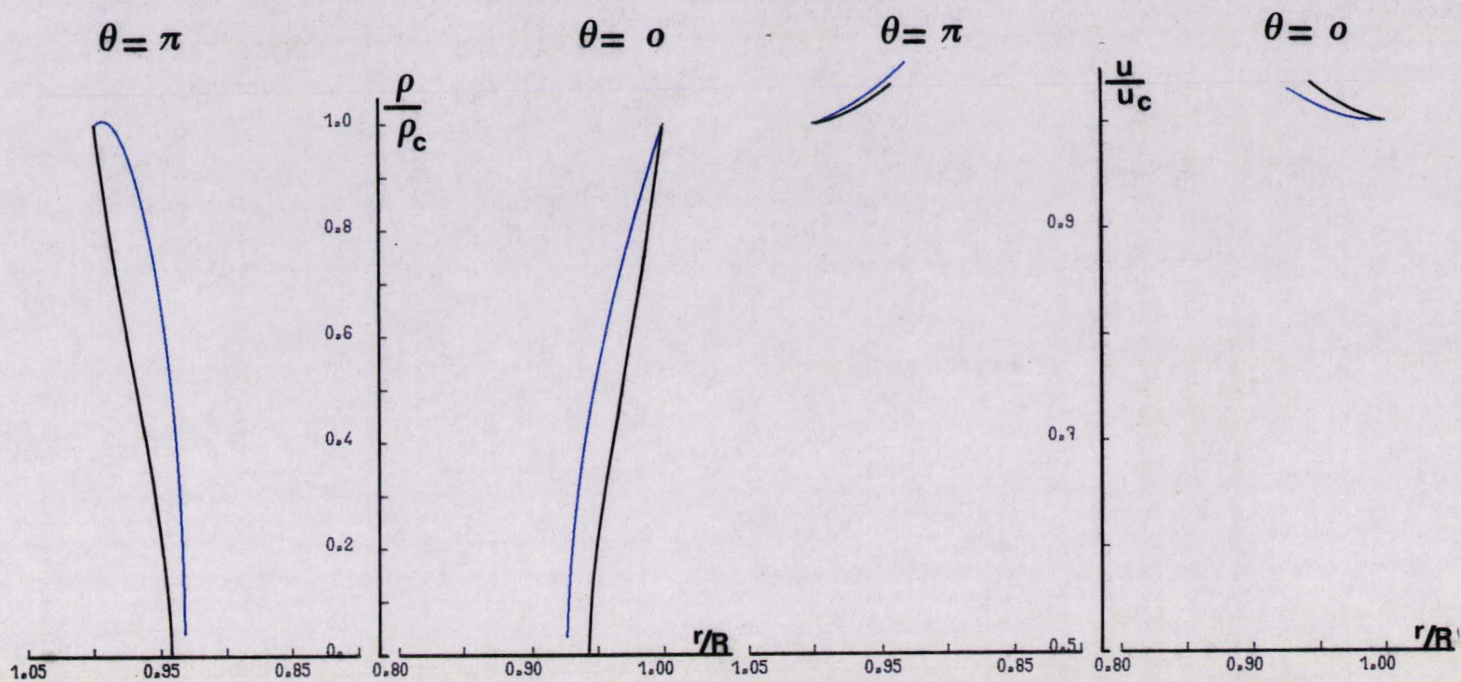
—  $M_c = \infty$   
 —  $M_c = 5.$



$\mathcal{V} = 12$        $\alpha = 1$        $\bar{M} = 0.$

Répartitions vues dans le repère mobile

—  $M_c = \infty$   
 —  $M_c = 5.$



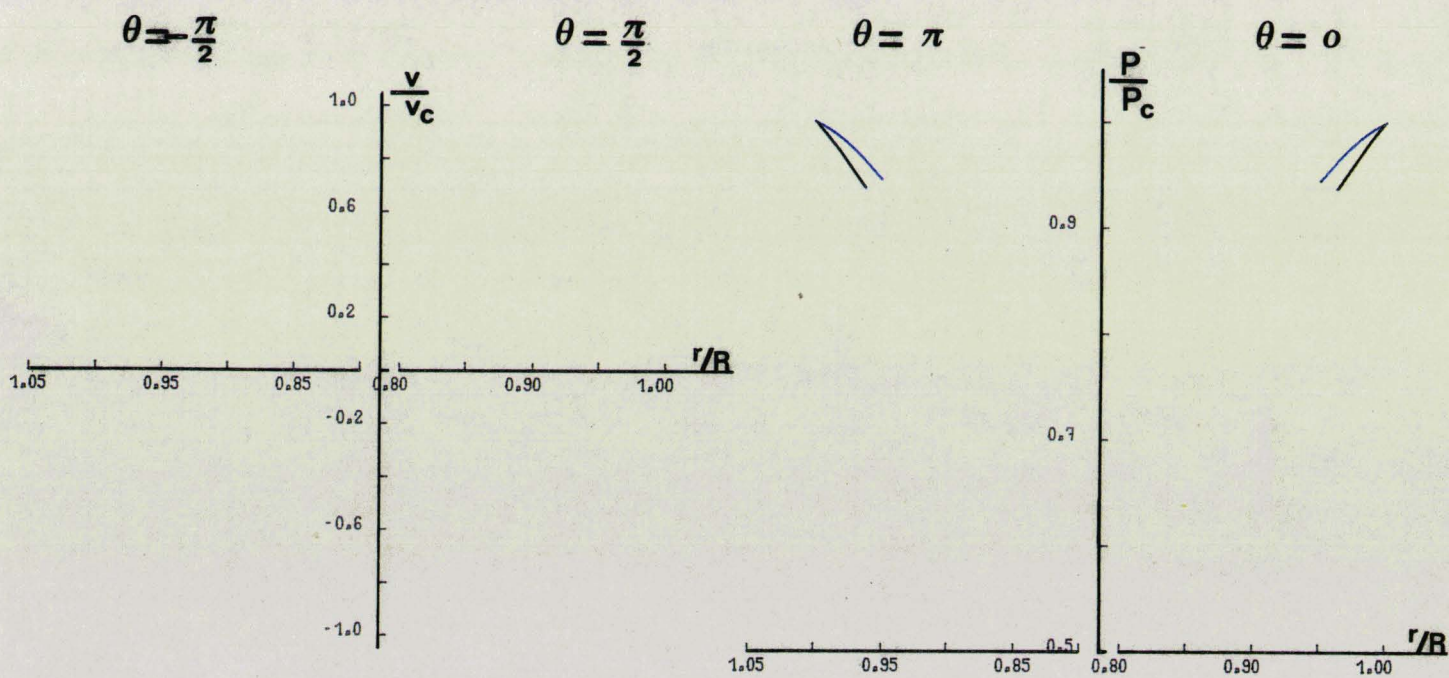
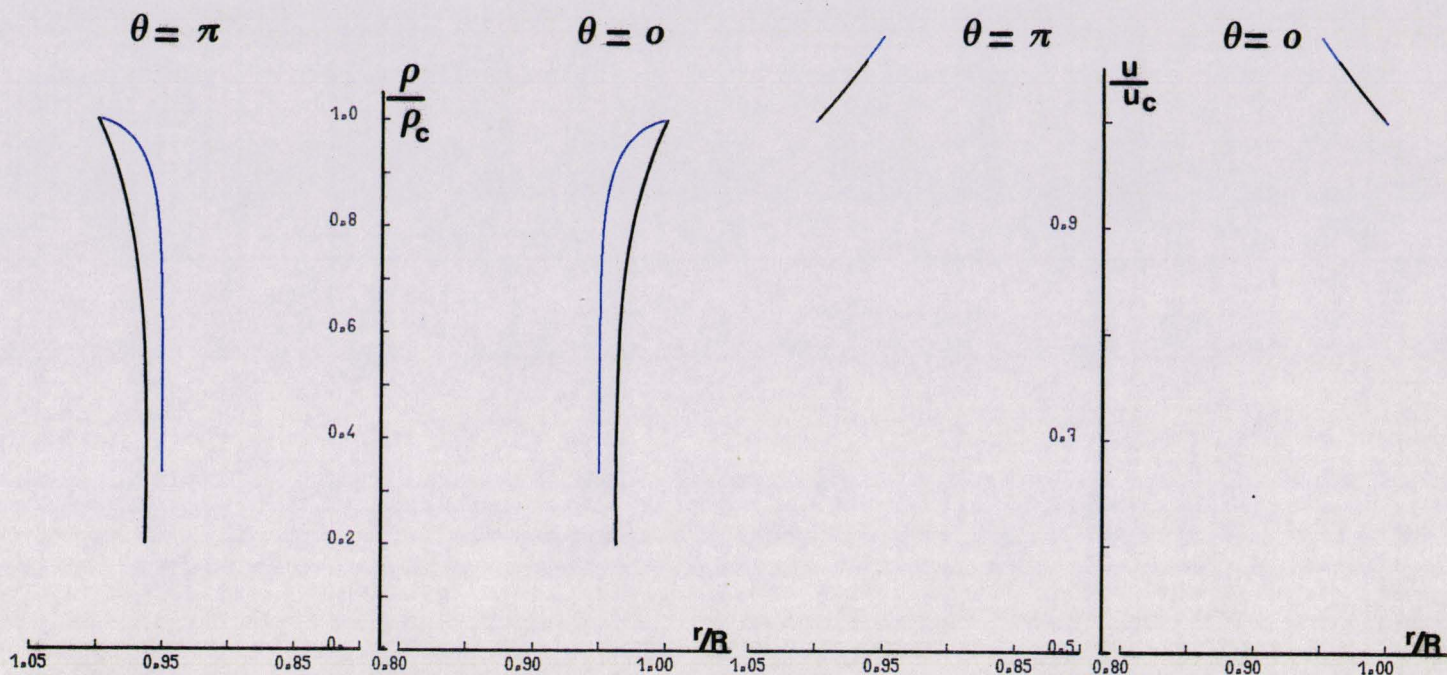
$\gamma = 1.2$

$\alpha = 1$

$\bar{M} = 0.8$

Répartitions vues dans le repère mobile

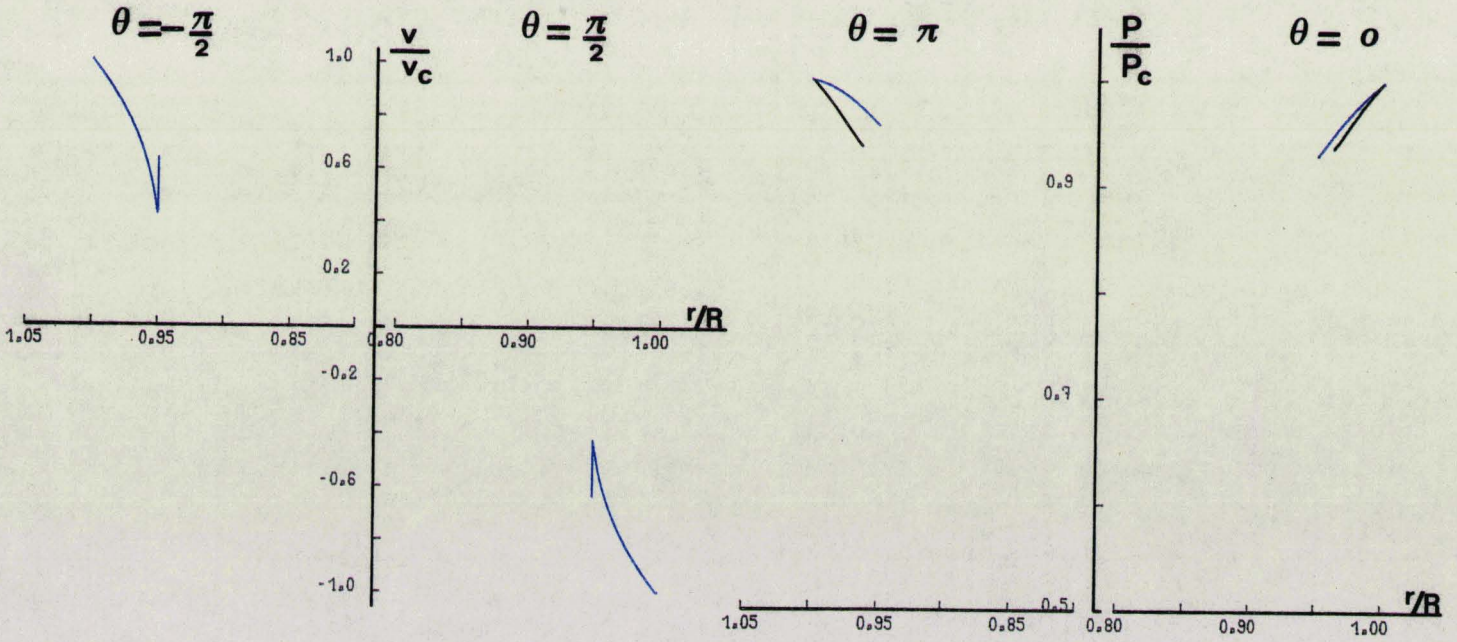
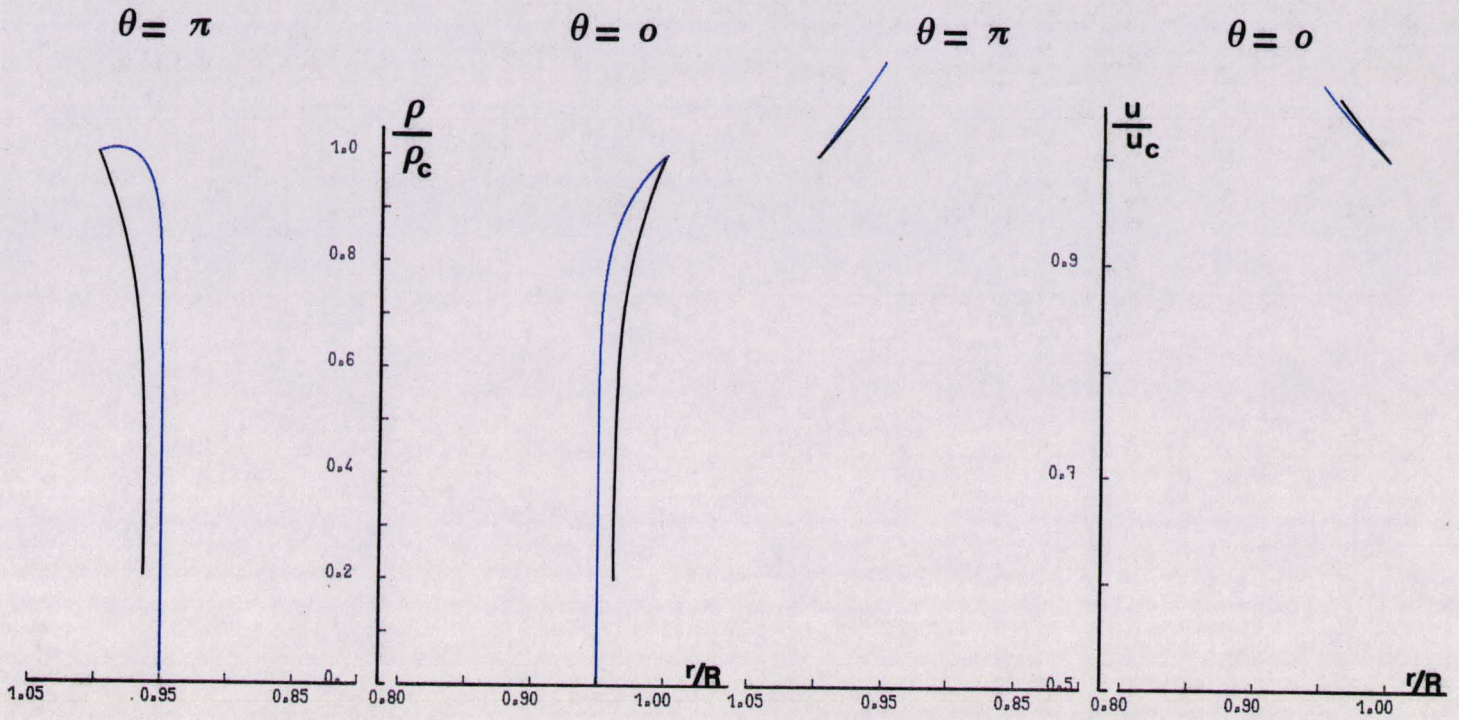
—  $M_c = \infty$   
 —  $M_c = 5.$



$\gamma = 1.2$        $\alpha = 2$        $\bar{M} = 0.$

Répartitions vues dans le repère mobile

—  $M_c = \infty$   
 —  $M_c = 5.$



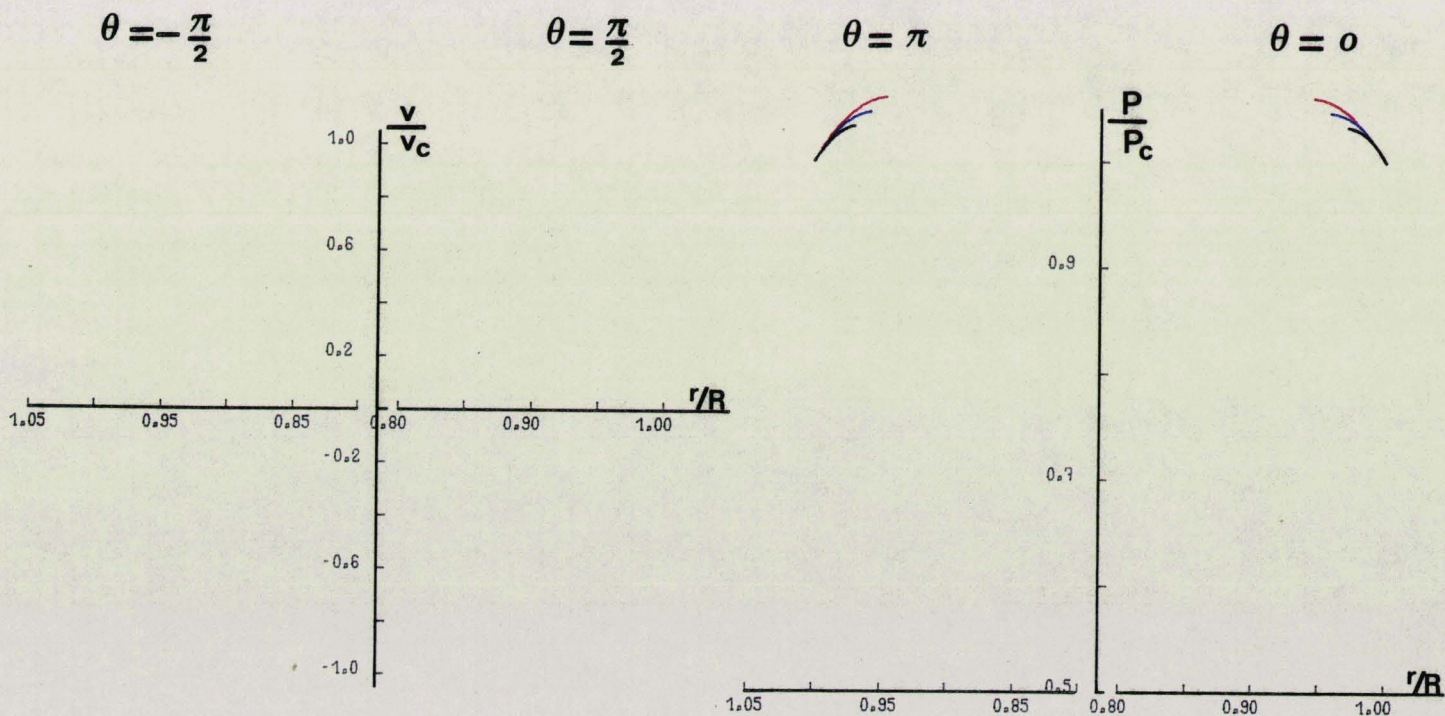
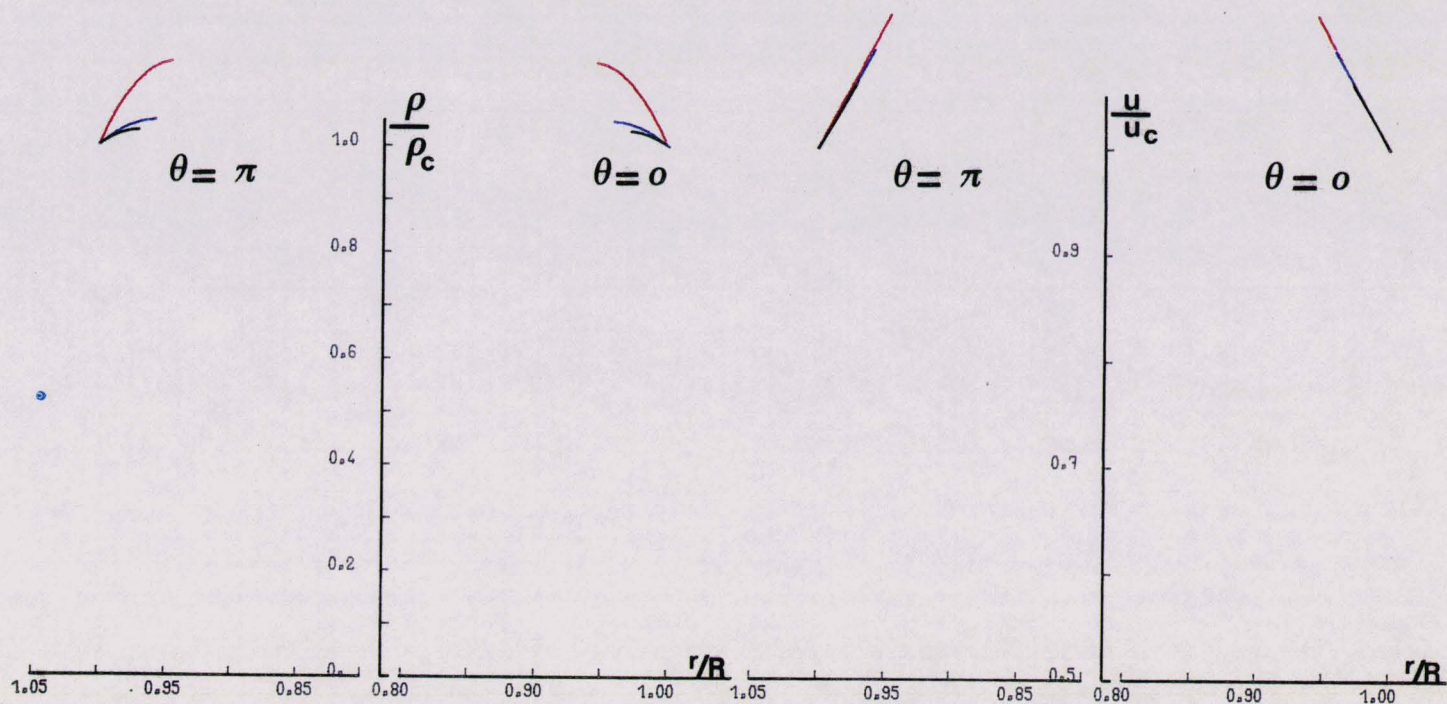
$\gamma = 12$

$\alpha = 2$

$\bar{M} = 0.8$

Répartitions vues dans le repère mobile

- $M_c = \infty$
- $M_c = 5.$
- $M_c = 3.5$



$\gamma = 1.2$

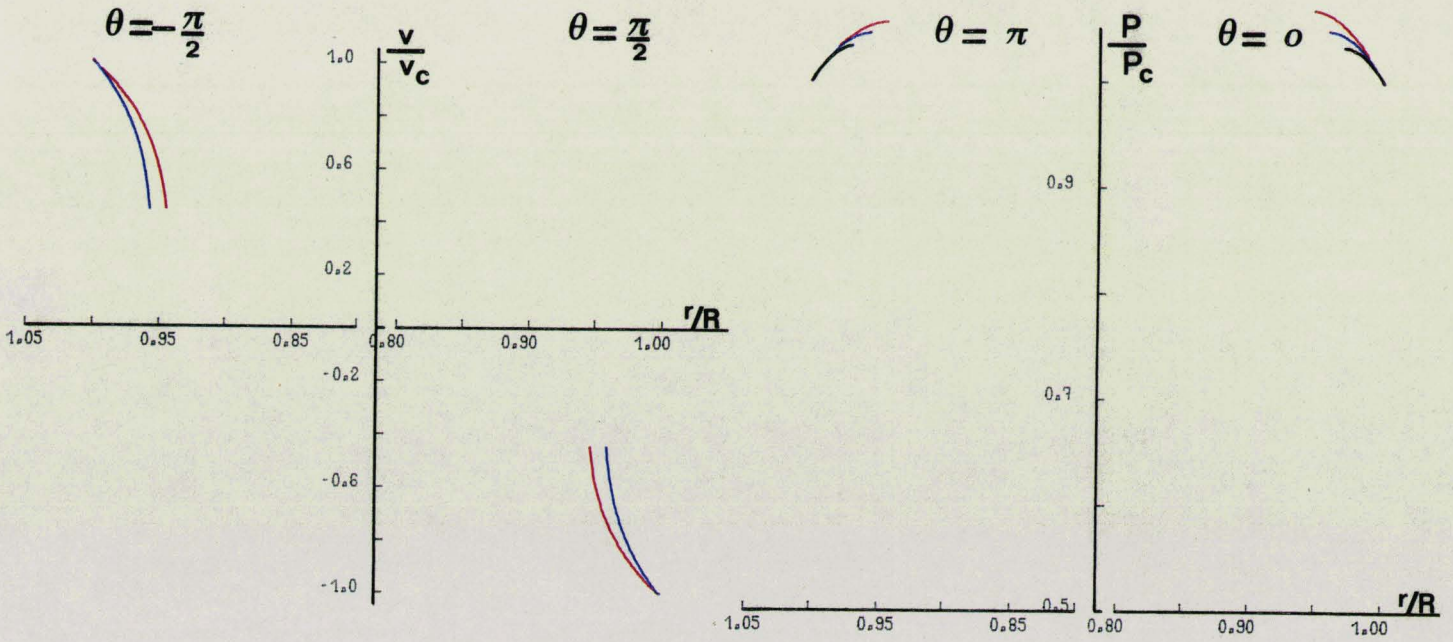
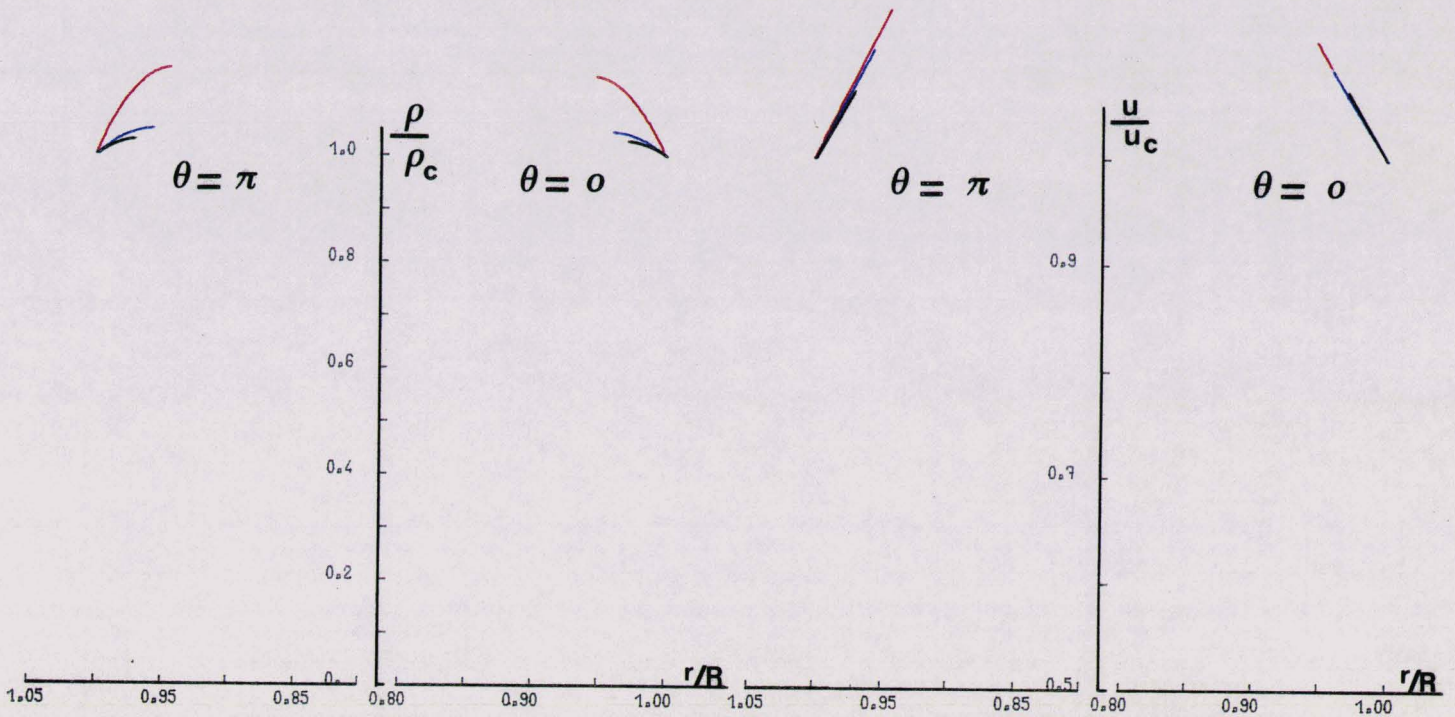
$\alpha = 3$

$\bar{M} = 0.$

Répartitions vues dans le repère mobile

Fig.92

- $M_c = \infty$
- $M_c = 5.$
- $M_c = .35$

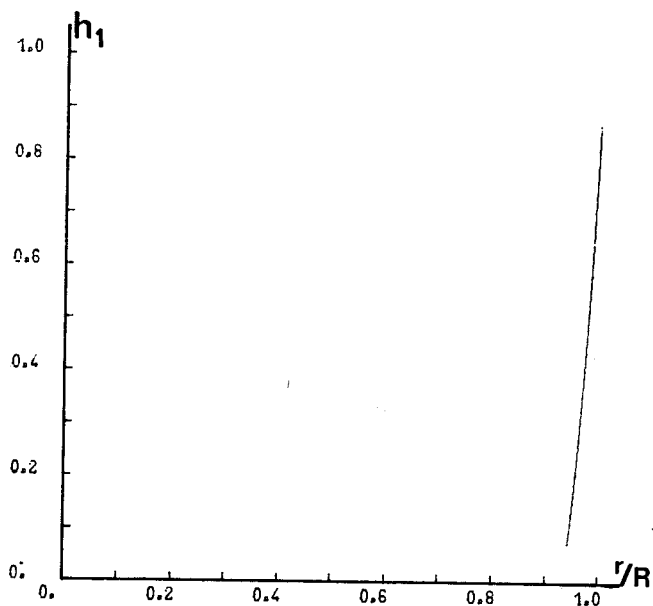


$\gamma = 1.2$

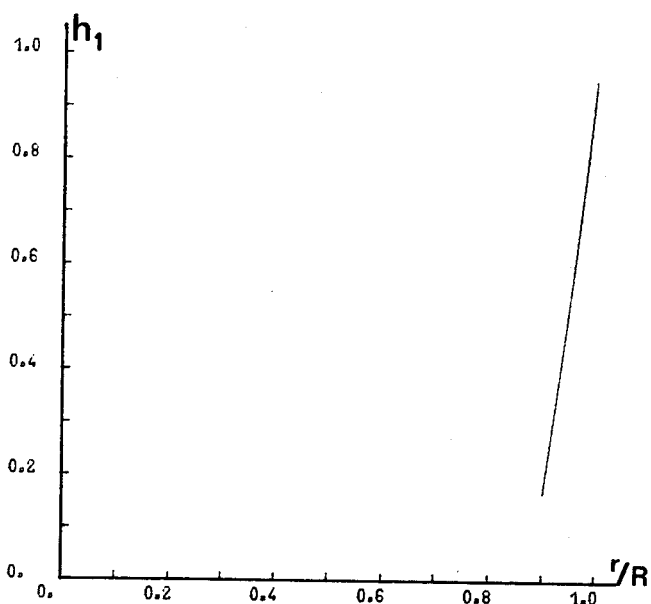
$\alpha = 3$

$\bar{M} = 0.8$

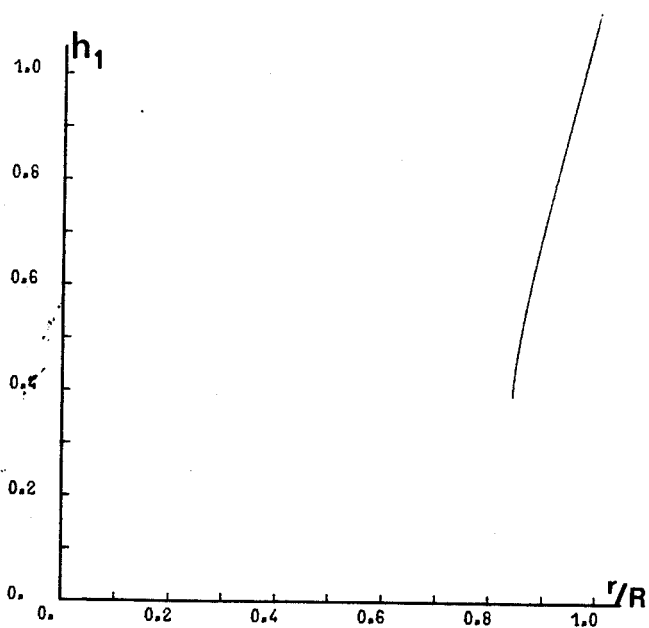
Répartitions vues dans le repère mobile



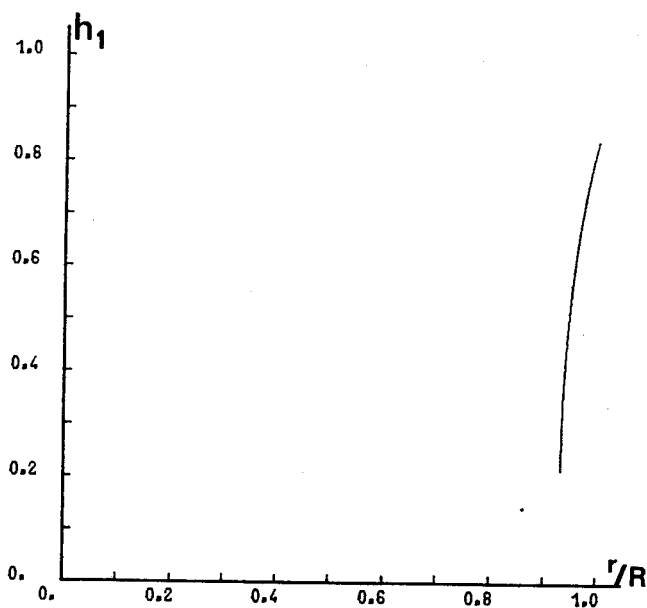
$\alpha = 1 \quad \gamma = 1.2$



$\alpha = 1 \quad \gamma = 1.4$

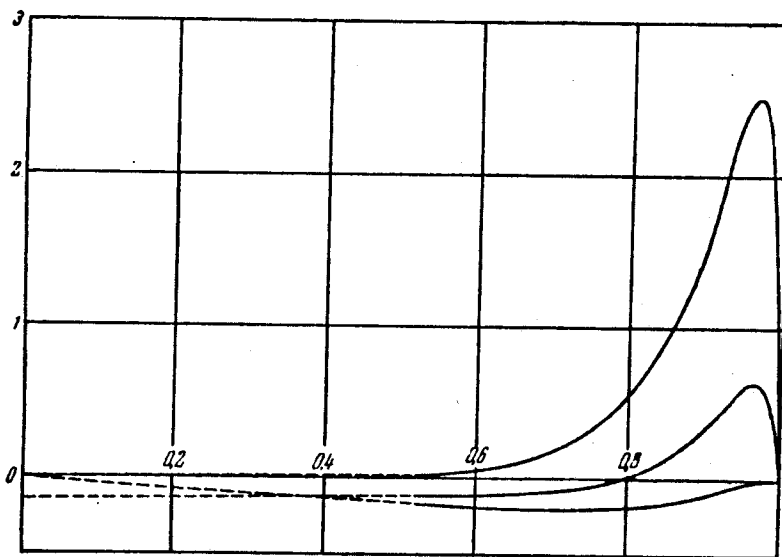
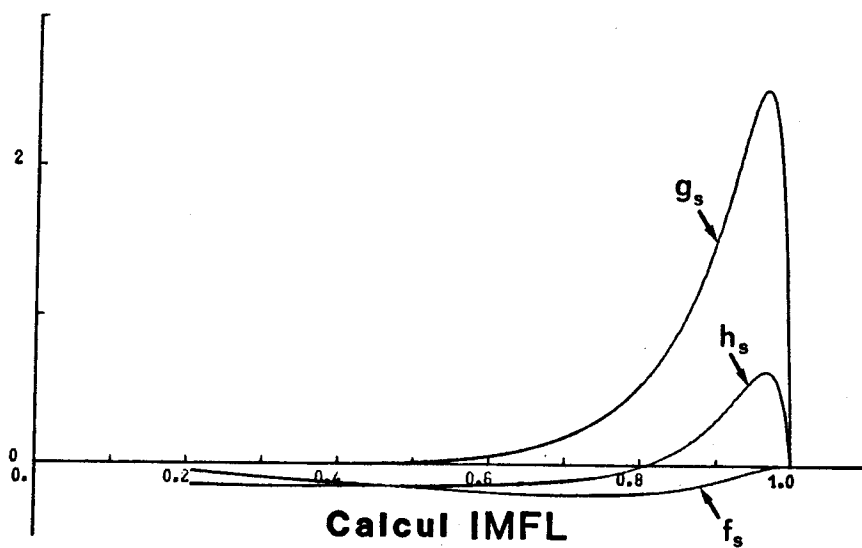


$\alpha = 1 \quad \gamma = 1.8$



$\alpha = 2 \quad \gamma = 1.4$

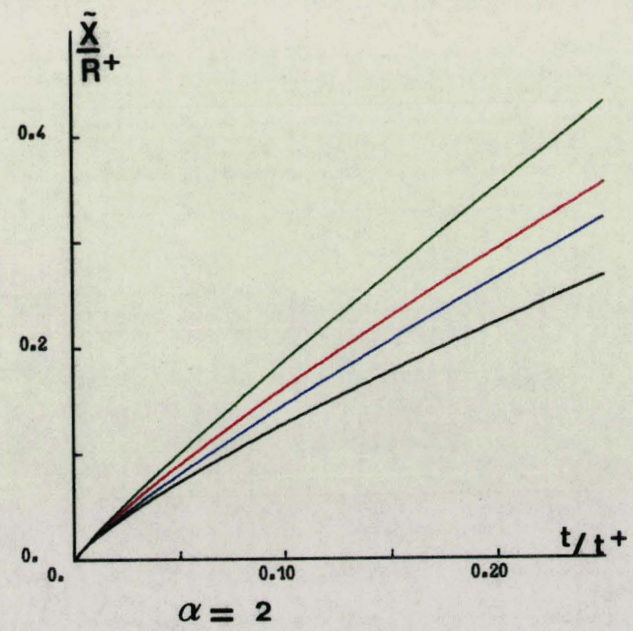
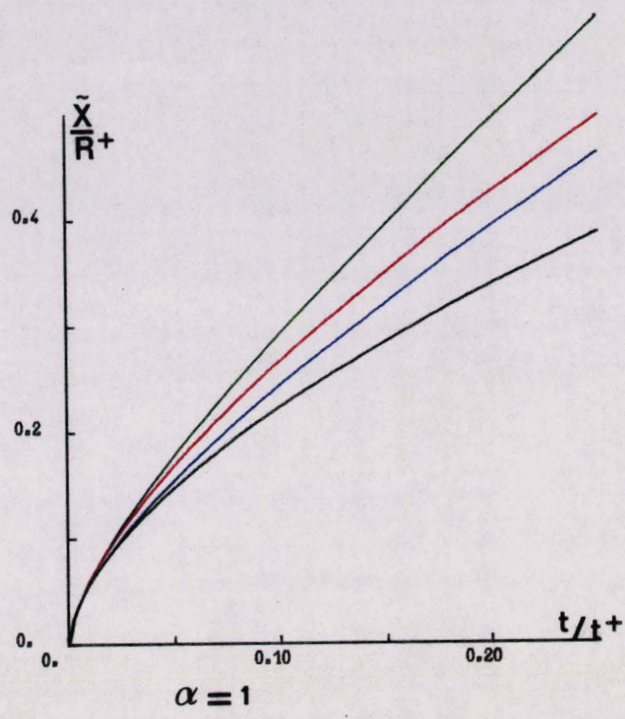
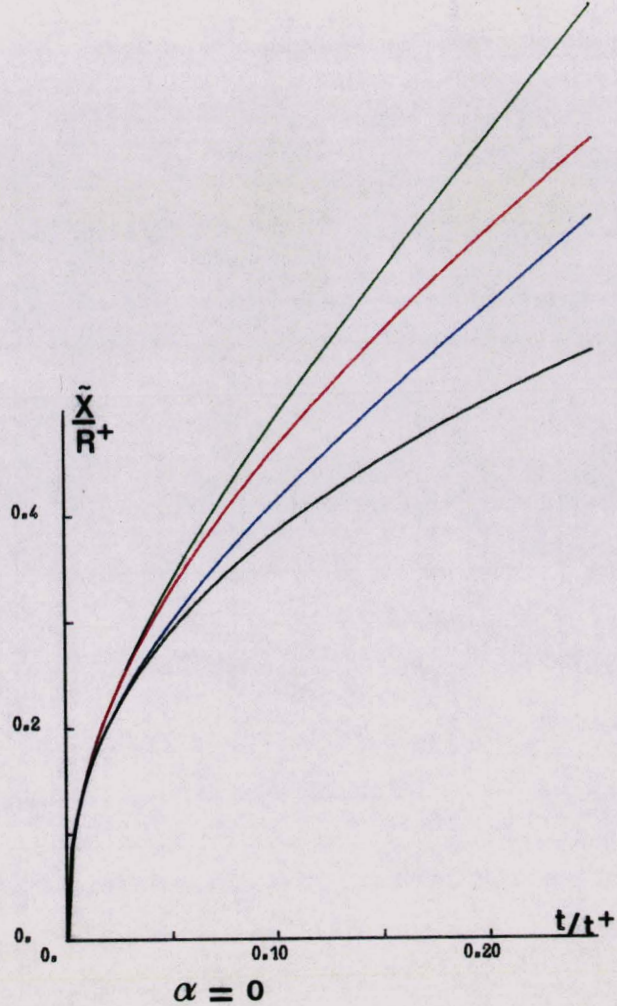
Fonction  $h_1$



Réf <3>

Comparaison avec SEDOV



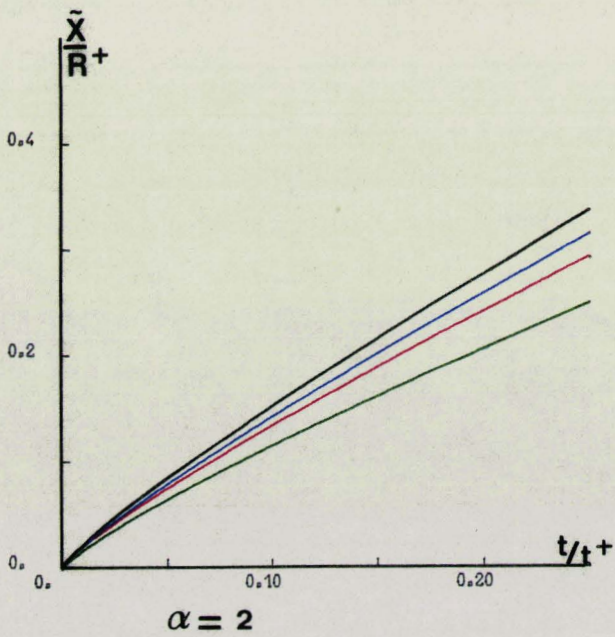
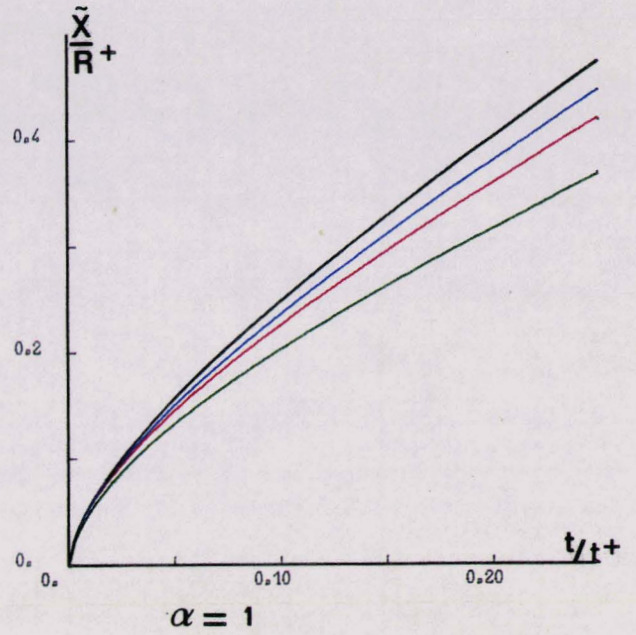
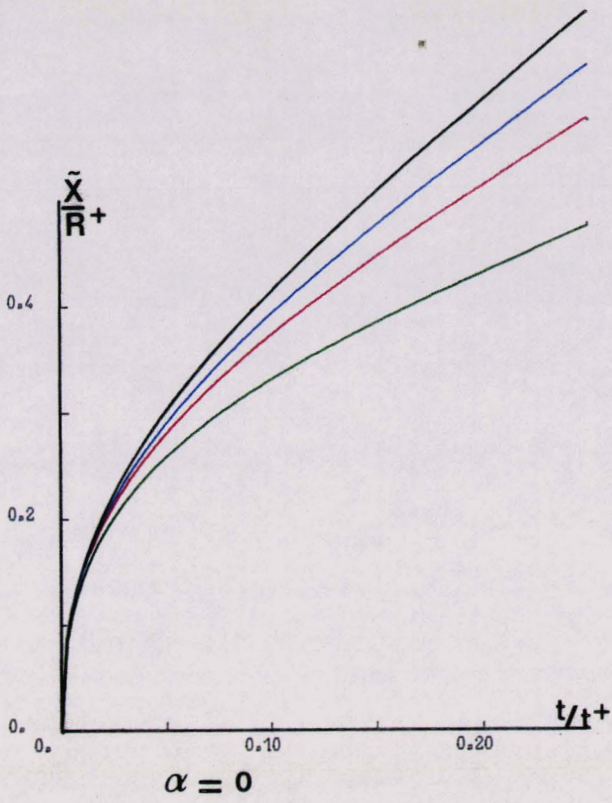


$\gamma = 14$

- Solution à similitude interne
- Effet de  $\bar{P}$  seule
- Effet d'ordre 1 du courant
- Solution d'ordre 2 complète

**Progression du choc en fonction de l'ordre  
d'approximation du modèle**

Repère fixe  $\theta = 0$

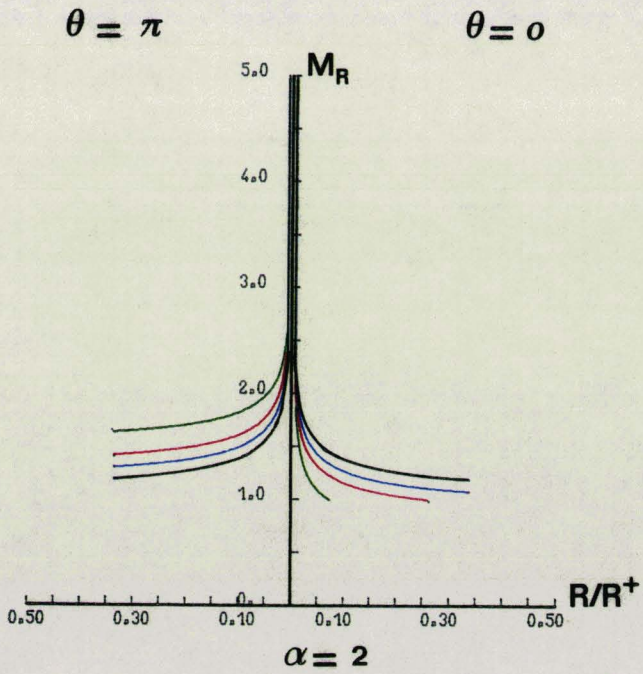
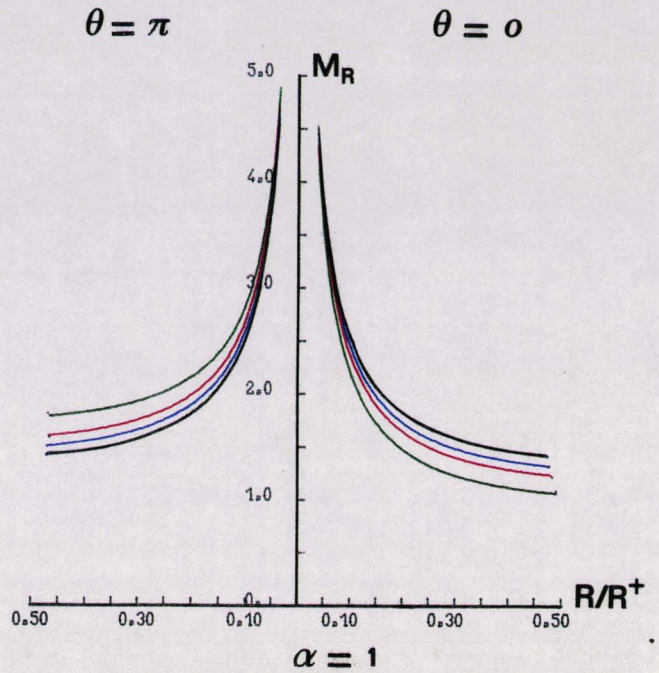
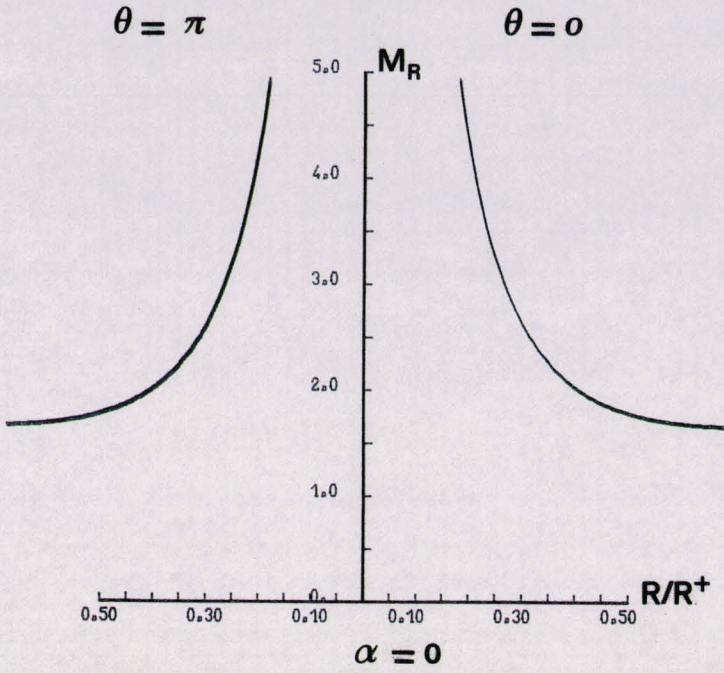


$\gamma = 1.4$

- $\bar{M} = 0$ .
- $\bar{M} = 0.2$
- $\bar{M} = 0.4$
- $\bar{M} = 0.8$

Progression du choc en  $\theta = \pi$  pour différentes valeurs de  $\bar{M}$

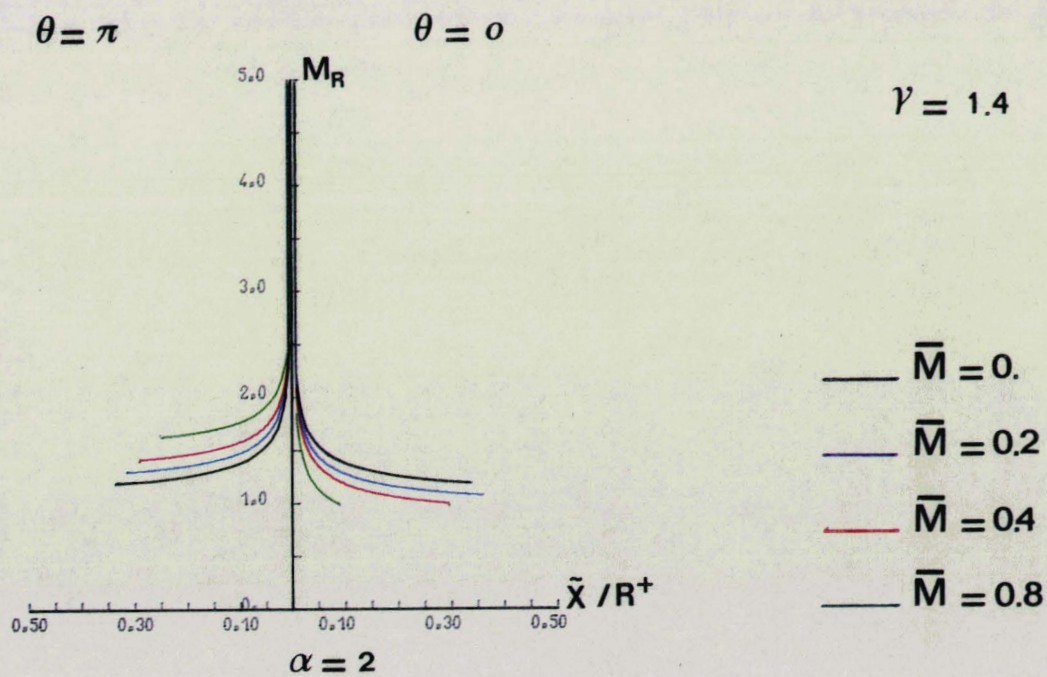
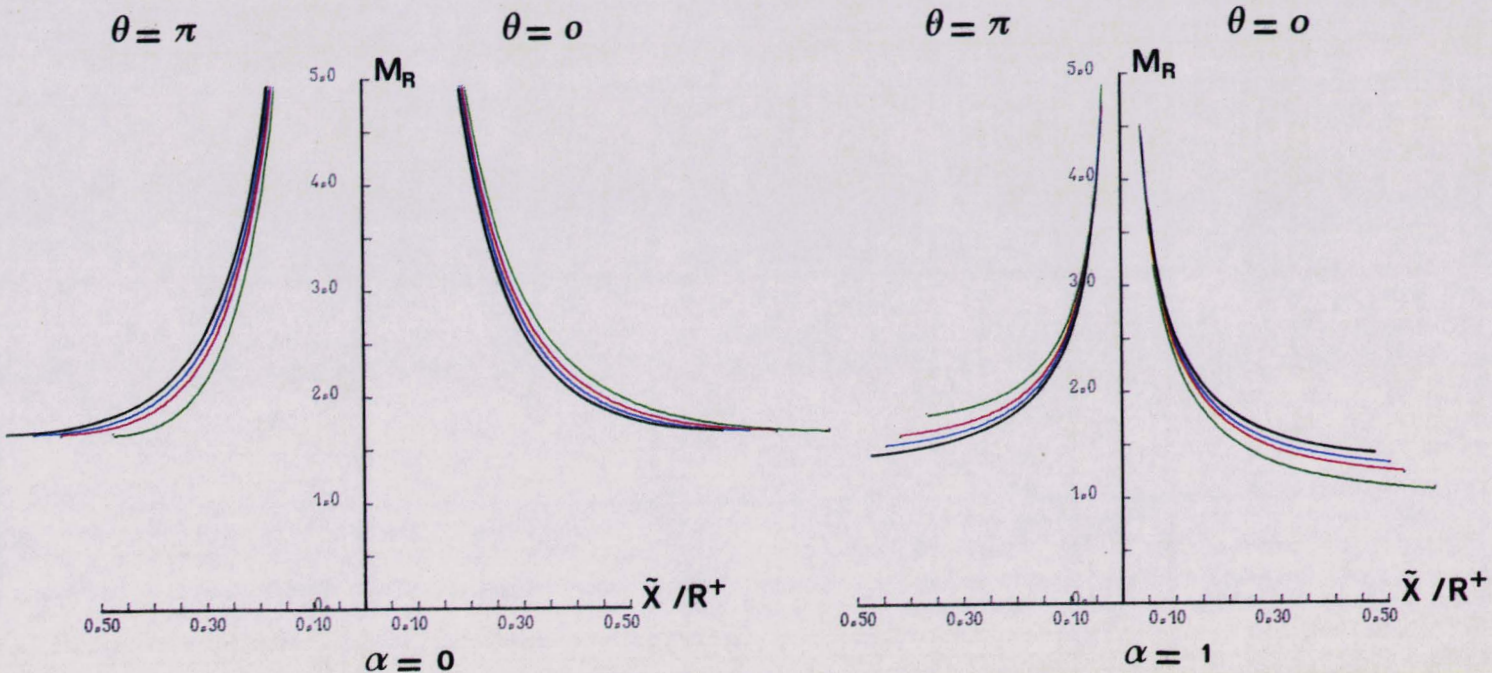
Repère fixe



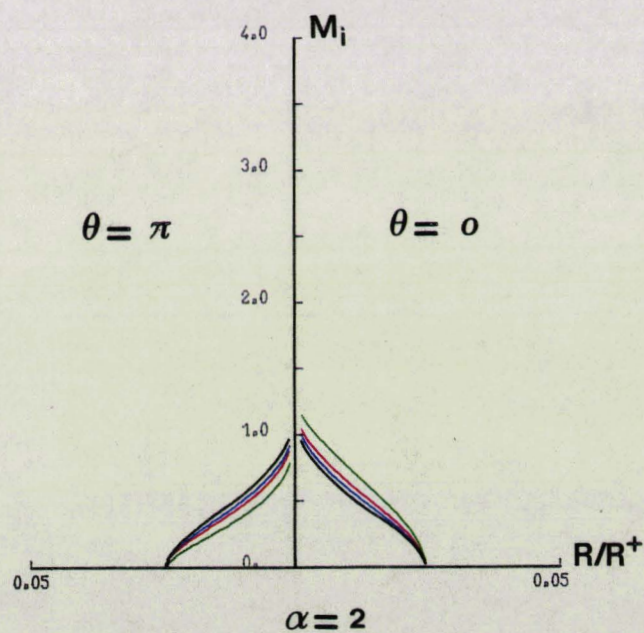
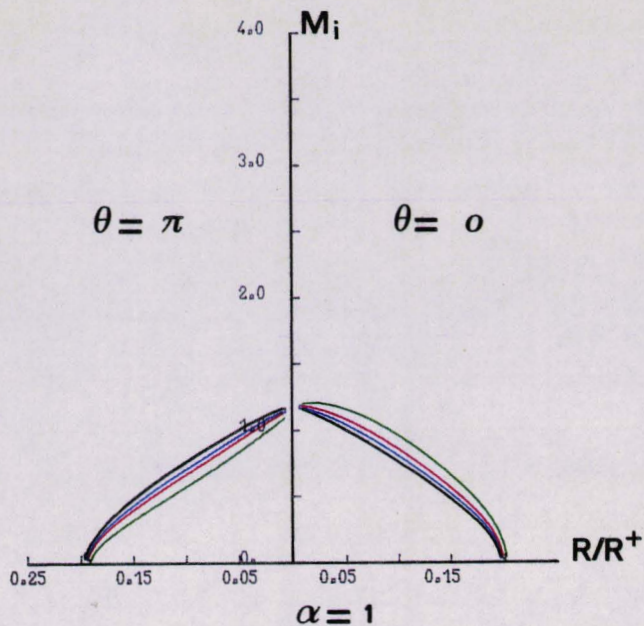
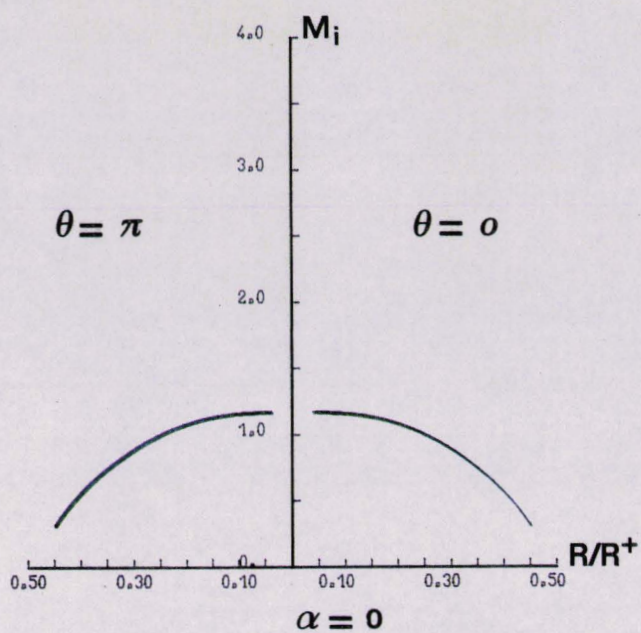
$\gamma = 1.4$

- $\bar{M} = 0.$
- $\bar{M} = 0.2$
- $\bar{M} = 0.4$
- $\bar{M} = 0.8$

Evolution de  $M_R = \frac{\omega - \bar{u}_n}{\bar{c}}$  sur l'axe de symétrie dans le repère mobile



Evolution de  $M_R = \frac{\omega - \bar{u}_n}{\bar{c}}$  sur l'axe de symétrie dans le repère fixe



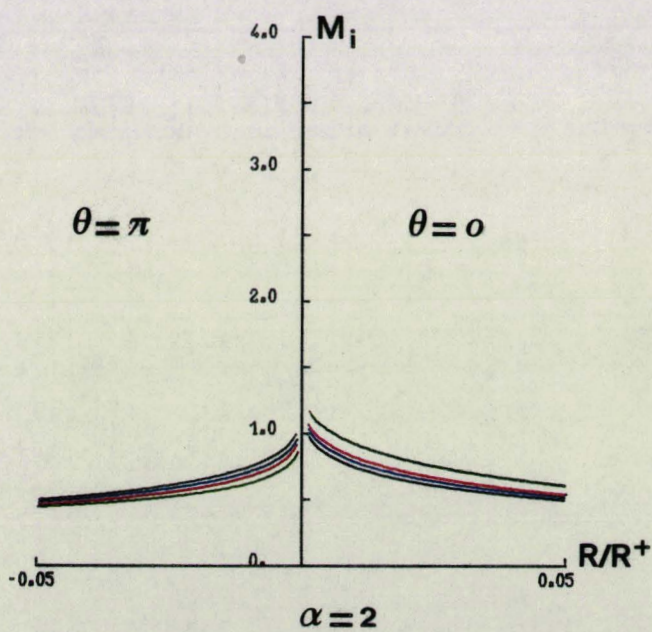
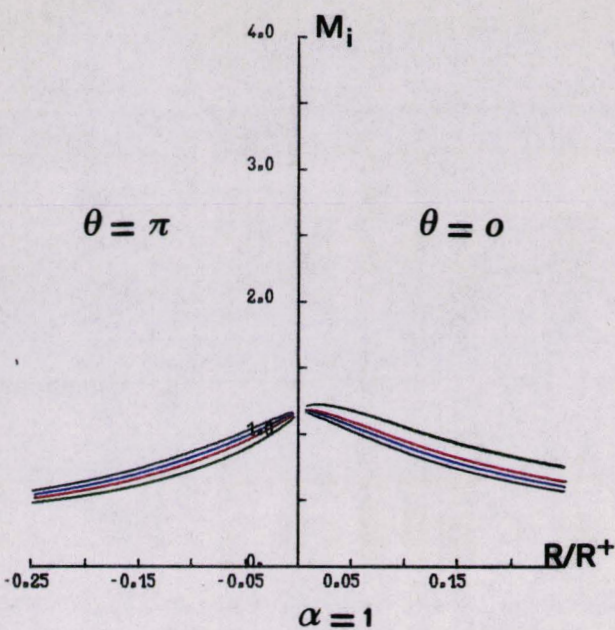
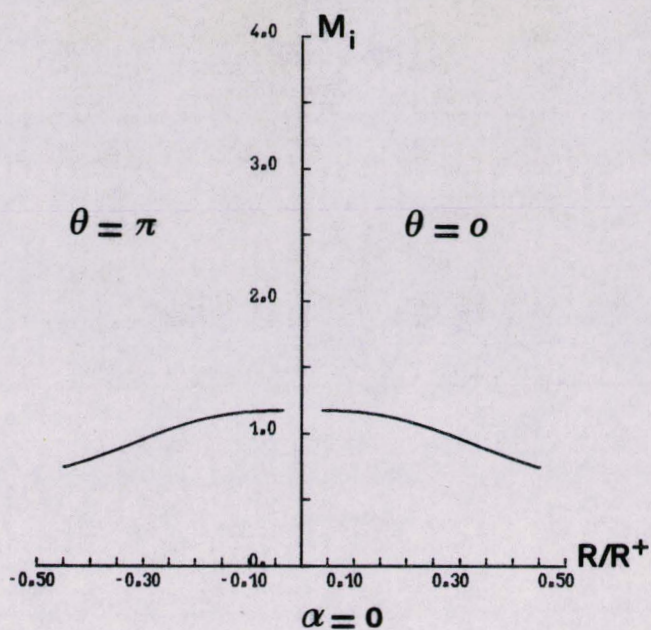
$\gamma = 1.8$

- $\bar{M} = 0.$
- $\bar{M} = 0.2$
- $\bar{M} = 0.4$
- $\bar{M} = 0.8$

**Nombre de Mach local sur la face intérieure du choc**

**par rapport au repère mobile**

**Evolution sur l'axe de symétrie déduite des conditions sur le choc**



$\gamma = 1.8$

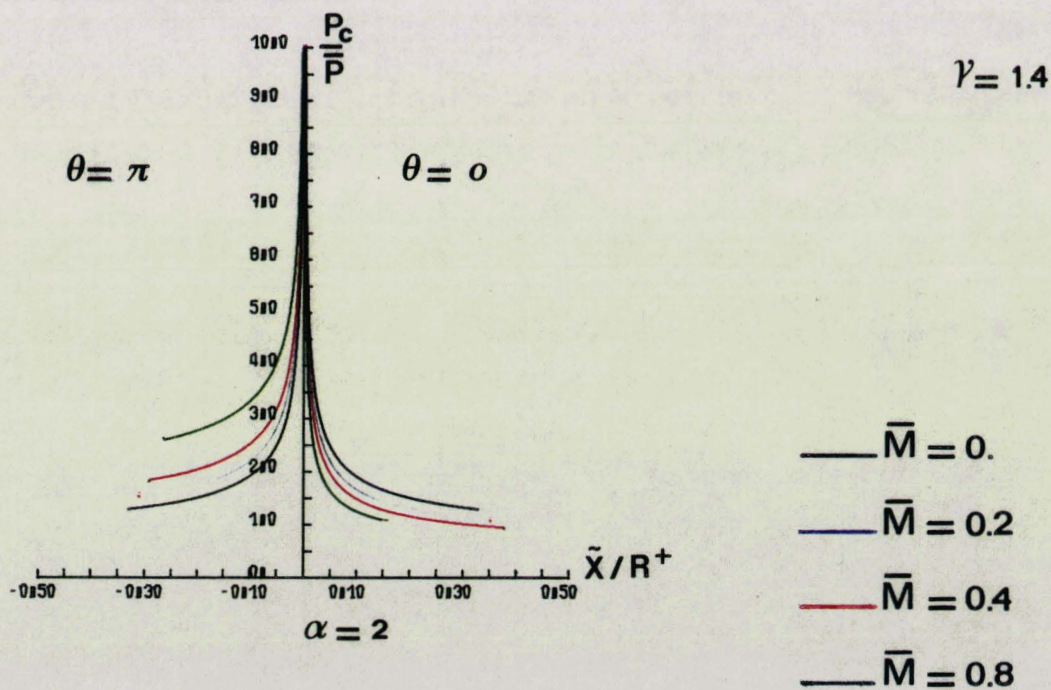
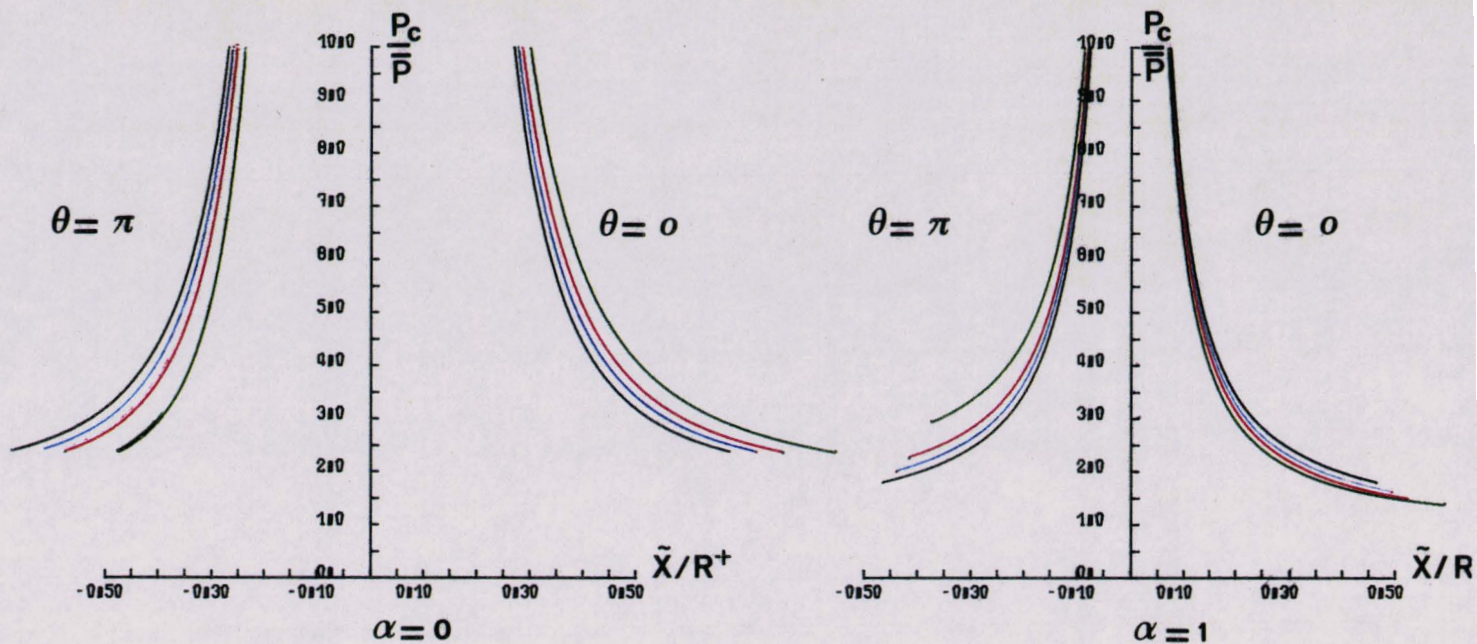


- $\bar{M} = 0.$
- $\bar{M} = 0.2$
- $\bar{M} = 0.4$
- $\bar{M} = 0.8$

**Nombre de Mach local sur la face intérieure du choc**

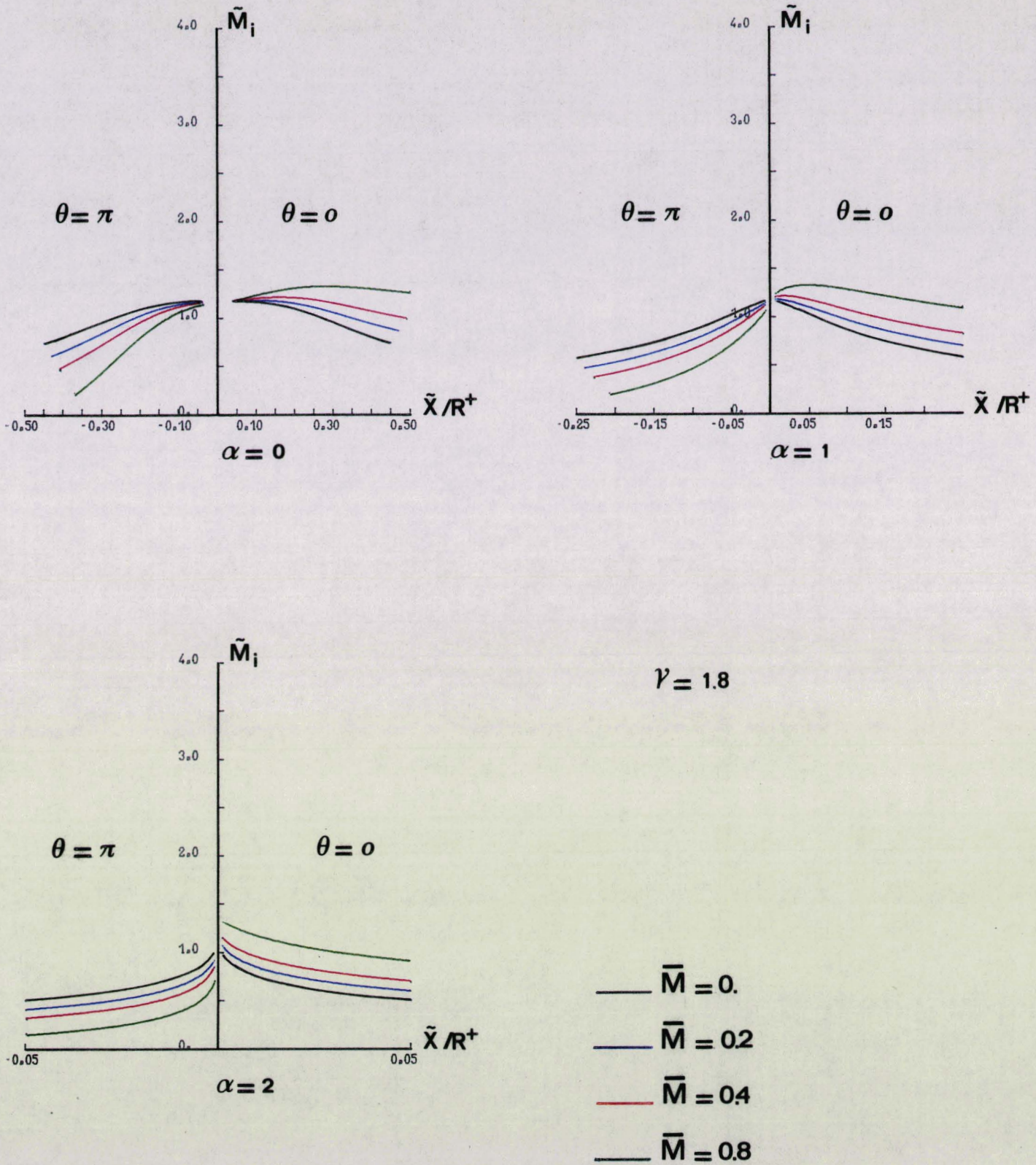
**par rapport au repère mobile**

**Evolution sur l'axe de symétrie déduite de la progression du choc**



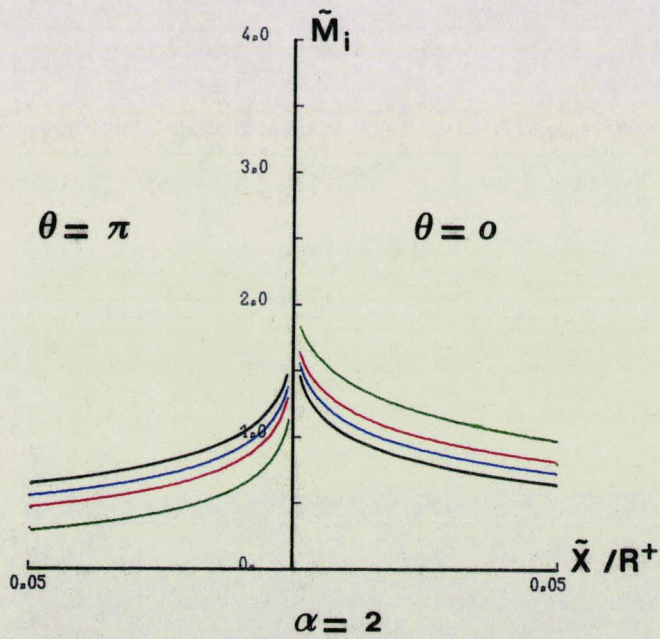
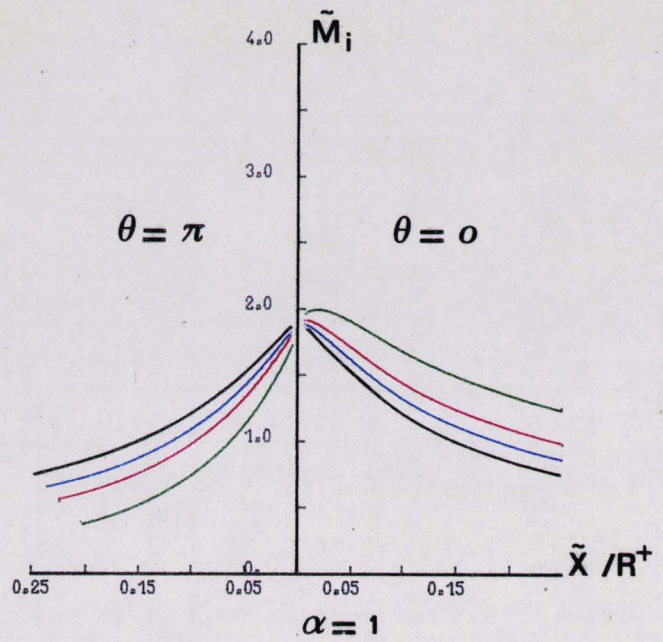
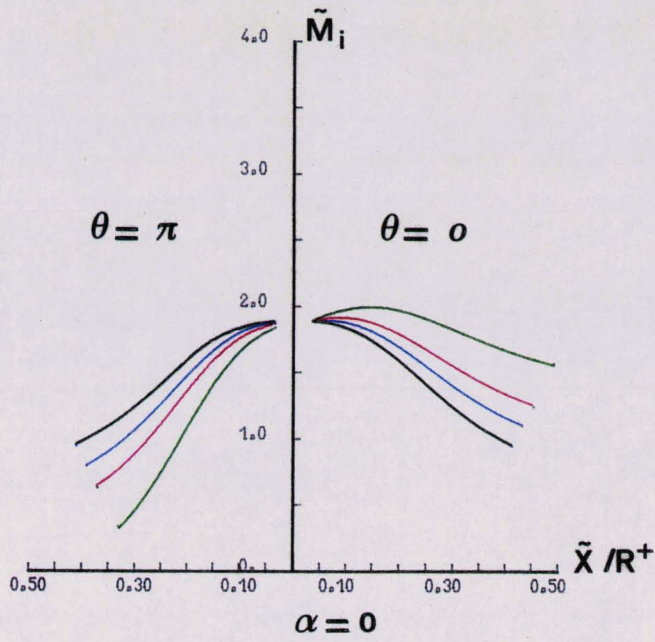
Evolution sur l'axe de symétrie de  $P_c/\bar{P}$  en fonction  
de la position du choc dans le repère fixe

Calcul à partir du développement de  $P^*$  sur le choc



Evolution sur l'axe de symétrie du nombre de Mach local sur la face intérieure du choc par rapport au repère fixe

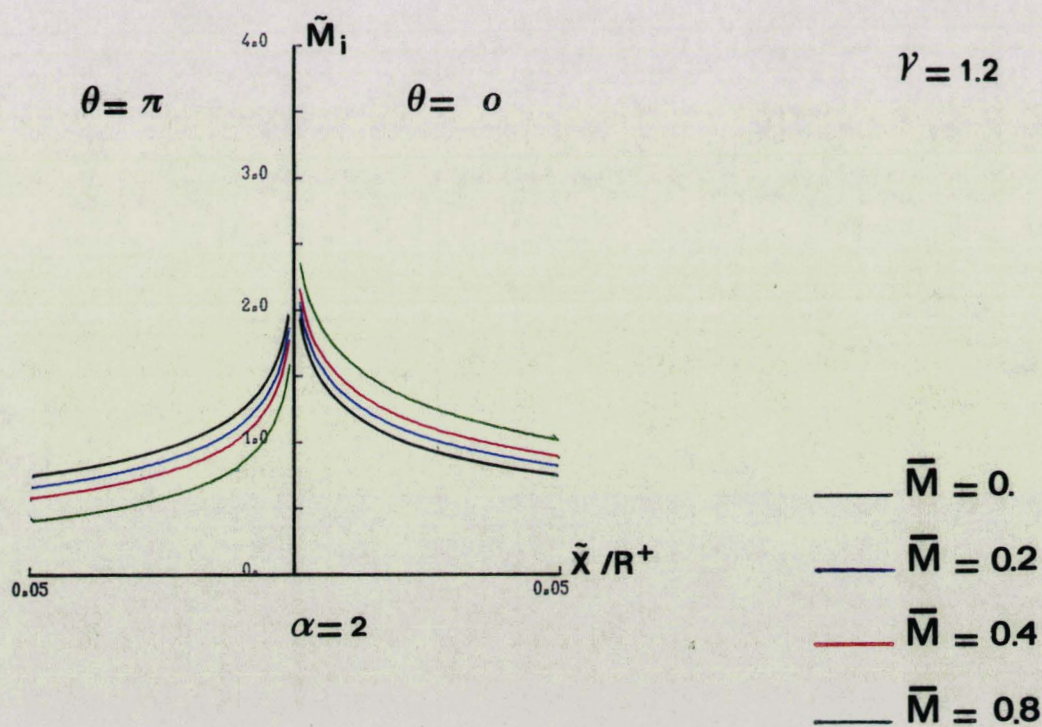
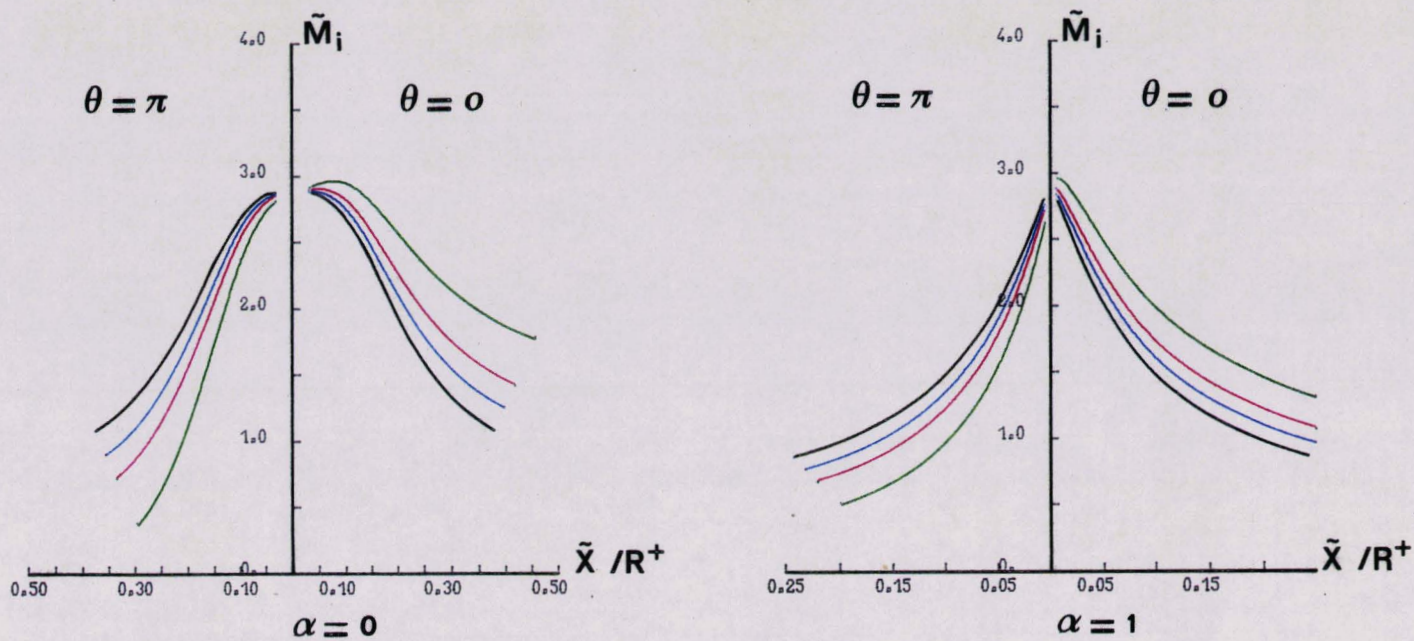




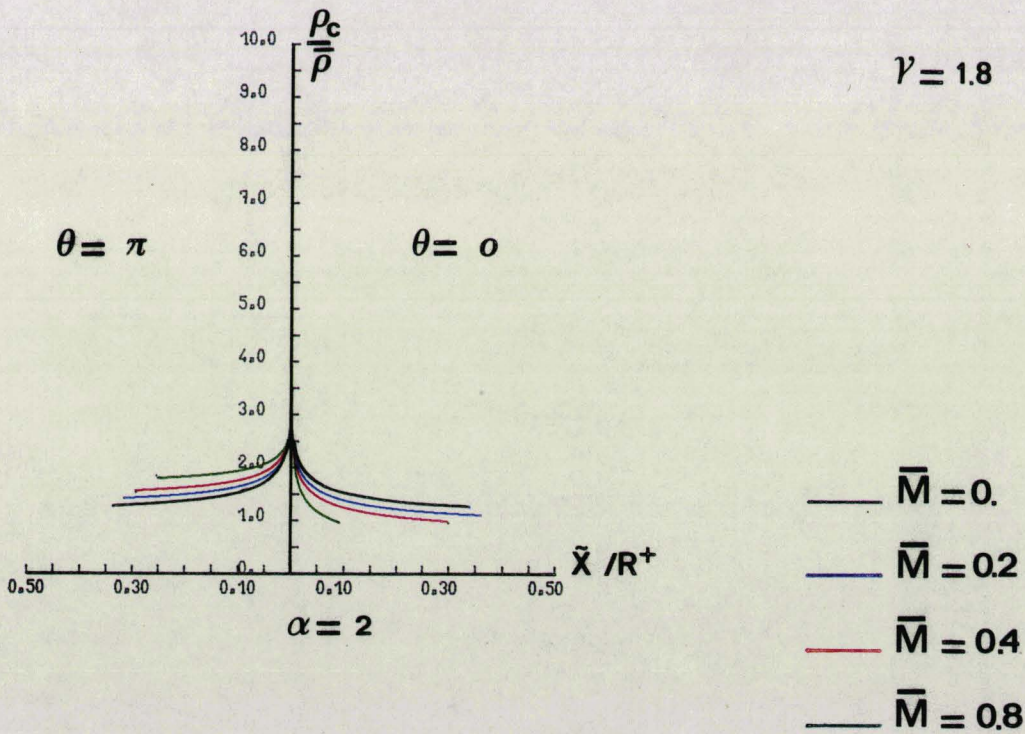
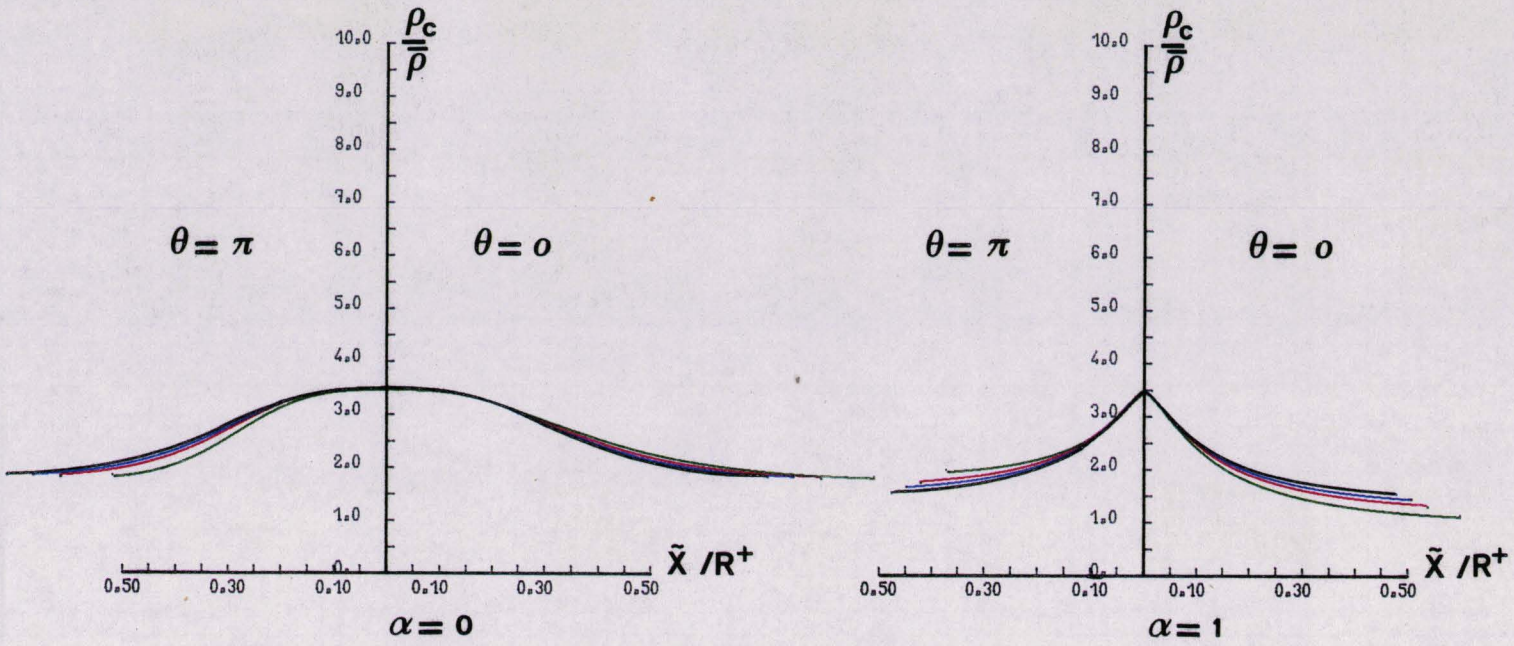
$\gamma = 1.4$

- $\bar{M} = 0.$
- $\bar{M} = 0.2$
- $\bar{M} = 0.4$
- $\bar{M} = 0.8$

**Evolution sur l'axe de symétrie du nombre de Mach local sur la face intérieure du choc par rapport au repère fixe**



**Evolution sur l'axe de symétrie du nombre de Mach local  
 sur la face intérieure du choc par rapport au repère fixe**

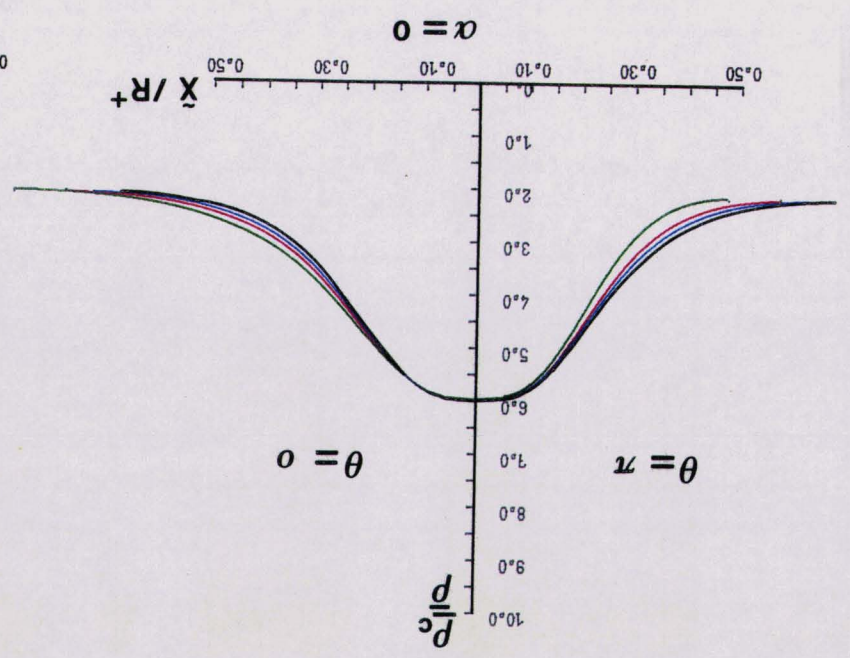
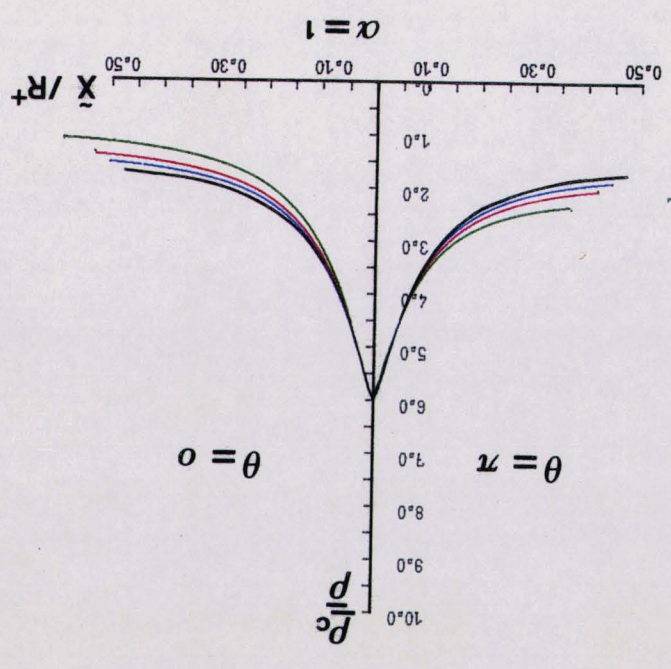
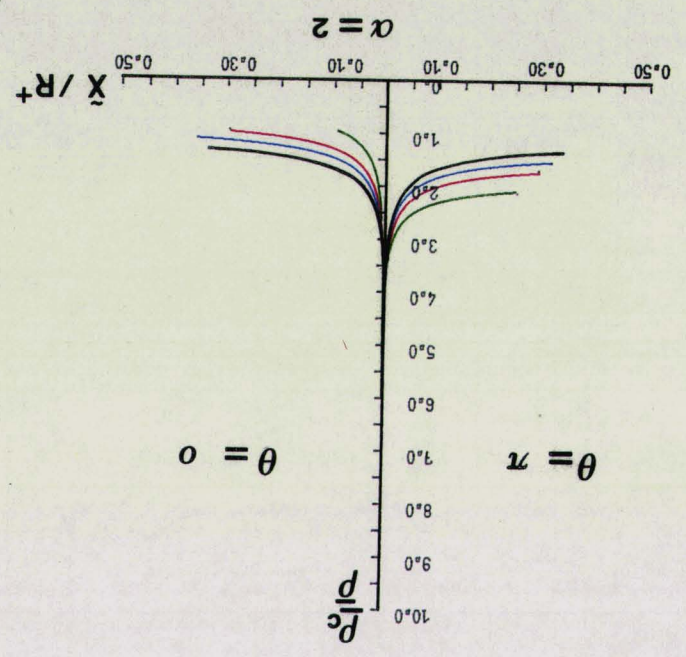


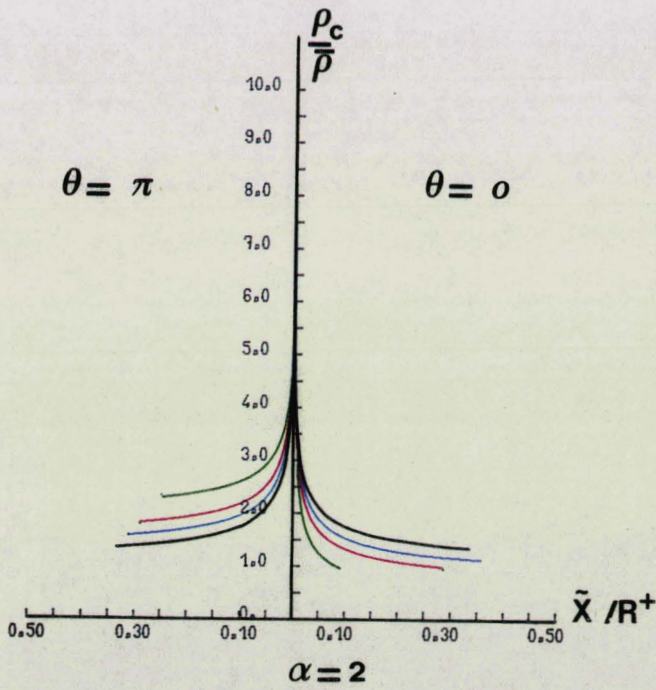
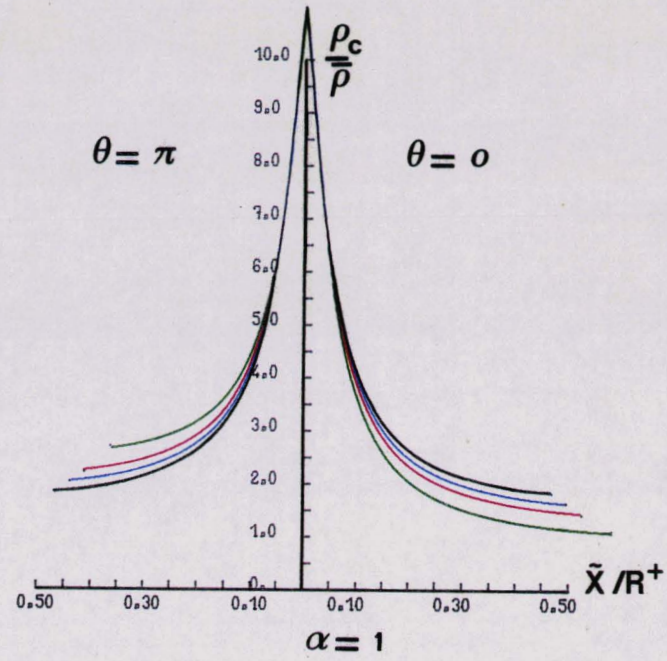
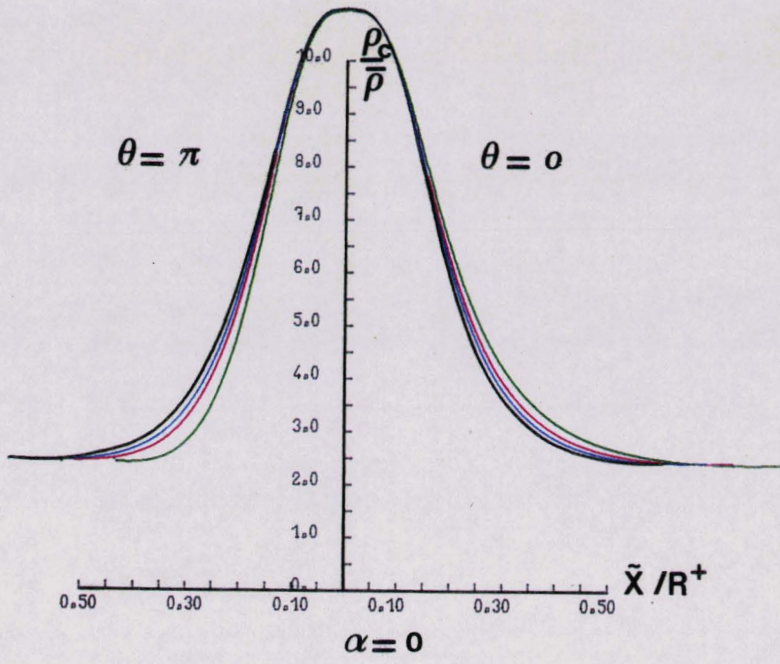
Evolution sur l'axe de symétrie de  $\rho_c / \bar{\rho}$  en fonction de la position du choc dans le repère fixe

Evolution sur l'axe de symétrie de  $\rho/\rho_c$  en fonction de la position du choc dans le repère fixe

- $\bar{M} = 0.8$
- $\bar{M} = 0.4$
- $\bar{M} = 0.2$
- $\bar{M} = 0$

$\gamma = 1.4$

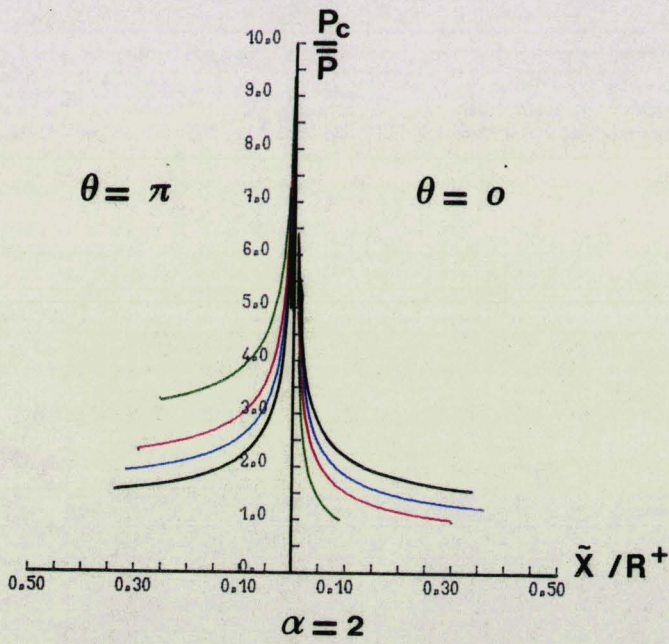
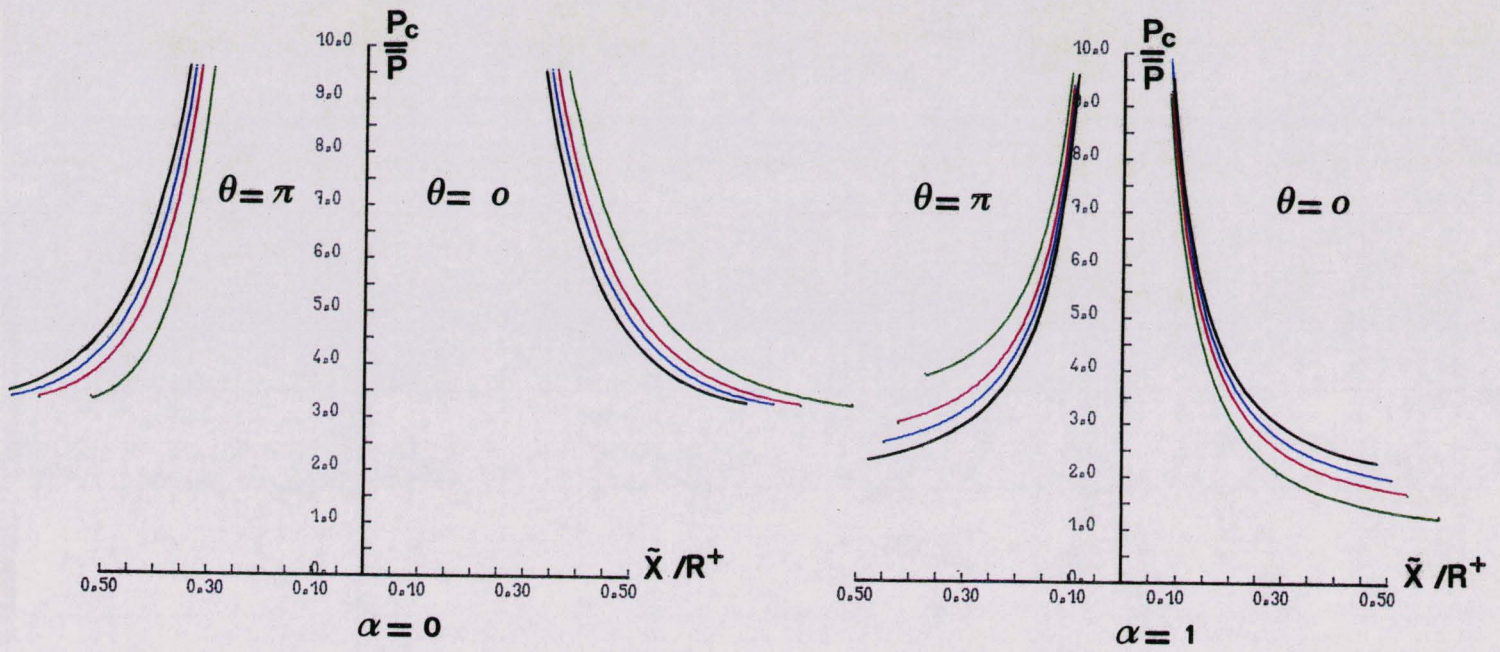




$\gamma = 1.2$

- $\bar{M} = 0.$
- $\bar{M} = 0.2$
- $\bar{M} = 0.4$
- $\bar{M} = 0.8$

**Evolution sur l'axe de symétrie de  $\rho_c / \bar{\rho}$  en fonction de la position du choc dans le repère fixe**



$\gamma = 1.8$

- $\bar{M} = 0.$
- $\bar{M} = 0.2$
- $\bar{M} = 0.4$
- $\bar{M} = 0.8$

**Evolution sur l'axe de symétrie de  $P_c/\bar{P}$  en fonction de la position du choc dans le repère fixe**

Evolution sur l'axe de symétrie de  $P_c/P$  en fonction de la position du choc dans le repère fixe

- $\bar{M} = 0.8$
- $\bar{M} = 0.4$
- $\bar{M} = 0.2$
- $\bar{M} = 0.$

$\gamma = 1.4$

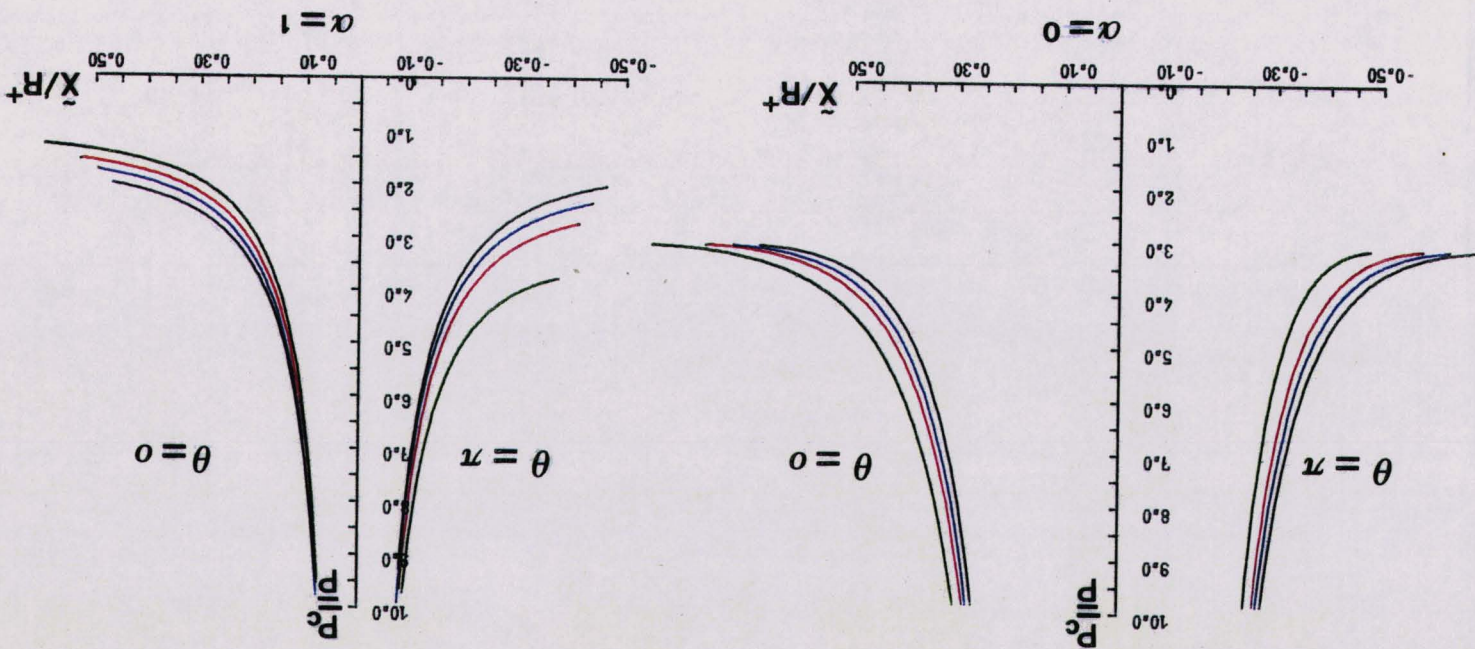
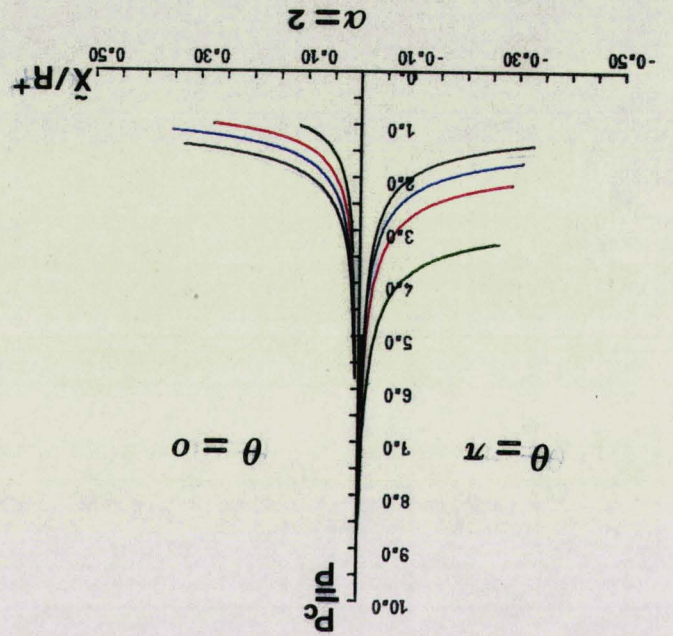
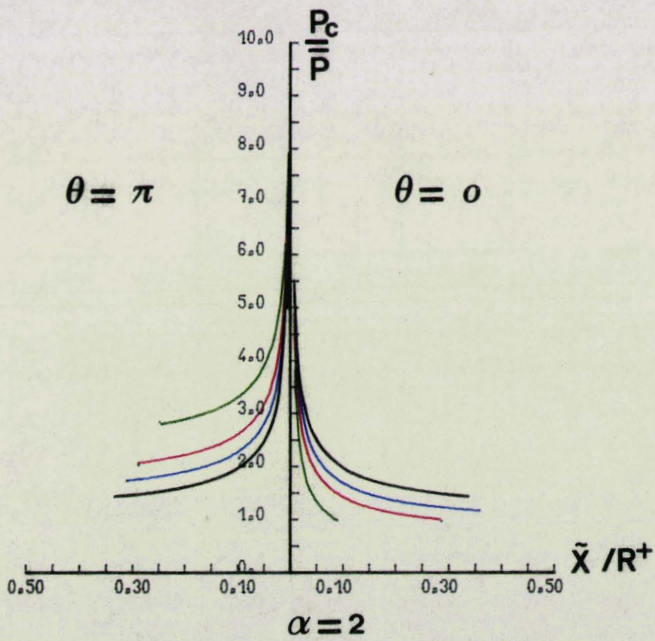
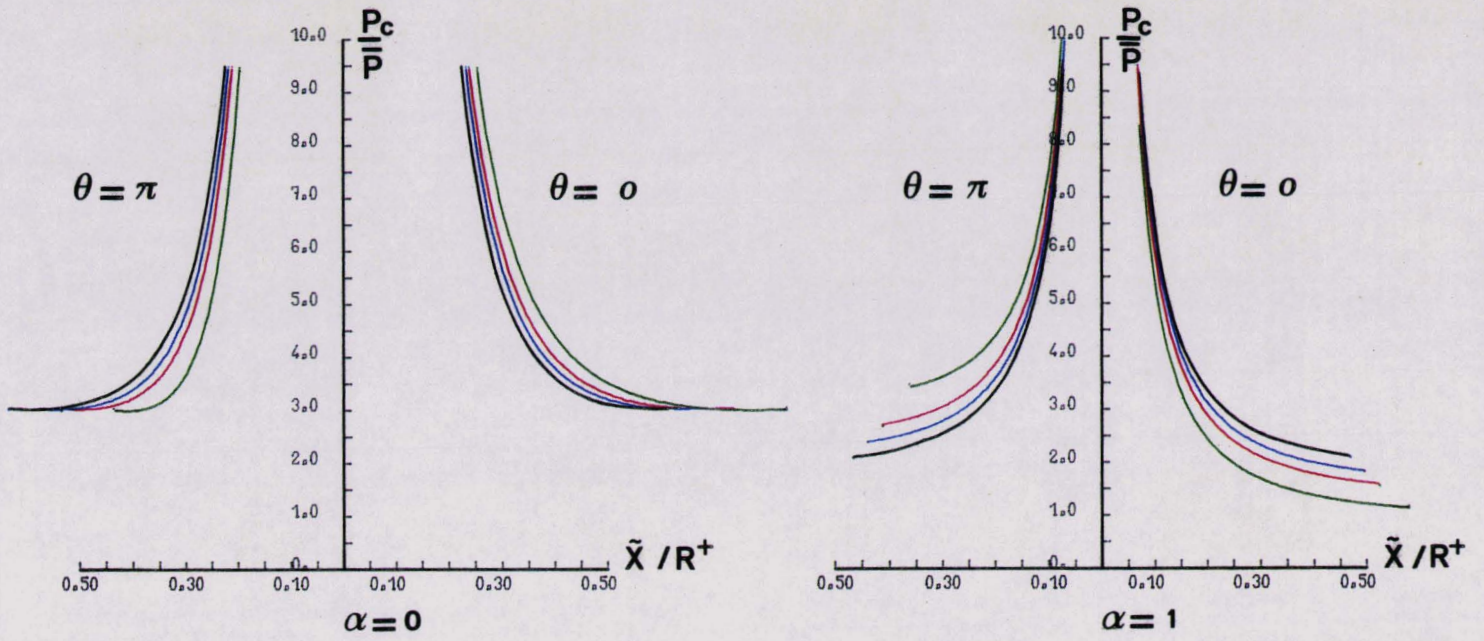


Fig. 109



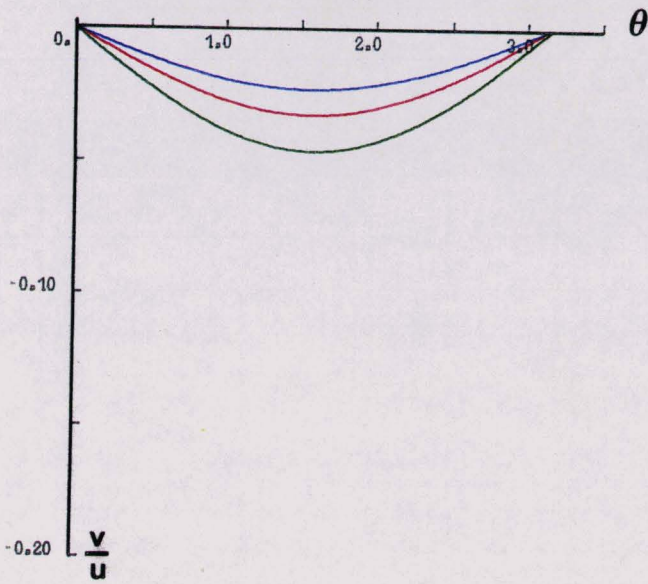
$\gamma = 1.2$

- $\bar{M} = 0.$
- $\bar{M} = 0.2$
- $\bar{M} = 0.4$
- $\bar{M} = 0.8$

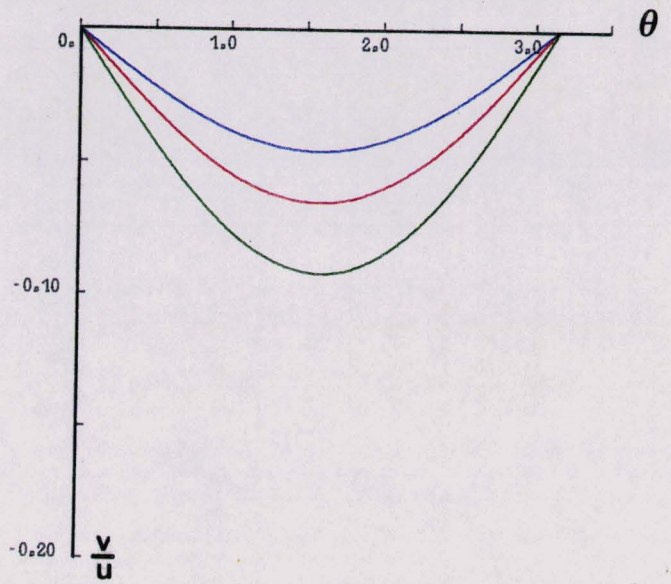
**Evolution sur l'axe de symétrie de  $P_c/\bar{P}$  en fonction de la position du choc dans le repère fixe**



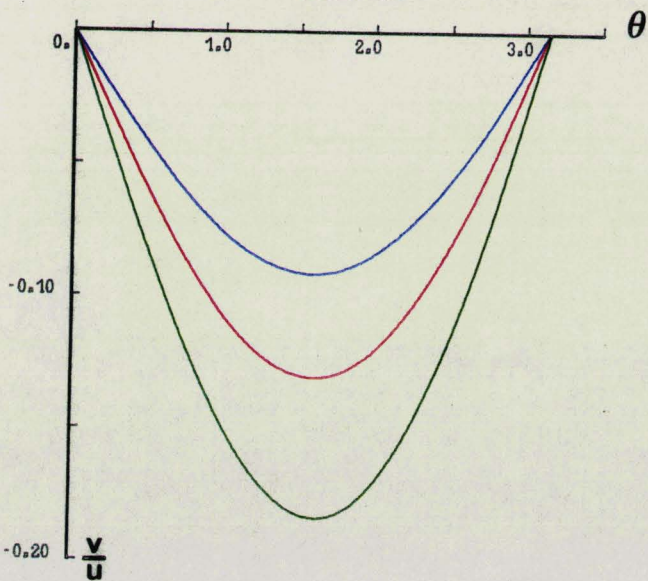
$\bar{M} = 0.2$



$\bar{M} = 0.4$



$\bar{M} = 0.8$



$\gamma = 14$

$\alpha = 1$

—  $M_c = 5.$

—  $M_c = 3.5$

—  $M_c = 2.5$

Evolution du rapport  $v/u$  sur le choc en fonction de  $\theta$

dans le repère principal

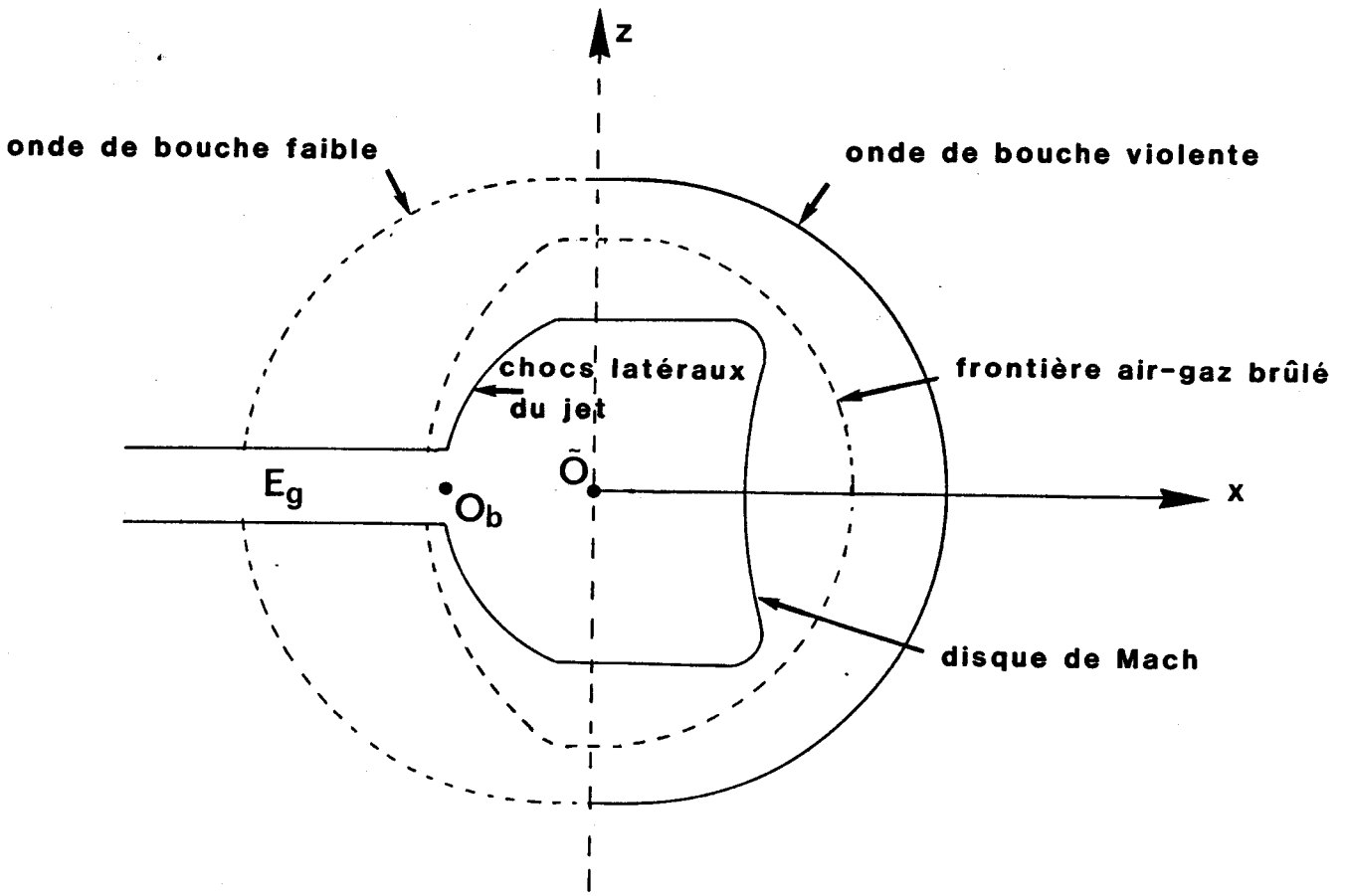


Schéma du tir réel

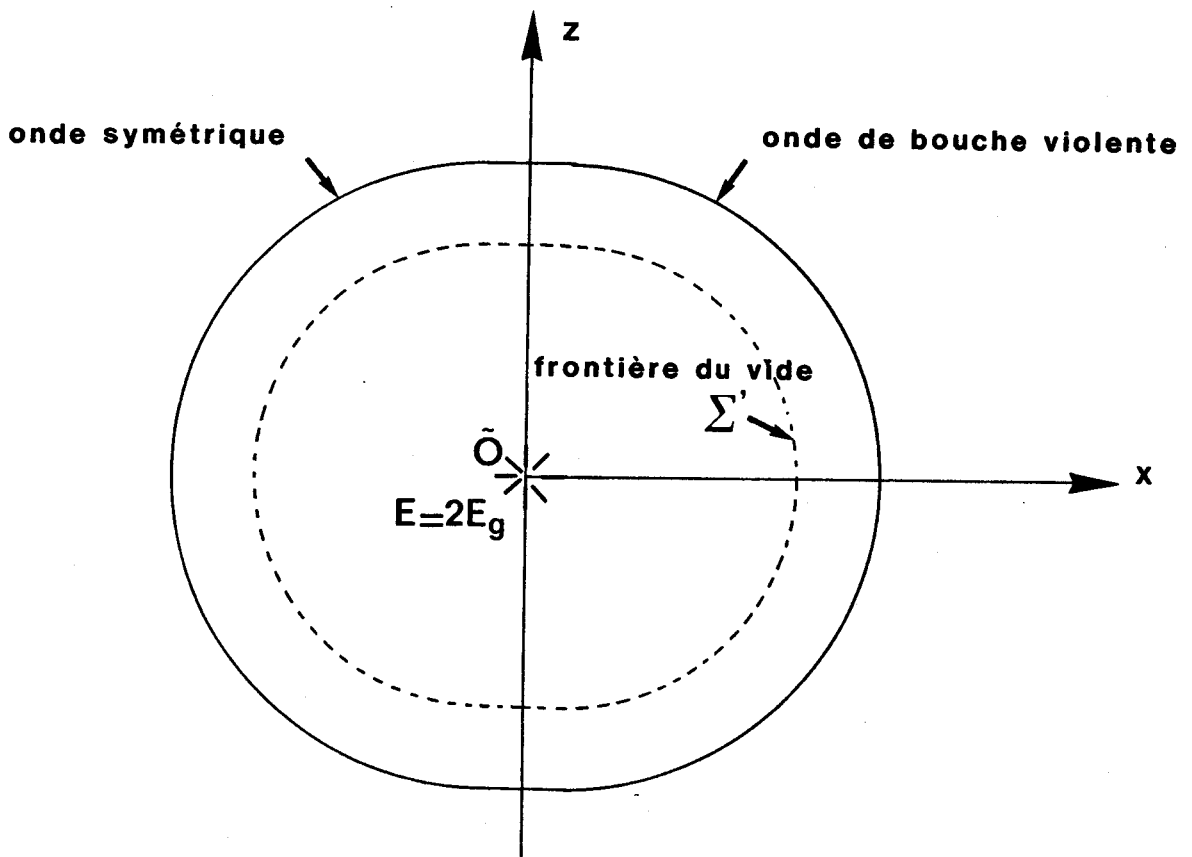
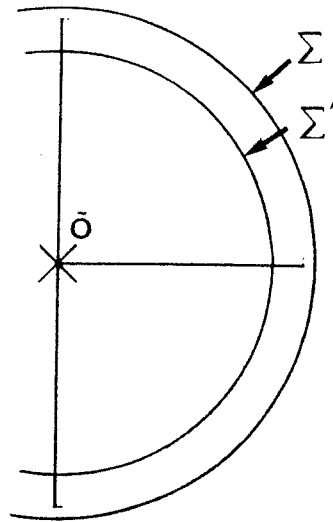


Schéma de l'explosion isotrope équivalente

Visualisation

calcul



Tir pour  $\bar{M} = 0$

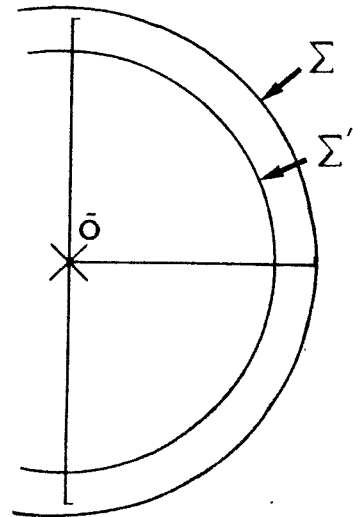
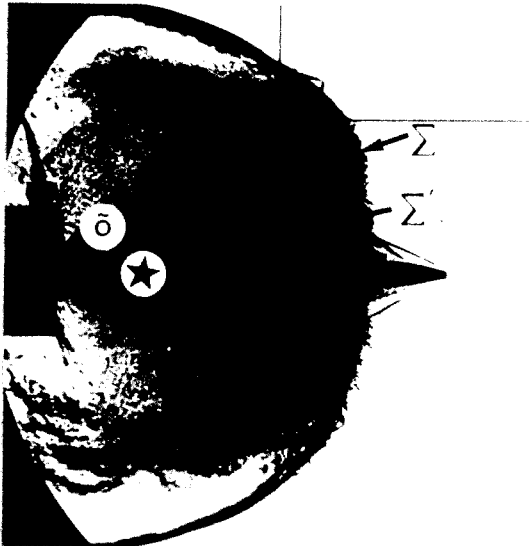
Tir

$$P_g = 290 \text{ bars}$$

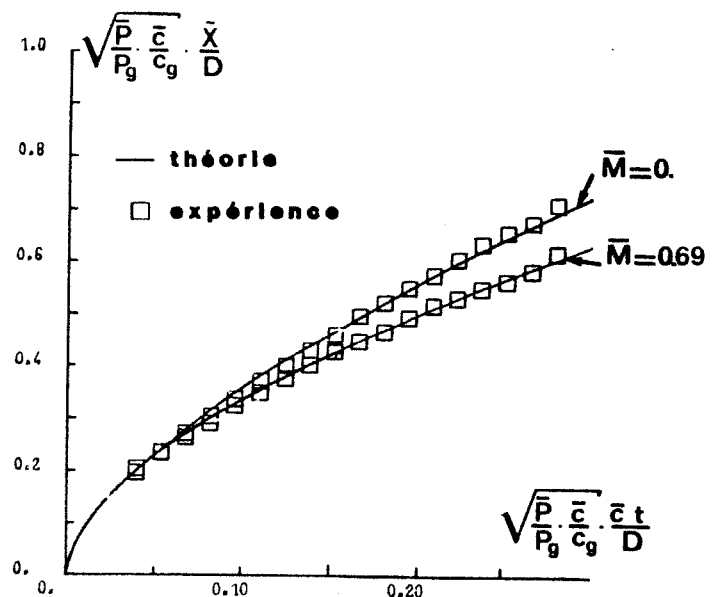
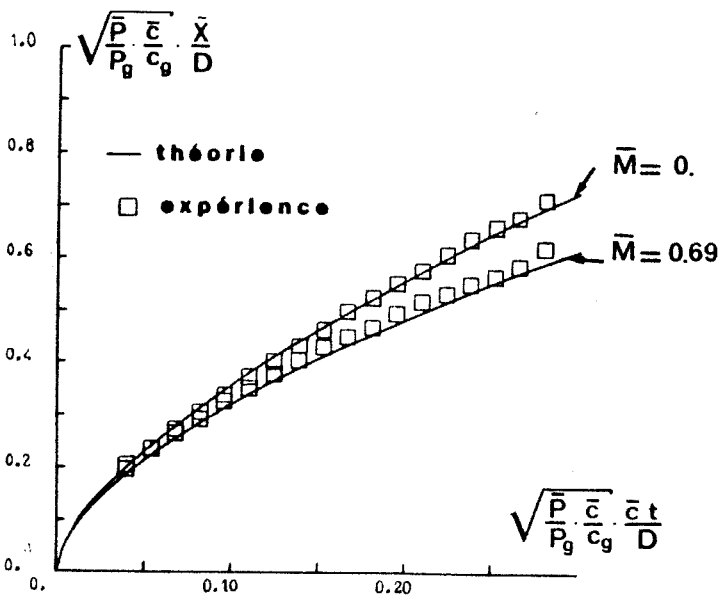
$$c_g = 780 \text{ m/s}$$

$$\gamma_g = 1.25$$

$$D = 7.62 \text{ mm}$$



Tir à  $\bar{M} = 0,69$



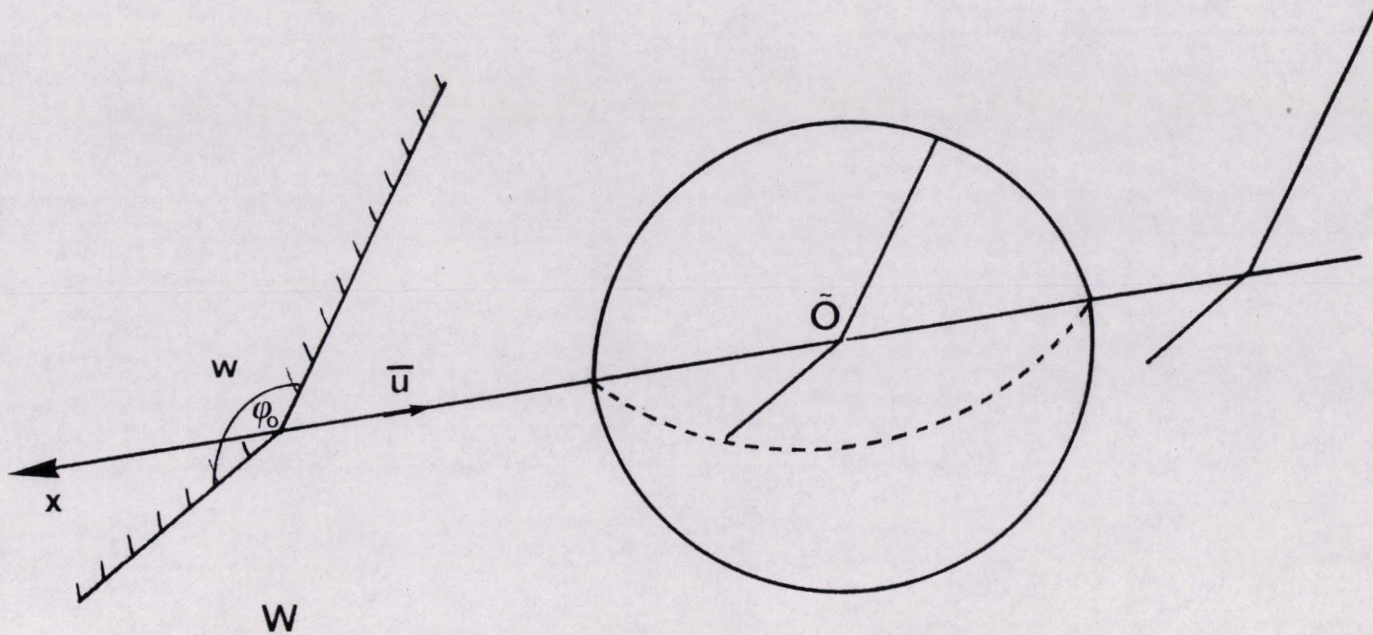
Calcul direct

$\bar{O}$ : à 25 mm en avant de la bouche

$t=0$ : 32  $\mu\text{s}$  après le débouchage du canon

calcul avec effet

du courant différé de 35  $\mu\text{s}$



Explosion dans un dièdre infini

fuselage



plan d'entrée  
de la prise d'air



Canon dans un fuselage

## RESUME

L'écoulement consécutif au tir des armes à feu est étudié expérimentalement à l'aide de visualisations ultra-rapides et de mesures de pressions instationnaires. La prépondérance de l'effet de l'onde de bouche (ou onde de souffle) est mise en évidence. Les principes de la similitude physique sont appliqués à l'étude de l'onde de bouche : les paramètres sans dimensions régissant le phénomène sont obtenus et leur influence analysée. On aboutit ainsi à la définition d'une méthode expérimentale d'essais sur modèles pour l'étude de l'effet du tir sur le milieu environnant. Une modélisation réaliste dans le cas du tir très intense permet d'assimiler celui-ci à l'écoulement causé par une explosion violente anisotrope. L'étude mathématique des équations générales de l'explosion violente décèle une similitude interne mise à profit pour simplifier le problème. On démontre que l'anisotropie de la forme géométrique de l'onde de choc produite par l'explosion est beaucoup moins accentuée que celle de l'apport d'énergie. De ce fait, et si on se borne à représenter la propagation du choc, on peut considérer l'onde comme issue d'une explosion isotrope. A partir du développement asymptotique de la solution bien connue du problème de l'explosion violente isotrope dans un milieu infini au repos, on obtient les effets de la vitesse et de la pression du milieu extérieur lorsqu'il est en translation uniforme. La solution, traitée par une méthode de petites perturbations, permet de mettre la loi de propagation de l'onde de choc sous une forme analytique universelle. Le calcul numérique de cet écoulement a été réalisé. Les résultats théoriques ont été confrontés avec succès à l'expérience dans le cas du tir d'arme. Le mémoire se termine par l'application de la théorie de l'explosion au problème de l'interaction du tir d'un canon embarqué avec le fonctionnement des prises d'air d'un avion militaire.

## MOTS CLES

BALISTIQUE INTERMEDIAIRE  
TIR D'ARME  
ONDES DE CHOC  
EXPLOSIONS VIOLENTES  
SIMILITUDE PHYSIQUE  
SIMILITUDE INTERNE