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COMPUTATION OF THE MOTION OF A LINER UNDER THE IMPACT OF A UNIFORM GAS FLOW

by

L. GUERRI, P. STELLA and A. TARONI

1966

Joint Nuclear Research Center
Ispra Establishment - Italy

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SUMMARY

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1. Introduction

We consider the following problem:

Given a plane metallic liner at rest with constant density and pressure. At time $t = 0$ a detonation wave hits the liner, this detonation being generated in an explosive in contact with the liner. We make the simplifying hypothesis that the detonation gas is in a uniform state with constant velocity, pressure and density. The pressure of the liner is negligible compared to that of the gas. Under the impact of a strong detonation wave the metallic liner behaves like an hydrodynamic medium.

We have then a Riemann problem and with the given initial data, a shock wave is generated in both the media. As is well known, the uniform states behind the shock in the liner and the gas are defined by the Rankine-Hugoniot conditions on the shock fronts and the supplementary condition that the velocity and pressure in the two media behind the shock fronts be the same.

The thickness of the gaseous medium is supposed to be much greater than that of the liner, so that we must take into account the reflexion of the shock on the other wall of the liner. This reflexion is represented by a centered rarefaction wave and may be easily determined.

We do not consider here the successive phase of reflexion of the rarefaction wave on the wall of the liner in contact with the detonation gas.

Along these lines we can determine the solution of the problem. The same problem is then solved step by step with a finite difference method. The good agreement between the solutions determined in two different ways permits to apply with confidence the numerical scheme to more general situations.

In fact the problem here described has been set up as a simplified model for the following problem to be studied in a later report: to determine the motion of an explosively driven liner in cylindrical geometry. The hypothesis of the uniform state of the detonation products is not made. This problem must be solved numerically and to test the efficiency of the numerical scheme to be employed the simplified version has been considered.

Manuscript received on August 16, 1966

2. The state equation of the gas and the liner (*)

We have the usual symbols:

u velocity
p pressure
ρ density
e specific internal energy
S entropy
T temperature
X eulerian coordinate
h lagrangean coordinate
t time

The detonation products are treated as a polytropic gas with state equation:

$$p = (\gamma-1)e\,\rho \qquad \gamma = 3$$

The metallic liner is treated as a idrodynamic medium.
e is equal to:

$$(2.1) \qquad e(\rho,T) = e_c(\rho) + e_{th}(\rho,T) + e_f(\rho,T)$$

e_c potential energy to which is due the coesion of the metal
e_{th} contribution due to the thermal energy of the atoms
e_f contribution due to the motion of free electrons.

It is:

$$p(\rho,T) = -\rho^2\, T \int_0^T \frac{\partial e(\rho,\xi)}{\partial \rho}\, \frac{d\xi}{\xi^2}$$

Hence the pressure too has the additive form:

(*) For this paragraph see (2) of bibliography.

(2.2) $$p(\rho,T) = p_c(\rho) + p_{th}(\rho,T) + p_f(\rho,T)$$

with :

$$p_c = \rho^2 \frac{de_c}{d\rho} \qquad e_c = \int \frac{p_c}{\rho^2} d\rho$$

In particular the following formulae are used for e and p :

(2.3) $$e = e_c(\rho) + c_v(T-T_o + \frac{E_o}{c_v}) + \frac{\beta}{2} \left(\frac{\rho_{ok}}{\rho}\right)^{1/2} T^2$$

(2.4) $$p = p_c(\rho) + \rho\gamma(\rho)c_v(T-T_o + \frac{E_o}{c_v}) + \rho_{ok} \frac{\beta}{4} \left(\frac{\rho_{ok}}{\rho}\right)^{1/2} T^2$$

c_v, β, E_o, ρ_{ok} constants
ρ_{ok} density at absolute temperature T = 0 and pressure p = 0
For $p_c(\rho)$ and $e_c(\rho)$ various analitical expressions have been proposed, suggested by theoretical considerations and experimental results.
The following formulae have been used in the numerical computations:

(2.5) $$p_c(\rho) = \sum_{j=1}^{7} a_j \left(\frac{\rho}{\rho_{ok}}\right)^{1+j/3}$$

which holds good for pressures up to 10^{15} dyne/cm^2 ($\simeq 10^9$ atm) and:

(2.6) $$e_c(\rho) = \int_{\rho_{ok}}^{\rho} \frac{p_c(\xi)}{\xi^2} d\xi = \frac{1}{\rho_{ok}} \sum_{j=1}^{7} \frac{3}{j} a_j \left(\frac{\rho}{\rho_{ok}}\right)^{j/3}$$

With (2.5) and (2.6) the following expression for $\gamma(\rho)$ has been adopted:

(2.7) $$\gamma(\rho) = \frac{1}{3} + \frac{\rho}{2} \frac{d^2p_c/d\rho^2}{dp_c/d\rho}$$

J.P. Somon has proposed the following simple form for p_c and e_c valid for pressures up to 10^{12} dyne/cm^2 :

(2.8) $$p_c = c_o^2 \rho_{ok} \left(\frac{\rho}{\rho_{ok}}\right)^2 \left(\frac{\rho}{\rho_{ok}} - 1\right)$$

(2.9) $$e_c = \frac{c_o^2}{2} \left(\frac{\rho}{\rho_{ok}} - 1\right)^2$$

ρ_o and c_o are normal density and sound speed. With (2.8) and (2.9) the following expression for γ has been adopted:

$$\gamma(\rho) = \frac{2}{3} + \frac{\rho}{2} \frac{d^2(p_c \rho^{-2/3})/d\rho^2}{d(p_c \rho^{-2/3})/d\rho} \tag{2.10}$$

$$= \frac{2}{3} \frac{14(\rho/\rho_{ok}) - 5}{7(\rho/\rho_{ok}) - 4}$$

A good approximation is given by :

$$\gamma \simeq \gamma(\rho_{ok}) = 2 \tag{2.11}$$

The term with T^2 in the expressions of e and p may be neglected for pressures less than 10^{13} dyne/cm^2.
The numerical tests carried out show a good agreement between the results obtained with and without the term T^2. Neglecting this term we obtain:

$$e(\rho,p) = e_c(\rho) + \frac{1}{\rho\gamma(\rho)} (p - p_c(\rho)) \tag{2.12}$$

$$p(\rho,e) = p_c(\rho) + \rho\gamma(\rho) (e - e_c(\rho)) \tag{2.13}$$

3. The Riemann problem for the liner and the detonation products

We consider the following problem:

At the initial time t = 0 the liner and the gas, both of them at constant state, are in contact. The liner is at rest, the gas has uniform velocity directed toward the liner. Moreover the thickness of the liner is much less than that of the gas. We want to follow the evolution of the phenomenon

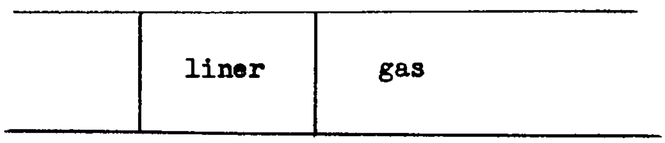

FIG. 1

Until the perturbation generated in the liner does not reach the free surface of the liner we have a Riemann problem. The solution is defined by four constant states S_l^o S_l^1 S_g^o S_g^1 : S_l^o S_g^o are the initial states of the liner and the gas. S_l^1 S_g^1 are the states determined by the interaction between the two media.

In our case S_l^1 and S_g^1 are related to S_l^o and S_g^o by means of shock waves respectively backward and forward.

S_l^1 and S_g^1 are determined by the Rankine-Hugoniot conditions plus the conditions:

$$u_l^1 = u_g^1 \qquad p_l^1 = p_g^1 \tag{3.1}$$

To determine u^1 p^1 ρ_l^1 ρ_g^1 we proceed in the following way:

We consider the Hugoniot equation for each of the two media:

$$H(\rho,p) = 0 \tag{3.2}$$

with :

$$H(\rho,p) = e(\rho,p) - e(\rho_o,p_o) + \frac{1}{2}(p+p_o)\left(\frac{1}{\rho_o} - \frac{1}{\rho}\right)$$

This equation defines all the states which can be connected to the state S^o by a shock. When an analitical expression is not available or too complicate to obtain (as in the case of the liner) the curve H = 0 may be computed pointwise by some numerical procedure.

The u corresponding to ρ,p which satisfy equation (3.2), m y be computed by means of formula

$$(u-u_o)^2 = \left(\frac{1}{\rho_o} - \frac{1}{\rho}\right)(p - p_o) \tag{3.3}$$

from which

$$u = u_o \pm \sqrt{\left(\frac{1}{\rho_o} - \frac{1}{\rho}\right)\left(p - p_o\right)} \tag{3.4}$$

The velocities on the two sides of a shock front satisfy the relation

$$u_{left} > u_{right}$$

independently on which side the shock faces.
Hence in (3.4) there is the sign - for the liner and the sign + for the gas.
We consider now the Hugoniot curves for the liner and the gas:

$$H_l = 0 \qquad H_g = 0$$

in the ρ,p plane. We must find a point $P_l = (\rho_l, p)$ on H_g and a point $P_g = (\rho_g, p)$ on H_g such that the corresponding u_l and u_g, computed by means of (3.3) are equal:

$$u_l = u_g \tag{3.5}$$

To solve numerically this problem we put the equations

$H_l = 0$ and $H_g = 0$ in the form

$\rho = \rho_l(p)$ and $\rho = \rho_g(p)$

the functions ρ_l and ρ_g are tabulated or given by means of a formula.

We explore the p-axis with a sufficiently small step Δp (starting from p_g^o since $p_g^1 > p_g^o$), interpolating if necessary and compute

$$p \begin{array}{l} \nearrow \rho_l \rightarrow u_l \\ \searrow \rho_g \rightarrow u_g \end{array}$$

We choose that value of p corresponding to which relation (3.5) is satisfied.

. . . .

4. Reflexion of the shock wave on the wall of the liner

The Riemann solution is modified when the shock front reeches the other face of the liner. The reflexion of the shock on the other face of the gas is not considered since by hypothesis the thickness of the gas is much greater than that of the liner, and may be considered semi-infinite.

We determine the state of the liner in this new phase with the aid of some simple considerations.

a) The solution is unique.

b) A state bounded by a straight characteristic along which u and c are constant is a constant state or a simple wave.

c) The liner being treated as an ordinary hydrodynamic medium, we cannot have a rarefaction shock wave.

A discontinuity of this kind is immediately resolved as a rarefaction waves in the origin of the discontinuity.

When the shock wave in the liner reaches the wall, the liner is in a constant compressed state S_1^1 while at this free wall there is a negligible pressure $p_1^o \simeq 0$. Let x_1 be the abscissa of the wall and t_1 the time at which the shock hits the wall. The discontinuity in this point is resolved by c) into a centered rarefaction wave connecting the st te S_1^1 with the st te S_1^2 adiacent to the wall.

The state S_1^2 is bounded to the right by the tail characteristic of the rarefaction wave and by b) is a constant state. It follows that the trajectory of the wall is a straight line

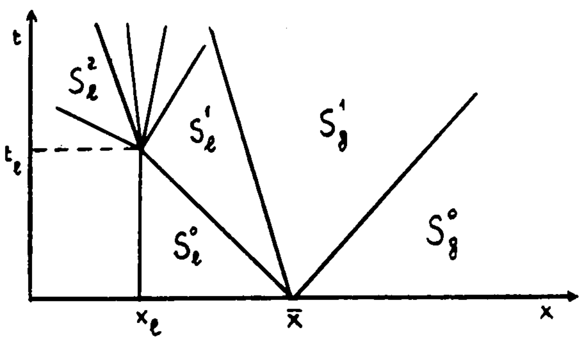

Fig. 2

The C^+ characteristics of the centered wave pass trough (x_1, t_1) and have direction:

(4.1) $$\frac{dx}{dt} = u + c$$

u and c have constant values along each characteristic.
The head characteristic has direction:

$$\frac{dx}{dt} = u_1 + c_1$$

The direction of the tail of the rarefaction wave is computed by means of the Riemann invariants.

We put: $$I(\rho) = \int_{\rho_o}^{\rho} \frac{c}{\rho}\, d\rho$$

and $$R^{\pm} = u \pm I$$

The quantity R^- is constant through the three regions S_1^1, rarefaction wave, S_1^2. On the tail characteristic C^* :

(4.3) $$u^* - I^* = u_1 - I_1$$

and

(4.4) $$I^* = I_o = I(\rho_o) = 0$$

Hence the direction is :

$$\frac{dx}{dt} = u^* + c^*$$

and the state S_1^2 is :

$$u_2 = u^*$$

$$c_2 = c^* = c_o$$

$$\rho_2 = \rho^* = \rho_o$$

$$p_2 = p_o = 0$$

For the cases which have been treated the shock is the liner was a weak one.

The variation of R^+ when passing from S_1^o to S_1^1 is negligible and ve have, with good approximation:

$$u_o + I_o = I_o \simeq u_1 + I_1 \qquad (u_o = 0) \tag{4.5}$$

R^- is invariant through the simple wave, hence:

$$u_2 - I_2 = u_1 - I_1$$

Beside: $\quad I_2 = I^* = I_o$

Hence:

$$u_2 - I_o = u_1 - I_1 \tag{4.6}$$

From (4.5) and (4.6) it follows:

$$u_2 \simeq 2u_1 \tag{4.7}$$

To conclude:
We can determine directly:

$$S_1^1,\ S_g^1,\ x_1,\ t_1,\ S_1^2$$

the centered rarefaction wave, and in particular the direction of the head and tail characteristics of the wave. In first approximation:

$$u_2 \simeq 2u_1$$

In the computation of $R^{\pm}$ the quantity:

$$I = \int^{\rho} \frac{c}{\rho}\, d\rho$$

has sometime been substituted with the quantity:

$$I_c = \int^{\rho} \frac{c_c}{\rho}\, d\rho$$

where: $c_c = \dfrac{dp_c}{d\rho}$

i.d. in the state equation of the liner only the term p_c has been considered. In this way the integral I_c is easier to calculate.

Until p is less than 10^6 atm. the error due to the substitution of p with p_c is less than 5% (see Somon pp. 38).

Hence:

$$I \simeq I_e$$

5. <u>Numerical solution of the problem</u>

We introduce the lagrangean coordinate h :

$$(5.1) \qquad h = \frac{1}{\rho_o} \int_{X(0,t)}^{X(h,t)} \rho(\xi,t)d\xi = x - x_1$$

where $x = X(h,0)$

x_1 is the free wall of the liner

$\bar{x}$ is the interface liner-gas

Differentiating (5.1) with respect to h we obtain:

$$1 = \frac{\rho}{\rho_o}\frac{\partial X}{\partial h}$$

with (5.2) $\rho = \begin{cases} \rho_1 & h < \bar{h} = \bar{x} \\ \rho_g & h > \bar{h} \end{cases}$

and (5.3) $\rho_o = \begin{cases} \rho_1^o & h < \bar{h} \\ \rho_g^o & h > \bar{h} \end{cases}$

The system to be solved, in lagrangean form, is:

$$
(5.4)\qquad
\begin{aligned}
1 &= \frac{\rho}{\rho_o}\frac{\partial X}{\partial h} \\
u &= \frac{\partial X}{\partial t} \\
\frac{\partial u}{\partial t} &= -\frac{1}{\rho_o}\frac{\partial p}{\partial h} \\
\frac{\partial e}{\partial t} &= \frac{p}{\rho^2}\frac{\partial \rho}{\partial t} \\
p &= F(\rho, e)
\end{aligned}
$$

When $h < \bar{h}$ we have the liner, hence:

$$\rho_o = \rho_1^o \qquad \rho = \rho_1 \qquad p = p_1 \qquad e = e_1$$

When $h > \bar{h}$ we have the gas, hence

$$\rho_o = \rho_g^o \qquad \rho = \rho_g \qquad p = p_g \qquad e = e_g$$

In order to obtain the state equation of the liner, we consider the relations:

$$(5.5)\qquad e = e_c(\rho) + c_v\left(T - T_o + \frac{E_o}{c_v}\right) + \left(\frac{\rho_{ok}}{\rho}\right)^{1/2}\frac{\beta}{2}T^2$$

$$(5.6)\qquad p = p_c(\rho) + \rho\gamma(\rho)c_v\left(T - T_o + \frac{E_o}{c_v}\right) + \rho_{ok}\left(\frac{\rho_{ok}}{\rho}\right)^{1/2}\frac{\beta}{4}T^2$$

(see § 2).

If we neglect the terms in T^2 we get:

$$(5.7)\qquad p = p_c(\rho) + \rho\gamma(\rho)\,(e - e_c(\rho))$$

In the general case we proceed as follows:

From (5.5) we get:

(5.8) $$\left(\frac{\rho_{ok}}{\rho}\right)^{1/2} \frac{\beta}{2} T^2 + c_v T + (e_c - e + E_o - c_v T_o) = 0$$

Since: e_c, E_o, c_v, β, γ, $T-T_o$, $T_o - \frac{E_o}{c_v}$

are positive, it follows that $e > e_c$ and the last term of (5.8) is negative. Thus we have only one positive root:

$$T = \frac{-c_v + \sqrt{c_v^2 + 2\left(\frac{\rho_{ok}}{\rho}\right)^{1/2} \beta(e - e_c + c_v T_o - E_o)}}{\left(\frac{\rho_{ok}}{\rho}\right)^{1/2} \beta}$$

We substitute this expression in (5.6) and we obtain p as function of e,ρ

(5.9) $$p = p(e,\rho)$$

In the same way we could express e as function of p,ρ.
The state equation of the gas is:

(5.10) $$p = (\gamma - 1)\, e\rho \qquad \gamma = 3$$

The differential system (5.4) must be solved with given initial and boundary conditions. In our case the initial conditions at time $t = 0$ are:

$$p = p_1^o = 0, \quad u = u_1^o = 0, \quad \rho = \rho_1^o \qquad h < \bar{h} \qquad \text{(liner)}$$

$$p = p_g^o, \quad u = u_g^o, \quad \rho = \rho_g^o \qquad h > \bar{h} \qquad \text{(gas)}$$

The boundary conditions ($t = 0$) are:

$p = 0$ when $h = 0$ $\qquad$ $p = p_g^o$ when $h = h_g$

h_g lagrangean coordinate of a gas particle, great enough so that we don't have to consider the shock reflexion in the gas. The second boundary condition may be substituted with:

$$u = u_g^o \qquad \text{or} \qquad \rho = \rho_g^o$$

In lagrangean coordinate the path of the interface liner-gas is the vertical line:

$$h = \bar{h}$$

Thus the distinction between the two media is automatic. In eulerian coordinates this trajectory is more difficult to compute since it cuts across the net on which we apply the numerical scheme. Another advantage of the lagrangean coordinates is the possibility to use different Δh-steps for different media if necessary. It is quite difficult to do so in eulerian coordinates. To solve numerically the differential system (5.4) use has been made of the following scheme (see Richtmyer):

$$\frac{u_j^{n+1} - u_j^n}{\Delta t} = -\frac{1}{\rho_o}\left(\frac{p_{j+1/2}^n - p_{j-1/2}^n}{\Delta h} + \frac{q_{j+1/2}^n - q_{j-1/2}^n}{\Delta h}\right)$$

$$\frac{X_j^{n+1} - X_j^n}{\Delta t} = u_j^{n+1}$$

$$\frac{1}{\rho_{j+1/2}^{n+1}} = \frac{1}{\rho_o}\,\frac{X_{j+1}^{n+1} - X_j^{n+1}}{\Delta h}$$

(5.10)

$$\frac{e_{j+1/2}^{n+1} - e_{j+1/2}^n}{\Delta t} = \frac{p_{j+1/2}^n}{(\rho_{j+1/2}^n)^2}\,\frac{\rho_{j+1/2}^{n+1} - \rho_{j+1/2}^n}{\Delta t}$$

$$p_{j+1/2}^{n+1} = F\left(\rho_{j+1/2}^{n+1}, e_{j+1/2}^{n+1}\right)$$

$$q_{j+1/2}^n = \begin{cases} a^2 \rho_{j+1/2}^n (u_{j+1}^n - u_j^n)^2 & \text{if } u_{j+1}^n - u_j^n < 0 \\ 0 & \text{if } u_{j+1}^n - u_j^n > 0 \end{cases}$$

with the stability condition:

$$\Delta t < \frac{\Delta X}{c}$$

The Richtmyer's pseudo-viscosity term q is introduced in order to deal with the shock discontinuities. For the problem treated a = 2.

We employ a staggered net. In the points with integer index j we compute X_j, u_j in the other points we compute $p_{j+1/2}$, $\rho_{j+1/2}$, $e_{j+1/2}$, $q_{j+1/2}$. In this scheme it is convenient that the interface liner-gas be coincident with a point $\bar{j}$.

With regard to the boundary condition:

$$p = p_1^o = 0 \qquad \text{at} \qquad h = 0$$

we remark that we can exchange the role of the indices j and j ± 1/2 and compute $X_{j+1/2}$ $u_{j+1/2}$ and p_j, ρ_j, e_j, q_j. Hence we can attribute to h = 0 the index j = 0 or j = 1/2.

At $h = h_g$ (last gas particle) we can choose one of the conditions

$$u = u_g^o \qquad \rho = \rho_g^o \qquad p = p_g^o$$

6. Numerical results

We give here the results for a typical case. The data are given in the C.G.S. system.

$x_1 = 3$ first wall of liner

$\bar{x} = 3.8$ interface liner-gas

$x_g = 9$ second face of gaseous medium

Initial state S_1^o of liner:

$u_o = 0$

$p_o = 10^6$

$\rho_o = 8.93$

$c_i = 3.97.10^5$

Initial state S_g^o of gas:

$u_o = - 2.10^5$

$p_o = 2.72.10^{11}$

$\rho_o = 1.7$

$c_o = 7.10^5$

The state equation is (2.13) i.d. the term T^2 has been dropped. p_c, e_c, γ are given respectively by (2.5) (2.6) (2.7). In connexion with these formulae we have:

$c_v = 3.926.10^6$

$T_o = 300\ {}^oK$

$E_o = 7.87.10^8$

$\rho_{o_K} = 9.024$

$$\beta = 2$$
$$a_1 = 4.0283 \cdot 10^{12}$$
$$a_2 = -3.0889 \cdot 10^{13}$$
$$a_3 = 7.1612 \cdot 10^{13}$$
$$a_4 = -7.7928 \cdot 10^{13}$$
$$a_5 = 4.0096 \cdot 10^{13}$$
$$a_6 = -6.9194 \cdot 10^{12}$$
$$a_7 = 0$$

The direct solution is first computed according to paragraphs 3 and 4. The results are summed up in Tables 1 and 2.

As already said the comparison between the direct solution and the solution computed by means of a finite difference scheme is carried out only for $t < \bar{t}$ time at which the rarefaction front reaches the interface liner-gas. When using a finite difference scheme with a pseudo-viscosity term the shock discontinuities are not represented by sharp discontinuities but rather as zones of rapid variation of the hydrodynamic quantities. For this reason and due also to the effects of round off and approximation errors the shock position can be given only with a certain approximation . The same is true with regard to the head and tail characteristics of the rarefaction wave.

The shock trajectory in liner and gas, the interface trajectory, the head and tail characteristics of the rarefaction wave obtained by means of the direct method (D.M.) and the finite difference scheme (F.D.) are given in Tables 3,...,7. Subsequently the results of the finite difference scheme at various times are presented.

TABLE 1

States of liner and gas

	S_l^o	S_l^1	S_l^2	S_g^o	S_g^1
u	0	$-9.025 \cdot 10^4$	$-1.805 \cdot 10^4$	$-2 \cdot 10^5$	$-9.025 \cdot 10^4$
p	10^6	$4.23 \cdot 10^{11}$	10^6	$2.72 \cdot 10^{11}$	$4.23 \cdot 10^{11}$
ρ	8.93	1.0787.10	8.93	1.7	1.966
c	$3.97 \cdot 10^5$	$5.37 \cdot 10^5$	$3.97 \cdot 10^5$	$6.93 \cdot 10^5$	$8.03 \cdot 10^5$

TABLE 2

Shock fronts and rarefaction wave

Shock speed in liner : $U_l = -5.244 \cdot 10^5$

" " " gas : $U_g = -6.112 \cdot 10^5$

Trajectory of shock front in liner : $X = \bar{x} + U_l t$

" " " " " gas : $X = \bar{x} + U_g t$

" " liner-gas interface : $X = \bar{x} + u_1 t$

$(u_1 = u_l^1 = u_g^1)$

Origin of rarefaction wave : (x_l, t_l) $x_l = 3$ $t_l = 1.526 \cdot 10^{-6}$

Head charact. of rarefaction wave $X = x_l + (t-t_l)\,(u_l^1 + c_l^1)$

Tail " " " " $X = x_l + (t-t_l)\,(u_l^2 + c_l^2)$

Intersection of head charact. of rarefaction wave and interface trajectory:

$X = 3.551$ $\bar{t} = 2.759 \cdot 10^{-6}$

TABLE 3

Shock trajectory in liner

t	X(D.M.)	X(F.D.)
$1.424 \cdot 10^{-7}$	3.725	3.70
2.673 "	3.660	3.66
3.891 "	3.596	3.61
5.093 "	3.533	3.54
6.271 "	3.471	3.48
7.434 "	3.410	3.42
8.590 "	3.35	3.37
9.736 "	3.290	3.30
$1.088 \cdot 10^{-6}$	3.229	3.24
1.203 "	3.169	3.17
1.318 "	3.109	3.11

TABLE 4

Shock trajectory in gas

t	X(D.M.)	X(F.D.)
$2.673 \cdot 10^{-7}$	3.963	3.94
5.093 "	4.111	4.15
7.434 "	4.254	4.21
9.736 "	4.395	4.36
$1.203 \cdot 10^{-6}$	4.535	4.50
1.433 "	4.676	4.65
1.663 "	4.816	4.85
2.125 "	5.099	5.11
2.356 "	5.240	5.24
2.592 "	5.380	5.37

TABLE 5

Interface trajectory

t	X(D.M.)	X(F.D.)
$2.673 \cdot 10^{-7}$	3.776	3.781
5.093 "	3.754	3.758
7.434 "	3.733	3.737
9.736 "	3.712	3.716
$1.203 \cdot 10^{-6}$	3.691	3.695
1.433 "	3.670	3.674
1.663 "	3.650	3.654
1.894 "	3.629	3.633
2.125 "	3.608	3.612
2.356 "	3.587	3.591
2.592 "	3.566	3.569

TABLE 6

Head characteristic of rarefaction wave

t	X(D.M.)	X(F.D.)
$1.779 \cdot 10^{-6}$	3.113	3.14
1.894 "	3.164	3.18
2.009 "	3.216	3.24
2.125 "	3.267	3.28
2.240 "	3.319	3.34
2.356 "	3.371	3.39
2.473 "	3.423	3.44
2.592 "	3.476	3.49
2.712 "	3.53	3.55

TABLE 7

Tail characteristic of rarefaction wave

t	X(D.M.)	X(F.D.)
$1.779 \cdot 10^{-6}$	3.055	2.99
1.894 "	3.080	3.02
2.009 "	3.105	3.05
2.125 "	3.130	3.07
2.240 "	3.155	3.10
2.356 "	3.180	3.13
2.473 "	3.205	3.16
2.592 "	3.231	3.18
2.712 "	3.257	3.20

Acknowledgments

We wish to acknowledge the support of Dr. J.P. Somon of Euratom Group on Fusion (Frascati, Rome) on whose behalf the problem has been studied.

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4.3739E-01	3.0490E 00	-9.7069E-02	8.9300E 00	8.2932E 05	3.9675E 05
5.8318E-01	3.0653E 00	-9.4030E-02	8.9300E 00	8.2932E 05	3.9675E 05
7.2898E-01	3.0816E 00	-9.0991E-02	8.9300E 00	8.2932E 05	3.9675E 05
8.7478E-01	3.0980E 00	-8.9753E-02	8.9300E 00	8.2932E 05	3.9675E 05
1.0206E 00	3.1143E 00	-8.8514E-02	8.9300E 00	8.2932E 05	3.9675E 05
1.1664E 00	3.1306E 00	-8.7072E-02	8.9300E 00	8.2932E 05	3.9675E 05
1.3122E 00	3.1469E 00	-8.5629E-02	8.9300E 00	8.2932E 05	3.9675E 05
1.4580E 00	3.1633E 00	-8.4591E-02	8.9300E 00	8.2932E 05	3.9675E 05
1.6038E 00	3.1796E 00	-8.3553E-02	8.9300E 00	8.2932E 05	3.9675E 05
1.7496E 00	3.1959E 00	-8.2735E-02	8.9300E 00	8.2932E 05	3.9675E 05
1.8953E 00	3.2122E 00	-8.1917E-02	8.9300E 00	8.2932E 05	3.9675E 05
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1.4725E 01	8.1529E 00	-2.0000E 05	1.7000E 00	2.7200E 11	6.9282E 05
1.4871E 01	8.1692E 00	-2.0000E 05	1.7000E 00	2.7200E 11	6.9282E 05
1.5017E 01	8.3244E 00	-2.0000E 05	1.7000E 00	2.7200E 11	6.9282E 05
1.5163E 01	8.3408E 00	-2.0000E 05	1.7000E 00	2.7200E 11	6.9282E 05
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1.5746E 01	8.6838E 00	-2.0000E 05	1.7000E 00	2.7200E 11	6.9282E 05
1.5892E 01	8.8390E 00	-2.0000E 05	1.7000E 00	2.7200E 11	6.9282E 05

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4.3739E-01	3.0419E 00	-7.2100E 04	1.0124E 01	2.4490E 11	4.8232E 05
5.8318E-01	3.0559E 00	-7.8711E 04	1.0417E 01	3.1500E 11	5.0301E 05
7.2898E-01	3.0699E 00	-8.5322E 04	1.0576E 01	3.5934E 11	5.1654E 05
8.7478E-01	3.0835E 00	-8.8339E 04	1.0739E 01	4.0367E 11	5.2973E 05
1.0206E 00	3.0971E 00	-9.1356E 04	1.0768E 01	4.1205E 11	5.3371E 05
1.1664E 00	3.1106E 00	-9.0480E 04	1.0798E 01	4.2043E 11	5.3767E 05
1.3122E 00	3.1241E 00	-8.9605E 04	1.0781E 01	4.1558E 11	5.3609E 05
1.4580E 00	3.1376E 00	-8.9463E 04	1.0764E 01	4.1073E 11	5.3451E 05
1.6038E 00	3.1512E 00	-8.9322E 04	1.0789E 01	4.1789E 11	5.3579E 05
1.7496E 00	3.1646E 00	-9.0275E 04	1.0814E 01	4.2505E 11	5.3707E 05
1.8953E 00	3.1781E 00	-9.1229E 04	1.0803E 01	4.2188E 11	5.3723E 05
2.0411E 00	3.1916E 00	-9.0196E 04	1.0792E 01	4.1870E 11	5.3738E 05
2.1869E 00	3.2052E 00	-8.9163E 04	1.0788E 01	4.1755E 11	5.3630E 05
2.3327E 00	3.2187E 00	-8.9793E 04	1.0784E 01	4.1640E 11	5.3521E 05
2.4785E 00	3.2322E 00	-9.0423E 04	1.0799E 01	4.2095E 11	5.3662E 05
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3.9365E 00	3.3672E 00	-9.0288E 04	1.0800E 01	4.2153E 11	5.3687E 05
4.0823E 00	3.3807E 00	-9.0591E 04	1.0813E 01	4.2514E 11	5.3769E 05
4.2281E 00	3.3942E 00	-9.0895E 04	1.0804E 01	4.2271E 11	5.3741E 05
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4.5197E 00	3.4212E 00	-9.0084E 04	1.0800E 01	4.2163E 11	5.3706E 05
4.6655E 00	3.4347E 00	-9.0523E 04	1.0804E 01	4.2298E 11	5.3699E 05
4.8113E 00	3.4482E 00	-9.0962E 04	1.0804E 01	4.2309E 11	5.3736E 05
4.9571E 00	3.4617E 00	-9.0659E 04	1.0804E 01	4.2321E 11	5.3774E 05
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5.2487E 00	3.4887E 00	-9.0493E 04	1.0796E 01	4.2115E 11	5.3677E 05
5.3944E 00	3.5022E 00	-9.0629E 04	1.0799E 01	4.2238E 11	5.3715E 05
5.5402E 00	3.5157E 00	-9.0587E 04	1.0802E 01	4.2362E 11	5.3752E 05
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5.8318E 00	3.5427E 00	-9.0476E 04	1.0790E 01	4.2081E 11	5.3677E 05
5.9776E 00	3.5562E 00	-9.0408E 04	1.0791E 01	4.2179E 11	5.3690E 05
6.1234E 00	3.5697E 00	-9.0482E 04	1.0792E 01	4.2277E 11	5.3703E 05
6.2692E 00	3.5832E 00	-9.0556E 04	1.0785E 01	4.2200E 11	5.3680E 05
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6.5608E 00	3.6103E 00	-9.0396E 04	1.0759E 01	4.2173E 11	5.3614E 05
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