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CALCULATION OF SPALL BASED ON A ONE-DIMENSIONAL MODEL

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Mark L. Wilkins

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ABSTRACT

The detonations of a high explosive in contact with a metal plate can cause the plate to spall or fracture. In order to quantitatively describe the phenomena a one-dimensional model of the H. E. plate system is assumed. The problem is then analyzed in terms of the interactions of compression and rarefaction waves. Quantitative predictions of spall using the one-dimensional model are compared to experiment and the agreement is found to be good.

INTRODUCTION

Consider a one-dimensional model of an H. E. metal plate system. Since a detonation front is always followed by a rarefaction, the pressure at the H. E. plate interface decreases rapidly with time. Therefore the transmitted shock in the metal attenuates gradually behind the front because the rarefaction travels at a greater velocity than the shock. Upon reaching the plate's front surface where the normal stress must be zero the pressure wave is reflected as a receding rarefaction wave. This wave drops the pressure from its initial value to zero, the rarefaction wave proceeding forward is already decreasing the pressure so that when the two rarefactions cross the pressure falls below zero. The negative pressure or tension is related to the amount the pressure has dropped behind the initial shock wave when the rarefaction from the front surface has reached a given position. In Figure 1 the tension is approximately the pressure drop "h" that has entered the material before the receding rarefaction has reached the metal-H. E. interface and is reflected as a second shock wave.

If either the magnitude or rate of increase of tension is great enough the plate may fracture or spall.

THE CALCULATIONAL MODEL

The one-dimensional hydrodynamic equations were solved by the finite difference technique of von Neumann and Richtmyer.[1] The tension profiles for three different plate thicknesses were calculated using a high speed computer together with an assumed equation of state and a method of simulating the burning of H. E. The equation of state of the metal in compression was obtained from experimentally measured Hugoniot points. However, in the tension region, a Hooke's law of the form $P = a\left(\frac{\rho}{\rho_0} - 1\right)$ was assumed. Here ρ_0 is the reference density expressed in grams per cc. A perfect gas law equation of state was used for the H. E.[2]

Since the finite difference approximation is based on a Lagrangian description the physical quantities of each mass element are known at any instant of time. Consequently, it is possible to allow the material to split at a zone boundary by introducing the appropriate free surface boundary conditions. By this technique material separation or spalling may be achieved when the tension falls below a specified amount. Other spall criteria based on strain rate, internal energy, momentum transferred, etc., may be easily introduced.

EXPERIMENTAL TECHNIQUE

To measure the front surface velocity of H. E. driven plates the usual pin technique and optical methods were used. The experiments used 10 cm of Composition B ignited by a plane wave generator. The other dimensions were chosen to maintain a one-dimensional model during the time of interest.

To measure the change in velocity of the front surface of a metal plate a magnetic method was developed. The plate is the conductor advancing through parallel magnetic field lines The voltage generated per unit length of the plate is described by

$$\frac{V}{L} = \vec{v} \times \vec{B}$$

V = voltage
L = length of plate
v = velocity
B = magnetic field

In order to measure the voltage and hence the plate velocity, two small wires are placed normal to the plate. As the plate advances into the wires, contact is maintained and the voltage is recorded on oscilloscopes as a function of time.

DISCUSSION

By examining a plot of the front surface velocity, a time history of the plate successive accelerations may be discerned. The time interval between consecutive pushes is equal to the transit time of a receding rarefaction wave plus the time of a compression wave. From the previously determined equation of state of the metal the shock velocity at the pressure given by the H. E. can be calculated. The velocity of the rarefaction wave is very nearly equal to the shock velocity, so an easy calculation gives the time interval between consecutive accelerations of the plate front surface.

The time interval calculated from this simple model agrees with the solution given by the difference equations and also with the experimental results for thin metal plates. As the thickness of the plate increases, the time between consecutive accelerations is longer than the calculated times. It is assumed that the plate has spalled or fractured and the previous simple calculation is no longer valid. A complete analysis of the wave interactions together with a criterion for fracture verifies this assumption. The results of the finite difference calculations which take into account the spall phenomenon correctly predict the time intervals between accelerations found experimentally.

Intuitively increasing the thickness of the plate should have the following effects:

1. A larger part of the rarefaction wave could enter the material.
2. The pulse shape is changed causing higher strain rates.
3. The time which a specified plane in the plate is under tension will increase due to the increase in transit time.

Any of the above mechanisms may cause the maximum dynamic strain in the plate to be exceeded, thus allowing the material to fracture or spall.

Other forms of the equation of state in the negative pressure region as well as different spall criteria have been investigated on the computer. The simple model presented here illustrated the effectiveness of the computer as a method of analysis.

RESULTS

Figures 1, 2, and 3 illustrate the results of finite difference calculations which do not contain a spall criterion and the corresponding experimental results. Figure 1 shows the results of 10 cm of H. E. driving a 0.375-cm-thick uranium plate. The agreement between the experiment and calculation is good and it is concluded that the plate did not spall. Figures 2 and 3 show the corresponding results when the plate has a thickness of 0.545 cm and 0.75 cm. For these cases the acceleration times as measured by experiment do not agree with the calculated times. The conclusion is that the material has spalled and momentum can no longer be transferred. Thus the spalled portion of the plate flies off with the momentum characteristic of the pressure from the head of the original shock minus the amount of momentum transferred back by tension before spall occurred.

The decrease in front surface velocity between accelerations shown by the calculations results from the tensions in the plate. Experimentally this is not observed since only average velocities are measured in the time interval between accelerations.

The calculations were repeated using a spall criterion of -0.050×10^{12} dynes/cm^2, i.e., the material was allowed to separate if the tension at any point in the material exceeded this amount. Figures 4 and 5 show the results of these calculations as compared to experiment.

Similar calculations using other thicknesses of plates, and a spall criterion based upon tension of about -0.050×10^{12} dynes/cm^2 agreed with the experiment. The assumed equation of state in the region of negative pressure and the criteria for spall used are certainly not correct in every detail; however, the overall good agreement with experiment is justification for applying the technique to other H. E. metal plate systems.

CONCLUSION

As stated in the first section, spall results when two rarefactions cross. An obvious method to defeat spall would be to cancel one of the rarefactions. To accomplish this a void can be placed between the H. E. and the metal. The transmitted shock into the material now has a rising profile instead of a profile that falls behind the shock front. Figure 6 shows the results of calculation and experiment where a 1.5-cm void was introduced between the 0.75-cm plate and the H. E.

The experimental methods, while accurate for measuring the changes in front surface velocity, only give average velocities during the intervals between accelerations. It would take separate experiments to establish the slowing down of the front surface as predicted by the calculations. Experiments of this type are presently being conducted.

ACKNOWLEDGMENT

The calculational and experimental techniques used in this study are the results of contributions by many members of the Lawrence Radiation Laboratory.

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[2] W. E. Deal, Phys. Fluids 1, 523 (1958).

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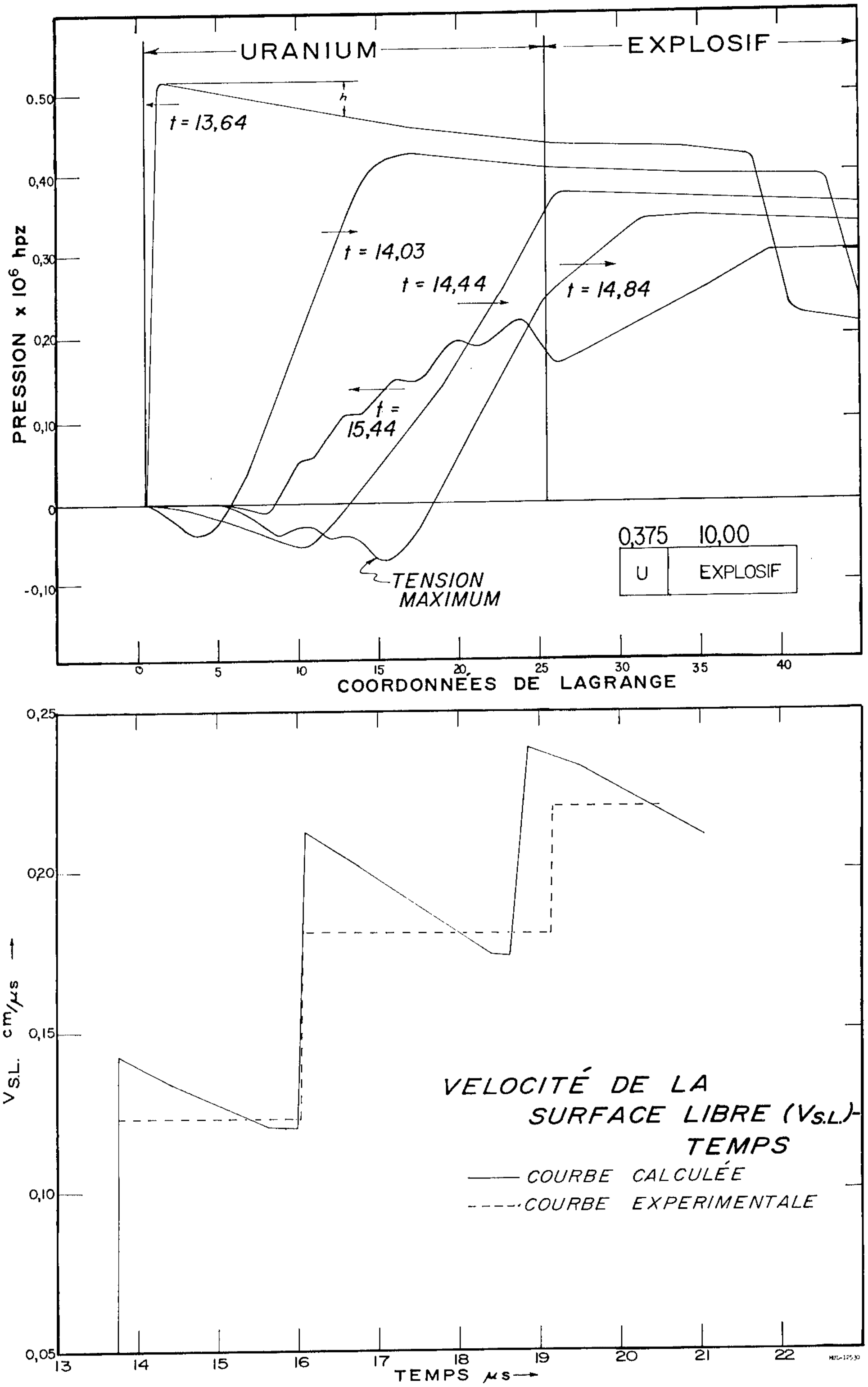

Fig. 1. Top: Pressure profiles at different times (pressure - Mb, time - μsec). Bottom: Front surface velocity vs time.

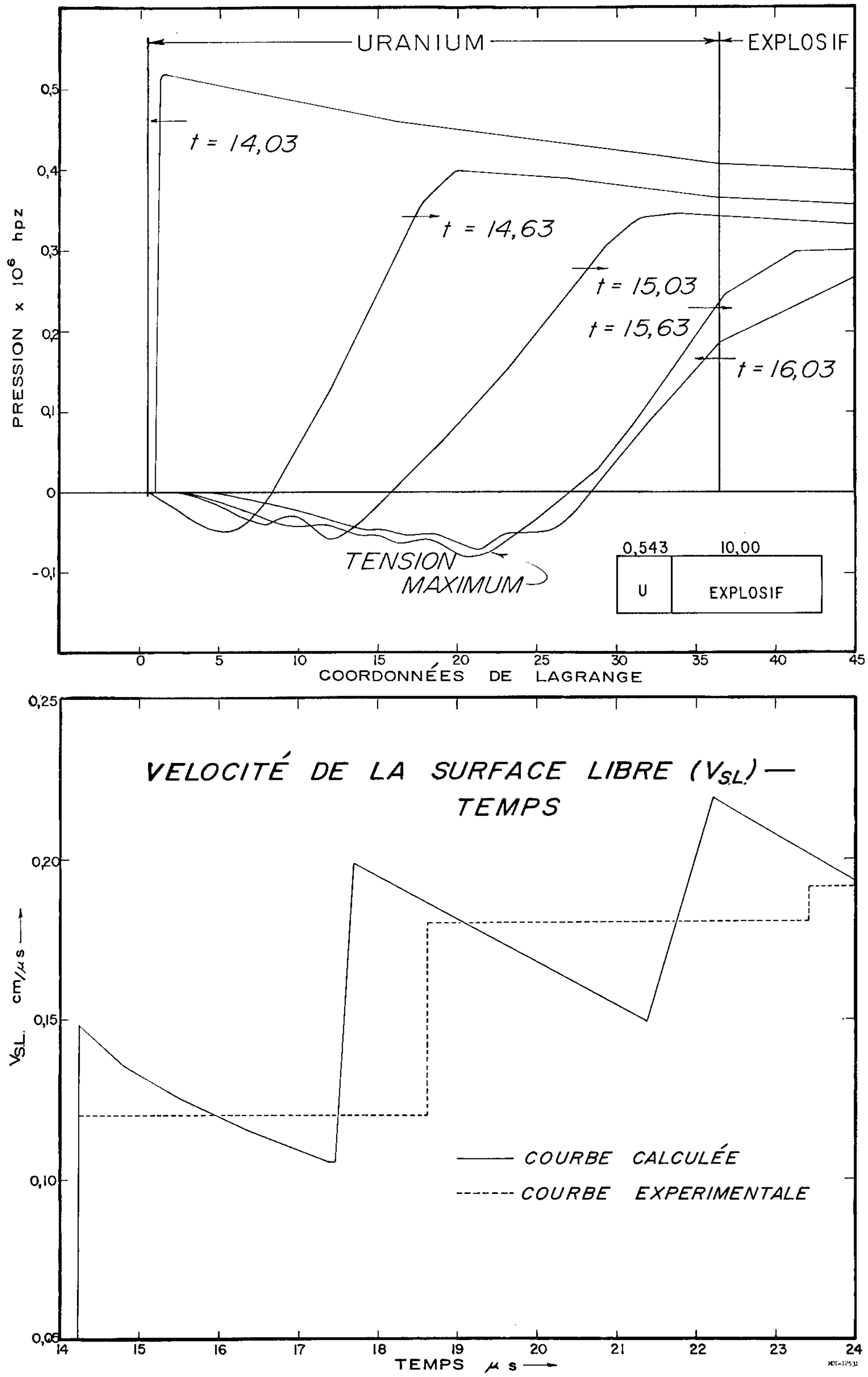

Fig. 2. Top: Pressure profiles at different times (pressure – Mb, time μsec). Bottom: Front surface velocity vs time.

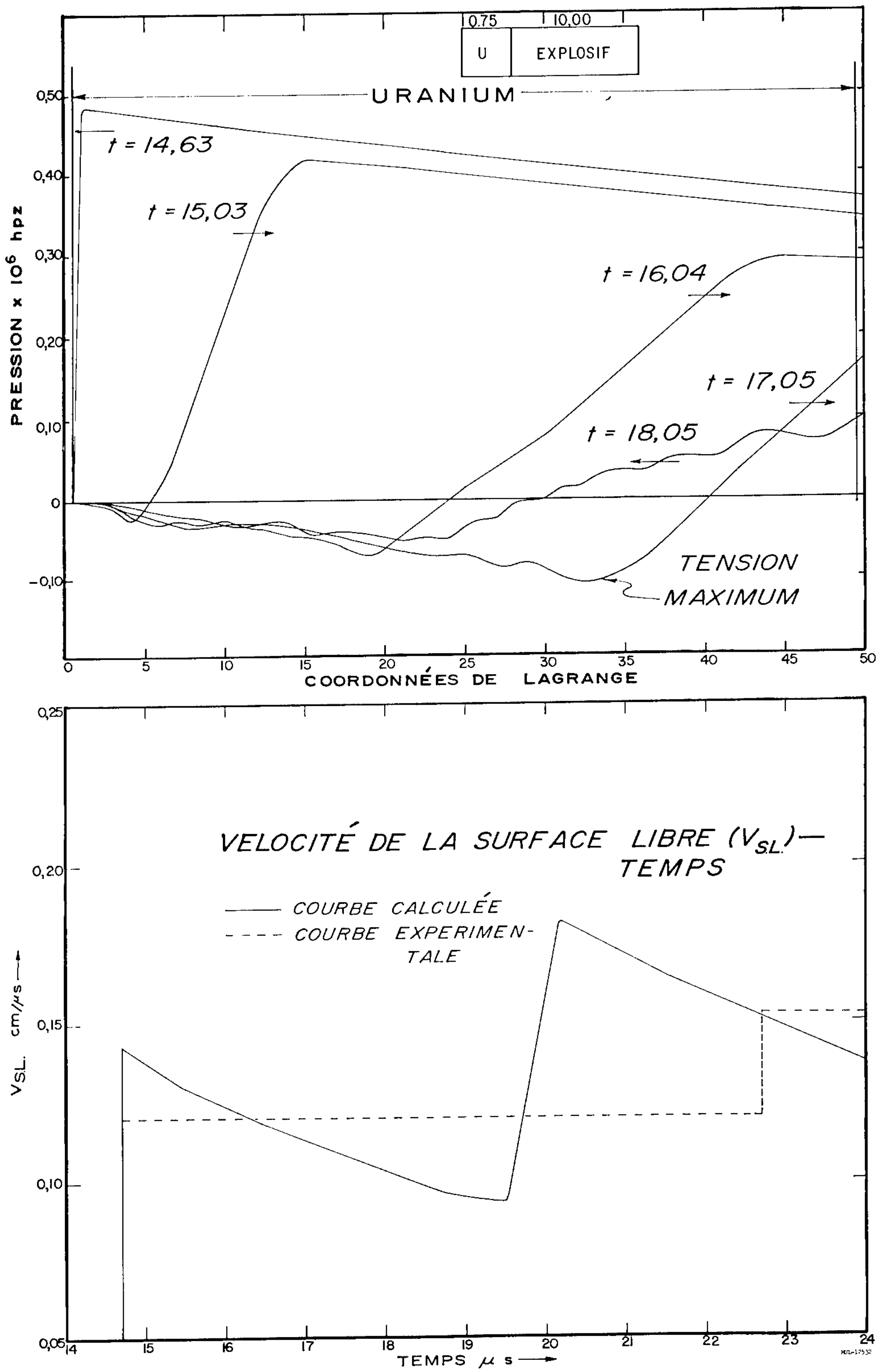

Fig. 3. Top: Pressure profiles at different times (pressure – Mb, time – μsec). Bottom: Front surface velocity vs time.

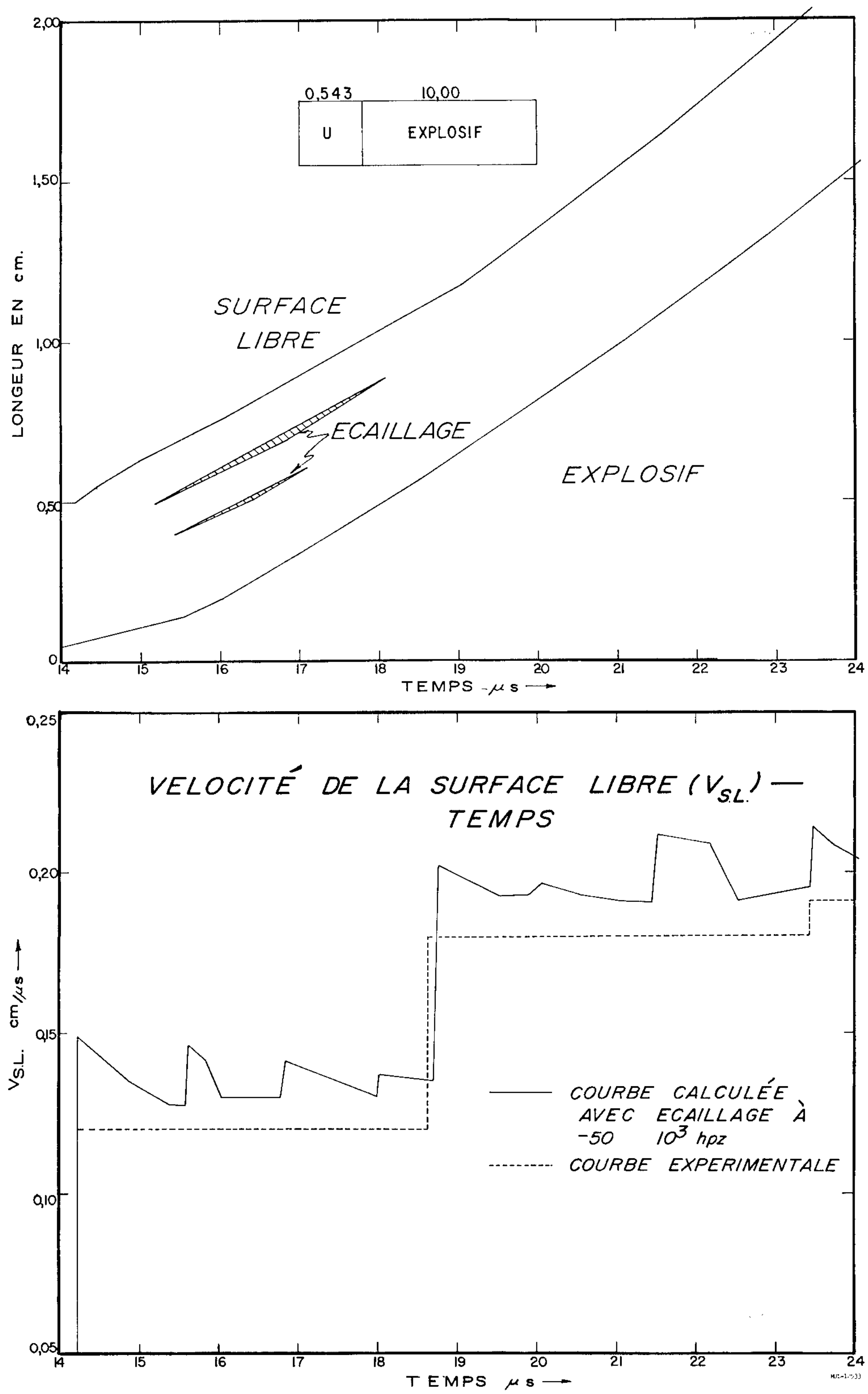

Fig. 4. Top: Distance vs time of uranium ("ecaillage" = spall). Bottom: Uranium front surface velocity vs time (where spall was allowed to occur at – 50 kb).

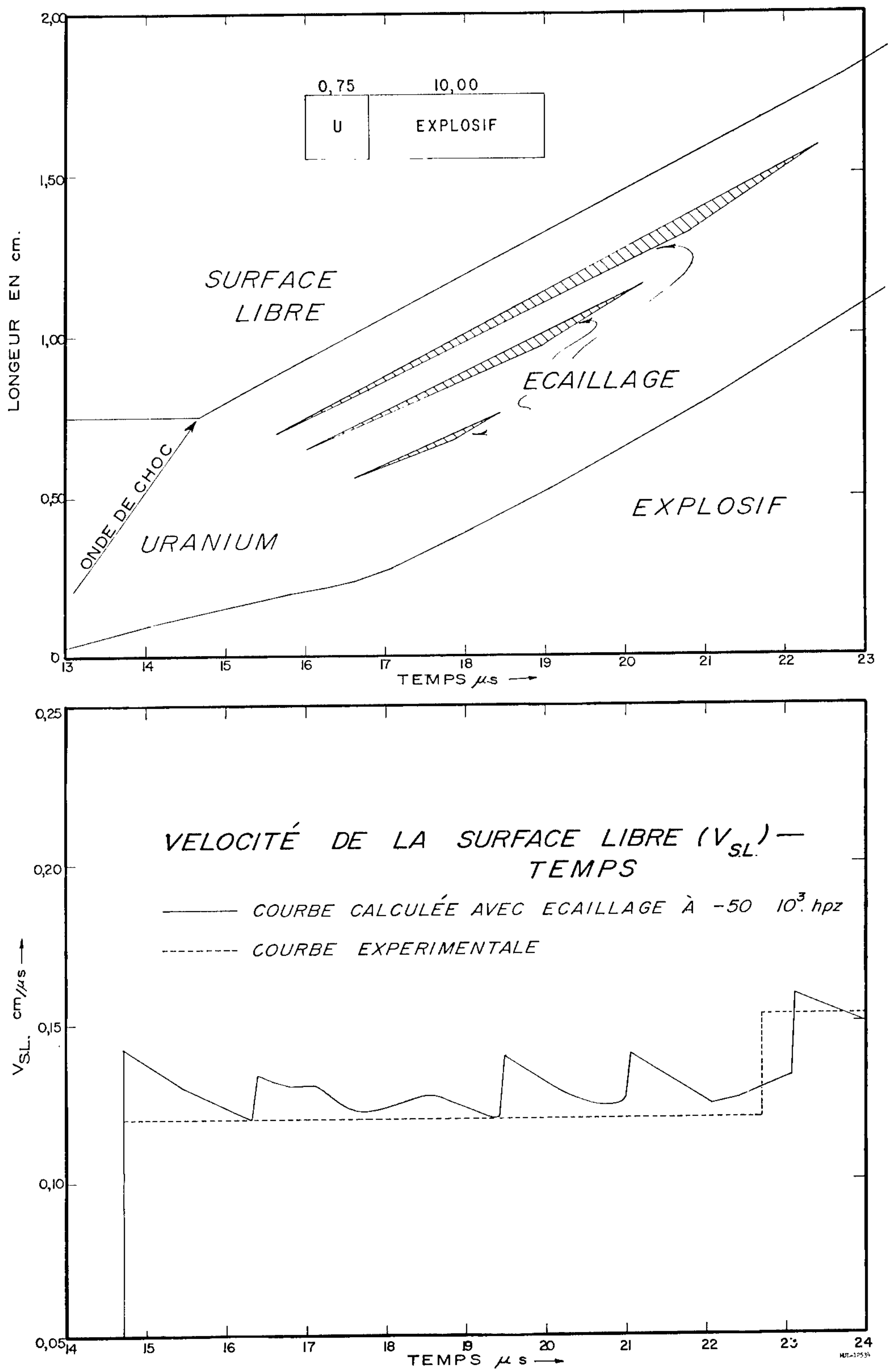

Fig. 5. Top: Distance vs time of uranium ("ecaillage" = spall). Bottom: Uranium front surface velocity vs time (where spall was allowed to occur at – 50 kb).

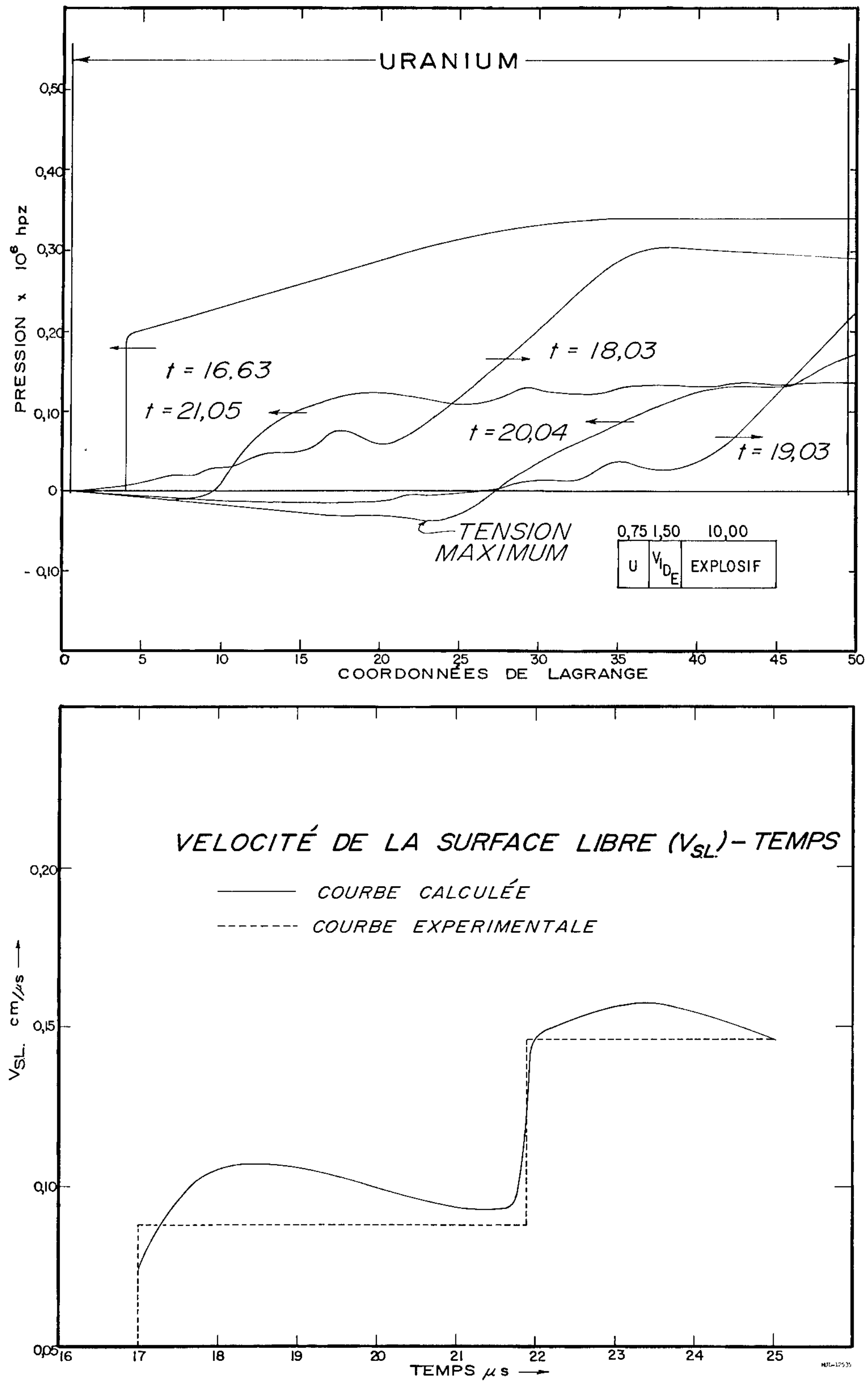

Fig. 6. Top: Pressure profile in uranium at different times ("vide" = void). Bottom: Uranium front surface velocity vs time.