Shock Tubes in Rarefied Gas Flow Research

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In any real fluid motion there exists regions in space-time in which the fluid is far from thermodynamic equilibrium. The relative extent of these non-equilibrium regions is determined by the ratio of the molecular relaxation times and the corresponding length scales to the macroscopic time and space scales appropriate to the flow. Gas flow within such non-equilibrium regions is properly called "rarefied". In recent years the shock tube has become a rather efficient tool in the investigations of rarefied gas flows and I intend to illustrate progress in this use through a discussion of some very recent and typical investigations of the GALCIT group carried out under NASA sponsorship.

I. Shock tubes and instrumentation

Two shock tubes are being used, a 17" diameter and a 6" diameter tube; the non-equilibrium regions in the larger tube are some centimeters in extension, the smaller tube trades size for high temperatures. The newer 6" tube incorporates some design features which are of some interest and are illustrated in the first two figures: The tube sections are held together and centered without the use of bolts and without welding of flanges to the sections. The figure is self-explanatory. Furthermore the diaphragms used in the tube are only roughly cut out; they are crimped and finished within the tube by means of a hydraulic press and fired using a downstream knife edge arrangment. (Fig. 1, Fig. 2)

The experiments are carried out using the usual heat gauges, the fast pressure gauge of Baganoff, a new, very much improved, electron beam densitometer, Sturtevant's fast mass spectrometer and a limited amount of optical and spectroscopic instrumentation.

II. The "tail" of the shock

The first example of work in progress concerns the detailed density distribution within the shock wave in a monatomic gas. Our former numerical computations of the Krook model showed the existence of an extensive precursor at high Mach numbers. Recent theoretical work of Narasimha (Ref. 1) has clarified the physical reason for its existence and shown the relation to earlier work of Liubarskii (Ref. 2) There is no doubt that this "tail", or better precursor, is a necessary, important and quite interesting feature of the shock waves: Briefly, the temperature ratio across the shock increases with Mach number without bound while the velocity and density ratio are bounded. Consequently there are more very fast molecules downstream of the shock than upstream, these fast molecules have long mean free paths and diffuse forward. Except for some recent hot wire observations of Broadwell (Ref. 3) who studied the shock in front of a cylinder in rarefied flow, the precursor has not been demonstrated experimentally. To find it experimentally in the density distribution requires great accuracy and the corresponding measurements are only now in progress. The figures show the improved densitometer traces (obtained by B. Schmidt) from which we hope the precursor will be demonstrated. In particular Fig. 3 shows the resolution of these recent densitometer traces. Within this kind of resolution any lack of non-uniform flow behind the shock wave, due to wall boundary layer effects, etc., shows up and has to be corrected out. Unfortunately these boundary layer effects increase with increasing Mach number and decreasing pressure, i.e., in the same direction as the precursor effect itself. Figs. 4, 5 illustrate the slow increase in density behind a shock at low pressure levels.

III. Shock reflection

The development of fast heat gauges and in particular the fast pressure gauge makes feasible studies of the detailed processes in the reflection of shock waves from solid walls. The reflection of a shock wave of finite thickness from a real wall is an intriguing problem. Experimentally one can measure both the heat flow and the stress distribution history, quantities which should be much more sensitive indicators of the appropriate kinetic model than, say, the density distribution of a propagating shock wave. Theoretically the problem is very much harder than the simple propagating shock since it involves always two independent variables. A set of measurements has been made by J. Smith (Ref. 4) and compared with Navier-Stokes computations of J. Petty (Ref. 5). As expected, agreement between Navier-Stokes theory and experiments becomes poor already at quite low Mach numbers. This is illustrated in Figs. 6 and 7.

This work as well as the earlier shock trajectory studies of Sturtevant and Slachmuylders can be extended into many directions including an overall study of surface interaction effects.

IV. Mass spectroscopic studies of argon ionization

Ions effusing through orifices in the tube end wall are sampled with a fast Nier-type mass spectrometer (Fig. 8). The time history of a specific component can be followed for times of the order of a 50 μ sec or more, e.g., Fig. 9. This method is extremely promising provided a realistic interpretation of the sampling process can be given. The argon ionization in the presence of impurity atoms, primarily hydrogen, have been used as a test case. Reproducible and internally consistent results have been obtained: The activation energies of A and H have been measured as 12.4 ± 0.7 ev and 9.4 ± 1.1 ev respectively. Both values agree with the energy, corresponding to the first excited level and are thus consistent with previous measurements for A (B. Sturtevant and C. Wang, Ref. 6 (to be published)).

The impurity effect appears consequently to be due to a large cross section rather than due to a low activation energy. In any case the results give us confidence that the sampling process can be handled satisfactorily The way the sampling process is handled is illustrated in Fig. 10: the ions and electrons diffuse by ambipolar diffusion into the growing thermal layer until the sink effect of the orifice becomes predominant. Consequently the process is much like the diffusion in the Langmuir probe problem.

The impurity level in the shock tubes is still uncomfortably high. While the leak rate has been rendered negligible, the tubes cannot be baked out at present and hence adsorbed gases, in particular water vapor, are responsible for the background impurities. Here lies no doubt a future technical development in shock tube design which is quite straight-forward in principle but sometimes hard to apply. To bake a 17" shock tube of nearly 90' length in a laboratory is a rather uncomfortable idea!

V. Xenon ionization relaxation at high temperatures

The last sample problem concerns the use of end wall pressure-history measurements applied to a study of the xenon ionization. The ionization in xenon proceeds in its final stage so rapidly that the overall structure of the shock contains two quite distinct elements: A shock wave connecting the initial and a "frozen" final state followed by an ionization "front" through which the final equilibrium state is reached. The density and temperature jumps through the ionization front are large, the pressure change small. The reflected shock interacts with the ionization front and the reflected interaction waves influence the pressure history at the wall. Consequently an intelligent interpretation of the end wall time history permits the simultaneous measurement of the relaxation time both behind the incoming and reflected shock waves. The results are illustrated in the last figures.

Fig. 11 shows the construction of an x, t diagram from an interpretation of the wall pressure history. Fig. 12 demonstrates the relaxation time measurements. A following paper by J. Smith will contain all details of the measurements and their interpretation.

References

1. Narasimha, R., Asymptotic Solutions for the Distribution Function in Nonequilibrium Flows. I. The Weak Shock as and Illustration, J. Fluid Mech. (to appear).

2. Liubarskii, G. Ya., Soviet Physics-JETP 13 (1961) 740.

3. Broadwell, James E., Private Communication; see also Broadwell, James E., and Rungaldier, Harold, Proc. 5th Intl. Sym. on Rarefied Gas Dynamics, C. L. Brundin, ed., Academic Press, New York, 1967.

4. Smith, J. A., and Baganoff, D., Measurements of Normal Stress and Heat Flux within a Reflecting Shock Wave, APS Bulletin, June 1966, p. 618.

5. Petty, James S., Reflection of a Plane Shock Wave from a Normal Isothermal Wall, APS Bulletin, June 1966, p. 618.

6. Sturtevant, B., and Wang, C. P., Mass Spectrometric Studies of Impurity Ionization in Shock-Heated Argon, AGARD 28th Propulsion and Energetics Panel Meeting on Recent Advances in Aerothermochemistry, May 16-20, 1966, Oslo, Norway.

Discussion

COMMENT by W. Low: With respect to the first part of Prof. Liepman's paper on experimental evidence of precursors, I have the following comment. When you investigate the microwave attenuation as a function of time under reasonable high resolution and fair sensitivity you can notice a long tail. This may be caused by the free high energy electrons associated with such a precursor.

ANSWER: The precursor I discussed in the talk is composed of high energy neutrals. For low electron concentration similar effects are expected since the interaction potential for electrons is very soft.

COMMENT by O. Laporte: How did you see the shock? This must have been the frozen shock.

ANSWER: Strictly speaking the "shock" contains a sharp pressure front followed at some distance by an ionization front across which the pressure hardly changes, but density and temperature rise and drop respectively. I often referred only to the pressure front as the "shock" during the talk.

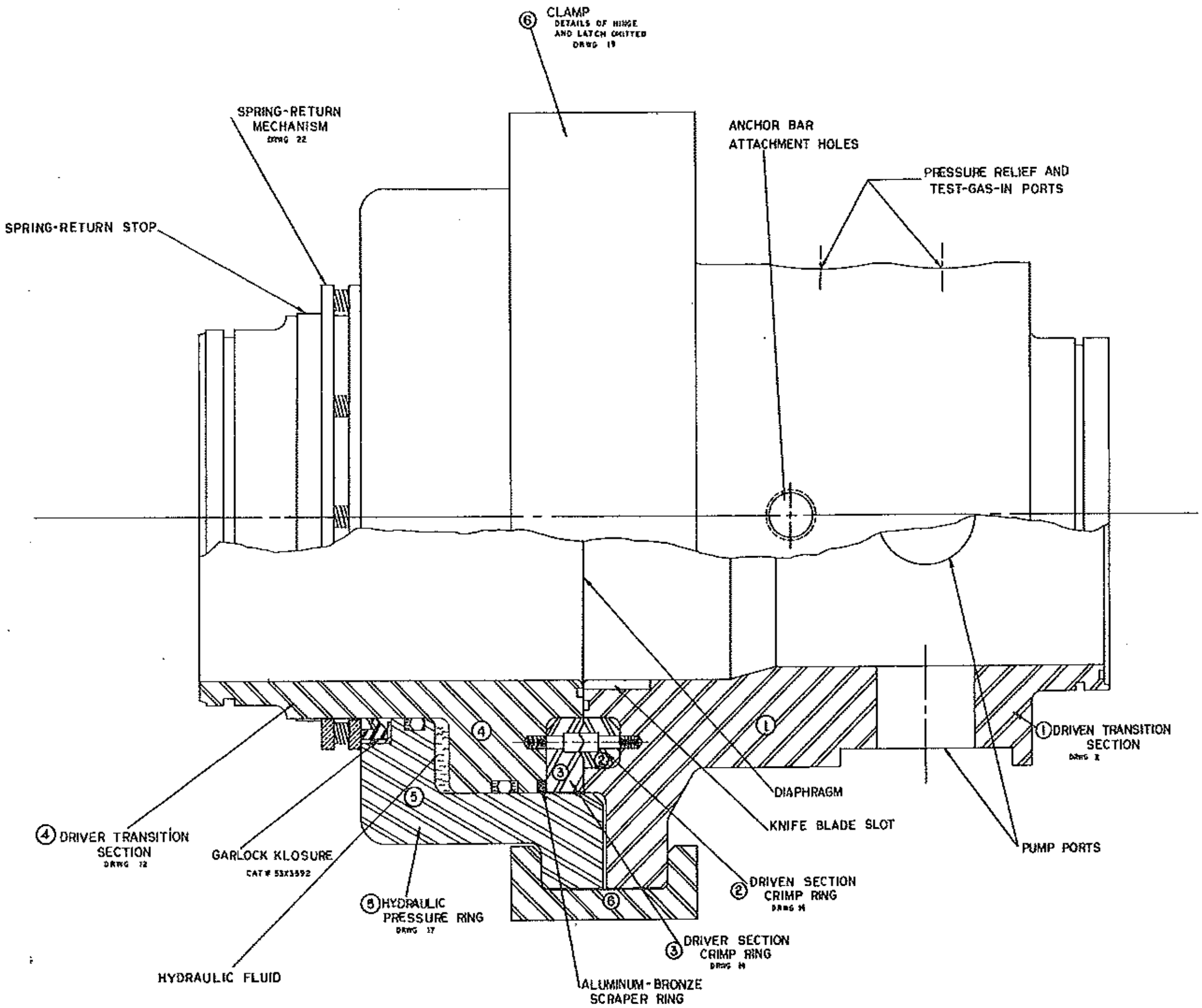
COMMENT by A. Frohn: In my measurements of the density distribution in argon shock waves [1)2)], I was able to detect density changes in front of the shock wave of 1 % of the density behind the shock wave. But we found no density increase ahead of the shock wave. These measurements were in the Mach number range 1, 6 M_s 9.

1) A. Frohn, Forschung, Febr. (1966)
2) Schultz-Grunow and A. Frohn, Symposion on Rarefied Gas Dynamics (1964).

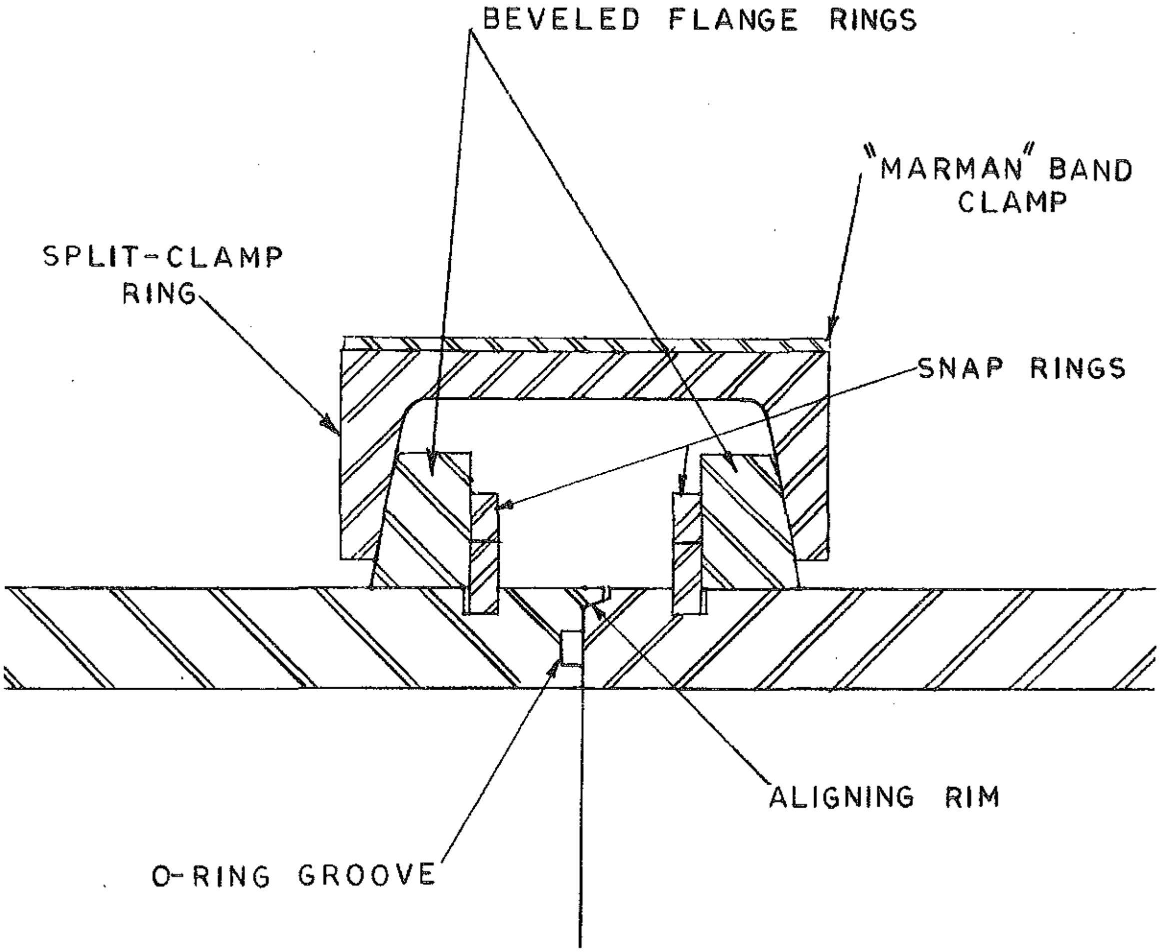
ANSWER: I do not believe that it is possible at comparatively low Mach-numbers to detect the "tail" if the flow behind the shock is disturbed as it will be by the boundary layer. Furthermore even in front there must exist a small but possibly significant boundary-layer or rather wall-viscous or transversal effect because the front of the shock cannot intersect the wall without a transverse precursor.
So I believe that the accuracy of your measurements of the shock structure proper is less than you estimate.

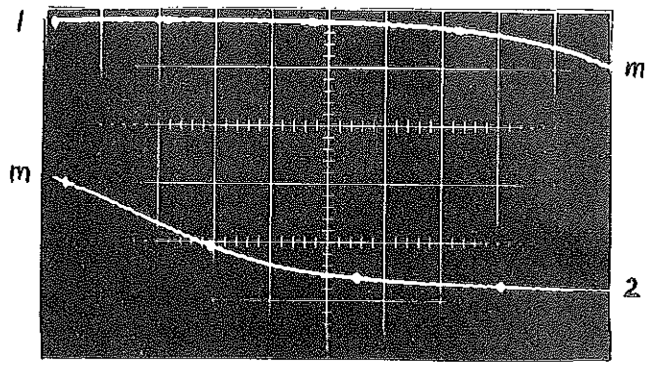
COMMENT by A.K. Oppenheim: The enterprising study presented in this paper raises a number of questions; I shall limit myself to only two:
1) How do you account for the difference between the experimental and theoretical pressure disturbance.
2) Why optical measurements have not been resorted yet, and what program of study do you have in this respect.

ANSWER: 1) the p_{xx} disturbance shown refers to the measured force at the wall and contains besides the thermodynamic pressure the normal viscous stress which is not necessarily given by the Navier-Stokes theory. In fact the point of the measurement is precisely the difference between the real stress and the one predicted by the Chapman-Enskop procedure.
2) Like everybody else we are developing Laser-optics for use in shock tubes but have not yet obtained any significant results worth reporting.



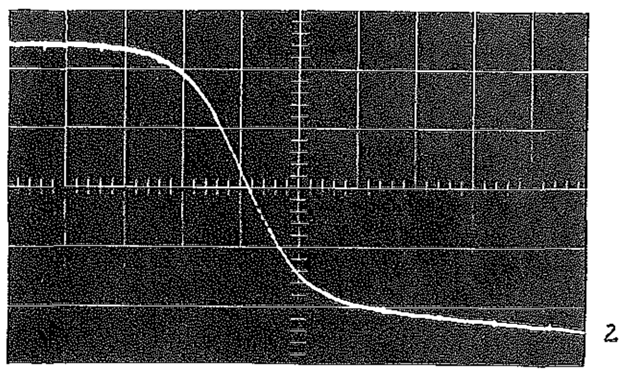
⑥ CLAMP
DETAILS OF HINGE AND LATCH OMITTED
SPRING-RETURN MECHANISM
SPRING-RETURN STOP
ANCHOR BAR ATTACHMENT HOLES
PRESSURE RELIEF AND TEST-GAS-IN PORTS
④ DRIVER TRANSITION SECTION
GARLOCK KLOSURE
⑤ HYDRAULIC PRESSURE RING
HYDRAULIC FLUID
ALUMINUM-BRONZE SCRAPER RING
③ DRIVER SECTION CRIMP RING
② DRIVEN SECTION CRIMP RING
DIAPHRAGM
KNIFE BLADE SLOT
PUMP PORTS
① DRIVEN TRANSITION SECTION


BEVELED FLANGE RINGS
"MARMAN" BAND CLAMP
SPLIT-CLAMP RING
SNAP RINGS
ALIGNING RIM
O-RING GROOVE



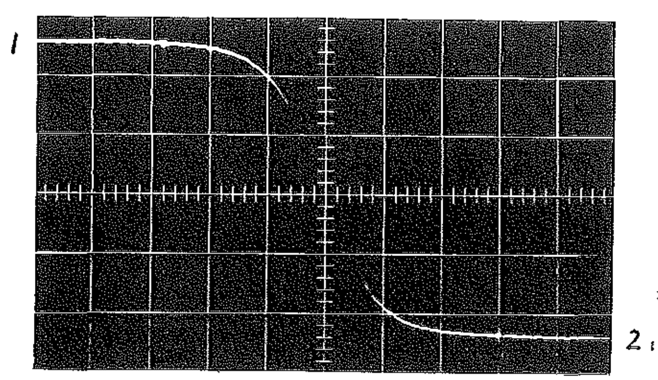
ARGON: $p_1 = 15\ \mu$
$M_s = 4.03$ 2 μs/div

Fig. 3



ARGON: $p_1 = 15\ \mu$
$M_s = 4.03$ 5 μs/div

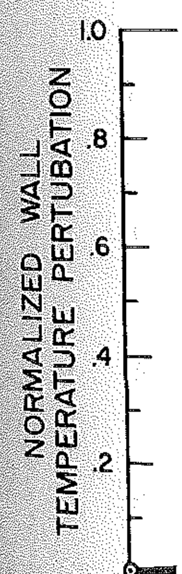
Fig. 4



ARGON: $p_1 = 50\ \mu$
$M_s = 3.89$ 1.6 μs/div

Fig. 5

Fig.



Fig

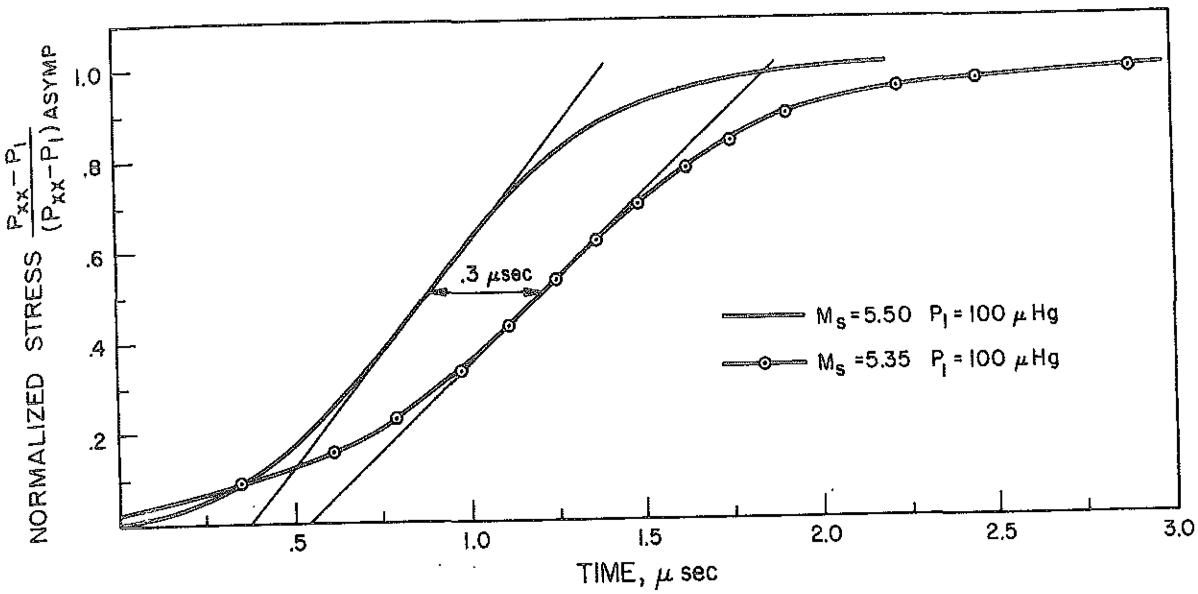


Fig. 6 END-WALL P_{XX} HISTORY; ARGON

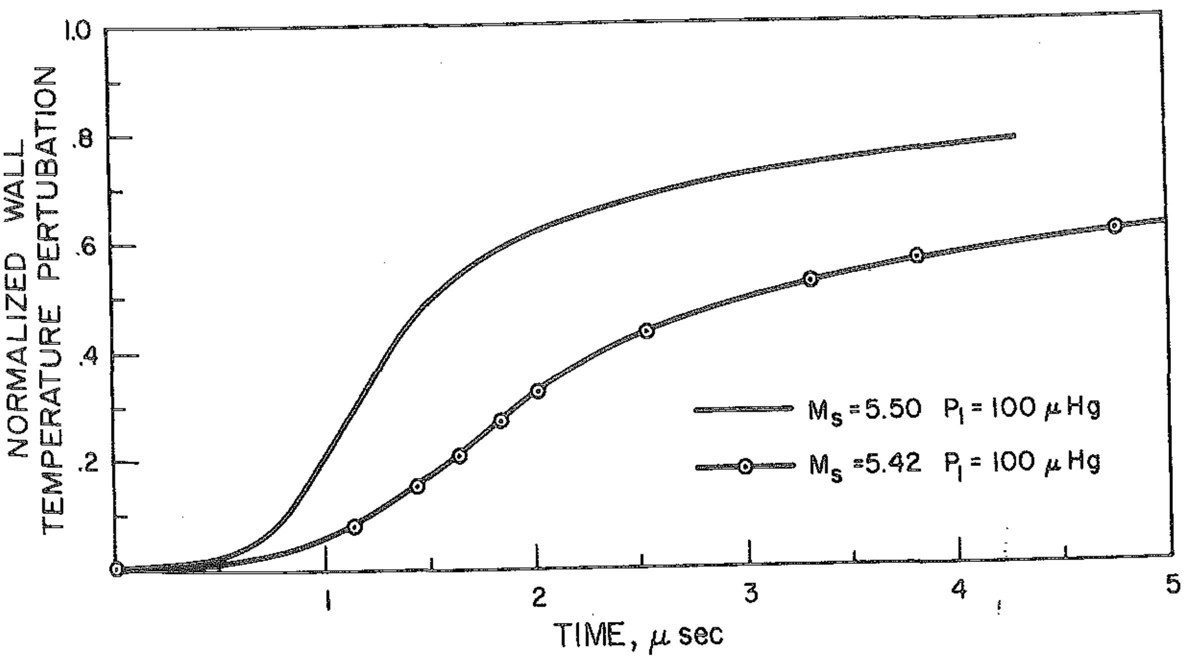
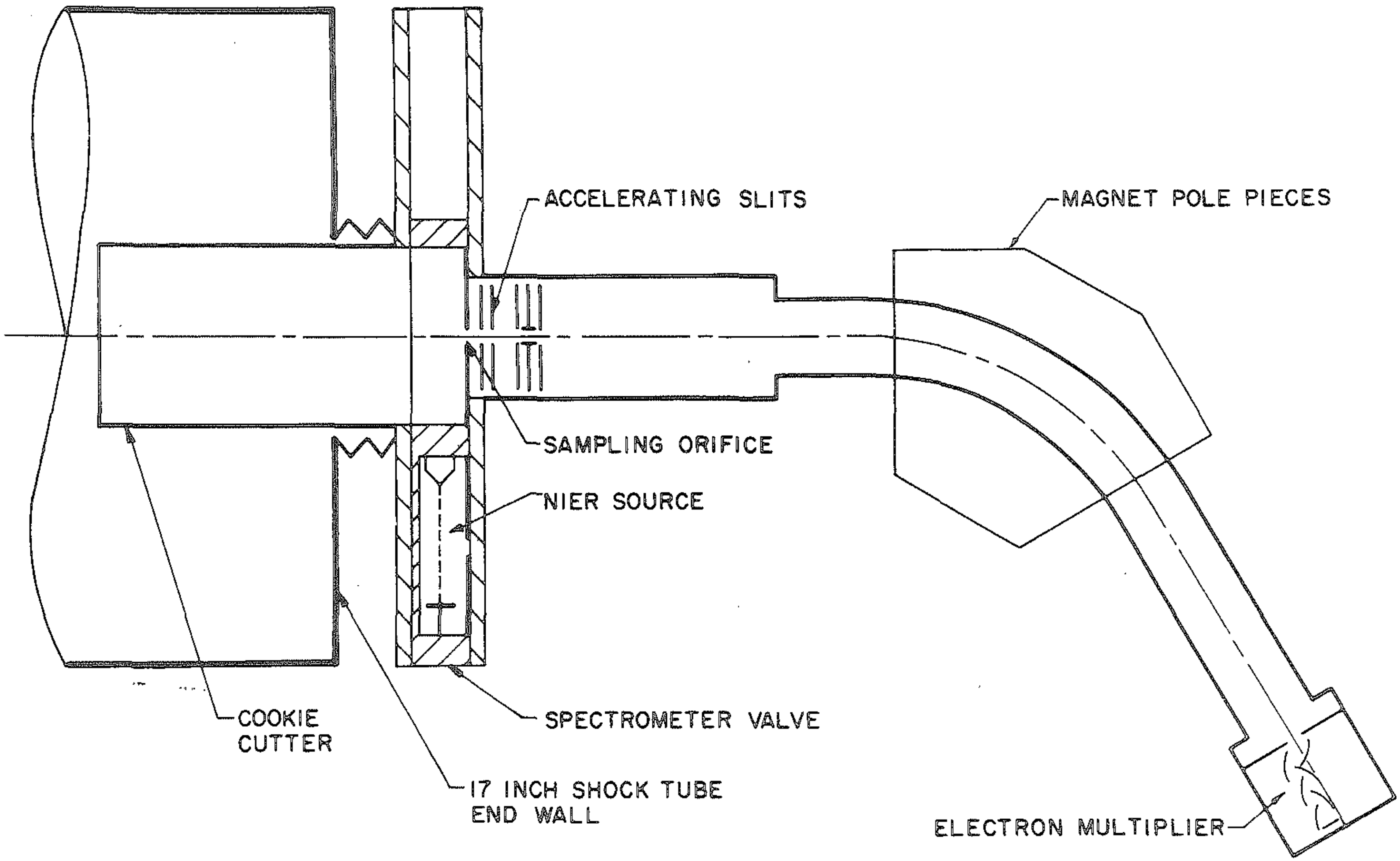
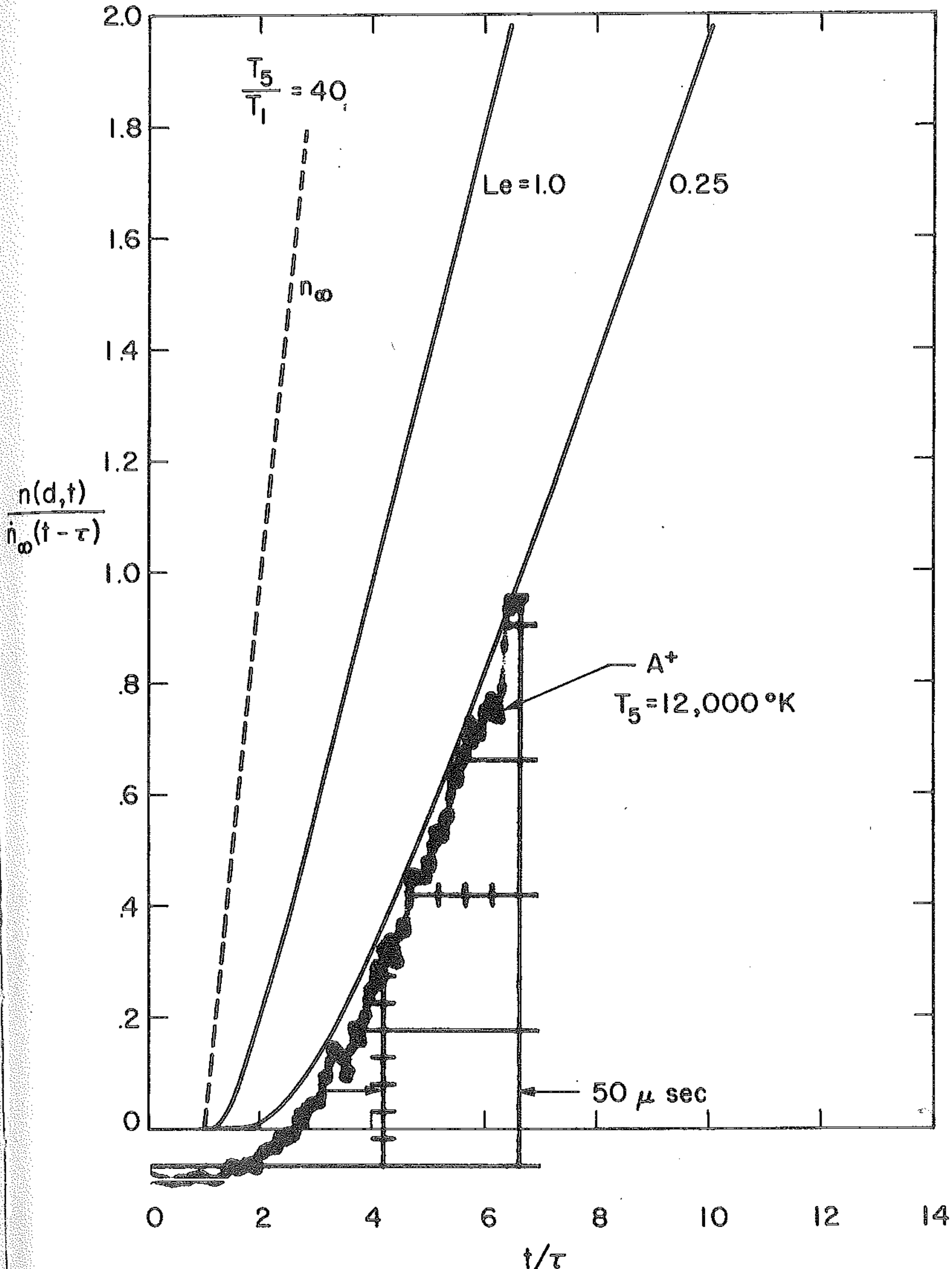


Fig. 7 END-WALL TEMPERATURE HISTORY; ARGON


ACCELERATING SLITS
MAGNET POLE PIECES
SAMPLING ORIFICE
NIER SOURCE
COOKIE CUTTER
SPECTROMETER VALVE
17 INCH SHOCK TUBE END WALL
ELECTRON MULTIPLIER



$\frac{T_5}{T_1} = 40$
n_∞
Le = 1.0
0.25
A^+
$T_5 = 12,000\,°K$
50 μ sec
$\frac{n(d,t)}{\dot{n}_\infty(t-\tau)}$
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
0
2
4
6
8
10
12
14
t/τ

Fig. 9

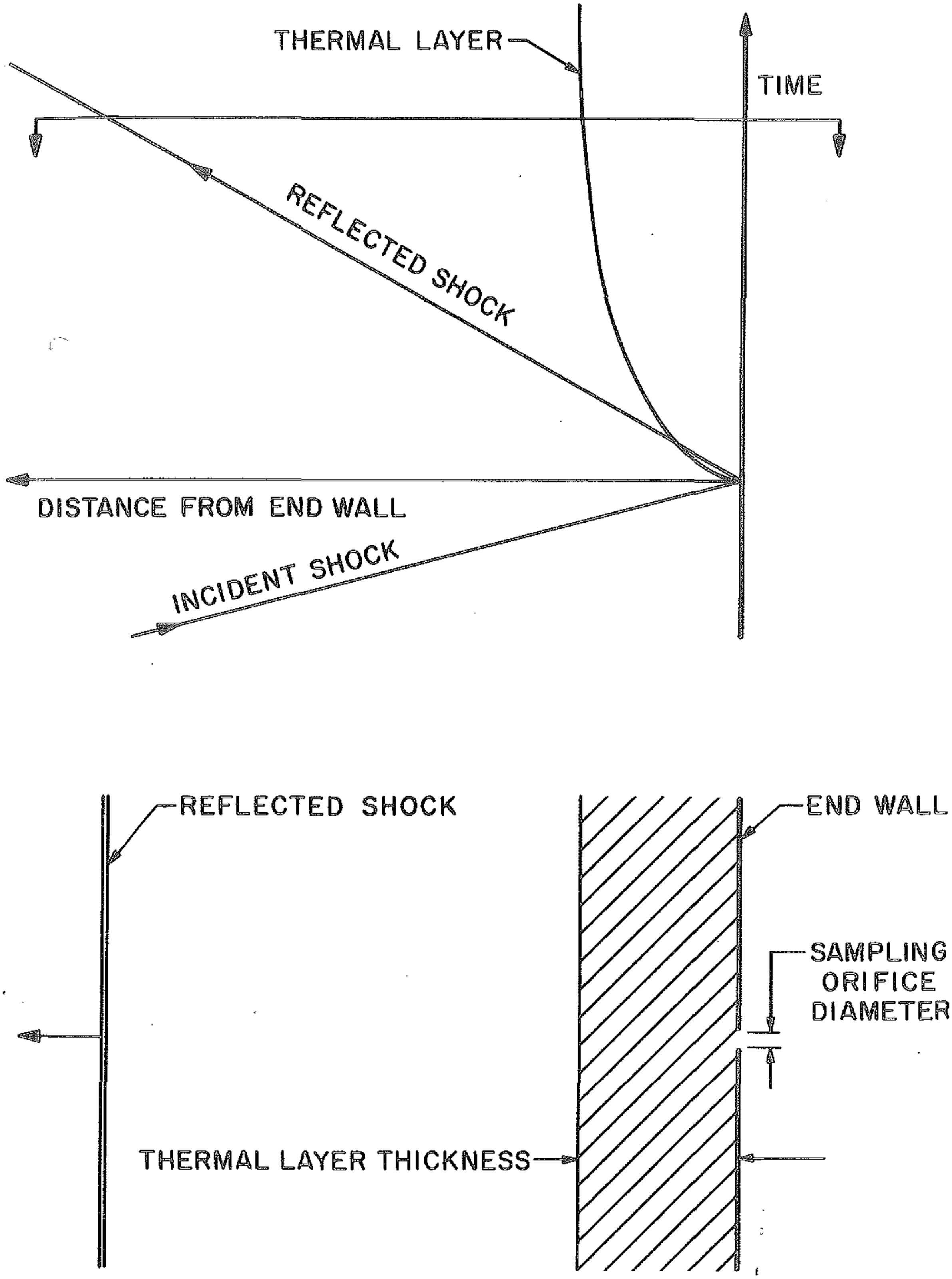
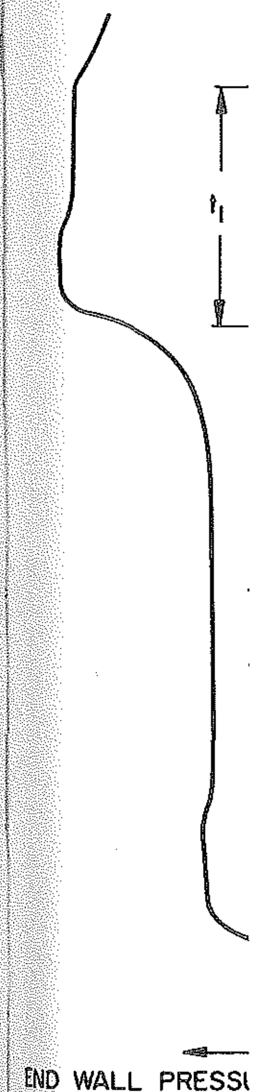
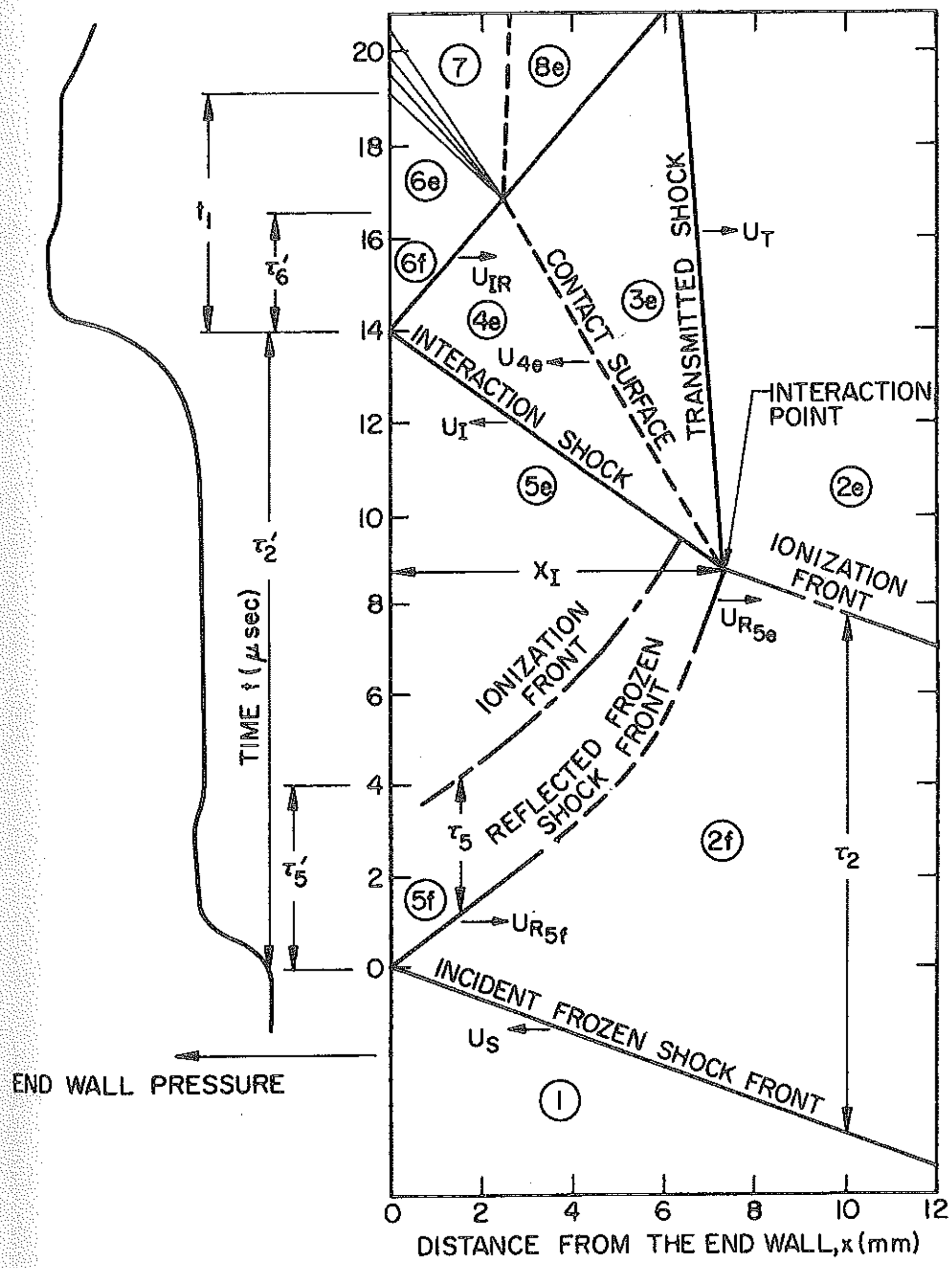

THERMAL LAYER
TIME
REFLECTED SHOCK
DISTANCE FROM END WALL
INCIDENT SHOCK
REFLECTED SHOCK
END WALL
SAMPLING
ORIFICE
DIAMETER
THERMAL LAYER THICKNESS

Fig. 10





x-t DIAGRAM FOR SHOCK REFLECTION PROCESS IN XENON; M_S=15.1, P_1=.5 mm Hg

Fig. 11

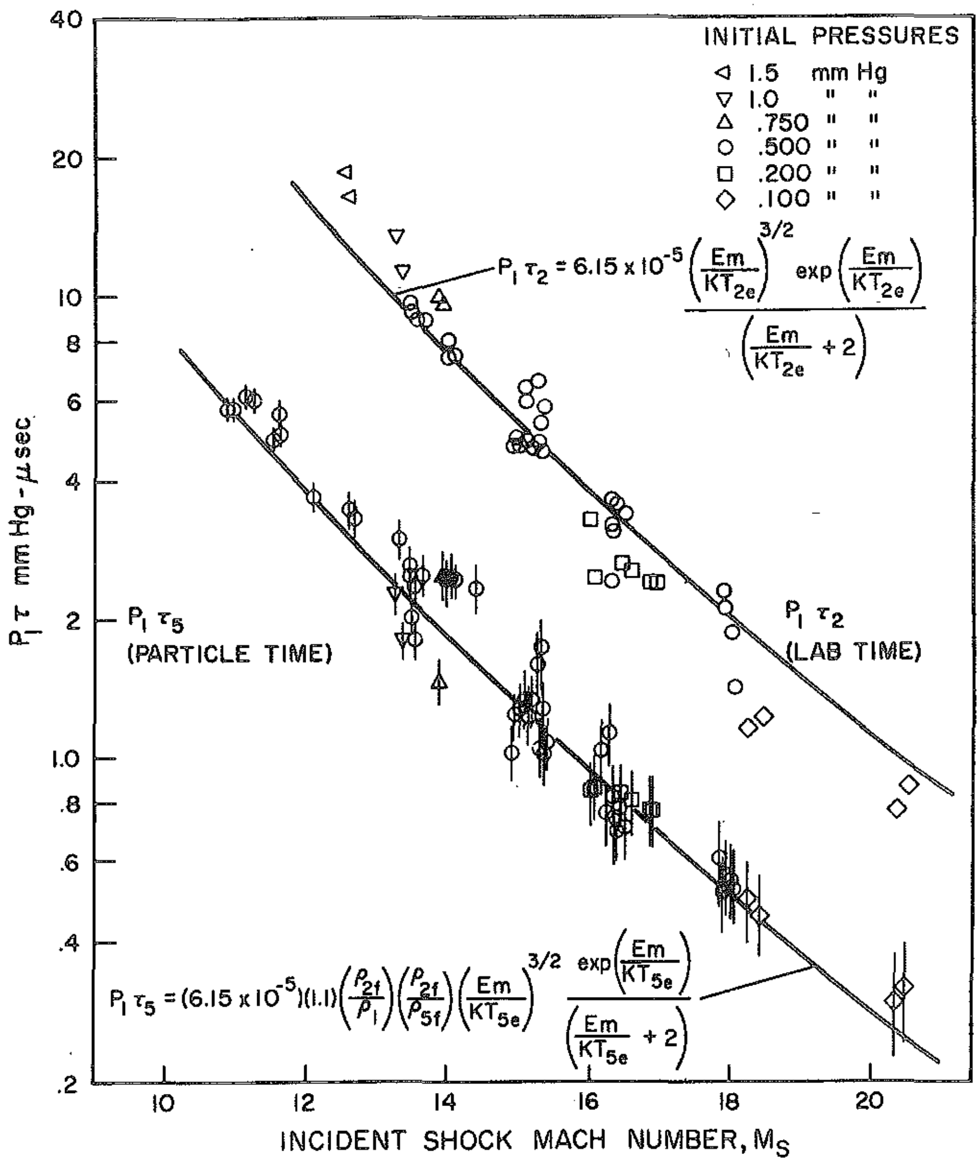


Figure COMPARISON BETWEEN EXPERIMENTAL RESULTS AND PREDICTED VALUES OF $P_1\tau_5$ USING EQUATION

Fig. 12