

## Shock Tube Testing

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### INTRODUCTION

A shock tube<sup>1,2</sup> consists of a high-pressure (driver) section and a low-pressure (driven) section which are separated from each other by a rupture diaphragm. When the diaphragm is ruptured, the compression wave quickly generates a shock wave into the low-pressure medium. The transient zone of shock-heated and shock-compressed driven gas produced in this manner can be utilized to cause the initiation of condensed-phase, unstable (explosive) systems.

This paper indicates the background and nature of such shock tube techniques and briefly summarizes the technique employed in pure environmental shock tests (PEST) at the Armour Research Foundation.

### GENERAL BACKGROUND

The first application of a shock tube technique for assessing the explosive sensitivity of condensed-phase systems was reported by Gey and Bennett in 1955.<sup>3</sup> For many years the Foundation has employed this technique in qualitative<sup>4,5</sup> tests of the explosive sensitivity of various unstable materials, and more recently in a quantitative study of the initiation of lead azide.<sup>6</sup> Other investigators<sup>7,8,9,10</sup> have reported the use of the shock tube for the initiation of several composite propellants. Currently the Foundation is extending these studies to liquid monopropellant systems.

Briefly, the shock tube is used as a research tool for producing a transient zone of shock-heated and shock-compressed driven gas which can be made to contact the surface of a condensed-phase, unstable system. Under certain conditions, a time delay can be measured from shock contact to the detection of an explosive response or reaction runaway.

A shock tube is operated by adjusting the driven gas pressure and slowly increasing the driver (usually helium) gas pressure until the diaphragm ruptures. The compression wave rapidly generates a shock wave which propagates at nearly constant velocity into the low-pressure medium. State properties of the driven gas behind the incident and the reflected shock front can be calculated from the driver-to-driven gas pressure ratio at the instant of diaphragm rupture and the initial state of the driven gas. The calculated properties can be experimentally confirmed with suitable instrumentation to measure shock pressures, shock temperatures and traverse velocities between two or more fixed stations.

The surface of a test sample may be exposed to a quiescent or a flowing shocked gas environment wherein conductive and forced convective heating effects are respectively enhanced. An ideal quiescent condition can be generated by flush-mounting a test sample on the end plate of a shock tube. In this location, the sample surface is exposed to the twice shocked (incident and reflected) driven gas environment, which remains essentially static until the rarefaction wave arrives from the driver section. A flowing condition is generated by mounting a test sample

aerodynamically in the center or along the periphery, of the shock tube. In such positions, the sample is exposed to the transient zone of shocked gas environment which sweeps across the surface.

When the surface of a condensed-phase, unstable system is exposed to the quiescent or flowing shocked gas environment, the following experimental data are known or can be calculated or measured at time of contact:

- C - composition of the driven gas
- $T_g$  - temperature of the shock-heated driven gas
- $P_g$  - pressure of the shock-compressed driven gas
- $T_o$  - surface temperature of the condensed-phase system.

A time delay to explosive response can be measured, during which interval it is practically impossible to monitor the infinitesimal variations in  $T_g$ ,  $P_g$ , and  $T_t$  (the surface temperature at time  $t$ ), or the extent of decomposition near the surface. Basically then, the experimental data that are measured or controlled in such shock testing techniques include: (1) a definition of the state of the shocked driven gas in terms of say, composition, temperature, and pressure (2) the initial surface temperature of the test sample exposed to said environment and (3) a time interval (delay) from moment of contact to detection of explosive response.

Explosive response can be determined by various experimental techniques. For example, the time at which pressure, electrical conductivity, or luminosity transitions occur can be recorded respectively by pressure transducers, conductivity probes, and a photographic (or photocell) record of flame luminosity. The Foundation has employed the detection of the generated explosion "noise" or vibration upon the end plate mount as a simple technique for identifying an explosive response. It should also be mentioned that the resulting time delay should be within the relatively constant conditions of the first incident and/or reflected shock exposure, so that the analytical complications that can be incurred because of subsequent shocks of diminished intensity can be avoided.

Based on a heat transfer analysis,  $T_t$  can be estimated. The correlation of  $T_t$  with the time delay,  $t_d$ , then serves to indicate reaction mechanisms by permitting the identification of runaway temperatures, activation energies, and other initiating phenomena. Whether the ignition mechanism involves a runaway reaction in the condensed-phase, as developed by Hicks,<sup>11</sup> or the establishment of a gaseous reaction zone adjacent to the surface, as suggested by McAlevy, et al.,<sup>9</sup> appears to be in doubt. The difficulty in these approaches is the assumption that  $T_t$  can be adequately estimated by a heat transfer analysis. Severe complications can arise due to surface irregularities in the case of solids (unless single crystal faces are employed), and to vapor pressure and vaporization phenomena in the case of liquids.

Recently, a number of thermodynamic models have been proposed<sup>12</sup> for various steady-rate processes. These models utilize the arguments of ordinary thermodynamics to relate the flow of mass, volume and heat to the properties (chemical potential, pressure and temperature) of terminal parts of a system which are linked by a gradient region or part-on-the-line. A simplified application of this procedure is in order for the problem of explosion initiation, or sensitivity, because of the likelihood that definable stationary states exist across the gradient regions of steady-rate flames.

One objective of studies conducted at the Foundation is based on the premise that the order of explosive response (i.e., sustaining decomposition, deflagration and detonation) for an unstable system is characterized by a unique energetic situation. Thus, contact of an energy-rich zone (e.g., the flame zone or an

artificial environment) with a potentially energy-rich zone (e.g., a layer of relatively undisturbed explosive) can result in a characteristic time delay for a subsequent rate of propagation. By varying the magnitude, rate, and mode of energy release from an artificial environment to the surface of an unstable medium, it should be possible to evaluate specific energetic susceptibilities of unstable systems.

For example, in the pure environmental shock test, relative measures of the magnitude, rate and mode of energy release from the shocked driven gas environment to the surface of a condensed-phase system might be ascertained from the shock intensity, the pressure, and the composition of the driven gas (varying degrees of freedom), respectively.

### EXPERIMENTAL

A schematic diagram of the shock tube used for a study of the initiation of lead azide at the Armour Research Foundation is shown in Fig. 1,<sup>\*</sup> which also indicates a detailed time-distance sequence of events. The sample was positioned on the back plate of the shock tube as shown in Fig. 2, which indicates the composite array of equipment, instrumentation and electrical circuitry.

Transient shock pressures were recorded by photographing the output of a Kistler PZ-6 miniature pressure transducer and PT-6 amplifier-calibrator unit on a Tektronix 535 oscilloscope. Triggering of the Tektronix 535 oscilloscope was effected internally by the reception of the shock pressure output from the Kistler gage, and both the pressure and the  $V_2$  voltage of the conductivity circuit (see Fig. 2) were simultaneously displayed at the 100-kc chopping rate of a Tektronix 53/54-c dual preamplifier.

Triggering of the Tektronix 545 oscilloscope sweep was effected by less than a 0.1-volt rise in  $V_1$  (of the conductivity circuit), and both the negative voltage output of the Kistler gage and  $V_1$  were displayed at the 100-kc chopping rate of a CA dual preamplifier unit. This was done as a means of obtaining magnified records of the extremely fast conductivity transient.

The criterion of explosion response was the characteristic "ring" of the Kistler gage output when explosion noise was generated at the sample site and transmitted through the end plate and wall of the shock tube to the gage position. The response time was calibrated by spark initiation of lead azide samples.

The results of typical tests are shown in Fig. 3. Photographs of oscilloscope traces with and without azide samples are included to enable the identification of the respective traces. It can be seen that the shock pressure, a time delay (due to "ring"), and conductivity voltage transients are recorded. The data for these tests are summarized in Table 1. Since the driver-to-driven gas pressure ratio ( $P_4/P_1$ ) was accurately measured, this value was used to define the Mach number of the incident shock,  $M_g$ , from a report by Alpher and White.<sup>13</sup> From  $M_g$ , the values of the reflected shock pressure and temperature,  $P_g$  and  $T_g$  (the former usually being confirmed by the oscilloscope record), were obtained by the use of tables.<sup>14</sup> Tests have been conducted with nitrogen, helium, argon and carbon dioxide as driven gases over Mach numbers ranging from about 2 to 7.

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Table 1

DATA FROM PURE ENVIRONMENTAL SHOCK TESTS  
WITH LEAD AZIDE AND NITROGEN DRIVEN GAS

Test No.	$P_1$ , psia	$P_4/P_1$	$M_s$	$T_g$ , °K	$P_g$ , psia	$t_d$ , $\mu$ sec
115	0.467	500	5.09	3100	97.5	103
116	0.460	517	5.11	3200	100	-
119	0.767	301	4.69	2700	134	69
120	0.770	304	4.69	2700	135	-
131	1.55	150	4.18	2220	206	24
132	1.545	156	4.19	2230	206	-

DISCUSSION OF RESULTS

The data from our pure environmental shock testing of polycrystalline lead azide can be simply represented by plotting the logarithm of the product of the square of the reflected shock pressure and the time delay,  $\log (P_g^2 t_d)$ , as a function of the reciprocal of the reflected shock temperature,  $1/T_g$ . Figure 4 displays such a plot for shock test data obtained with nitrogen as a driven gas. Additional data with other driven gases are presented in this form in Fig. 5. Attempts were made to evaluate the data by a heat transfer analysis based on published data<sup>15</sup> and independent calculations at the Foundation. The increase in surface temperature was estimated to vary from 10 to 50°C. The difficulty with such analyses is that a flat planar surface must be assumed, which is experimentally inadequate unless single crystal faces are exposed to the shock environment.

The vaporization of fuel and a subsequent gas phase runaway reaction mechanism<sup>9</sup> appears to explain the results obtained in solid propellant tests; however the possibility of such a mechanism being operative in the decomposition of lead azide seems remote. Further conjecture regarding the interpretation of shock tube results is inappropriate at this time. A more sophisticated analysis must be delayed until sufficient data are available for the development of composite views.

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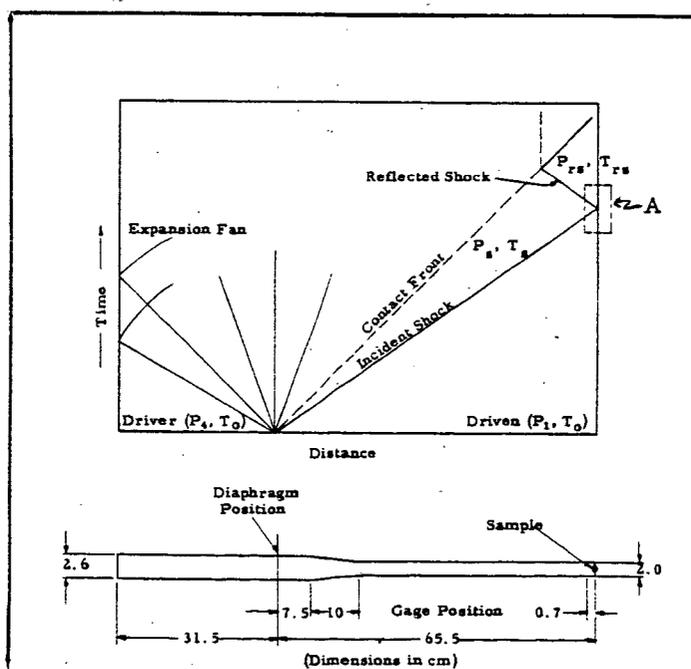
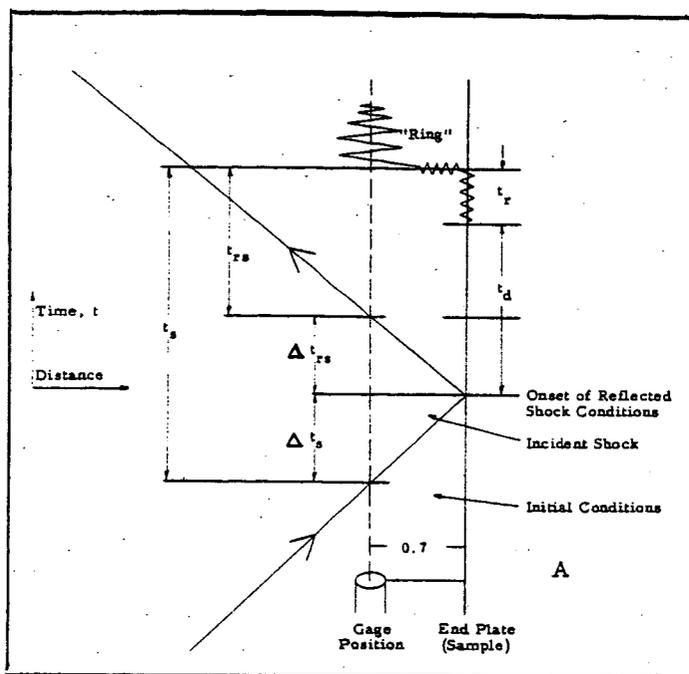


Fig. 1 Shock Tube Profile and Schematic of Time-Distance Events

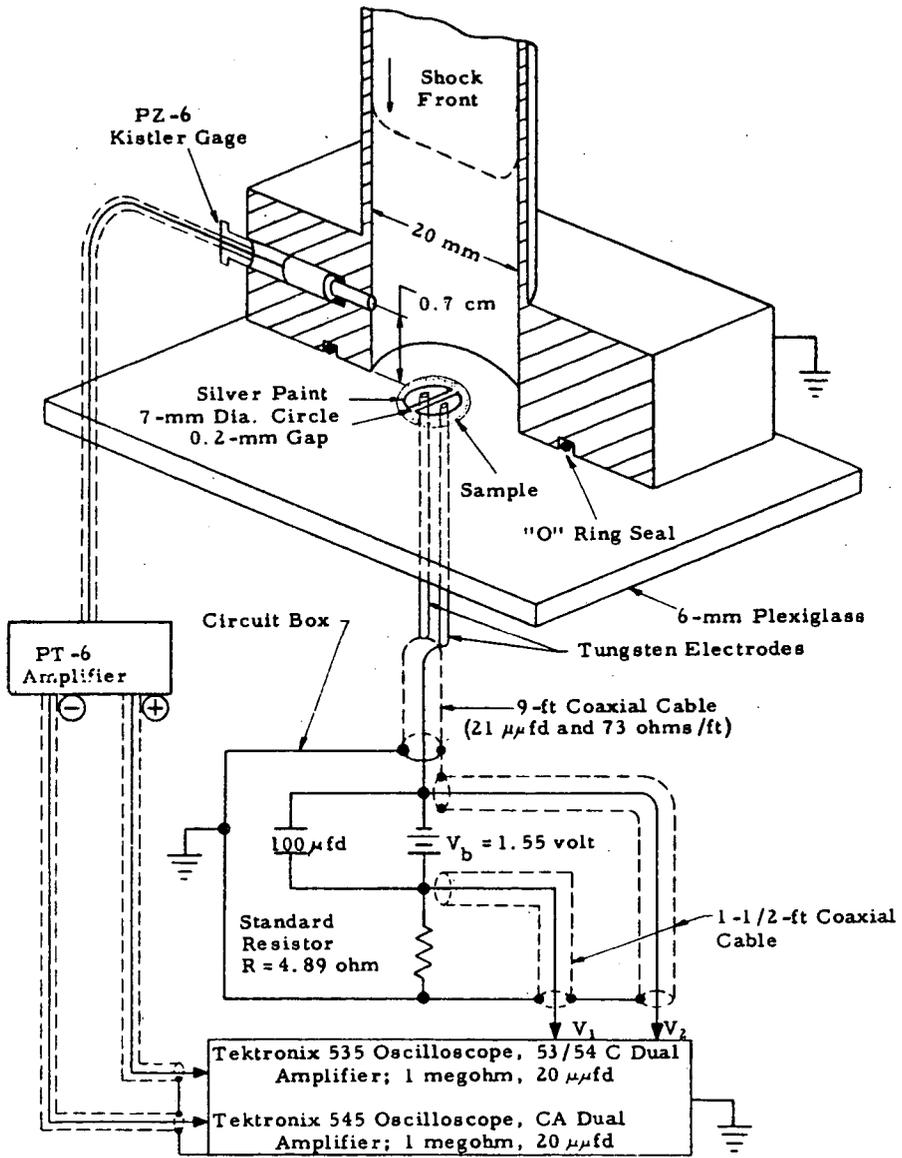


Fig. 2 Composite Details of Shock Test Set-Up

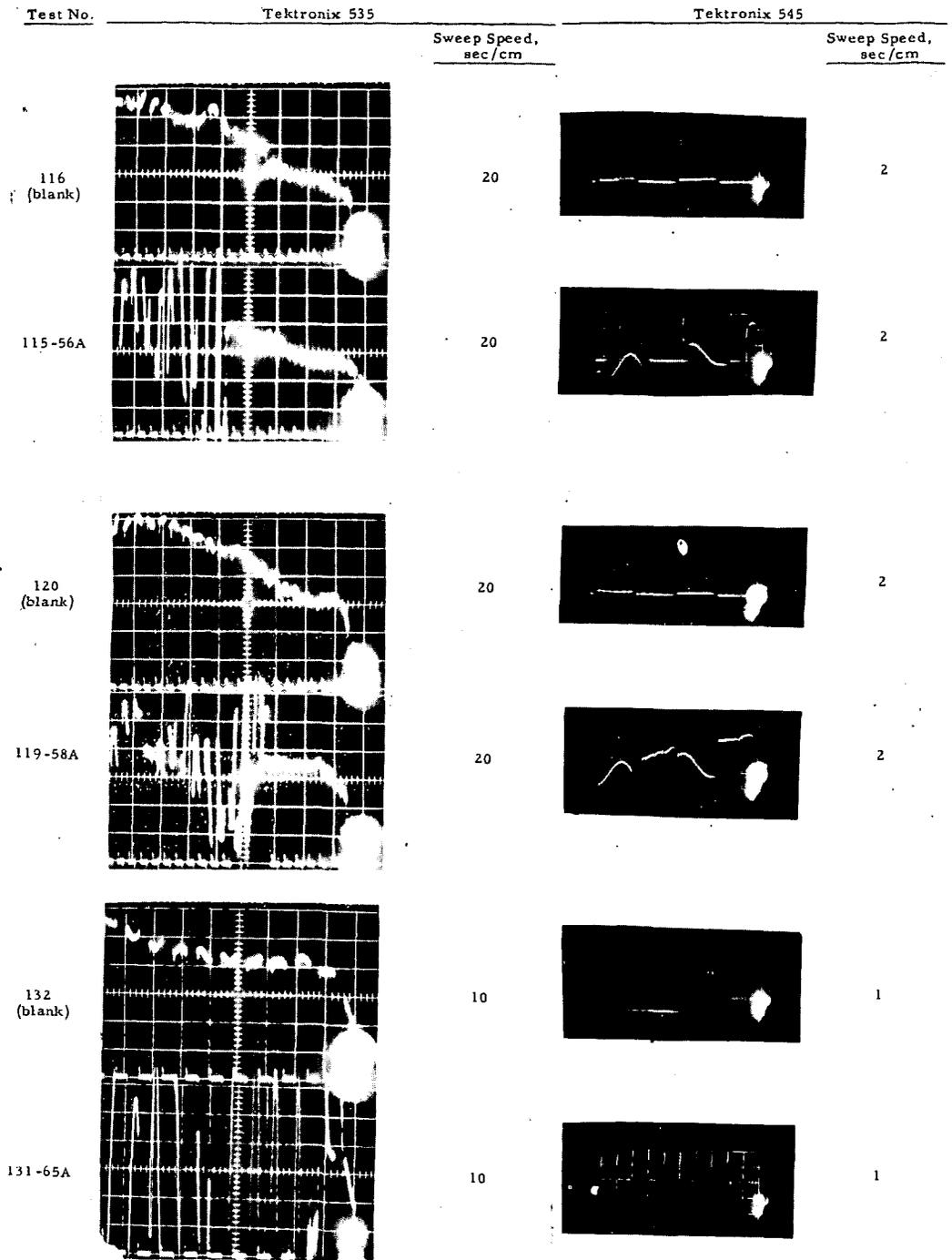


Fig. 3 Photographs of Pressure-Voltage Transients in Shock Tube Testing

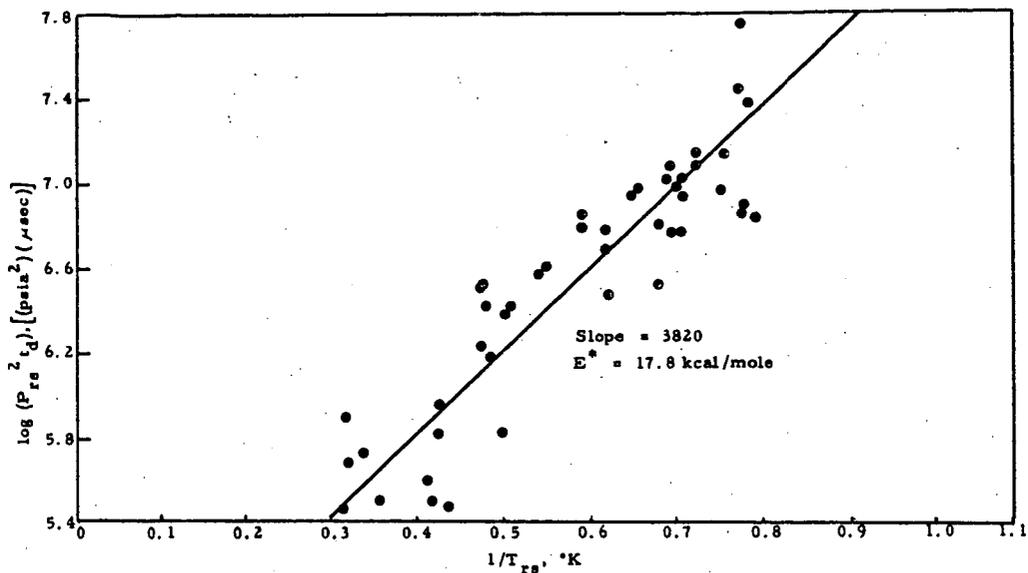


Fig. 4  $\log(P_{rs}^2 t_d)$  as a Function of  $1/T_{rs}$  for Shock Test Data Obtained with Unpressed Lead Azide and Nitrogen

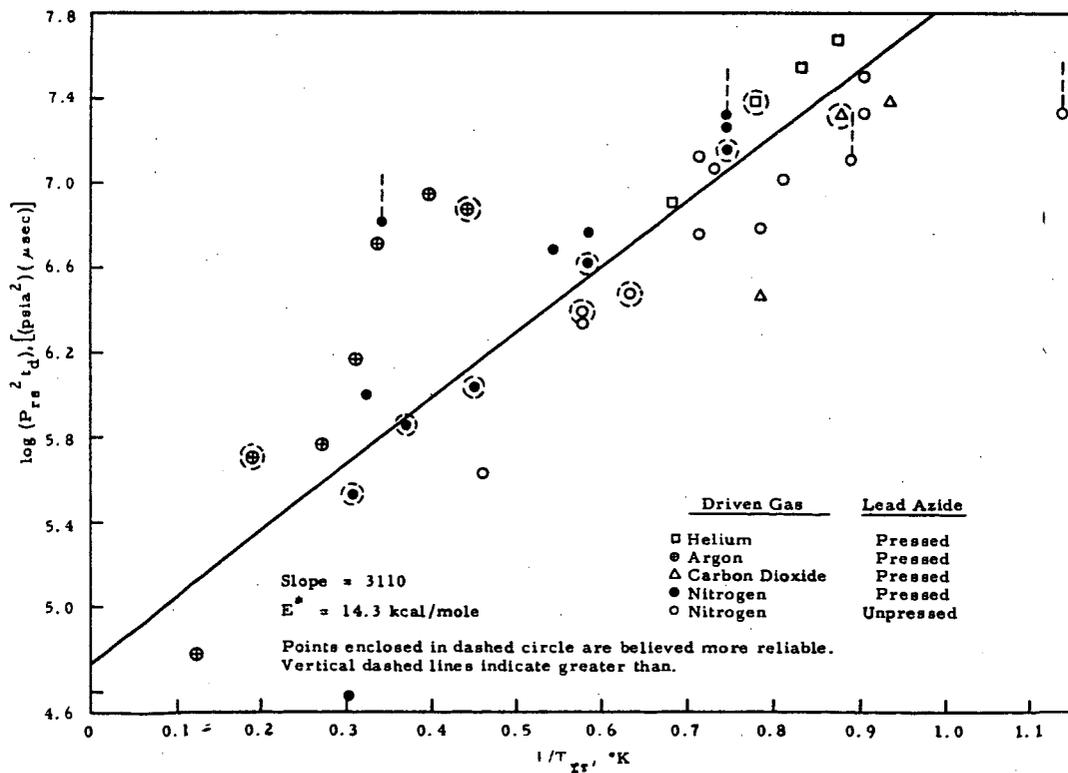


Fig. 5  $\log(P_{rs}^2 t_d)$  as a Function of  $1/T_{rs}$  for Shock Test