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AN ANALYSIS OF SMALL SCALE GAP TEST SENSITIVITY DATA USING POROSITY THEORY AND NONREACTIVE SHOCK HUGONIOTS

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WHITE OAK LABORATORY

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BY
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An analysis was performed of Small Scale Gap Test (SSGT) sensitivity data using nonreactive shock Hugoniots, and a recently developed concept which relates sensitivity to porosity. The basic idea of the concept is that detonation is achieved, regardless of porosity, when a critical thermal energy is induced into the explosive by shock. This analysis supports the validity of this notion, both for TATB-like explosives, for which it was conceived, and for other explosive materials as well.

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AN ANALYSIS OF SMALL SCALE GAP TEST SENSITIVITY DATA USING POROSITY THEORY AND NONREACTIVE SHOCK HUGONIOTS

The work leading to this report was done under the task "Explosion Initiation and Safety" SF33-354-314/18462. This report permits the use of small amounts of experimental data at one set of conditions, to generate critical sensitivity data over a broad spectrum of conditions. This information is of interest in safety and reliability studies and design of explosive systems.

The author acknowledges the work of Dr. D. J. Pastine and Dr. R. R. Bernecker in the development of the porosity theory without which the work reported here could not have been done.

J. W. Enig

J. W. ENIG
By direction

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I. INTRODUCTION AND BACKGROUND

The Small Scale Gap Test (SSGT)[1] is a method for indirectly determining the shock sensitivity of an explosive. In this test a shock is transmitted into an explosive through an attenuating barrier, a column of polymethyl-methacrylate (PMMA). The shock sensitivity is defined as that shock pressure required to initiate the detonation of the explosive 50% of the time.

The SSGT supplies information on the shock strength needed in the PMMA, at the PMMA/explosive interface, in order to detonate the explosive which is at some given initial porosity.

It would be more meaningful, however, to know, or to be able to calculate, the pressure in the explosive rather than in the attenuator. This can be done by the usual impedance matching technique if the appropriate Hugoniot equation of state is known for the explosive as well as for the attenuator. To obtain a nonreactive Hugoniot for the explosive, even at a single porosity, requires considerable time and experimental effort; to measure Hugoniots at a number of porosities is ordinarily economically unfeasible. It is therefore desirable that some method be available to generate from a single available nonreactive Hugoniot determined for an explosive at a given density (porosity), the Hugoniots at any other stated densities for that explosive. It would also be desirable, given the sensitivity of an explosive at some density, to be capable of predicting the sensitivity at any other stated density. It is just such a set of relationships that this report evaluates.

The theory, which is detailed elsewhere,[2] provides a method for computing the shock Hugoniots of explosives as a function of their initial porosities, provided one Hugoniot at a stated porosity is known. This allows one to compute from SSGT data, by impedance matching, the pressure transmitted into the explosive by the PMMA, since the Hugoniot for PMMA is available. The procedural technique for making the calculation is detailed in Appendix A. In addition, the concept provides a set of equations relating the shock pressure within the explosive to the thermal energy density, E_t, immediately behind the shock wave. For a given explosive and test configuration, E_t by the concept is constant at the 50% initiation point. The equations which relate to the evaluation of E_t are given in Appendix B. In Table 1 are listed the values of

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[1] J. N. Ayres, L. J. Montesi, and R. J. Bauer, "Small Scale Gap Test (SSGT) Data Compilation: 1959-1972 Volume I Unclassified Explosives," NOLTR 73-132, 26 Oct 1973.

[2] D. J. Pastine, R. R. Bernecker, and R. J. Bauer, "Theoretical Relationship between Initiating Shock Pressure and Porosity in Secondary Explosives," Fourth International Conference on High Pressure (AIRAPT), 25-29 Nov 1974, in Kyoto, Japan, to be published in the proceedings.

E_t calculated from the critical initiation pressures, P_c. The listed porosity, p, was calculated as $p = 1 - \rho/\rho_{TMD}$, where ρ is the initial explosive density and ρ_{TMD} is the theoretical maximum (voidless) density (TMD) of the explosive. The significance of the results in the table are discussed below.

It is emphasized that the porosity/sensitivity concept requires at least one experimental sensitivity datum point and one nonreactive Hugoniot equation of state for the explosive before it can be applied.

II. OBJECTIVES OF THIS PROGRAM

The purposes of this program of analysis were three-fold:

(a) to determine the validity of the recently developed porosity concept[2] derived for TATB-like explosives when used in the SSGT,

(b) to determine whether this concept could be extended to other explosives, and

(c) to predict the sensitivity of a given explosive at any density from 60% of the theoretical maximum density up to the TMD with a minimum of experimental data.

The explosives discussed in this report are: PETN, TNT, DATB, TATB, DATB/Zytel 95/5, and DATB/Zytel 90/10. The required Hugoniot equations of state were obtained as follows: for PETN from reference 3; for TNT, DATB, and TATB from reference 4; the values for DATB/Zytel mixtures were assumed to be the same as for DATB alone. The SSGT values were obtained from reference 1. Using equations A-1, A-5, and B-1, E_t was calculated for each explosive at each porosity. The calculated critical pressures, particle velocities, and thermal energies required for initiation of these explosives are given in Table 1 along with the loading pressures and calculated densities and porosities of the explosives. The calculated values of E_t for each explosive were examined and it was found that E_t is in fact approximately a constant for each explosive for all observed porosities. E_t was then averaged for each explosive and, using the relationships given in Appendix B, the critical initiation pressure as a function of porosity was calculated and plotted for each explosive. These plots are shown in Figures 1 through 6.

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[3] J. Roth, "Shock Sensitivity and Shock Hugoniots of High Density Granular Explosives," Fifth Symposium on Detonation, 18-21 Aug 1970.

[4] N. L. Coleburn and T. P. Liddiard, Jr., "Hugoniot Equations of State of Several Unreacted Explosives," J. Chem. Phys., 44, 5, 1 Mar 1966.

III. DISCUSSION AND CONCLUSIONS

The theoretical predictions of the critical pressures were in good agreement with experimental results with certain exceptions. These exceptions are discussed below. The agreement of theoretical and experimental values for the plots is within 10%. For some explosives, the agreement is much better than this.

There are a number of possible sources of error, any one of which could be responsible for the disagreement between the theoretical and experimental values for the critical pressure:

(a) Errors in determining the density of the explosive would have a significant effect on the critical pressure, especially at densities near the TMD.

(b) Batch-to-batch variation in particle size and chemical purity could cause batch-to-batch variation in sensitivity.

(c) The nonreactive Hugoniots were measured at low values of particle velocity and linearized. The true nonreactive Hugoniot is, however, nonlinear. Unfortunately, the sparsity of relevant data makes it difficult to determine the amount of nonlinearity. It would, however, have some effect on the critical pressure.

(d) The porosity concept assumes a uniform distribution of voids. As the porosity goes to zero in certain explosives, this assumption becomes less and less valid. The nonuniform distribution of voids causes the sensitivity to decrease; that is, the actual critical pressure is significantly greater than the predicted value. This problem is demonstrated on the TNT curve, for porosities less than 0.017.

For TATB at porosities above 0.075, the predictions are good, but at lower values of porosities (higher densities), the curve differs significantly from experimental values. Since the porosity concept had been developed for TATB and the only material which did not have good predictability in the SSGT was TATB, an apparent contradiction existed.

The available SSGT calibration curve relating pressure to barrier thickness is linear for barrier thicknesses greater than 2.5 mm. It is non-linear and not well defined for lesser thicknesses. Unfortunately, the barrier thicknesses for the 50% functioning points of TATB at the densities of 1.840 and 1.887 (Table 1) were smaller than 2.5 mm. Thus, the estimate of the critical pressure at these two densities was subject to considerable error and is most likely the cause of the poor agreement found at these densities.

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[5] D. Price and T. P. Liddiard, Jr., "The Small Scale Gap Test: Calibration and Comparison with the Large Scale Gap Test," NOLTR 66-87, 7 Jul 1966.

On the basis of the good agreement between the theoretical prediction of the critical pressure and the experimental data, and the fact that the few differences can be reasonably explained, these studies support the validity of the recently developed porosity concept for most secondary explosives. It is also apparent from the fit of the critical pressure versus porosity curve of Figures 5 and 6 that the concept holds true for explosive compositions desensitized with nonreactive materials, e.g., binders, lubricants, pelletizing agents.

Previously, to estimate the SSGT shock sensitivity of an explosive material at a density other than at a testing value, one would interpolate or extrapolate the data from the two closest points or from a curve fitted to all of the available data. These methods are not based on the operative hydrodynamic and thermodynamic parameters, and are therefore of questionable accuracy.

The porosity/sensitivity concept, on the other hand, enables us to generate other Hugoniot equations of state and to predict sensitivities using a single Hugoniot and a single sensitivity point. These latter values are often available for many explosives. This method has a distinct advantage because no further interpolation or extrapolation of the data is necessary, and one has a much greater degree of confidence in the result than can be obtained from the SSGT data alone.

To make estimates of explosive system reliability and/or safety, one must know the critical pressure required to initiate the explosive. Since the material we are to initiate is the explosive, it is more useful to know the critical pressure in the explosive than the critical pressure in the PMMA attenuator of the SSGT. Utilization of the porosity/sensitivity concept permits the computation of the desired parameter--the critical pressure in the explosive--if one Hugoniot equation of state at a given porosity is available.

The porosity concept appears applicable to desensitized explosive compositions. It would be valuable to have a theoretical relationship between the percentage of diluent in the composition and the critical thermal energy. One possible approach would be to treat the diluent as "solid holes". This work would complement the current concept.

TABLE 1 POROSITY/SENSITIVITY DATA

Explosive	Loading Pressure (kpsi)	Density (gm/cc)	Porosity	P_c (Kbar)	U_p (mm/μsec)	E_t (Joules/mm^3)	Notes
PETN	4	1.355	.2388	4.98	.2954	.07844	
	8	1.440	.1910	5.11	.2605	.06576	
	8	1.499	.1579	4.20	.2023	.04397	
	16	1.576	.1146	6.71	.2384	.05866	
	16	1.600	.1011	6.61	.2219	.05198	
	32	1.681	.0556	9.88	.2497	.05991	
	32	1.708	.0404	11.35	.2620	.06284	
	64	1.775	.0028	20.13	.3663	.10833	
					Average	.06022	
TNT	4	1.353	.1805	14.58	.5144	.15939	
	6	1.386	.1605	12.34	.4404	.11786	
	7	1.413	.1442	16.79	.5118	.15338	
	8	1.466	.1121	18.24	.4945	.13634	
	11	1.489	.0981	20.21	.5087	.13901	
	16	1.549	.0618	24.47	.5211	.12739	
	19	1.561	.0545	26.91	.5455	.13478	
	19	1.568	.0503	27.63	.5489	.13344	
	32	1.623	.0170	35.35	.5936	.12550	
	64	1.651	.0000	57.02	.8057	.24087	
					Average	.13634	

NOTES: * Items not used in computing average

TABLE 1 POROSITY/SENSITIVITY DATA (Continued)

Explosive	Loading Pressure (kpsi)	Density (gm/cc)	Porosity	P_c (Kbar)	U_p (mm/μsec)	E_t (Joules/mm^3)	Notes
DATB	4	1.231	.3310	23.56	.8711	.48217	
	4	1.233	.3299	23.78	.8740	.48588	
	4	1.255	.3179	23.93	.8573	.47257	
	8	1.339	.2723	29.61	.8889	.52534	
	8	1.365	.2582	28.18	.8400	.47227	
	10	1.455	.2092	34.83	.8653	.50684	
	13	1.442	.2163	35.26	.8842	.52929	
	16	1.514	.1772	37.48	.8476	.48327	
	16	1.518	.1750	36.26	.8265	.45886	
	16	1.655	.1005	54.46	.9160	.52811	
	32	1.662	.0967	51.56	.8757	.47638	
	32	1.665	.0951	51.23	.8687	.46694	
	32	1.676	.0891	54.00	.8881	.48418	
	32	1.738	.0554	63.39	.9179	.48125	
	37	1.701	.0755	56.64	.8896	.47217	
	50	1.732	.0587	64.14	.9322	.50314	
	64	1.763	.0418	76.69	1.0155	.58709	*
	64	1.775	.0353	74.30	.9790	.52708	
					Average	.49151	
TATB	4	1.519	.2130	43.19	.9427	.67332	
	8	1.645	.1477	60.06	1.0061	.77597	
	8	1.727	.1052	83.29	1.1276	.97953	
	16	1.762	.0870	93.21	1.1647	1.04023	
	32	1.840	.0466	142.47	1.3989	1.55119	*
	64	1.887	0223	312.80	2.1643	4.40774	*
					Average	.86724	

NOTES: * Items not used in computing average

TABLE 1 POROSITY/SENSITIVITY DATA (Continued)

Explosive	Loading Pressure (kpsi)	Density (gm/cc)	Porosity	P_c (Kbar)	U_p (mm/μsec)	E_t (Joules/mm^3)	Notes
DATB/ZYTEL 95/5	4	1.192	.3522	28.26	1.0041	.62939	
	4	1.210	.3424	28.79	.9969	.62656	
	8	1.358	.2620	37.04	.9945	.66317	
	8	1.366	.2576	37.02	.9862	.65321	
	16	1.529	.1690	48.86	.9845	.65507	
	16	1.534	.1663	46.60	.9504	.60806	
	32	1.657	.0995	59.42	.9681	.59441	
	32	1.661	.0973	65.32	1.0258	.67290	
					Average	.63785	
DATB/ZYTEL 90/10	4	1.167	.3658	30.23	1.0687	.70449	
	8	1.342	.2707	38.76	1.0380	.72066	
	16	1.512	.1783	52.58	1.0493	.75063	
	32	1.617	.1212	64.60	1.0691	.75727	
	64	1.676	.0691	77.69	1.1307	.82780	
					Average	.75217	

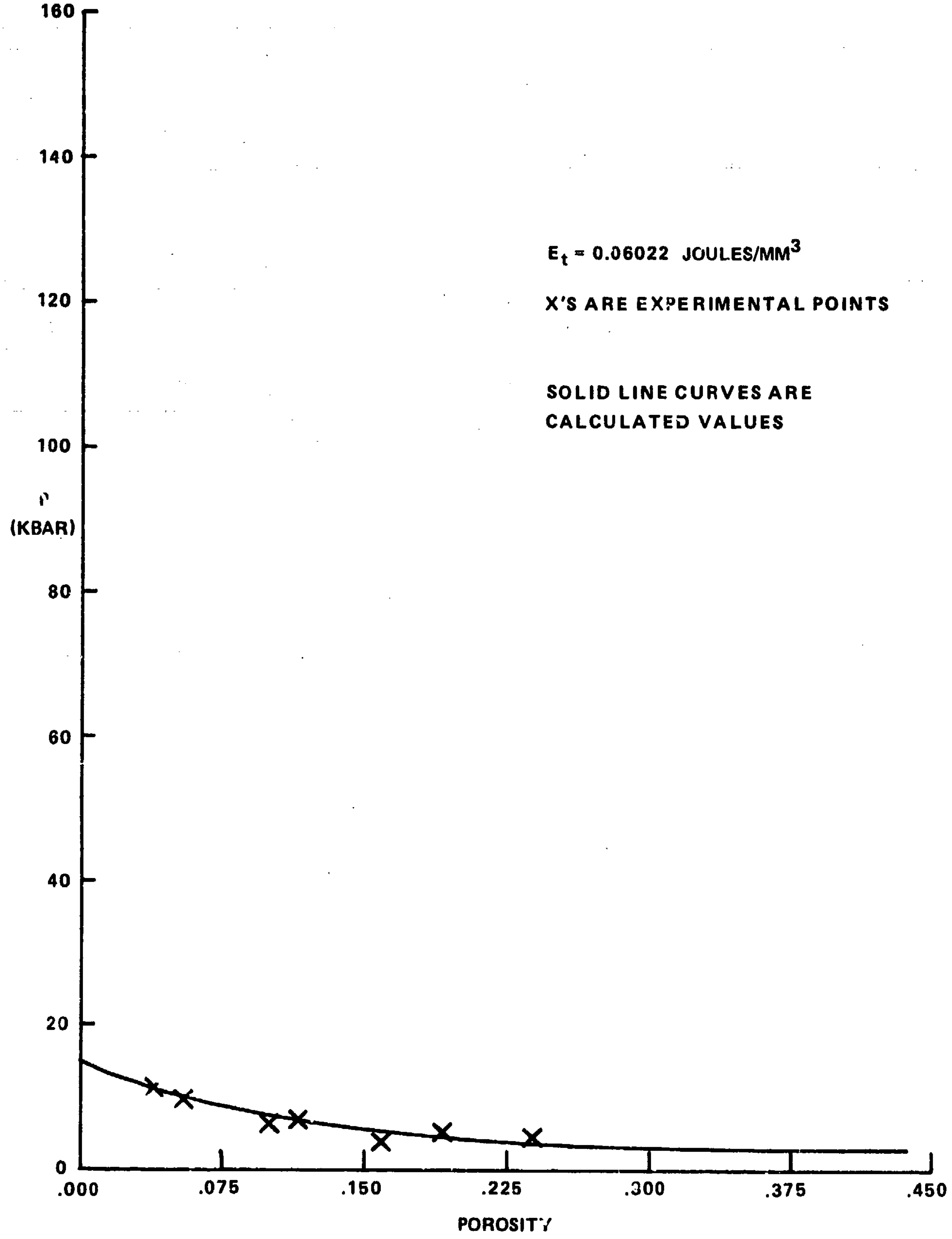

FIG. 1 SENSITIVITY VS POROSITY CURVE FOR PETN

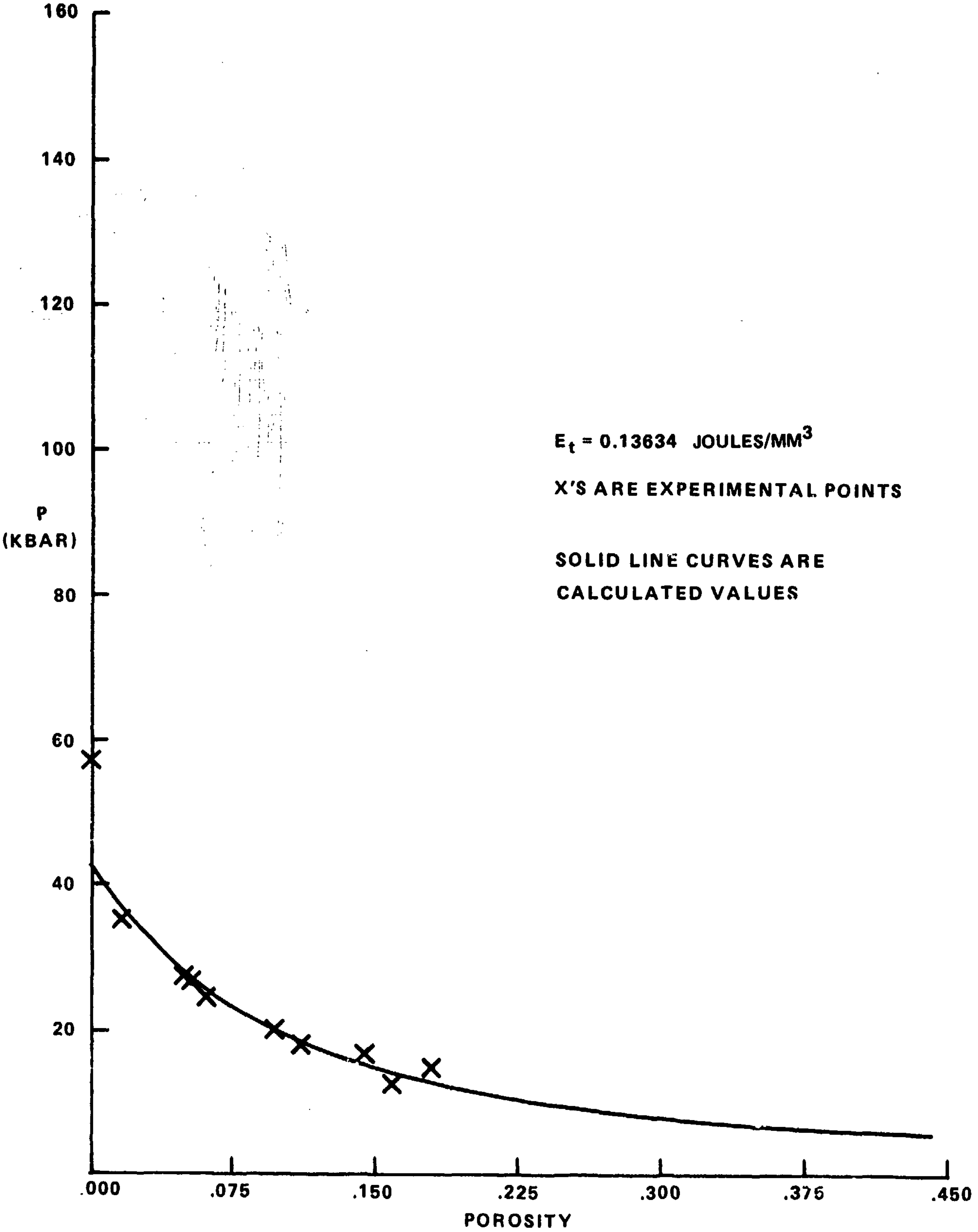

FIG. 2 SENSITIVITY VS POROSITY CURVE FOR TNT

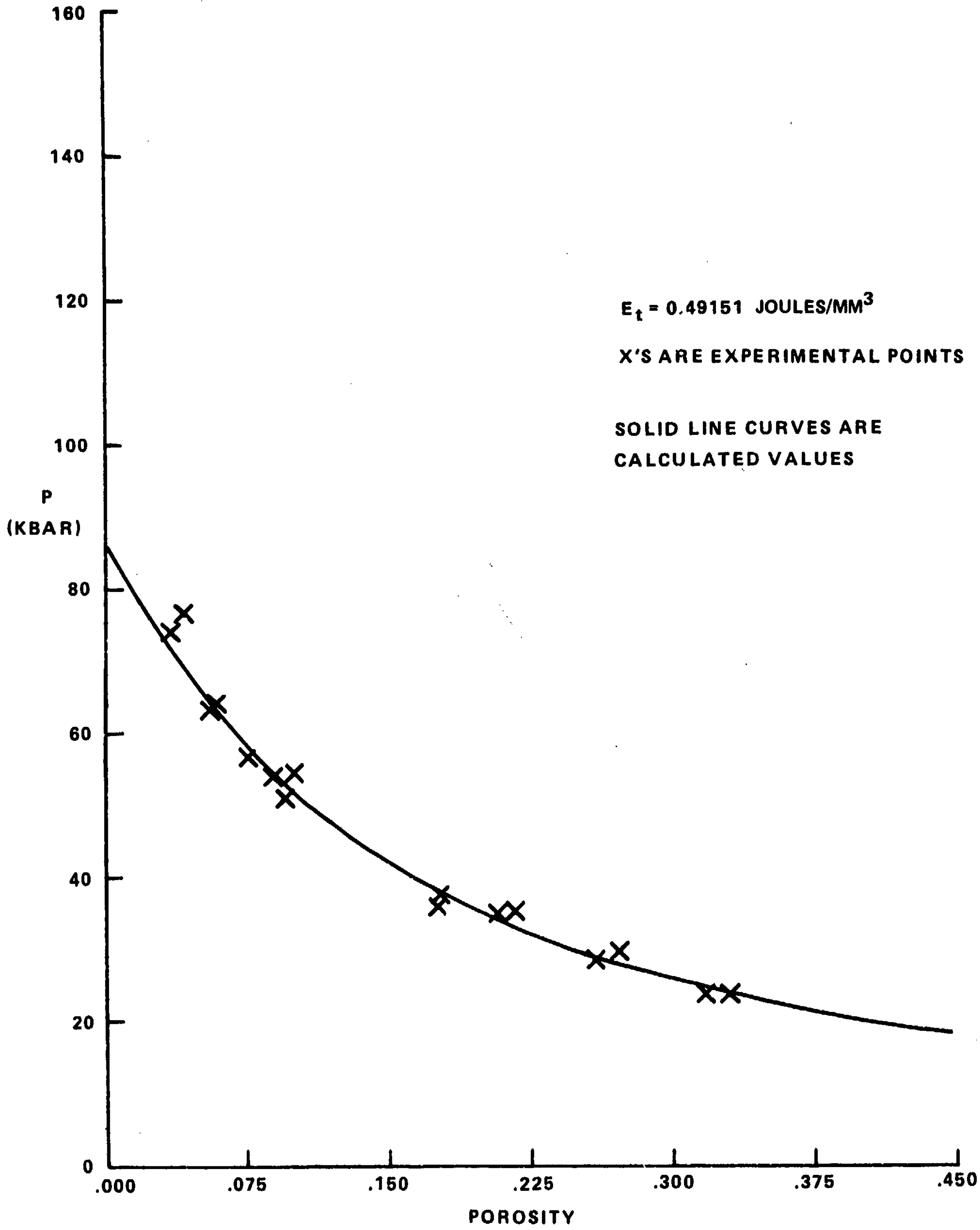

FIG. 3 SENSITIVITY VS POROSITY CURVE FOR DATB

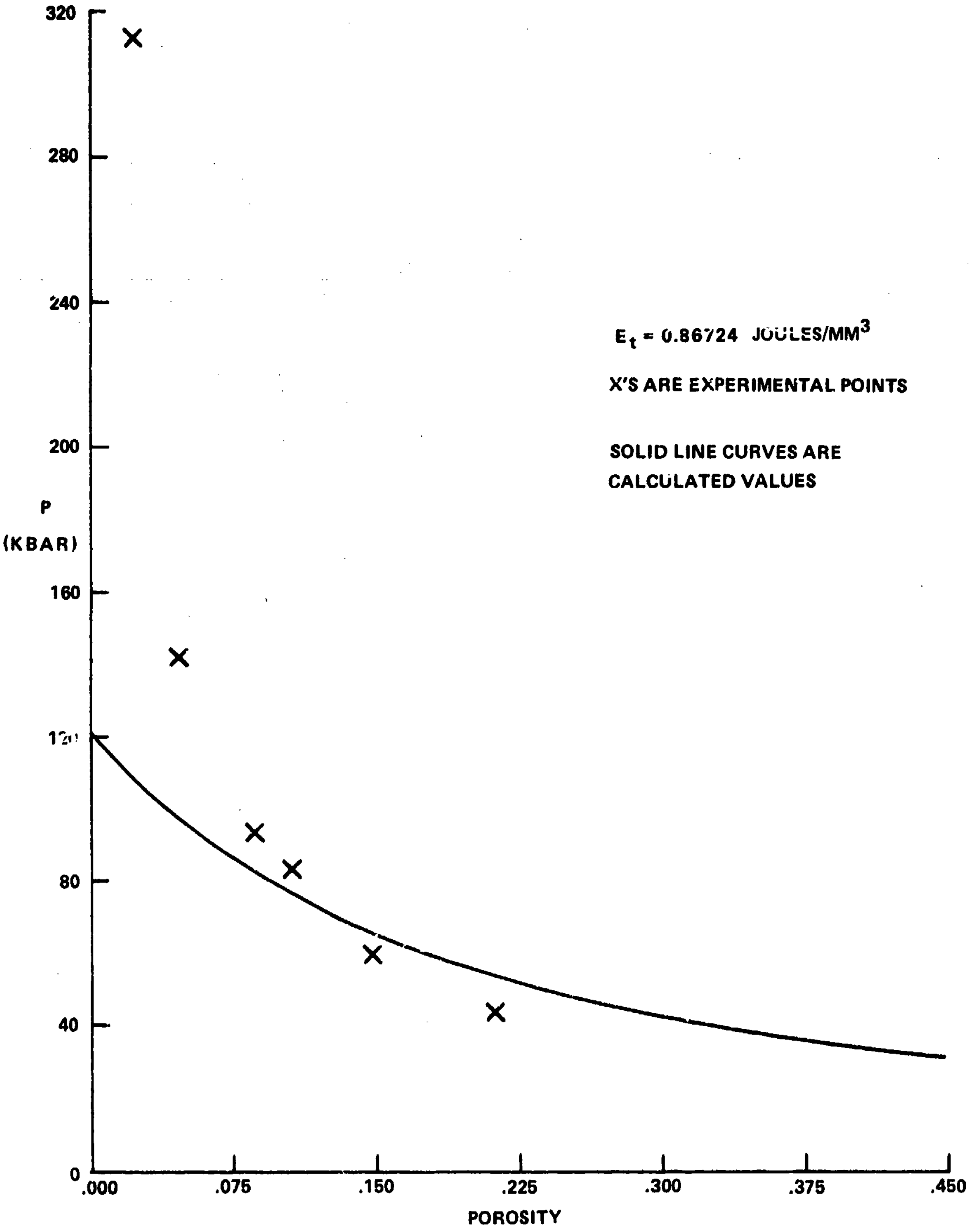

FIG. 4 SENSITIVITY VS POROSITY CURVE FOR TATB

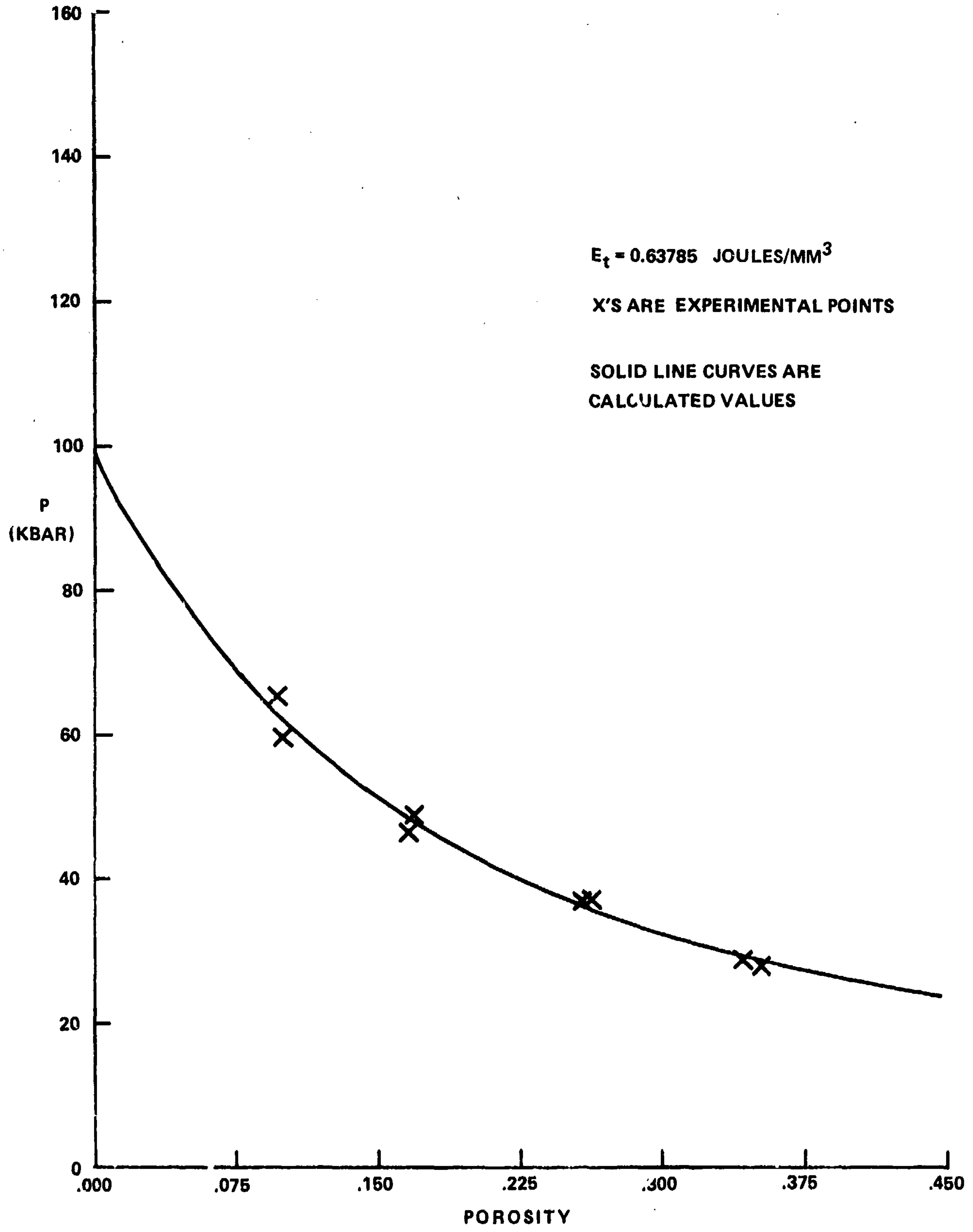

FIG. 5 SENSITIVITY VS POROSITY CURVE FOR DATB/ZYTEL 95/5

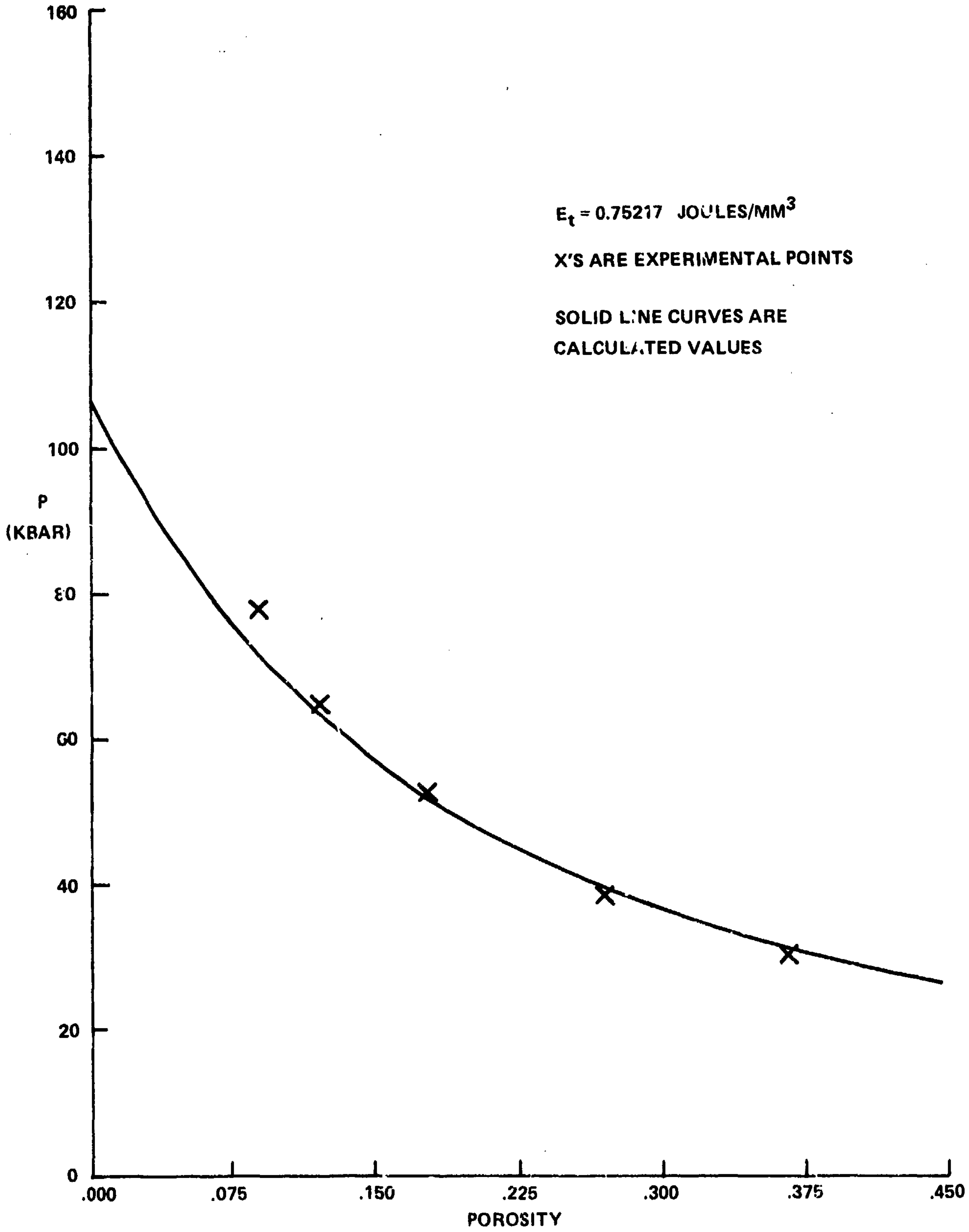

FIG. 6 SENSITIVITY VS POROSITY CURVE FOR DATB/ZYTEL 90/10

APPENDIX A

CALCULATION OF SHOCK HUGONIOTS

1. The nonreactive shock Hugoniot for some given secondary explosive at a particular density is calculated according to the porosity concept[A-1] in the following way:

$$u_p^2(P,p) + u_p^2(P,0) + \frac{P}{2\rho_{TMD}} \frac{p}{1 - p} \tag{1}$$

where u_p is the particle velocity of the explosive,

P is the pressure in the explosive,

p is the porosity of the explosive, and

ρ_{TMD} is the theoretical maximum density (TMD) of the explosive.

$$U_s = C + Bu_p \tag{2}$$

and

$$P = \rho_o u_p U_s . \tag{3}$$

where U_s is the shock velocity in the explosive, C and B are the constants of the linearization equation (C being the sound speed intercept and B, the slope) and ρ_o is the density at which the nonreactive shock Hugoniot was determined.

2. Inserting equation (2) into (3) and solving for u_p^2, we obtain,

$$u_p^2(P,p_o) = \frac{1}{2} \frac{C^2}{B^2} \left[1 + 2 \frac{PB}{\rho_o C^2} - \sqrt{1 + 4 \frac{PB}{\rho_o C^2}} \right] , \tag{4}$$

where p_o is the porosity associated with ρ_o, by

$$p_o = 1 - \rho_o/\rho_{TMD} .$$

Inserting equation (4) into (1), substituting p_o for p, and solving for $u_p^2(P,0)$, we get

---

[A-1] D. J. Pastine, R. R. Bernecker, and R. J. Bauer, "Theoretical Relationship between Initiating Shock Pressure and Porosity in Secondary Explosives," published in the Proceedings of the Fourth International Conference on High Pressure (AIRAPT), Kyoto, Japan, Mar 1975.

$$u_p^2(P,0) = \frac{1}{2}\frac{C^2}{B^2}\left[1 + 2\frac{PB}{\rho_o C^2} - \sqrt{1 + 4\frac{PB}{\rho_o C^2}}\right] + \frac{P}{2\rho_{TMD}}\,\frac{p_o}{1 - p_o} \quad . \qquad (5)$$

With equation (5), equation (1) may be solved for any porosity.

3. We now make use of shock impedance matching theory[A-2] to solve for the critical pressure in DATB at a density of 1.775 gm/cc: ρ_{TMD} = 1.84 gm/cc,[A-3] B = 1.892,[A-4] C = 2.449 mm/μsec,[A-4] ρ_o = 1.780 gm/cc,[A-4] p_o = 0.0326, and p = 0.353. Inserting these numbers into equations (1) and (5) and plotting P as a function of u_p, we get the solid line in Figure A-1.

The Hugoniot equations for PMMA are:[A-5]

$$P = \rho u_p U_s \qquad (6)$$

$$U_s = \begin{cases} 2.7228 + 4.0667u_p - 10.9051u_p^2 + 10.6912u_p^3, & (7) \\ \qquad \text{for } 0.03\ \text{mm/μsec} < u_p < 0.5363\ \text{mm/μsec} & \\ 2.561 + 1.595u_p, \text{ for } u_p > 0.5363\ \text{mm/μsec} & (8) \end{cases}$$

where P is the pressure in the PMMA,

U_s is the shock velocity in the PMMA,

u_p is the particle velocity in the PMMA, and

ρ is the original density of the PMMA (1.185 gm/cc).

Plotting P as a function of u_p we get the dashed line in Figure A-1.

At a density of 1.775 gm/cc, the SSGT sensitivity of DATB is 8.882 DBg,[A-3] which corresponds to a shock pressure of 60.22 Kbar in the PMMA.[A-6] A PMMA Hugoniot reflected about the vertical line passing through 60.22 Kbar on the PMMA Hugoniot is shown in Figure A-1.

[A-2] G. E. Duvall and G. R. Fowles, "Shock Waves," High Pressure Physics and Chemistry, 2, Chapter 9, Academic Press, 1963.

[A-3] J. N. Ayres, L. J. Montesi, and R. J. Bauer, "Small Scale Gap Test (SSGT) Data Compilation: 1959-1972 Volume I Unclassified Explosives," NOLTR 73-132, 26 Oct 1973.

[A-4] N. L. Coleburn and T. P. Liddiard, Jr., "Hugoniot Equations of State of Several Unreacted Explosives," J. Chem. Phys., 44, No. 5, 1 Mar 1966.

[A-5] J. O. Erkman, D. J. Edwards, A. R. Clairmont, Jr., and D. Price, "Calibration of the NOL Large Scale Gap Test; Hugoniot Data for Polymethyl Methacrylate," NOLTR 73-15, 4 Apr 1973.

[A-6] D. Price and T. P. Liddiard, Jr., "The Small Scale Gap Test: Calibration and Comparison with the Large Scale Gap Test," NOLTR 66-87, 7 Jul 1966.

The reflected PMMA Hugoniot intersects the nonreactive shock Hugoniot for DATB at 1.775 gm/cc at a pressure of 74.30 Kbar and a u_p of 0.979 mm/μsec.

These are respectively the critical pressure and critical particle velocity of DATB at an original density of 1.775 gm/cc. This result was obtained by a graphical solution in Figure A-1, but was performed by a computer program as an iterative solution.

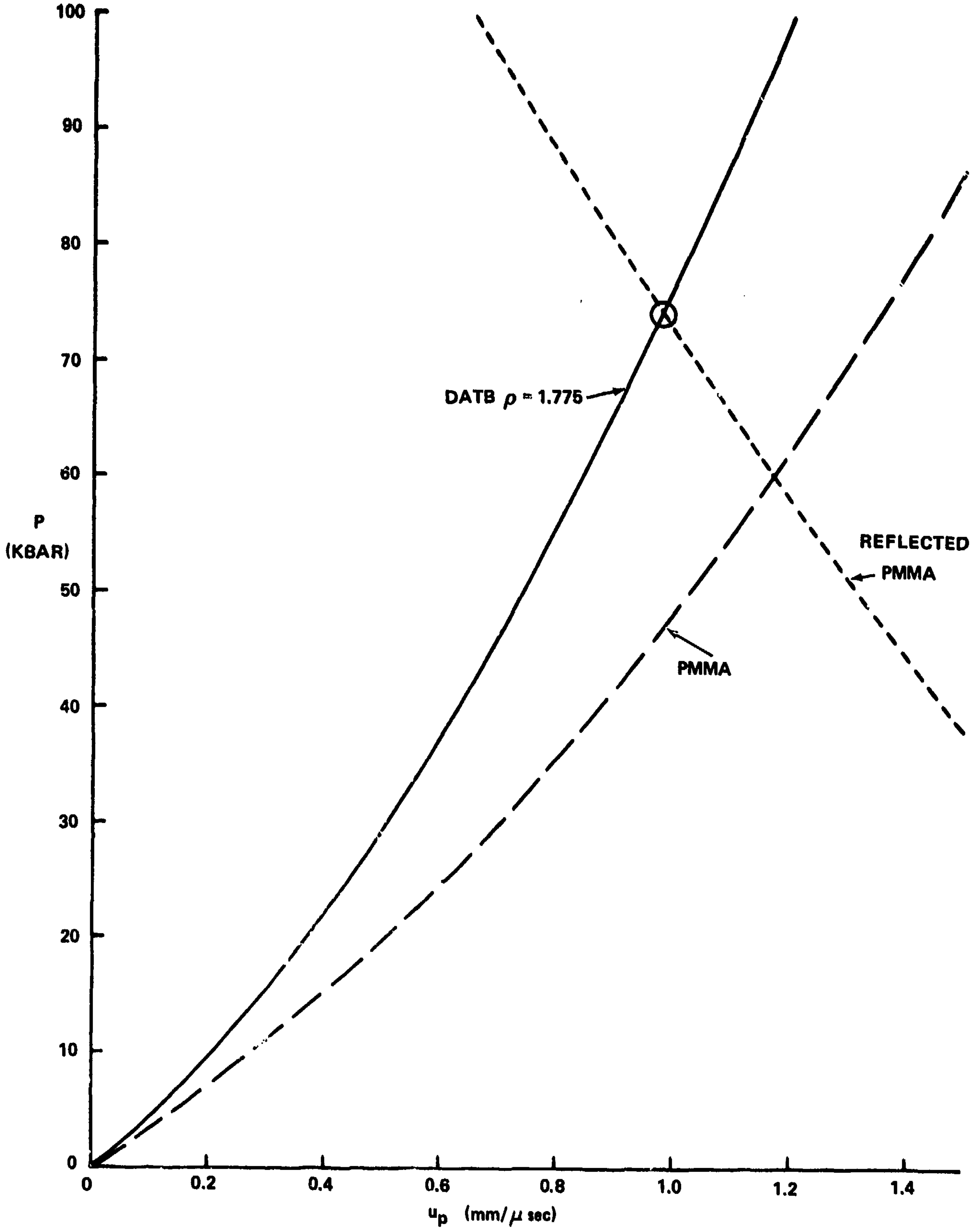

FIG. A–1 HUGONIOT–MATCHING PLOTS

APPENDIX B

CALCULATION OF CRITICAL ENERGY DENSITIES

The specific critical thermal energy per unit volume is calculated with the relation,

$$E_t = \frac{\rho_{TMD} C^2}{1-\eta} \left\{ \frac{\Pi\eta}{2(1-\eta B)^2} + \frac{\eta^2}{2(1-\eta B)^2} - \frac{1}{B^2}\left[(1-\eta B)^{-1} + \ln(1-\eta B) - 1 \right] \right\} \quad (1)$$

where E_t is the critical thermal energy per unit volume,

Π is a function of porosity: $\Pi = p/(1-p)$,

η is a function of the specific volume behind the initiating shock wave:

$\eta = 1 - v/v_i$,

$v_i = 1/\rho_{TMD}$,

p is the initial porosity (the fraction of the initial volume which consists of holes, and

B and C are as defined in the text.

For the example of the DATB at a density of 1.775 gm/cc, E_t is 0.52708 Joules/mm^3.

To generate the critical pressure versus porosity plots, we made use of the following equation:

$$\Pi = \frac{2(1-\eta B)^2}{\eta} \left\{ \frac{\bar{E}_t v_i (1-\eta)}{C^2} - \frac{\eta^2}{2(1-\eta B)^2} + \frac{1}{B^2}\left[(1-\eta B)^{-1} + \ln(1-\eta B) - 1 \right] \right\} \quad (2)$$

where $\bar{E}_t$ is the average critical thermal energy per unit volume for a given explosive (except for the asterisked items in the "Notes" column of Table 1).

Equation (2) relates the porosity to the specific volume behind the initiating shock wave. In order to relate the porosity to the critical pressure, the latter volume was used to find the associated shock pressure by means of the theoretically determined shock Hugoniot for the porosity under consideration.