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AN INVERSE ANALYSIS OF
ELECTROTHERMAL-CHEMICAL (ETC) GUN
EXPERIMENTAL DATA

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An inverse analysis is presented as one method of assessing ballistic control exhibited in electrothermal-chemical (ETC) experimental gun firings. The analysis attempts to determine the decomposition or gas generation rate necessary to satisfy an energy balance equation as gleaned from available experimental data. The apparent functional relationship between the electrical energy input and working fluid mass consumed is examined. As applied in this report, the inverse analysis of ETC gun firing data is essentially an energy balance between projectile kinetic energy, gas kinetic energy, and gas internal energy. Lagrange assumptions are made for the pressure gradient and gas velocity. Thermochemistry is assumed to be variable depending on the plasma energy to working fluid mass ratio. A sample database consisting of 20-mm and 30-mm gun firings is examined.

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1. INTRODUCTION

The electrothermal-chemical (ETC) gun, generically shown in Figure 1, is a propulsion concept which utilizes a low mass, high energy plasma to initiate and, hopefully, control the combustion/vaporization of the working fluid (propellant) during the ballistic cycle. Controlling combustion (exothermic working fluid) or vaporization (endothermic working fluid) of the working fluid in the ETC gun is necessary in order to tailor the pressure-time profile in the gun. Theoretically, tailoring the pressure-time profile to obtain a "flatter" and extended pressure curve should result in enhanced performance (increased muzzle energy) and provide a "softer" launch environment to enhance projectile integrity, especially for "smart" projectiles. In addition, precise control of the pressure history should also allow for the required projectile velocity repeatability required of indirect fire support (artillery) applications.
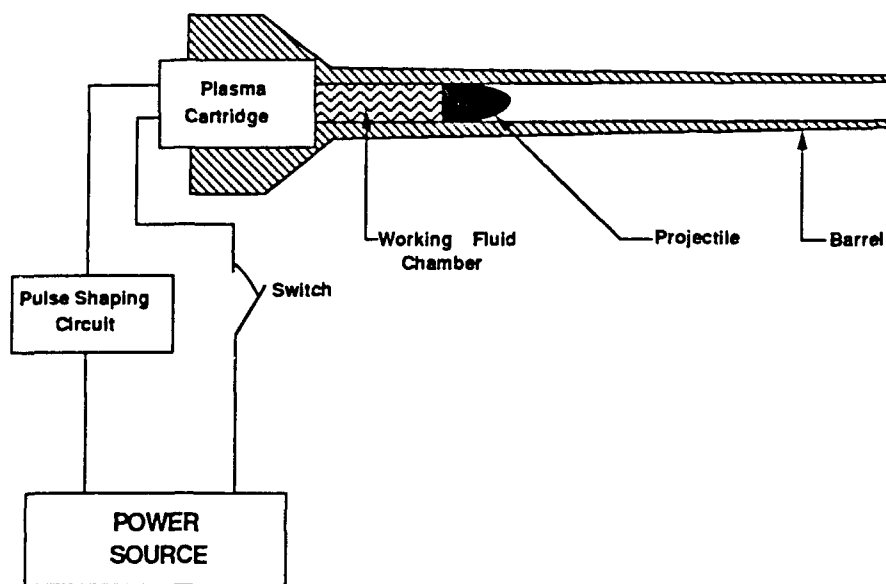
Figure 1. <u>Schematic of ETC Gun.</u>

One method of assessing the control exerted by the plasma on the combustion/vaporization process is through the use of an inverse analysis which computes the decomposition or gas generation rate of the working fluid given experimental measurements of pressure, projectile motion, and plasma energy histories as an input to the model. If the plasma is controlling the process, then the inverse analysis should show decomposition rates to be a "strong" function of the plasma input (plasma energy-time input).

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To illustrate the method, an inverse analysis of 20-mm and 30-mm ETC firings using an exothermic working fluid is presented. The objective is to ascertain to what extent these experimental ETC firings indicate control of the working fluid combustion by the plasma energy input to the gun. The results of the inverse analysis for these data sets are viewed as qualitative since the experimental measurements are not precise; for example, the projectile position is not accurately known from the experimental data.

2. MODEL DESCRIPTION

The derivation is traditional (Hunt 1951). At any given time, let Q be the total energy available, U the internal energy of the gas, and W the work performed by the gas. Then

$$Q = U + W + Losses . \tag{1}$$

A number of estimates exist for calculating losses due to heat loss, recoil, projectile resistance, projectile rotational energy, shocked air ahead of the projectile and energy in compression of the working fluid. In small caliber guns, heat loss can be significant. However, in the current implementation for a qualitative comparison between a number of small caliber shots, losses are assumed to be similar in each firing. Thus, the "losses" term is taken to be zero.

The total available energy at the time in which a fraction $z(t)$ of a total charge mass C has been burnt in a closed vessel is

$$Q = Cz(t) \int_{T_{ref}}^{T_o} c_v(T) dT \tag{2}$$

where c_v is the specific heat at constant volume of the gases at any temperature T, T_o is the flame temperature and T_{ref} is a reference temperature. Since only changes of energy will be considered, the actual value for T_{ref} is not significant.

Since work is performed in the gun, the gas temperature T is less than the flame temperature T_o, and the internal energy is given by

$$U = Cz(t) \int_{T_{ref}}^{T} c_v(T) \, dT \ . \tag{3}$$

The work performed by the gas is the kinetic energy of the projectile and kinetic energy of the gas. The kinetic energy of the projectile at any time is

$$KE(projectile) = \frac{1}{2} m v_p^2(x,t) \tag{4}$$

where $v_p(x,t)$ is the projectile velocity and m is the projectile mass.

The kinetic energy of the gas, KE(gas), is determined in a similar manner. However, since both the velocity and mass of gas can vary along the length of the gun,

$$KE(gas) = \frac{1}{2} \int_o^{x_p(t)} \rho(x,t) \, A(x) \, v_g^2(x,t) \, dx \tag{5}$$

where x_p is the projectile base position at time t, $\rho(x,t)$, $v_g(x,t)$ and $A(x)$ are respectively the fluid density, fluid velocity, and cross sectional area of the gun at position x.

To integrate Equation 5, the Lagrange assumption that the gas velocity $v_g(x,t)$ is linear from the breech at position 0.0 to the projectile base at x_p, with constant spatial density $\rho(t)$, that is,

$$v_g(x,t) = \frac{x}{x_p} v_p(t) \quad \text{and} \quad \frac{\partial \rho(x,t)}{\partial x} = 0 \tag{6}$$

is utilized. Then, assuming a constant area A for the gun, Equation 5, upon substitution of Equation 6, becomes

$$KE(gas) = \int_o^{x_p(t)} \frac{1}{2} \rho(t) A \left(\frac{x}{x_p(t)} v_p(t) \right)^2 dx \tag{7}$$

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$$= \frac{1}{2} \rho(t) A \frac{v_p^2(t)}{x_p^2(t)} \int_o^{x_p(t)} x^2 \, dx \tag{8}$$

or,

$$= \frac{1}{6} \rho(t) \, A \, x_p(t) \, v_p^2(t) \tag{9}$$

$$KE\,(gas) = \frac{1}{6} C \, v_p^2(t) \tag{10}$$

assuming that the total charge is accelerated and uniformly distributed. Substituting Equations 2, 3, 4, and 10 into Equation 1,

$$Cz(t) \int_{T_{ref}}^{T_o} c_v(T) \, dT = Cz(t) \int_{T_{ref}}^{T} c_v(T) \, dT + \frac{1}{2} m v_p^2(t) + \frac{1}{6} C v_p^2(t) \tag{11}$$

or,

$$Cz(t) \int_{T}^{T_o} c_v(T) \, dT = \frac{1}{2} m v_p^2(t) + \frac{1}{6} C v_p^2(t) \ . \tag{12}$$

Assuming an average value of c_v in the temperature range, $T(t)$ to T_o yields

$$Cz(t) \, \overline{c_v} \, (T_o - T(t)) = \frac{1}{2} m v_p^2(t) + \frac{1}{6} C v_p^2(t) \ . \tag{13}$$

If $v_p(t)$ can be obtained experimentally, then Equation 13 has two unknowns, z and T. A Nobel-Able covolume equation of state,

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$$\overline{P(t)} \left(V_c + x_p(t) A - \frac{m_a}{\rho_a} - \frac{C(1-z(t))}{\rho_c(t)} - bCz(t) \right) = \frac{RT(t)}{MW} Cz(t) \quad , \tag{14}$$

provides a second condition on the system. In Equation 14, $\overline{P}(t)$ represents the space-mean pressure based on the Lagrange ballistic assumptions, V_c the original free chamber volume, $x_p(t)$ the projectile travel, A the cross-sectional area of the tube, m_a the mass of air in the chamber, ρ_a the density of air, $\rho_c(t)$ the working fluid or charge density which has been calculated from a compressible equation of state, b the covolume correction, R the universal gas constant, and MW the molecular weight of reaction products. The effect of air in the chamber, m_a / ρ_a, is included since ETC firings can have large initial ullage.

The equation of state for the unvaporized fluid is in the form (Gough 1989)

$$\rho_c(t) = \begin{cases} \rho_o \left(1 + \dfrac{(P(t) - P_o)}{K_1} \right) & \text{if } K_2 = 0 \\[4mm] \rho_o \left(1 + \dfrac{K_2}{K_1} (P(t) - P_o) \right)^{1/K_2} & \text{if } K_2 \neq 0 \end{cases} \tag{15}$$

where $P(t)$ is the breech pressure and ρ_o is the fluid density at the initial breech pressure P_o (ambient in these calculations) assuming that the bulk modulus, K_p, is at most a linear function of pressure,

$$K_p = K_1 + K_2 (P(t) - P_o) . \tag{16}$$

Using the standard definition of impetus, $I = \dfrac{RT_o}{MW}$, Equation 14 is solved for T.

$$T(t) = \frac{\overline{T_o P(t)} \left[V_c + x_p(t) A - \dfrac{m_a}{\rho_a} - \dfrac{C(1-z(t))}{\rho_c(t)} - bCz(t) \right]}{ICz(t)} . \tag{17}$$

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The average value of c_v is expressed as

$$\overline{c_v} = \frac{I}{T_o(\gamma - 1)} \quad (18)$$

where γ is the ratio of specific heats.

Substituting Equations 17 and 18 into Equation 13 and solving for $z(t)$ at any time yields

$$z(t) = \frac{\frac{1}{2}m v_p^2(t)\left(1 + \frac{1}{3}\frac{C}{m}\right) + \frac{\overline{P(t)}}{(\gamma - 1)}\left(V_c + x_p(t)A - \frac{m_a}{\rho_a} - \frac{C}{\rho_c(t)}\right)}{\frac{1}{(\gamma - 1)}\left(CI + \overline{P(t)}\left(bC - \frac{C}{\rho_c(t)}\right)\right)}. \quad (19)$$

Experimental data are utilized to solve Equation 19 directly for z by providing chamber pressure from which the space-mean pressure $\overline{P(t)}$ is calculated assuming a Lagrange gradient. Experimental projectile position, $x_p(t)$, is utilized not only to calculate the projectile velocity $v_p(t)$, but also to determine the gun volume at any time. The initial charge mass, C, the bore area, A, and the projectile mass, m, are determined from the experiment. Propellant density, $\rho_c(t)$, is calculated from Equation 15. It is noted that in the calculation, each timestep is independent of any other timestep. The specification of the thermochemical values (impetus I, ratio of specific heats γ, and covolume b) is discussed in detail below.

3. NUMERICAL APPROACH

As mentioned earlier, each time step is independent of any other time step. Thus, Equation 19 can be solved algebraically for $z(t)$. However, since impetus, I, ratio of specific heat, γ, and covolume, b, are functions of $z(t)$ (see Section 5), it is necessary to iterate several times. Basically, to compute $z_{n+1}(t)$ at time t_{n+1}, values for I, γ, and b at time t_n are used in Equation 19 to determine $z'_{n+1}(t)$. New values of I, γ and b are then determined based upon $z'_{n+1}(t)$ and used in Equation 19 to determine the next approximation, $z''_{n+1}(t)$ to $z_{n+1}(t)$. This process continues until successive approximations are within the derived tolerance.

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4. VALIDATION

In order to validate the inverse analysis, a 120-mm gun firing was simulated with a standard lumped parameter interior ballistic code, IBHVG2 (Anderson 1987) developed by the U.S. Army Ballistic Research Laboratory (BRL). The resulting IBHVG2 breech pressure history and projectile position were used as input to the inverse code. A comparison of the IBHVG2 calculation and the inverse analysis (ETINV) for mass consumed is shown in Figure 2. As can be seen, the inverse analysis accurately reproduces the time history of propellant mass burnt. However, as discussed elsewhere (Gough 1990), inaccuracies in the experimental data can lead to variability in the amount of mass burnt as determined by an inverse analysis. Thus, as discussed above, the inverse analysis is best viewed as a qualitative picture of the combustion process.

The ETC experimental database examined in this report consists of six 20-mm shots using titanium hydride and water, and three 30-mm shots using titanium hydride and water. All firings were performed at GT-Devices (Greig 1989), a subsidiary of General Dynamics Land Systems. A summary of the major physical parameters for the shots analyzed is shown in Table 1.

Table 1. Summary of 21-mm and 30-mm Initial Conditions

Tube Diameter	Chamber Volume	Working Fluid	Projectile Mass	Working Fluid Mass	Projectile Travel	Maximum EE Input
21 mm	72.4 cm^3	50 % TiH$_2$ & 50% H$_2$0	20 g	64.0 to 64.64 g	199 cm	~500 kJ
30 mm	206.0 cm^3	50% TiH$_2$ & 50% H$_2$0	100 g	168.84 g	300 cm	~400 kJ

A number of experimental measurements is available for each shot. The experimental data is used to determine plasma energy delivered to the combustion chamber, chamber pressure, and projectile position as functions of time.

As an example, the electrical or plasma energy computed from the product of the experimental voltage and current for a 20-mm shot, Shot 249, is shown in Figure 3. Pressure histories for Shot 249 are shown in Figure 4. Gages are located in the combustion chamber, and in the barrel at 13 cm, 14 cm, 18 cm, 88 cm, and 168 cm of projectile travel. The initial position of the projectile is at tube origin.

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Mass Burned Computed by IBHVG2
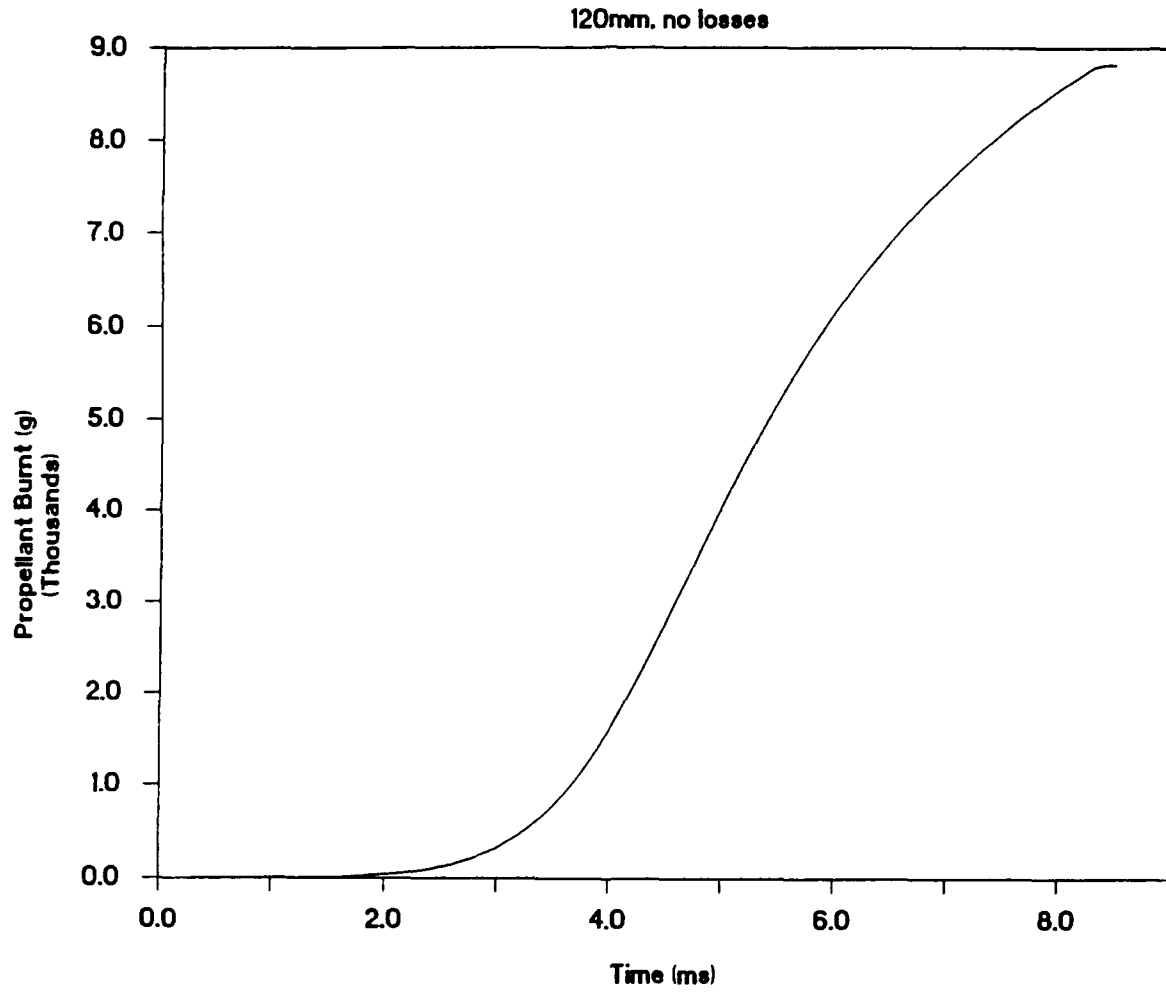
120mm, no losses

Figure 2a. Comparison of IBHVG2 Results With the Inverse Analysis.

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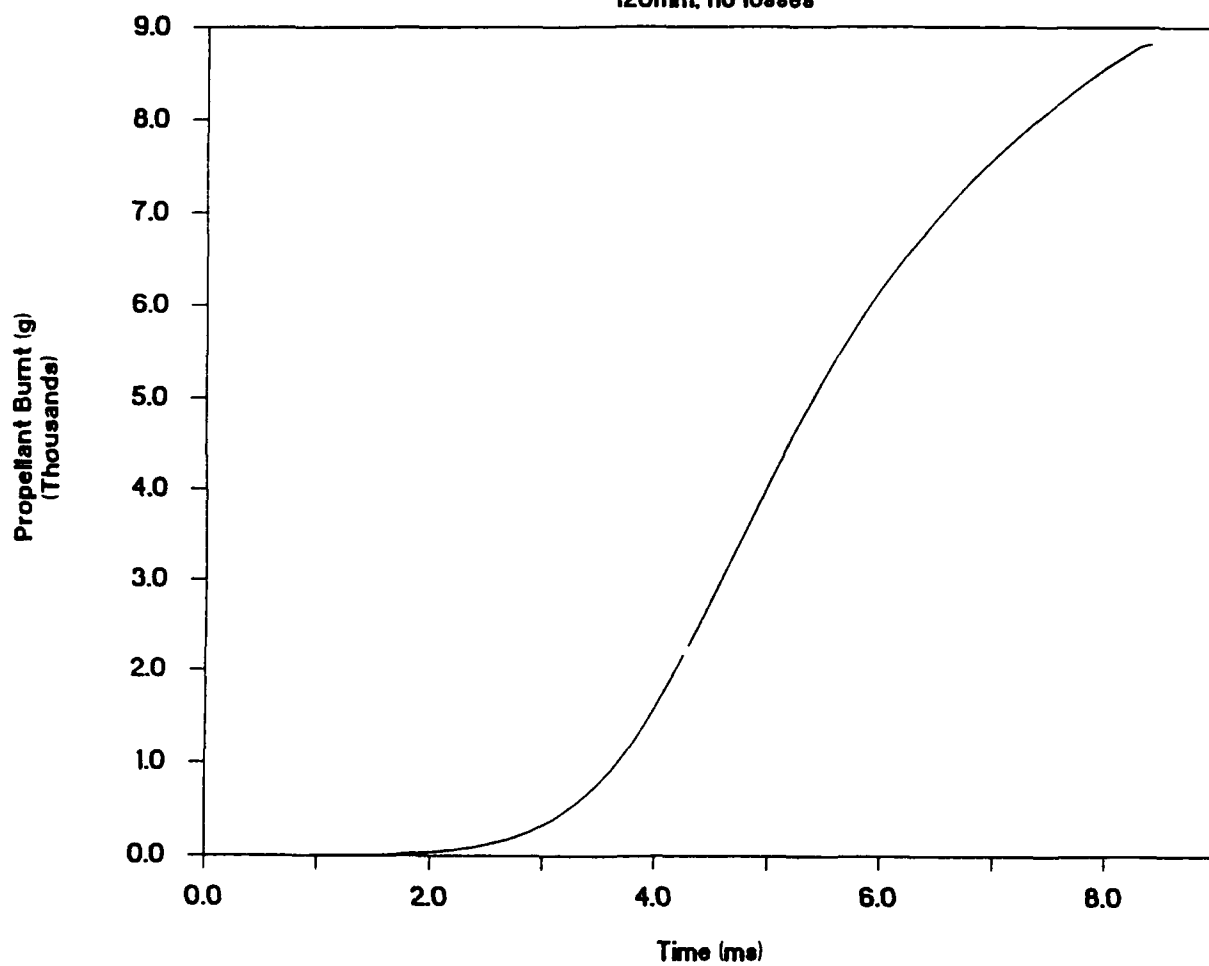# Mass Burned Computed by Inverse Code

120mm, no losses

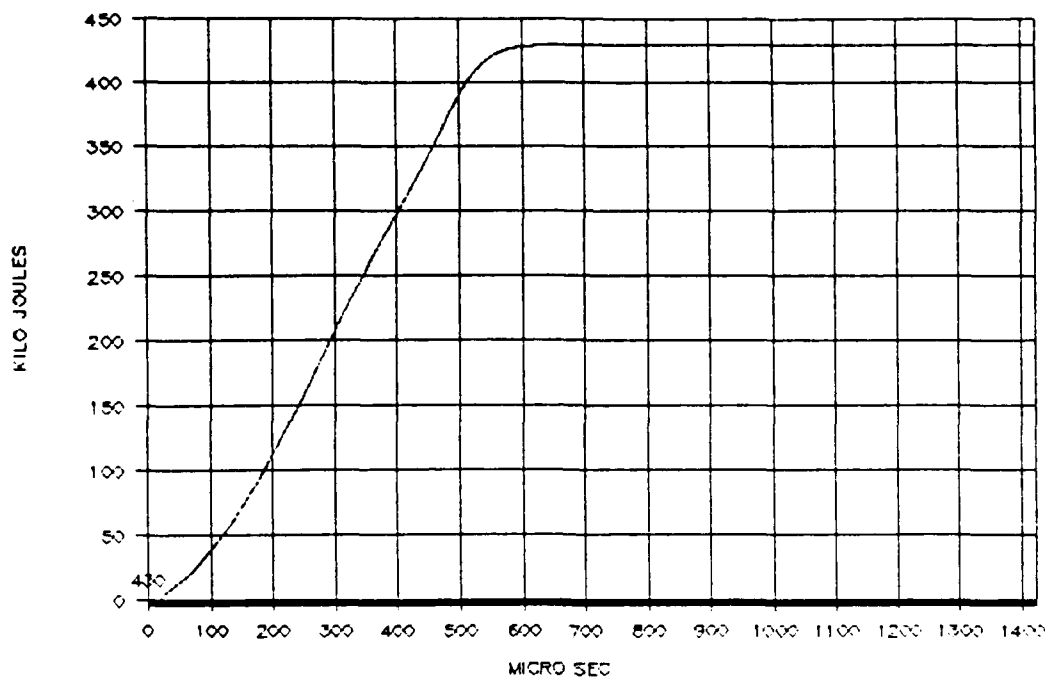Figure 2b. Comparison of IBHVG2 Results With the Inverse Analysis.

Figure 3. Electrical/Plasma Energy for 20-mm Shot 249.
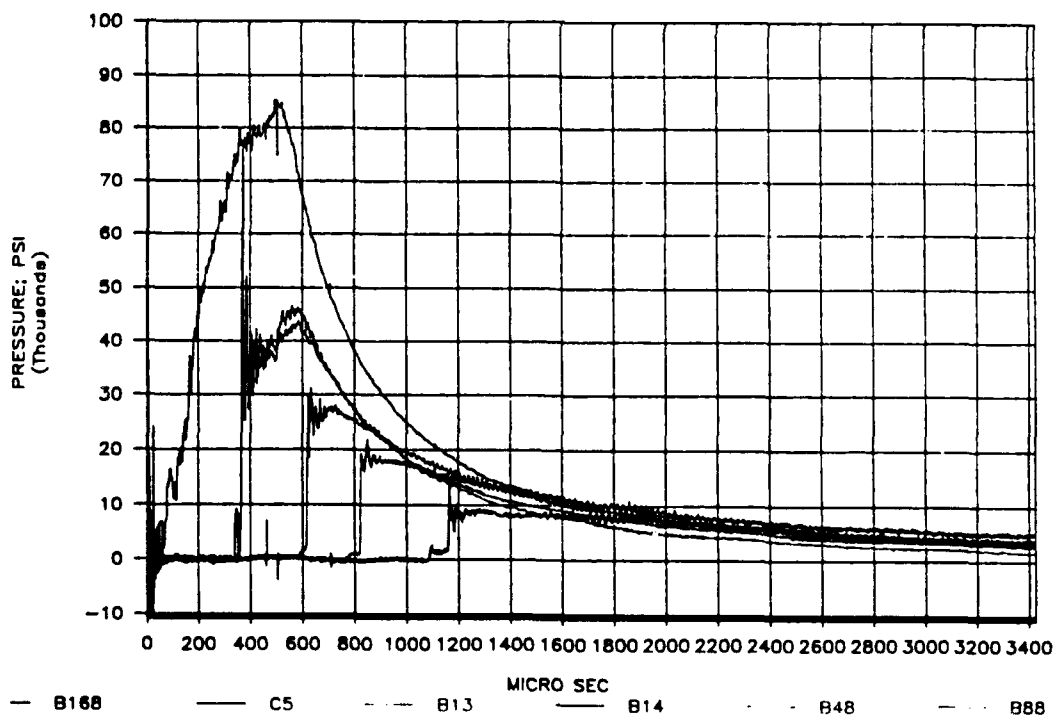

Figure 4. Recorded Pressure Histories for 20-mm Shot 249.

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For the majority of firings analyzed, the chamber pressure data is smoothed since the pressure history is "noisy." To illustrate, consider the chamber pressure for Shot 249, Figure 4, which is particularly "noisy" for the first 47 μs. To perform the smoothing, a low-pass filter is applied to the data, and the pressure history resulting from an inverse Fast Fourier Transform (FFT) is used in the analysis, a technique commonly utilized in the liquid propellant gun community. A comparison between the original data set and the data set resulting from the inverse FFT is shown in Figure 5. The filtering process is seen to maintain the characteristics of the data while removing the high frequency noise.

Projectile position is derived from arrival times at the barrel gage locations. Using the time of arrival at the barrel gage location, together with the actual gage locations, an interpolating fourth-degree polynomial of position as a function of time can be obtained. Experimental muzzle velocity, as measured by laser-velocity trap data, correlates very well with velocity predicted by the least-square fit (Greig 1989). In addition, any available radar data are utilized to confirm projectile position. However, in general, the radar data are not of sufficient fidelity to utilize in the inverse model. The polynomial method of determining projectile travel distorts the initial estimate of projectile motion prior to the first pressure probe since it is an extrapolation, as shown in Figure 6 for Shot 249. The projectile begins motion at 73 μs, and the projectile travel is negative from 73 μs to 133 μs. To eliminate negative projectile travel in the analysis, a quadratic fit is applied over the time from 73 μs to 133 μs using zero travel at 73 μs and the calculated travel at 133 μs. The resulting estimated projectile travel history is shown in Figure 7 for Shot 249. However, this procedure calls into question results obtained for approximately the first 15% of the analysis as a function of time.

The accuracy of the inverse analysis is dependent on accurate experimental data for plasma energy delivered to the combustion chamber, chamber pressure history, and projectile travel. Thus, since much of the needed information from the titanium hydride and water firings is inferred, as opposed to directly measured, the analysis of these firings is useful only as a comparison between experiments with similar initial conditions (i.e., gun geometry, plasma energy, etc.). An accurate estimation of gas generation rate will require precise experimental data.

5. THERMOCHEMISTRY

The specification of the thermochemical properties of the working fluid must consider the input of the plasma. Therefore, a series of BLAKE (Freedman, private communication) runs are performed with
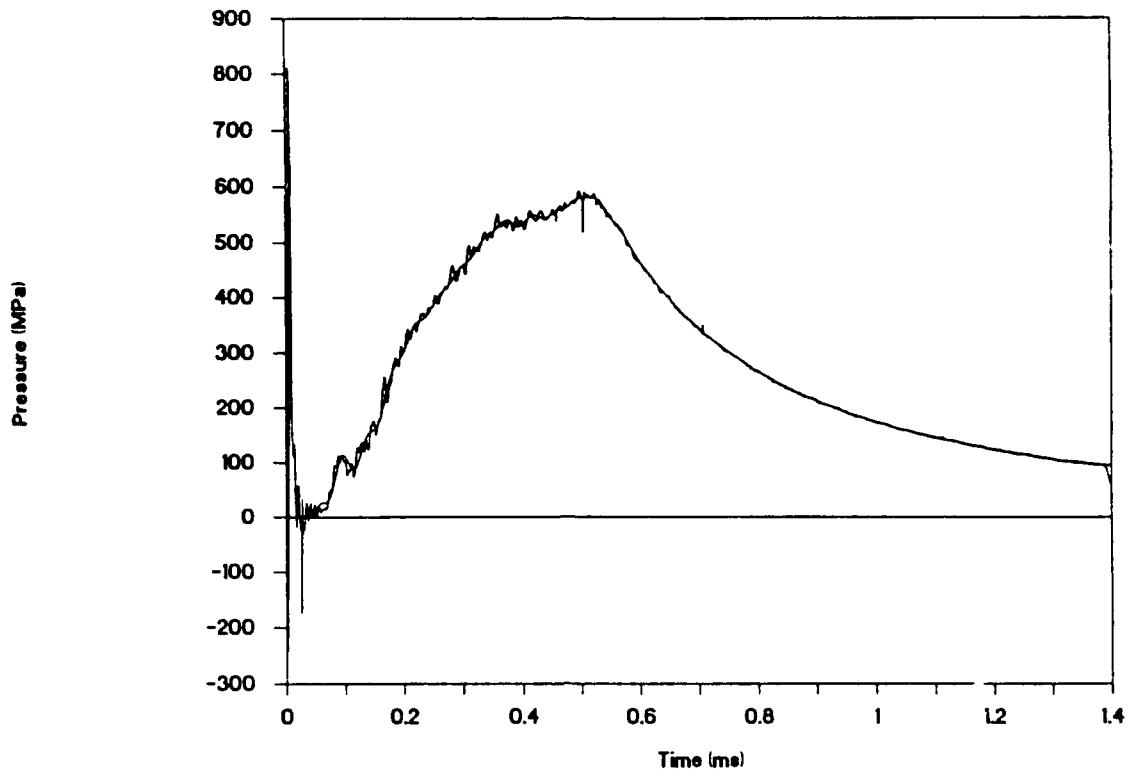
Figure 5. Comparison Between Chamber Pressure Gage History and Filtered Chamber Pressure Gage History for 20-mm Shot 249.
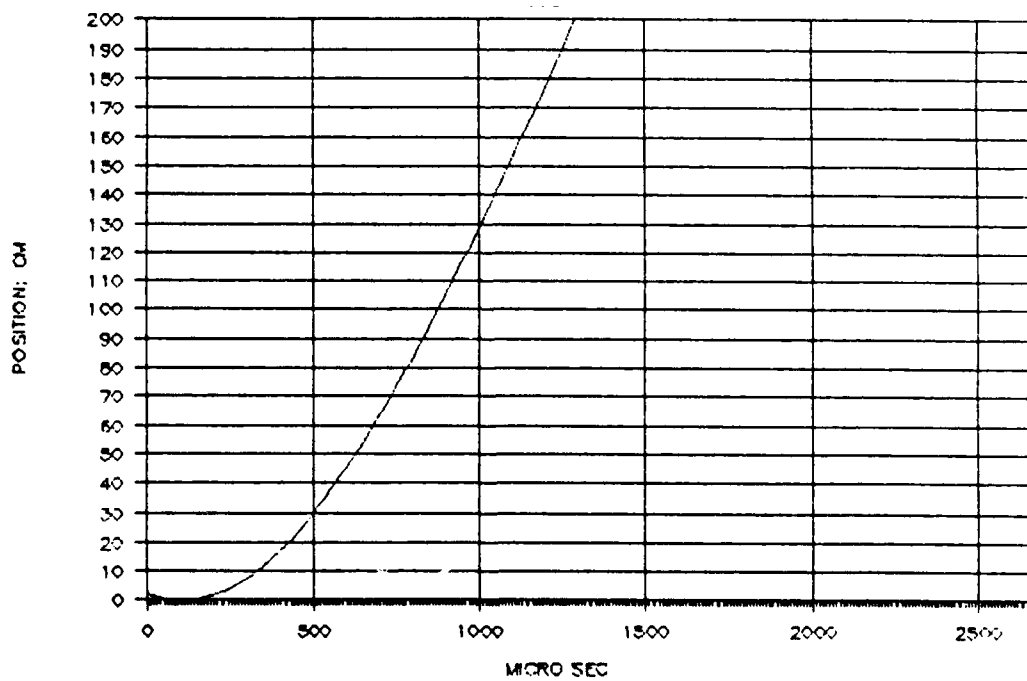
Figure 6. Projectile Position Derived From a Polynomial Least-Squares Fit to Barrel Gage Arrival Times for 20-mm Shot 249.

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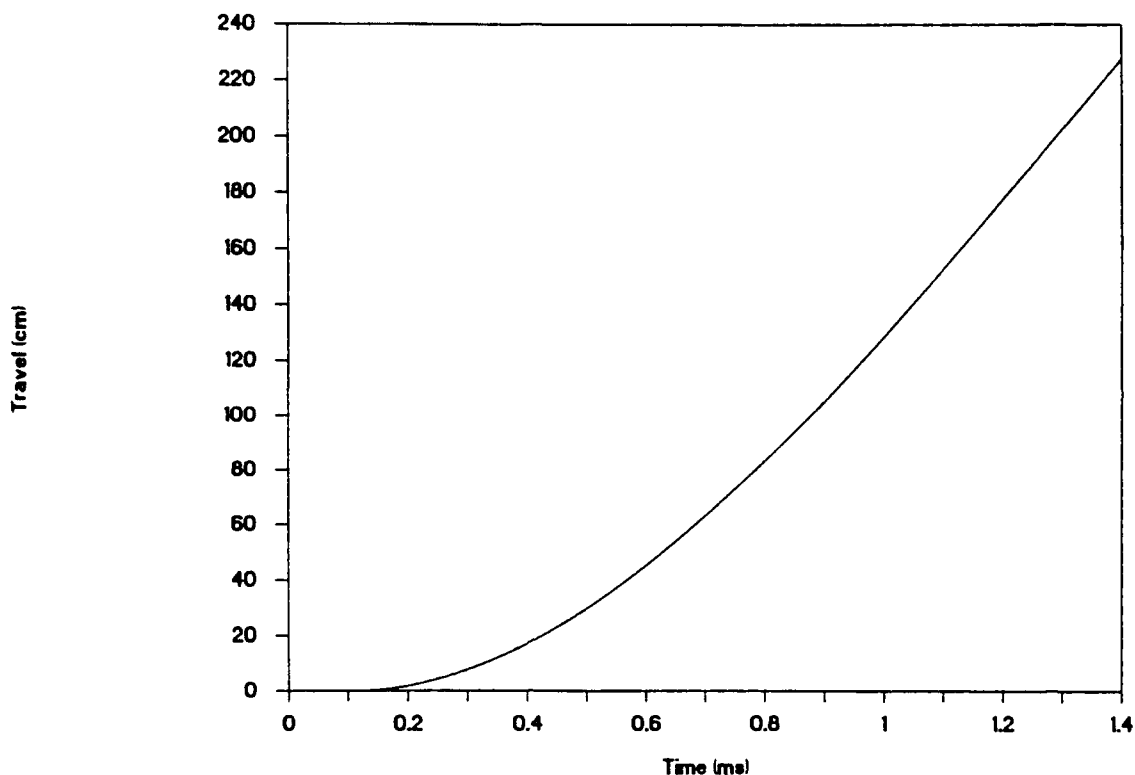
Figure 7. Projectile Position Derived From a Polynomial Least-Squares Fit to Barrel Gage Arrival
Times for 20-mm Shot 249 After 133 μs, Together With a Quadratic Fit From 73 μs to
133 μs.

varying amounts of plasma energy input (Bunte and Oberle 1989). In the BLAKE calculations, the plasma

energy is assumed to mix uniformly with some amount of working fluid, and the ratio of electrical energy

input to working fluid mass is referred to as the electrical energy density. Based on the electrical energy

density, BLAKE then defines an impetus, ratio of specific heats, temperature and molecular weight for

the mixture. In the inverse analysis, the plasma energy is assumed to mix only with the dissociated

working fluid as determined iteratively from Equation 19. Since the BLAKE entries are not defined above

approximately 6,000 K where ionization would occur, the impetus values are extended with a linear

regression line to define electrical energy densities outside the table range.

Impetus for a mixture of 50% TiH_2 and 50% H_2O as a function of electrical energy density is shown

in Figure 8 for the BLAKE calculations and is denoted by the square boxes. The linear regression line

is shown in Figure 8 as well, and is given by

$$Impetus = 134.238 * (EE\ density) + 424.69.$$

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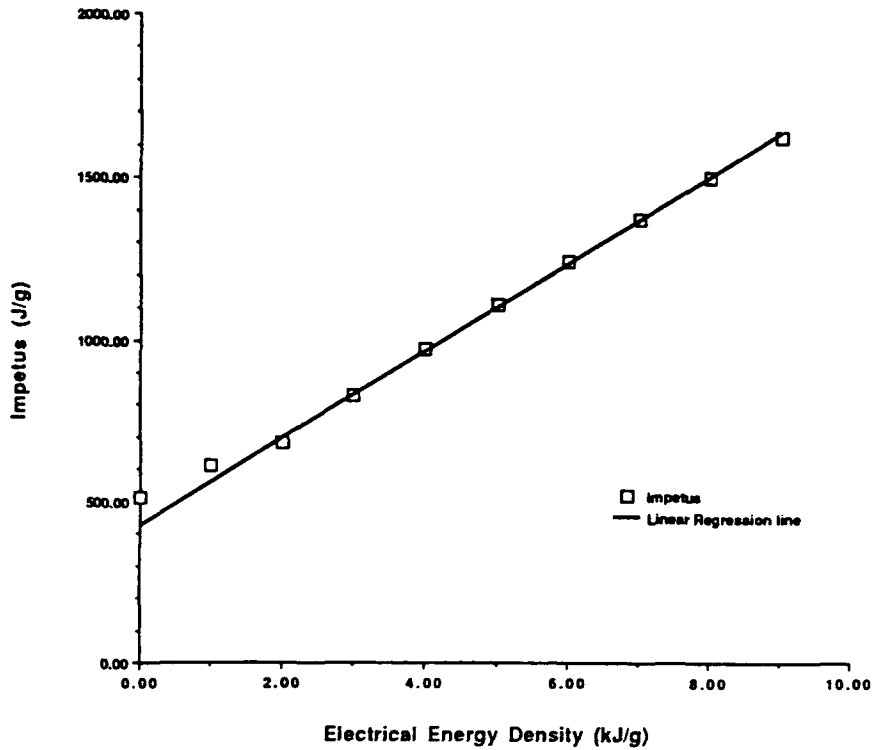
Figure 8. Impetus of TiH$_2$/H$_2$O With Electrical Energy Added.

The variable thermochemistry values are shown in Table 2. As can be seen from an examination of Table 2, the values of gamma and the covolume for electrical energy densities producing gas temperatures above 5,000 K are held constant at the last BLAKE calculation at 9 kJ/g. Although not accurate, better thermochemical data does not exist at the present time.

6. RESULTS OF INVERSE ANALYSIS

The inverse analysis assesses ballistic control exhibited in the experiment by inferring the relationship between electrical energy added to the system by the plasma and the amount of working fluid consumed. The delivery of electrical energy to the system is first discussed for the experimental shots. Results of the inverse analysis are then shown for 20-mm and 30-mm gun data with working fluid titanium hydride and water.

Electrical energy input in kilojoules vs. time in milliseconds is shown in Figure 9 for the six 20-mm firings (Shots 240, 249, 250, 257, 258, and 259). The shape of the curves is quite similar with a variation in pulse length and total energy. The 30-mm experiments are firings in which initial conditions and the

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Table 2. Thermochemistry of 50% TiH_2 and 50% H_2O

EE Density (KJ/g)	Temperature (K)	Impetus (J/g)	Gamma (-)	Covolume (cm^3/g)
0	1,627	511	1.1685	0.655
1	1,950	612	1.1685	0.655
2	2,162	679	1.2722	0.655
3	2,630	826	1.2553	0.668
4	3,078	969	1.2443	0.675
5	3,502	1,106	1.2370	0.681
6	3,899	1,239	1.2325	0.690
7	4,265	1,368	1.2302	0.702
8	4,604	1,495	1.2294	0.717
9	4,917	1,622	1.2299	0.735
10	—	1,767	1.2299	0.735
20	—	3,109	1.2299	0.735
30	—	4,451	1.2299	0.735
40	—	5,794	1.2299	0.735
50	—	7,136	1.2299	0.735
60	—	8,478	1.2299	0.735
70	—	9,821	1.2299	0.735
80	—	11,163	1.2299	0.735
90	—	12,506	1.2299	0.735
100	—	13,848	1.2299	0.735

delivery of electrical energy are nearly the same. Thus, these shots (Shots 39, 40, and 43A) form a repeatability series for this gun configuration. As shown in Figure 10, approximately 350 kJ of electrical energy is delivered as a simple ramped input over approximately 1.4 ms.

To assess the dependence of working fluid consumed on plasma energy input, the results are presented as groups of normalized electrical energy input vs. normalized working fluid consumed. The normalized curve (Figures 11 and 12) is obtained by dividing electrical energy by the maximum electrical energy

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Figure 9. Electrical Energy Input (kJ) as a Function of Time (ms) for 20-mm Gun Firings.
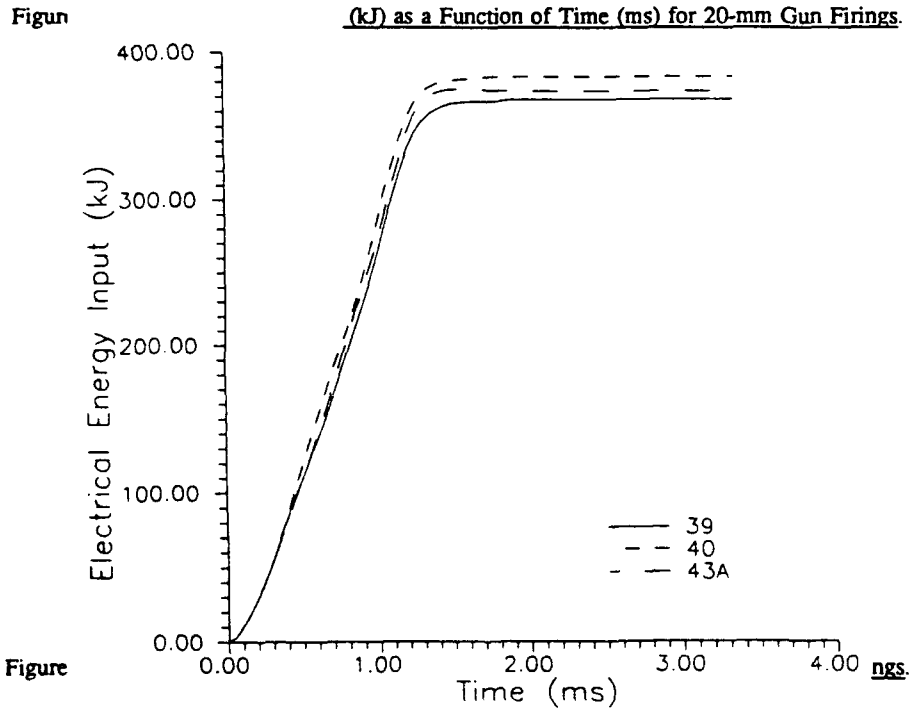
Figure 10. Electrical Energy Input (kJ) as a Function of Time (ms) for 30-mm Gun Firings.

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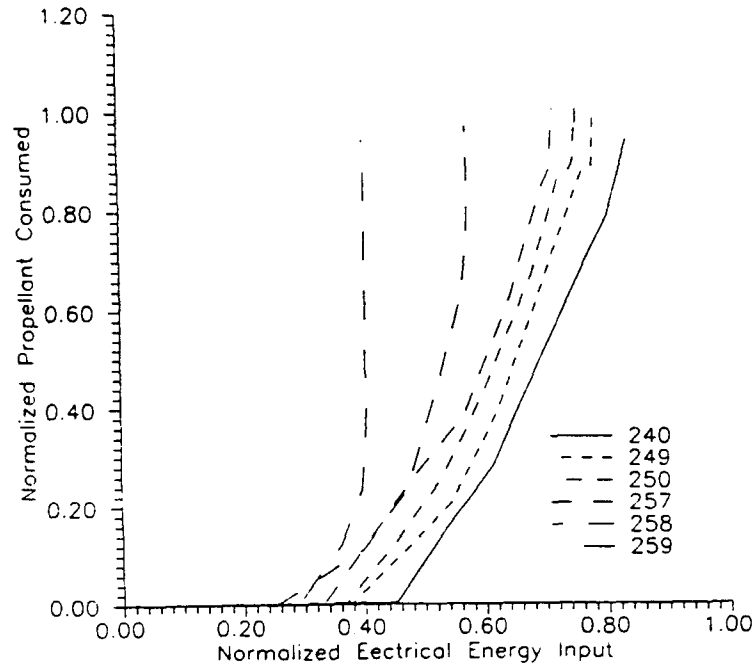
Figure 11. Normalized Electrical Energy Input vs. Normalized Working Fluid Consumed for 20-mm Gun Firings.

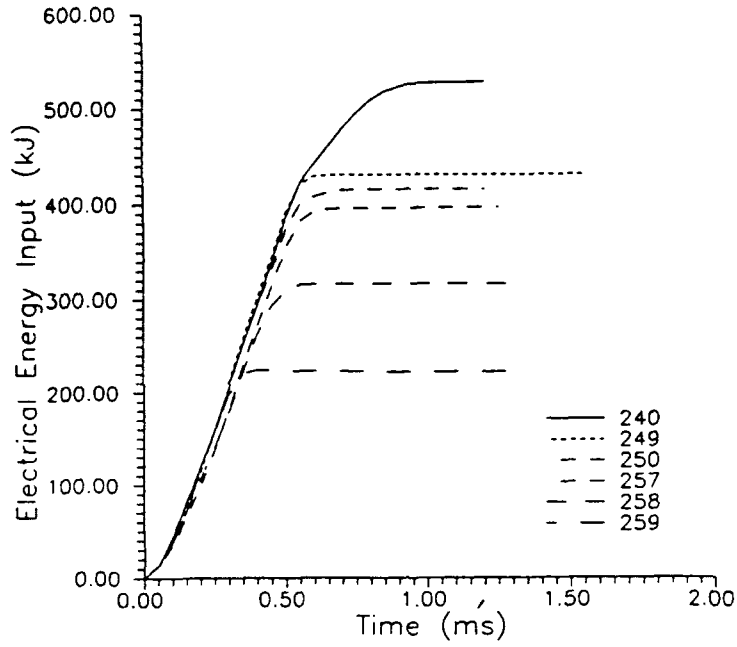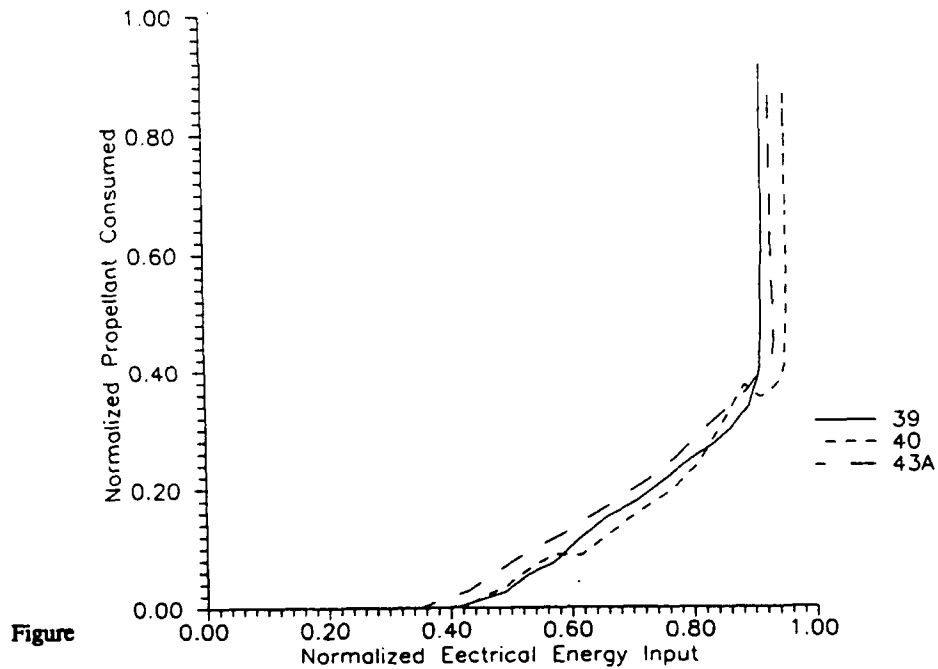

Figure 12. Normalized Electrical Energy Input vs. Normalized Working Fluid Consumed for 30-mm Gun Firings.

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input and the mass consumed by the maximum mass of working fluid in the experiment. The computed mass of working fluid consumed is shown in Appendix B for each shot, with the sample input/output in Appendix A.

The results for the 20-mm shots with titanium hydride and water as the working fluid are shown in Figure 11. From Figure 9 the electrical energy input is a simple ramp. Although the mass of working fluid consumed (Figure 11) does indicate some linearity as a function of electrical energy, the results provide no evidence that the plasma energy input drives the ballistic response for the entire ballistic cycle.

The 30-mm shots using titanium hydride and water as the working fluid are shown in Figure 12. These shots form a set of repeatability experiments. As shown in Figure 10, the approximately 350 kJ of electrical energy is deposited uniformly over approximately 1.2 ms in each experiment. As can be seen in Figure 12, the working fluid response is similar in all three experiments. As in the 20-mm experiments, although the plasma energy is applied uniformly, the rate of working fluid mass consumed appears toincrease during the ballistic cycle. Although the mass fraction of working fluid consumed appears to occur similarly in the experiments, it is not evident that the plasma controls the ballistic process.

In both experimental data sets, an increase in the rate of working fluid consumed over time is observed. In order to identify the role of plasma energy as the driving mechanism in the gas generation rate, shots in which the initial plasma input is substantially varied should be fired and compared.

An analysis of several firings with water as the working fluid was attempted. It is possible to devise an extended thermochemical description of the mixture of water and electrical energy similar to Table 2. However, as demonstrated by Gough (1990) and verified in the analysis of experimental data, the dependence of pressure on the fraction of working fluid consumed is weak for endothermic fluids for all electrical energy densities. As opposed to exothermic fluids, the possibility of multiple roots and bifurcation in the inverse analysis makes water firings unsuitable for inverse analysis. Thus, these firings are not further discussed in this report.

7. SURFACE AREA RATIO

A second method to investigate control of the ballistic process is to ascertain the surface area of the reacting working fluid. If the process is not controlled, it would be expected that the total reacting surface

area would display large fluctuations. To determine an apparent surface area, the experimental breech pressure and working fluid mass consumed (as computed from the inverse analysis) are used to compute a surface area ratio (current surface area to initial surface area) under the assumption of a pressure dependent combustion law for the working fluid reaction. Although the results are qualitative, the ratio provides some insight into the behavior of the surface which is in contact with the hot gases. Surface area ratios in solid propellants are well behaved.

A pressure dependent burn rate of JA2 propellant ($r = 0.12 \, P^{0.95}$, r in cm/s) and an initial surface area equal to the cross-sectional area of the chamber are assumed. Then for each percent mass consumed, the ratio of the current to the initial surface area can be computed. The selection of the initial surface area as the cross-sectional area of the chamber is arbitrary. However, changing the value of the initial surface area preserves the shape of the surface area ratio curve but changes its magnitude. Thus, the surface area ratio curves should not be viewed in terms of absolute magnitude but only in terms of characteristic shape. The results are similarly affected by the choice of burn rate law. Figure 13 shows the surface area ratio for three 20-mm firings, Shots 240, 249, and 259, with titanium hydride and water as the working fluid. For the first 50% of the mass consumed the ratios show minor fluctuations except for the early portions of the graph where the data is questionable due to the inaccuracies in the early portion of projectile travel. Unfortunately, the surface area ratios fluctuate sharply after approximately 50% of the working fluid mass has been consumed, especially Shot 249. In the experiments, the plasma continues to enter the chamber until almost all of the working fluid has been consumed as seen in Figure 11. Thus, the working fluid surface area appears to be well behaved only initially.

For comparison, the geometry of an inhibited, monolithic grain with dimensions suggested by the initial working fluid configuration is theoretically burned under the same pressure-dependent conditions. The surface area ratio as a function of percent mass consumed is shown in Figure 13 and is seen to be progressive and well-behaved.

8. CONCLUSIONS

An inverse analysis has been presented as one method of assessing ballistic control exhibited in ETC experimental gun firings. The analysis attempts to determine the decomposition or gas generation rate necessary to satisfy an energy balance equation as gleaned from available experimental data. The quantitative values of working fluid mass consumed are dependent on accurate experimental breech
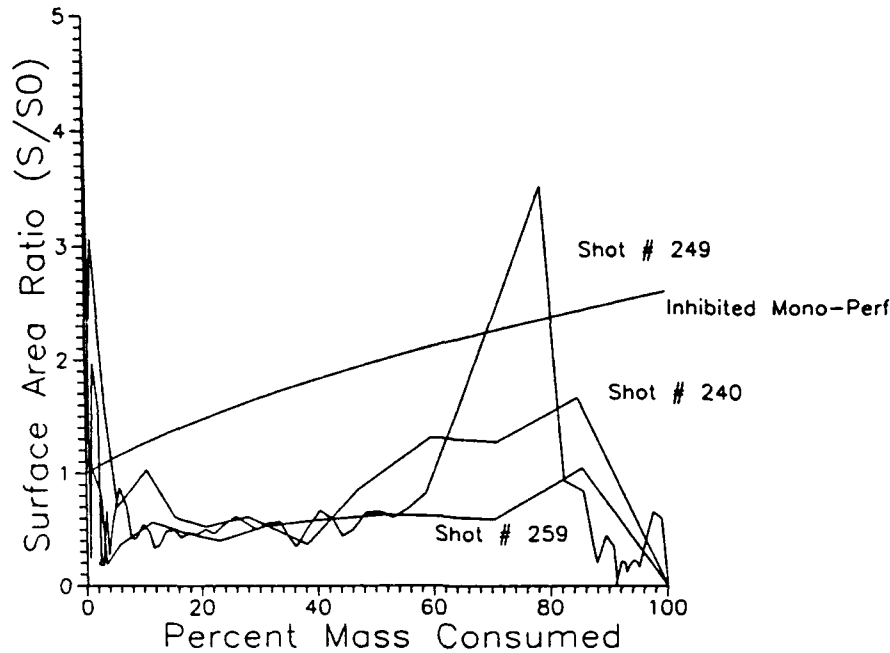
Figure 13. Surface Area Ratio for 20-mm Shots 240, 249 and 259 Compared to Inhibited, Monolithic Grain.

pressure measurements and projectile position as well as the assumption of the form of the pressure gradient.

The analysis was applied to 20-mm and 30-mm experimental firings (rear plasma injection) using titanium hydride and water as the working fluids. The results of the analysis are viewed as qualitative for these data sets and suggest:

(1) For the firings analyzed, there is little evidence to indicate that the electrical energy input plays a dominant role in the amount of working fluid consumed.

(2) A large fluctuation in surface area occurs for the titanium hydride and water system when approximately 50% of the mass has been consumed regardless of the presence or absence of plasma energy in the configuration analyzed.

20

(3) Accurate measurement of projectile position through in-bore radar is needed to accurately establish the volume behind the projectile.

(4) The potential coupling between plasma energy input and working fluid mass consumed is obscured by the lack of comparable data sets in which the plasma energy input history is significantly varied.

(5) Additional work is needed in defining the thermochemistry of working fluid/electrical energy combinations.

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9. REFERENCES

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APPENDIX: A

SAMPLE INPUT

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Enter the file containing input file names.

Inverse Electrothermal Gun Code

Pressure-time file:250tvp.IN
Proj motion-time file:250tvpp.IN
Proj travel-time file.

Electrical energy-time file:250tvce.IN
Initial data file:250init.IN
Chamber volume (cm^3)=   72.40000
Tube diameter (cm)=   2.1   Area (cm^2)=   3.46361
Projectile position (cm)=   0.00000
Projectile mass (kg)=   0.02
Working fluid mass (g)= 64.64000
Initial working fluid density (g/cm^3)=   1.59000
Tolerance required in mass consumed=   0.00100
Time start (sec)=0.00000000
Time increment (sec)=0.00005000
Time end (sec)=0.00120000
Initial guess for mass consumed (g)=   0.10000
Initial value of beta, fraction of wf moving (-)=   1.00000
Mass of air initially in chamber (g)=   0.03750
Bulk modulus of WF at .e atmosphere (MPa)=5000.00000
Derivative of bulk modulus wrt pressure (-)=   8.00000

Thermochemical data file:tihextra.prn

TIME	CHAM PR	BASE PR	PROJ TRAV	PROJ VEL	EL EN DEN	CUM WF
(ms)	(MPa)	(MPa)	(cm)	(cm/s)	(MJ/kg)	(g)
0.00	0.10	0.04005	0.0000	0.00	0.000	0.00000
0.05	2.89	1.15726	0.3916	7831.56	19259.860	0.00079
0.10	98.12	39.29342	0.7832	7831.56	2101.635	0.02080
0.15	200.20	80.17240	1.1747	7831.56	1811.112	0.04470
0.20	338.07	135.38190	1.5663	27364.79	1433.635	0.08227
0.25	413.63	165.64180	3.9112	55843.03	1198.416	0.12971
0.30	493.50	197.62530	7.1506	73255.77	1039.150	0.19483
TIME=	0.00035	NO CONVERGENCE				
0.40	573.84	229.79470	16.1227	105250.30	17.629	16.52764
0.45	577.92	231.42860	21.7618	119858.60	11.768	28.05256
0.50	588.95	235.84870	28.1085	133558.50	8.616	43.34926
0.55	559.01	223.85940	35.1177	146363.10	7.105	56.13565
0.60	473.38	189.56690	42.7448	158286.10	7.172	56.85619
0.65	403.04	161.39790	50.9463	169340.30	7.109	57.92583
0.70	355.40	142.31970	59.6788	179538.80	6.588	62.86549
0.75	306.18	122.61100	68.9001	188895.20	6.544	63.38555
0.80	263.75	105.61900	78.5683	197422.40	6.623	62.64100
0.85	235.21	94.18995	88.6424	205134.10	6.418	64.93068
All fluid consumed.						
Solution continues to balance energy.						
0.90	213.39	85.45189	99.0817	212043.00	6.418	66.28542
0.95	190.69	76.36062	109.8466	218163.30	6.418	66.49628
1.00	171.73	68.76966	120.8980	223505.80	6.417	66.69440
1.05	156.52	62.67997	132.1973	228086.30	6.417	67.08662
1.10	143.31	57.38857	143.7066	231917.30	6.417	67.33691
1.15	130.72	52.34921	155.3890	235012.50	6.416	67.08495
1.20	119.08	47.68684	167.2078	237381.90	6.416	66.46645

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APPENDIX B:

INVERSE SIMULATION OF 20-MM AND 30-MM FIRINGS OF TiH$_2$/H$_2$0

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Shot 240

Electrical Energy (kJ)

Propellant Consumed (g)

Time (ms)

Shot 249

Electrical Energy (kJ)

Propellant Consumed (g)

Time (ms)

32

Shot 250

33

Shot 257

Electrical Energy (kJ)

Propellant Consumed (g)

Time (ms)

Shot 258

Shot 259

Electrical Energy (kJ)

Propellant Consumed (g)

Time (ms)

Shot 39

Shot 40

Electrical Energy (kJ)

Propellant Consumed (g)

Time (ms)

38
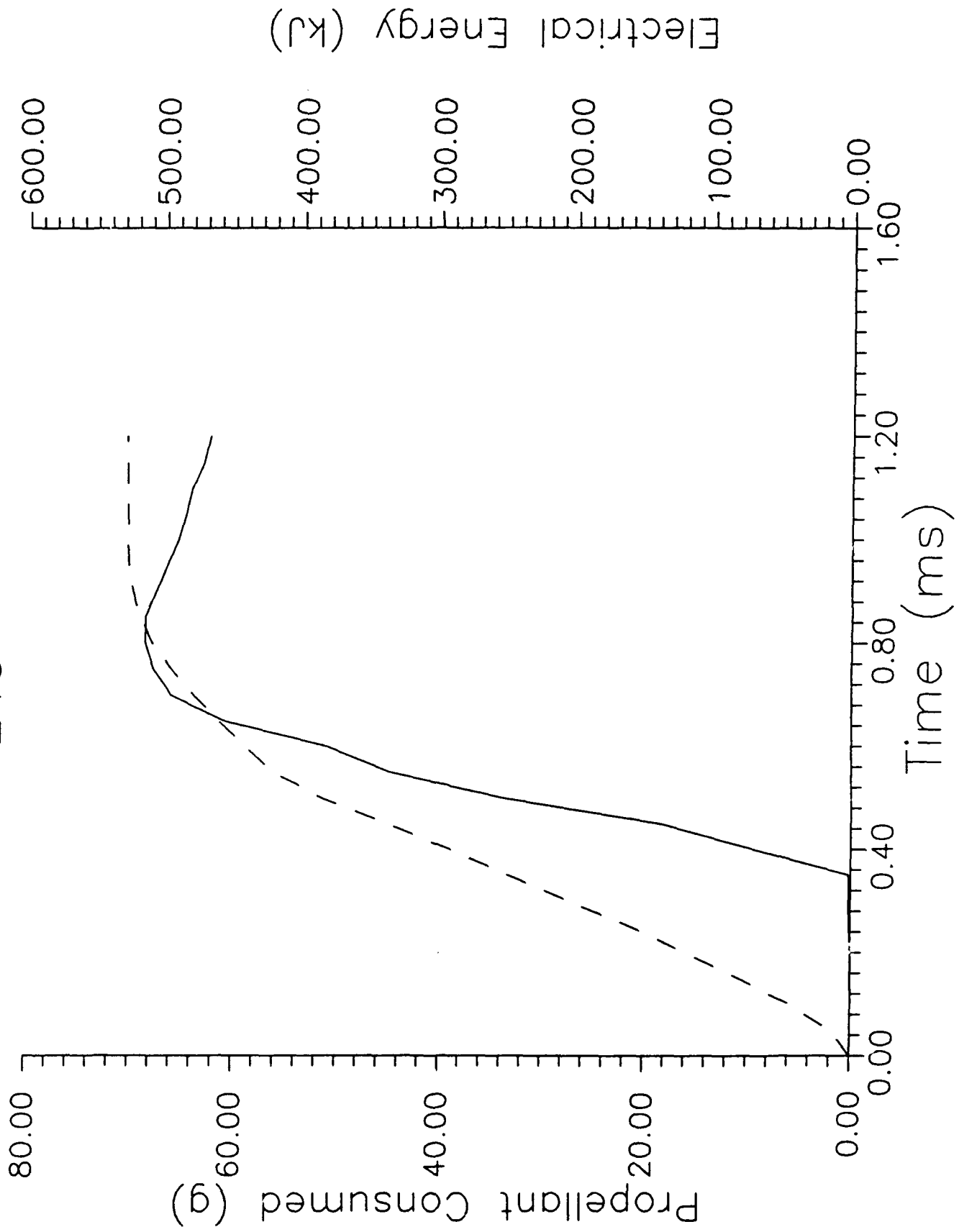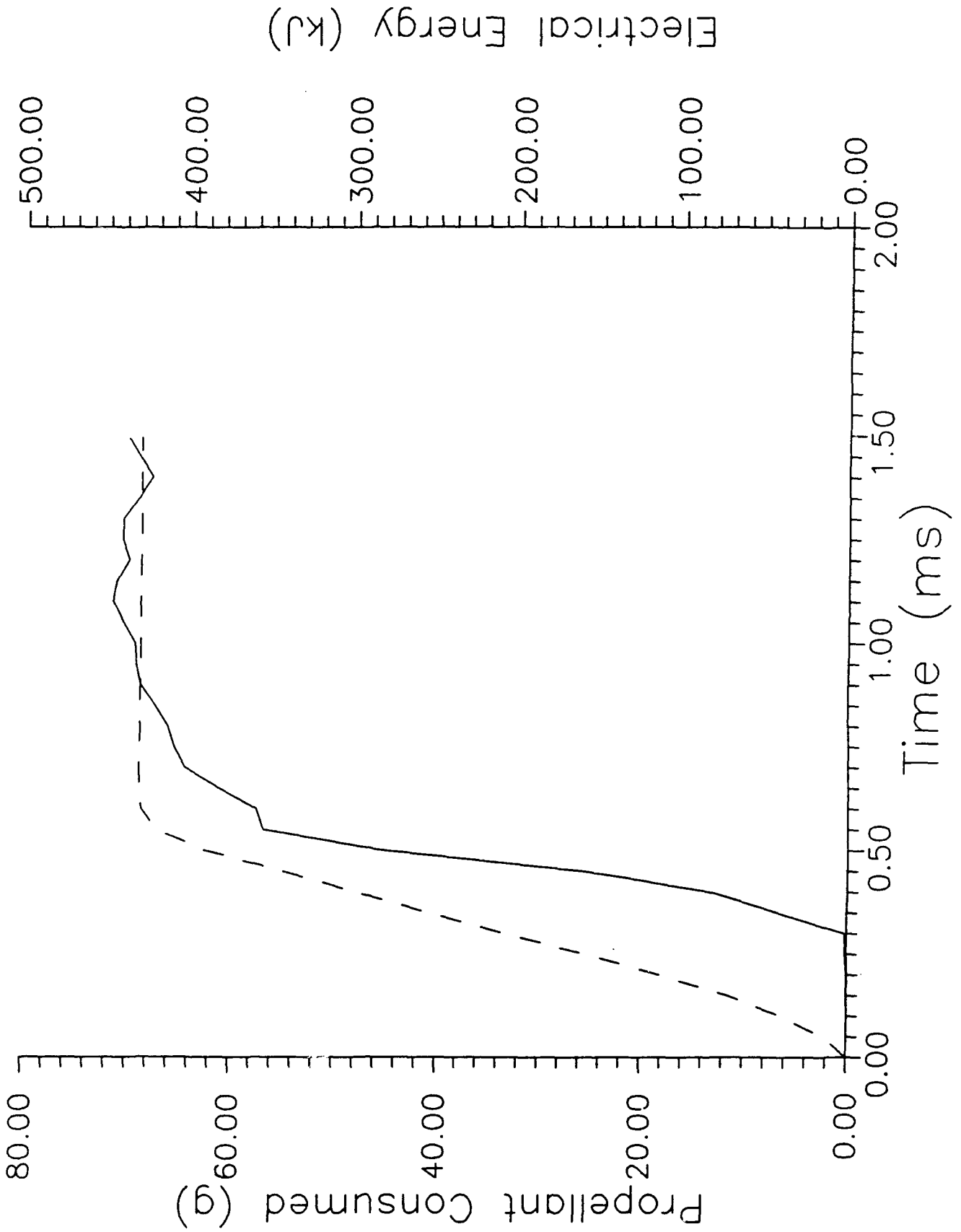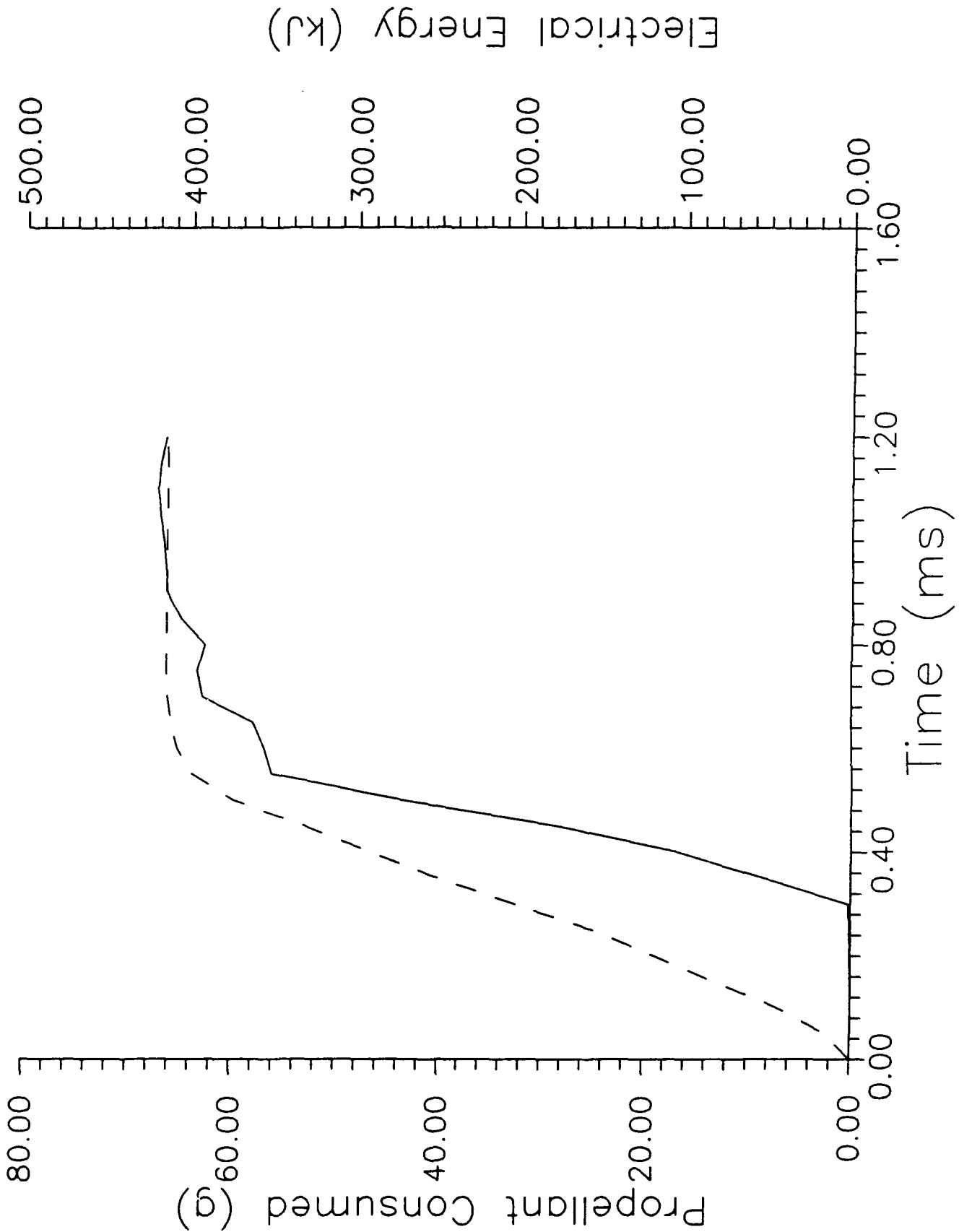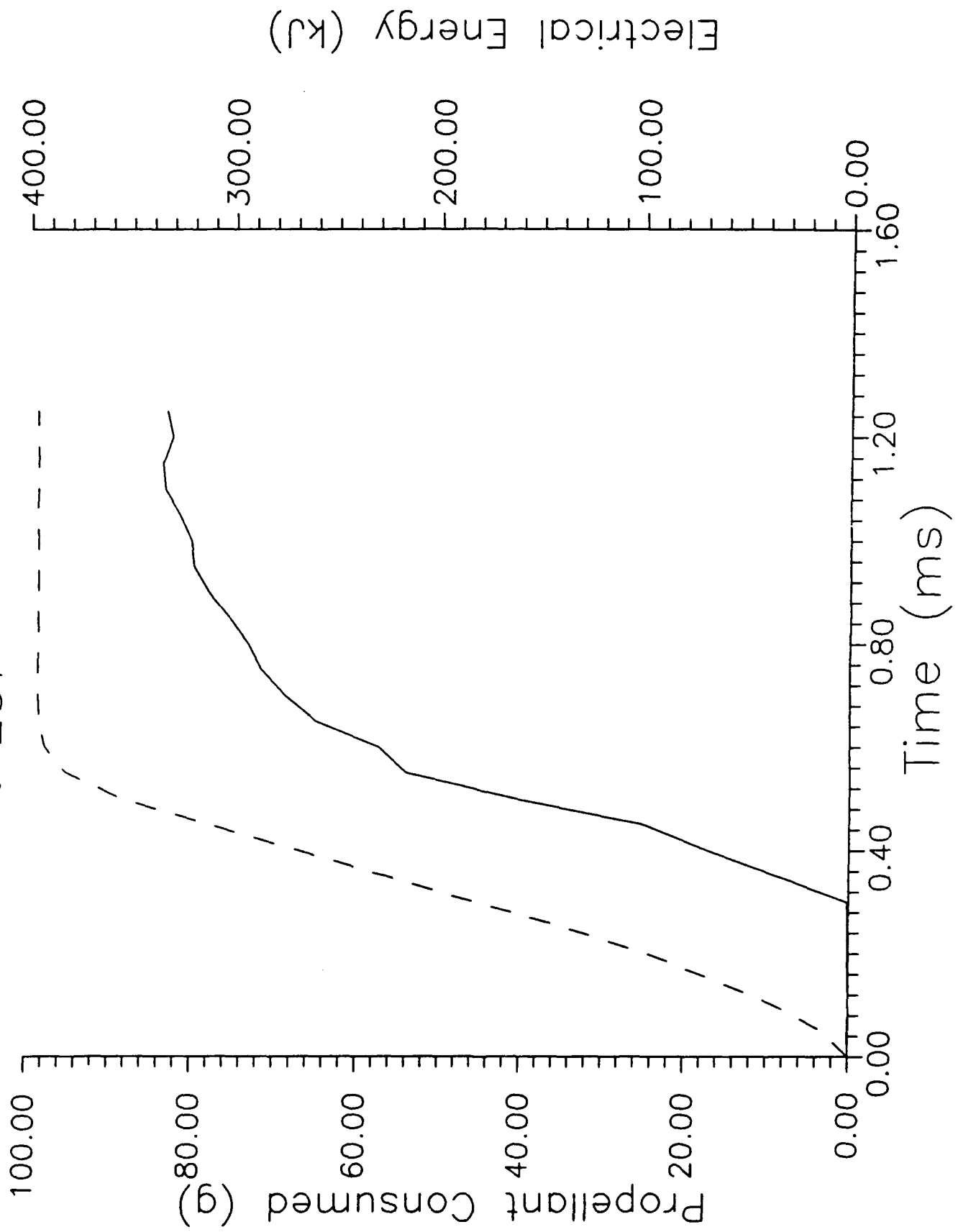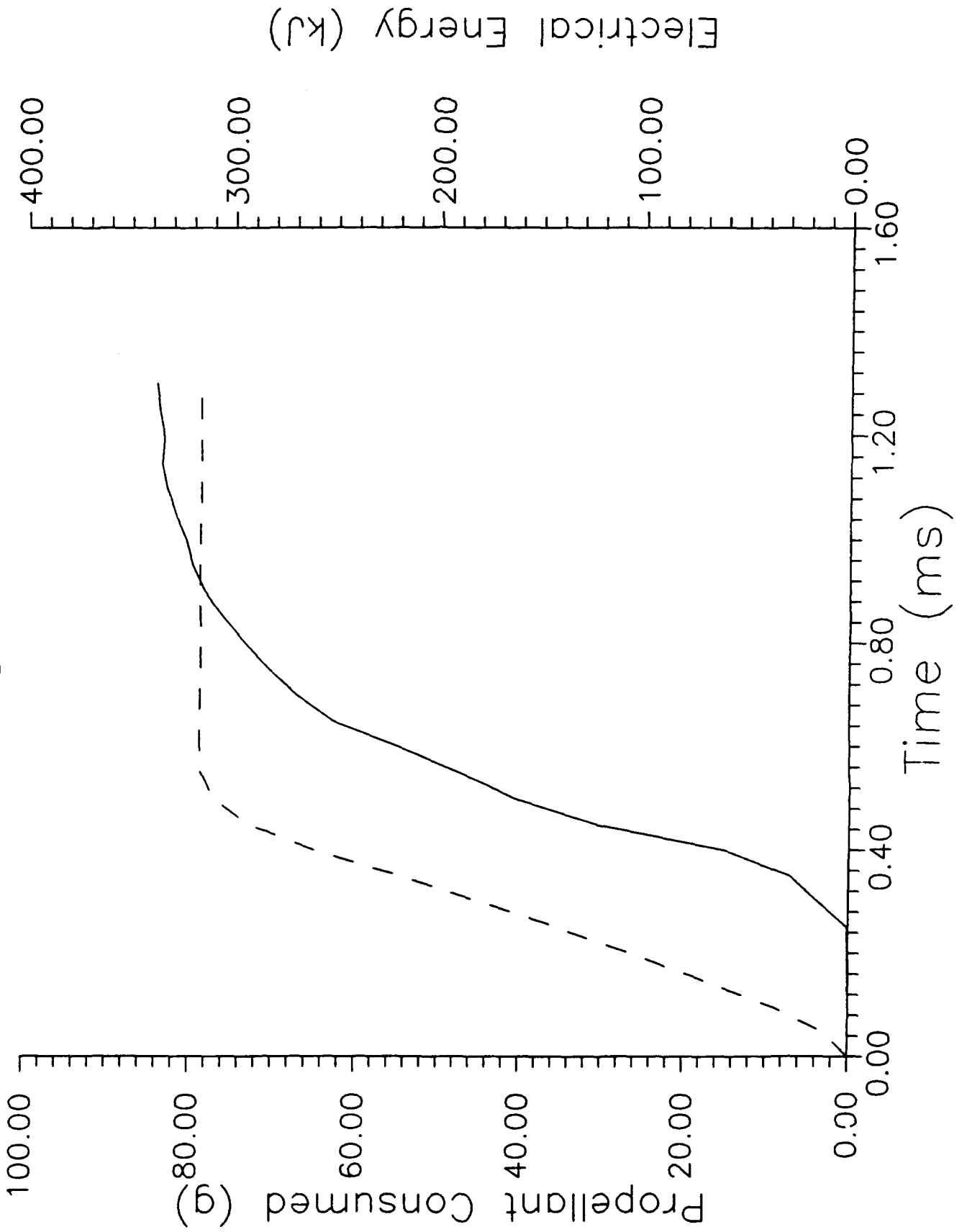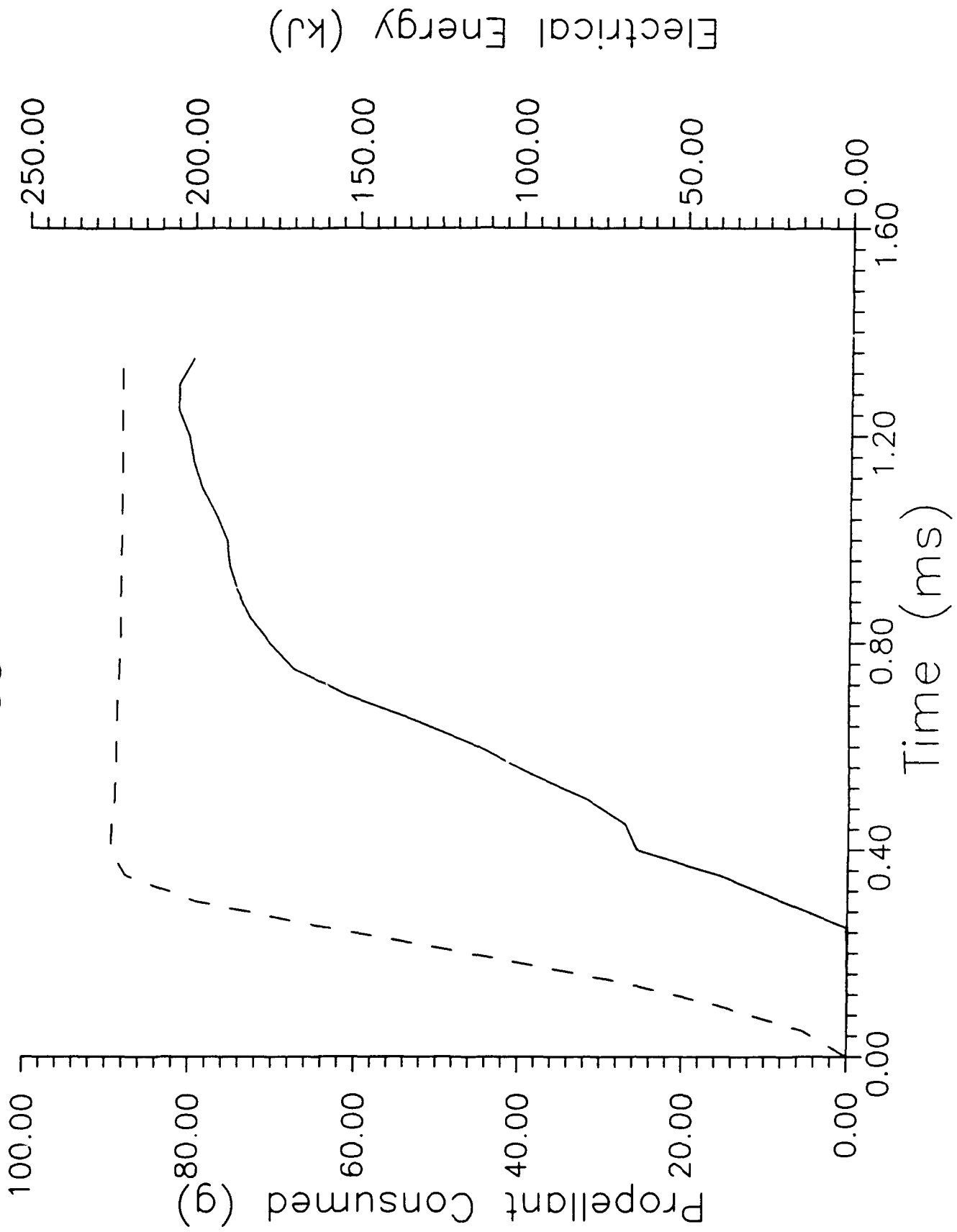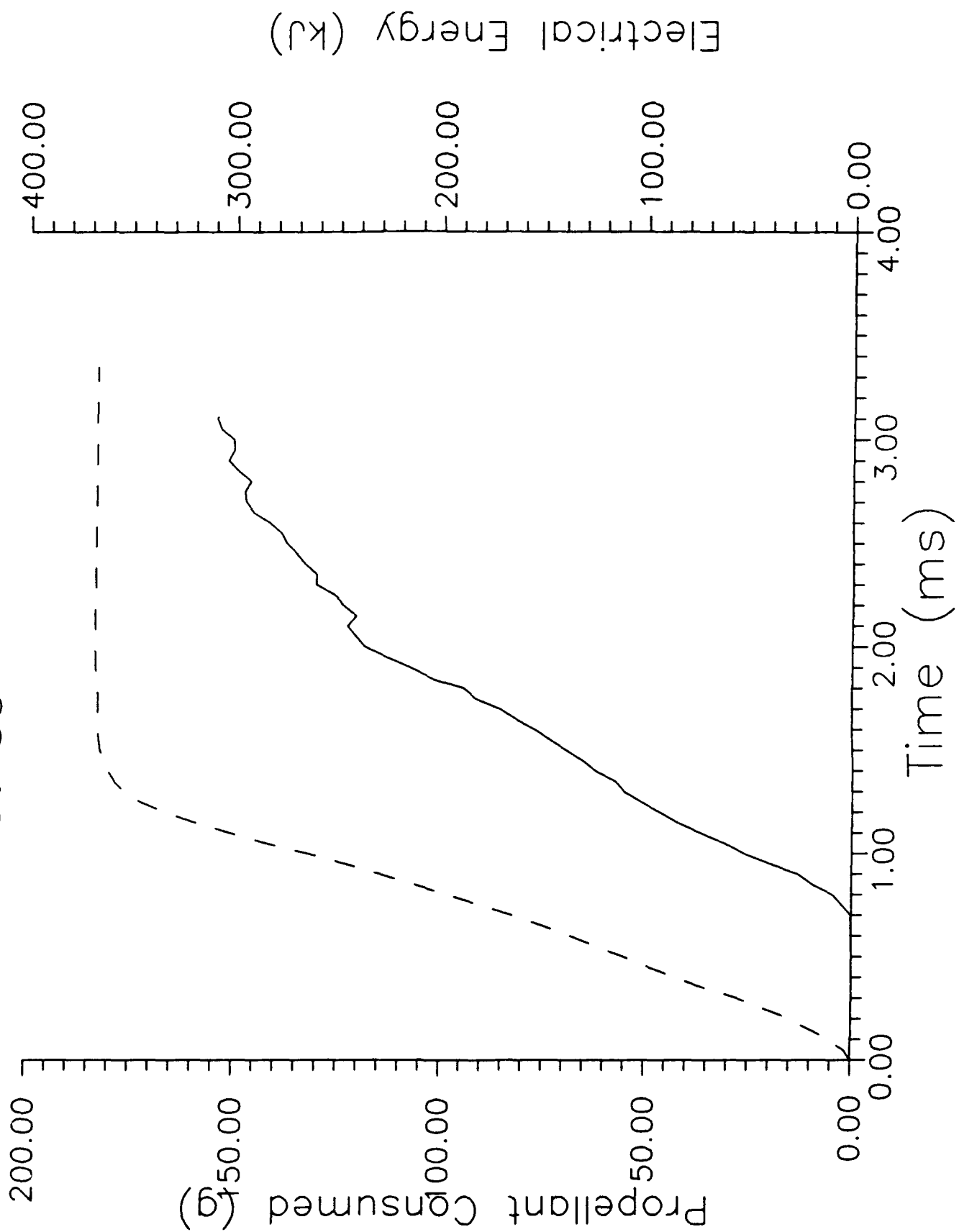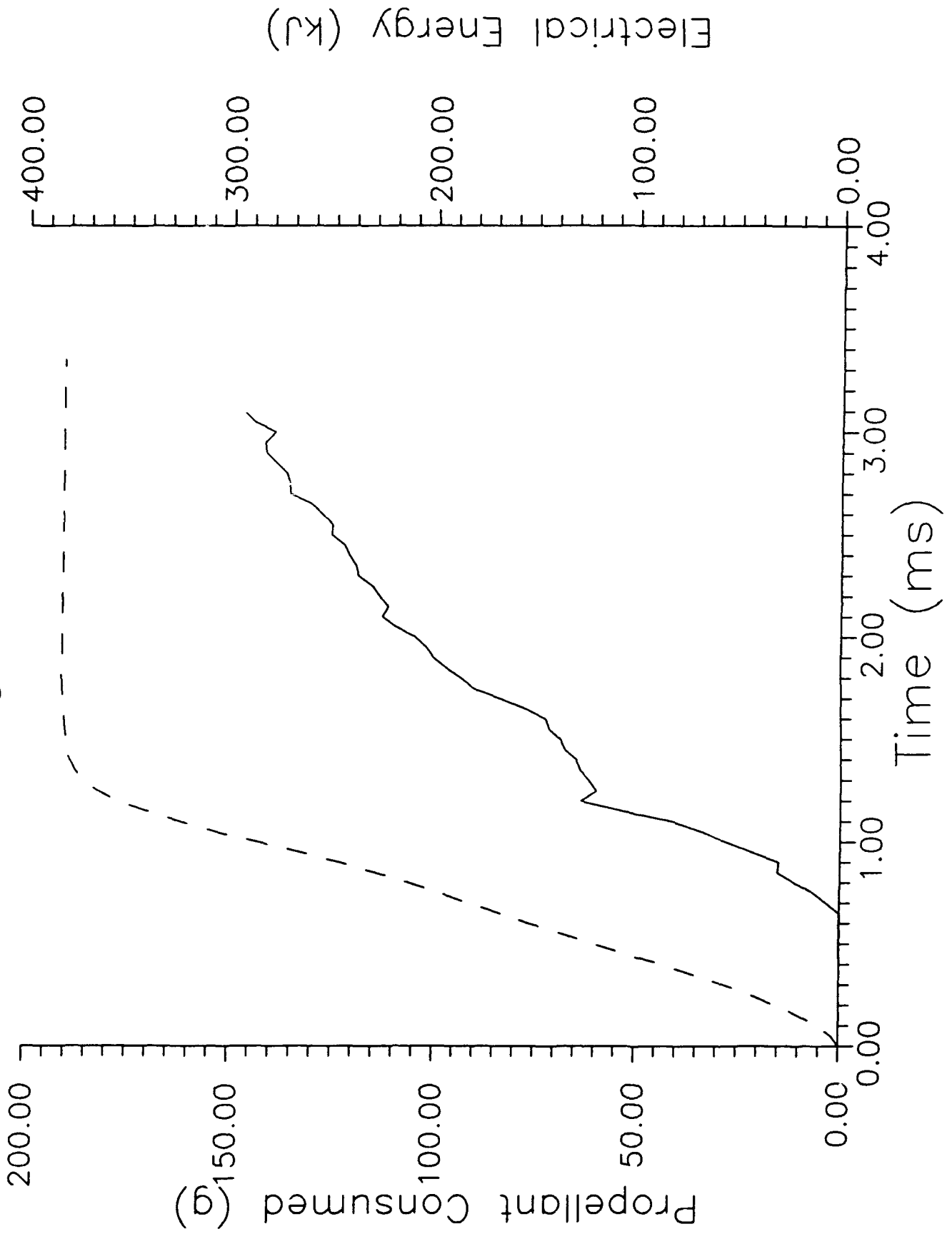
Shot 43A
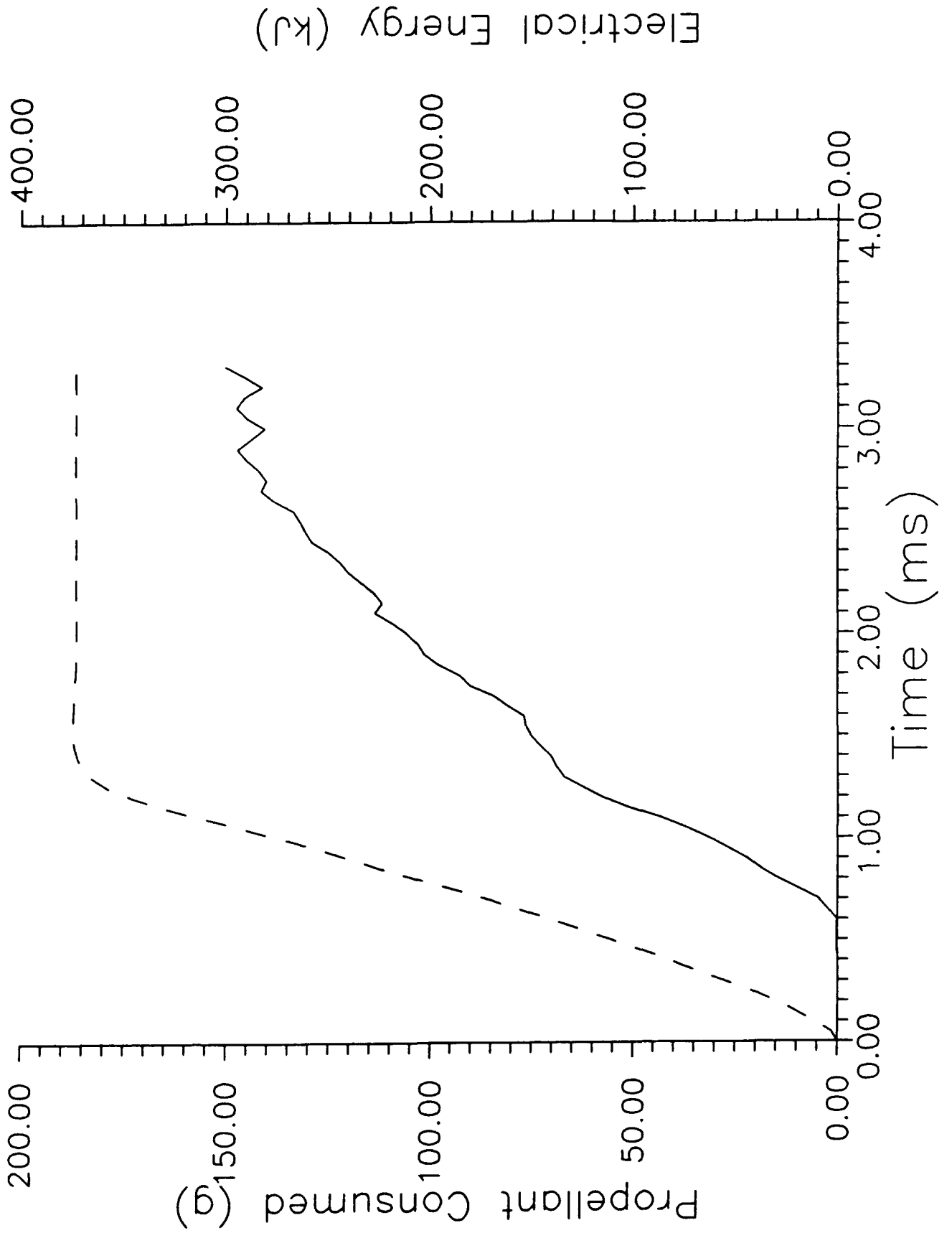
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APPENDIX C:

SOURCE CODE LISTING

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```
      PROGRAM ETINVBC
C
C ADD COMPRESSION OF WORKING FLUID - JULY 1990
C
C CONSIDER BETA--AMT OF FLUID WHICH MOVES
C APRIL 1990
C INVERSE PROGRAM TO CALCULATE INTERACTION RATE
C OF WORKING FLUID AND PLASMA FROM ET DATA
C ASSUMING LAGRANGE PRESSURE GRADIENT
C
C TYPE ETINVBC (WAIT FOR QUESTION ABOUT INPUT FILE!!)
C
      IMPLICIT REAL (A - H, O - Z)
      PARAMETER (NPT = 150, NPTT = 50)
      COMMON /NAME/ PRESIN, TRAVIN, ELECIN, THERIN, INITIN
      COMMON /DATA/ PRTIM (1:NPT), PRES (1:NPT),
     1   TRTIM (1:NPT), TRAV (1:NPT),
     2   VEL (1:NPT), ELTIM (1:NPT), ELEC (1:NPT)
      COMMON /OUT/ WFTIM (NPT), WFCUM (NPT)
      COMMON /NUMBER/ NPR, NTR, NEL, NTH, ITRVEL, NWF
      COMMON /START/ CHVOL, AREA, WFMASI, RHOI,
     1   PROJI, PROJW, TOL, TIMINC,
     2   TIMEND, WAIR, BM, DERBM
      COMMON /CURRENT/ TIME, PRESCH, TRAVPR,
     1   ELECEN, TEMP, RIMPET, GAMMA,
     2   COVOL, WF1, WF2, ELDEN, SPMPR, VELP, BETA, BASEPR, CM,
     3   Z, RHO, ENCOMP
      COMMON /OPTIONS/ IBETA, ICOM
      COMMON /THERMO/ ELDEN1 (1:NPTT), TEMP1 (1:NPTT), RIMP1 (1:NPTT),
     1   GAMMA1 (1:NPTT), COVOL1 (1:NPTT)
C
      CHARACTER*20 ETIN, PRESIN, TRAVIN, ELECIN, THERIN, INITIN
C
      WRITE (*, 6000)
 6000 FORMAT(10X,' Enter the file containing input file names.')
      READ (*, 5000) ETIN
      OPEN (15, FILE = ETIN)
      REWIND (15)
C
C LINE 1: PRESSURE
C LINE 2: PROJECTILE TRAVEL
C LINE 3: ELECTRICAL ENERGY INPUT
C LINE 4: THERMOCHEMICAL VALUES BASED ON ELECTRICAL ENERGY INPUT
C LINE 5: INITIAL DATA
C Each file contains descriptor on line 1, number of points on line 2,
C time vs parameter on other lines or thermochems.
      READ (15, 5000) PRESIN
      READ (15, 5000) TRAVIN
      READ (15, 5000) ELECIN
```

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```
      READ (15, 5000) THERIN
      READ (15, 5000) INITIN
      CALL OUTPUT (1)
      CALL PRESS (1)
      CALL TRAVEL (1)
      CALL ELECTR (1)
      CALL INITIAL
      CALL THERM (1, IREAC)
      CALL OUTPUT (2)
C
C INITIALIZE AT TIME=0.
C SET UP ARRAY FOR WF TO FIND DERIVATIVE
      TIME = 0.0
      WF2 = 0.
      WFTIM (1) = 0.0
      WFCUM (1) = 0.0
      IEND = 0
      NWF = 1
      CALL PRESS (2)
      CALL TRAVEL (2)
      CALL THERM (2, IREAC)
      CALL OUTPUT (3)
C
C TAKE FIRST TIME STEP
      TIME = TIME + TIMINC
C
C INITIAL GUESS FOR MASS OF FLUID CONSUMED IN INITIAL
C ITERATE TO MATCH THERMOCHEMS WITH MASS CONSUMED
 1000 CONTINUE
      CALL PRESS (2)
      CALL TRAVEL (2)
      CALL ELECTR (2)
      M = 0
C
C IF IREAC=0, NO REACTION (EL EN DENSITY NOT LARGE ENOUGH)
C IF IREAC=1, REACTION
 1010 CONTINUE
      CALL THERM (2, IREAC)
      IF (IREAC .EQ. 0) THEN
        CALL SPMEAN
        CALL OUTPUT (3)
        TIME = TIME + TIMINC
        GO TO 1000
      END IF
C
      CALL STATE
C
C M IS COUNTER--CONVERGE BEFORE 100 STEPS OR SKIP
      IF (M .GT. 100) THEN
```

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```fortran
          WRITE (*, 6010) TIME
 6010     FORMAT(1X,' TIME=',F10.5,' NO CONVERGENCE')
          TIME = TIME + TIMINC
          GO TO 1000
        END IF
        IF ((ABS (WF1 - WF2)) .LE. TOL) THEN
C FILL ARRAY FOR WF TO FIND DERIVATIVE
          NWF = NWF + 1
          WFTIM (NWF) = TIME
          WFCUM (NWF) = WF2
          CALL OUTPUT (3)
          TIME = TIME + TIMINC
C
C END CONDITIONS
          IF (TIME .GT. TIMEND) GO TO 1020
          IF (WF2 .LE. 0.) GO TO 1020
C END IF ALL FLUID CONSUMED
          IF ((WF2 .GE. WFMASI) .AND. (IEND .EQ. 0)) THEN
            WRITE (*, *) ' All fluid consumed.'
            WRITE (*, *) ' Solution continues to balance energy.'
            IEND = 1
          END IF
C
C READY TO TAKE ANOTHER STEP
          WF1 = WF2
          GO TO 1000
        ELSE
          WF1 = WF2
          M = M + 1
          GO TO 1010
        END IF
C
 5000 FORMAT (A20)
C
C POST PROCESSING--TAKE DERIVATIVES
 1020 CONTINUE
      CALL OUTPUT (4)
      CLOSE (26, STATUS = 'KEEP')
      CLOSE (27, STATUS = 'KEEP')
      CLOSE (28, STATUS = 'KEEP')
      CLOSE (29, STATUS = 'KEEP')
      STOP
      END
C *********************************
      SUBROUTINE PRESS (IOPT)
C
      IMPLICIT REAL (A - H, O - Z)
      PARAMETER (NPT = 150, NPTT = 50)
      COMMON /NAME/ PRESIN, TRAVIN, ELECIN, THERIN, INITIN
```

```fortran
      COMMON /DATA/ PRTIM (1:NPT), PRES (1:NPT),
     1   TRTIM (1:NPT), TRAV (1:NPT),
     2   VEL (1:NPT), ELTIM (1:NPT), ELEC (1:NPT)
      COMMON /NUMBER/ NPR, NTR, NEL, NTH, ITRVEL, NWF
      COMMON /CURRENT/ TIME, PRESCH, TRAVPR,
     1   ELECEN, TEMP, RIMPET, GAMMA,
     2   COVOL, WF1, WF2, ELDEN, SPMPR, VELP, BETA, BASEPR, CM,
     3   Z, RHO, ENCOMP
C
      CHARACTER*20 PRESIN, TRAVIN, ELECIN, THERIN, INITIN, IDENT
C
C
C IOPT=1 READ FILE
C TIME IN MS, PRESSURE IN MPA
C CHANGE TIME TO SEC
C CHANGE PRESSURE FROM MPA TO CONSISTENT UNITS WITH CGS SYSTEM
C BY MULTIPLYING BY 1.0E7 CONVERSION CONSTANT
C
      IF (IOPT .EQ. 2) GO TO 1000
      OPEN (21, FILE = PRESIN, STATUS = 'OLD', IOSTAT = IOS, ERR = 1010)
      REWIND (21)
 1010 CONTINUE
      IF (IOS .NE. 0) WRITE (*, 6000) IOS
 6000    FORMAT(' ERROR OPENING PRESSURE FILE:',I5)
      READ (21, 5000) IDENT
      WRITE (*, 6010) PRESIN
C        WRITE(*,620) IDENT
      READ (21, *) NPR
      DO 1020 I = 1, NPR
        READ (21, *) PRTIM (I), PRES (I)
C CHANGE TO SEC AND CGS SYSTEM
        PRTIM (I) = PRTIM (I)*1.0E-3
        PRES (I) = PRES (I)*1.0E7
 1020 CONTINUE
      GO TO 1030
C
C IOPT=2 INTERPOLATE
 1000 CONTINUE
      TIMTOL = ABS (TIME - .1E-10)
      IF ((TIME .EQ. 0.0) .or. (TIMTOL .EQ. 0.)) THEN
        PRESCH = PRES (1)
        CALL SPMEAN
      END IF
      DO 1040 I = 2, NPR
        IF (TIME .EQ. PRTIM (I)) PRESCH = PRES (I)
        IF (TIME .GT. PRTIM (I - 1)) THEN
          PRESCH = PRES (I - 1) + (PRES (I) - PRES,(I - 1))*
     1        ((TIME - PRTIM (I - 1))/(PRTIM (I) - PRTIM (I - 1)))
        END IF
```

```
 1040 CONTINUE
C
 5000 FORMAT (A80)
 6010 FORMAT(' Pressure-time file:',A20)
 8000 FORMAT(' Pressure-time ident:',A20,/)
 1030 CONTINUE
      RETURN
      END
C ********************************
      SUBROUTINE TRAVEL (IOPT)
C
C DETERMINE PROJECTILE TRAVEL
C CALL SUBROUTINE TO DETERMINE PROJECTILE VELOCITY
      IMPLICIT REAL (A - H, O - Z)
      PARAMETER (NPT = 150, NPTT = 50)
      COMMON /NAME/ PRESIN, TRAVIN, ELECIN, THERIN, INITIN
      COMMON /DATA/ PRTIM (1:NPT), PRES (1:NPT),
     1   TRTIM (1:NPT), TRAV (1:NPT),
     2   VEL (1:NPT), ELTIM (1:NPT), ELEC (1:NPT)
      COMMON /NUMBER/ NPR, NTR, NEL, NTH, ITRVEL, NWF
      COMMON /CURRENT/ TIME, PRESCH, TRAVPR,
     1   ELECEN, TEMP, RIMPET, GAMMA,
     2   COVOL, WF1, WF2, ELDEN, SPMPR, VELP, BETA, BASEPR, CM,
     3   Z, RHO, ENCOMP
      COMMON /OPTIONS/ IBETA, ICOM
C
      CHARACTER*20 PRESIN, TRAVIN, ELECIN, THERIN, INITIN, IDENT
C
      IF ((IOPT .NE. 1) .AND. (IOPT .NE. 2))
     1   WRITE (*, *) ' Error in Subroutine Travel.'
C
C IOPT=1 READ FILE
C IF 2ND LINE IS 1: TIME IN MS, TRAVEL IN CM
C IF 2ND LINE IS 2: TIME IN MS, TRAVEL IS IN CM, VELOCITY IN CM/S
C CHANGE TIME TO SEC
C TRAVEL MUST BE IN CM
C VELOCITY IN CM/S
C
      IF (IOPT .EQ. 2) GO TO 1000
      OPEN (21, FILE = TRAVIN, STATUS = 'OLD', IOSTAT = IOS, ERR = 1010)
      REWIND (21)
 1010 CONTINUE
      IF (IOS .NE. 0) WRITE (*, 6000) IOS
 6000    FORMAT(' ERROR OPENING TRAVEL FILE:',I5)
      READ (21, 5000) IDENT
      WRITE (*, 6010) TRAVIN
C        WRITE(*,620) IDENT
C ITRVEL=1 FOR TIME, TRAVEL PAIRS
C ITRVEL=2 FOR TIME, TRAVEL, VELOCITY PAIRS
```

```
      READ (21, *) ITRVEL
      IF (ITRVEL .EQ. 1) WRITE (*, 6020)
      IF (ITRVEL .EQ. 2) WRITE (*, 6030)
      IF ((ITRVEL .NE. 1) .AND. (ITRVEL .NE. 2)) THEN
        WRITE (*, 6040)
        STOP
      END IF
      READ (21, *) NTR
      DO 1020 I = 1, NTR
C
C READ TIME-TRAVEL IF ITRVEL=1
C CHANGE TIME TO SEC
C **IBHVG2
C CHANGE TRAVEL TO CM (GIVEN IN .1 MM), VEL TO CM/SEC
C        IF (ITRVEL .EQ. 1) THEN
C          READ(21,*) TRTIM(I),TRAV(I)
C          TRTIM(I)=TRTIM(I)*1.0E-3
C          TRAV(I)=TRAV(I)*0.01
C        ENDIF
C
C READ TIME-TRAVEL-VELOCITY IF ITRVEL=2
C        IF (ITRVEL .EQ. 2) THEN
C          READ(21,*) TRTIM(I),TRAV(I),VEL(I)
C          TRTIM(I)=TRTIM(I)*1.0E-3
C          TRAV(I)=TRAV(I)*0.01
C          VEL(I)=VEL(I)*0.1
C        ENDIF
C***
C TIME IN MS, TRAVEL GIVEN IN CM
      IF (ITRVEL .EQ. 1) THEN
        READ (21, *) TRTIM (I), TRAV (I)
        TRTIM (I) = TRTIM (I)*1.0E-3
      END IF
C
 1020 CONTINUE
      GO TO 1030
C
C IOPT=2 INTERPOLATE
 1000 CONTINUE
      IF (TIME .EQ. 0.) THEN
        TRAVPR = TRAV (1)
        VELP = 0.0
      END IF
C
C ITRVEL=1 HAVE JUST TIME-TRAVEL
      IF (ITRVEL .EQ. 1) THEN
        DO 1040 I = 2, NTR
          IF (TIME .EQ. TRTIM (I)) THEN
            TRAVPR = TRAV (I)
```

```
            CALL VELPR (I)
            GO TO 1030
          END IF
          IF (TIME .GT. TRTIM (I - 1)) THEN
            TRAVPR = TRAV (I - 1) + (TRAV (I) - TRAV (I - 1))*
     1           ((TIME - TRTIM (I - 1))/(TRTIM (I) - TRTIM (I - 1)))
            CALL VELPR (I)
          END IF
 1040    CONTINUE
      END IF
C
C ITRVEL=2 HAVE TIME-TRAVEL-VELOCITY
      IF (ITRVEL .EQ. 2) THEN
        DO 1050 I = 2, NTR
          IF (TIME .EQ. TRTIM (I)) THEN
            TRAVPR = TRAV (I)
            VELP = VEL (I)
            GO TO 1030
          END IF
          IF (TIME .GT. TRTIM (I - 1)) THEN
            TRAVPR = TRAV (I - 1) + (TRAV (I) - TRAV (I - 1))*
     1           ((TIME - TRTIM (I - 1))/(TRTIM (I) - TRTIM (I - 1)))
            VELP = VEL (I - 1) + (VEL (I) - VEL (I - 1))*
     1           ((TIME - TRTIM (I - 1))/(TRTIM (I) - TRTIM (I - 1)))
          END IF
 1050    CONTINUE
      END IF
C
 5000 FORMAT (A80)
 6010 FORMAT(' Proj motion-time file:',A20)
 8000 FORMAT(' Proj motion-time ident:',A20,/)
 6020 FORMAT(' Proj travel-time file.',/)
 6030 FORMAT(' Proj velocity-time file.',/)
 6040 FORMAT(' Error--unknown type file.',/)
 1030 CONTINUE
      RETURN
      END
C ********************************
      SUBROUTINE ELECTR (IOPT)
C
      IMPLICIT REAL (A - H, O - Z)
      PARAMETER (NPT = 150, NPTT = 50)
      COMMON /NAME/ PRESIN, TRAVIN, ELECIN, THERIN, INITIN
      COMMON /DATA/ PRTIM (1:NPT), PRES (1:NPT),
     1   TRTIM (1:NPT), TRAV (1:NPT),
     2   VEL (1:NPT), ELTIM (1:NPT), ELEC (1:NPT)
      COMMON /NUMBER/ NPR, NTR, NEL, NTH, ITRVEL, NWF
      COMMON /CURRENT/ TIME, PRESCH, TRAVPR,
     1   ELECEN, TEMP, RIMPET, GAMMA,
```

```fortran
    2  COVOL, WF1, WF2, ELDEN, SPMPR, VELP, BETA, BASEPR, CM,
    3  Z, RHO, ENCOMP
       COMMON /OPTIONS/ IBETA, ICOM
C
       CHARACTER*20 PRESIN, TRAVIN, ELECIN, THERIN, INITIN, IDENT
C
       IF ((IOPT .NE. 1) .AND. (IOPT .NE. 2))
    1  WRITE (*, *) ' Error in Subroutine Electr.'
C
C IOPT=1 READ FILE
C ELECTRICAL ENERGY IS CUMULATIVE
C TIME IN MS, ELECTRICAL ENERGY IN kJ
C CHANGE TIME TO SEC
C
       IF (IOPT .EQ. 2) GO TO 1000
       OPEN (21, FILE = ELECIN, STATUS = 'OLD', IOSTAT = IOS, ERR = 1010)
       REWIND (21)
 1010  CONTINUE
       IF (IOS .NE. 0) WRITE (*, 6000) IOS
 6000    FORMAT(' ERROR OPENING ELECTRICAL ENERGY FILE:',I5)
       READ (21, 5000) IDENT
       WRITE (*, 6010) ELECIN
C       WRITE(*,620) IDENT
       READ (21, *) NEL
       DO 1020 I = 1, NEL
         READ (21, *) ELTIM (I), ELEC (I)
         ELTIM (I) = ELTIM (I)*1.0E-3
 1020  CONTINUE
       GO TO 1030
C
C IOPT=2 INTERPOLATE
 1000  CONTINUE
       IF (TIME .EQ. 0.) ELECEN = ELEC (1)
       DO 1040 I = 2, NEL
         IF (TIME .EQ. ELTIM (I)) ELECEN = ELEC (I)
         IF (TIME .GT. ELTIM (I - 1)) THEN
           ELECEN = ELEC (I - 1) + (ELEC (I) - ELEC (I - 1))*
    1          ((TIME - ELTIM (I - 1))/(ELTIM (I) - ELTIM (I - 1)))
         END IF
 1040  CONTINUE
C
 5000 FORMAT (A80)
 6010 FORMAT(' Electrical energy-time file:',A20)
 8000 FORMAT(' Electrical energy-time ident:',A20,/)
 1030 CONTINUE
       RETURN
       END
C *******************************
       SUBROUTINE INITIAL
```

```
C
      IMPLICIT REAL (A - H, O - Z)
      PARAMETER (NPT = 150, NPTT = 50)
      COMMON /NAME/ PRESIN, TRAVIN, ELECIN, THERIN, INITIN
      COMMON /START/ CHVOL, AREA, WFMASI, RHOI,
     1   PROJI, PROJW, TOL, TIMINC,
     2   TIMEND, WAIR, BM, DERBM
      COMMON /CURRENT/ TIME, PRESCH, TRAVPR,
     1   ELECEN, TEMP, RIMPET, GAMMA,
     2   COVOL, WF1, WF2, ELDEN, SPMPR, VELP, BETA, BASEPR, CM,
     3   Z, RHO, ENCOMP
      COMMON /OPTIONS/ IBETA, ICOM
C
      CHARACTER*20 PRESIN, TRAVIN, ELECIN, THERIN, INITIN, IDENT
C
      OPEN (21, FILE = INITIN, STATUS = 'OLD', IOSTAT = IOS, ERR = 1000)
      REWIND (21)
 1000 CONTINUE
      IF (IOS .NE. 0) WRITE (*, 6000) IOS
 6000 FORMAT(' ERROR OPENING INITIAL DATA FILE:',I5)
C
C CHAMBER VOLUME IN CM^3
C INITIAL PROJECTILE POSITION IN CM WITH 0.0 AT ORIGIN OF TUBE
C TUBE DIAMETER IN CM--AREA IN CM^2
C PROJECTILE MASS IN KG
C INITIAL MASS OF WORKING FLUID IN GRAMS
C DENSITY OF WORKING FLUID IN G/CM^3
C TIME INCREMENT IN SEC
      READ (21, 5000) IDENT
      WRITE (*, 6010) INITIN
C     WRITE(*,620) IDENT
      READ (21, *) CHVOL
      WRITE (*, 6020) CHVOL
C TUBE DIAMETER
      READ (21, *) DIAM
      AREA = 3.141592654*(DIAM/2.)*(DIAM/2.)
      WRITE (*, 6030) DIAM, AREA
C PROJECTILE INITIAL POSITION AND MASS (CHANGE KG TO G)
      READ (21, *) PROJI
      IF (PROJI .NE. 0.0) WRITE (*, *)
     1   ' Change needed--proj not zeroed.'
      READ (21, *) PROJW
      WRITE (*, 6040) PROJI, PROJW
      PROJW = PROJW*1000.
C WORKING FLUID INITIAL MASS
      READ (21, *) WFMASI
      WRITE (*, 6050) WFMASI
      READ (21, *) RHOI
      WRITE (*, 6060) RHOI
```

```
      RHO = RHOI
C TOLERANCE IN ITERATION
      READ (21, *) TOL
      WRITE (*, 6070) TOL
C TIME IN SEC
      READ (21, *) TIME
      READ (21, *) TIMINC
      READ (21, *) TIMEND
      WRITE (*, 6080) TIME, TIMINC, TIMEND
C INITIAL GUESS FOR MASS OF WORKING FLUID CONSUMED
      READ (21, *) WF1
      WRITE (*, 6090) WF1
C READ INITIAL VALUE OF BETA
C OPTIONS FOR BETA:
C      BETA IS INITIAL VALUE OF WORKING FLUID MOVING--
C         LAGRANGE ASSUMPTION IS BETA=1, I.E. ALL FLUID MOVES
C         IF BETA=0., FLUID IS AT REST
C      CHANGE FRACTION OF BETA MOVING IF IBETA=1
C         IF IBETA=0, LET BETA=CONSTANT (INITIAL VALUE)
C         IF IBETA=1, LET BETA=Z (FRACTION OF WF REACTED)
      READ (21, *) BETA, IBETA
      WRITE (*, 6100) BETA
      IF (IBETA .EQ. 1) THEN
        WRITE (*, 6110) IBETA
        Z = 0.
      END IF
C MASS OF AIR INITIALLY IN CHAMBER
      READ (21, *) WAIR
      WRITE (*, 6120) WAIR
C
C OPTION - COMPRESSION OF WORKING FLUID
C  IF ICOM=0, DO NOT CONSIDER COMPRESSION
C  IF ICOM=1, CONSIDER COMPRESSION
      READ (21, *) ICOM
      IF ((ICOM .NE. 0) .AND. (ICOM .NE. 1)) WRITE (*, *) 'Error--ICOM'
C BM=BULK MODULUS OF FLUID AT ONE ATMOSPHERE (MPa)
C DERBM=DERIVATIVE OF BULK MODULUS WITH RESPECT TO PRESSURE
      IF (ICOM .EQ. 1) THEN
        READ (21, *) BM, DERBM
        WRITE (*, 6130) BM, DERBM
C CHANGE TO CGS
        BM = BM*1.0E7
      END IF
C
5000 FORMAT (A80)
6010 FORMAT(' Initial data file:',A20)
8000 FORMAT(' Initial data ident:',A20)
6020 FORMAT(' Chamber volume (cm^3)=',F15.5)
6030 FORMAT(' Tube diameter (cm)=',F6.1,2x,' Area (cm^2)=',F12.5)
```

```
6040 FORMAT(' Projectile position (cm)=',F10.5,
     1          2X,/' Projectile mass (kg)=',F10.2)
6050 FORMAT(' Working fluid mass (g)='F10.5)
6060 FORMAT(' Initial working fluid density (g/cm^3)=',F10.5)
6070 FORMAT(' Tolerance required in mass consumed=',F10.5)
6080 FORMAT(' Time start (sec)=',F10.8,/' Time increment (sec)=',
     1     F10.8,/' Time end (sec)=',F10.8)
6090 FORMAT(' Initial guess for mass consumed (g)=',F10.5)
6100 FORMAT(' Initial value of beta, fraction of wf moving (-)=',F10.5)
6110 FORMAT(' Option: ibeta=',I5,/,
     1'   If ibeta=0 fraction moving is constant',/,
     2'   If ibeta=1, fraction moving=fraction decomposed')
6120 FORMAT(' Mass of air initially in chamber (g)=',F10.5)
6130 FORMAT(' Bulk modulus of WF at one atmosphere (MPa)=',F10.5,/,
     1' Derivative of bulk modulus wrt pressure (-)=',F10.5,/)
C
      CLOSE (21)
      RETURN
      END
C *******************************
      SUBROUTINE THERM (IOPT, IREAC)
C
      IMPLICIT REAL (A - H, O - Z)
      PARAMETER (NPT = 150, NPTT = 50)
      COMMON /NAME/ PRESIN, TRAVIN, ELECIN, THERIN, INITIN
      COMMON /NUMBER/ NPR, NTR, NEL, NTH, ITRVEL, NWF
      COMMON /START/ CHVOL, AREA, WFMASI, RHOI,
     1 PROJI, PROJW, TOL, TIMINC,
     2 TIMEND, WAIR, BM, DERBM
      COMMON /CURRENT/ TIME, PRESCH, TRAVPR,
     1 ELECEN, TEMP, RIMPET, GAMMA,
     2 COVOL, WF1, WF2, ELDEN, SPMPR, VELP, BETA, BASEPR, CM,
     3 Z, RHO, ENCOMP
      COMMON /OPTIONS/ IBETA, ICOM
      COMMON /THERMO/ ELDEN1 (1:NPTT), TEMP1 (1:NPTT), RIMP1 (1:NPTT),
     1 GAMMA1 (1:NPTT), COVOL1 (1:NPTT)
C
      CHARACTER*20 PRESIN, TRAVIN, ELECIN, THERIN, INITIN, IDENT
C
      IF ((IOPT .NE. 1) .AND. (IOPT .NE. 2))
     1 WRITE (*, *) ' Error in Subroutine Electr.'
C
C IOPT=1 READ FILE
      IF (IOPT .EQ. 2) GO TO 1000
C BASED ON AMOUNT OF ELECTRICAL ENERGY INPUT
      OPEN (21, FILE = THERIN, STATUS = 'OLD', IOSTAT = IOS, ERR = 1010)
      REWIND (21)
1010 CONTINUE
      IF (IOS .NE. 0) WRITE (*, 6000) IOS
```

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```
6000 FORMAT(' ERROR OPENING THERMOCHEM DATA FILE:',I5)
C
C ELECTRICAL ENERGY DENSITY (Elec en/mass fluid in chamber) IN kJ/G
C TEMPERATURE IN K
C IMPETUS IN J/G
C GAMMA, RATIO OF SPECIFIIC HEAT, UNITLESS
C COVOLUME IN CM^3/G
C CONVERT JOULES TO CGS: 1 JOULE=1.0E7 G-CM^2/S^2
      READ (21, 5000) IDENT
      WRITE (*, 6010) THERIN
C     WRITE(*,620) IDENT
      READ (21, *) NTH
      DO 1020 I = 1, NTH
        READ (21, *) ELDEN1 (I), TEMP1 (I), RIMP1 (I),
     1     GAMMA1 (I), COVOL1 (I)
C ELECTRICAL ENERGY DENSITY IN kJ/G
        RIMP1 (I) = RIMP1 (I)*1.0E+7
 1020 CONTINUE
      GO TO 1030
C
 1000 CONTINUE
C ELECTRICAL ENERGY DENSITY=CUMULATIVE ELEC ENERGY/CUMULATIVE WF REACTED
      IF (WF1 .LT. 0.0) THEN
        WRITE (*, 6020)
      END IF
C ASSUME FIRST LINE OF TABLE IS 0.
      IF ((WF1 .LE. 0.) .OR. (TIME .EQ. 0.)) THEN
        TEMP = TEMP1 (1)
        RIMPET = RIMP1 (1)
        GAMMA = GAMMA1 (1)
        COVOL = COVOL1 (1)
        GO TO 1030
      END IF
C
      IF (WF1 .GT. 0.) ELDEN = ELECEN/WF1
C
C IF WF CONSUMED, FIX THERMOCHEMS AT FINAL VALUE
      IF (WF1 .GT. WFMASI) ELDEN = ELECEN/WFMASI
C
C IF EL EN DENSITY NOT LARGE ENOUGH FOR REACTION,
C COMMUNICATE TO MAIN WITH IREAC=0 AND SKIP THIS STEP
      IF (ELDEN .LT. ELDEN1 (1)) THEN
        IREAC = 0
        GO TO 1030
      END IF
C
      DO 1040 I = 2, NTH
        IF (ELDEN .EQ. ELDEN1 (I)) THEN
          TEMP = TEMP1 (I)
```

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            RIMPET = RIMP1 (I)
            GAMMA = GAMMA1 (I)
            COVOL = COVOL1 (I)
         END IF
         IF (ELDEN .GT. ELDEN1 (I - 1)) THEN
            TEMP = TEMP1 (I - 1) + (TEMP1 (I) - TEMP1 (I - 1))*
     1         ((ELDEN - ELDEN1 (I - 1))/(ELDEN1 (I) - ELDEN1 (I - 1)))
            RIMPET = RIMP1 (I - 1) + (RIMP1 (I) - RIMP1 (I - 1))*
     1         ((ELDEN - ELDEN1 (I - 1))/(ELDEN1 (I) - ELDEN1 (I - 1)))
            GAMMA = GAMMA1 (I - 1) + (GAMMA1 (I) - GAMMA1 (I - 1))*
     1         ((ELDEN - ELDEN1 (I - 1))/(ELDEN1 (I) - ELDEN1 (I - 1)))
            COVOL = COVOL1 (I - 1) + (COVOL1 (I) - COVOL1 (I - 1))*
     1         ((ELDEN - ELDEN1 (I - 1))/(ELDEN1 (I) - ELDEN1 (I - 1)))
         END IF
         IREAC = 1
 1040 CONTINUE
C
C IF FALL OUTSIDE ARRAY
      IF (ELDEN .GT. ELDEN1 (NTH)) THEN
         TEMP = TEMP1 (NTH)
         RIMPET = RIMP1 (NTH)
         GAMMA = GAMMA1 (NTH)
         COVOL = COVOL1 (NTH)
         WRITE (26, *) ' OUTSIDE THERM ARRAY'
      END IF
C
 5000 FORMAT (A80)
 6010 FORMAT(' Thermochemical data file:',A20)
 8000 FORMAT(' Thermochemical data ident:',A20,/)
 6020 FORMAT(' Error in Subroutine Electr--El En Density negative.')
C
 1030 CONTINUE
      RETURN
      END
C ******************************
      SUBROUTINE STATE
C
      IMPLICIT REAL (A - H, O - Z)
      COMMON /START/ CHVOL, AREA, WFMASI, RHOI,
     1   PROJI, PROJW, TOL, TIMINC,
     2   TIMEND, WAIR, BM, DERBM
      COMMON /CURRENT/ TIME, PRESCH, TRAVPR,
     1   ELECEN, TEMP, RIMPET, GAMMA,
     2   COVOL, WF1, WF2, ELDEN, SPMPR, VELP, BETA, BASEPR, CM,
     3   Z, RHO, ENCOMP
      COMMON /OPTIONS/ IBETA, ICOM
C
C DETERMINE SPACE-MEAN PRESSURE
      CALL SPMEAN
```

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```
C
C IF ICOM=0, DO NOT CONSIDER COMPRESSION OF WF
C IF ICOM=1, CONSIDER COMPRESSION OF WF
C    ENCOMP IS ENERGY PER UNIT MASS STORED BY COMPRESSED FLUID
C       --NEED TO MULTIPLY BY AMT OF FLUID UNVAPORIZED
      IF (ICOM .EQ. 0) THEN
        RHO = RHOI
        ENCOMP = 0.0
      END IF
      IF (ICOM .EQ. 1) CALL COMPRES
C
C CUMULATIVE FLUID CONSUMED FROM ENERGY EQN, P 105, BK 9
      GAM1 = GAMMA - 1.
      DIV = RIMPET/GAM1 + SPMPR*(COVOL/GAM1 - 1./(RHO*GAM1))
C
      TOP = (CHVOL - WFMASI/RHO + TRAVPR*AREA)*(SPMPR/GAM1)
     1    + VELP*VELP*((1./6.)*CM*PROJW + .5*PROJW)
     2    + (1. - Z)*WFMASI*ENCOMP
C
      Z = (1./WFMASI)*(TOP/DIV)
      WF2 = Z*WFMASI
C
      RETURN
      END
C ********************************
      SUBROUTINE SPMEAN
C
      IMPLICIT REAL (A - H, O - Z)
      COMMON /START/ CHVOL, AREA, WFMASI, RHOI,
     1   PROJI, PROJW, TOL, TIMINC,
     2   TIMEND, WAIR, BM, DERBM
      COMMON /CURRENT/ TIME, PRESCH, TRAVPR,
     1   ELECEN, TEMP, RIMPET, GAMMA,
     2   COVOL, WF1, WF2, ELDEN, SPMPR, VELP, BETA, BASEPR, CM,
     3   Z, RHO, ENCOMP
      COMMON /OPTIONS/ IBETA, ICOM
C
C SPACE MEAN PRESSURE EQUALS CHAMBER PRESSURE (IF EXPERIMENTAL)
C    SPMPR=PRESCH
C
C SPACE-MEAN PRESSURE FROM LAGRANGE GRADIENT
C ASSUME PRESCH IS A PRESSURE MEASUREMENT AT THE BREECH
C INCREASE PROJECTILE MASS BY 5% TO ACCOUNT FOR FRICTION
C CHARGE TO MASS RATIO, CM, IS INITIAL MASS OF WORKING FLUID
C   DIVIDED BY MASS OF PROJECTILE
C    projw=1.05*PROJW
C For test case, no friction
      ALPHA = WF2/WFMASI
C
```

```
C CONSIDER BETA=FRACTION OF FLUID WHICH MOVES
C IF BETA=0., ALL THE FLUID IS AT REST
C IF BETA=1., ALL THE WF MOVES (LAGRANGE ASSUMP)
      IF (IBETA .EQ. 1) BETA = Z
      CM = (WFMASI*(ALPHA + BETA*(1. - ALPHA)) + WAIR)/PROJW
      IF (CM .LE. 0.0) WRITE (*, *) ' Error in Spmean--C/M <= 0.'
      SPMPR = ((1. + 1./3.*CM)/(1. + 1./2.*CM))*PRESCH
      BASEPR = (1./(1. + 1./3.*CM))*SPMPR
C
      RETURN
      END
C *******************************
      SUBROUTINE COMPRES
C
C DETERMINE DENSITY OF COMPRESSED WORKING FLUID
C DETERMINE ENERGY OF COMPRESSION
C
      IMPLICIT REAL (A - H, O - Z)
      PARAMETER (NPT = 150, NPTT = 50)
      COMMON /START/ CHVOL, AREA, WFMASI, RHOI,
     1    PROJI, PROJW, TOL, TIMINC,
     2    TIMEND, WAIR, BM, DERBM
      COMMON /CURRENT/ TIME, PRESCH, TRAVPR,
     1    ELECEN, TEMP, RIMPET, GAMMA,
     2    COVOL, WF1, WF2, ELDEN, SPMPR, VELP, BETA, BASEPR, CM,
     3    Z, RHO, ENCOMP
      COMMON /OPTIONS/ IBETA, ICOM
      COMMON /DATA/ PRTIM (1:NPT), PRES (1:NPT),
     1    TRTIM (1:NPT), TRAV (1:NPT),
     2    VEL (1:NPT), ELTIM (1:NPT), ELEC (1:NPT)
C
C LET BULK MODULUS BE AT MOST A LINEAR FCN OF PRESSURE
      IF (BM .LE. 0.0) WRITE (*, *) 'ERROR--BM<=0.0'
      IF (DERBM .EQ. 0.0) THEN
        RHO = RHOI*(1. + (PRESCH - PRES (1))/BM)
      ELSE
        RHO = RHOI*(1. + (DERBM/BM)*(PRESCH - PRES (1)))**(1./DERBM)
      END IF
C
C ENERGY PER UNIT MASS STORED BY COMPRESSED FLUID
      IF ((DERBM .EQ. 0.0) .OR. (DERBM .EQ. 1.0)) THEN
        ENCOMP = - 1.*(PRESCH - PRES (1))/RHO + (BM/RHOI)*
     1      LOG (1. + (PRESCH - PRES (1))/BM)
      ELSE
        ENCOMP = - 1.*(PRESCH - PRES (1))/RHO + (BM +
     1      DERBM*(PRESCH - PRES (1)))
     2      /((DERBM - 1.)*RHO) - BM/((DERBM - 1.)*RHOI)
      END IF
C
```

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      RETURN
      END
C ********************************
      SUBROUTINE VELPR (I)
C
C DETERMINE PROJECTILE VELOCITY
C
      IMPLICIT REAL (A - H, O - Z)
      PARAMETER (NPT = 150, NPTT = 50)
      COMMON /DATA/ PRTIM (1:NPT), PRES (1:NPT),
     1    TRTIM (1:NPT), TRAV (1:NPT),
     2    VEL (1:NPT), ELTIM (1:NPT), ELEC (1:NPT)
      COMMON /NUMBER/ NPR, NTR, NEL, NTH, ITRVEL, NWF
      COMMON /START/ CHVOL, AREA, WFMASI, RHOI,
     1    PROJI, PROJW, TOL, TIMINC,
     2    TIMEND, WAIR, BM, DERBM
      COMMON /CURRENT/ TIME, PRESCH, TRAVPR,
     1    ELECEN, TEMP, RIMPET, GAMMA,
     2    COVOL, WF1, WF2, ELDEN, SPMPR, VELP, BETA, BASEPR, CM,
     3    Z, RHO, ENCOMP
      COMMON /OPTIONS/ IBETA, ICOM
C
C CENTERED DIFFERENCE
      IF (I .EQ. NTR) THEN
         VELP = (TRAV (I) - TRAV (I - 2))/(2.*
     1       (TRTIM (I) - TRTIM (I - 1)))
      ELSE
         VELP = (TRAV (I + 1) - TRAV (I - 1))/(2.*
     1       (TRTIM (I) - TRTIM (I - 1)))
      END IF
C
      RETURN
      END
C ********************************
      SUBROUTINE DER (TIME, IOPT, AMT, AMTDER)
C
C FINDS DERIVATIVES:  USED FOR dE/dt and dWF/dt
C ASSUMES CONSTANT STEP SIZE FOR TIME
C
      IMPLICIT REAL (A - H, O - Z)
      PARAMETER (NPT = 150, NPTT = 50)
      COMMON /DATA/ PRTIM (1:NPT), PRES (1:NPT),
     1    TRTIM (1:NPT), TRAV (1:NPT),
     2    VEL (1:NPT), ELTIM (1:NPT), ELEC (1:NPT)
      COMMON /OUT/ WFTIM (NPT), WFCUM (NPT)
      COMMON /NUMBER/ NPR, NTR, NEL, NTH, ITRVEL, NWF
C
C IF IOPT=1, FIND DER OF ENERGY
C IF IOPT=2, FIND DER OF WF
```

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```
      IF (IOPT .EQ. 1) GO TO 1000
      IF (IOPT .EQ. 2) GO TO 1010
C
      IF ((ABS (TIME - 1.E-10)) .EQ. 0.0) THEN
         AMT = 0.0
         AMTDER = 0.0
         GO TO 1020
      END IF
C
C IOPT=1, DERIVATIVE OF ELEC EN
 1000 CONTINUE
      DO 1030 I = 2, NEL
        IF (TIME .EQ. ELTIM (I)) THEN
           AMT = ELEC (I)
           IMARK = I
           GO TO 1040
        END IF
        IF (TIME .GT. ELTIM (I - 1)) THEN
           AMT = ELEC (I - 1) + (ELEC (I) - ELEC (I - 1))*
     1        ((TIME - ELTIM (I - 1))/(ELTIM (I) - ELTIM (I - 1)))
           IMARK = I
        END IF
 1030 CONTINUE
C IF GREATER THAN LAST POINT, USE LAST POINT
C CENTERED DIFFERENCE
 1040 CONTINUE
      IF (IMARK .EQ. NEL) THEN
         AMT = ELEC (NEL)
         AMTDER = (ELEC (IMARK) - ELEC (IMARK - 2))/(2.*(ELTIM (IMARK)
     1      - ELTIM (IMARK - 1)))
      ELSE
         AMTDER = (ELEC (IMARK + 1) - ELEC (IMARK -
     1      1))/(2.*(ELTIM (IMARK)
     2      - ELTIM (IMARK - 1)))
      END IF
C
      GO TO 1020
C
C IOPT=2 DERIVATIVE OF WF
 1010 CONTINUE
C
      DO 1050 I = 2, NWF
        IF (TIME .EQ. WFTIM (I)) THEN
           AMT = WFCUM (I)
           IMARK = I
           GO TO 1060
        END IF
        IF (TIME .GT. WFTIM (I - 1)) THEN
           AMT = WFCUM (I - 1) + (WFCUM (I) - WFCUM (I - 1))*
```

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     1        ((TIME - WFTIM (I - 1))/(WFTIM (I) - WFTIM (I - 1)))
            IMARK = I
         END IF
 1050 CONTINUE
C IF GREATER THAN LAST POINT, USE LAST POINT
C CENTERED DIFFERENCE
 1060 CONTINUE
      IF (IMARK .EQ. NWF) THEN
         AMT = WFCUM (NWF)
         AMTDER = (WFCUM (IMARK) - WFCUM (IMARK - 2))/(2.*(WFTIM (IMARK)
     1        - WFTIM (IMARK - 1)))
      ELSE
         AMTDER = (WFCUM (IMARK + 1) - WFCUM (IMARK -
     1        1))/(2.*(WFTIM (IMARK)
     2        - WFTIM (IMARK - 1)))
      END IF
C
 1020 CONTINUE
      RETURN
      END
C *******************************
      SUBROUTINE OUTPUT (IOPT)
C
      IMPLICIT REAL (A - H, O - Z)
      PARAMETER (NPT = 150, NPTT = 50)
      COMMON /START/ CHVOL, AREA, WFMASI, RHOI,
     1    PROJI, PROJW, TOL, TIMINC,
     2    TIMEND, WAIR, BM, DERBM
      COMMON /CURRENT/ TIME, PRESCH, TRAVPR,
     1    ELECEN, TEMP, RIMPET, GAMMA,
     2    COVOL, WF1, WF2, ELDEN, SPMPR, VELP, BETA, BASEPR, CM,
     3    Z, RHO, ENCOMP
      COMMON /OPTIONS/ IBETA, ICOM
      COMMON /DATA/ PRTIM (1:NPT), PRES (1:NPT),
     1    TRTIM (1:NPT), TRAV (1:NPT),
     2    VEL (1:NPT), ELTIM (1:NPT), ELEC (1:NPT)
      COMMON /OUT/ WFTIM (NPT), WFCUM (NPT)
      COMMON /NUMBER/ NPR, NTR, NEL, NTH, ITRVEL, NWF
      COMMON /NAME/ PRESIN, TRAVIN, ELECIN, THERIN, INITIN
      CHARACTER*20 PRESIN, TRAVIN, ELECIN, THERIN, INITIN
C
C FILE 28 IS OUTPUT FOR DETAILS OF WORKING FLUID
C FILE 27 IS ENERGY BALANCE
C FILE 26 IS ERROR FILE AND MESSAGES
      IF (IOPT .EQ. 1) THEN
         WRITE (*, 6000)
         OPEN (26, FILE = 'MESSAGES.OUT')        .
         OPEN (27, FILE = 'ENERGY.OUT')
         OPEN (28, FILE = 'WORKFL.OUT')
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      OPEN (29, FILE = 'COMPRESS.OUT')
      GO TO 1000
      END IF
      IF (IOPT .EQ. 2) GO TO 1010
      IF (IOPT .EQ. 3) GO TO 1020
      IF (IOPT .EQ. 4) GO TO 1030
C
 1010 CONTINUE
      WRITE (*, 6010)
      WRITE (*, 6020)
      WRITE (27, 6030)
      WRITE (28, 6040)
      WRITE (29, 6050)
      GO TO 1000
C
 1020 CONTINUE
C CHANGE TO MPa AND TO JOULES
      TIMMS = TIME*1.0E+3
      PRESCH = PRESCH*1.0E-7
      BASEPR = BASEPR*1.0E-7
      SPMPR = SPMPR*1.0E-7
      WRITE (*, 6060) TIMMS, PRESCH, BASEPR, TRAVPR, VELP, ELDEN, WF2
      write (26, 6070) timms, presch, basepr
      rimpet = rimpet*1.0e-7
      enused = (rimpet/(gamma - 1.))*wf2
      enkp = .5*projw*velp*velp*1.0e-7
      alpha = wf2/wfmasi
      cm = (wfmasi*(alpha + beta*(1. - alpha)) + wair)/projw
      enkg = (1./6.)*cm*projw*velp*velp*1.0e-7
      vol = chvol - covol*wf2 - (wfmasi - wf2)/rho + travpr*area
      enigas = spmpr*vol/(gamma - 1.)
      encom = (1. - z)*wfmasi*encomp*1.0e-7
      if (enused .ne. 0.0)
    1    enerr = ((enused - enkp - enkg - enigas - encom)/enused)*100.
      write (27, 6080) timms, enused, enkp, enkg, enigas, encom, enerr
      write (29, 6090) timms, rho, encomp, encom
C
      GO TO 1000
C
C IF IOPT=1, FIND DER OF ENERGY
C IF IOPT=2, FIND DER OF WF
 1030 CONTINUE
      TIME = 0.0
      TIMEND = WFTIM (NWF)
      TIM2 = 0.0
      EL = 0.0
      WF = 0.0
      ELDEN = 0.0
      ELDER = 0.0
```

```fortran
          WFDER = 0.0
          WRITE (28, 6100) TIM2, EL, WF, ELDEN, ELDER, WFDER
          DO 1040 I = 1, NPT
            TIME = TIME + TIMINC
            IF (TIME .LE. TIMEND) THEN
              CALL DER (TIME, 1, EL, ELDER)
              CALL DER (TIME, 2, WF, WFDER)
              IF (WF .NE. 0.0) ELDEN = EL/WF
              TIM2 = TIME*1.E+3
C ELDEN IN MJ/s, WFDER IN kg/s
              ELDER = ELDER*.001
              WFDER = WFDER*.001
              WRITE (28, 6100) TIM2, EL, WF, ELDEN, ELDER, WFDER
            ELSE
              GO TO 1000
            END IF
 1040 CONTINUE
C
 6000 FORMAT(/,' Inverse Electrothermal Gun Code',//)
 6010 FORMAT(1X,' TIME ',2X,'CHAM PR',2X,
     1       ' BASE PR ',3X,'PROJ TRAV',2X,' PROJ VEL',5X,'EL EN DEN',
     2       2X,'CUM WF')
 6020 FORMAT(2X,' (ms) ',2x,2x,'(MPa)',3x,2x,1x,'(MPa)',1x,2x,
     1       2x,'(cm)',3x,2x,3x,'(cm/s)',2x,2x,2x,'(MJ/kg)',1X,
     2       2X,1X,'(g)',/)
 6060 FORMAT(1X,F6.2,2X,F7.2,2X,F10.5,2X,F9.4,2X,F10.2,2X,F9.3,2X,F10.5)
 6070 format(1x,f6.2,2x,f15.7,2x,f15.7)
 6030 format(1x,'ENERGY BALANCE',//,
     1       1x,'time',7x,'enused',10x,'KE proj',9x,'KE gas',8x,
     2       'Intgas',5x,'En comp',5x,'Error %',
     3       /,1x,'(ms)',7x,' (J) ',11x,' (J) ',9x,' (J) ',10x,' (J)',
     4       10x,' (J)')
 6080 format(1x,f10.3,1x,f15.2,1x,f10.2,1x,f10.2,1x,f12.2,1X,F10.2,1x,
     1       F6.1)
 6040 FORMAT(1x,'WORKING FLUID AND ELECTRICAL ENERGY SUMMARY',//,
     1       1x,1x,'TIME',1x,3x,'EL EN',2x,5x,'WF CUMULATIVE',1X,1x,
     2       'EL EN DENSITY',1x,'ELEC DER',1X,2x,'WF DER',
     3       /,1x,1X,'(ms)',1X,3x,'(kJ)',3X,11X,'(G)',6x,4X,'(MJ/kg)',5X,
     4       2x,'(MJ/s)',2X,3x,'(kg/s)')
 6100 FORMAT(1x,f6.3,1x,f10.2,1x,f15.5,1x,f15.5,1x,f10.2,1x,f10.2)
 6050 FORMAT(1x,'timms(ms),rho(g/cc),encomp(J/g),encom(J)')
 6090 FORMAT(1x,f6.3,1x,f8.5,1x,f20.5,1x,f10.5)
C
 1000 CONTINUE
      RETURN
      END
C ********************************
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