Expanded Ignition Effectiveness Tests of Selected Igniter Materials with Navy Propellants

Contract No. N00174-81-C-0453
Mod P00006

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FINAL REPORT

on

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Performance Period
October 1982 - September 1983

Submitted to
Gun Systems Engineering
Naval Ordnance Station
Indian Head, MD 20640

Submitted by
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**Varney, A. Michael and Martino, John**

**Applied Combustion Technology, Inc.**

**Gun Systems Engineering**

**Naval Ordnance Station**

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**Diagnostic ignition experiments have been conducted using a high-pressure flow through combustor to evaluate the ignition effectiveness of black powder, boron potassium nitrate, magnesium-teflon-viton, nitrocellulose, boron molybdenum trioxide and ammonium perchlorate with five propellants—NACO, NOSOL-318, NOSOL 363, LOVA, and PYRO. Twenty-one (21) series of experiments have been conducted to determine the**
20. Ability of various igniter materials to ignite gun propellants beyond the immediate vicinity of the gun igniter—that is after filtering through and being cooled by an inert propellant simulant zone positioned between the igniter and the live propellant. The ignition effectiveness has been determined quantitatively by the amount of igniter thermal energy, based on its heat of explosion, required to ignite a propellant 50 percent of the time. Analyses and results are given which present the relative effectiveness of the igniter materials in terms of the different ignition stimuli (e.g., gases, liquids, and solids ratios).
This report summarizes project analyses and results for the experimental documentation of the ignition effectiveness of BP, BKNO₃, NC, MTV, BMoO₃, and AP igniter materials with NACO, NOSOL-318, NOSOL-363, LOVA, and PYRO propellants. The experimental program was conducted under Contract N00174-81-C-0453, Mod P00006 for the Naval Ordnance Station, Indian Head, Maryland from October 1982 to September 1983 by Applied Combustion Technology, Inc., Orlando, Florida. Mr. Charles Irish served as technical monitor for NOSIH and Dr. Michael Varney served as Principal Investigator for Applied Combustion Technology, Inc.
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1.0 INTRODUCTION

1.1 Background

Diagnostic experiments have been conducted to characterize the ignition effectiveness of selected igniter materials with Navy propellants under simulated gun firing conditions. Experimental firings have been conducted with a high pressure, flow through combustor to determine the ability of various igniter materials to ignite gun propellants beyond the immediate vicinity of the gun igniter—that is after filtering through and being cooled by an inert propellant simulant zone positioned between the igniter vents and the live propellant. Ignition effectiveness is determined quantitatively by the amount of igniter thermal energy, based on its heat of explosion, required to ignite a propellant 50 percent of the time. With the determination of the ignition effectiveness of a variety of ignition materials which have a wide range in their distribution of physical states, one can in principle determine the more effective combinations of physical states (hot gases, vapors, liquids, and solids), heat of explosion, flame temperature, and oxidizer content leading to effective igniter characterization. Successful implementation of this approach would then provide a basis for searching for better igniter materials for existing primers, or for new igniter designs for new guns, or for existing guns with difficult ignition conditions.

1.2 Summary

In previously completed efforts (Ref. 1), Applied Combustion Technology, Inc. conducted seventeen (17) series of ignition effectiveness tests with NACO, NOSOL-318, and NOSOL-363 propellants using BP, BKNO₃,
MTV, and BMOO₃ igniter materials. The previous results, presented in References 1 and 2, are complemented by twenty-one (21) additional experimental series in the current project, bringing the total data base to 37 Bruceton-style ignition effectiveness test series (one series for BMOO₃ was inconclusive and is not included in the data reduction).

During the current project, Applied Combustion Technology, Inc. has achieved the following goals:

1. Conducted twenty-one (21) series of ignition effectiveness tests with NACO, LOVA, NOSOL-318 and PYRO propellants using BP, BKNO₃, NC, MTV, BMOO₃, and AP igniter materials.

2. Conducted Bruceton sensitivity analyses to determine 50 percent firepoint ignition energy levels for all 37 series of ignition effectiveness test data using new, experimentally determined NOSIH heat of explosion data.

3. Developed an analytical data reduction model to correct igniter charge energy levels for convective losses to an inert simulant packed bed.

Comparisons between experimentally determined data and theoretical calculations are presented herein with test data, analyses, and conclusions. Of the data acquired, the firing results of NACO and LOVA propellants are the most complete. A review of the composite firing data suggests that igniter product gas phase mass fractions on the order of 30-50 percent are essential for propellant ignition at minimum input pressure levels. Further, the results obtained suggest the importance of
igniter product liquid phase mass fractions for achieving an in-depth propellant ignition boundary. LCVA 50 percent ignition energy levels were observed to be 2-3 times greater than observed for NACO propellant. LOVA ignition energy requirements were found to be significantly reduced by the presence of oxidizer species in the igniter (AP); LOVA ignition sensitivity with AP was equivalent to the energy requirements for the easy-to-ignite NACO propellant with conventional materials.
2.0 EXPERIMENTAL

2.1 Hardware Description

Ignition effectiveness experiments have been conducted using a high pressure, flow through combustor, Figure 2.1. The igniter assembly is designed to accommodate a 20 mm electric primer which is used to initiate up to one cubic inch (16 cm$^3$) of pyrotechnic material; igniter discharge into the combustion chamber bore is via five axial vents arranged symmetrically about a centerline vent. The internal volume of the combustion chamber is 620 cm$^3$, minus the volume of the igniter vent assembly, and is equipped with six access ports to monitor pressure response and/or light generation during propellant ignition and flame spreading. Aft end closure of the combustion chamber is achieved by an axially ported insert which is sized to permit pressure buildup during propellant ignition and adequate venting during combustion. A complete hardware description is provided in Reference 3.

2.2 Experimental Procedures

2.2.1 Igniter Calibration Tests

Each of the igniter materials utilized in the ignition effectiveness tests was evaluated for output performance (bed input) by installing a pressure transducer into the centerline axial vent and firing into the IECD bore, which had been filled with inert simulant to provide propellant back pressure effects on the igniter outflow. A three point curve was generated for each igniter material as a function of igniter charge loading for the igniter masses shown in Table 2.1.
NOTE: Zone 1 - Inert Simulant Bed Length ($L_1$)
Zone 2 - Live Propellant Bed Length ($L_2$)
Zone 3 - Inert Simulant Bed Length ($L_3$)
Table 2.1 Igniter Calibration Test Series

<table>
<thead>
<tr>
<th>BP</th>
<th>BKNO₃</th>
<th>NC</th>
<th>MTV</th>
<th>AP</th>
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<tr>
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Each igniter calibration record was utilized for analytical treatment of the ignition effectiveness data and is presented in Section 3.0, Data Analysis.

2.2.2 Ignition Effectiveness Tests

Ignition effectiveness tests were conducted using the IECD with fixed zone lengths of inert simulant separating the igniter vent exit plane and the live propellant zone, as shown in Figure 2.2. Diagnostic firings were conducted for selected combinations of six igniter materials, five propellants, and four inert simulant zone lengths, as shown in Table 2.2. Seventeen (17) series of tests were previously conducted (Ref. 1) and twenty-one (21) new series of test data have been generated in the current project; data and data analyses for 37 series of tests is presented herein. Igniter material characterization and propellant characterization are presented in Tables 2.3 and 2.4, respectively. Heat of explosion values were experimentally determined by NOSIH using a Parr bomb pressurized with nitrogen to 25 atmospheres. Other values shown in Table 2.3 were calculated using NASA-Lewis chemical equilibrium calculations for a chamber pressure of 500 psia expanding to 14.7 psi. Ignition effectiveness was determined quantitatively by the amount of thermal energy, based on its heat of explosion, required
Figure 2.2 Igniter Assembly and Typical Test Configuration
### Table 2.2
**IECD BRUCETON TEST MATRIX**

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Table 2.3 Igniter Material Characterization  
(NASA-Lewis)

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<th>MTV</th>
<th>AP</th>
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<td>100.0</td>
<td>90.8</td>
<td>100.0</td>
<td>75.6*</td>
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*Balance Water Vapor

1Material  Composition
1-BP  Black powder (ffg)
2-BKNO₃ 23.7% B, 70.7% KNO₃, 5.6% Laminac
3-NC IMR 4895
4-MTV Magnesium-Teflon-Viton (54%/30%/16%)
5-AP Ammonium perchlorate
Table 2.4 Propellant Geometrical Characterization

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<th>Propellant</th>
<th>Grain Dimensions</th>
<th>Charge (g)</th>
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<th>Bed Length (in)</th>
<th>Porosity (d'less)</th>
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1 Seven (7) perf grains
2 CAB/ATEC
to ignite the propellant 50 percent of the time as determined by an up-and-down (Bruceton) test technique (Reference 4). Each test grouping included a series of pre-Bruceton shots to determine the approximate 50 percent firepoint as the starting energy level for a limited Bruceton series consisting of ten (10) shots each. Test data for each event included a Yes/No fire observation and an in-bore oscilloscope record of the pressure-time profile resulting from the igniter input and subsequent propellant combustion. A complete run log of the IECD ignition diagnostic tests is included as Appendix A, where firing data have been arranged in order to ascending inert simulant bed length from 0.0 inches to 2.0 inches.

2.3 Fifty Percent Firepoint Results

2.3.1 Fifty Percent Firepoint Data

Twenty-one (21) series of Bruceton tests were conducted in the current project to evaluate the ignition effectiveness of BP, BKNO₃, NC, MTV, BMoO₃, and AP igniter materials with NACO, LOVA, NOSOL-318, and PYRO propellants for selected zone one inert bed thicknesses ranging from 0.0 inches to 2.0 inches. Initial data reduction consisted of reading the in-bore oscilloscope records of each shot to record pertinent pressure-time data, as indicated in Figure 2.3 and listed below:

1. \( P_{20} \) - Maximum igniter pressure in the bed prior to propellant ignition
2. \( P_{21} \) - Pressure value in the bed prior to onset of propellant ignition
3. \( P_{2\text{max}} \) - Maximum combustion pressure in the bed
4. \( t_{\text{ign}} \) - Ignition delay time from event initiation to onset of propellant combustion pressure rise
Figure 2.3 Pressure-time Nomenclature Assigned to IECD Data Reduction
5. $t_{\text{peak}}$ - Time from event initiation to peak combustion pressure

Oscilloscope data for all twenty-one (21) ignition effectiveness tests are presented in Appendix B.

Each Bruceton series conducted in Reference 1 and the current project, as shown in the experimental matrix, Table 2.5, was statistically reduced using a sensitivity method developed by Brownlee and Hodges (Reference 4) for small sample numbers to determine the 50 percent firepoint means (mass) presented in Table 2.6. Due to the limited number of shots in each Bruceton type series, the calculated means are subject to question; however, the calculated results are expected to be indicative of the relative ignition effectiveness of the igniter materials tested. Each of the mass means was multiplied by the experimentally determined heat of explosion to determine the 50 percent igniter energies presented in Table 2.7 and Figure 2.4. The data in Table 2.7 and Figure 2.4 indicate that the igniter energy requirements increase with increasing inert simulant bed thickness showing that the inert simulant zone is acting as an energy barrier, either by selectively blocking igniter materials and/or simply acting as an energy absorber during the inert heating phase. (This point is addressed more completely in the Data Analysis section).

2.3.2 Assessment of Data

A review of the NACO 50 percent firepoint data, Figure 2.4, suggests that the BP and BKNO$_3$ igniter streams are more effective than the MTV and the NC igniter materials. The general agreement of the NACO data for a bed length of 1.0 inch for all igniter materials suggests that the inert simulant zone is
### Table 2.5: Ignition Effectiveness Experiments: Fifty Percent Firepoint Results

**EXPERIMENTAL MATRIX**

<table>
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<th>Propellant</th>
<th>Bed Length (in)</th>
<th>Igniter Material</th>
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Table 2.6 Ignition Effectiveness Experiments: Fifty Percent Firepoint Results

IGNITER CHARGE MASS (g)

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<th>Propellant</th>
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NF = No Fire
Table 2.7 Ignition Effectiveness Experiments: Fifty Percent Firepoint Results

IGNITER CHARGE ENERGY (kcal)

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</table>
Figure 2.4 Fifty Percent Igniter Energy as a Function of Inert Bed Thickness
acting as a thermal sink and not very effective in selectively filtering the igniter products. This conclusion is based in part on the NC diagnostic tests where relatively poor igniter behavior was observed with unburned NC being a large fraction of the igniter "product" stream. If this line of thought is followed, the unburned NC contained in the igniter stream is effective in reaching the live propellant zone for an inert zone thickness of 1.0 inches, but is filtered out by the 1.5 inch and 2.0 inch inert zones, as indicated by the increase in ignition energy from 1.0 kcal to 2.2 kcal and 2.6 kcal, respectively. If this is correct, then an important conclusion can be reached with regard to the upstream energy transfer for the unburned NC igniter material. Specifically, if it is assumed that a portion of the NC is blocked by the inert zone and burns in the inert zone, then this energy liberation goes into heating the inert simulant and is not returned to the igniter gas stream in a time frame which can aid in the propellant ignition process. This observation tends to suggest that high solids igniter systems will be effective in stimulating a narrow zone adjacent to the vent location, but will be relatively poor in achieving a spatially in-depth ignition boundary.

NOSOL-318 ignition energy levels for an inert simulant zone thickness of 1.5 inches are relatively independent of igniter material type. The limited NOSOL-363 data indicate that BP and NC are more effective igniter materials than BKNO₃ and MTV. This observation suggests that the low gas content of the BKNO₃ and MTV products is contributing to a relatively large energy loss in the inert zone due to increased
residence time (low transit velocity) for vapor and liquid phase transitions prior to entering the live propellant zone.

Ignition effectiveness data for LOVA propellants, Figure 2.4, generally indicate the low vulnerability aspects of the propellant system with significantly higher igniter energy levels required from all igniter materials tested, with the exception of the oxidizer rich products ammonium perchlorrate igniter. Test data acquired for an inert simulant zone thickness of 0.0 inch (e.g., no inert simulant separating the igniter vents and the live propellant) exhibit ignition energy levels ranging from 2.0 kcal to 3.2 kcal for conventional igniter materials (BP, BKNO₃, NC, and MTV) and 1.0 kcal for the oxidizer rich AP igniter material. This observation suggests that the initial decomposition products of LOVA propellant are fuel rich, presumably in the gas phase, and are extremely reactive with the AP products.

Further support for the LOVA gas phase reaction step is indicated by the bed ignition pressure data presented in Table 2.8. Excluding the AP results for the moment, the lowest conventional igniter material energy level was for BP at a bed thickness of 0.0 inch and occurred at a bed pressure level of 1,300 psia. By contrast, the NC igniter system at \( L_1 = 0.0 \) inch required 3.2 kcal for LOVA ignition and occurred at a bed pressure level of 200 psia. In experiments which resulted in NO propellant ignition situations, no unburned igniter material was found in the housing or in the propellant bed (for tests conducted with \( L_1 = 0.0 \)), except for the AP igniter system, and consequently, is presumed to have burned in the
Table 2.8 Ignition Effectiveness Experiments: Fifty Percent Firepoint Results

BED IGNITION PRESSURE - $P_{20}$ (psia)

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Igniter Material</th>
<th>Inert Bed Length (in)</th>
<th>BP</th>
<th>BKNO₃</th>
<th>NC</th>
<th>MTV</th>
<th>BMO₃</th>
<th>AP</th>
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<tr>
<td>NACO</td>
<td></td>
<td>0.0</td>
<td>500</td>
<td>200</td>
<td>30</td>
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<td>30</td>
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<td></td>
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<td>300</td>
<td>100</td>
<td>100</td>
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<td>30</td>
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<td></td>
<td></td>
<td>1.5</td>
<td>700</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>30</td>
</tr>
<tr>
<td></td>
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<td>2.0</td>
<td>1300</td>
<td>1000</td>
<td>200</td>
<td>900</td>
<td>NF</td>
<td>600</td>
</tr>
<tr>
<td>LOVA</td>
<td></td>
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<td>1400</td>
<td>1100</td>
<td>600</td>
<td>600</td>
<td>600</td>
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<td>1.5</td>
<td>1200</td>
<td>700</td>
<td>80</td>
<td>400</td>
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<td>400</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>1400</td>
<td>1200</td>
<td>1800</td>
<td>700</td>
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<td>900</td>
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<td>700</td>
<td>900</td>
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<tr>
<td>NOSOL-363</td>
<td></td>
<td>0.0</td>
<td>1400</td>
<td>900</td>
<td>1800</td>
<td>700</td>
<td>900</td>
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<tr>
<td>PYRO</td>
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<td>0.0</td>
<td>1400</td>
<td>900</td>
<td>1800</td>
<td>700</td>
<td>900</td>
<td>900</td>
</tr>
</tbody>
</table>

NOTE: $P_{20}$ is measured at a fixed axial location with respect to the igniter vent exit; consequently, as the inert bed length varies, the bed ignition pressure location moves relative to the live propellant zone.
propellant region. Since the NC bed pressures were low relative to the BP bed pressures, it is presumed that the LOVA gas phase reaction did not contribute to the ignition energy balance, thus requiring a larger input from the NC igniter system. Another possibility is that the LOVA first step gas products are adversely affecting the NC product stream, thus inhibiting the NC/LOVA ignition sequence. It is interesting to note that the LOVA ignition energy levels correlate with the measured bed pressure levels, for conventional igniter materials, as shown in Table 2.9 below.

Table 2.9 LOVA Ignition Effectiveness at \( L_1 = 0.0 \) inch

| Ign
ter | \( P_{20} \) Bed Pressure Level (psia) | Products Gas Phase Mass Fraction (%) | Fifty Percent Igniter Charge Energy (kcal) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>600</td>
<td>75.6</td>
<td>1.0</td>
</tr>
<tr>
<td>B2</td>
<td>1,300</td>
<td>54.8</td>
<td>2.0</td>
</tr>
<tr>
<td>( \text{KNO}_3 )</td>
<td>1,000</td>
<td>24.7</td>
<td>2.4</td>
</tr>
<tr>
<td>MN</td>
<td>900</td>
<td>0.3</td>
<td>2.6</td>
</tr>
<tr>
<td>NC</td>
<td>200</td>
<td>90.8</td>
<td>3.2</td>
</tr>
</tbody>
</table>

The high theoretical products gas phase mass fraction for NC (90.8%) and the low bed pressure level is a further indication that the NC combustion is taking place in the bed and not in the igniter housing, or that the reaction is being inhibited by the LOVA products. Although BKNO\(_3\) and MTV have relatively high mass fractions of product vapor and liquid phase materials (see Table 2.3), which should be more effective in the propellant inert heating and first decomposition step, the decreased igniter gas phase content apparently results in lower bed pressure levels and subsequent reduced reactivity of the LOVA decomposition.
In comparison, the AP igniter system produced 600 psi and required only 1.0 kcal for LOVA ignition. Ignition results for an inert bed thickness of 1.5 inches show the same relatively ignitibility difference between the conventional materials and the oxidizer rich AP igniter material, with energy levels of approximately 4 kcal being observed for conventional igniter materials as contrasted to 2.1 kcal for the AP igniter material.
3.0 DATA ANALYSIS

3.1 Qualitative Description of IECD Ignition Process

The IECD igniter venting process consists of an igniter jet which enters a finite thickness bed of inert simulant grains followed by a finite thickness bed of live propellant grains. The igniter jet is comprised of up to four different inert, or chemically active, stream types:

1. Hot gases,
2. Hot vapors capable of undergoing a phase change to either a liquid state or a solid state,
3. Hot liquids capable of undergoing a phase change to a solid state, and
4. Hot solids.

The manner in which the inert simulant bed affects each of these streams is speculation, but is postulated as follows. First, the inert simulant acts as a radiation buffer which is effective in reducing the igniter radiation incident upon the live propellant zone; consequently, the primary propellant ignition stimulus is presumed to be associated with the energy transported by the flowing igniter stream. Under this presumption, it then becomes important to establish the buffering effect of the inert simulant zone upon the multi-phase igniter stream as it flows from the igniter vent through the inert simulant. Since the inert simulant zone consists of a large number of randomly positioned pellets, it is reasonable to assume that the gas stream can pass through the inert bed relatively easily while experiencing a loss in both pressure and temperature prior to entering the live propellant zone, the losses being
dependent upon the porosity and length of the inert simulant zone. Considering next the hot vapors, one can presume that the vapors can pass through the inert bed with the same relative ease as the hot gas stream; however, the pressure loss and temperature drop experienced by the gases and vapors would tend to drive the vapors toward a change in phase, with subsequent phase change energy release, presumably to a liquid which would be relatively effective in the inert heating phase of the live propellant ignition process. With regard to the hot liquids contained in the igniter stream, one can envision that the inert zone pellets may become wetted by the liquid stream during the flow process, thus reducing the initial liquid content potentially available for the live propellant zone. Of perhaps more significance is the possibility that the liquids initially present in the igniter products may undergo a phase change from liquid to solid within the confines of the inert zone, thus significantly reducing the potential effectiveness of the igniter stream to initiate combustion in the live propellant zone. Finally, if one applies the previous logic to the igniter solids flowing through the inert simulant bed, the higher trajectory momentum of the solids makes them less capable of traversing the inert zone without impacting the inert simulant pellets and becoming trapped in the inert zone, thus reducing the ignition potential of the igniter stream.

3.2 Analytical Procedures

The ignition effectiveness experiments presented in the previous section included data for zone one inert simulant bed thickness of 0.0, 1.0, 1.5, and 2.0 inches and presented 50 percent firepoint results
based upon igniter energy levels (e.g., mass times HOE). Since the igniter energy level represents the maximum theoretical energy available to the packed bed system of inert simulant and live propellant, the 50 percent ignition energy levels previously presented need to be corrected to account for the energy losses experienced while flowing through the inert simulant bed. The analyses presented in this section provide a simplified approach for correcting the ignition energy levels for convective heat transfer losses while neglecting the perhaps more important effects of phase changes and particle entrapment.

Referring to Figure 3.1, the physical process is envisioned to consist of the following steps:

1. Igniter products are generated in the igniter housing at a pressure, $P_c(t)$, and a flame temperature, $T_f$. The assumption is made that the condensed phase products occupy negligible volume with respect to the gas phase.

2. Under the assumption of an ideal gas law and isentropic conditions, igniter products flow from the housing cavity via choked vents and expand supersonically to the bed free flow area (bore area minus blockage by pellets).

3. A strong normal shock is assumed to occur at the entrance to the packed bed, characterizing the subsonic flow field incident to the packed bed.

4. A spatially uniform flow field is assumed in the axial direction (e.g., no spatial gradients in pressure and temperature are considered.)
Figure 3.1 Schematic Representation of IECD Showing Igniter Control Volume
5. Bed convective heat losses are determined as a function of time in response to the experimentally measured igniter housing pressure-time curve, \( P_c(t) \).

### 3.2.1 Igniter Mass Flux Characterization

Using the previous assumptions, the experimentally measured pressure-time curve, \( P_c(t) \), is attributed to the gas phase products and may be used to calculate the igniter vent exit gas phase flow rate, \( \dot{m}_g \)

\[
\dot{m}_g = \frac{D^* A_p c P_c(t)}{\sqrt{\frac{R c T_c}{\gamma g_c}}}
\]  \( \text{(1)} \)

For sonic conditions, the compressible flow function, \( D^* \), is given by

\[
D^* = \left( \frac{\gamma+1}{2} \right)^{\frac{\gamma+1}{\gamma(1-\gamma)}}
\]  \( \text{(2)} \)

The mass of igniter products in the gas phase, \( m_g \), is given by integrating the mass flux curve from the onset of ignition until expansion is complete.

\[
m_g = \int_0^{T_{\text{final}}} \dot{m}_g \, dt
\]  \( \text{(3)} \)

Substituting equations (1) and (2) into equation (3) under the assumption that the gas phase products temperature, \( T_c \), is equal to the flame temperature, \( T_p \), gives
The initial igniter mass, $m_0$, is known for each experiment; consequently, the condensed phase products mass, $m_{cp}$, is given by

$$m_{cp} = m_o - m_g - m_r - m_{ub}$$  \hspace{1cm} (5)

where

- $m_o$ = initial charge mass
- $m_g$ = mass of gas phase products
- $m_r$ = post-test mass of residue remaining in igniter housing
- $m_{ub}$ = mass of unburned igniter material blown out of igniter vent into bed

In each test, the post-test residue mass was small for each igniter material; consequently, the pseudo-condensed phase mass (products plus unburned igniter material) can be determined from equation (5). Assume that the products condensed phase flow rate is proportional to the gas phase flow rate

$$\dot{m}_{cp} = \beta \dot{m}_g$$  \hspace{1cm} (6)

where $\beta$ is defined by

$$\beta = \frac{m_{cp}}{m_g}$$  \hspace{1cm} (7)

Equations (4) and (5) provide two independent relations to solve for the three unknowns ($m_g$, $m_{ub}$, and $\beta$).
If the unburned solids were zero, then $\beta$ would be uniquely determined by the pressure-time curve; however, since this is not the case for NC, a third relationship is required and will be provided by the energy balance equations.

3.2.2 Igniter Energy Characterization

The total exit energy flux, $\dot{E}_e'$ will be considered to be comprised of the gas phase and the pseudo-condensed phase (products plus unburned) material streams

$$\dot{E}_e = \dot{E}_g + \dot{E}_{cp}$$ (8)

The gas phase energy flux, $\dot{E}_g$, is given by

$$\dot{E}_g = \dot{m}_g \left( C_{pg} T_e + \frac{V_e^2}{2} \right)$$ (9)

For sonic conditions at the vent exit, $T_e$ and $V_e$ may be expressed in terms of the chamber temperature, $T_c$, to give

$$\dot{E}_g = \dot{m}_g \left[ C_{pg} \left( \frac{2T_p}{\gamma+1} \right) + \frac{\gamma R T_p}{(\gamma+1)} \right]$$ (10)

where $T_c$ has been assumed equal to $T_p$.

If one assumes no velocity lag between the gas phase and the condensed phase materials, the condensed phase energy flux is given by (approximately)

$$\dot{E}_{cp} \approx \dot{m}_{cp} \left( h_{cp} + \frac{V_e^2}{2} \right) + \dot{m}_{ub} \left( h_{ub} + \frac{V_e^2}{2} \right)$$ (11)

In the present analysis, the condensed phase products will be assumed to be at the gas phase flame temperature, $T_p'$, and the unburned solids will be assumed to be at their original soak temperature, $T_{so}$. Since $\dot{m}_{cp}$ is a function of $\beta$, equation (11) may be rewritten as
Closure of the balance equations and the proper solution for $\beta$ is given by integrating the exit energy flux over the ballistic cycle to obtain the total energy leaving the vents

$$E_e = \int_0^{T_{\text{final}}} E_e \, dt$$

(13)

The total energy calculated by equation (13) is compared to the theoretical igniter charge energy given by mass times HOE in an iterative fashion for $\beta$ until a converged energy balance solution is achieved under the assumption that the unburned material flow rate is zero. If convergence is not achieved, then the unburned material flow rate is increased by a finite amount and the products condensed phase mass is reduced using equation (5) so that a mass balance is maintained. The final iterative solution provides the value of $\beta$ that satisfies both the mass balance and energy balance equations simultaneously.

3.2.3 Bed Energy Loss Characterization

The igniter flow is assumed to expand from the vent orifice (throat) into the packed bed where a normal shock is formed, thus reducing the flow through the bed to subsonic conditions. Since the vent area is well specified and sonic throat conditions are assumed, the Mach number incident to the normal shock is determined by the area ratio for the vent flow.
expansion process. Define the bed porosity, $\varepsilon_1$, as

$$\varepsilon_1 = 1 - \frac{n_1 \bar{V}_{g1}}{V_1} \quad (14)$$

where $n_1 = \text{number of grains in zone 1}$
$$\bar{V}_{g1} = \text{individual grain volume}$$
$$V_1 = \text{bore volume of IECD in zone 1}$$

If it is assumed that there is a large number of pellets per unit length of bed, then the expansion area ratio, $(A/A^*)$, is given by

$$\left(\frac{A}{A^*}\right)_1 = \frac{\varepsilon_1}{n_v} \left(\frac{D_1}{D_e}\right)^2 \quad (15)$$

where $n_v = \text{number of axial vents}$
$$D_e = \text{vent diameter}$$
$$D_1 = \text{IECD bore diameter}$$

The upstream incident Mach number is calculated from isentropic flow relations and is used with normal shock relations to fully specify the subsonic flow through the packed bed, including the following variables:
- $M_1(t) = \text{IECD in-bore Mach number}$
- $P_1(t) = \text{IECD in-bore static pressure}$
- $T_1(t) = \text{IECD in-bore static temperature}$
- $\rho_1(t) = \text{IECD in-bore static density}$
- $V_1(t) = \text{IECD in-bore velocity}$

With the gas dynamic variables determined as a function of time, the heat transfer to the packed bed can be calculated from the following Nusselt number correlation (Reference 5)
Ru, 22+ PrI/3 (16)

\[ \text{Nu}_1 = 2 + 0.4 \left( \frac{\text{Re}_1}{\varepsilon_1} \right)^{2/3} \text{Pr}^{1/3} \]  

where

\[ \text{Nu}_1 = \frac{h_{gL} D_{gL}}{k_{gL}} \]

The gas phase Reynolds number, \( \text{Re}_1 \), and thermal conductivity, \( k_{gL} \), depend upon viscosity, \( \mu \), and Prandtl number, \( \text{Pr} \), which are given by (Reference 6)

\[ \mu_1 = 0.76 \times 10^{-3} \left( \frac{T_1}{537} \right)^{1.5} / (T_1 + 198) \]  

and

\[ \text{Pr}_1 = \frac{4\gamma}{(9\gamma - 5)} \]  

The local heat transfer rate to the grains, \( \dot{Q}_1 \), is given by

\[ \dot{Q}_1 = h_{gL} A_{s1} \left( T_1(t) - T_s(t) \right) \]  

where \( h_{gL} \) = gas phase heat transfer coefficient  
\( A_{s1} \) = total grain heat transfer area  
\( T_s(t) \) = grain surface temperature

The gas phase heat transfer coefficient, \( h_{gL} \), is obtained from the Nusselt number correlation given in equation (16)

\[ h_{gL} = \frac{\text{Nu}_1 k_{gL}}{D_{gL}} \]

The single grain surface area is given by

\[ A_{sg} = \frac{\pi}{2} \left( D_{gL}^2 - n_p l_d p_l^2 \right) + \pi D_{gL} L_{gL} + n_p \pi d_p p_l L_{gL} \]  

(20)
where \( n_{pl} \) = number of perforations
\( d_{pl} \) = perf diameter
\( D_{gl} \) = grain diameter
\( L_{gl} \) = grain length

The total grain heat transfer area, \( A_{sg} \), is given by

\[
A_{sg} = n_l^*A_{sg}
\]  

(21)

where \( n_l \) is the total number of grains for each experiment.

The grain surface temperature, \( T_s(t) \), is provided by one-dimensional, unsteady heating under the assumption that the grain thermal penetration zone is small in comparison to the propellant radius.

\[
\frac{T_s(t) - T_0}{T_1(t) - T_0} = 1 - \left[ \exp \left( \frac{h \sqrt{\alpha_{ts}}}{k_s} \right) \right]^* \left[ 1 - \text{erf} \left( \frac{h \sqrt{\alpha_{ts}}}{k_s} \right) \right]
\]

(22)

where \( \alpha_{ts} \) = grain thermal diffusivity
\( k_s \) = grain thermal conductivity
\( T_0 \) = initial temperature

The heat transfer rate, \( Q_1 \), may now be solved by equation (19) and integrated over the ballistic cycle to give the total heat transferred to the grains during the heating cycle, \( Q_1 \), shown in the following equation.
\[
Q_1 = \int_0^{t_{\text{final}}} \dot{Q}_1 \, dt
\]  

(23)

In a similar manner, the heat transfer loss from the stream to the wall, \( Q_{wl} \), may be calculated by integrating

\[
\dot{Q}_{wl} = \left( \frac{k_{gl}}{D_1} \right) \left[ 0.023 \left( \frac{u_{gl}}{D_1 \rho_1 v_1} \right)^{0.2} \Pr_1^{-2/3} \right] x
\]

\[
\left( T_1(t) - T_w \right)
\]

(24)

where \( T_w \) = IECD wall temperature (assumed constant)

The corrected energy incident to the live propellant in zone 2 is defined as \( E_{50} \) and is given by

\[
E_{50} = E_e - Q_1 - Q_{wl}
\]

(25)

where \( E_e \) = total energy leaving igniter vents

\( Q_1 \) = total energy transferred to grains

\( Q_{wl} \) = total energy transferred to wall

These equations, although approximate in nature, will provide an order to magnitude assessment of the energy differential which exits between the igniter housing exit plane and the plane incident to the live propellant zone. Improvements in the procedure are warranted, particularly by including axial gradients in the packed bed and developing the effects of phase change and condensed phase trapping.
3.3 Data Analysis Results

The data analysis procedures presented in the previous section have been utilized to evaluate the igniter performance and to correct the 50 percent firepoint results for convective energy losses to the packed bed and IECD bore wall.

3.3.1 Igniter Calibration Data

Each igniter calibration pressure-time curve was tabulated into five pairs of pressure-time data, Table 3.1, and used as input conditions for the analysis model previously presented. Calculated gas phase mass fractions for the igniter product stream have been compared with theoretical values as determined by NASA-Lewis code computations (Table 2.3) and are presented in Table 3.2. Experimental values for BP are in reasonably good agreement with NASA-Lewis code values suggesting that the igniter behavior for the BP is reasonably good (Recall that the igniter system was originally designed for BP). Gas phase mass values for the four other igniter materials based upon integrated p-t data indicate that the gas production in the igniter cavity is low. This observation indicates that unburned igniter materials are contained in the vent exit streams. This conclusion is consistent with experimental observations for NC and AP tests; however, no unburned BKNO₃ or MTV has ever been observed in the ignition effectiveness tests.

3.3.2 Corrected Zone Two Input Energy

Using the igniter calibration data previously presented in Table 3.1, bed and wall energy losses were determined as a function of igniter charge mass for each of the igniter materials used in the ignition
Table 3.1 Igniter Calibration Data

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Igniter</th>
<th>Mass (g)</th>
<th>t₁</th>
<th>p₁</th>
<th>t₂</th>
<th>p₂</th>
<th>t₃</th>
<th>p₃</th>
<th>t₄</th>
<th>p₄</th>
<th>t₅</th>
<th>p₅</th>
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<tbody>
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<td>300</td>
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<td>900</td>
<td>.4</td>
<td>600</td>
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<td>0</td>
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*No Scope Record
### Table 3.2 Igniter Calibration Data

**Product Mass Fraction: Gas Phase**

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*Experimental calculations based upon one shot each.*
effectiveness tests. The calculated energy losses were then subtracted from the igniter total energy to give a corrected zone two input energy as a function of igniter mass. These results, presented in Appendix C for BP, BKNO₃, NC, MTV, and AP permit the graphical determination of corrected energy levels for 50 percent igniter mass test values which lie between the three igniter calibration charge masses.

Using the experimentally determined 50 percent firing point mass quantities previously presented in Table 2.6, corrected zone two input energies have been determined for all ignition effectiveness experiments and are presented in Table 3.3. Corrected zone two input energies for NACO and LOVA propellants, respectively, are presented in Figures 3.2 and 3.3 for BP, BKNO₃, NC, MTV, and AP igniter materials as a function of zone one inert bed length (L₁). If the process for determining the bed energy losses was correct (including thermophysical properties), one would expect the corrected energy levels to have a zero slope with zone one thickness changes. The NACO data for BP and BKNO₃, Figure 3.2, exhibit this general trend and suggest that the 50 percent firepoint for NACO is about 1.0 kcal. The NACO results for NC and MTV both appear to agree with the 1.0 kcal ignition energy value at L₁ = 1.0 inch, but both exhibit increasing ignition energy requirements with increasing zone one length. Since BP igniter material exhibited high products gas phase mass fractions and the energy correction procedures are based on gas phase convection heat transfer, the NC and MTV trends tend to suggest that other heat loss mechanisms are dominant.

The LOVA results presented in Figure 3.3 for conventional igniter materials indicate that the
Table 3.3 Ignition Effectiveness Experiments:
Fifty Percent Firepoint Results

Corrected Zone Two Input Energy (kcal)

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Figure 3.2 Corrected Zone Two Input Energies for NACO Propellant as a Function of Inert Bed Length
Figure 3.3 Corrected Zone Two Input Energies for LOVA Propellant as a Function of Inert Bed Length
ignition energy requirements for LOVA are approximately twice as great as the NACO requirements. By contrast, the oxidizer rich AP igniter data indicate that the ignitibility boundary of LOVA propellant can be significantly reduced by the presence of oxidizer rich species in the igniter stream. The LOVA data for BP, BKNO₃, and MTV show a slightly increasing slope for bed thicknesses up to 1.0 inch with a noticeable slope increase from 1.0 inch to 1.5 inches. These results indicate that the convective energy correction procedures previously developed are not adequate for LOVA propellant.

Corrected zone two input energies for NACO and LOVA propellants are presented in Figure 3.4 for BP, BKNO₃, NC, MTV, and AP igniter materials as a function of theoretical flame temperature \(T_p\) at 500 psia. NACO data are shown for inert bed lengths of 1.5 inches and 2.0 inches and show no definitive energy minimum correlation with flame temperature. In fact, low ignition energy levels of 1 kcal were observed for BP \((1930^\circ K)\) and BKNO₃ \((2890^\circ K)\), whereas high ignition energy levels of 2 kcal were observed for NC \((2350^\circ K)\) and MTV \((2650^\circ K)\). The LOVA results exhibited the same general trends for conventional igniter materials and a low ignition energy level of 1 kcal for AP \((1400^\circ K)\).

Additional corrected zone two energy input correlations are shown in Figures 3.5-3.8 for NACO and LOVA propellants as a function of the igniter products mass fraction. Figures 3.5 and 3.6 present the corrected zone two input energy for NACO and LOVA propellants, respectively, as a function of the liquid phase mass fraction where it can be seen that ignition energy requirements decrease as the liquid phase mass fraction
Figure 3.4 Corrected Zone Two Input Energies for LOVA and NACO Propellant as a Function of Igniter Material Flame Temperature
Figure 3.5 Corrected Zone Two Input Energies for NACO Propellant as a Function of Liquid Phase Mass Fraction
Figure 3.6 Corrected Zone Two Input Energies for LOVA Propellant as a Function of Liquid Phase Mass Fraction
Figure 3.7 Corrected Zone Two Input Energies for NACO Propellant as a Function of Gas Phase Mass Fraction
Figure 3.8 Corrected Zone Two Input Energies for LOVA Propellant as a Function of Gas Phase Mass Fraction
increases from 0.0 (NC) to about 0.4 (BP), followed by a sharp increase at a mass fraction of 0.48 (MTV). This trend suggests that liquid phase products are beneficial, but that something present in the BP stream is absent in the MTV igniter stream. Figures 3.7 and 3.8 present the corrected zone two input energy for NACO and LOVA propellants, respectively, as a function of gas phase mass fraction where an ignition energy minimum is observed at a gas phase mass fraction of 0.5 (BP). Both MTV (0.3% gas) and NC (91% gas) exhibit two-fold increases in ignition energy requirements relative to BP. These results suggest that the establishment of a gas phase convective flow field is necessary to the propellant ignition process. Since BP and MTV both have comparable liquid phase mass fractions, which should favor propellant heating (particularly for the higher temperature MTV liquid), the increased performance of the BP igniter system appears to be a result of the gas phase's ability to convectively drive the liquid phase through the propellant bed. By referring to Figures 3.5 and 3.6, one could speculate that if MTV had a higher gas phase mass fraction (say 25% to 50% gas), the ignition energy requirements for MTV would be greatly reduced. On the other hand, the NC results suggest that an all gas chemically inert igniter will perform as poorly as a system with a low gas mass fraction (MTV). Figures 3.5-3.8 suggest that the optimum igniter product stream would consist of 30-50% in the gas phase and 30-50% in the liquid phase. It is felt that the 30-50% liquid phase mass fraction could be partitioned between the solid phase and the liquid phase depending upon the ignition boundary pattern desired in the propellant bed. That is, if a higher solids mass fraction were
present, the propellant would trap the hot particles and propellant ignition would occur locally near the vents. On the other hand, if a higher liquid mass fraction were used, the igniter vent jet would penetrate the propellant bed more completely and a more distributed propellant ignition boundary would be formed.

3.4 Some Qualitative Observations

Although the major focus of the project was placed upon determining fifty percent firepoint ignition energy levels, several general observations were made during the experimental portions of the project, especially for NO-fire situations, and will be presented in this section.

In experiments conducted with NACO propellant, propellant ignition was easy to achieve for relatively low igniter energy levels with all igniter materials tested. In each Bruceton series, the tests usually consisted of 5-6 YES-fires and 5-6 NO-fires and, in all cases, the post-test NO-fire propellant was closely examined. In general, the NACO propellant surface showed evidence of a melt layer forming with the presence of craters randomly located on the surface. In general, post-test propellant weighings indicated a five percent mass loss had occurred. In most NO-fire experiments with BP, BKNO₃, and MTV, the NACO propellant grains were fused together by the frozen melt layer. This situation was never observed in the NC experiments (although the melt layer was observed), presumably because the igniter pressure pulse was too low in magnitude or of insufficient duration to promote the fusing action. The implication of these observations is that perhaps the propellant form function during the early stages of burning bears no resemblance at all to
the packed bed grain geometry, and in actuality, much less area is available for surface burning in the propellant ignition phase than codes would predict as necessary for proper ignition transfer.

In experiments conducted with LOVA propellant, initial tests were conducted with the same igniter configuration as was utilized with NACO, NOSOL-363, and NOSOL-318 propellants without achieving any propellant ignitions (e.g., no bed pressure rise other than the igniter input pulse) even though LOVA propellant mass loss as great as fifty percent of the original mass had taken place. Initial speculation was that the igniter jet axial velocity was too high to permit ample residence time for the LOVA first step decomposition products to fully react (with sufficient exothermic heat release) to initiate propellant combustion. Igniter vent changes to larger vents (e.g., reduced vent axial velocity) improved the situation slightly, but no prompt LOVA ignitions were achieved and LOVA "erosive" mass loss was approaching 75 percent of the original charge. In order to provide greater residence time between the igniter products and the LOVA products, the bed axial flow velocity was lowered by reducing the IECD aft closure bleed orifice by 40 percent. When this change was made, prompt ignitions were achieved. These observations suggest that there exists a gas phase ignition step which is rather slow and requires a reaction time on the order of the flow transit time. These tests, in conclusion, show that it was reasonable to assume that the LOVA gas phase decomposition products would be fuel rich and, consequently, the reaction could be accelerated by the presence of oxidizer species in the igniter stream. Subsequent tests were conducted
with an oxidizer rich igniter (100% AP) and LOVA ignition energy requirements were reduced 2-3 times relative to firings conducted with conventional igniter materials. Although these firings are not conclusive, there is strong evidence to suggest the presence of an active, fuel rich LOVA gas phase decomposition step.
4.0 REFERENCES


## APPENDIX A

### Ignition Effectiveness Test

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*Mass (g) column includes the mass of the igniter and propellant.*
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A-19
IECD IGNITON EFFECTIVENESS TEST DATA
(Inert Simulant Zone 1 Thickness 1.50 in)

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A-20
### IECD Ignition Effectiveness Test Data

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(Inert Simulant Zone 1 Thickness 1.50 in)

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(LOVA EXPLORATORY)

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APPENDIX B

Ignition Effectiveness Oscilloscope Data

Note: Symbols used in Data Log

* - No Data Record
> - (P_{2\text{max}}) Peak Off-scale
< - (t_{\text{ign}}) Primer pulse and propellant ignition merged
< - (t_{\text{peak}}) Peak off scale, time at last trace location
n/a - Primer only
Y - Yes, Propellant ignition did occur
N - No, Propellant ignition did not occur
### INERT SIMULANT BED LENGTH - L₁ = 0.00 in

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**B-18**
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APPENDIX C

Corrected Zone 2 Input Energy as a Function of Igniter Mass: Working Curves
Figure C.1, Corrected Zone Two: Input Energy: BP Calibration Data
Figure C.2 Corrected Zone Two Input Energy: BKNO₃ Calibration Data
Figure C.3  Corrected Zone Two Input Energy: NC Calibration Data
Figure C.4 Corrected Zone Two Input Energy: MTV Calibration Data
Figure C.5 Corrected Zone Two Input Energy: AP Calibration Data