BRL-TR-3120

(2)

TECHNICAL REPORT BRL-TR-3120

BRL

SHOCK TUBE STUDIES OF THE IGNITION OF TRIETHANOL AMMONIUM NITRATE IN NITROUS OXIDE: PRELIMINARY RESULTS

RICHARD A. BEYER

JUNE 1990

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

Destroy this report when it is no longer needed. DO NOT return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1990	Interium Mar 89 - Sep 89

4. TITLE AND SUBTITLE
SHOCK TUBE STUDIES OF THE IGNITION OF TRIETHANOL AMMONIUM NITRATE IN NITROUS OXIDE: PRELIMINARY RESULTS

5. FUNDING NUMBERS
1L161102AH43

6. AUTHOR(S)
RICHARD A. BEYER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
BRL-TR-3120

11. SUPPLEMENTARY NOTES
Published in Proceedings, 1989 JANNAF Combustion Meeting.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release;
distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
Triethanol ammonium nitrate (TEAN) has been shown to ignite and burn with significant light emission and pressure generation in a nitrous oxide/argon mixture heated in a shock tube. Ignition threshold is above 1300 K. Ignition delay is a function of pressure and temperature of the gas. Ignition in similar oxygen mixtures takes place in shorter times and at lower temperatures than with N_2O. Calculations on the rate of thermal decomposition of the N_2O indicate that this process may be important of the time scale of ignition.

14. SUBJECT TERMS
Liquid Propellant, Triethanol Ammonium Nitrate, Shock Tube, Ignition

15. NUMBER OF PAGES
23

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

Intentionally Left Blank

LIST OF FIGURES

Intentionally Left Blank

ACKNOWLEDGEMENT

This study was initiated following discussions with Nathan Klein of BRL on the decomposition and pathways to ignition of hydroxyl ammonium nitrate (HAN) based liquid propellants. Dr. Klein also provided the samples of triethanol ammonium nitrate (TEAN) crystals. Dr. William R. Anderson of BRL provided assistance with the N_2O decomposition calculations.

Intentionally Left Blank

I. INTRODUCTION

Liquid propellants based on aqueous solutions of hydroxyl ammonium nitrate (HAN) and various fuels have been the subject of extensive studies.[1] In particular, the propellants designated LP1845 and LP1846, where the fuel is triethanol ammonium nitrate (TEAN), have been the focus of ignition studies in our laboratory.[2] It is strongly suggested as a result of these and other studies that the order of involvement of the components is water (evaporation), HAN (thermal decomposition), and TEAN (oxidation/thermal decomposition). Because the TEAN is subjected to the nitrogen oxides formed in HAN decomposition, it is possible that it is either oxidized directly or that it thermally decomposes with its products reacting for energy release. In the present study, we present preliminary results for a study of the direct oxidation of TEAN by the predominant nitrogen oxide expected in this environment, nitrous oxide (N_2O).

II. THE STABILITY OF NITROUS OXIDE

Although one would like to perform these studies in a straightforward experiment where the TEAN is introduced into a flow of the hot oxidizer, some care must be taken. In particular, although N_2O is quite stable under ambient conditions, it is well known to decompose at the temperatures that might be required for rapid ignition of a solid material. For this reason, a brief effort was made to calculate the times over which experiments could be done with hot N_2O before it had substantially decomposed. In addition to the loss of the initial oxidizer, one must also be concerned with the growth of product species which might be much more reactive. Although any decomposition of the oxidizer is of course a part of the reaction process, it is desirable that any observations are made with a knowledge of the composition of the gases present.

Calculations to model the thermal decomposition of N_2O were performed using the CHEMKIN package of subroutines.[3] A simple model was used by adapting a sample problem at the end of the manual. We assumed a zero dimensional, homogeneous distribution of all reactants under constant pressure, adiabatic conditions. The kinetic scheme and associated rate constants which were used are given in Table 1. Values were taken from the literature, but this was not intended to be a rigorous modeling effort; rather it was simply desired to get an order of magnitude estimate of the time available for observations in hot N_2O.

Typical results for the mixtures and temperatures of these experiments are shown in Figure 1. Two major trends are quite apparent in this figure. The first is that with increasing temperature, the amount of time available for experiment before major loss of N_2O goes down rapidly. The second trend is that available time goes down rapidly with pressure. Not shown here is the additional dependence of N_2O lifetime on dilution. As the N_2O is diluted further by argon, the lifetime also increases. In all cases, it is quite clear that there is probably not time available for a heated flow experiment. In fact, following these calculations, it was decided that this study could probably be performed best in a shock tube where the temperature and pressure are raised almost instantaneously on the time scales of expected reactions. As a shock tube was becoming available for ignition studies at the time of these calculations, studies were pursued with it.

Table 1. Kinetic Pathways and Rate Parameters for N_2O Decomposition Modeling

Reaction	A Factor	b	Ea
$N + O_2 = NO + O$	6.40E09	1.0	6280.
$N + NO = N_2 + O$	3.30E12	0.30	0.
$NO_2 + M = NO + O + M$	1.10E16	0.	66000.
$NO_2 + O = NO + O_2$	1.00E13	0.	600.
$N_2O + M = N_2 + O + M$	1.60E14	0.	51600.
$N_2O + O = NO + NO$	1.00E14	0.	28200.
$N_2O + O = N_2 + O_2$	1.00E14	0.	28200.

III. EXPERIMENTAL

The shock tube used in these studies is stainless steel with a 98 mm inside diameter. The driver section is 1.2 m long; the driven (test) section is 6.2 m long in the configuration used in the present study. For "typical" test conditions, with a 0.0075 inch thick Mylar polyester diaphragm, an initial test section pressure of 70 Torr (9.2 KPa) and a driver pressure of 70 psi (470 KPa) of helium yield an incident shock Mach number near 2.9. Calculated temperature and pressure values behind this shock are 804 K and 0.93 atm (93 KPa). The calculated values after passage of the reflected shock for these same initial conditions are 1360 K and 4.5 atm (450 KPa). Pressure gauge measurements have been used to verify that the actual values reached are near the values calculated over the range of interest here. Various combinations of initial test pressure and diaphragm thickness are used to obtain desired pressure/temperature combinations. Using pure helium as the driver gas gives useful test times on the order of one millisecond; these values are adequate for ignition times here, which are typically 500μs or less.

The layout of the test end of the shock tube is shown in Figure 2. The main instrumentation consists of piezoelectric pressure transducers mounted at positions 55 and 768 mm from the end wall to follow the shock wave propagation and a 1P28 photomutiplier tube (PMT) which is mounted to record the light through a window in the end wall of the shock tube. Light detected by the PMT is filtered by neutral density filters (typical density 2.0 to 3.0) and a red-pass colored glass filter which passes light below 550 nm. It is expected that the detected light during combustion is dominated by sodium emission. The output of the pressure transducers and PMT are recorded by a digital scope; the records are ported to a computer for analysis as required. The sample of TEAN to be ignited is placed on a one inch diameter disk with feathered edges mounted in the center of the tube 210 mm from the end wall. The TEAN is ground to a fine powder of unknown particle size; typical sample size is about 20 mg. In the course of an experiment, the incident shock sweeps the powder off the disk and disperses it in the region between the disk and the end wall. The experiment may be done such that the incident pressure and temperature are high enough to ignite the sample. Alternatively, and in most of the present observations, the incident temperature rise can be low enough that the reflected shock and its associated temperature rise are

required to ignite the sample. In a typical case near 1360 K, TEAN particles moving with the gas velocity behind the incident shock interact with the reflected shock wave approximately 500μsec after passage of the incident shock. Pressure records with the disk present do not differ measurably from those without, indicating that perturbation to the flow is minimal. Thermochemical calculations are made of the characteristics of the incident and reflect shock to obtain predicted pressure and temperature conditions in the tube. The pressure is measured directly; as long as these measurements agree with the calculations, it is assumed that behavior is reasonably ideal and that the predicted temperature is achieved.

IV. OBSERVATIONS

A typical photomultiplier record is shown in Figure 3 for a calculated[4] reflected shock pressure of 4.6 atmospheres (0.46 MPa) and a temperature of 1460 K. Zero time in this and other similar plots is the calculated time that the smallest TEAN particles, those assumed to move with the gas velocity behind the incident shock, interact with the reflected shock. The two curves are clearly distinguishable by intensity; however, a careful comparison of the intensities and shapes at early times shows little difference in that region. Attempts to subtract the background from the signal has shown that very small changes in the background make big differences in the apparent time of onset of ignition based on the light signal. Thus, unless either the background light can be greatly suppressed or much better reproducibility can be achieved, quantifying measurements such as this will be difficult. Ignition at a slightly lower temperature and pressure is shown in Figure 4, with values of 3.2 atm (0.32 MPa) and 1460 K. In this second case, the delay before ignition is sufficient to separate the resulting light from the background. Also shown in the figure is the difference between the ignition signal and the background. For these conditions, this difference curve, including the negative portion, has been found to be quite reproducible. The negative portion of the difference curve is probably due to a decrease in the background when the TEAN is present. The cause is unknown; it may be due either to cooling or obscuration. In cases such as this one, it is clear that one could define a consistent and reproducible criterion for ignition.

In addition to the evidence of ignition from the emitted light, pressure records show clear increase in pressure when ignition occurs, especially when it occurs past the peak pressure. In Figure 5 is shown the pressure differential from an event at 1350 K along with the corresponding light emission. As can be seen, the pressure pulse at station one and light emission are well correlated. In general such pressure differences show this behavior in these experiments; however, the signal to noise can be much less than desired. In the example shown in Figure 5, the additional pressure from TEAN combustion is near one atmosphere, almost one-fourth the maximum pressure of the reflected shock.

A limited number of observations were made with a similar mixture of oxygen in argon, the goal being to compare light and pressure signals if ignition were to occur. Based on light emission records, the main observations were that (1) there is ignition in oxygen with corresponding light intensity well above the background level and (2) the ignition takes place at lower temperatures and probably with shorter delay times than with N_2O under the same conditions.

V. DISCUSSION

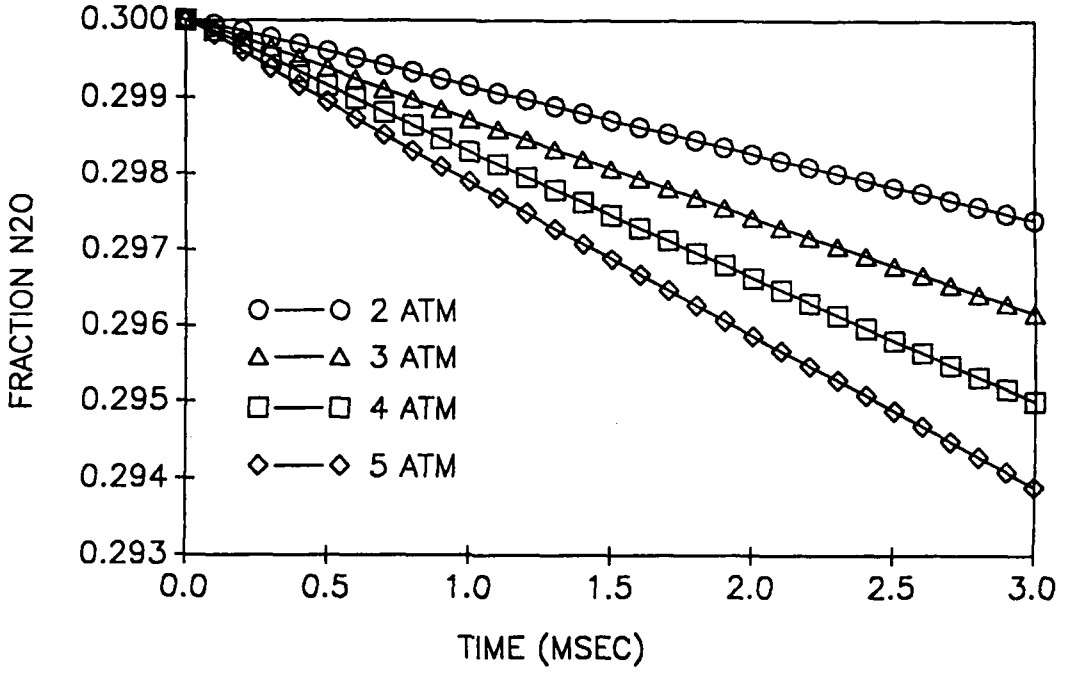
While it is clear from both the light emission and pressure records that ignition of the TEAN is occurring, some ambiguity of the significance of these observations remains. The first is related to the degree and effect of any decomposition of the nitrous oxide. Clearly further studies in the characterization of the gas composition versus time needs to be done. This goal probably can be met by diagnostics on the presence of NO_2 or other products in the decomposition process. Refinement of the model rate constants and pathways of decomposition could also be pursued to determine probable limits of composition versus time. The observation that oxygen ignition is more prompt than with N_2O suggests that the N_2O decomposition either is not as fast as we calculate or the products do not substantially accelerate the ignition reactions. This question can also be addressed by decreasing the concentration of oxidizer in the inert gas.

Another element of this work which requires refinement is the definition of time to ignition of the solid material. The signal-to-background ratio may be greatly improved by use of a narrow band optical filter at the wavelength of some key combustion radical such as OH or CN. In this case one could use the earliest light as evidence for ignition of the smallest solid particles. Alternative definitions are being developed. This definition is critical to establishment of ignition delay versus temperature and pressure. The use of high-speed photography for distiction by spatial location of the light emission is also a possibility.

A third question which remains to be addressed is whether the TEAN is reacting as a solid or first undergoes thermal decomposition followed by gas phase reactions. Attempts will be made in continuing studies to characterize the process more fully, as well as to measure the kinetics parameters.

VI. SUMMARY

We have shown that TEAN powder ignites and burns with significant light emission and pressure generation in a nitrous oxide/argon mix. Ignition threshold appears to be above 1300 K. Ignition delay is a function of the temperature and pressure of the gas. Ignition in oxygen takes place in shorter times and at lower temperatures than with N_2O. Our calculations indicate that the thermal decomposition of the N_2O may be important in our observations. Studies are presently underway to address various aspects of these observations.



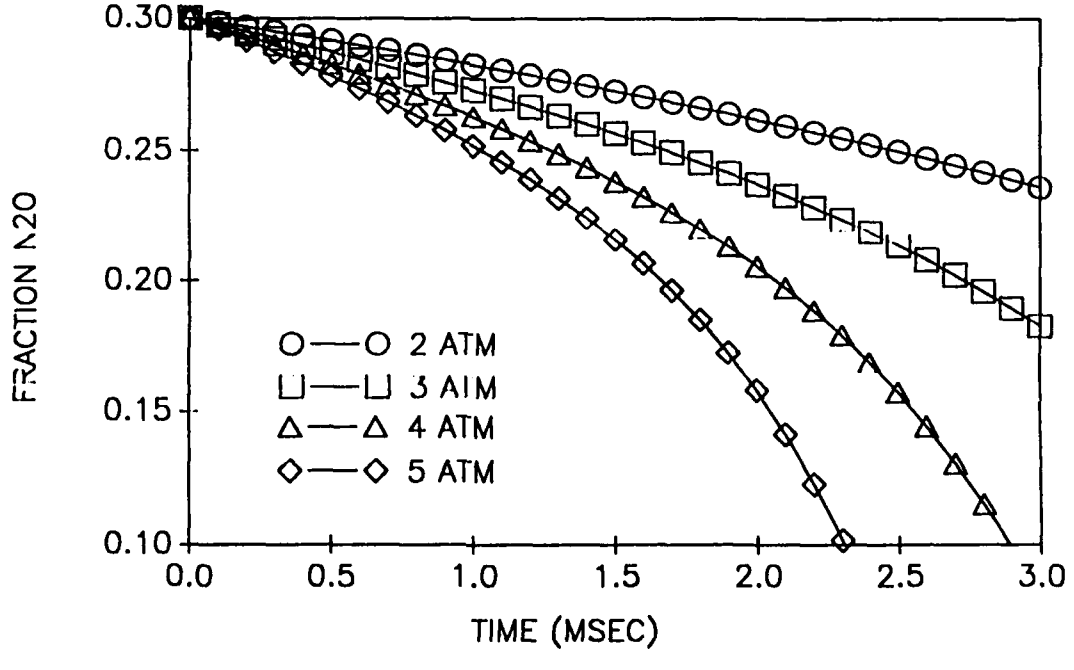


Figure 1. Calculated fraction of N_2O as a Function of Time for Various Pressures at (a) 1200 K and (b) 1400 K

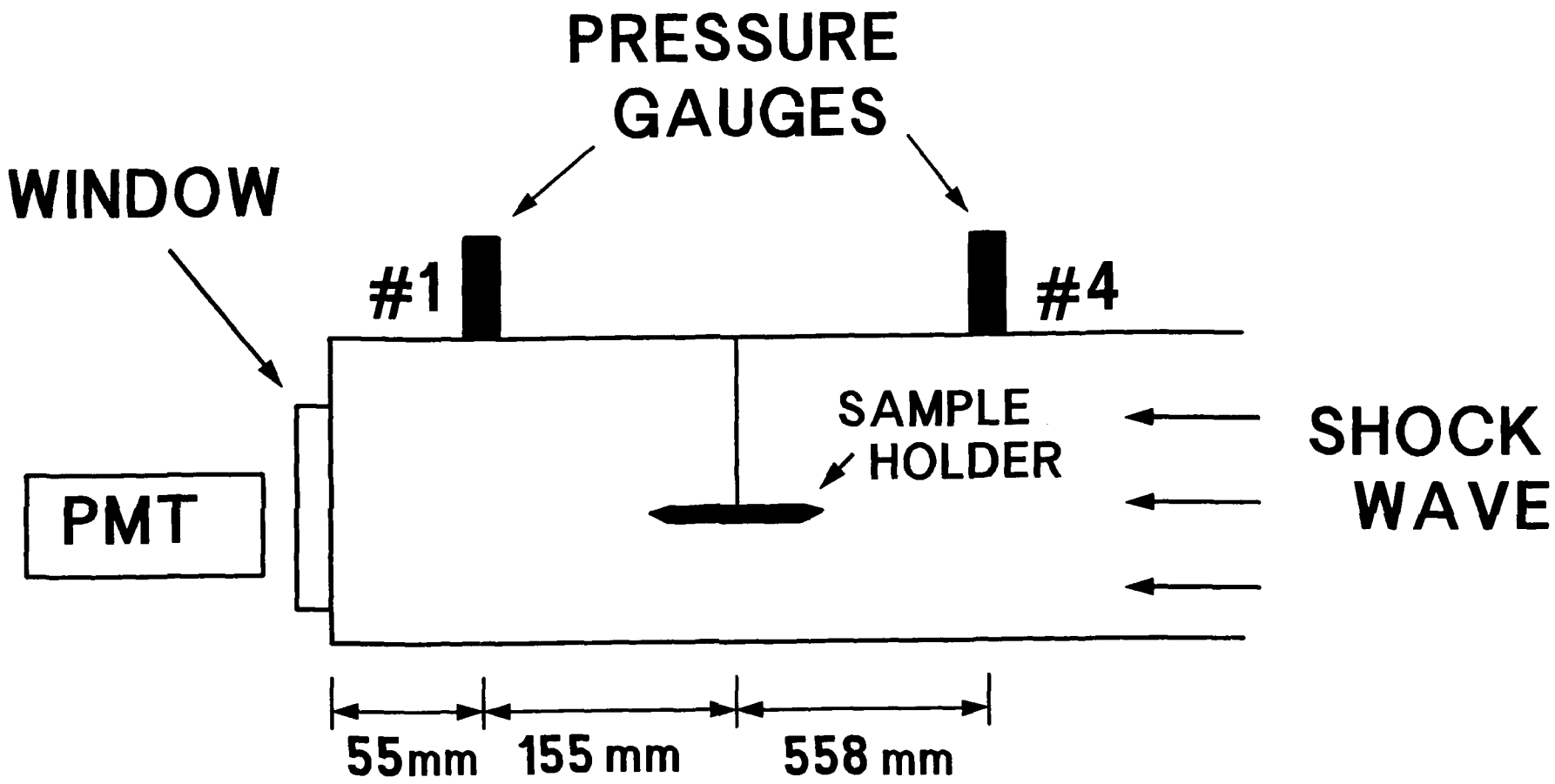


Figure 2. Schematic Diagram of Test End of Shock Tube

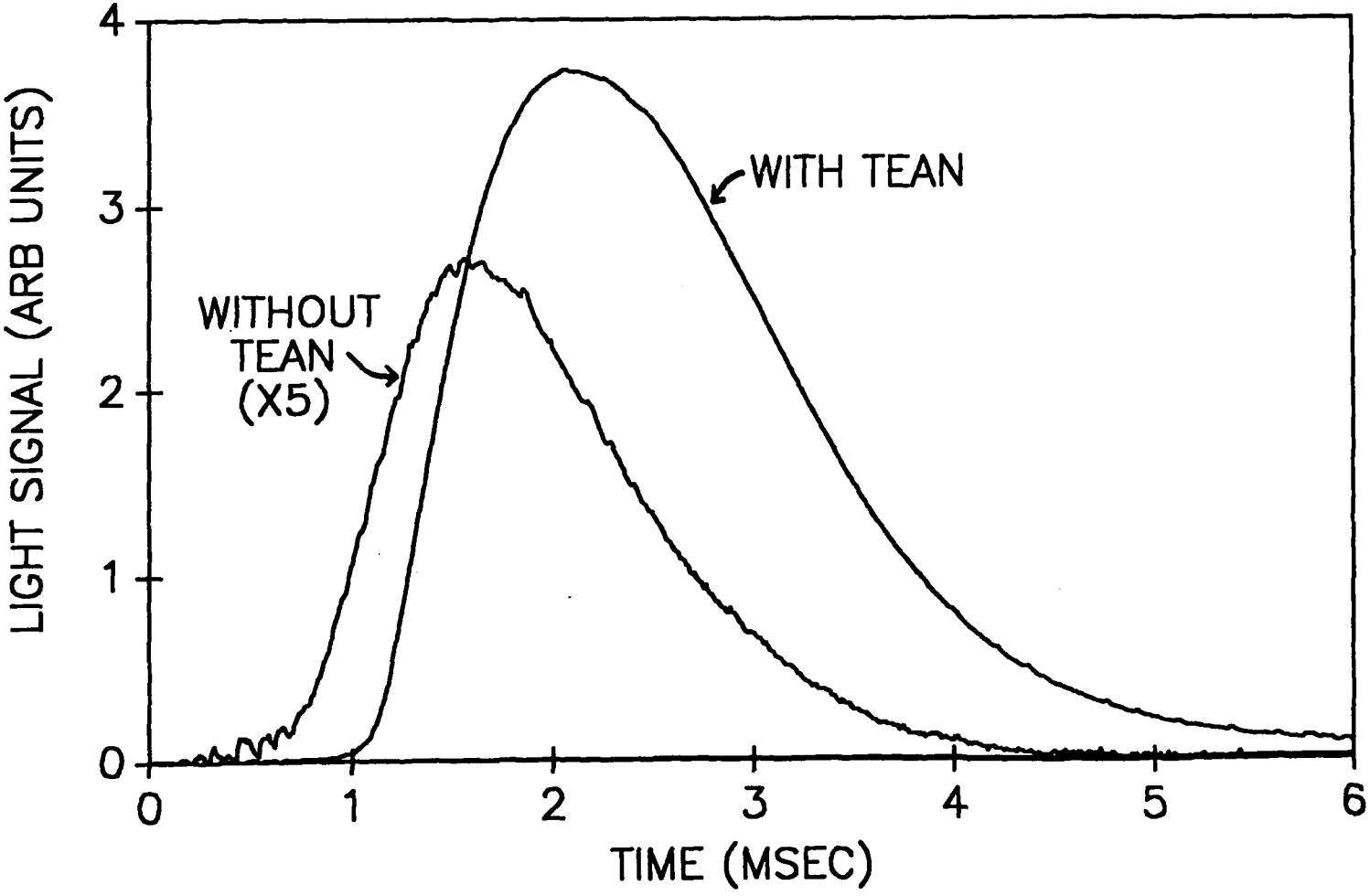


Figure 3. Light Signals With and Without TEAN in N_2O Shocked to 1500 K and 4.6 Atm Pressure

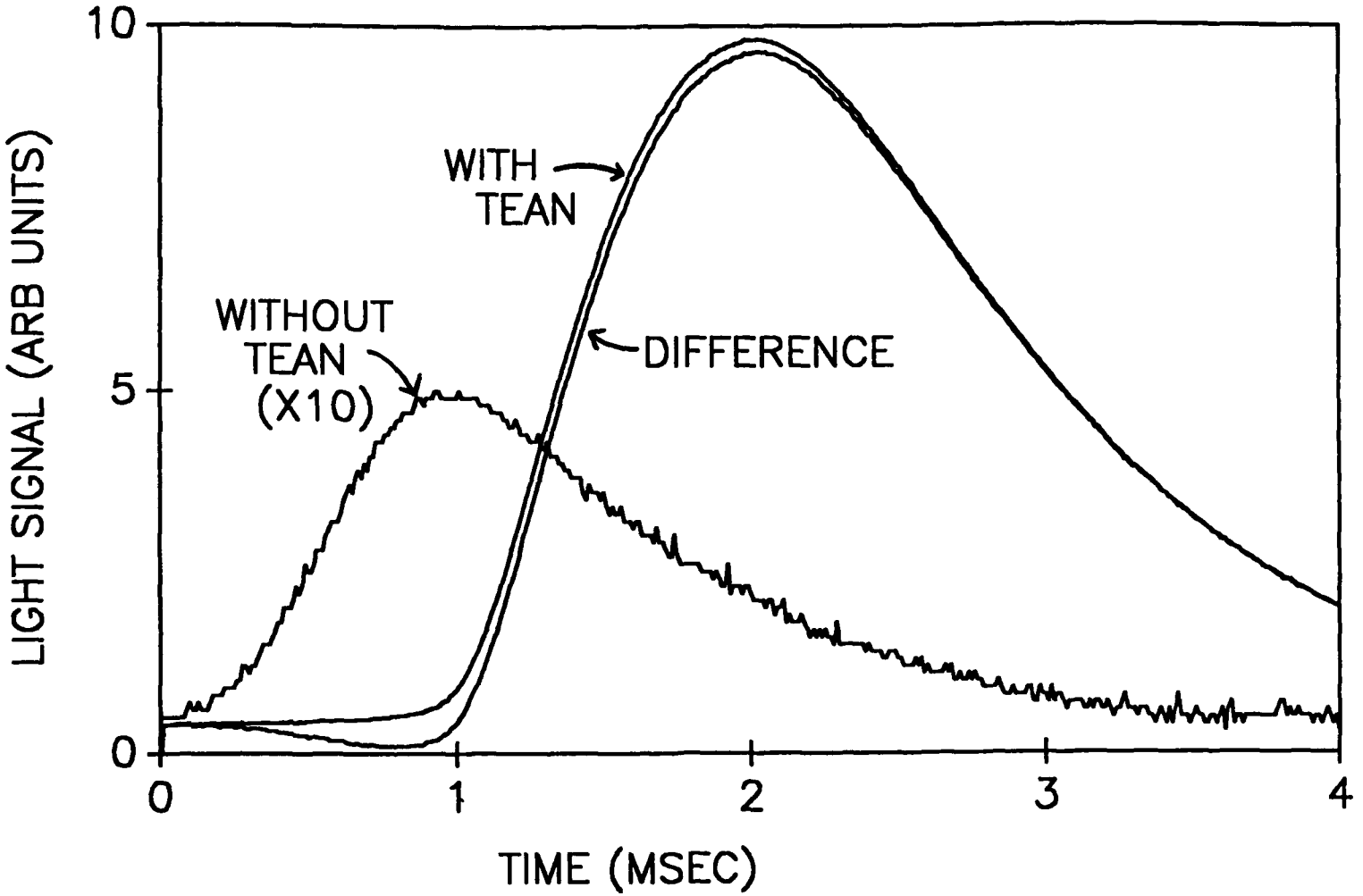


Figure 4. Light Signals With and Without TEAN in N_2O Shocked to 1460 K and 3.2 Atm Pressure

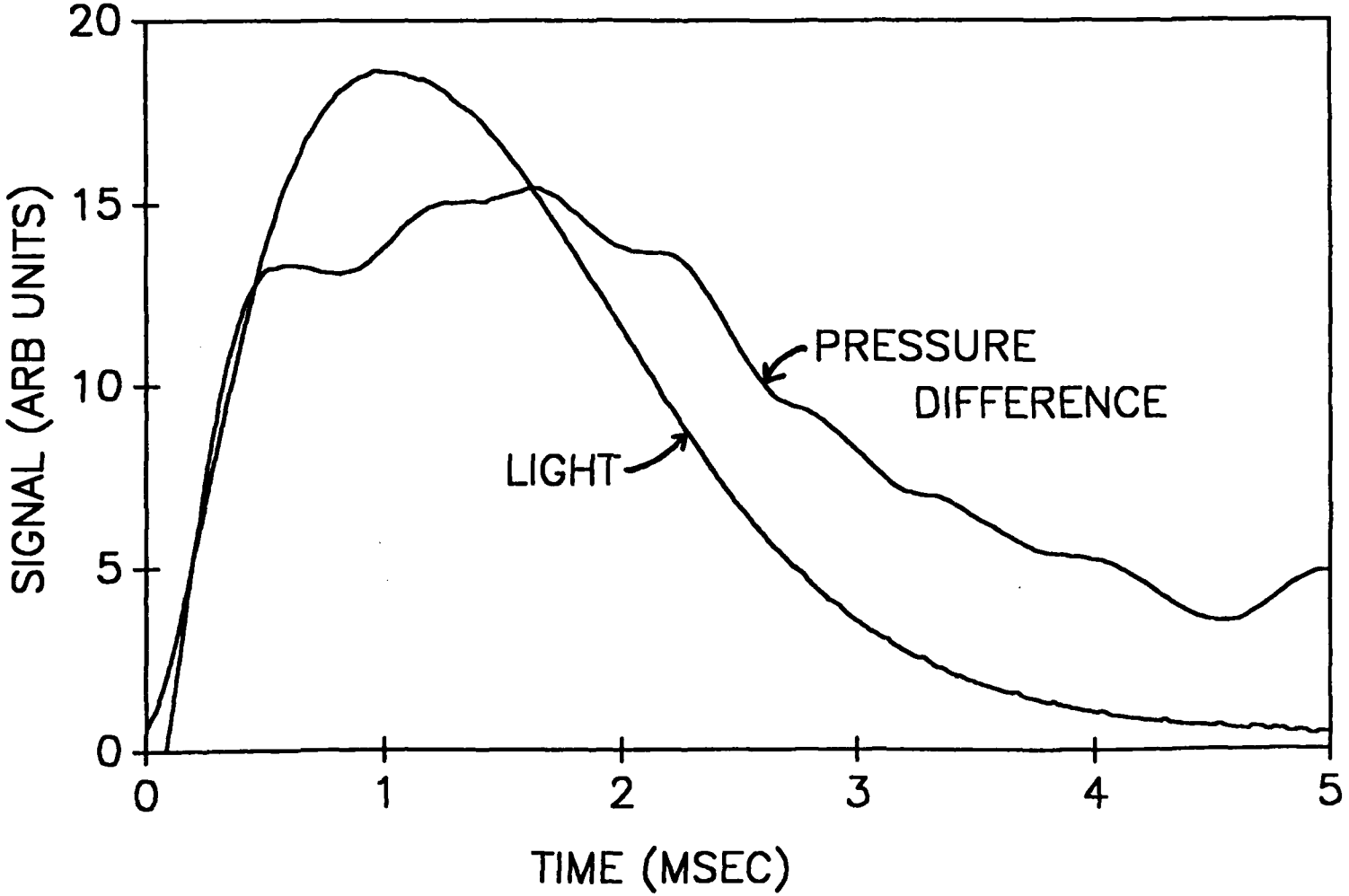


Figure 5. Difference of Pressure Pulses and Light Emission from TEAN in N_2O Shocked to 1350 K and 4.5 Atm

Intentionally Left Blank

REFERENCES

1. M.M. Decker, N. Klein, E. Freedman, C. Leveritt, and J. Wojciechowski, "HAN-Based Liquid Gun Propellants: Physical Properties," BRL-TR-2864, 1987.

2. R.A. Beyer, "Continuing Studies of Liquid Propellant Drops in Hot, High Pressure Environments," Proceedings, 24th JANNAF Combustion Meeting, CPIA Publication No. 476, Vol. III, p. 199, 1987.

3. R.J. Kee, J.A. Miller, and T.H. Jefferson, "CHEMKIN: A General-Purpose, Problem-Independent, Transportable, FORTRAN Chemical Kinetics Code Package," Sandia National Laboratories Report No. SAND80-8003, March 1980.

4. S. Gordon and B.J. McBride, "A Computer Program for Computation of Complex Chemical Equilibrium Compositions....," NASA SP-273, 1971.

Intentionally Left Blank

No of Copies	Organization
1	Office of the Secretary of Defense OUSD(A) Director, Live Fire Testing ATTN: James F. O'Bryon Washington, DC 20301-3110
2	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145
1	HQDA (SARD-TR) WASH DC 20310-0001
1	Commander US Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333-0001
1	Commander US Army Laboratory Command ATTN: AMSLC-DL Adelphi, MD 20783-1145
2	Commander US Army, ARDEC ATTN: SMCAR-IMI-I Picatinny Arsenal, NJ 07806-5000
2	Commander US Army, ARDEC ATTN: SMCAR-TDC Picatinny Arsenal, NJ 07806-5000
1	Director Benet Weapons Laboratory US Army, ARDEC ATTN: SMCAR-CCB-TL Watervliet, NY 12189-4050
1	Commander US Army Armament, Munitions and Chemical Command ATTN: SMCAR-ESP-L Rock Island, IL 61299-5000
1	Commander US Army Aviation Systems Command ATTN: AMSAV-DACL 4300 Goodfellow Blvd. St. Louis, MO 63120-1798

No of Copies	Organization
1	Director US Army Aviation Research and Technology Activity Ames Research Center Moffett Field, CA 94035-1099
1	Commander US Army Missile Command ATTN: AMSMI-RD-CS-R (DOC) Redstone Arsenal, AL 35898-5010
1	Commander US Army Tank-Automotive Command ATTN: AMSTA-TSL (Technical Library) Warren, MI 48397-5000
1	Director US Army TRADOC Analysis Command ATTN: ATAA-SL White Sands Missile Range, NM 88002-5502
(Class. only) 1	Commandant US Army Infantry School ATTN: ATSH-CD (Security Mgr.) Fort Benning, GA 31905-5660
(Unclass. only) 1	Commandant US Army Infantry School ATTN: ATSH-CD-CSO-OR Fort Benning, GA 31905-5660
1	Air Force Armament Laboratory ATTN: AFATL/DLODL Eglin AFB, FL 32542-5000
	Aberdeen Proving Ground
2	Dir, USAMSAA ATTN: AMXSY-D AMXSY-MP, H. Cohen
1	Cdr, USATECOM ATTN: AMSTE-TD
3	Cdr, CRDEC, AMCCOM ATTN: SMCCR-RSP-A SMCCR-MU SMCCR-MSI
1	Dir, VLAMO ATTN: AMSLC-VL-D

No. of Copies	Organization
4	Commander US Army Research Office ATTN: R. Ghirardelli D. Mann R. Singleton R. Shaw P.O. Box 12211 Research Triangle Park, NC 27709-2211
2	Commander Armament RD&E Center US Army AMCCOM ATTN: SMCAR-AEE-B, D.S. Downs SMCAR-AEE, J.A. Lannon Picatinny Arsenal, NJ 07806-5000
1	Commander Armament RD&E Center US Army AMCCOM ATTN: SMCAR-AEE-BR, L. Harris Picatinny Arsenal, NJ 07806-5000
2	Commander US Army Missile Command ATTN: AMSMI-RK, D.J. Ifshin W. Wharton Redstone Arsenal, AL 35898
1	Commander US Army Missile Command ATTN: AMSMI-RKA, A.R. Maykut Redstone Arsenal, AL 35898-5249
1	Office of Naval Research Department of the Navy ATTN: R.S. Miller, Code 432 800 N. Quincy Street Arlington, VA 22217
1	Commander Naval Air Systems Command ATTN: J. Ramnarace, AIR-54111C Washington, DC 20360
1	Commander Naval Surface Warfare Center ATTN: J.L. East, Jr., G-23 Dahlgren, VA 22448-5000

No. of Copies	Organization
2	Commander Naval Surface Warfare Center ATTN: R. Bernecker, R-13 G.B. Wilmot, R-16 Silver Spring, MD 20903-5000
5	Commander Naval Research Laboratory ATTN: M.C. Lin J. McDonald E. Oran J. Shnur R.J. Doyle, Code 6110 Washington, DC 20375
1	Commanding Officer Naval Underwater Systems Center Weapons Dept. ATTN: R.S. Lazar/Code 36301 Newport, RI 02840
2	Commander Naval Weapons Center ATTN: T. Boggs, Code 388 T. Parr, Code 3895 China Lake, CA 93555-6001
1	Superintendent Naval Postgraduate School Dept. of Aeronautics ATTN: D.W. Netzer Monterey, CA 93940
3	AL/LSCF ATTN: R. Corley R. Geisler J. Levine Edwards AFB, CA 93523-5000
1	AL/MKPB ATTN: B. Goshgarian Edwards AFB, CA 93523-5000
1	AFOSR ATTN: J.M. Tishkoff Bolling Air Force Base Washington, DC 20332
1	OSD/SDIO/UST ATTN: L. Caveny Pentagon Washington, DC 20301-7100

No. of Copies	Organization
1	Commandant USAFAS ATTN: ATSF-TSM-CN Fort Sill, OK 73503-5600
1	F.J. Seiler ATTN: S.A. Shackleford USAF Academy, CO 80840-6528
1	University of Dayton Research Institute ATTN: D. Campbell AL/PAP Edwards AFB, CA 93523
1	NASA Langley Research Center Langley Station ATTN: G.B. Northam/MS 168 Hampton, VA 23365
4	National Bureau of Standards ATTN: J. Hastie M. Jacox T. Kashiwagi H. Semerjian US Department of Commerce Washington, DC 20234
1	Aerojet Solid Propulsion Co. ATTN: P. Micheli Sacramento, GA 95813
1	Applied Combustion Technology, Inc. ATTN: A.M. Varney P.O. Box 17885 Orlando, FL 32860
2	Applied Mechanics Reviews The American Society of Mechanical Engineers ATTN: R.E. White A.B. Wenzel 345 E. 47th Street New York, NY 10017
1	Atlantic Research Corp. ATTN: M.K. King 5390 Cherokee Avenue Alexandria, VA 22314
1	Atlantic Research Corp. ATTN: R.H.W. Waesche 7511 Wellington Road Gainesville, VA 22065
1	AVCO Everett Research Laboratory Division ATTN: D. Stickler 2385 Revere Beach Parkway Everett, MA 02149
1	Battelle Memorial Institute Tactical Technology Center ATTN: J. Huggins 505 King Avenue Columbus, OH 43201
1	Cohen Professional Services ATTN: N.S. Cohen 141 Channing Street Redlands, CA 92373
1	Exxon Research & Eng. Co. ATTN: A. Dean Route 22E Annandale, NJ 08801
1	Ford Aerospace and Communications Corp. DIVAD Division Div. Hq., Irvine ATTN: D. Williams Main Street & Ford Road Newport Beach, CA 92663
1	General Applied Science Laboratories, Inc. 77 Raynor Avenue Ronkonkama, NY 11779-6649
1	General Electric Armament & Electrical Systems ATTN: M.J. Bulman Lakeside Avenue Burlington, VT 05401
1	General Electric Ordnance Systems ATTN: J. Mandzy 100 Plastics Avenue Pittsfield, MA 01203
2	General Motors Rsch Labs Physics Department ATTN: T. Sloan R. Teets Warren, MI 48090

No. of Copies	Organization
2	Hercules, Inc. Allegheny Ballistics Lab. ATTN: W.B. Walkup E.A. Yount P.O. Box 210 Rocket Center, WV 26726
1	Honeywell, Inc. Government and Aerospace Products ATTN: D.E. Broden/ MS MN50-2000 600 2nd Street NE Hopkins, MN 55343
1	Honeywell, Inc. ATTN: R.E. Tompkins MN38-3300 10400 Yellow Circle Drive Minnetonka, MN 55343
1	IBM Corporation ATTN: A.C. Tam Research Division 5600 Cottle Road San Jose, CA 95193
1	IIT Research Institute ATTN: R.F. Remaly 10 West 35th Street Chicago, IL 60616
2	Director Lawrence Livermore National Laboratory ATTN: C. Westbrook M. Costantino P.O. Box 808 Livermore, CA 94550
1	Lockheed Missiles & Space Co. ATTN: George Lo 3251 Hanover Street Dept. 52-35/B204/2 Palo Alto, CA 94304
1	Los Alamos National Lab ATTN: B. Nichols T7, MS-B284 P.O. Box 1663 Los Alamos, NM 87545
1	National Science Foundation ATTN: A.B. Harvey Washington, DC 20550

No. of Copies	Organization
1	Olin Corporation Smokeless Powder Operations ATTN: V. McDonald P.O. Box 222 St. Marks, FL 32355
1	Paul Gough Associates, Inc. ATTN: P.S. Gough 1048 South Street Portsmouth, NH 03801-5423
2	Princeton Combustion Research Laboratories, Inc. ATTN: M. Summerfield N.A. Messina 475 US Highway One Monmouth Junction, NJ 08852
1	Hughes Aircraft Company ATTN: T.E. Ward 8433 Fallbrook Avenue Canoga Park, CA 91303
1	Rockwell International Corp. Rocketdyne Division ATTN: J.E. Flanagan/HB02 6633 Canoga Avenue Canoga Park, CA 91304
4	Sandia National Laboratories Division 8354 ATTN: R. Cattolica S. Johnston P. Mattern D. Stephenson Livermore, CA 94550
1	Science Applications, Inc. ATTN: R.B. Edelman 23146 Cumorah Crest Woodland Hills, CA 91364
3	SRI International ATTN: G. Smith D. Crosley D. Golden 333 Ravenswood Avenue Menlo Park, CA 94025
1	Stevens Institute of Tech. Davidson Laboratory ATTN: R. McAlevy, III Hoboken, NJ 07030

No. of Copies	Organization
1	Thiokol Corporation Elkton Division ATTN: S.F. Palopoli P.O. Box 241 Elkton, MD 21921
1	Morton Thiokol, Inc. Huntsville Division ATTN: J. Deur Huntsville, AL 35807-7501
3	Thiokol Corporation Wasatch Division ATTN: S.J. Bennett P.O. Box 524 Brigham City, UT 84302
1	United Technologies ATTN: A.C. Eckbreth East Hartford, CT 06108
3	United Technologies Corp. Chemical Systems Division ATTN: R.S. Brown T.D. Myers (2 copies) P.O. Box 49028 San Jose, CA 95151-9028
1	Universal Propulsion Company ATTN: H.J. McSpadden Black Canyon Stage 1 Box 1140 Phoenix, AZ 85029
1	Veritay Technology, Inc. ATTN: E.B. Fisher 4845 Millersport Highway P.O. Box 305 East Amherst, NY 14051-0305
1	Brigham Young University Dept. of Chemical Engineering ATTN: M.W. Beckstead Provo, UT 84058
1	California Institute of Tech. Jet Propulsion Laboratory ATTN: L. Strand/MS 512/102 4800 Oak Grove Drive Pasadena, CA 91009

No. of Copies	Organization
1	California Institute of Technology ATTN: F.E.C. Culick/ MC 301-46 204 Karman Lab. Pasadena, CA 91125
1	University of California Los Alamos Scientific Lab. P.O. Box 1663, Mail Stop B216 Los Alamos, NM 87545
1	University of California, San Diego ATTN: F.A. Williams AMES, B010 La Jolla, CA 92093
2	University of California, Santa Barbara Quantum Institute ATTN: K. Schofield M. Steinberg Santa Barbara, CA 93106
1	University of Colorado at Boulder Engineering Center ATTN: J. Daily Campus Box 427 Boulder, CO 80309-0427
2	University of Southern California Dept. of Chemistry ATTN: S. Benson C. Wittig Los Angeles, CA 90007
1	Case Western Reserve Univ. Div. of Aerospace Sciences ATTN: J. Tien Cleveland, OH 44135
1	Cornell University Department of Chemistry ATTN: T.A. Cool Baker Laboratory Ithaca, NY 14853
1	University of Delaware ATTN: T. Brill Chemistry Department Newark, DE 19711

No. of Copies	Organization
1	University of Florida Dept. of Chemistry ATTN: J. Winefordner Gainesville, FL 32611
3	Georgia Institute of Technology School of Aerospace Engineering ATTN: E. Price W.C. Strahle B.T. Zinn Atlanta, GA 30332
1	University of Illinois Dept. of Mech. Eng. ATTN: H. Krier 144MEB, 1206 W. Green St. Urbana, IL 61801
1	Johns Hopkins University/APL Chemical Propulsion Information Agency ATTN: T.W. Christian Johns Hopkins Road Laurel, MD 20707
1	University of Michigan Gas Dynamics Lab Aerospace Engineering Bldg. ATTN: G.M. Faeth Ann Arbor, MI 48109-2140
1	University of Minnesota Dept. of Mechanical Engineering ATTN: E. Fletcher Minneapolis, MN 55455
3	Pennsylvania State University Applied Research Laboratory ATTN: K.K. Kuo H. Palmer M. Micci University Park, PA 16802
1	Pennsylvania State University Dept. of Mechanical Engineering ATTN: V. Yang University Park, PA 16802
1	Polytechnic Institute of NY Graduate Center ATTN: S. Lederman Route 110 Farmingdale, NY 11735
2	Princeton University Forrestal Campus Library ATTN: K. Brezinsky I. Glassman P.O. Box 710 Princeton, NJ 08540
1	Purdue University School of Aeronautics and Astronautics ATTN: J.R. Osborn Grissom Hall West Lafayette, IN 47906
1	Purdue University Department of Chemistry ATTN: E. Grant West Lafayette, IN 47906
2	Purdue University School of Mechanical Engineering ATTN: N.M. Laurendeau S.N.B. Murthy TSPC Chaffee Hall West Lafayette, IN 47906
1	Rensselaer Polytechnic Inst. Dept. of Chemical Engineering ATTN: A. Fontijn Troy, NY 12181
1	Stanford University Dept. of Mechanical Engineering ATTN: R. Hanson Stanford, CA 94305
1	University of Texas Dept. of Chemistry ATTN: W. Gardiner Austin, TX 78712
1	University of Utah Dept. of Chemical Engineering ATTN: G. Flandro Salt Lake City, UT 84112

No. of Copies	Organization
1	Virginia Polytechnic Institute and State University ATTN: J.A. Schetz Blacksburg, VA 24061
1	Freedman Associates ATTN: E. Freedman 2411 Diana Road Baltimore, MD 21209-1525

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. BRL Report Number BRL_TR-3120 Date of Report JUN 90

2. Date Report Received _____

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) _____

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) _____

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. _____

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) _____

CURRENT ADDRESS

Name

Organization

Address

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the New or Correct Address in Block 6 above and the Old or Incorrect address below.

OLD ADDRESS

Name

Organization

Address

City, State, Zip Code

(Remove this sheet, fold as indicated, staple or tape closed, and mail.)

---FOLD HERE---

DEPARTMENT OF THE ARMY
Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 210[illegible]-5066
OFFICIAL BUSINESS

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

BUSINESS REPLY MAIL
FIRST CLASS PERMIT No 0001, APG, MD

POSTAGE WILL BE PAID BY ADDRESSEE

Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-9989

---FOLD HERE---