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AN ASSESSMENT OF NONDESTRUCTIVE TESTING TECHNOLOGIES FOR CHEMICAL WEAPONS MONITORING

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ABSTRACT

The U.S. Department of Energy (DOE), with the U.S. Army Chemical Research, Development and Engineering Center (CRDEC) under the sponsorship of the Defense Nuclear Agency (DNA), completed testing of Nondestructive Evaluation (NDE) technology on live agent systems. The tests were conducted at Tooele Army Depot during August 1992. The Nondestructive Evaluation systems were tested for potential use in verifying chemical treaty requirements. Five technologies, two neutron and three acoustic, were developed at DOE laboratories. Two systems from the United Kingdom (one neutron and one acoustic) were also included in the field trials. All systems tested showed the ability to distinguish among the VX, GB, and Mustard. Three of the systems (two acoustic and one neutron) were used by On-Site Inspection Agency (OSIA) personnel.

SUMMARY

The U.S. Department of Energy (DOE) and Defense Nuclear Agency (DNA) have sponsored the development Nondestructive Evaluation (NDE) technology. The technology development has focused upon nondestructive measurements that will aid verification of chemical treaty requirements. Initial feasibility tests, conducted in May 1991, demonstrated that the NDE systems under development could provide low-cost, low-operational impact alternatives to direct sampling and analysis.

Following the initial feasibility tests, workshops and peer reviews evaluated the results. Based upon these reviews, the U.S. Department of Energy and the Defense Nuclear Agency selected the following key technologies for further development and assessment of their full capabilities.

1. Ultrasonic Pulse Echo (UPE)
   - developed by Pacific Northwest Laboratories (PNL)

2. Acoustic Resonance Spectroscopy (ARS)
   - developed by Los Alamos National Laboratory (LANL)

3. Portable Isotopic Neutron Spectroscopy (PINS)
   - developed by Idaho National Engineering Laboratory (INEL)

4. Ion-tube Neutron Spectroscopy (INS)
   - developed by Lawrence Livermore National Laboratory (LLNL)

5. Noncontacting Acoustic/Ultrasonic Signature Analysis (NAUSA)
   - developed by Idaho National Engineering Laboratory (INEL)

During August of 1992 field trials were again held at Tooele Army Depot. The field trials provided data for evaluating the following issues.

- Quantify the capability of NDE technology to distinguish among the chemical agents VX, GB, Mustard and Lewisite in marked storage facility conditions.

- Demonstrate the use of NDE technology on fused, burstered and propellant-filled munitions.

- Evaluate the capability of NDE to correctly identify liquid versus solid munitions.

- Evaluate the field use of selected NDE systems using OSIA operators and gain an operational perspective from OSIA personnel.

- Evaluate the synergistic improvement of using multiple NDE technologies using surrogate munitions.
- Evaluate the effects of agent purity on NDE measurements systems.
- Promote international acceptance of NDE technology by including participants from the United Kingdom.

The test initially proposed to accomplish this measurement was a "blind" test designed so that the NDE operators would not know the identity of the munition being tested. Blind testing has the advantage of being simple to administer and allows a common analysis for all NDE systems. However, safety constraints that must be used when handling chemical munitions made blind testing impossible. In particular, it is contrary to Army regulations to have more than one type of chemical munition a single storage building. Therefore, a test matrix was developed that provided the opportunity to examine replicate 155-mm munitions. Using replicate measurements on the 155-mm munitions allowed statistics to be developed for each NDE system that quantify the capability to distinguish among VX, GB and Mustard.

Two analytical methods were used to analyze data from the Tooele field trials. One method of analysis was the t-test of significance. The t-test statistics were calculated from the following equation.

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)}{\sqrt{\frac{(N_1-1)V_1 + (N_2-1)V_2}{N_1 + N_2 - 2}}\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}}$$

where:

$\bar{x}_1$ = *mean of sample* 1
$\bar{x}_2$ = *mean of sample* 2
N_1 = *number of observations of sample* 1
N_2 = *number of observations of sample* 2
V_1 = *variance of sample* 1
V_2 = *variance of sample* 2
$\mu_1 - \mu_2$ = *hypothesis regarding the difference of the means*

The second method of data analysis used simple binomial statistics. The data for some NDE systems did not produce intermediate values which could easily be analyzed using a t-test. When this occurred simple binomial

statistics were used to provide an estimate of the capability in distinguishing the difference among the agents.

The field trials conducted at TEAD included testing on surrogate munitions. A set of thirty 155-mm munitions was filled with liquids that simulated the chemical munitions of VX, GB and Mustard. Two basic sets of simulants were used. One set simulated the chemical elemental ratios used in agents and was appropriate for testing the neutron systems. The other set simulated the density and viscosity of chemical agents as closely as possible and was intended for use with the acoustic systems. Testing at Tooele showed that the munitions with the chemical elemental ratios worked very well for the neutron systems (see Appendix IV for comments by the PINS system). Tests conducted by the acoustic systems on non-toxic liquids that closely matched agent densities and viscosities were not as successful.

CONCLUSIONS

The testing conducted at Tooele Army Depot provided a large engineering data base that may be used to evaluate the role of nondestructive technology for chemical treaty verification and aid in developing NDE technology for treaty verification. In addition to providing the policy community with data on the capability of the selected NDE systems, data from this test has been used by the principal investigators to improve decision algorithms. However, because no blind testing could be conducted, the data from this should not be construed as an accurate estimate of the operational capability of the NDE systems.

Specific conclusions from the testing are listed below.

Performance of NDE Systems

The general performance of NDE systems was good. All systems showed the capability to distinguish among VX, GB and Mustard *in munitions with known fills* with good reliability. The tests demonstrated the strengths and weaknesses of each system for a variety of applications.

PINS Neutron System

The PINS system showed the capability to distinguish among VX, GB, Mustard, Lewisite and high-explosive munitions with good reliability. The PINS system also demonstrated the capability to identify chemical agents in overpacked and storage/shipping containers. The PINS system has an important capability of detecting the actual chemical elements of the container being tested. However, the PINS system requires approximately one thousand seconds for measurements.

The PINS system would best be used to confirm the contents of bulk containers and small munitions selected at random.

Ultrasonic Pulse Echo

The UPE system showed the ability to distinguish VX, GB, and Mustard in bulk storage containers with good reliability. The UPE system also demonstrated the capability to classify munitions into like categories very well using simple time of flight. However, the UPE system as configured for the Tooele tests was not "user friendly" and created frustration for OSIA operators who used the system. The UPE system should be packaged into a smaller instrument and the software should be written to automate the data acquisition and analysis process. The UPE system would best be used to complement the PINS system in identification of bulk storage containers and verifying the fill level of bulk storage containers. The UPE system can also be used to classify munitions into categories and to simply confirm the presence or absence of liquid inside a container.

Acoustic Resonance Spectroscopy

The ARS system demonstrated the capability to distinguish among VX, GB, Mustard and high explosive munitions and bulk storage containers if the system can develop templates from actual containers. If actual munitions or containers are not available to develop templates, the ARS system can classify munitions into like categories. The ARS system could also be used to determine liquid level if a container were filled to various levels and used to provide a calibration curve. The ARS system is very "user friendly". The ARS system would best be used by complementing the PINS system in verifying the contents of munitions. The PINS system would confirm the proper chemical

elements for a few munitions and the ARS would show that all other munitions in that lot were the same.

Noncontact Laser Acoustic Resonance

The Noncontact Laser Acoustic System showed the ability of to distinguish among VX, GB, Mustard and high explosive munitions with good reliability. Like the ARS system, the Noncontacting Acoustic\Ultrasonic Signature Analysis system requires a set of munitions of known contents to develop a statistical base which can then be used to sort unknown munitions.

SURROGATE TESTING

The field trials conducted at Tooele Army Depot included surrogate munitions with simulants for VX, GB and Mustard. The simulants were divided into two groups; one group simulated the chemical elemental composition of the three agents and the other group simulated the physical properties of the agents.

Surrogate munitions that simulated the chemical elemental composition provided very good tests for the neutron systems. The munitions that simulated the physical properties provided reasonable simulation for Mustard and VX, however, the simulant for GB was not as good. The work with simulants proves that simulants can be developed for testing that would allow blind testing to be conducted with the NDE systems. Blind testing would be an excellent method to test true "unknown" munitions and is recommended for developing an acceptance test for the NDE systems.

ACRONYMS

ARS	Acoustic Resonance System
CRDEC	Chemical Research, Development and Engineering Center
CW	Chemical Warfare
DNA	Defense Nuclear Agency
DOE	Department of Energy
GB	A chemical nerve agent - Also known as Sarin
H	A chemical agent - Also known as Mustard
INEL	Idaho National Engineering Laboratory
INS	Ion Tube Neutron System
L	A chemical agent - Also known as Lewisite
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
NDE	Nondestructive Evaluation
OSIA	On-Site Inspection Agency
PINS	Portable Isotopic Neutron Spectroscopy
PNL	Pacific Northwest Laboratory
TEAD	Tooele Army Depot
UPE	Ultrasonic Pulse Echo
VX	A chemical nerve agent
WP	White Phosphorus

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Conducting a test as complex as the field trials at Tooele require the help of many people. To all those who helped the author is grateful.

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1.0 INTRODUCTION

The U.S. Department of Energy (DOE) and Defense Nuclear Agency (DNA) have jointly sponsored the development of Nondestructive Evaluation (NDE) technology. The technology development has focused upon noninvasive methods that will aid chemical treaty verification requirements. Initial feasibility tests, conducted in May 1991, demonstrated that NDE systems under development could provide low-cost, low-operational-impact alternatives to direct sampling and analysis. The test operations took place within chemical munition storage bunkers, the open air bulk container storage yard, and the conventional munitions storage area. (See DOE report DOE/ID-10346; *Nondestructive Evaluation Tests on Chemical Weapons and Containers at Tooele Army Depot - Final Draft*, author Alan Preszler.)

Following the Tooele tests, workshops and peer reviews evaluated the results. Based upon these reviews, the U.S. Department of Energy and the Defense Nuclear Agency selected key technologies for further development and assessment of their full capabilities. The NDE technologies selected for evaluation are listed below.

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During August of 1992 field trials were again held at Tooele Army Depot. The field trials provided data for evaluating the following issues:

- Quantify the capability of NDE technology to distinguish among the chemical agents VX, GB, Mustard, and Lewisite in marked storage facility conditions.

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- Evaluate the capability of NDE to correctly identify liquid versus solid munitions.

- Evaluate the field use of selected NDE systems using OSIA operators and gain an operational perspective from OSIA personnel.

- Evaluate the synergistic improvement of using multiple NDE technologies using surrogate munitions.

- Evaluate the effects of agent purity on NDE measurements systems.

- Promote international acceptance of NDE technology by including participants from the United Kingdom.

The scope of the tests conducted at Tooele Army on NDE systems required many resources including:

- OSIA personnel (to evaluate the field use capability of the NDE equipment)

- The following chemical weapons (CW) munitions and bulk storage containers at Tooele Army Depot:

  - 105-mm Projectiles, GB cartridges (fused/burstered)
  - 155-mm Projectiles, VX filled
  - 155-mm Projectiles, GB filled High Purity
  - 155-mm Projectiles, GB filled Low Purity
  - 155-mm Projectiles, Mustard filled
  - 155-mm Projectiles, Surrogates for VX, GB and Mustard
  - 8-inch Projectiles, VX filled
  - One Ton Mustard Containers
  - One Ton GB Containers
  - Lewisite
  - MC-1 Bomb GB filled
  - MC-1 Bomb Unknown
  - M55 Rocket VX filled
  - Spray Tank VX filled
  - Surrogate Item
    - 3 One Ton Containers*
      1 Empty
      1 1/3 full
      1 Standard fill
      * All water fill
    - 8 155-mm Projectiles, ethylene glycol M121
    - 8 155-mm Projectiles, empty M121
    - 8 155-mm Projectiles, solid (wax filled or sand) M121

- 3 55-gal. drum
  Empty
  Water (1/2)
  Water (3/4)

- High Explosive Munitions
  - 155mm Projectile High Explosive (Comp B)
  - 155mm Projectiles White Phosphorus

All munition testing occurred with munitions in their normal storage condition. No munition handling or movement was required except that the shipping container for the VX spray tanks was opened to allow the acoustic systems to examine the VX spray tank.

This report summarizes the results of the testing that occurred at Tooele in August 1992.

The NDE systems tested at Tooele are configured from commercial components. These systems use acoustic energy and radiation (neutron) interactions to collect information which can aid in identification and quantification of the fill agent. A description of the systems is provided in Section 4.0.

2.0 PERFORMANCE OF NDE SYSTEMS

Testing the strengths and weaknesses of the NDE systems at TEAD required access to a variety of bulk storage containers and munition configurations. The items examined by each NDE system are shown in Tables 2.1 and 2.2.

TABLE 2.1. Summary of Munitions Tested

Item Tested	Ultrasonic Pulse Echo	Acoustic Resonance	Noncontact Laser Acoustic	Portable Isotropic Neutron	Ion-Tube Neutron Source
155 mm GB Low Purity	No Test	22	16		No Test
155 mm GB High Purity	19	28	16	5	No Test
155 mm VX	18	44	16	5	2
155 mm H	No Test	39	17	5	2
105 mm GB		51	12	5	2
8-inch VX		24	16	No Test	
Spray Tank VX	8	50	4	5	2
MC-1 Bomb		68	16	5	2
M55 Rocket	No Test	No Test	No Test	5	2
One Ton H	33	58	15	5	2
One Ton GB	26	49		5	2
One Ton L	No Test	No Test	No Test	5	2
155 mm High Explosive (Comp B)	5	45	22	5	2
155 mm White Phosphorous	5	61	22	5	2

TABLE 2.2. Summary of Surrogates Tested

Item Tested	Ultrasonic Pulse Echo	Acoustic Resonance	Noncontact Laser Acoustic	Portable Isotropic Neutron	Ion-Tube Neutron Source
155 mm VX Simulant Property	5	17	5	No Test	No Test
155 mm GB Simulant Property	5	15	5	No Test	No Test
155 mm H Simulant Property	5	17	5	No Test	No Test
55 Gal. Drum	3	No Test	No Test	No Test	No Test
155 mm Ethylene Glycol	6	No Test	No Test	No Test	No Test
155 mm Empty		8	8		No Test
155 mm Sand		8	8	No Test	No Test
155 mm VX Chemical Elements	3	15	5	1	2
155 mm GB Chemical Elements	3	15	5	2	2
155 mm H Chemical		15	5	2	2
155 mm TNT		23	11	5	No Test
1 Ton Water Filled	3	3			

One of the major objectives of the field trials was to quantify the capability of the NDE systems to distinguish among VX, GB, and Mustard agents. A 155 mm munition was selected to develop the data for this measurement because all three chemical agents of interest are used in the munition. Using

a single munition type that was filled with all three agents had the added advantage of eliminating possible variability due to munition configuration.

The test initially proposed to accomplish this measurement was a "blind" test designed so the NDE operators would not know the identity of the munition being tested. Blind testing has the advantage of being simple to administer and allows a common analysis for all NDE systems. However, safety constraints that must be used when handling chemical munitions made blind testing impossible. In particular, it is contrary to Army regulations to have more than one type of chemical munition a single storage building. Therefore, a test matrix was developed that provided the opportunity to examine replicate 155 mm munitions. Using replicate measurements on the 155 mm munitions allowed statistics to be developed for each NDE system that quantify the capability to distinguish among VX, GB, and Mustard.

Since blind testing was not possible, a test matrix was developed which provided data that would allow an upper bound estimate of the capability of NDE systems on munitions of known fill type. The test matrix had several constraints and assumptions. The constraints play an important role in evaluating NDE systems and as detailed below.

1) <u>Constraint:</u> All munitions are clearly marked or otherwise identifiable as to chemical content and they cannot be moved.

   <u>Consequence:</u> The test cannot be "blind" to the analyst in the field. Some consideration was given to separating the data acquisition from the data analysis. However, due to scheduling constraints during the test, blind data analysis was not used.

2) <u>Constraint:</u> It is not feasible, with respect to schedule, to randomize the order of measurement among replicates and fill types. Attempting to totally randomize measurements would require a team to set up equipment; measure one replicate of a fill type, say Fill Type VX; take down equipment; and move to several other locations (may be up to 10 miles away) to measure the random fill type, for example, high explosive (Comp B).

   <u>Consequence:</u> Lack of randomization will result in a possible bias in the measurements. For example, if a calibration error is occurring during the measurement of Fill Type GB, that error will affect each replicate of fill type GB in the order of measurement. If the replicate measurements were randomized, then this calibration error would be randomly distributed among the fill types. Consequently, when randomization is

employed among replicates and fill types, the calibration error cannot create a bias in the measurements. Other sources of variation include variability due to operator fatigue and time of day. These could also act to create a bias in the same way. During testing, randomization among replicates will be done to the extent practical.

3) Assumption: Each system produces an "intermediate" value that is used in the decision algorithm.

   Consequence: The "intermediate" quantitative values from each system are used to determine the precision of each system. This will be accomplished by looking at the variability among replicates of a given fill type. Hypothesis tests can be performed to assess the ability of the system to discriminate between fill types based on the replicate variability. If an intermediate value cannot be determined for a system, then simple binomial statistics (number of correct classifications per total number of samples) are used to determine confidence bounds.

Analytical methods used to quantify the capability to distinguish VX, GB and Mustard are described in the following Section. A qualitative description of each system's performance in terms of effect of ambient temperature, effects of munition configuration, and OSIA inspector comments is also provided.

2.1 ANALYSIS METHODS

The NDE systems tested at TEAD use energy (either acoustic or radiation) which interacted with the munition being tested. The interaction of energy with the munition caused a response which was then measured and analyzed to determine the presence and type of fill in the munition. Analyzing the energetic response that is measured from the munition involves determining intermediate values. Using "intermediate" values and hypothesis testing allows one to quantify the capability of the NDE systems to differentiate between chemical agents. If intermediate values are not reported by the principal investigator, then simple binomial statistics are used to analyze data. A brief description of the analysis techniques follows.

Data from Tables 2.3 and 2.4 are used to illustrate the two methods of analyzing data from the Tooele field trials. One method will use "intermediate" values and the other method will use simple (yes, no) binomial statistics.

The first method of analysis will illustrate the use of intermediate values. The ultrasonic pulse echo system measured speed of sound as an

intermediate value. If one applies a t-test of significance to the speed of sound data in Table 2.4, the speed of sound measurements made by both teams show a difference which is significant to the 1% level. This means that only 1% of the time would the speed of sound measurements among the agents VX, GB, and Mustard be measured to be the same when in fact the measurements are different.

The t-test statistics were calculated from the following equation.

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)}{\sqrt{\frac{(N_1-1)V_1 + (N_2-1)V_2}{N_1 + N_2 - 2}}\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}}$$

where:

$\bar{x}_1$ = *mean of sample* 1
$\bar{x}_2$ = *mean of sample* 2
N_1 = *number of observations of sample* 1
N_2 = *number of observations of sample* 2
V_1 = *variance of sample* 1
V_2 = *variance of sample* 2
$\mu_1 - \mu_2$ = *hypothesis regarding the difference of the means*

A t-test of significance shows that measuring the speed of sound can distinguish among VX, GB, and Mustard.

The second method of data analysis will illustrate the use of simple binomial statistics. If speed of sound is not used as an intermediate value for the pulse echo system, an estimate of the capability in distinguishing the difference among the agents can be determined by the following example. If one applies the automated decision algorithm developed for the Pulse Echo system (see Supplement 1 in Appendix A), all of the ton containers and all but one spray tank would have been identified properly. The results of such an algorithm are shown in Table 2.3 below.

TABLE 2.3. Results of Automated Analysis for Pulse Echo System

Agent	# of Incorrect Categorizations	Number of Samples	Lower 95% Confidence Bound
GB	0	16	83%
VX	1	8	53%
Mustard	0	23	87%

The lower confidence bound is calculated from binomial statistics using the following equation:

$$1 - \sum_{X=D}^{N} \frac{N!}{X!\,(N-X)!} (P)^{X}(1-P)^{N-X} = 95\%\ \textit{Lower Confidence Level}$$

where N = Number of Samples
D = Number of Samples Correctly Identified
P = Lower Confidence Bound

The two methods of analysis illustrate a problem which often occurs in analyzing test data and drawing conclusions based upon analysis. Data from both analysis does not seem to be consistent; t-test data suggest that the pulse echo system should have excellent performance on large containers while the binomial data appear to indicate the performance is not really excellent. The reasons for the apparent discrepancy are the assumptions used in each analysis. The t-test uses an assumption that the speed of sound data are normally distributed (e.g., the data follows a gaussian distribution). This assumption allows the use of small sample sizes (5-15) to develop the performance data for the UT system.

The binomial analysis does not make any assumptions about the data. Consequently, the binomial analysis requires many samples (55-100) to develop the same level of confidence (95% probability of correct detection with a 95% confidence level) as the t-test. Based upon the t-test data, one would expect that if the pulse echo system had been tested upon a larger sample of one-ton containers, say 55, the two analysis would be consistent.

Therefore, when binomial statistics are used in this report on small sample sizes, the reader is cautioned that the lower bound confidence level is exactly that--the lowest possible performance level based upon the small number of samples that were tested during the field trials. Larger sample sizes were not used in the field trials because of time limitations. Testing at Tooele took eight days; more time was not available because of impacts to the normal mission of the storage depot.

2.2 TEST RESULTS OF THE ULTRASONIC PULSE ECHO SYSTEM

The basic principle of operation of the pulse echo system is similar to sonar. A pulse of ultrasonic energy is propagated into the container through the wall by means of a transducer coupled to the wall. This pulse of energy travels through the wall and into the contents of the container. When the pulse reaches an obstruction within the container, it is reflected back to, and through, the wall to be detected by the transducer. The interval between the time the pulse enters the container and the time of the return of the echo is measured. If the container is empty, no echo will be observed since ultrasound does not propagate in air to any great extent. If the container is filled with a rigid solid, the time interval will be very short. However, for a liquid fill, the interval will be relatively long.

The field trial tests revealed some strengths and weaknesses of the present system. For inspection of large bulk storage containers, this technology performed very well and provided quantitative physical information unavailable from any other technology tested during this exercise. Both container fill level and the speed of sound in the fluid were obtained with high accuracy and with relative ease. A single pulse/echo measurement was needed to obtain the fluid sonic speed of sound. Movement of the acoustic transducer along the wall of the shell until the echo signal disappeared established the fluid fill level. Accomplishment of all necessary measurements required about one minute. Excellent data were obtained by both the OSIA team and the PNL team with one-ton Mustard and GB containers and with VX spray tanks. The results are summarized in Table 2.4.

TABLE 2.4. Average Velocities from Measurements with One-Ton Mustard Tanks, One-Ton GB Tanks, and VX-Filled Spray Tanks

Agent (Temp °C)	Speed of Sound (in/μsec)	Standard Deviation (in/μsec)	3 X Standard Deviation (in/μsec)
*** PNL TEAM ***			
H (30 °C)	0.0544	0.0005	0.0015 (23 samples)
GB (23 °C)	0.0446	0.0006	0.0018 (16 samples)
VX (23 °C)	0.0519	0.0002	0.0006 (4 samples)
*** OSIA TEAM ***			
H (30 °C)	0.0540	0.0006	0.0018 (10 samples)
GB (23 °C)	0.0443	0.0004	0.0012 (10 samples)
VX (23 °C)	0.0507	0.002	0.007 (4 samples)

Mustard, GB, and VX are clearly differentiated based on the differences in speed of sound. The PNL team showed differentiation out to three standard deviations, while the OSIA team can distinguish the three agents at the one standard deviation level. These results are particularly impressive since the velocities of Mustard and VX differ by only 5%. In addition, the average velocities measured by both teams agreed to within 1% in all three cases. The measured values also agreed within 2% in all three cases with measurements performed by Dr. Norman of the U.K. (unpublished results).

Speed of sound in burstered munitions can be measured using two transducers and a simple triangulation formula. Excellent results were obtained in the laboratory using this technique. However, the fixtures which were used in the field did not provide the same quality of data.

Table 2.5 summarizes the results of the pulse echo system on 155-mm munitions using the speed of sound fixture.

TABLE 2.5. Average Velocities and Attenuations from Measurements with 155-mm Shells Filled with GB and VX (23°C)

Agent	Speed of Sound (in/μsec)	Standard Deviation (in/μsec)	Pulse Echo Time (μsec)	Standard Deviation (μsec)	Atten (dB/m)	Standard Deviation (dB/m)
*** PNL TEAM ***						
GB	0.047	0.003	63.12	0.49	63	6
VX	0.051	0.003 (9 Samples)	54.75	0.66	67	17
*** OSIA TEAM ***						
GB	0.048	0.004	63.29	0.49	56	8
VX	0.053	0.001 (10 Samples)	54.26	0.29	61	11

A t-test using the speed of sound measurements in Table 2.5 shows the pulse echo system can distinguish between VX and GB at the 5% level of significance (5% of the time GB and VX will be measured the same when they are different). The pulse echo system was not able to get meaningful data on 155-mm Mustard munitions. It is not known exactly why no data were obtainable with Mustard 155-mm rounds. The acoustic signals suggest that the bursters on these shells were larger in diameter than usual or that the Mustard fill was solid. Reflected signals from the burster appeared to lie in the ringdown signal due to the steel wall, making the signal unusable. Sources at TEAD indicate that these shells did not have larger diameter bursters. No resolution of this question has been arrived at yet. Table 2.5 also shows that pulse echo time of flight measurements on both agent and surrogate munitions may also be used to classify munitions as the same or different.

Very poor results were obtained with 105-mm shells, 205-mm shells, and MC-1 bombs, all of which contain a burster. Fixtures were available and were used for the 105- and 205-mm shells. In the MC-1 bombs, which have a diameter of about 16 inches, no fixture was available and measurements were attempted by simply holding the transducers in place manually. In measurements with these munitions, the only truly repeatable signal we could obtain was the

pulse echo signal reflected from the burster wall. The pitch/catch signal was often difficult to distinguish.

2.3 ACOUSTIC RESONANCE SPECTROSCOPY

Performance of the Acoustic Resonance Spectroscopy (ARS) system is also divided into performance on 155-mm munitions and performance on large containers.

The ARS system operates by measuring the spectrum of a known munition or container and using the measured spectra to develop a template. The template of the known munition or container is then compared to the spectra of an "unknown munition" to decide if the unknown is the same or different. Currently, templates developed by the system that was used in field trials cannot be extrapolated to different geometries. For example, the template developed for 155-mm munitions cannot be used for 8-inch munitions. The principal investigator indicates that it may be possible, using mathematical modeling, to extend the templates' usage to munitions of the same basic geometry but different sizes (e.g., the 155-mm munition spectra's template could be used to examine 122-mm or 8-inch munitions).

Performance data for the ARS system was developed by collecting all data first, developing templates for each munition type, and analyzing all the acquired data by a cross-correlation algorithm. Performance of the ARS system on 155-mm munitions is summarized in Table 2.6.

TABLE 2.6. Summary of ARS Performance on All Munitions

Agent Type	# of Incorrect Categorizations	# Samples	95% Lower Confidence
GB (High Purity)	0	13	79%
GB (Low Purity)	0	13	79%
Mustard	0	16	83%
VX	0	15	82%
White Phosphorus	0	23	95%
TNT	0	15	82%

The 95% lower confidence bound shown for the ARS system was developed using simple binomial statistics as was done for the pulse echo system. Table 2.6 shows that the ARS system did an excellent job in categorizing like 155-mm munitions into the same class.

Some additional performance information can be extrapolated from Table 2.6. If one collapses the data from all liquid and solid munitions in the table, the ability of the ARS system to distinguish between liquid and solid munitions has a lower confidence bound of 92%.

The performance of the ARS system on large containers is summarized in Table 2.7. Again the ARS system did an excellent job categorizing like agent/containers.

TABLE 2.7. 1-Ton Container Results

Team	Agent Type	Number of Incorrect Categorization	Number of Samples (Tested)	90% Lower Confidence	95% Lower Confidence
LANL	Mustard	0	32	93	91
	GB	0	24	91	88
OSIA	Mustard	0	26	90	89
	GB	0	21	89	87

2.4 NONCONTACTING ACOUSTIC\ULTRASONIC SIGNATURE ANALYSIS

The Noncontacting Acoustic\Ultrasonic Signature Analysis system operates on the principle that the contents of a container (liquid or solid) affect the vibrational characteristics of the container. Specifically, the vibration characteristics that are of interest are the resonant frequencies and amplitudes which are affected by the liquid fill. As with the other systems, the performance of the noncontact-laser system will be divided into large containers and 155-mm munitions. The performance of the Noncontacting Acoustic/Ultrasonic Signature Analysis system on 155-mm munitions is described below in Table 2.8.

TABLE 2.8. Performance of Noncontacting Acoustic/Ultrasonic Signature Analysis System

Agent Type	# of Incorrect Categorizations	# Samples	95% Lower Confidence
GB (Low Purity)	0	16	83%
GB (high Purity)	0	16	83%
Mustard	0	17	83%
VX	0	16	83%
White Phosphorus	0	23	87%
TNT	0	15	83%

Again, the lower 95% confidence bound is calculated by binomial statistics. No data on the performance of the Noncontacting Acoustic/ Ultrasonic Signature Analysis system on large containers is available.

2.5 PORTABLE ISOTOPIC NEUTRON SYSTEM (PINS)

Neutrons, by their absence of electrical charge, are very penetrating radiations. The low energy neutrons produced by radioisotopic sources, e.g., californium-252 (^{252}Cf) or americium-241-beryllium (^{241}Am-Be), easily penetrate the steel casing of an artillery projectile or chemical storage container. Neutrons interact with the fill materials, producing gamma rays characteristic of the chemical elements within the munition or container. The gamma rays are also very penetrating. Therefore, they escape the munition; and the element-specific gamma-ray energy and intensity signature can be recorded by a radiation detector. Thus, the type of fill inside a munition can be deduced by correlating the chemical elements detected by neutron activation with chemical elements in chemical agents. Since the PINS system detects chemical elements by neutron activation, the performance of the PINS system is independent of container type. Table 2.9 summarizes the performance of the PINS system summed over munition/container type.

TABLE 2.9. Performance of PINS System

Agent Type	# Samples	# Correct by Human Expert Analysis	Lower 95% Confidence Bound	# Correct by Computer	Lower 95% Confidence Bound
GB	13	11	76	11	76
Mustard	5	4	34	3	19
VX	9	9	72	9	72
Lewisite	2	2	22	2	22
High Explosive	6	5	42	4	27
White Phosphorus	2	2	22	2	22

2.6 RESULTS OF ION-TUBE NEUTRON SOURCE

No performance data in terms of intermediate values or summary tables of correct versus incorrect identification were provided for the Ion-Tube Neutron system. The principal investigator's report is included in Appendix E.

2.7 RESULTS OF TESTING ON SURROGATES

The field trials conducted at TEAD included testing on surrogate munitions. A set of thirty 155-mm munitions was filled with liquids that simulated the chemical munitions of VX, GB, and Mustard. Two basic sets of simulants were used. One set simulated the chemical elemental ratios used in agents and was appropriate for testing the neutron systems. The other set simulated the density and viscosity of chemical agents as closely as possible and was intended for use with the acoustic systems. Table 2.10 shows the simulants that were used in the field trials.

Testing at Tooele showed that the munitions with the chemical elemental ratios worked very well for the neutron systems (see Appendix D for comments by the PINS system). Tests conducted by the acoustic systems on non-toxic

liquids that closely matched agent densities and viscosities were not as successful.

Table 2.11 compares the measured sound speed for actual agents versus the speed of sound in the simulants. The data in Table 2.11 suggests that the sound speeds are close and could be used for the pulse echo system as simulants. However, data from the ARS system indicates the simulants do not work well for that system. At the time of this writing, it is not clear why the measured response of the simulants differs significantly for the ARS system.

TABLE 2.10. Chemical Simulants Used in Field Trials

Agent	Physical Property Simulate	Chemical Element Simulant
Mustard (HD)	2-Chlorophenol	50% Dimethyl Sulfide 50% 1,2 Dicholoroethane
GB	Triethyl Phosphate	7% Perfluoro (methyl-cyclohexane) 73% Triethylphosphite 20% Heptane
VX	Tributyrin	33% Proplyamine 33% Dimethyl Sulfide 33% Triethylphosphite

TABLE 2.11. Comparison of the Physical Properties of Simulants vs Agents

Surrogate	Sound Speed (in/μsec)	Density gm/ml 20 C	Viscosity cp @ 20 C	Chemical Agent	Sound Speed (in/μsec)	Density gm/ml 20 C	Viscosity cp
Tri-ethyl Phosphate	.0500	1.063	1.48	GB	.0446	1.094	1.54
Tributryn	.0530	1.030	9.6	VX	.0522	1.012	12.40
2-Cholophenol	.0560	1.241	4.411	Mustard	.0556	1.27	4.479

3.0 CONCLUSIONS AND RECOMMENDATIONS

The testing conducted at Tooele Army Depot provided a large engineering data base which may be used to evaluate the role of nondestructive technology for chemical treaty verification and aid in developing NDE technology for treaty verification. As an example, the data from this test has been used by the principal investigators to improve decision algorithms. However, because no blind testing could be conducted, the data from this should not be construed as an accurate estimate of the operational capability of the NDE systems. Blind testing of the proposed NDE system is essential for deciding the ultimate role of NDE technology in CW verification. Specific conclusions from the testing are listed below.

3.1 PERFORMANCE OF NDE SYSTEMS

The general performance of NDE systems was good. All systems showed the capability to distinguish among VX, GB, and Mustard *in munitions with known fills* with good reliability. The tests demonstrated the strengths and weaknesses of each system for a variety of applications.

- PINS Neutron System - The PINS system showed the capability to distinguish among VX, GB, Mustard, Lewisite and high-explosive munitions with good reliability. The PINS system also demonstrated the capability to identify chemical agents in overpacked and storage/shipping containers. The PINS system has an important capability of detecting the actual chemical elements of the container being tested. However, the PINS system requires approximately one thousand seconds for measurements.

  The PINS system would best be used to confirm the contents of bulk containers and small munitions selected at random.

- Ultrasonic Pulse Echo - The UPE system showed the ability to distinguish VX, GB, and Mustard in bulk storage containers with good reliability. The UPE system also demonstrated the capability to classify munitions into like categories very well using simple time of flight. However, the UPE system, as configured for the Tooele tests, was not "user friendly" and created frustration for OSIA operators who used the system. The UPE system should be packaged into a smaller instrument and the software should be written to automate the data acquisition and analysis process. The UPE system would best be used to complement the PINS system in identification of bulk storage containers and verifying the fill level of bulk storage containers. The UPE system can also be

used to classify munitions into categories and to simply confirm the presence or absence of liquid inside a container.

- Acoustic Resonance Spectroscopy - The ARS system demonstrated the capability to distinguish among VX, GB, Mustard and high-explosive munitions and bulk storage containers if the system can develop templates from actual containers. If actual munitions or containers are not available to develop templates, the ARS system can classify munitions into like categories. The ARS system could also be used to determine liquid level if a container were filled to various levels and used to provide a calibration curve. The ARS system is very "user friendly". The ARS system would best be used by complementing the PINS system in verifying the contents of munitions. The PINS system would confirm the proper chemical elements for a few munitions and the ARS would show that all other munitions in that lot were the same.

  The field trials conducted at Tooele Army Depot demonstrated that both acoustic techniques can be used to rapidly screen large numbers of declared items; e.g., hundreds of CW artillery munitions. ARS can identify liquid-filled munitions and can categorize munitions of similar fill type. UPE measurements can measure the speed of sound in, and can determine fill level in, bulk storage containers. The complementary nature of the acoustic systems makes combining the technologies a logical recommendation. This recommendation was made at a workshop sponsored by DNA in October 1992.

  As a result of the recommendation made during the workshop, DOE and DNA agreed that DNA would fund development of a joint Pulse Echo/Acoustic Resonance Spectroscopy system (an acronym PEAR).

- Noncontact Laser Acoustic Resonance - The Noncontact Laser Acoustic System showed good ability to distinguish among VX, GB, Mustard, and high-explosive munitions. Like the ARS system, the Noncontacting Acoustic\Ultrasonic Signature Analysis system requires a set of munitions of known contents to develop a statistical base which can then be used to sort unknown munitions.

3.2 SURROGATE TESTING

The field trials conducted at Tooele Army Depot included surrogate munitions with simulants for VX, GB, and Mustard. The simulants were divided into two groups. One group simulated the chemical elemental composition of the three agents and the other group simulated the physical properties of the agents.

Surrogate munitions that simulated the chemical elemental composition provided very good tests for the neutron systems. The munitions that simulated the physical properties provided reasonable simulation for Mustard

and VX, however, the simulant for GB was not as good. The work with simulants proves that simulants can be developed for testing that would allow blind testing to be conducted with the NDE systems. Blind testing would be an excellent method to test true "unknown" munitions and is recommended for developing an acceptance test for the NDE systems.

APPENDIX A

REPORT OF ULTRASONIC PULSE ECHO SYSTEM

APPENDIX A

REPORT OF ULTRASONIC PULSE ECHO SYSTEM

Tooele NDE Field Trials
Report of Ultrasonic Pulse Echo System

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EQUIPMENT DESCRIPTION

The ultrasonic pulse echo system described in this section may be used to determine the speed of sound of an agent and classify munitions in like categories. The basic principle of operation is similar to sonar. A pulse of ultrasonic energy is propagated into the container through the wall by means of a transducer coupled to the wall. This pulse of energy travels through the wall and into the contents of the container. When the pulse reaches an obstruction within the container, it is reflected back to, and through, the wall to be detected by the transducer. The interval between the time the pulse enters the container and the time of the return of the echo is measured. If the container is empty, no echo will be observed since ultrasound does not propagate in air to any great extent. If the container is filled with a rigid solid, the interval will be very short. A liquid fill produces a long interval. Using two transducers and a triangulation algorithm, the speed of sound can be measured independent of munition geometry.

There is other information available that is useful for detecting the case where the contents are granular or in powder form. Here, an echo will not be present, but the multiple echoes from the internal boundary of the container wall will be sufficiently different from those obtained when air, liquid, or solid are present as to permit a differentiation. When liquid level is sought, the operator simply moves the transducer upwards until the echo from the internal obstruction disappears.

If the container is a munition, the obstruction may be the burster or the opposite wall. If it is a bulk storage container, the obstruction is the opposite wall of the container. Thus, the same system can be used (with different transducers) for both situations. The ultrasonic pulse echo system may be used on any munition configuration where direct access to outside surface of the munition is possible.

The equipment consists of an assemblage of commercial products. The USD-10 is a rugged, self contained, digital ultrasonic flaw detector that can be powered from an AC outlet or battery pack. In a single module the unit contains a pulser, a receiver, and a display. The detector also has a built-in microprocessor controller. Figure A.1 provides a picture of the system. The notebook computer shown in the picture is used for data storage and transfer.

As configured for the testing at Tooele, the ultrasonic pulse echo system measured the following liquid properties:

- Speed of sound for the fill
- Attenuation of the liquid fill
- Liquid fill level

The information provided by the ultrasonic pulse echo system included:

- Agent fill type
- Fill level of the liquid in munitions or bulk storage containers
- Physical state of the agent (e.g., liquid or solid)

RESULTS OF TESTING

Tests conducted at Tooele revealed some strengths and weaknesses of the present system. For inspection of tanks this technology performed very well and provided quantitative physical information unavailable from any other technology tested during this exercise. Both munition fill level and the speed of sound in the fluid were obtained with high accuracy and with relative ease. A single pulse/echo measurement was needed to obtain the fluid sonic speed of sound. Movement of the acoustic transducer along the wall of the shell until the echo signal disappeared established the fluid fill level. Accomplishment of all necessary measurements required about one minute. Excellent data were obtained by both the OSIA team and the PNL team with one-ton mustard and GB containers and with VX spray tanks. These data will be reviewed below.

Results obtained with burstered munitions were not as favorable. To determine fluid sonic speed of sound in these munitions, two transducers were necessary. A pitch/catch time of flight measurement was needed besides the pulse/echo measurement. A different fixture for attaching the transducers to the munitions was required for each type of munition. Great care must be exercised in examination of the acoustic signals to obtain meaningful results. Poor acoustic speed of sound results were obtained for 105 mm, eight inch, and MC-1 bombs. Good results were obtained with 155 mm shells, with which we have had much more experience and an improved fixture design. It is clear that with the proper fixtures, good sonic speed of sound data are possible using the UT system. However, there is no method for avoiding the use of a fixture and it is possible that a different fixture will be required for each munition of different diameter. Finally, considerable knowledge and appreciation of ultrasonic phenomena will be required of the operator of the instrument. Besides measurement of ultrasonic speed of sound in the fluids, measurements of acoustic attenuation with burstered munitions were made. These measurements, which depend in part on the fluid viscosity, were made to provide a second signature which could be used for discrimination among different agents. However, the data collected at this test have sufficient scatter in the measured attenuation to make this discrimination technique unusable. The measured attenuation will also depend strongly on munition geometry, and thus cannot serve as a fluid property measurement independent of the container holding the fluid.

Fluid fill level was measured for each munition type using the pulse/echo measurements, which provided consistent and reliable timing information for each shell type. Always the shells examined were nearly full and no appreciable variation in fill level was observed.

Sonic speed of sound within the fluid can be measured for burstered munitions if careful measurements are made using properly designed transducer fixtures and advanced measurement devices. The cost for obtaining this information lay primarily in the requirement for highly skilled and knowledgeable operators. The complexity of the necessary measurements and the time required for the measurement is greater than that for a simple pulse/echo time of flight measurement, and it seems that this condition is inescapable. Data obtained with burstered munitions is described below.

RESULTS WITH ONE-TON CONTAINERS AND SPRAY TANKS

Measurements with these containers were performed using only the USD-10 ultrasonic flaw detector and a single transducer operated in the pulse echo mode. All these tanks were in the horizontal position. Since there are no obstructions along the axis of these containers an ultrasonic pulse introduced anywhere along the perimeter of a container will travel to the opposite wall and return to the transducer upon reflection. Upon transmission into the fluid, the ultrasonic pulse disperses into a broad beam, but the portion of the pulse which strikes the wall exactly opposite the transducer will be returned to the transducer. Measurement of the ultrasonic speed of sound in the fluid becomes very simple. The diameter of the container can be measured with a tape measure and the tank wall thickness can be measured ultrasonically, so that the sound path in the fluid is determined. The ultrasonic time of flight to the opposite wall and back is measured with the USD-10. Sonic speed of sound in the fluid is then simply the sound path of ultrasound in the fluid divided by the flight time. Fill level was determined by moving the transducer upward along the perimeter of a tank and observing the return echo on the USD-10 display screen. This return echo disappears when the transducer is positioned above the fluid level (ultrasound will not propagate through air or any other gas). The location of the transducer where the return echo disappears shows the fluid level in the tank.

The method described above works when the fill level is greater than half full, which was the case for all examined containers except one. If the fill level is less than one half, a return echo from the opposite wall cannot be obtained. In such cases the best approach is to position the transducer on the bottom of the container (if possible) and look for a return echo from the fluid surface. Fluid level can still be determined by moving the transducer along the perimeter of the container and observing changes in the ringdown signal or a reduction of noise in the return signal.

A compilation of representative data obtained for one-ton mustard tanks, one-ton GB tanks, and VX-filled spray tanks is shown in Tables A.1, A.2, and A.3, respectively. Table A.4 summarizes the results. Mustard, GB, and VX are clearly differentiated based on the differences in acoustic velocities. The

TABLE A.1. Ultrasonic Velocities in One Ton Mustard Tanks @ 30°C

Tank ID	Round Trip Total Time of Flight (microseconds)	Ultrasonic Velocity (inches/microsec)	Fill Level (*) inches
*** PNL TEAM ***			
D33810	1061	0.0546	9
D36881	1054	0.0550	8.5
D50002	1069	0.0542	6.5
D44664	1061	0.0546	8
D77488	1061	0.0546	7
D45183	1084	0.0534	> 10
D52183	1061	0.0546	7
D43039	1069	0.0542	5.5
D52225	1054	0.0550	9
D46730	1061	0.0546	8.5
D42104	----	-----	Empty
*** OSIA TEAM ***			
5	1079	0.0534	6
15	1055	0.0547	7
11	1068	0.0540	6
14	1050	0.0549	6
13	1080	0.0534	5
10	1074	0.0537	6
8	1056	0.0546	6
12	1086	0.0531	6
16	1062	0.0543	6
15	1056	0.0546	6

Wall Thickness = 0.5 inches (4.3 μsec)
Diameter = 30.5 inches (29.5 inches liquid diameter)
(*) Distance is from top of tank to the fluid surface

TABLE A.2. Ultrasonic Velocities in One-Ton GB Tanks @ 23°C

Tank ID	Round Trip Total Time of Flight (microseconds)	Ultrasonic Velocity (inches/microsec)	Fill Level (*) (inches)
*** PNL TEAM ***			
D75425	1350	0.0438	5
D22442	1310	0.0452	4.5
D01635	1350	0.0438	5.5
D84169	1321	0.0448	5.5
D51323	1336	0.0443	5.5
D43164	1328	0.0446	5.5
D83602	1336	0.0443	< 5.5
D52606	1299	0.0456	7
D81956	1317	0.0449	6
D84389	1328	0.0446	5.5
*** OSIA TEAM ***			
D86033	1340	0.0439	3
D30818	1330	0.0443	3
D01635	1350	0.0436	5
D22442	1340	0.0439	5
D75709	1320	0.0446	5
D77628	1310	0.0449	6
D25104	1330	0.0443	4
D28555	1320	0.0446	4
D21524	1330	0.0443	5
D77228	1320	0.0446	5

Wall Thickness = 0.53 inches (4.6 μsec)
Diameter = 30.5 inches (29.97 liquid diameter)
(*) Distance is from top of tank to fluid surface

TABLE A.3. Ultrasonic Velocities in VX-Filled Spray Tanks @ 23°C

Tank ID	Round Trip Total Time of Flight (microseconds)	Ultrasonic Velocity (inches/microsec)	Fill Level (*) (inches)
*** PNL TEAM ***			
1	864	0.0518	4.5
2	864	0.0518	4.5
3	859	0.0521	4
4	859	0.0521	4.5
*** OSIA TEAM ***			
1	936	0.0474	---
2	852	0.0521	---
3	851	0.0522	---
4	865	0.0514	---

Wall Thickness = 0.1 inches
Diameter = 22.5 inches
(*) Distance is from top of tank to fluid surface

TABLE A.4. Average Velocities from Measurements with One-Ton Mustard Tanks, One-Ton GB Tanks, and VX-Filled Spray Tanks

Agent (Temp °C)	Velocity (in/microsec)	Standard Deviation (in/microsec)	3 X Standard Deviation (in/microsec)
*** PNL TEAM ***			
H (30 °C)	0.0544	0.0005	0.0015 (23 samples)
GB (23 °C)	0.0446	0.0006	0.0018 (16 samples)
VX (23 °C)	0.0519	0.0002	0.0015 (4 samples)
*** OSIA TEAM ***			
H (30 °C)	0.0540	0.0006	0.0018 (10 samples)
GB (23 °C)	0.0443	0.0004	0.0012 (10 samples)
VX (23 °C)	0.0508	0.002	0.007 (4 samples)

PNL team showed differentiation out to three standard deviations, while the OSIA team can distinguish the three agents at the one standard deviation level. These results are particularly impressive since the velocities of mustard and VX differ by only 5%. In addition, the average velocities measured by both teams agreed within 2% in all three cases. The measured values also agreed within 2% in all three cases with measurements reported by Dr. Norman of the U.K. (unpublished results).

RESULTS OBTAINED WITH FLUID FILLED BURSTERED MUNITIONS

The results for the determination of sonic velocities in fluids contained within burstered munitions were generally unfavorable except for 155-mm rounds. The goal here was to determine fluid speed of sound without knowledge of the internal configuration of the shell. In particular, no prior knowledge of the burster diameter was assumed. Two separate ultrasonic time of flight measurements are made. The first is the usual pulse/echo measurement with a single transducer while the second is a pitch/catch measurement using two transducers. Ultrasonic speed of sound in the fluid can be determined from these time-of-flight measurements through a triangulation calculation. Good results for sonic velocities were obtained for GB- and VX-filled 155-mm shells. The data for the GB and VX rounds are presented in Tables A.5 and A.6 and the results are summarized in Table A.8. A t-test using the speed of sound measurements in Table A.8 shows the pulse echo system can distinguish between VX and GB at the 5% level of significance (5% of the time GB and VX will be measured the same when they are different).

No data were obtained for mustard-filled shells. Good results were also obtained with surrogate shells. It is not known exactly why no data were obtainable with mustard 155 mm rounds. The acoustic signals suggest the bursters on these shells were larger in diameter than usual or the mustard fill was solid. Reflected signals from the burster appeared to lie in the ringdown signal due to the steel wall, making the signal unusable. We have been advised that these shells did not have larger diameter bursters, however.

Data were also collected on 155 mm shells containing high explosives (HE) and white phosphorous (WP). The most consistent results were obtained with the HE rounds. These shells contained no burster well. Pulse echo signals showed transmission of ultrasound through the entire munition, and therefore allowed calculation of the acoustic speed of sound through the high explosive. The results were quite consistent for the four munitions tested. We did not expect to obtain speed of sound information on this round, since shrinkage of the HE fill from the munition walls should make transmission of ultrasound impossible. Apparently sometimes the HE does not separate from the munition to create an air gap. In these cases the ultrasonic speed of sound can be accurately measured. The data from the four rounds which were tested are shown in Table A.7. The calculated speed of sound for high-explosive munitions was 0.064 in./microsec. This measurement does not correspond to the known speed of sound of Comp B (0.122 in./microsec). The experimental results suggest that the munition was a smoke round with a liquid in the round. We are attempting to trace the reason for the inconsistent data.

TABLE A.5. Ultrasonic Velocities and Attenuation in 155-mm GB-Filled Shells

Shell ID	Pulse/Echo Time of Flight (microsec)	Ultrasonic Velocity (in/microsec)	Attenuation (dB/m)
*** PNL TEAM ***			
8	63.4	0.050	67
9	63.8	0.043	52
10	63.8	0.046	62
13	62.5	0.047	70
12	62.5	0.045	65
11	63.4	0.045	69
1	62.9	0.046	63
2	62.9	0.052	57
3	62.9	0.050	60
*** OSIA TEAM ***			
1	63.5	0.052	60
2	62.8	0.044	64
3	63.2	0.047	43
4	63.0	0.046	61
5	62.8	0.047	43
6	64.0	0.046	48
7	62.6	0.043	61
8	63.4	0.049	65
9	64.0	0.046	53
10	63.6	0.046	57

TABLE A.6. Ultrasonic Velocities and Attenuation in 155-mm VX-Filled Shells

Shell ID	Pulse/Echo Time of Flight (microsec)	Ultrasonic Velocity (in/microsec)	Attenuation (dB/m)
*** PNL TEAM ***			
2	54.2	0.053	95
14	55.1	0.050	52
15	54.0	0.053	69
10	55.6	0.050	77
6	55.4	0.049	56
9	53.7	0.045	91
3	55.1	0.055	61
13	54.6	0.053	50
12	55.1	0.052	60
*** OSIA TEAM ***			
6	54.0	0.054	108
7	54.6	0.053	57
2	53.9	0.053	76
1	54.4	0.050	74
3	54.6	0.053	56
14	54.6	0.053	48
15	54.2	0.052	54
13	54.2	0.053	52
11	53.9	0.054	70

TABLE A.7. Average Velocities from Measurements with 155-mm Shells Filled with High Explosive

Shell ID	Pulse-Echo Time of Flight (microsec)	Ultrasonic Velocity (in/microsec)
1	160.2	0.065
1	161.3	0.064
2	161.3	0.064
3	160.2	0.065

TABLE A.8. Average Velocities and Attenuations from Measurements with 155-mm Shells Filled with GB, VX, and HE

Agent	Velocity (-in/microsec)	Standard Deviation (in/microsec)	Pulse Echo Time (microsec)	Standard Deviation (microsec)	Atten (dB/m)	Standard Deviation (dB/m)
*** PNL TEAM ***						
GB	0.047	0.003	63.12	0.49	63	6
VX	0.051	0.003 (9 Samples)	54.75	0.66	67	17
HE	0.064	0.001 (4 Samples)	160.75	0.63		
*** OSIA TEAM ***						
GB	0.048	0.004			56	8
VX	0.053	0.001 (10 Samples)			61	11

The data obtained from WP-filled shells were not easily interpretable. These shells were equipped with a burster well. White phosphorus is expected to be in solid form at temperatures below about 100 F. Pulse/echo measurements were obtained on four of these shells, but the results were inconsistent. The return signals were quite noisy. The pulse/echo time of flight, which proved to be the most reliable measurement for all other munitions, varied widely for the three shells examined. These munitions were manufactured from 1954 to 1969, and the ultrasonic flight times ranged from 143 microseconds (1954 shell) to 113 microseconds (1969 shell). These times suggest rather slow ultrasonic velocities, about 0.02 in./microsec. However, the scatter and noise in our data make this conclusion unreliable. Experience

with this munition type suggests that the pulse/echo method should only be used to tell liquid from solid.

In the cases of WP and HE rounds, fill level could be determined using the pulse echo measurements, just as for all other munitions. For the rounds examined the shells were nominally full.

Very poor results were obtained with 105-mm shells, 205-mm shells, and MC-1 bombs, all of which contain a burster. Fixtures were available and were used for the 105- and 205-mm shells. In the case of the MC-1 bombs, which have a diameter of about 16 inches, no fixture was available and measurements were attempted by simply holding the transducers in place manually. In measurements with these munitions, the only truly repeatable signal that we were able to obtain was the pulse echo signal reflected from the burster wall. The pitch/catch signal was difficult to distinguish in most cases. The fixtures designed for use in these tests did not function as well as the one used with the 155-mm munitions. These fixtures were constructed late in this program and were untested in the laboratory due to a lack of representative surrogate shells. Even when clean pitch/catch signals were available, analysis of the data gave velocities which were lower than accepted values by a factor of two. The deficiencies in these measurements can most likely be corrected by construction of more useful fixtures, using a design similar to that used for the 155-mm rounds. However, a separate fixture will very likely be required for each shell type.

RESULTS OF TESTS WITH SURROGATES

Fifteen surrogate rounds were tested to see if they would serve as useful alternatives to VX, GB, and mustard. There were five 155-mm shells each of tri-ethyl phosphate (GB simulant), tributyrin (VX simulant), and 2-chlorophenol (mustard simulant). Results of measurements for the ultrasonic velocities and attenuations are shown in Table A.9. The ultrasonic velocities as measured with the fixture have insufficient spread to discriminate among them based upon speed of sound. However, the pulse echo times of flight in the liquids show that a simple time-of-flight measurement can classify all three liquids as the same or different.

CONCLUSIONS

The most consistent, reliable, and easily obtainable signal which is provided by the ultrasonic system tested at Tooele is the simple pulse/echo time-of-flight signal. This system works extremely efficiently with the large containers or any container not having a burster. Very reliable and accurate speed of sound information is obtained with a single, simple measurement. Also, fill level can be obtained very easily. No system tested at Tooele provides as much quantitative and definite information for these large containers. The results obtained with the one-ton mustard and GB tanks and with the VX-filled spray tanks conclusively show our ability to differentiate these agents based on the speed of sound of ultrasound through these fluids.

TABLE A.9. Average Velocities and Attenuations from Measurements with 155 mm Shells Filled with Surrogate Liquids

Surrogate	Velocity (in/μsec)	Standard Deviation (in/μsec)	Pulse Echo Time (μsec)	Standard Deviation (μsec)	Atten (dB/m)	Standard Deviation (dB/m)
*** PNL TEAM ***						
Tri-ethyl Phosphate	0.051	0.002	52.49	0.52	49	12
Tributyrin	0.051	0.003	48.73	0.59	70	11
2-Chloro-phenol	0.053	0.002	46.33	0.52	63	8

OSIA personnel can make these measurements with comparable accuracy with only minimal training.

Use of this ultrasonic system for examination of burstered munitions can be accomplished reliably but at the cost of greater complexity of the measurement, and significantly more operator expertise and familiarity with ultrasonic phenomena are necessary. A fixture for placement of the transducers on the munition is necessary. It is likely that several fixtures will be required to cover the entire range of sizes of these munitions. We obtained good data with the 155-mm diameter GB- and VX-filled shells, but poor data with 155-mm mustard rounds and all munitions of other diameters. Our experience with the 155-mm shells shows that speed of sound measurements with burstered munitions are possible using properly designed fixtures and appropriate time-of-flight measurement instrumentation. While computer automation of the data collection process will eventually decrease the required measurement times, it does not appear that these measurements will ever be of comparable simplicity as the pulse/echo measurements. Measurements of this kind should probably be performed by highly skilled personnel. Measurement of acoustic attenuation for these munitions does not appear attractive. On individual rounds the measured attenuation depends on acoustic coupling and we observed too large a range in values to provide a useful material signature. In addition, shell geometry greatly influences these measurements so that results with the same agent cannot be compared among different shell sizes. Speed of sound measurements, on the other hand, provide a fluid property which is independent of shell geometry.

It is recommended that the pulse/echo measurement method be used for examination of large containers. This technique can be employed almost immediately. Measurement of ultrasonic speed of sound in agents contained in burstered shells should be developed further with the goals of automation of the measurement process and simplicity and flexibility in fixture design. It is probably not wise to develop this pulse/echo and pitch/catch method for use by general OSIA personnel, but for use by a specialized team. Measurement of acoustic attenuation as an agent identifier should probably be reconsidered

and discarded unless compelling reason is found for its continued investigation.

SUPPLEMENT 1.0
ULTRASONIC PULSE ECHO ALGORITHM FOR AGENT SELECTION

The algorithm that is used by the ultrasonic pulse echo system to decide agent type using speed of sound data is quite simple. The process is outlined below in a step fashion.

- Measure the Temperature
- Measure the Time of Flight in the Container and the Container Wall
- Measure the Diameter of the Container

- Determine the Speed of Sound in the Container

  - The Speed of Sound in a container without a burster is given by:

$$C = (2*D)/T$$

where C = Speed of Sound
D = Diameter of Container
T = Time of Flight of Inside Diameter

  - The Speed of Sound in a container with a Burster is given by:

$$C_L = \frac{2}{T_1}\left[\left(\frac{D}{2}\left\{1 - \left(\frac{T_2^2 - T_1^2 \cos\frac{L}{D}}{T_2^2 - T_1^2}\right)\left[1 - \left\{1 - \left(\frac{T_2^2 - T_1^2}{T_2^2 - T_1^2 \cos\frac{L}{D}}\right)^2\right\}^{1/2}\right]\right\}\right) - WT\right]$$

where C = Speed of Sound of Liquid in Container
D = Diameter of Munition
WT = Wall Thickness of Munition
T1 = Pulse echo time of Flight
T2 = Pitch Catch time of Flight
L = Distance between Transducers

- Correct the Measured Speed of Sound to a Standard Speed of sound @ 20 degree C for all three agents using the following correction:

$$C_{ct} = C_L - (A_{gt} * (Temp - 20))$$

where Cct = Temperature Corrected Speed of Sound

Agt = Agent Temperature Coefficient
-0.000121 in/μsec/°C for Mustard
-0.000134 in/μsec/°C for GB
-0.000109 in/μsec/°C for VX

Temp = Temperature of Munition

- Compare the "Corrected Speed of sound" to the following Table.

AGENT	Upper Velocity Limit in/μsec	Lower Velocity Limit in/μsec
Mustard	0.0570	0.0530
VX	0.0528	0.0480
GB	0.0460	0.0430

APPENDIX B

ACOUSTIC RESONANCE SPECTROSCOPY SYSTEM

APPENDIX B

ACOUSTIC RESONANCE SPECTROSCOPY SYSTEM

DRAFT REPORT

Results of tests carried out at the Tooele Army Depot during August 19-26, 1992

by

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EQUIPMENT DESCRIPTION

The Acoustic Resonance Spectroscopy (ARS) system consists of three primary components: (1) DSA200 Digital Synthesizer and Analyzer unit, (2) Notebook computer, and (3) Transducer fixture. The heart of the ARS system is the DSA200 unit which is a rectangular box approximately the size of a regular Notebook computer and contains a circuit board and rechargeable batteries. The weight of the DSA200 unit is approximately 6 lbs. including battery. The battery lifetime for continuous operation varies between 6 and 8 hours depending on the operating conditions and the unit can be fully charged in less than 4 hours. The battery life can be considerably improved by using rechargeable zinc oxide batteries when they become available in a few months.

We have used two separate ARS systems for the tests at Tooele Army Depot conducted during August 19 through August 26, 1992. One system was independently operated by two OSIA inspectors and the other system was used by the Los Alamos National Laboratory (LANL) team. The Notebook computer used by the OSIA team was a Zenith Z-NOTE 325L while the LANL system used a Gateway 2000 486DX Notebook computer. Both of these systems could be operated using internal long life Nickel metal hydride rechargeable batteries. We were able to carry out the entire day's assignments with a fully charged system. At the end of the day, both the DSA200 unit and the Notebook computers were recharged from 110 VAC outlets.

The transducer fixture consisted of an aluminum holder, two 1/2 inch diameter piezoelectric transducers, and one voltage amplifier. The transducers were held with metal rings inside a Teflon ribbon with two holes. The transducers were approximately 1 inch apart. The Teflon ribbon was attached to the aluminum holder and provided flexibility for transducer alignment on munition surface. Disc shaped Neodymium-Boron-Iron magnets were firmly attached on the front face of the piezoelectric transducers and provided easy coupling between transducers and the item being tested. The transducer

fixture was connected to the DSA200 unit with a 30 feet long electrical cable. The maximum length of the cable can be as much as 100 feet. One of the transducers was used as a transmitter to excite vibrations on the item being tested while the second transducer detected the minute resonant vibrations that resulted. Typical drive signal for the transmitter was only 0.5 V and the detected resonant vibration signal was less than 200 mV and corresponded to vibration amplitudes of the order of 100 angstroms. The excitation power was less than 1 mW and was distributed over the entire munition being tested and never localized at a given spot. The total weight of the entire ARS system is approximately 12 lbs including batteries. The equipment is portable and, although not specifically designed for field use, reasonably rugged. In fact, the OSIA system survived a several foot drop to the ground and functioned normally after that.

We also provided a miniature video (Private Eye) display that can be worn on the head over a mask. This was specifically designed for situations where bright sunlight affected the readability of the computer. During our tests at Tooele, we never encountered a situation where we actually needed to use this miniature video display unit. For a portable system that is specifically designed for one-man operation of the ARS system, this miniature display could prove to be very useful.

The DSA200 system contains all the necessary electronics and computer hardware for carrying out the frequency sweep measurements. The Notebook computer provides the supervisory control functions and analysis of data including data storage and graphics display. Typical sweep time used for most of the tests was 25 seconds. When the data analysis algorithms are optimized, this sweep (measurement) time can be reduced to 15 seconds depending on the munition type needed to be tested.

MUNITIONS TESTED

The following is a list of munitions tested by both the LANL and the OSIA team during the period between August 19 and August 26, 1992. The parenthetical notations of "property" and "nuclear" in items 16 through 21 refer to surrogate liquids matched for physical property and elemental characteristics for nuclear experiments, respectively.

Index	*Munition Type*	*Numbers Tested*	
		LANL	*OSIA*
1	105-mm GB	17	34
2	1-Ton GB	24	25
3	155-mm GB (Low Purity)	14	8
4	155-mm GB (High Purity)	13	15
5	MC-1 Bomb GB	25	43
6	1-Ton Mustard	32	26
7	155-mm Mustard	17	22
8	155-mm HE M483A1 (ICM)	20	14
9	M107 HE	29	16
10	155-mm VX	15	29

11	155-mm WP	31	30
12	8-inch VX	16	8
13	M106 TNT	17	6
14	Spray Tank VX+Empty	24	26
15	155-mm Empty	8	
16	155-mm Surrogate GB(Property)	15	
17	155-mm Surrogate H (Property)	17	
18	155-mm Surrogate VX(Property)	17	
19	155-mm Surrogate GB(Nuclear)	15	
20	155-mm Surrogate H (Nuclear)	15	
21	155-mm Surrogate VX(Nuclear)	15	
22	155-mm Surrogate Sand	8	
23	1-Ton Surrogate	22	
Total Number of measurements:		426	302

The numbers on the two right hand columns indicate the number of measurements made. In some cases, multiple measurements were made on the same item, in particular, on the surrogate items. In most cases, however, the number of measurements correspond directly to the number of munitions tested.

ALGORITHM

The results (using *all* data sets) for eight classes of 155-mm munitions are presented in Appendix I. We are unable to provide statistically meaningful confidence levels to our measurements at this stage. We would like to point out that Appendix I contains *all* data sets and not specially selected ones. This analysis does not include fill-level variation correction and correction for weight when pallets are piled on top of each other (in some cases 3 levels of pallets on top). These corrections will further improve our analysis but will take time to implement. Even without the necessary corrections and refinements, the results presented in Appendix A are quite encouraging. Please see the section on Preliminary Data Analysis for more details.

In the ARS technique, one obtains an acoustic signature of a CW item using the frequency sweep measurement and compares the essential features of that signature with those from known template signatures of various classes of munitions to determine which template signature the unknown signature best correlates with. This is the mode that the instrument was used in Tooele. Our goal was to determine if one could classify CW munitions by their acoustic signatures. We accomplished this goal by first developing template signatures for various classes of munitions and using those templates as the reference signature, compared the rest of the data sets from all classes. We then tabulated the results in terms of correct matching (correlation) of data sets from a given class with the template of that class. Alternatively, one could also pool all the data from different classes of munitions and sort them out according to type based on their unique acoustic signature properties. In the following, we describe the method behind the algorithm we used.

The essential features of an acoustic signature consists of three parameters: (i) the resonance frequencies over a certain range, (ii) the peak amplitudes corresponding to the resonance frequencies, and (iii) the sharpness Q (Q is the ratio of the center frequency to the width of the resonance curve) of the resonance curves. We found that for the case of artillery shells such as 155-mm, 105-mm, M107 rounds etc., we could successfully classify the munition category (in this case, same shell type but containing different agent types) by using the resonance frequency information only. For robustness, however, one could use all three parameters listed above. For the case of 1-ton containers, we used a slightly different and simpler approach. We found that the resonance Qs and the number of peaks are very different for Mustard and GB filled containers. Simply counting the peaks that exceed a certain threshold amplitude value adequately clustered the two sets of data. We discuss the algorithm used for the classification of artillery shells in greater detail below.

Basic Concept of the Algorithm: Find best match (correlation) of a set of resonant frequencies of unknown munitions with those of known munitions (reference *templates*).

Working Premises:

A given munition item (e.g., artillery shell) possesses a set of *well-defined* and *reproducible* resonant frequencies (acoustic spectrum).

A *subset* of these resonant frequencies can be excited and detected depending on the manner in which the excitation is impressed upon the munition item (e.g., number of transducers, spacing between transducers, transducer placement, type of transducer etc.)

Munition items of the same kind (shell type) and fill type have *nominally identical* sets of resonant frequencies but can have small variations on a finer scale that depend on the condition of the munition.

Making a Template:

This is required to generate a reference signature of a certain category of munition. Data from an unknown munition is then compared (correlated) against a whole set of such templates and the best match is picked. The following steps describe the procedure used in generating a CW munition signature template.

1. Acquire ARS data sets on N identical (size, shell type, fill type etc.,) munition items.

2. Identify resonant peaks (frequencies) above a threshold amplitude (noise) value for each data set and compile those into a single template file: (# of datasets with resonance at frequency f) vs. f in the form of a bar-code.

3. Replace each cluster of closely spaced peaks with a single centrally weighted peak: choose frequency window width to allow for expected

frequency variation (e.g., due to tolerance variation, different fill level, different temperature, different loading etc.,) in individual peak frequencies among the data-sets (munition items).

4. Slide window along frequency axis. When the number-of-peak count within the window at any given position exceeds a threshold count (a certain percentage of N), that count value is assigned to the centroid (center of mass) frequency (calculated with respect to count distribution within the window).

   Note: Template is not corrupted by inclusion of an accidental bad data-set because a minimum (threshold) number of data-sets must have a peak within the frequency window. Consequently, random isolated peaks have no effect on Template generation.

   The window width is selected on the basis of a trade-off between normal frequency variation accommodation and sensitivity of discrimination

Munition Identification Using Cross-Correlation:

Determine peak positions (above a noise threshold) in the acoustic spectrum of an unknown munition item.

Cross-correlate the above peak positions (unknown data-set) with template data derived from multiple munitions (reference data).

The above mathematical cross-correlation process provides the following information:

Total number of peaks that are common (within a predefined frequency spread-frequency window) to both Template and unknown.

To determine which class the unknown item falls into, the unknown data set is cross-correlated with all the known Templates. The Template that provides the highest number determines the class for the unknown item. For a completely unknown munition (i.e., no reference Template available for that class), the highest cross-correlation number gives an idea of the best possible match even if it is not the correct one. Similarly, the second highest number provides a measure of the second best guess and so on.

TEST RESULTS

In the following we show examples of typical acoustic spectra (raw data) for various types of munitions that we tested. We have not included every type of munition we tested but only the ones we thought would be of interest. We would like to remind the reader not to take this raw information and start comparing every wiggle in the graphs. A proper analysis of this raw data involves looking at various parameters of the spectra and not simply compare wiggles. Important parameters are the sharpness (Q) of the spectral lines, subtle frequency shifts in the right places (frequencies) where the liquid-shell coupling is the greatest, amplitude trend at higher frequencies,

characteristics of the fundamental modes, high frequency content which may appear as noisy signal to the untrained eye, frequency dependent frequency shift, random frequency shift etc. Taking all these parameters into consideration allows us to account for fill level variation and the effect of loading, such as pallets on top of pallets etc., on the spectra. The simple algorithm described above does not take into account most of these parameters and thus underestimates the true potential of the ARS technique.

Figure B.1 shows the comparability of the data within a given class. This figure shows an overlay of several data sets for 155-mm Mustard filled rounds. Important to note are the actual frequencies and not the amplitudes or the nature of the shape. Eight munition data sets were selected randomly in this case, without paying any attention to whether or not the munitions were tested under identical conditions such as pallet loading. This provides a kind of worst case scenario. As can be seen, the spectra are quite repeatable.

Figure B.2 compares the spectra of 155-mm Mustard and GB. Note the large difference in the Q(sharpness) values for an individual peak: 34 for H as compared to 268 for GB. The average <Q> values are slightly different from these figures. Heavier and thicker liquids produce higher damping (lower Q) than lighter liquids such as GB. Q depends on a combination of factors such as viscosity, density and to some extent on the speed of sound in a complex manner. Also note how the H-data gradually damps out at higher frequencies. Another distinguishing characteristic is the obvious frequency shift to higher frequency for the lighter fluid.

Figure B.3 presents a comparison between 155-mm VX and GB. The average <Q> values show a difference, 158 for VX as compared to 221 for GB. The GB in this case is the high purity GB. The frequency shifts are also quite obvious. This frequency shift, based on limited sampling, appears to be much larger than the variability observed within a given class. Again, the differentiation algorithm can take into account various other factors besides the simple frequency shift.

Figure B.4 shows a comparison between 1-Ton mustard and 1-Ton GB data. Following our discussion above, it is worth pointing out how the GB data show higher frequency content (noisier data by naked eye) as compared to the H data. This is another example of the effect of damping by the liquid. The heavier H damps out a lot of the vibrational modes of the front curved face where the measurements are made. In the case of the Ton containers it is more effective to simply compare the first spectral moment of the spectra instead of comparing each individual spectral line which will vary greatly. Even by eye, one can see that the H-data are shifted to lower frequency as compared to the GB data. So by examining even only these two simple parameters it is possible to distinguish between H and GB in Ton containers. Actual fill level determination will require calibration and we have not processed this information yet. Figure B.5 shows the resonance peak count data for both H and GB in a histogram form. All data sets (see Table 1) are included in this histogram. As expected, the H data are all clustered on the left side of the plot and separated from the GB cluster on the right. This allows for a quick discrimination of the two types of munitions tested. The large spread observed for the GB data have various reasons. For example, the GB containers were stacked

four levels as compared to only two levels for the H. The large pressure on the very bottom containers may have resulted in a damping effect on the vibrational characteristics of the circular front face and thus produced somewhat lower count. There also could be some variation in fill level among all the containers: an emptier container would produce higher count. A somewhat more robust algorithm will be able to account for such variations but we have not had a chance to implement them yet. All these deficiencies notwithstanding, we were able to achieve 100 percent correct classification as shown below. These results of the 1-Ton container data are summarized below. Measurements from both the LANL and OSIA teams are presented. The confidence levels were derived from simple Binomial statistics which significantly underestimates the true value. At the present time, we do not have a better method for estimating a confidence level and associate that with the simple algorithm that we used.

TABLE B.1. 1-Ton Container Results

Team	Agent Type	Number of Incorrect Categorization	Number of Samples (Tested)	90% Lower Confidence	95% Lower Confidence
LANL	Mustard	0	32	93	91
	GB	0	24	91	88
OSIA	Mustard	0	26	90	89
	GB	0	21	89	87

Figure B.6 shows typical data from MC-1 bombs. Most data within the class show good repeatability. Again, the data analysis here is very similar to Ton containers. For comparison we have presented the data taken from the Lakeside bomb. Simple examination of this data by eye indicates two possible explanations for the large shift in the data toward lower frequency for the Lakeside bomb. It indicates that there is possibly some water inside and, most likely, the shell has thickened and also has weakened (become less stiff) due to extensive rusting.

Figure B.7 presents an interesting case of the 155-mm HE ICM that contains grenades. The characteristics of this data are very different from that of simple HE filled munitions such as Comp-B and TNT that have no burster core. The sharp peaks identified by arrows correspond to the circumferential vibration modes. The frequency separation f between consecutive peaks show gradual increase. This is due to the fact that the top part of the shell is tapered (conical) and thus have gradually smaller circumference as it

approaches the top. After proper processing of the data, it may be possible to identify munitions such as ICMs.

An example of spray tank data is shown in Figure B.8. In this case, the measurements were made on the outside container of the spray tank to see if it is possible to determine if a spray tank container contains an empty tank (or no tank) without ever opening the container. The principle behind this is that a fully loaded spray tank will stress the struts in the container differently than an empty tank. The effect of this stress should show up as frequency shifts. Consequently we have taken data on both loaded and unloaded containers. The data shown are suggestive of the fact that it may be possible to determine the container loading effect as mentioned above but are insufficient to allow any definitive claims to be made at this stage. We feel it is worthwhile pursuing this approach more systematically.

Finally, we would like to point out that we were able to take data on 155-mm shells that were in the interior of the palette. This was possible because the probe (transducer fixture) used was quite small and could be inserted through the space available near the neck of the munition shells. This probe size can be reduced further without affecting the sensitivity of the measurements. All measurements were made without moving the munitions.

Preliminary Data Analysis:

The attached listing (Appendix I) shows the results of our correlation algorithm for determining if a munition belongs within a class and also to differentiate among munitions from different classes (liquids such as H, VX, GB etc.). The algorithm first establishes a baseline information template from data taken from known classes of munitions. This template then includes all the variability in the spectra that one observes in the data from real munitions. Once templates for various munitions are established, the acoustic resonance spectrum from any unknown munition then can be cross-correlated with this template quickly. In this listing, we have taken the data files from our measurements and run them through this algorithm to see how well the unknown raw data correlated with the known templates. At this time, we cannot provide any quantitative confidence level to the results except using simple Binomial statistics approach which seriously underestimates the true confidence level. The listing provides the best match (first), the second best match, and the third best match from the known templates. A completely unknown munition will produce results that would pick out a type which it comes closest to from the known templates. This algorithm can be significantly refined and made more robust if proper correction factors for fill-level variations and weight on top of munitions (e.g., pallets on top of pallets) are taken into account. This robustness can be further improved by including the Q-factors in the correlation algorithm.

Note: The OSIA results include data that were incorrectly taken such as saturated peaks (*amplifier saturation*) that make it difficult to identify peaks. Even then, the correct identifications were the second choice. With refined algorithm the identification process can be made more robust.

TABLE B.2. 155-mm Round Data

155-mm	LANL DATA		OSIA DATA	
Agent Type	Number of Incorrect Categorization	Number of Samples	Number of Incorrect Categorization	Number of Samples
GB (High Purity)	0	13	0	20
GB (Low Purity)	0	13		Includes both Low and High
Mustard	0	16	2	17
VX	0	15	1	14
White Phosphorus	0	23		
TNT	0	15		

In Table B.2, we have shown the GB data in two different ways. The LANL data were tested with a sharper discrimination (frequency) window that enabled the distinction between low and high purity GB. It is a simple matter to widen the discrimination window and only retain the ability to discriminate GB from other agents. This was done with the OSIA data as an example. In other words, it is quite simple to make the ARS discrimination less sensitive for broader classification capabilities but it does have the ability of much finer discrimination.

In the Table B.3, we summarize the data from various 155-mm shells and combine the data taken by the LANL and OSIA team. We have also discarded the known bad data sets (as described above) from the OSIA data list.

It is worth pointing out that the templates for each class of munition tested (specifically the 155-mm rounds), are almost entirely interchangeable between the LANL and OSIA data. This is notwithstanding the fact that the OSIA team only took half as many data points than the LANL team (1000 vs 2000). Consequently, the OSIA team acquired data twice as fast. Normally the frequency sweep speed affects the measurement of sharp resonance Qs but we found this to be minimal enough that it did not affect the final results. This gives us some confidence in the algorithm and the procedures adapted for the ARS measurement. We believe with further refinement of the algorithm, a template reference library of various classes of munitions can be reliably

TABLE B.3. Combined LANL and OSIA data for 155-mm rounds

Agent Type	Number of Incorrect Categorization	Number of Samples (Tested)	90% Lower Confidence	95% Lower Confidence
Mustard	0	31	93	91
GB	0	46	95	93
VX	0	28	92	90
TNT	0	15	86	82
White Phosphorus	0	23	90	88

generated even if the data are obtained from different sources and different people operating the equipment.

Surrogates: The data from the surrogates are classified as separate categories from the real agent-filled munitions by our algorithm. This implies that the property matched surrogates used do not represent the real munition. On close visual examination of the data we found the reasons for this discrepancy. Figures B.9 and B.10, respectively, compare the VX and H surrogate data with the real munition data. In the VX data, the resonance Qs are reasonably matched but the frequencies are way off. Figure B.9 overlays multiple data sets to show that there is a systematic difference. In Figure B.10, the Mustard data shows that the resonance frequencies are reasonably close but the resonance Qs are dramatically different. In the case of the Mustard data, we do not know the real physical condition of the agent. It is possible that the agent has physically degraded and significantly thickened and the shell wall-liquid interface properties are altered to a large degree than what could be expected from fresh agent. This effect cannot be reproduced by the surrogates. These are mere speculations since we do not have any direct knowledge of the exact state of the agent inside the rounds. On the face of the available information, we have to conclude that the physical property matched munitions do not represent the real ones from the ARS point of view. This also implies that the ARS technique is reasonably resistant to spoofing.

Application Matrix: We feel that the particular strength of the ARS technique is in rapidly screening a large number of munitions to determine a given class. Because of the nature and the sensitivity of this technique this technique can also be used for safety check in munitions and also for quality control. For instance, it may be possible to detect voids or detachment of

contents such as Comp-B, TNT etc., from the inside wall. We have not explored all different possibilities. We do not want leave the impression that we can ever image the contents of munitions.

Our current test system is comprised of two separate units. It is rather straightforward to combine both these units into one The system can be operated by a single person as it is designed but two-person operation in the field is recommended. The weight of the entire ARS system can be as little as 10 lbs including batteries. For much longer continuous operation, however, an additional battery pack may be required which will increase the weight by 2-4 lbs. This battery weight can be significantly reduced when the new high-efficiency zinc-air rechargeable batteries are available. The present system has the built-in design for wireless data communication between the DSA200 unit and the Notebook computer. For situations where some treaty limited items need to be monitored for a long duration such wireless communication may be desirable for remote monitoring. The power consumption of the DSA200 unit is low enough that it can be operated from a commercially available 1 foot-square size solar cell power generation unit.

The ARS system, in its present implementation, does not provide fill level information directly. However, such information can be extracted if the system is calibrated against known fill levels. We are currently working on developing algorithms to derive universal fill-level calibration that can be used for given type (shape) of munitions such as 105-mm, 155-mm, M106, M107 etc. All 1-Ton containers thus can have a single calibration. For 55-gallon drums, the situation is slightly different. Because of the fact that the metal skin of the drum is very thin compared to the artillery shells and the 1-ton containers, it is possible to directly determine the fill level in such drums by moving the transducers on the outer surface of the drum vertically. The local mechanical vibrations damp out severely when there is liquid present on the other side. In this case the frequency sweep is done very fast because detailed resonance information is not required. The same magnetically attached transducers are used.

The ARS technique does not directly determine physical properties of chemical agents but primarily determines if the acoustic spectra from a known baseline matches the spectrum from an unknown munition. For completely unknown munitions, however, it is still possible to determine the general nature of the fill such as solid, liquid or gel without having known baseline information. From our modeling efforts, we feel that it may be possible to scale information from one size of munition to the other. This improvement will take time to develop and verify on real munitions.

CONCLUSIONS AND RECOMMENDATIONS

We found the exercise at Tooele very useful. It provided us with a lot of important information that we did not have before regarding the nature of the acoustic signature for different types of munitions. Also, it was very important to have the feedback from the OSIA inspectors regarding the operation of the system under realistic conditions. This will help us improve the

system further. The extensive amount of data that we were able to gather will help us significantly in refining our algorithms.

Based on our preliminary data analysis, we were able to differentiate between VX, GB and Mustard and also between solid and liquid fill. In addition we found the ARS technique to be sensitive enough to provide information beyond that. Once we have completed processing all our data, we will be able to provide a list of capabilities of this system.

We feel the system is not ready for field deployment yet and requires a certain amount of hardware and software modifications. Some of these modifications are straightforward and can be carried out in a relatively short period of time. The algorithms need also be further refined to minimize false positives. Achieving full potential of this technique will require at least one more year's worth of R&D effort. Based on the results so far, we are very optimistic that the system can be improved significantly so that it can become a truly reliable tool for chemical weapons treaty verification. Simple variations of the ARS technique can produce instruments that can be very useful in treaty verification. In particular, we feel that a very simple (hand-held calculator size) system can be built that can, in less than 5 seconds, determine if a munition is solid or liquid filled. Based on our laboratory studies, it appears to be possible to directly probe the chemical agent inside munitions and receive information regarding both chemical and physical nature of the agent. The technique is another variation of the ARS technique. If this is realized, it may be possible to test unknown munitions without being affected by munition size, shape, or wall thickness. The development of this technique will require at least a year's worth of effort. Our recommendation will be to not field the ARS system immediately without the improvements mentioned. In any case, we recommend that complimentary techniques be used in conjunction with the ARS technique. For example, the ARS technique may be used for quick screening of munitions whereas other techniques such as PINS can be used on a small sample to determine the chemical nature of the agent. For fill level measurement in bulk containers, UPE is a better solution at the present time.

SUMMARY

Same templates worked for both LANL and OSIA data although each team used different number of data points and widely different sweep rates.

Measurement time between 15-20 seconds and 1000 or less data points in a data set seem quite acceptable. A typical data set can be ~2 kByte. This implies that approximately 60,000 measurements can be stored in a typical 120 MByte hard disk drive of a Notebook computer and 1,000 data sets in a high-density floppy diskette.

Majority of the munitions tested at Tooele produced good quality data and the data were well behaved and as expected. A few bad cases were found but there was no way to determine why they were bad without actually opening up the munition. There was no way to verify the nature of the contents.

It was possible to discriminate between real munitions and surrogate-filled (physical property matched liquids) munitions. This indicates that the ARS technique is reasonably resistant to spoofing. Further studies are required.

Contents (GB, H) of 1-ton containers could be discriminated regardless of fill level and other variations.

ICMs have unique characteristics and can be easily discriminated.

The results of the spray-tank container loading are inconclusive but the method does show some promise and deserves further investigation.

Determination of fill-level in bulk storage containers will require modeling and further analysis of the data.

Besides identifying seven different fill types, this technique was successful in discriminating between high and low purity GB.

Determination of physical properties (speed of sound, density, and viscosity) of chemical agents is possible with the ARS technique but will require further study.

A simpler system (hand-held calculator size) adapted from the present ARS technique can be built that can provide rapid (~2 second) discrimination between conventional (solid) and chemical or biological munitions.

Configuration dependent pattern in the acoustic signature could be identified from the data gathered at Tooele. It may be possible to use this information in scaling data from unknown munition types to match against known templates. This approach looks promising and deserves further study.

The recent exercise at Tooele showed that the ARS technique can be fine tuned to determine the state of the agent fill such as solidification, stratification, degradation etc., but would require systematic study before such features can be implemented.

With further refinement of the algorithm and improved hardware (transducers and electronics) the ARS technique can be made very reliable. The Tooele tests helped identify several specific improvements that need to be made to the existing system before it can be fielded.

APPENDIX B.1

CORRELATION ALGORITHM RESULTS

Nomenclature:

The first four letter designation of munition type in binary munition data below (1st Column). Example: GH550601 refers to 155-mm High Purity GB and ".bin" refers to the fact that it is stored in binary form in the computer

GH55:	155-mm High Purity GB	(GB-hi)
GL55:	155-mm Low Purity GB	(GB-low)
HO55:	155-mm Mustard	(H)
VX55:	155-mm VX	(VX)
WP55:	155-mm White Phosphorous	(WP)
TNT6:	M106 TNT	(TNT)
S55G:	155-mm Surrogate GB (Physical Property)	(GB-Sur)
S55H:	155-mm Surrogate H (Physical Property)	(H-Sur)
S55V:	155-mm Surrogate VX (Physical Property)	(VX-Sur)

Munition Data	Best Correlation	Second Best Correlation	Third Best Correlation	Number of Peaks used
GH550601.bin	1st: GB-hi	2nd: VX	3rd: H-Sur	(87)
GH550702.bin	1st: GB-hi	2nd: GB-low	3rd: GB-Sur	(73)
GH550503.bin	1st: GB-hi	2nd: GB-Sur	3rd: H-Sur	(58)
GH55XX04.bin	1st: GB-hi	2nd: GB-low	3rd: WP	(60)
GH550305.bin	1st: GB-hi	2nd: GB-low	3rd: H-Sur	(94)
GH550806.bin	1st: GB-hi	2nd: WP	3rd: GB-Sur	(68)
GH550107.bin	1st: GB-hi	2nd: GB-low	3rd: WP	(64)
GH550208.bin	1st: GB-hi	2nd: WP	3rd: GB-Sur	(54)
GH550a01.bin	1st: GB-hi	2nd: H-Sur	3rd: GB-low	(54)
GH550c02.bin	1st: GB-hi	2nd: GB-Sur	3rd: WP	(59)
GH550d03.bin	1st: GB-hi	2nd: WP	3rd: GB-low	(53)
GH550g04.bin	1st: GB-hi	2nd: GB-low	3rd: H-Sur	(82)
GH550n05.bin	1st: GB-hi	2nd: VX-Sur	3rd: WP	(75)
GL551301.bin	1st: GB-low	2nd: VX	3rd: GB-hi	(58)
GL551502.bin	1st: GB-low	2nd: VX	3rd: GB-hi	(80)
GL551603.bin	1st: GB-low	2nd: GB-hi	3rd: H	(52)
GL550904.bin	1st: GB-low	2nd: GB-hi	3rd: WP	(52)
GL551105.bin	1st: GB-low	2nd: WP	3rd: GB-hi	(36)
GL551006.bin	1st: GB-low	2nd: GB-hi	3rd: VX	(64)
GL551407.bin	1st: GB-low	2nd: WP	3rd: TNT	(50)
GL551208.bin	1st: GB-low	2nd: VX	3rd: TNT	(70)
GL550a09.bin	1st: GB-low	2nd: VX	3rd: GB-hi	(78)
GL559b10.bin	1st: GB-low	2nd: GB-hi	3rd: VX	(76)
GL550c11.bin	1st: VX-Sur	2nd: H-Sur	3rd: WP	(40)
GL550d01.bin	1st: GB-low	2nd: WP	3rd: VX	(55)
GL550e02.bin	1st: GB-low	2nd: WP	3rd: VX	(55)
GL550f03.bin	1st: GB-low	2nd: GB-hi	3rd: H-Sur	(67)

H0551001.bin	1st: H	2nd: WP	3rd: VX-Sur	(11)
H0551302.bin	1st: H	2nd: VX-Sur	3rd: H-Sur	(13)
H0551403.bin	1st: H	2nd: GB-Sur	3rd: H-Sur	(17)
H0551604.bin	1st: H	2nd: VX-Sur	3rd: GB-Sur	(13)
H0551505.bin	1st: H	2nd: H-Sur	3rd: WP	(16)
H0550406.bin	1st: H	2nd: TNT	3rd: H-Sur	(14)
H0550607.bin	1st: H	2nd: H-Sur	3rd: VX-Sur	(15)
H0550508.bin	1st: H	2nd: VX-Sur	3rd: H-Sur	(21)
H0550109.bin	1st: H	2nd: H-Sur	3rd: VX-Sur	(17)
H0551110.bin	1st: H	2nd: H-Sur	3rd: TNT	(12)
H0550211.bin	1st: H	2nd: VX-Sur	3rd: H-Sur	(13)
H0550312.bin	1st: H	2nd: H-Sur	3rd: VX-Sur	(12)
H0550813.bin	1st: H	2nd: VX-Sur	3rd: H-Sur	(15)
H0550914.bin	1st: H	2nd: VX-Sur	3rd: TNT	(12)
H0550716.bin	1st: H	2nd: H-Sur	3rd: VX-Sur	(11)
H0557c17.bin	1st: H	2nd: H-Sur	3rd: VX-Sur	(15)
VX551401.bin	1st: VX	2nd: GB-low	3rd: TNT	(67)
VX551302.bin	1st: VX	2nd: TNT	3rd: GB-low	(47)
VX551503.bin	1st: VX	2nd: GB-low	3rd: H	(68)
VX551104.bin	1st: VX	2nd: TNT	3rd: GB-hi	(48)
VX551005.bin	1st: VX	2nd: TNT	3rd: H	(64)
VX551206.bin	1st: VX	2nd: GB-low	3rd: VX-Sur	(57)
VX550907.bin	1st: VX	2nd: GB-low	3rd: GB-hi	(55)
VX550808.bin	1st: VX	2nd: GB-low	3rd: TNT	(53)
VX550709.bin	1st: VX	2nd: VX-Sur	3rd: TNT	(66)
VX550510.bin	1st: VX	2nd: TNT	3rd: GB-low	(57)
VX550411.bin	1st: VX	2nd: GB-low	3rd: GB-hi	(49)
VX550612.bin	1st: VX	2nd: H	3rd: GB-low	(60)
VX550313.bin	1st: VX	2nd: GB-low	3rd: VX-Sur	(67)
VX550214.bin	1st: VX	2nd: GB-hi	3rd: GB-low	(66)
VX550101.bin	1st: VX	2nd: TNT	3rd: VX-Sur	(53)
WP550401.bin	1st: WP	2nd: GB-low	3rd: TNT	(41)
WP550502.bin	1st: WP	2nd: GB-low	3rd: GB-Sur	(42)
WP55XX03.bin	1st: WP	2nd: TNT	3rd: VX-Sur	(33)
WP551504.bin	1st: WP	2nd: H	3rd: GB-low	(24)
WP550807.bin	1st: WP	2nd: GB-low	3rd: GB-hi	(37)
WP550708.bin	1st: WP	2nd: VX-Sur	3rd: GB-hi	(42)
WP550609.bin	1st: WP	2nd: H-Sur	3rd: GB-hi	(40)
WP551010.bin	1st: WP	2nd: GB-hi	3rd: GB-low	(45)
WP550911.bin	1st: WP	2nd: GB-Sur	3rd: H	(33)
WP551212.bin	1st: WP	2nd: GB-low	3rd: GB-hi	(30)
WP551313.bin	1st: WP	2nd: TNT	3rd: H	(15)
WP551314.bin	1st: WP	2nd: VX-Sur	3rd: TNT	(34)
WP551915.bin	1st: WP	2nd: GB-low	3rd: H	(40)
WP551816.bin	1st: WP	2nd: GB-low	3rd: VX	(36)
WP552017.bin	1st: WP	2nd: GB-hi	3rd: GB-Sur	(35)
WP551718.bin	1st: WP	2nd: H	3rd: GB-low	(42)
WP550019.bin	1st: WP	2nd: GB-hi	3rd: GB-Sur	(50)
P550120.bin	1st: WP	2nd: GB-hi	3rd: GB-low	(40)
WP550221.bin	1st: WP	2nd: H	3rd: TNT	(34)
WP550a22.bin	1st: WP	2nd: VX	3rd: GB-hi	(45)
WP550g01.bin	1st: WP	2nd: GB-hi	3rd: GB-low	(34)

WP550h02.bin	1st: WP	2nd: GB-hi	3rd: H	(5)
WP550i03.bin	1st: WP	2nd: GB-hi	3rd: GB-low	(33)
TNT60101.bin	1st: TNT	2nd: WP	3rd: VX-Sur	(46)
TNT60303.bin	1st: TNT	2nd: VX-Sur	3rd: GB-Sur	(50)
TNT60404.bin	1st: TNT	2nd: VX-Sur	3rd: H-Sur	(25)
TNT60505.bin	1st: TNT	2nd: VX-Sur	3rd: GB-Sur	(45)
TNT60606.bin	1st: TNT	2nd: H-Sur	3rd: VX-Sur	(34)
TNT60707.bin	1st: TNT	2nd: H-Sur	3rd: H	(33)
TNT60808.bin	1st: TNT	2nd: VX-Sur	3rd: H-Sur	(47)
TNT60909.bin	1st: TNT	2nd: VX-Sur	3rd: H	(35)
TNT61010.bin	1st: TNT	2nd: VX-Sur	3rd: GB-Sur	(45)
TNT61111.bin	1st: TNT	2nd: VX-Sur	3rd: H-Sur	(38)
TNT61312.bin	1st: TNT	2nd: VX-Sur	3rd: H-Sur	(44)
TNT61213.bin	1st: TNT	2nd: VX-Sur	3rd: H-Sur	(41)
TNT61414.bin	1st: TNT	2nd: VX-Sur	3rd: GB-Sur	(38)
TNT61615.bin	1st: TNT	2nd: VX-Sur	3rd: H-Sur	(42)
TNT61516.bin	1st: TNT	2nd: WP	3rd: VX-Sur	(47)
S55G0301.bin	1st: GB-Sur	2nd: VX-Sur	3rd: H-Sur	(77)
S55G0302.bin	1st: GB-Sur	2nd: H-Sur	3rd: TNT	(61)
S55G0403.bin	1st: GB-Sur	2nd: WP	3rd: VX-Sur	(56)
S55G0404.bin	1st: GB-Sur	2nd: GB-low	3rd: GB-hi	(65)
S55G0105.bin	1st: GB-Sur	2nd: GB-hi	3rd: WP	(53)
S55G0106.bin	1st: GB-Sur	2nd: WP	3rd: GB-hi	(49)
S55G0207.bin	1st: GB-Sur	2nd: H-Sur	3rd: H	(50)
S55G0208.bin	1st: GB-Sur	2nd: H-Sur	3rd: H	(53)
S55G0509.bin	1st: GB-Sur	2nd: GB-hi	3rd: VX-Sur	(46)
S55G0510.bin	1st: GB-Sur	2nd: WP	3rd: H-Sur	(55)
S55G0301.bin	1st: GB-Sur	2nd: TNT	3rd: H-Sur	(82)
S55G0402.bin	1st: GB-Sur	2nd: GB-hi	3rd: VX	(50)
S55G0103.bin	1st: GB-Sur	2nd: WP	3rd: GB-hi	(50)
S55G0204.bin	1st: GB-Sur	2nd: H-Sur	3rd: VX-Sur	(56)
S55G0505.bin	1st: GB-Sur	2nd: VX	3rd: H	(49)
S55H0201.bin	1st: H-Sur	2nd: H	3rd: VX-Sur	(54)
S55H0202.bin	1st: H-Sur	2nd: VX-Sur	3rd: H	(58)
S55H0103.bin	1st: H-Sur	2nd: VX-Sur	3rd: GB-Sur	(49)
S55H0305.bin	1st: H-Sur	2nd: VX-Sur	3rd: H	(42)
S55H0306.bin	1st: H-Sur	2nd: VX-Sur	3rd: H	(61)
S55H0507.bin	1st: H-Sur	2nd: VX-Sur	3rd: TNT	(60)
S55HXX08.bin	1st: H-Sur	2nd: VX-Sur	3rd: H	(63)
S55H0509.bin	1st: H-Sur	2nd: VX-Sur	3rd: H	(70)
S55H0410.bin	1st: H-Sur	2nd: VX-Sur	3rd: H	(47)
S55H0411.bin	1st: H-Sur	2nd: VX-Sur	3rd: H	(53)
S55H0301.bin	1st: H-Sur	2nd: VX-Sur	3rd: H	(37)
S55H0302.bin	1st: H-Sur	2nd: VX-Sur	3rd: H	(76)
S55H0203.bin	1st: H-Sur	2nd: VX-Sur	3rd: GB-low	(78)
S55H0104.bin	1st: H-Sur	2nd: GB-Sur	3rd: TNT	(54)
S55H0405.bin	1st: H-Sur	2nd: VX-Sur	3rd: H	(67)
S55H0506.bin	1st: H-Sur	2nd: VX-Sur	3rd: GB-low	(62)
S55V0501.bin	1st: VX-Sur	2nd: H	3rd: TNT	(46)
S55V0502.bin	1st: VX-Sur	2nd: H-Sur	3rd: GB-Sur	(68)
S55V0503.bin	1st: VX-Sur	2nd: H-Sur	3rd: TNT	(50)
S55V0204.bin	1st: VX-Sur	2nd: H	3rd: H-Sur	(72)

S55V0405.bin	1st: VX-Sur	2nd: H-Sur	3rd: TNT	(51)
S55V0406.bin	1st: VX-Sur	2nd: H-Sur	3rd: TNT	(43)
S55V0307.bin	1st: VX-Sur	2nd: H-Sur	3rd: H	(55)
S55V0308.bin	1st: VX-Sur	2nd: H-Sur	3rd: TNT	(62)
S55V0109.bin	1st: H	2nd: VX-Sur	3rd: H-Sur	(48)
S55V0110.bin	1st: VX-Sur	2nd: H	3rd: H-Sur	(42)
S55V0511.bin	1st: VX-Sur	2nd: H	3rd: H-Sur	(66)
S55V0112.bin	1st: VX-Sur	2nd: H-Sur	3rd: H	(62)
S55V0501.bin	1st: VX-Sur	2nd: H-Sur	3rd: H	(45)
S55V0102.bin	1st: VX-Sur	2nd: H	3rd: H-Sur	(42)
S55V0303.bin	1st: VX-Sur	2nd: H-Sur	3rd: H	(48)
S55V0404.bin	1st: VX-Sur	2nd: H-Sur	3rd: TNT	(52)
S55V0205.bin	1st: VX-Sur	2nd: H-Sur	3rd: H	(46)

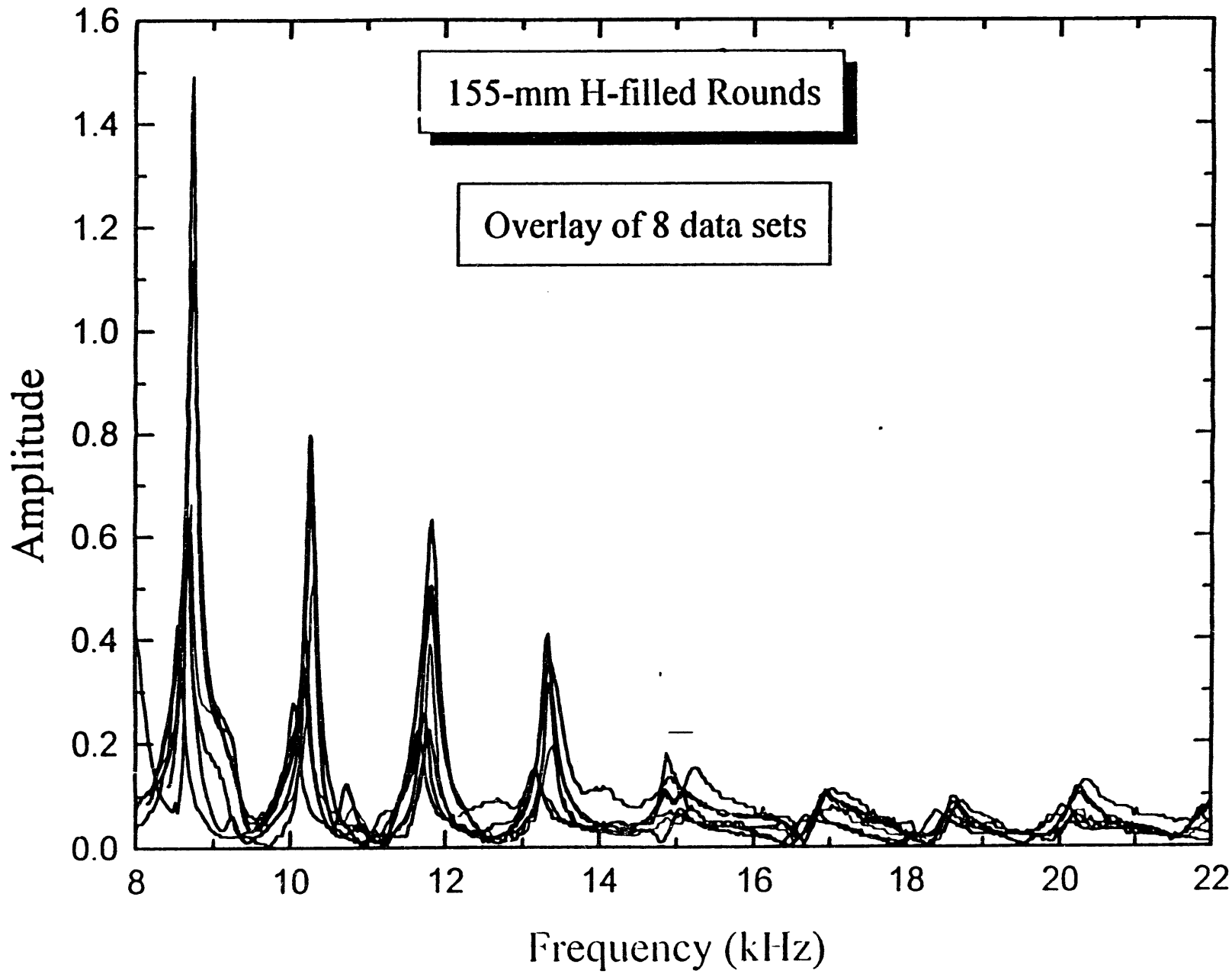

FIGURE B.1. Comparability of Data within Class

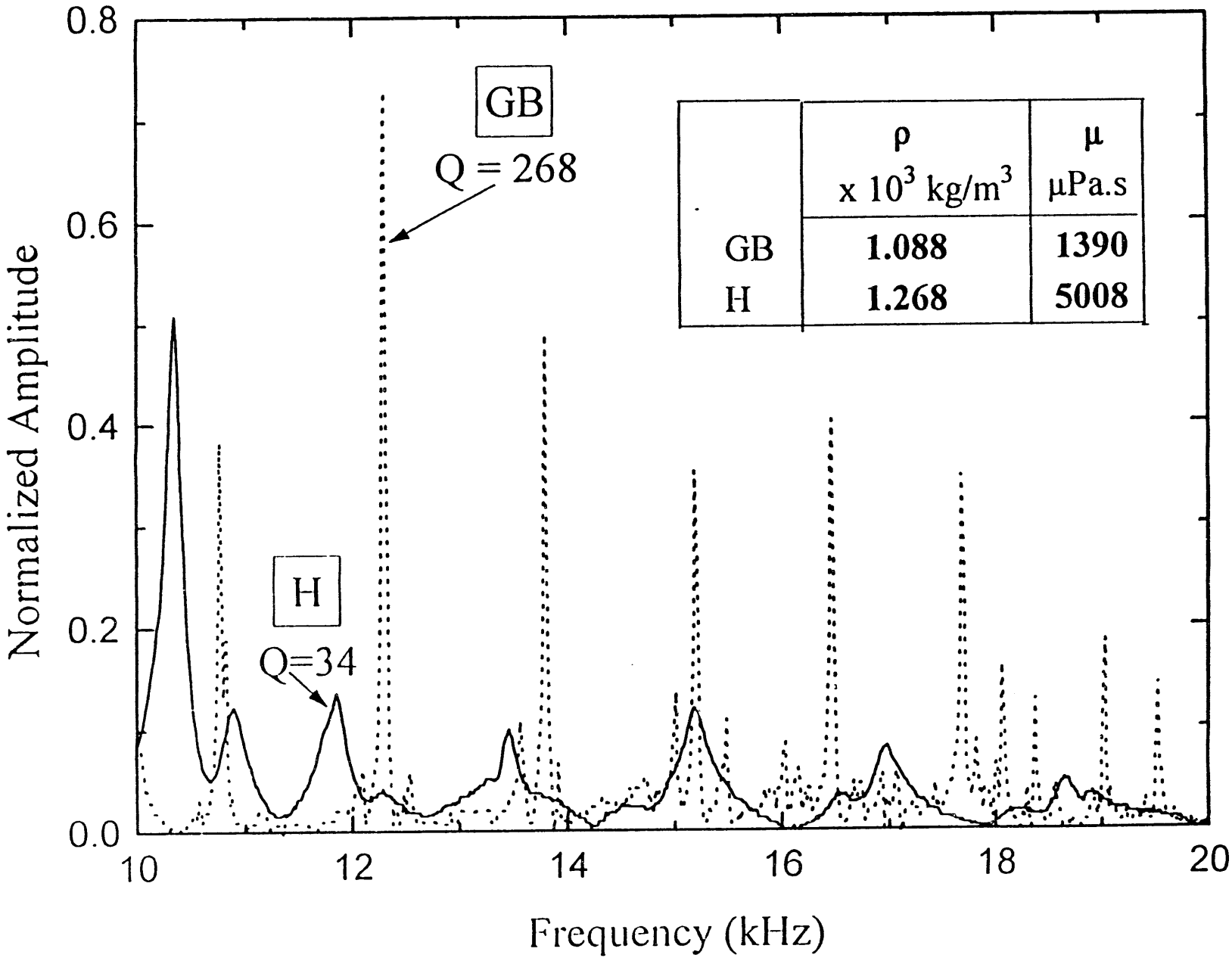

FIGURE B.2. Acoustic Spectra of 155-mm Rounds

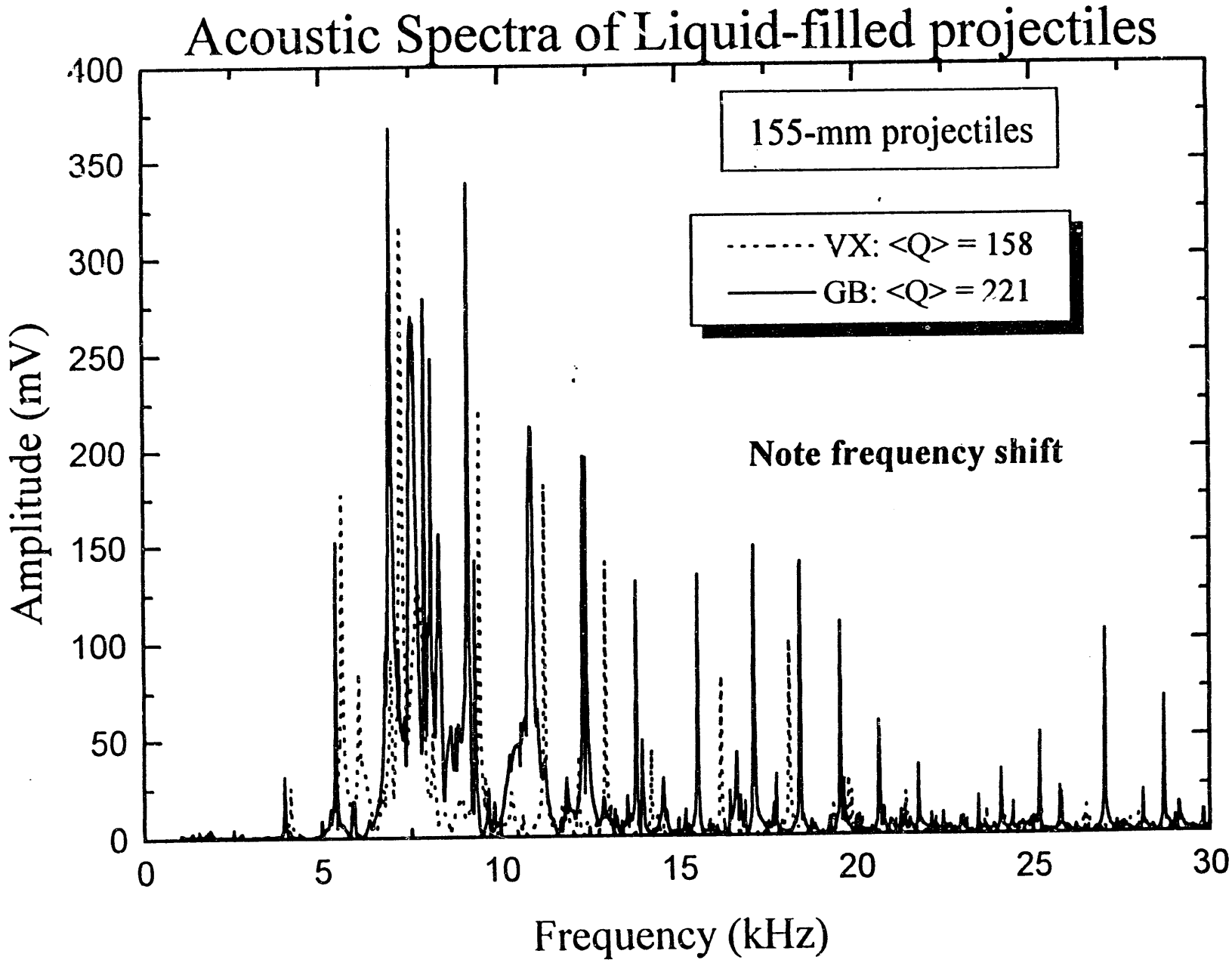

FIGURE B.3. Acoustic Spectra of Liquid-Filled Projectiles

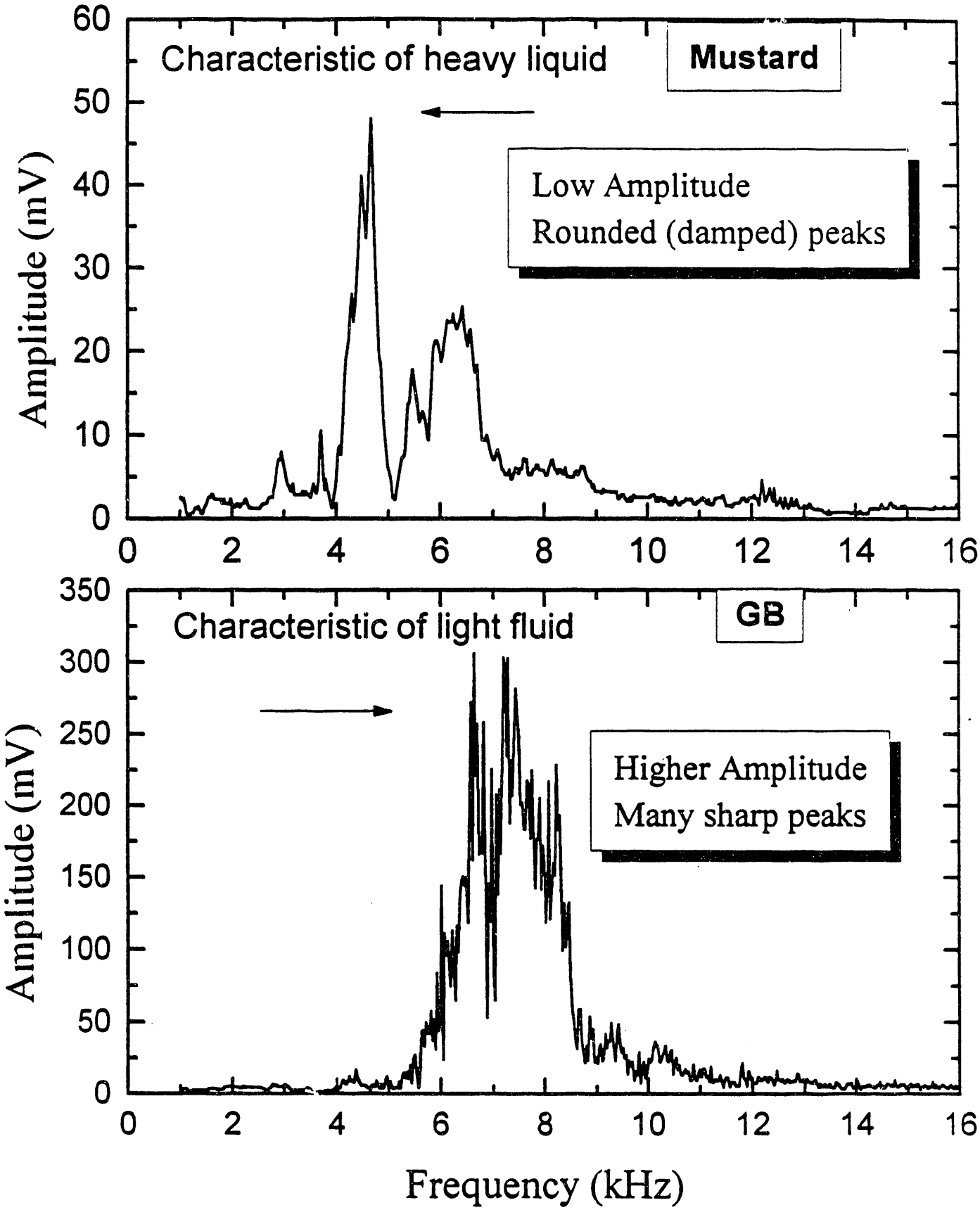

FIGURE B.4. Acoustic Spectra of 1-Ton Containers

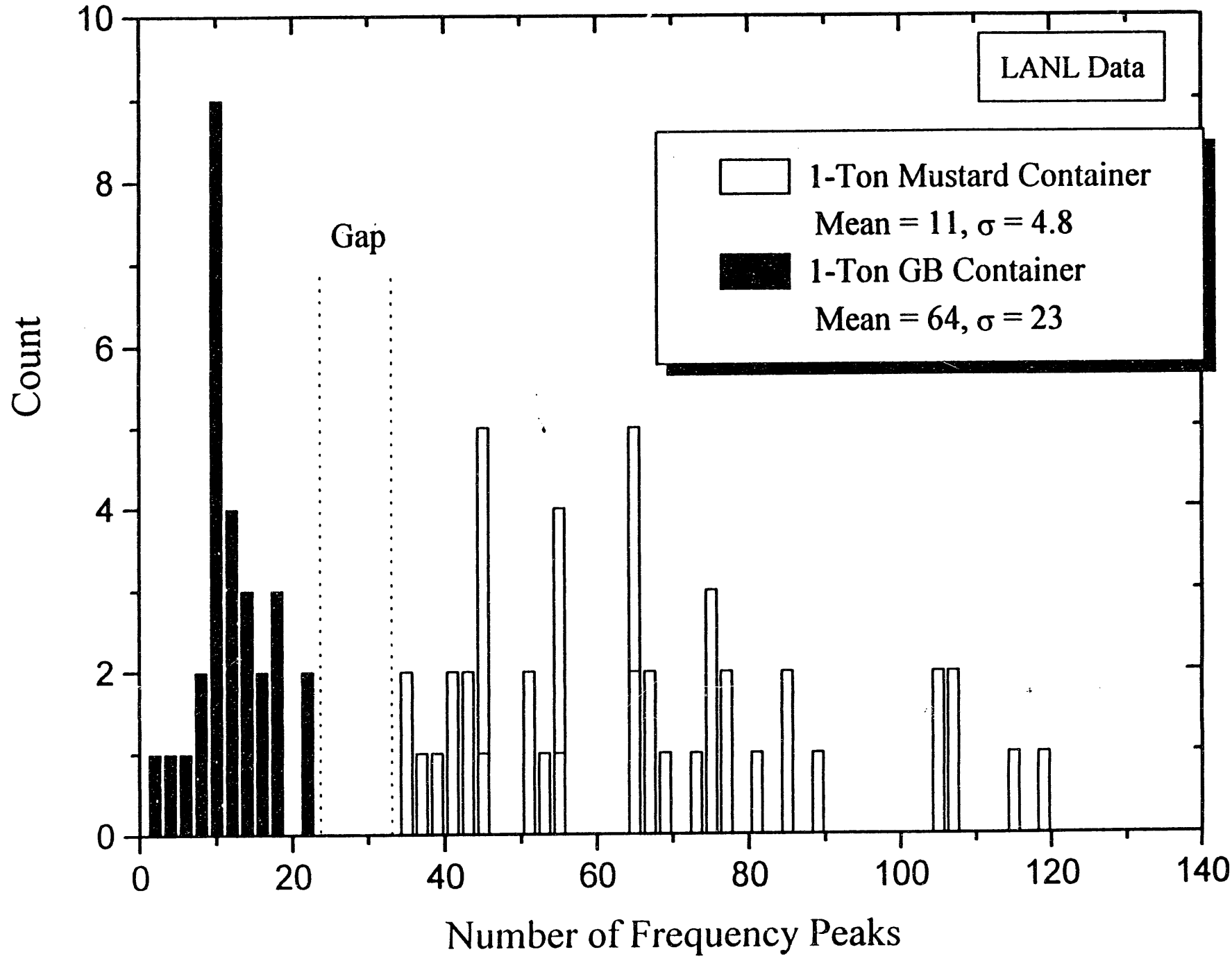

FIGURE B.5. Histogram of Number of Resonance Peaks

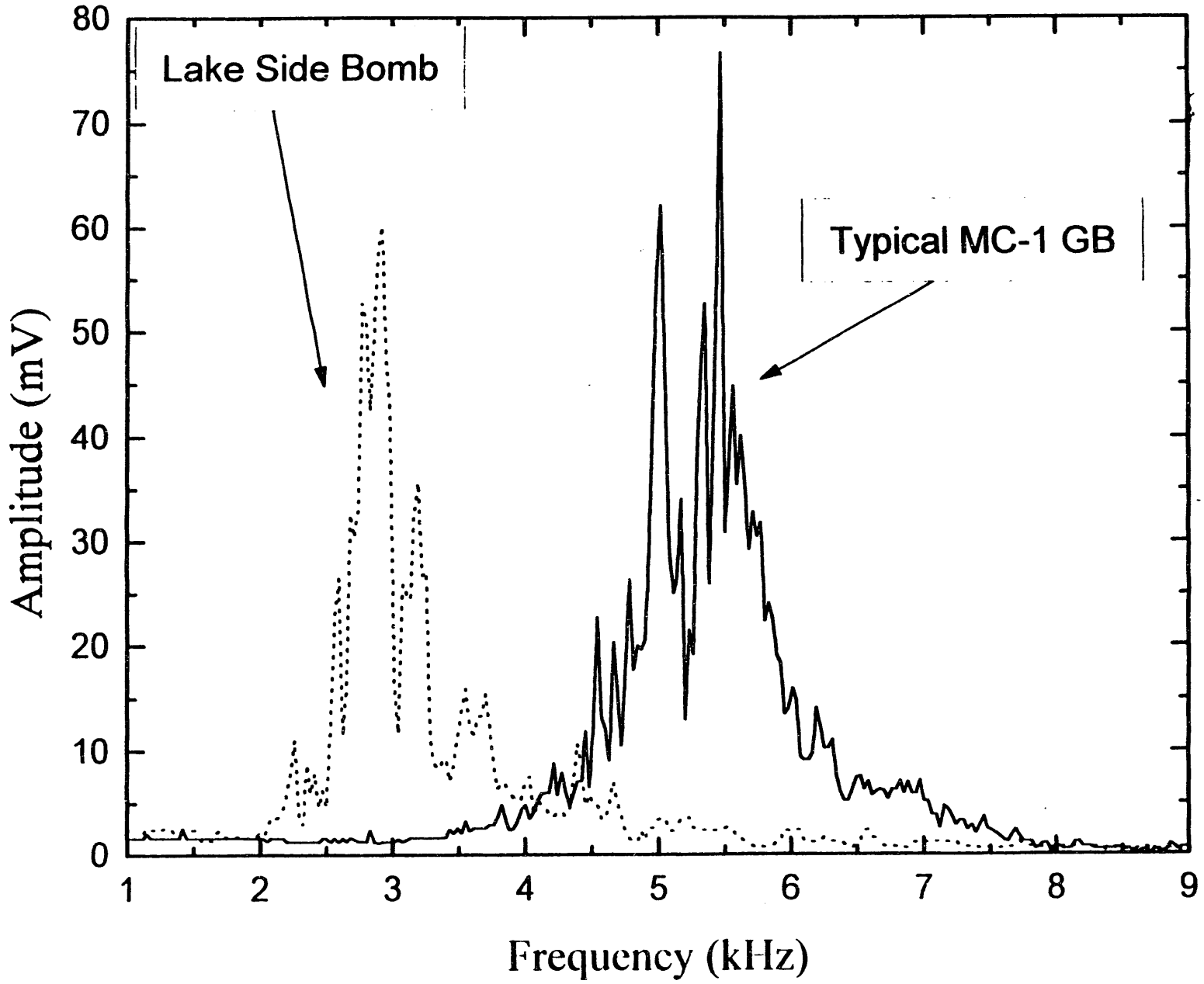

FIGURE B.6. Acoustic Spectrum of MC-1 Bomb GB

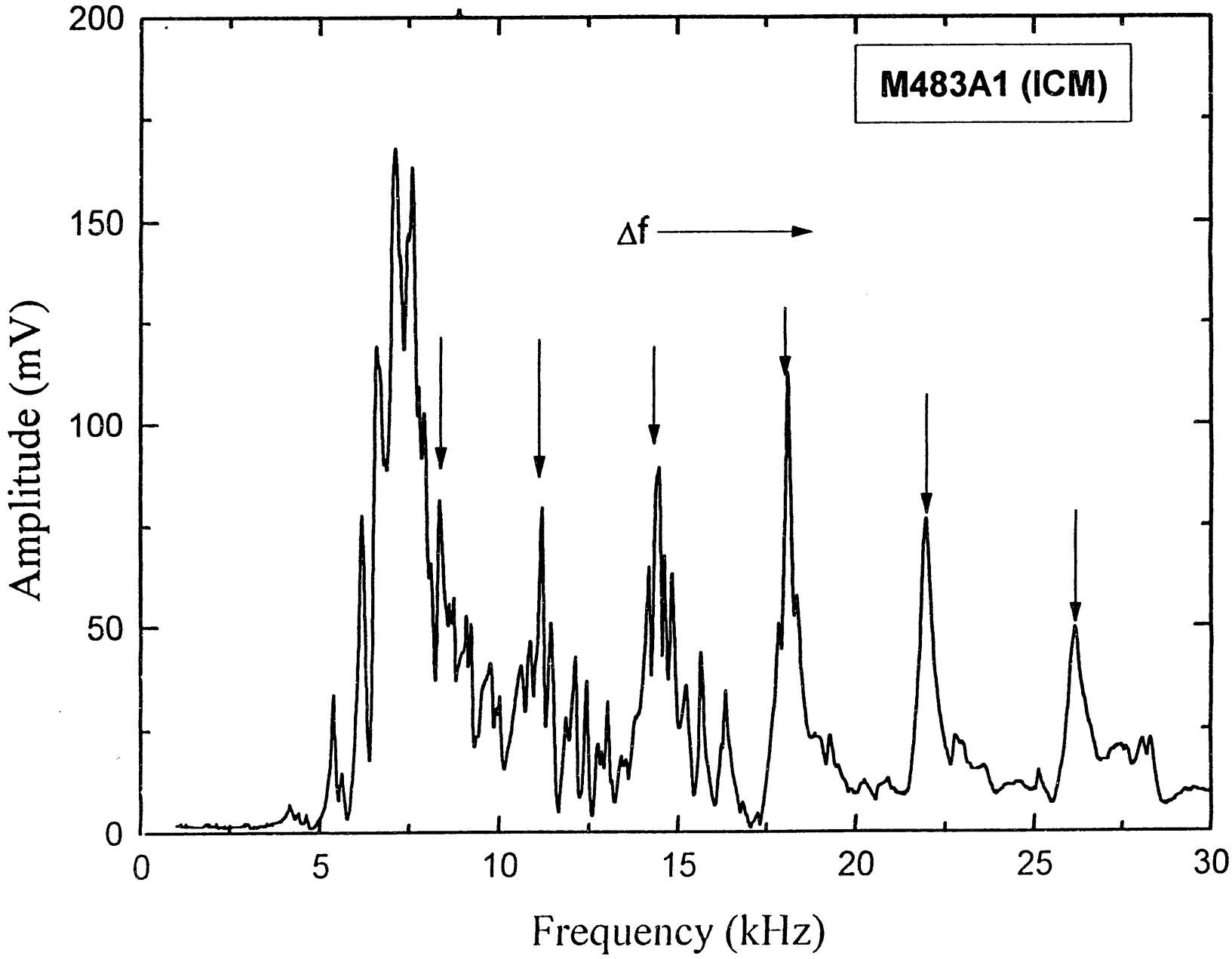

FIGURE B.7. Acoustic Spectrum of 155-mm HE Round

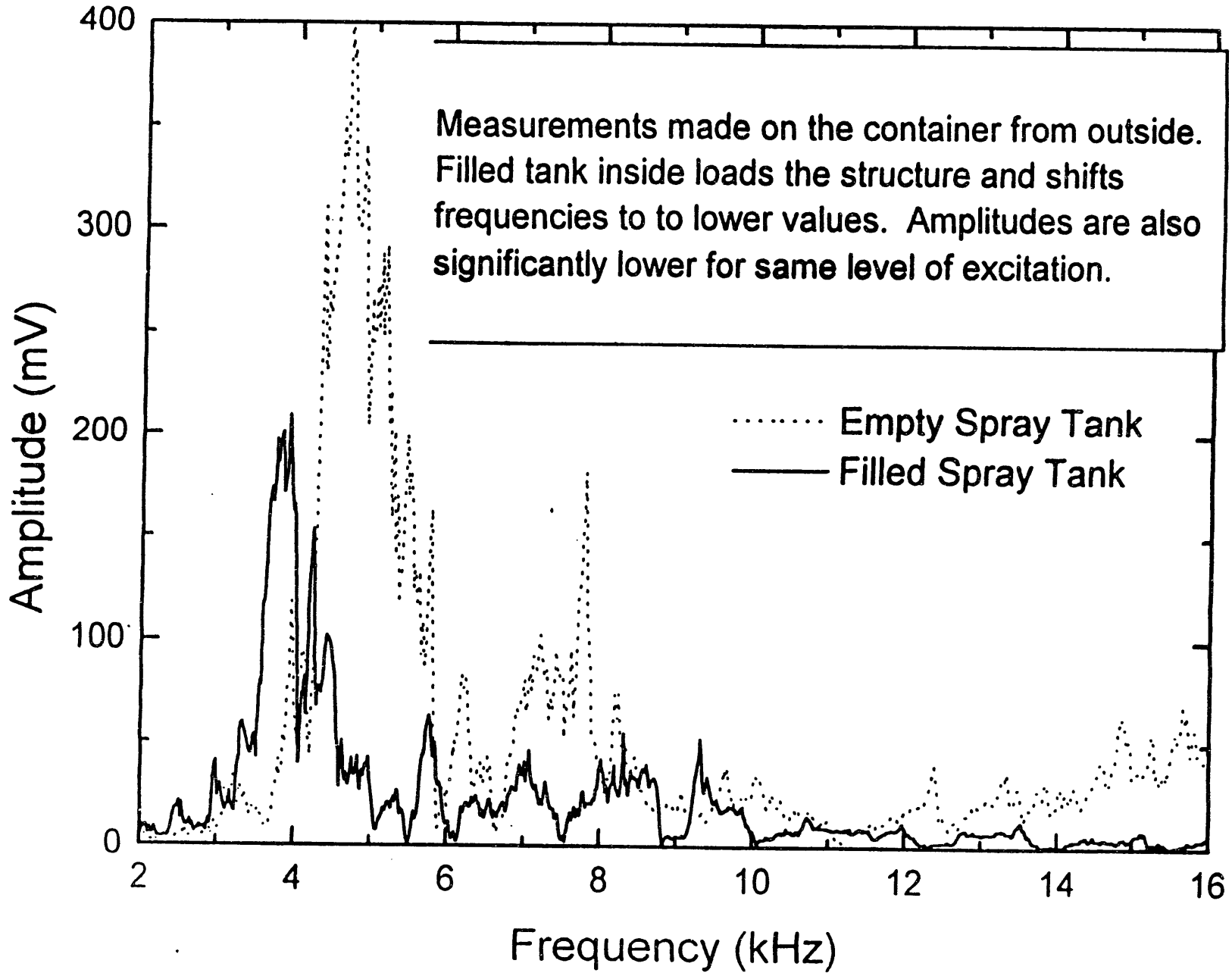

FIGURE B.8. Acoustic Spectrum of VX Spray Tank

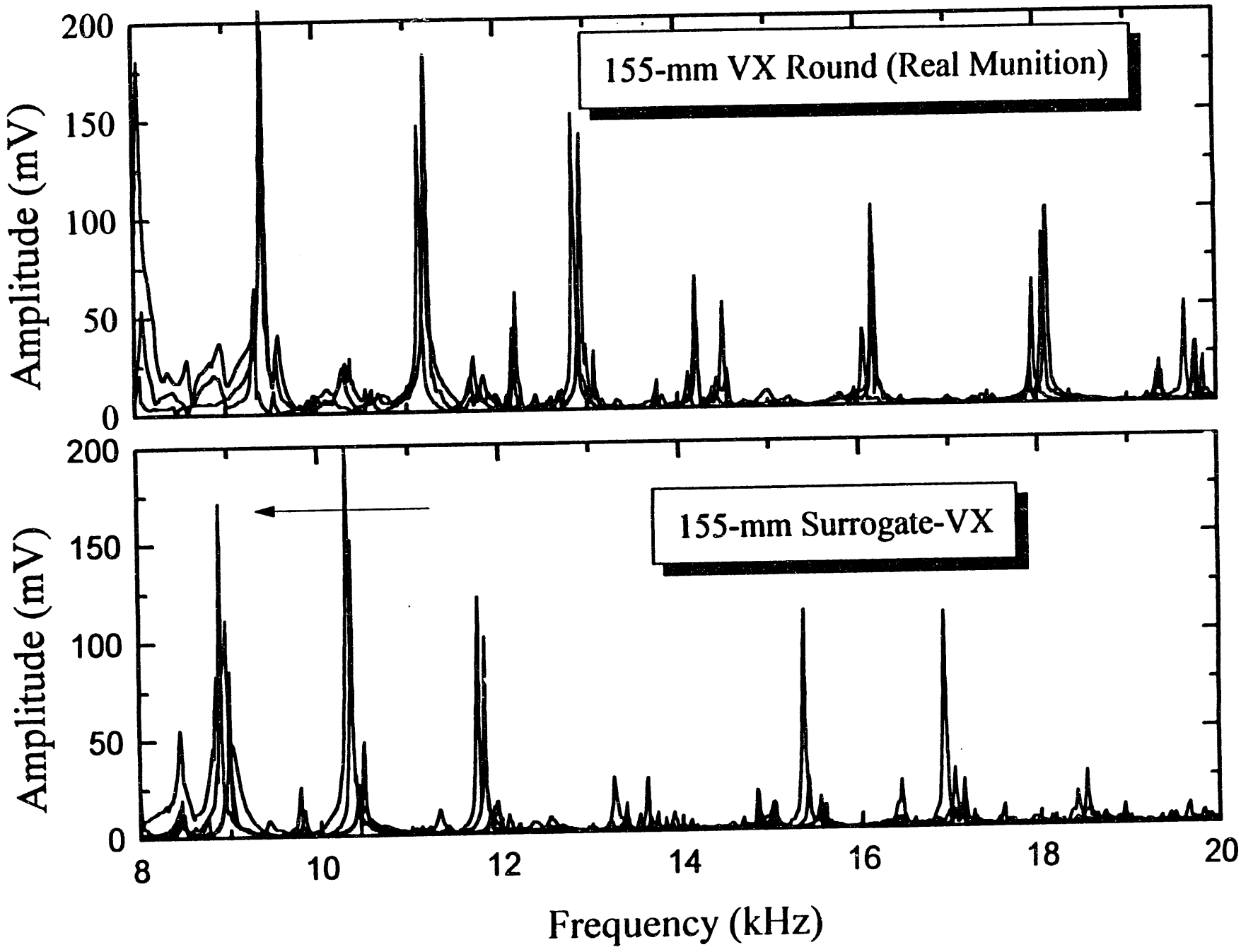

FIGURE B.9. Comparison of Real vs. Surrogate (Spoofability)

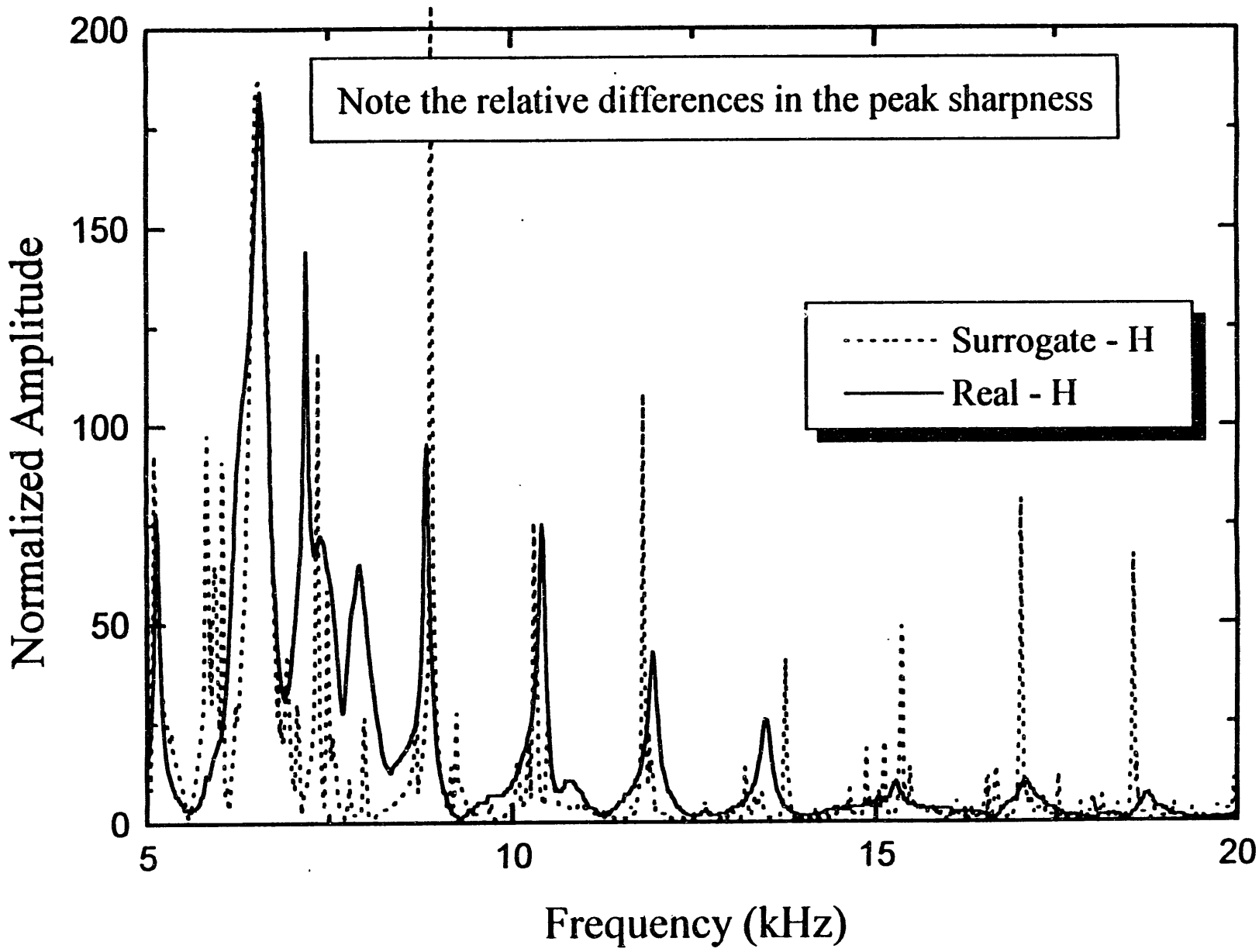

FIGURE B.10. Comparison Between Surrogate vs. Real (Spoofability Issue)

APPENDIX C

NONCONTACTING ACOUSTIC/ULTRASONIC SIGNATURE ANALYSIS SYSTEM

APPENDIX C

NONCONTACTING ACOUSTIC/ULTRASONIC SIGNATURE ANALYSIS SYSTEM

Draft Report of Preliminary Results from the Tooele Field Tests Conducted August 1992

David M. Tow
Idaho National Engineering Laboratory
September 4, 1992

EQUIPMENT DESCRIPTION AND LIST OF MUNITIONS TESTED

Exercises were conducted at the Tooele Army Depot (TEAD) during the period August 9-27, 1992 for the purpose of testing and evaluating chemical weapon inspection systems. The systems involved in the exercises were developed with funding from the Office of Arms Control for treaty verification use.

The Laser-Acoustic system developed at Idaho National Engineering Laboratory (INEL) included the following components:

a. a helium-neon laser vibrometer for detecting motion in munitions

b. an audio amplifier and loudspeaker for inducing motion in munitions

c. a portable computer with special data acquisition and analysis circuit boards for acquiring and analyzing munition vibration information.

The INEL inspection system operates on the principle that the chemical content of a container affects the vibrational characteristics of the container in an understandable way. Containers of interest in this work include munitions, such as artillery shells and bombs, and chemical agent storage containers. An example of a vibrational characteristic affected by fill type is resonant frequency; vibrational resonances of liquid-filled containers shift in frequency in response to changes in the specific gravity of the liquid. Other physical properties affecting vibrational characteristics include material state (i.e., liquid, powder, solid, etc.), viscosity of liquids, and elasticity of solids. Affected vibrational characteristics include resonant frequencies, damping rates, and vibrational amplitudes.

The INEL Laser-Acoustic inspection system employed during the 1992 Tooele tests was configured to acquire vibration spectra information over the frequency range of 800 Hz to 20 kHz. Test objects were excited to vibrate by broadband (white) noise emanating from a loudspeaker. The resulting surface motion was sensed using a noncontacting laser vibrometer. The vibrometer

signal was digitized at sample rates in excess of the Nyquist rate and Fourier transformed in real time. A running sum of the magnitudes of the frequency components was maintained until a specified number (usually 50 or 100) of Fourier transforms had been calculated. The length of the Fourier transforms was typically 2048. The typical sampling frequency was 50 Khz. The length of time required to compute a single spectrum by averaging 50 Fourier transforms was approximately 3 seconds. Standard procedure during the Tooele tests was to collect 4 spectra from each measurement point; two spectra were collected with a loudspeaker on and two with no loudspeaker excitation. Data acquisition at a single measurement point was therefore completed in approximately 12 seconds.

A variety of munitions and containers were inspected during the Tooele tests. A summary appears in the table below.

Item Description	Location	Number Inspected	Date
155 mm artillery shells containing a variety of surrogate fills	Bldg. 5118	53	8/13 8/19 8/20 8/21
Surrogate-filled ton containers	Bldg. 5118	3	8/20
VX spray tanks		4	8/20
Mustard ton containers	Mustard yard	15	8/21
Fused/burster 105 mm GB	Bldg. 1531	12	8/21
155 mm VX and 8-inch VX	Bldg. 2112	16	8/22
155 mm GB	Bldg. 1537	16	8/22
MC-1 GB bombs	Bldg. 1437	16	8/22
155 mm mustard	Bldg. 2301	17	8/24
155 mm VX	Bldg. 2112	16	8/24
155 mm GB	Bldg. 1537	16	8/24
M107 HE (comp B)		22	8/25
M106 TNT		11	8/25
155 mm white phosphorus		22	8/25

TEST RESULTS

A preliminary analysis of the 155 mm VX and GB data has been completed. A thorough analysis of the remainder of the data will require a considerable amount of time and effort. The 155 mm VX and GB data were studied first because a data base already exists of the vibrational characteristics of similar munitions. During the 1991 Tooele tests, seven 155 mm VX artillery shells and eight 155 mm GB artillery shells were inspected. A 3-nearest-neighbor clustering algorithm was found that differentiated between the VX and GB shells with 100% accuracy based on the 15 vibration spectra. That same algorithm was applied to the new VX and GB spectra. Using the old spectra (seven VX and eight GB) as a training set, the clustering algorithm correctly identified all 16 of the recently acquired GB shells, but only 10 of the 16 VX shells were correctly identified; i.e., 6 VX were incorrectly identified as GB. Adding the 32 newly acquired spectra to the training set, however, resulted in 100% accuracy in identifying both GB and VX in cross-validation experiments. A total of 47 spectra were available for use in the training set. In cross-validation experiments, the unknown spectrum is not included in the training set, so the size of the training set is actually 46.

The classification algorithm uses information about the frequency of four resonance peaks. Inspection of the recent VX data reveals that one of those four peaks (near 4 kHz) is missing or questionable in the spectra of several VX shells. Four of these shells were included in the six that were incorrectly identified when the old (1991) data was used as a training set. The 4 kHz resonance was present in these four VX shells; it was just not detected. It may not have been detected because the measurement point was too close to a nodal point. Or the 4 kHz resonance may not have been adequately excited. A more automatic data collection method that ensures the presence of resonance peaks of interest would result in better classification performance. In spite of the missing resonance peaks, the classification algorithm was 100% accurate when the larger training set was allowed. With this training set, the importance of the missing peak was apparently reduced.

CONCLUSIONS AND RECOMMENDATIONS

Differentiation between 155 mm VX and GB munitions was 100% accurate using the 3-nearest-neighbor clustering algorithm. Preliminary inspection of 155 mm mustard spectra suggests that the classification approach will also work for mustard artillery shells. The INEL Laser-Acoustic inspection system would benefit from the development of automatic data collection features that would, as a minimum, ensure the completeness of the data before moving on to the next specimen.

APPENDIX D

PORTABLE ISOTOPIC NEUTRON SYSTEM

APPENDIX D

PORTABLE ISOTOPIC NEUTRON SYSTEM

Performance of the INEL PINS Chemical Assay System at the 1992 Tooele NDE Field Trials: Draft Report

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31 August 1992

INTRODUCTION

Field trials of selected nondestructive evaluation (NDE) equipment for verification of the proposed treaties limiting chemical weapon (CW) agents was conducted at Tooele Army Depot, in Tooele, Utah, from 10 to 27 August 1992. The field trials were conducted with surrogates, actual chemical agents, and high explosive (HE) munitions.

The stated evaluation criteria[1] for each NDE system at the field trials are:

i. capability to correctly identify selected chemical agents
ii. suitability for field use
iii. identification of possibilities for synergistic improvements using multiple NDE technologies.

The Idaho National Engineering Laboratory (INEL) PINS Chemical Assay System, a neutron-based identification technique,[2] was included in the field trials. Two complete PINS systems were tested at Tooele. One system was operated by INEL physicists, to study and refine the system's performance. The second system was operated by military personnel from the U.S. On-Site Inspection Agency (OSIA), to evaluate its performance in the hands of non-expert users. OSIA will assess the PINS system in an independent report.

EQUIPMENT AND TEST METHODS

OPERATING PRINCIPLES

Neutrons, by their absence of electrical charge, are very penetrating radiations. The relatively low energy neutrons produced by radioisotopic sources, e.g. californium-252 (^{252}Cf) or americium-241-beryllium (^{241}Am-Be) easily penetrate the steel casing of an artillery projectile or chemical storage container. The neutrons interact with the fill materials, producing gamma rays characteristic of the chemical elements within the munition or container. The gamma rays are also very penetrating, hence they escape the munition and the element-specific gamma-ray energy and intensity signature can be recorded by a radiation detector.

NEUTRON SOURCE

PINS employs a microgram-strength (millicurie activity) californium-252 fission source, which produces about one million neutrons per second. The source is doubly encapsulated in concentric stainless steel capsules, and it is certified as "special form" by the U.S. Department of Transportation (DOT) for the International Atomic Energy Agency (IAEA). The source is transported in a DOT-approved type A, specification 7A five-gallon drum. This type of source is routinely shipped worldwide by common carrier.

GAMMA-RAY DETECTOR

The gamma-rays produced by neutron interactions are counted by a high-purity germanium (HPGe) detector. This type of detector provides energy res lution better than 0.15 % at 1332 keV, to resolve gamma-ray lines closely spaced in energy. The efficiency of the detector is 40% relative to a 3" x 3" sodium iodide (NaI[Tl]) detector at 1332 keV. The detector is mounted in an all-attitude cryostat for portability, and it weighs about 10 pounds. The cryostat holds a 24 hour supply of liquid nitrogen. The HPGe detector produces electrical pulses proportional in voltage to the gamma-ray energy deposited within its sensitive volume.

ELECTRONICS

The pulses from the detector are amplified, sorted into an energy spectrum, and stored in the memory of an EG&G Ortec Nomad Portable Multichannel Analyzer (MCA) coupled to a Compaq notebook PC. The computer displays the gamma-ray spectrum as it is acquired and serves as a flexible control panel for the instrument. The MCA unit is packaged in a briefcase-sized Zero-Halliburton aluminum case and weighs 23 pounds. The MCA also provides high voltage and preamplifier power to the HPGe detector, with a battery lifetime of six hours. Both the MCA and computer can also operate from AC line power.

COMPUTER

The notebook computer stores the complete gamma-ray spectrum from 0.1 to 11.0 MeV on the computer's hard disc for subsequent analysis and archiving. While the system is acquiring data, the MCA software performs nearly instant chemical element identification of operator-selected gamma-ray peaks, including energy and intensity. An off-line analysis software package is run after completion of data acquisition to analyze the complete spectrum, and its output includes a list of the chemical elements identified and the assay results, in plain English. The analysis takes about one minute. A separate analysis file is also written to disc.

MODERATOR/DETECTOR SHIELD/SUPPORT STAND

A 4" x 4" x 4" polyethylene moderator block is used to slow the neutrons from the ^{252}Cf source, increasing the probability of capture reactions. Two 2" x 4" x 4" bismuth blocks are placed between the moderator block and the HPGe detector, to "shadow shield" the detector from gamma rays produced in the source and moderator. An additional 4" x 4" x 4" bismuth block, bored out to

the diameter of the detector, provides shielding from gamma radiation Compton scattered from the floor or munition casing. A boron carbide plate 1/2" x 4" x 4" is placed between the two shadow shield blocks to minimize thermal neutrons reaching the HPGe detector, another boron carbide plate is placed at the front of the collimator block for the same purpose.

The source/shadow shield/detector assembly is supported by an aluminum stand with interchangeable aluminum legs. For measurements near the ground, short leg sections of 1", 2", 4", 8", and 16" are provided, and these sections may be combined to provide any length between 1" and 31". For measurements that require raising the equipment above 31", three aluminum photographer's monopods provide continuous adjustment from 28" to 84" above the floor.

AGENTS/CONTAINERS AND MUNITIONS ASSAYED

TABLE D.1. Items Assayed

Munition or Container	Fill	Comment
105 mm projectile	GB	fused, burstered
155 mm projectile	GB	M122
	HD	M110
	HE	M107, M483A1 (ICM)
	surrogates (3)	
	VX	M121A1
	WP	M110
M55 rocket	VX	
MC-1 bomb	GB	
	unknown	"lakeside"
TMU-28/B spray tank	VX	
DOT 500X ton container	GB	
	HD	
	L	

TEST RESULTS

The results summarized below in this section reflect the on-line observations of the experimenters while the measurements were in progress. It is possible that in a few cases the results will change following a more extended off-line review of the data.

One of the INEL research aims in the 1992 Tooele NDE Field Trials was to identify the minimum counting time to collect sufficient statistics in the relevant gamma-ray peaks for automatic identification of the contents of a given munition or container. To this end, data were collected for typically

100, 200, 500, and 1000 seconds for nearly all munitions. A few runs were extended to 2000 and 4000 seconds, to provide even better statistics.

GB-FILLED ITEMS

Assays were performed on nerve agent GB-filled 105 mm and 155 mm projectiles, MC-1 bombs, and ton containers. The presence of GB was inferred from the detection of characteristic hydrogen and phosphorus gamma rays, and from the absence of sulfur gamma rays, which distinguish VX from GB. The expected gamma rays were detected in all items assayed.

Special mention should be made of the GB-filled 105 mm projectile. This was one of the only two fused munitions assayed by the PINS system. It was also the most difficult item to assay, since it contains but 1.6 pounds of agent. The first attempts to assay this projectile were not quite successful, even with 4000 second counts. However, by changing the counting geometry from the standard configuration to a new arrangement, with the source, shadow shield, and detector aligned with the long axis of the projectile, a spectrum correctly identifying the fill was recorded in 1000 seconds.

An attempt was made to assay a pallet of GB-filled 105 mm cartridges inside their shipping boxes. The attempt was unsuccessful, as might be expected, since the position of the projectiles within the wooden shipping boxes is not marked externally.

HD-FILLED ITEMS

Assays were performed on mustard gas or agent HD-filled 155 mm projectiles and ton containers. The presence of HD was inferred from the detection of characteristic chlorine, hydrogen, and sulfur gamma rays. These gamma rays were detected in both items assayed. The chlorine gamma rays provided an exceptionally strong signal, easily recognizable in about 50 seconds.

HE-FILLED ITEMS

Assays were performed on high explosive 155 mm projectiles and a set of 155 mm cannon propelling charges or "powder bags" inside their shipping tube. The standard Composition B-filled M107 projectile, comparable in size and shape to the chemical-filled 155 mm projectiles, and the RDX-filled M483A1 Improved Conventional Munition were both assayed. The presence of HE was inferred from the detection of characteristic hydrogen and nitrogen gamma rays. These gamma rays were detected in all items assayed.

L-FILLED TON CONTAINER

Assays were performed on lewisite or agent L-filled ton containers. The presence of L was inferred from the detection of characteristic chlorine, and hydrogen gamma rays, and from the absence of sulfur gamma rays, helping distinguish L from HD. The expected gamma rays were detected in both ton containers assayed.

SURROGATE-FILLED 155-MM PROJECTILES

Assays were performed on inert 155 mm projectiles filled with GB, HD, and VX surrogates by Dugway Proving Grounds. The gamma ray signatures were quite similar to those recorded from actual 155 mm chemical-filled munitions.

VX-FILLED ITEMS

Assays were performed on nerve agent VX-filled 155 mm projectiles, M55 rockets, and TMU-28/B spray tanks. The presence of VX was inferred from the detection of characteristic hydrogen, phosphorus and sulfur gamma rays. These gamma rays were detected in all munitions assayed.

The M55 rockets were the other fused munitions examined with the PINS system. At first the automatic energy calibration routine, part of the analysis software package, did not run, due to the absence of iron[3] in the aluminum-body rocket and its fiberglass shipping/firing tube. By lining up the HPGe detector on a steel band holding the rockets to the pallet, the iron gamma rays were detected with sufficient intensity to perform the auto calibration and analysis. A small piece of iron, say 1/4" x 4" x 4", will suffice for this purpose in the future.

The spray tank is enclosed by a large shipping container. A measurement was performed inside an open shipping container, with the detector a few inches away from the spray tank. The VX agent was easily identified. An assay was also performed outside a shipping container. Again the agent was identified. It is not necessary to open the spray tank's shipping container for a PINS assay.

UNKNOWN-FILLED MC-1 BOMB

An assay was performed on an MC-1 bomb of unknown fill. Only hydrogen and iron capture gamma rays were observed in a 2000 second count. The gamma rays of chlorine, phosphorus, and sulfur were not observed. The assay results indicate that no blister agents, nerve agents, high explosive, or white phosphorus is present inside the "lakeside bomb."

WP-FILLED PROJECTILES

Assays were performed on a white phosphorus or WP-filled 155 mm projectile. The gamma ray signature is striking, and easily identifiable in 100 seconds. The 2233 keV phosphorus inelastic scattering gamma-ray peak is observed just above the 2223 keV hydrogen peak, with equal intensity.[4] Other phosphorus gamma rays are also observed.

RECOMMENDATIONS

SOFTWARE IMPROVEMENTS

The analysis package did not always identify the agent within a container or munition correctly. For example, the identification of mustard gas in ton containers, a fairly easy case for the PINS system, failed because of interference between a strong chlorine peak and an iron peak used for the energy calibration. The software was modified to use an alternate peak for energy calibration if the interference is detected, and the modified analysis code correctly analyzed all of the mustard yard assay data.

The software will be modified to operate reliably with all of the agent/munition combinations assayed at Tooele in 1992. In addition, we will expand the analysis routine to include methyl phosphonyl difluoride (DF, one half the fill of the binary projectile), nitrogen mustard (agent HN), phosgene (agent CG), and smoke pots (HC).

HARDWARE IMPROVEMENTS

We will explore the feasibility of using a faster analog-to-digital converter (ADC) in the MCA, to reduce system dead time, and hence, permit faster assays. Also, a temperature-dependent fault in the high-voltage shutdown circuit needs attention from the MCA manufacturer.

We expect to replace the present Compaq notebook PCs with another model with a faster processor and better screen visibility in direct sunlight.

The support table will be modified slightly to allow faster set up and simpler adjustment of the source/detector geometry.

APPLICATION VECTOR

It would be inappropriate for investigators who did not observe the performance of the other systems in detail to fill out the complete application matrix. Instead we contribute a column vector for the PINS system, with the vector components labeled as in the matrix example.

TABLE D.2. NDE Technology Application Vector

Application	PINS
Empty munitions	yes
Liquid vs. solid	no
Determination of chemical agent on known munition geometry	yes

Determination of chemical agent on unknown munition geometry	yes
determination of fill level	yes for tanks, ton containers*
determine if all munitions are the same	yes, but slow
currently fieldable by unskilled operator	yes
weight	86 pounds, excluding shipping containers
number of pieces in test system	12, counting as follows: HPGe detector (1) source (1) moderator (1) shadow shield (4) collimator (1) support table (1) MCA (1) computer (1) cable set (1) total (12)
measured ability to differentiate between GB, VX, H as found at Tooele	yes
number of people to carry and operate system	two

*Level measurement using PINS was demonstrated at the 1991 Tooele test. Ultrasonic Pulse Echo is really the method of choice for level measurement.

CONCLUSIONS

The PINS system detected the expected gamma ray signature for every agent/munition combination tested at Tooele in 1992. As in 1991, VX nerve gas was clearly distinguished from GB nerve gas, and from distilled mustard gas, agent HD. Lewisite (agent L) and white phosphorus (WP) were measured for the first time in 1992 with the PINS system, and, as expected, their gamma ray signatures permit clear distinction between each other, and agents GB, HD, and VX, and high explosives (HE). Measurements were also performed on three different high explosives: Composition B, RDX, and the propelling charge for 155 mm cannon, again yielding a distinct signature that cannot be confused with any of the chemical agents. Two of the munitions assayed, the GB-filled 105 mm projectile and the VX-filled M55 rocket are fused.

The automatic analysis software package operated correctly most of the time. An important feature is an automatic energy calibration routine, useful

both to OSIA inspectors and nuclear physicists. Ironically, most of the automatic analysis software problems can be traced to the improved signal-to-noise ratio provided by the redesigned shadow shielding of the detector. Several analysis routine problems were fixed and tested at Tooele. The remaining problem cases will be addressed in a new version of the analysis routine.

Minor upgrades to the experimental hardware are also suggested by the experiments.

ACKNOWLEDGMENTS

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NOTES

1. E. Wood, T.T. Taylor, and T. Clark, "Chemical Weapons (CW) Treaty Verification Technology Research and Development: Integrated Test and Evaluation Plan," Volume I, EAI Corporation report C1/92/003F, August 1992.

2. For a technical description of the PINS Chemical Assay System see A.J. Caffrey, J.D. Cole, R.J. Gehrke, and R.C. Greenwood, "Chemical Warfare Agent and High Explosive Identification by Spectroscopy of Neutron-Induced Gamma Rays, submitted to *IEEE Transactions on Nuclear Science*.

3. Since iron is common, and indeed plentiful, in most munitions and storage containers, the auto energy calibration routine looks for the 7631 and 7645 keV iron capture gamma rays to check the energy calibration of the spectrum.

4. There is little hydrogen inside the WP round, and about one-tenth of one percent of the hydrogen capture gamma rays that arise in the polyethylene moderator block leak through to the HPGe detector.

APPENDIX E

ION-TUBE NEUTRON SOURCE

APPENDIX E

ION-TUBE NEUTRON SOURCE

Neutron Interrogation to Identify Chemical Elements with an Ion-Tube Neutron Source (INS) at the Tooele Army Depot, August 1992

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SUMMARY

We have used a portable, electric ion-tube neutron source (INS) and high-resolution gamma ray detector to identify, nondestructively, the key constituent elements in a number of munitions and storage containers at Tooele Army Depot, and from the elemental makeup, infer the types of agent within each. The high energy (14 MeV) and pulsed character of the neutron flux from an INS provide a method of measuring, quantitatively, the oxygen, carbon, and fluorine content of materials in closed containers, as well as the other constituents that can be measured with low-energy neutron probes. The broad range of elements that can be quantitatively measured with INS-based instruments provides a capability of verifying common munition fills, as in the Tooele scenario; it provides the greatest specificity of any portable neutron-based technique for determining the full matrix of chemical elements in completely unrestricted sample scenarios. The specific capability of quantifying the carbon and oxygen content of materials should lead to a fast screening technique which, with room-temperature detectors, can discriminate, in measurement times on the order of a minute or less, between high-explosive and chemical agent filled containers. In this more limited application, Lewisite and mustard agents should also be readily distinguishable from one another, as well as from nerve agents. It may also be possible, with this method, to distinguish VX from GB. This general technology should have applications for rapid screening of other classes of organic based materials. The production of short lived radioactive nuclides by the high energy neutrons should be particularly applicable to monitoring the flow of hazardous materials in pipes.

INTRODUCTION

Neutron interrogation to identify chemical elements (NIICE) makes use of the characteristic gamma rays emitted by atomic nuclei when certain interactions with these penetrating, uncharged particles occur. The energy spectrum, and/or the temporal character of the gamma ray emissions, is usually unique for each type of atom. These gamma rays from the bombarded target sample can

be used to identify, nondestructively, the atomic elements present. By applying the appropriate spectral peak fitting techniques it is possible to infer, quantitatively, the atomic ratios for the target material.

In the case of high explosives (HE) and chemical weapons (CW), the quantitative ratios of the common constituents of organic materials, oxygen (O), carbon (C), and hydrogen (H), are sufficiently different to distinguish between these two classes. Other more "exotic" elements are also present in these materials: relatively high concentrations of nitrogen (N) in the explosives; and chlorine (Cl), sulfur (S), phosphorous (P), fluorine (F), and arsenic (As), as well as N, in differing amounts, in each of the CW agents--see Table E.1. Identification of the combinations of these elements in a sample is adequate not only to distinguish the CW materials from high explosives, but also to distinguish the CW agents from one another. For each of these elements there is one or more type of neutron interaction that generates one or more characteristic gamma rays that can be used for identification.

Both portable isotopic neutron sources (PINS) or ion-tube neutron sources (INS) can be used to excite enough of the exotic component elements of HE and CW agents to perform the necessary nondestructive evaluations (NDE) among the restricted set of materials in the Tooele scenario. The measurements reported here utilized an INS, together with a high-purity germanium (HPGe) γ-ray detector to identify the contents of several types of munitions and storage containers at Tooele Army Depot (TEAD), Utah during approximately two weeks of measurements in August, 1992.

The NIICE/INS technique of nondestructive evaluation differs from the PINS approach in two important ways:

1. The neutrons from a typical INS are more energetic--slightly above 14 MeV kinetic energy--than those from a PINS. Like neutrons from a PINS, they are emitted essentially isotropically. The higher neutron energy opens interaction channels other than neutron capture, which is the predominant mechanism by which low-energy neutrons generate characteristic gamma radiation when interacting with matter. In particular, the neutrons from an INS can generate characteristic gamma rays through inelastic scattering and particle exchange processes. These are the only neutron interactions that can be used for fast measurements of the carbon and oxygen content of materials. *A requirement to correctly identify arbitrary unknown materials poses a unique opportunity for the INS approach. The systematic false alarm rate will be much lower with ion-tube sources because of the superior ability to identify the more complete matrix of elemental constituents.*

2. The INS is electrically driven. Its neutron output can be turned on and off rapidly, either manually or under computer control. When an INS is in the "on" state, neutrons are emitted in pulses with approximately a 10% duty factor. For example, neutrons may be emitted for a 10-μs burst, followed by a 90-μs interval during which no neutrons emerge, followed by another 10-μs burst, *etc.* One can take advantage of this pulsed nature of the neutron emission to reduce the complexity of the detected gamma ray spectra, and to separate identical or similar gamma

TABLE E.1. Atomic Composition of Explosives and Chemical Agents

Whole numbers are atoms per actual molecule.
Others are number of atoms per pseudo-molecle of At.Wt.=100. (0.01="Trace")

No.	Name	Material	C	Al	Cl	P	F	S	Cu	Fe	As	H/C	O/C	N/N
1	AMATOL	Explosive	0.62									7.16	5.69	0.51
2	COMP A-3	Explosive	1.87									2.00	1.32	0.66
3	COMP A-5	Explosive	1.41									2.00	1.89	0.94
4	COMP B	Explosive	2.03									1.30	1.32	0.83
5	COMP C-4	Explosive	1.82									1.95	1.38	0.69
6	COMP H-6	Explosive	1.89	0.74	0.01							1.37	1.06	0.62
7	EXPLO-D	Explosive	6.00									1.00	1.17	0.67
8	HBX-3	Explosive	1.66	1.27	0.01							1.31	0.96	0.56
9	PBX-N5	Explosive	1.42						0.17			1.87	1.81	0.97
10	LX-14	Explosive	1.52									1.92	1.75	0.89
11	MINOL	Explosive	1.23	0.74								2.34	2.08	0.53
12	OCTOL	Explosive	1.78									1.45	1.51	0.91
13	TNT	Explosive	7.00									0.71	0.86	0.60
14	DESTEX	Explosive	2.73	0.71		0.01						0.80	0.73	0.45
15	PBX-N-103	Explosive	0.74	1.00	0.34							3.47	3.35	0.27
16	PBXN-3	Explosive	1.92									1.94	1.27	0.66
17	AFX-108	Explosive	2.10					0.01	0.01	0.01		1.96	1.17	0.54
18	PBXN-109	Explosive	1.87	0.74								1.80	0.98	0.52
19	Sulfur-mustard (HD)	CW Agent	4.00	0.00	2.00	0.00	0.00	1.00			0.00	2.00	0.00	0.00
20	Nitrogen Mustard (HN-2)	CW Agent	5.00	0.00	2.00	0.00	0.00	0.00			0.00	2.00	0.00	0.00
21	Lewisite	CW Agent	2.00	0.00	3.00	0.00	0.00	0.00			1.00	1.00	0.00	0.00
22	Sarin (GB)	CW Agent	4.00	0.00	0.00	1.00	1.00	0.00			0.00	2.50	0.50	0.00
23	Tabun (GA)	CW Agent	5.00	0.00	0.00	2.00	0.00	0.00			0.00	2.20	0.40	0.18
24	Soman (GD)	CW Agent	7.00	0.00	0.00	1.00	1.00	0.00			0.00	2.29	0.29	0.00
25	VX	CW Agent	11.0	0.00	0.00	1.00	0.00	1.00			0.00	2.36	0.18	0.04

ray spectral peaks which come from different reaction mechanisms. The ability to control the on/off state of the INS--particularly under computer control--is a feature that can also be exploited to detect some elements in a target sample via the characteristic energy (and possibly the characteristic lifetime) of radiation from short-lived isotopes produced by neutron bombardment of the sample. Positive identification of fluorine may depend on the use of this capability.

EQUIPMENT AND TEST METHOD

A simplified block diagram for the experimental apparatus is shown in Figure E.1. The INS and a HPGE γ-ray detector (with pre-amplifier) were placed adjacent to the target sample. For most measurements a "shadow shield" of lead, typically 8 inches thick, was placed between the neutron source and the detector to reduce the direct flux of neutrons from the source striking the detector. The INS was a MF Physics Model A-320 unit. It was a modified version of an off-the-shelf system designed for neutron well-logging applications, capable of operating at pulse repetition frequencies (PRF) of up to 10,000 Hz. The γ-ray detector was an ORTEC Model GMX-45200-P (45% N-type), with a 3-l liquid nitrogen reservoir. The HPGe pre-amplifier voltage was provided by a battery.

The PRF of the INS is variable. On the first measurements at TEAD (Run Nos. 100-128) the PRF was 5000 Hz; on the later measurements (Run Nos. 129-176) the PRF was 10,000 Hz. The duty factor was always fixed at the manufacturer-specified 10%. The maximum time-average neutron output of the INS was calibrated by the manufacturer to be 1.4×10^8 n/s at a PRF of 1000 Hz. This value is nominally independent of PRF, i.e., the pulse yield should be 1.4×10^4 n/pulse at 10,000 Hz, 1.4×10^5 n/pulse at 1000 Hz, etc. In practice, the average yield decreased somewhat at the highest PRFs.

In most runs a fast scintillation detector was placed at a fixed location near the neutron source to act as a relative flux monitor. Neutron signals from the scintillator, above a fixed threshold amplitude, were recorded on a fast scaler; the number of recorded counts served as a measure of the total neutrons from the source during the run. These neutron generated pulses, displayed on a Tektronix Model 7104 oscilloscope, could also be used to verify the timing of the gamma-ray gates. Since these were the first measurements made with this data collection system, the neutron monitor was a great convenience, but is generally not a necessity.

For most measurements, the neutron source, shadow shield, γ-ray detector, and neutron monitor were maintained in a fixed geometry in a wooden jig. In a few measurements the source and detector were positioned on opposite sides of the target, which, in effect, replaced the shadow shield.

Signals from the HPGe pre-amplifier were brought to an amplifier; the amplifier output was fed to two pulse-height analyzers (PHA) which were on cards in the data acquisition computer. Another card in the computer--a multichannel arbitrary waveform generator (AWFG)--was programmed to generate independent time gates for the two PHAs, as well as the drive pulses for the

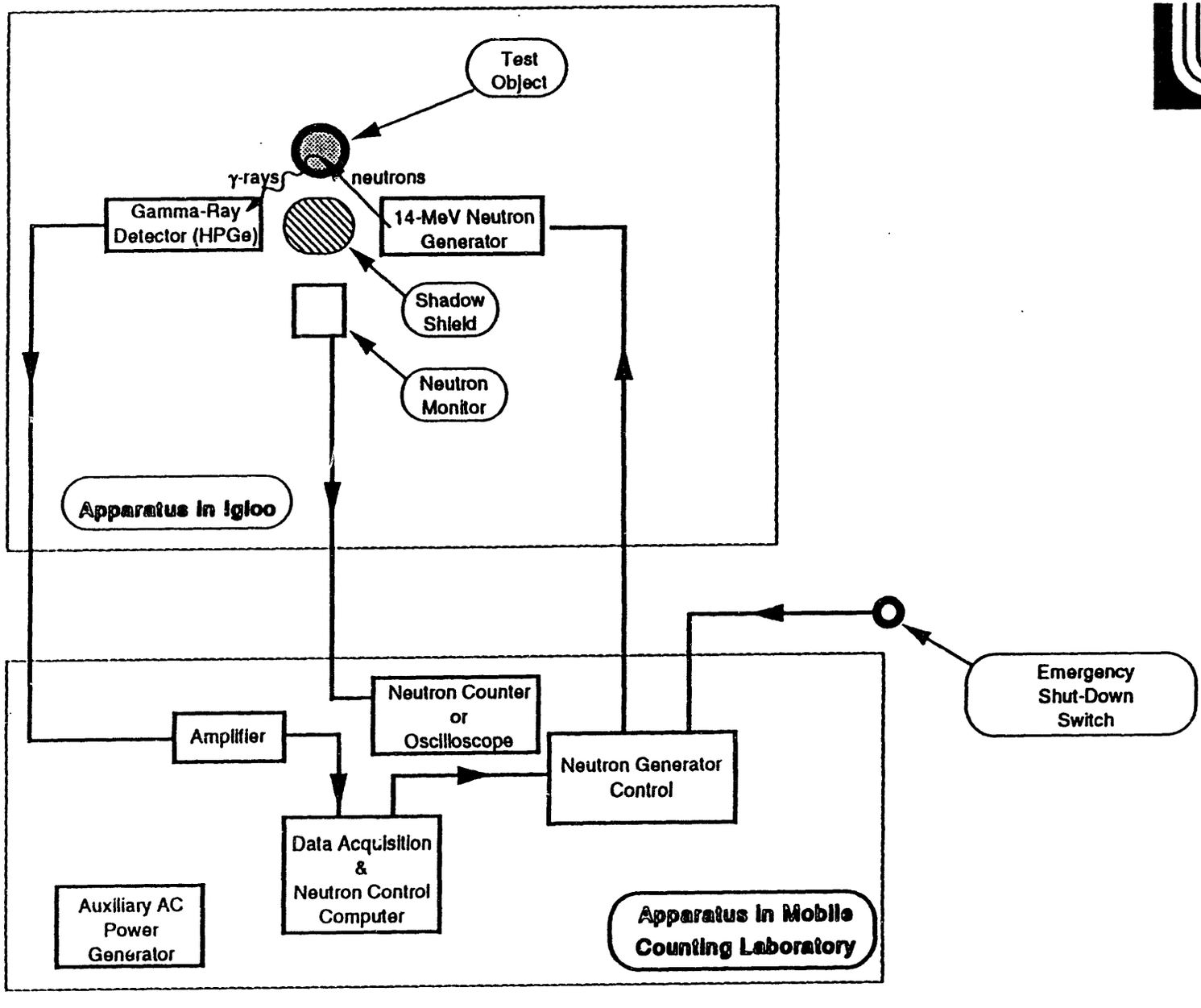


FIGURE E.1. Simplified Block Diagram of Apparatus

neutron generator. The measurement duration, gate widths, PRF, and appropriate delay times between the neutron drive pulse and the two PHA gate pulses, were software controlled. There was a delay of approximately 50 μs between the neutron generator drive pulse and the production of the neutron burst.

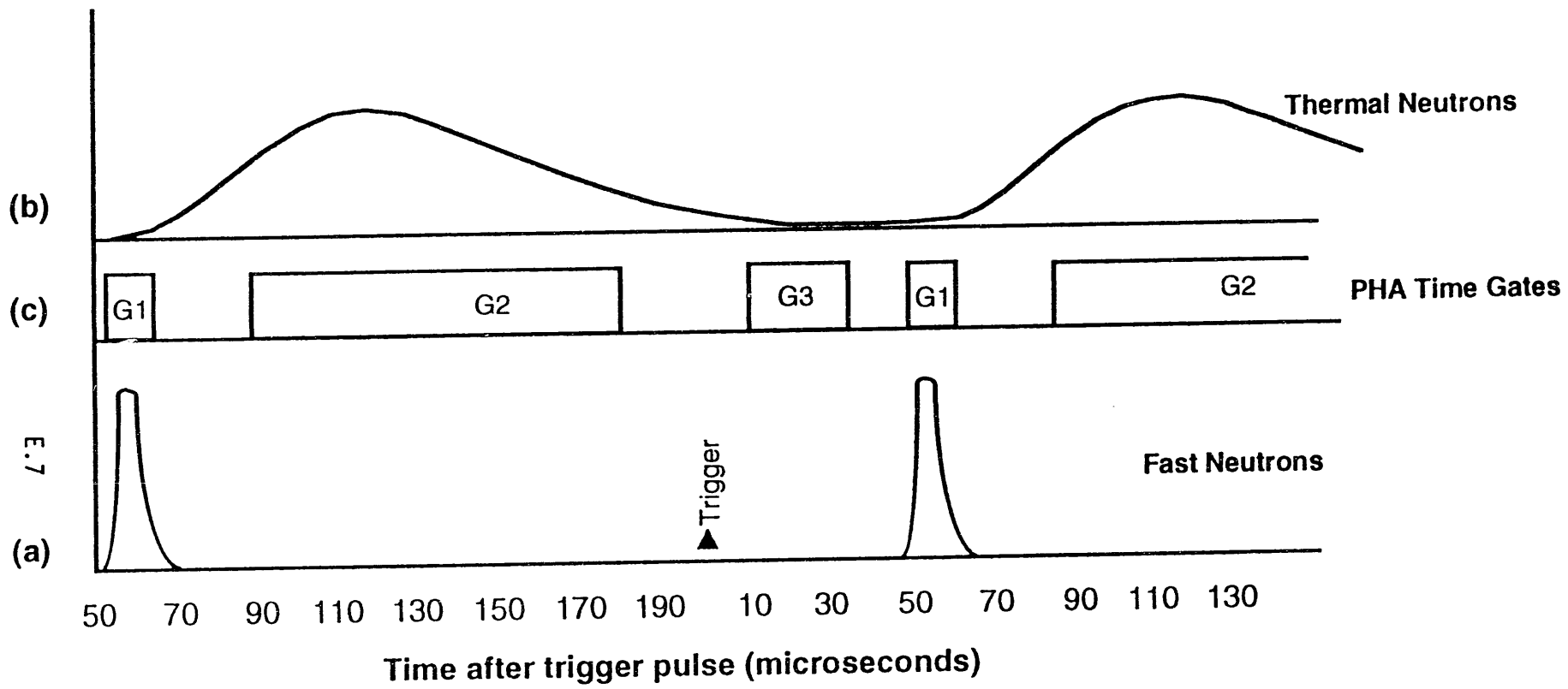
The amplifier, control/data-acquisition computer, and the INS control chassis were located in the LLNL nuclear instrumentation van. The van, which was equipped with a gasoline powered AC generator, could be located up to about 100 ft from the neutron generator and γ-ray detector. Electric power from the munition storage igloos was used for the experimental apparatus, except for three sets of measurements (on the Ton HD container, the WP artillery rounds, and the ICM rounds) in which the AC generator was utilized. The INS and the data-collection system each require 3-5 amps of AC power at 115 V.

Each measurement was begun and halted, and the two PHA spectra were recorded to a disk, by the computer. An emergency "kill" switch was attached by a 100-ft cable to the interlock connection on the INS control chassis. It could be used to shut off the neutron generator prior to the scheduled end of a measurement if required for personnel safety reasons. One of the assigned TEAD safety escorts maintained control of the kill switch during each measurement.

The acquisition/control computer was a Kontron laptop model, which could accommodate up to five cards for data acquisition, memory, etc. At TEAD, four of these slots were utilized for the two PHA boards, the waveform generator, and a memory board. It had not been possible to assemble and test all of the components of the Kontron system with the neutron generator, detector, and other electronics prior to the Tooele experiments.

The gating of the two PHAs is illustrated schematically in Figure E.2. Gate 1 (the "prompt gate" to the pulse height analyzer A) was open during most of the neutron pulse, while high-energy neutrons were striking the target. Gate 2 (the "delayed gate" to PHA B) was opened several tens of microseconds after the beam pulse ended. The delay assured that virtually all high-energy neutrons were absent from the target during the gate. Many neutrons that underwent multiple scattering and thermalized, would still be present in the target and undergoing capture reactors during Gate 2; they would tend to diffuse out of the target before the next fast neutron pulse occurred. Gate 2 was shut off well before the next beam pulse to assure that no photons generated by fast neutrons would be recorded in PHA B.

Gamma rays from inelastic scattering events (as well as some prompt photons from particle exchange processes) were recorded only in analyzer A. Gammas from thermal neutron capture were recorded preferentially in PHA B; since some thermalized neutrons remained in the sample until the following pulse, however, there was some "leakthrough" of neutron capture gammas in PHA A. Activation products with lifetimes longer than the inter-pulse interval emit gamma rays at essentially the same rate during both gates; they populate the spectra in both PHAs in proportion to the two gate lengths.



G1: Primarily inelastic scattering events, with small capture background

G2: Primarily thermal capture and delayed activation events

G3: Approximates capture & delayed activation background in G1.

FIGURE E.2. Neutron Flux Timing and Gates

The rate at which neutrons thermalize and diffuse out of a target sample depends on the size and composition of the sample, particularly on its hydrogen content. In principle the delay and length of Gate 2 can be optimized to enhance the detection efficiency for capture gamma rays in PHA B. In fact, since the dual-gate system had not been operated prior to the Tooele measurements, no optimization was done; Gate 2 was arbitrarily set at a width of approximately half of the inter-pulse interval, and was positioned so that it closed approximately 10 microseconds before the following neutron pulse. The leakthrough of capture gammas into PHA A could have been reduced by operating at lower repetition rates, but dead time and pile-up in the prompt gate would then have increased.

An approximate measure of the capture gamma leakthrough into Gate 1 could be obtained by using a third PHA with a gate the same length as Gate 1 but positioned just prior to each neutron pulse (represented as Gate 3 in Figure E.2); it would record approximately the same number and spectrum of capture gamma rays as Gate 1, but without the contribution of inelastic gammas. We were unable to incorporate the complexity of a third PHA into the system during the Tooele exercises.

For some samples, delayed spectra (with the neutron generator shut off) were collected following a generator-on run. These neutron-off runs were made to look at gamma rays from relatively long-lived activation products. Some of these gamma rays may be useful in identifying key elements, such as arsenic, in the target. Others can give information about background processes which an aid in the data analysis.

Since the INS can be turned on and off under computer control, it can, in principle, be operated in a sequenced mode to look for signature gamma rays from short-lived nuclides produced by neutron bombardment of a target. This is particularly attractive when the half-life of the nuclide is on the order of a minute or less; it appears to be ideally suited for identifying fluorine by looking at the 197.1 keV photons from ^{19}O (26.9 s half-life) generated by (n,p) reactions. This was not done at Tooele because the software for controlling the neutron generator and data collection boards for the sequencing operations had not been developed.

We did, in some later runs, look in the prompt gate for the same 197.1 keV photons due to inelastic scattering in fluorine. A peak was observed at that energy in those cases (both actual munitions and surrogates) in which fluorine was expected. Neutron capture in Ge (the principal detector component) can lead to a line at nearly the same energy. While this process would be suppressed in the prompt gate, it cannot yet be completely ruled out as a contributor to the observed line. It would not contribute to the source-off spectrum, however.

SAMPLES INVESTIGATED

Lewisite (L), sulfur-mustard (HD), and the nerve agents, GB and VX, were examined with the INS system. The L sample was in a steel-walled ton container. The HD samples were in 155-mm artillery rounds, as well as in a ton

container. The GB was in 105-mm rounds, an MC-1 bomb, and a ton container. VX was in 155-mm rounds, a spray tank, and M-55 rockets; the latter two munitions had aluminum shells, whereas all other munitions and containers were steel-walled. In addition, we examined a 155-mm white-phosphorous (WP) round, an MC-a bomb with unknown fill, and a conventional (ICM) 155-mm artillery round containing high-explosive. The chronological order in which these items were measured is shown in Table E.2.

TABLE E.2. Munitions and Storage Containers Measured

No.	Target Target Sample
1	Sulfur-Mustard (HD) 155-mm rounds
2	MC-1 Bomb Unknown contents
3	VX 155-mm rounds
4	Sarin (GB) 105-mm rounds (boxed, with propellant, bursters, fuses
5	VX Rockets
6	Sarin (GB) 1-Ton Container
7	Sulfur-Mustard (HD) 1-Ton Container
8	VX Spray Tank
9	Lewisite (L) 1-Ton Container
10	Sarin (GB) 105-mm rounds (horizontal pallets)
11	High Explosive (HE) 155-mm rounds (ICM)
12	White Phosphorous (WP) 155-mm rounds
13	CW Surrogates 155-mm rounds

In order to simplify the safety management of the neutron-based measurements, the INS measurements which were carried out in storage igloos were done at the same time that PINS measurements were being made on similar items in the same igloos. Although the INS and PINS experiments were generally physically separated sufficiently that the small background from one source caused negligible background for the other measurement, there were a few post-irradiation measurements with the INS shut off, in which thermal capture events generated by PINS neutrons caused a large background; those measurements were generally repeated with the PINS removed from the igloo.

EXPERIMENTAL RESULTS

IDENTIFICATION OF CHEMICAL ELEMENTS

Some of the more prominent gamma rays that should be useful for element identification are listed in Appendix E.1. Most of these have been identified (at least tentatively) in HPGe spectra in laboratory experiments at LLNL and/or in measurements on munitions or surrogates at TEAD. Some of these lines have only been observed in relatively large target samples. Lines seen by inelastic scattering may also be detectable as activation lines, at exactly the same energies, from (n,p) reactions; a daughter nucleus may beta-decay back to the original nucleus in the same state that is excited by inelastic scattering.

IDENTIFICATION OF CONTENTS OF MUNITIONS AND STORAGE CONTAINERS

For the limited set of materials at TEAD (with the possible exception of the unknown bomb) the identity of the fill can be inferred from the detected elements according to the following algorithm:

1. If a strong Cl signal is present, the material is either L or HD. (Weaker Cl signals have been seen from impurities in GB munitions.) Oxygen signal also small or absent.

    a. If sulfur is also detected, the material is HD.
    b. If no sulfur is detected, the material is probably L; this is confirmed by detection of As, and by low hydrogen signal (in fact, relatively low signal of all neutron capture reactions, especially Fe, due to limited neutron energy thermalization).
    c. If neither of the above criteria are met, the Cl signal may be suspected to come from an impurity.

2. If no Cl (or weak Cl), the material is HE, WP, or nerve agent.

    a. If N is present, but no phosphorous, fill material is HE.
    b. If P is present, but no F or S, the material is WP; the hydrogen signal should also be relatively weak.
    c. If P and S are present the material is VX; hydrogen signal also very prominent.

d. If P and F are present material is GB; hydrogen signal strength intermediate between VX and WP.

Table E.3 lists the subset of items at Tooele for which a qualitative analysis has been carried out. Some of the gamma ray lines by which the presence of the key elemental constituents are identified are listed in the table. In some cases, notably chlorine, many additional lines could be identified. Some of the assignments are tentative; further quantitative analysis of the spectra, which are in process, are needed for a positive identification. The above algorithm applied to the elements for each item yields a result consistent with the known contents.

An alternative approach can be used when only the broad category of the fill (i.e., explosive, nerve agent, or blister agent) is required it is only necessary to measure the relative amounts of O, H, and C in the materials. An experimental advantage would be the much shorter times required to obtain data than is required for identifying F, P, and S. With slightly longer measurement times, the relative amount of N can also be determined, and somewhat better discrimination obtained. An added advantage of this approach is that the relative amounts of O, H, C, and N can probably be measured using a room temperature bismuth germanate (BGO) detector. The separation of various types of He and CW agents is illustrated in Figures E.3a and E.3b. It appears that Lewisite can be easily identified by this method, and it may even be possible to distinguish VX from GB. Quantitative analysis of the O, H, C, and N by fitting the relevant spectral peaks is required for this approach. Since we have only recently acquired an adequate peak-fitting program, we have not yet carried out an analysis of the existing data using this approach.

HE materials, on the basis of their O/H/C/N ratios, are in fact separable from most common organic materials. The screening approach outlined above is applicable to detecting explosives in a much broader context than HE and CW discrimination. Although the separations of other classes of organics may not be as clean as for the HE case, the general method may be useful as an initial fast screening step for other types of materials.

RECOMMENDATIONS

Exploit the strength of the INS-based NDE technology, that is the broad range of interactions it can access, which results in greater specificity in determining the matrix of elemental constituents in unknown samples. Its ability to determine the carbon and oxygen content of materials should be particularly exploited.

RECOMMENDED HARDWARE MODIFICATIONS

The neutron generator can be made more user friendly. The manufacturer has indicated that the control chassis can be built on a card that can be incorporated into the control computer. This would reduce the system to three compact units (exclusive of ac power source): generator, detector unit (including stand and shielding), and data acquisition system (which would be

TABLE E.3. Element Identification/Gamma Ray Energies

Run No.	Target	Source/PRF	Gate 1 ("Inelastic") Energy (keV)	Element	Gate 2 ("Capture" Energy (keV)	Element	Residual Activation Energy (keV)	Element	Comments
109	HD 155-mm Proj.	on/5,000	2230	S	841 5421 6111 7414 8578	S S Cl Cl Cl			Many other Cl lines.
128	GB 1-Ton Container	on/5,000	1266 2233 1347 1357	P P F* F*	3522 6785	P P			*Weak lines No S observed
134	HD 1-Ton Container	on/10,000	2230	S	841 5241 1165 1951 1959 9790	S S Cl Cl Cl Cl			Many other Cl lines.
138	VX Spray Tank	on/10,000	2230 2233	S P	2380 2931 3220 5421 636	S S S S P*			*Tentative ID
144	L 1-Ton Container	on/10,000			6111 7414	Cl Cl			Other Cl lines No S observed Weak H line
147	L 1-Ton Container	off/10,000					559	As*	*Tentative ID
151	GB 105 mm Proj.	on/10,000	1266 2233 197 1357	P P F* F†					*Tentative ID †Weak line
153	HE (Comp B) 155 mm Proj. (ICM)	on/10,000	2313 5106 7028	N N N					H relatively weak.
159	WP 155-mm Proj.	on/10,000	1266 2223	P P					H and O relatively weak

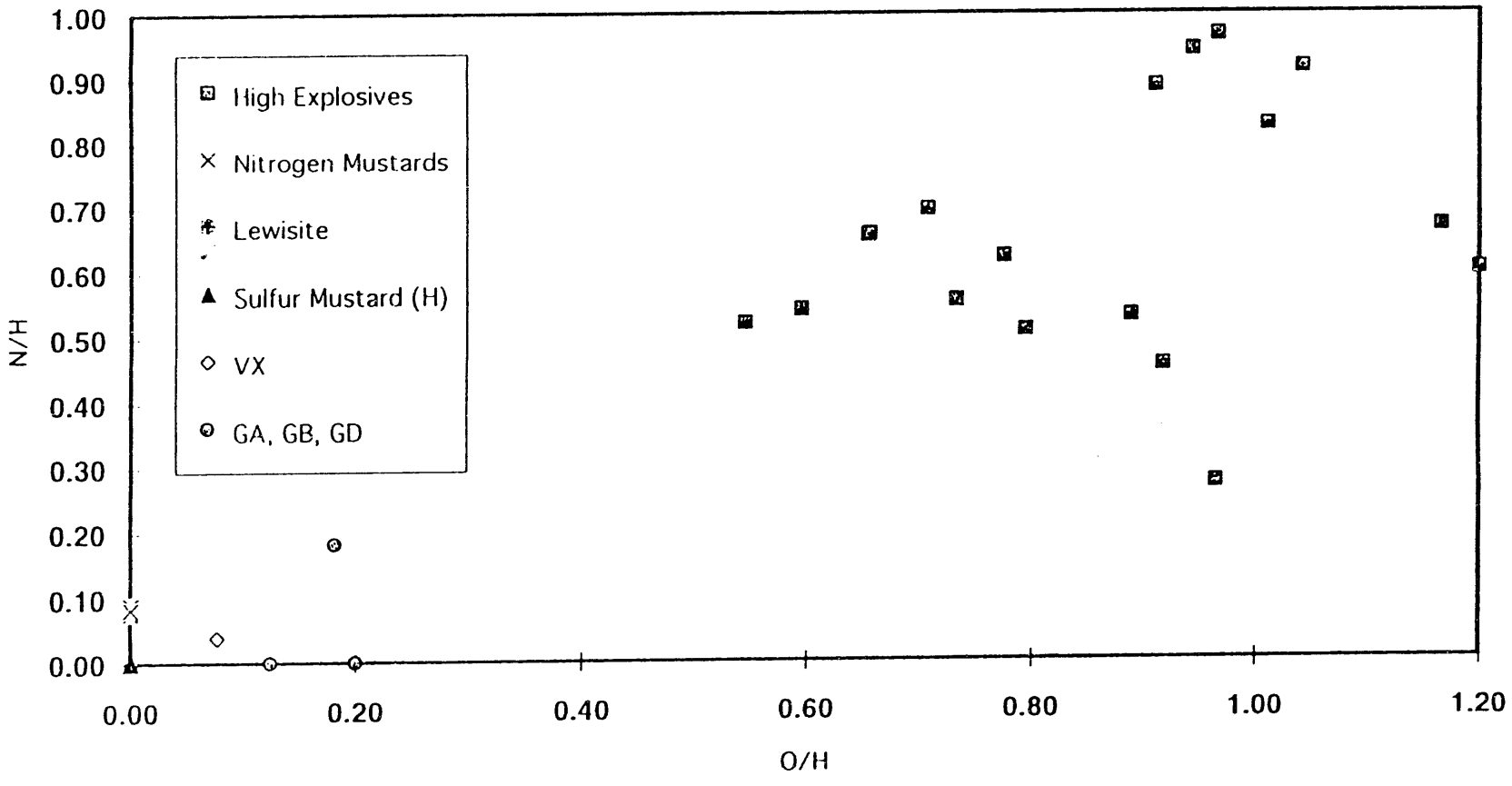


FIGURE E.3a. Munition Discrimination by N, O, H Atomic Ratios

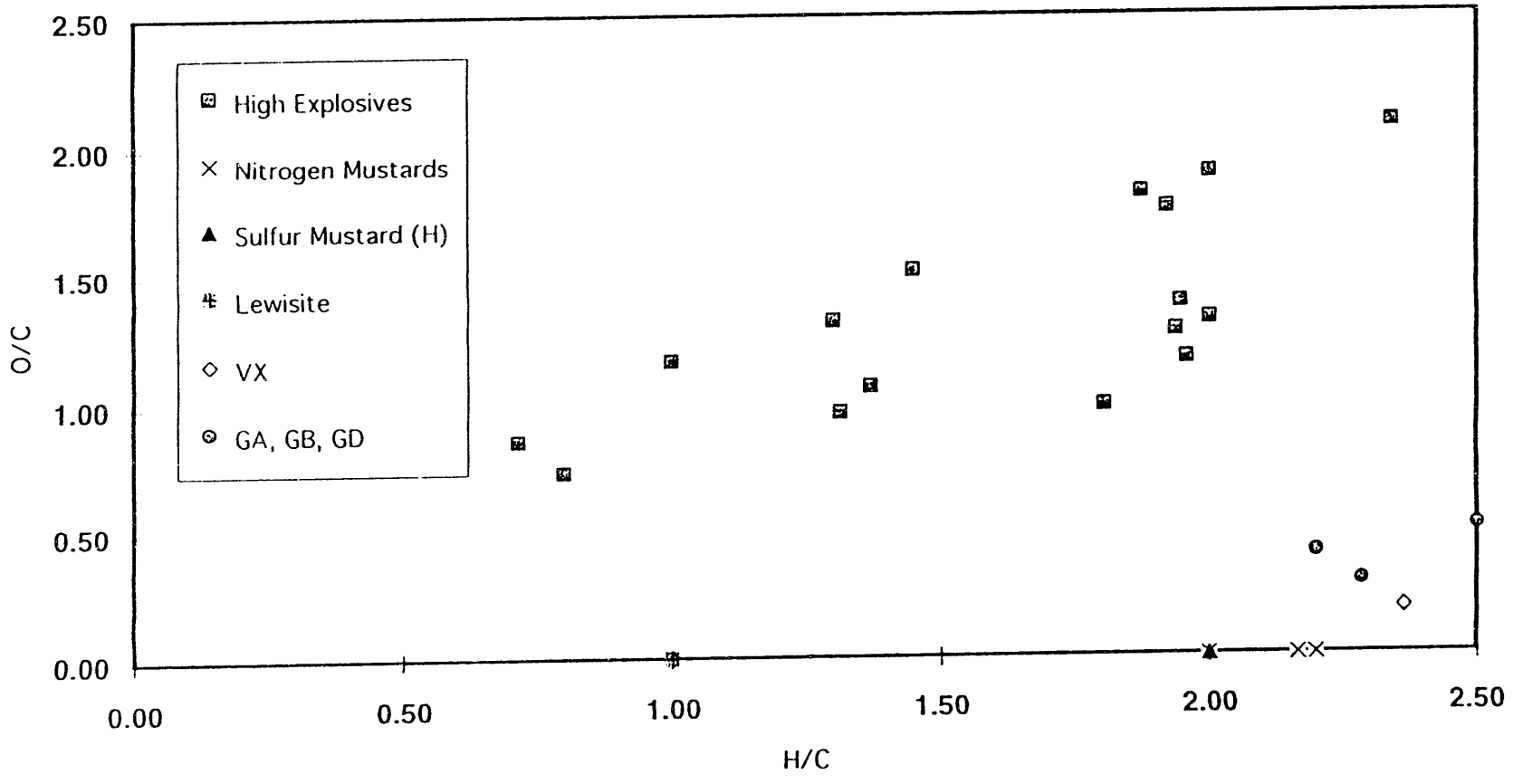


FIGURE E.3b. Munition Discrimination by O, H, C Atomic Ratios

suitcase sized). Where AC power is not readily available, the neutron generator could operate from a 5-amp portable generator. The data acquisition system could operate from rechargeable batteries or a small generator.

(The manufacturer has also indicated that ion-tube housing can be made shorter if it is made a slightly larger diameter. Such a shape modification may be useful for some applications.)

A faster analog to digital converter is desirable, particularly for PHA A to reduce the system dead time. Digital stabilization should be incorporated in the system for applications where high-resolution detectors are required.

The detector shielding should be improved.

Gate timing and operating parameters (e.g., PRF) should be optimized.

Use of a room-temperature, bismuth germanate (BGO) detector should be pursued. It appears possible to get adequate measurements of the C, O, H, and N composition of materials with an INS and a BGO detector to distinguish among the classes of materials with irradiation times of a minute or less.

RECOMMENDED SOFTWARE MODIFICATIONS

Software needs to be developed to automate the data collection process, including detector calibration and on-line peak fitting of signature gamma lines. The system should automatically run in a pulse sequence mode where that operation is indicated by acquired data or by operator input. Key elements (or element ratios) should be measured, and the probable agent material identified.

CONCLUSIONS

We have thus far performed a qualitative analysis of the data from at least one type of each material (VX, GB, HD, L, WP and high explosive) for which measurements were made at Tooele. For this specific type of chemical weapon discrimination scenario, the electric INS-based NDE technology correctly categorized the four chemical agents (GB, VX, HD, and L), as well as HE, and WP.

A more detailed analysis of the matrix of chemical components of the items investigated in these tests is under way. This type of quantitative determination of the chemical ratios, combined with the ability of the high-energy neutrons to excite a wide range of elements, can be applied to the identification of unknown materials in less restrictive scenarios.

ACKNOWLEDGEMENTS

We are indebted to a number of our colleagues at LLNL for assistance in putting together the INS system. We are particularly thankful to John Thorngate for much of the early work with the INS in preliminary experiments which laid the groundwork for the Tooele effort. Ken Dreyer provided the software for controlling the neutron generator and the data acquisition system. Arden Dougan has begun the process of quantitative analysis of the data with the new peak fitting routines. We want to acknowledge the Tooele Army Depot and EAI personnel for their outstanding on-site assistance, and Tom Taylor of PNL for his effort in coordinating the exercise.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

APPENDIX E.1
IDENTIFICATION OF KEY ELEMENTS OF CONVENTIONAL AND CW MUNITIONS

SIGNATURE GAMMA RAY ENERGIES

Fluorine

The capture cross section for fluorine is extremely small; no capture lines are useful for element identification.

Inelastic peaks have been observed at 197, 1240, and 1357 keV.

Activation lines should be visible at 6130 keV due to (n,α) reactions (7.1 s half-life), and at 197 keV and 1357 keV due to (n,p) reactions (27 s half-life). The 6130 keV activation can also be generated by 14 MeV neutrons through (n,P) reactions in oxygen.

Phosphorous

Phosphorous has several significant capture gamma ray lines, including 636, 2154, 3900, and 6785 keV.

There are inelastic peaks at 1266 and 2234 keV. The latter is very close to a sulfur inelastic peak, which has a larger cross section and may dominate when both S and P are present. The presence of both peaks can be qualitatively identified when both elements are present in similar quantities, however, and can be quantitatively separate by appropriate curve fitting techniques.

There is an activation line at 1779 keV with a half-life of 2.25 m, from the beta decay of ^{28}Al produced by (n,α) reactions in phosphorous. Although this process is fairly strong, ^{28}Al can also be produced by neutron capture in natural aluminum and/or by (n,p) reactions in silicon, both of which elements may be present in floors, support structures, the experimental apparatus, etc. The contribution to the 1779 keV activation line from Al and Si can be inhibited by appropriate shielding, and can, in principle, be measured and subtracted out using their other characteristic gamma rays.

Sulfur

Sulfur has fairly strong capture peaks at 841, 2380, and 5421 keV, and several others that can be identified in some cases. When there is iron in the target sample the 841 keV peak may be difficult to resolve, visually, from the large activation peak from iron at 846.8 keV, but the contribution from the latter can be separately determined, as noted in Sec III. Peak fitting methods can also be employed to get the separate contributions directly from the spectrum of PHA B.

Sulfur has several peaks due to inelastic scattering, the strongest of which is at 2230 keV. As noted above, this line is difficult to

resolve, visually, from the 2234 keV peak in phosphorous. It is also close to the 2223 keV hydrogen capture peak. Although the latter is suppressed in the prompt gate in which the inelastic sulfur peak occurs, it is so strong, in some cases, that the leakthrough can dominate the sulfur inelastic signal. A peak-fitting process can be used to separate, quantitatively, the contributions of all three elements in the 2223-2234 keV region.

There is no useful activation gamma ray line from sulfur.

Chlorine

Chlorine has a number of strong capture gamma ray lines from 517 keV to 7790 keV. Perhaps the most prominent is at 6111 keV, and the high energy of these gamma rays allows them to penetrate the walls of the munitions or containers. The whole suite of strong Cl capture lines provides fast and easy identification for that element.

There are some inelastic lines from chlorine, but they will not generally compete with the very strong capture gamma ray lines as a means of element identification.

Arsenic

Arsenic has a lot of relatively weak prompt capture gamma ray lines. The strongest lines, at 165 keV and 1534 keV, were not identified in the Lewisite capture data in the TEAD measurements. (The 165 keV line was below the energy threshold set for the B pulse-height analyzer.) Because of the toxicity of arsenic compounds, we have not yet performed experiments on As at LLNL.

Arsenic has several weak inelastic lines, none of which have been unambiguously identified in the analysis of the TEAD data thus far carried out.

There are activation lines for arsenic at 559 keV (26.3 h half-life) due to neutron capture, and at 596 and 635 keV (17.8 day half-life) due to (n,2n) reactions.

Hydrogen

There is a very strong capture line for hydrogen at 2223 keV. There are no inelastic or activation lines.

Oxygen

The capture cross section in oxygen is extremely small. There are no useful capture gamma ray lines.

There is a strong inelastic scattering line at 6130 keV. The same line appears from an activation product, with a 7.13 s half-life, due to

(n,p) reactions in ^{16}O; it can also be generated by (n,α) reactions in fluorine.

Carbon

The carbon capture cross section is very small; there are no useful prompt capture gamma rays.

There is a prominent, broad line at 4439 keV due to inelastic scattering.

There are no useful activation products from carbon. The 4439 keV activation line (20.2 ms half-life) due to (n,p) reactions in carbon has too high a threshold to be seen with 14 MeV neutrons.

Nitrogen

The capture cross section for nitrogen is fairly small. The strongest capture lines are at 1885, 5269, 5298, 5533, and 6322 keV. The slightly weaker line at the higher energy of 10829 keV may provide a better signature, since there is little or no background in that energy range.

There are fairly strong inelastic peaks at several energies, including 1632, 2313, 5106, and 7028 keV.

The only significant activation product is ^{13}N (9.97 m half-life; positron decay) which can be produced through the (n,2n) reaction. The only significant gamma ray from this product is the 511 keV positron annihilation photon, which is not unique in energy, but the reaction could be identified by a lifetime measurement.

Background Elements

Iron: There are numerous strong capture lines from iron, and several strong inelastic scattering lines, particularly at low energy. Some of these are close to signature lines of the HE and CW component elements listed above, but most are adequately separated in high-resolution detectors. The activation line at 846.8 keV interferes with a key sulfur capture line, but that situation can be resolved by methods previously noted.

Aluminum: The principal background problem with Al is the 1779 keV activation from neutron capture, which, as noted above, is identical to the (n,α) signature line from phosphorous. Aluminum generates several other lines that can be used to evaluate its background contribution, including lines from activation products, capture lines at 4133, 4260, 4734, and 7724 keV, and inelastic lines at 843, 1013, 1719, and 2210 keV.

Silicon: Silicon, like aluminum, produces a 1779 keV activation background. Like aluminum, its contribution can be evaluated from its other signature lines. There are capture lines 2093, 3539, and 4934 keV, and

at several other energies. The 1779 keV line also occurs in the inelastic scattering channel, and there are several other additional inelastic lines.

Lead: Lead was used as a shadow shield between the neutron source and the gamma detector. Neutron capture in lead generates photons at 6736 and 7367 keV, and (n,2n) reactions give activation lines (800 ms half-life) at 569 and 1063 keV. Background from lead has not been a problem in identifying other key elements.

Boron: Boron was used in neutron shielding material on some measurements. It produces a strong, broad line at 478 keV from the $^{10}B(n,\alpha)$ reaction to an excited state in ^{7}Li.

Germanium: Germanium background arises from neutron interactions in the detector, itself. There are capture lines at 175, 596, 868, and 3028 keV, and broad inelastic lines around 596 and 693 keV, and several other energies.

APPENDIX F

COMMENTS FROM OSIA PERSONNEL

APPENDIX F

COMMENTS FROM OSIA PERSONNEL

Comments from On-Site Inspection Agency Personnel

Personnel from the On-Site Inspection Agency were requested to participate in the field trials. Their participation helped assess the development of the Ultrasonic Pulse Echo, Acoustic Resonance and Portable Isotopic Neutron systems from a user viewpoint. As Dr. Caffrey noted in his acknowledgements, OSIA personnel took the time from their busy schedules to participate in the field trials with "great care and good humor".

As part of the OSIA evaluation, personnel were requested to fill in an equipment evaluation form. A copy of the evaluation form is provided below and the comments that OSIA personnel made concerning the equipment they used follow.

QUESTIONNAIRE FOR EQUIPMENT EVALUATION

NDE SYSTEM:

OPERATOR: **Date:**

1. Was the training time and instruction adequate? What recommendations do you have?

2. What equipment or equipment operation problems did you have?

3. Estimate how long the equipment would last in the test environment before it would have to be repaired/replaced.

4. How could the equipment be made to operate better in the field?

5. How could the equipment be made more user friendly?

6. What was your average setup time?

a. What was your average operation time per munition?

b. What was your average cleanup time?

7. Other comments:

QUESTIONNAIRE FOR EQUIPMENT EVALUATION

NDE SYSTEM: ARS

OPERATOR: 1 **Date:** 25 Aug 92

1. **Was the training time and instruction adequate? What recommendations do you have?** Training time was adequate. Two hours with instructors, then time for hands-on training. An operators manual would be useful when P.I.s are not present. A troubleshooting guide for equipment failures also would be useful.

2. **What equipment or equipment operation problems did you have?** Cables and connectors should be stronger. Some minor software problems occurred. Overall, fairly reliable.

3. **Estimate how long the equipment would last in the test environment before it would have to be repaired/replaced.** With minor improvements with cables and connectors, and an improved carrying case, no major problems should be expected in months of use.

4. **How could the equipment be made to operate better in the field?** A stronger transducer capable of being decon'd is required.

5. **How could the equipment be made more user friendly?** Already very user friendly, an easy-to-follow menu currently appears on the screen.

6. **What was your average setup time?** Less than 10 minutes.

a. **What was your average operation time per munition?** 24-40 seconds - depending on type of munition. This includes operator comments.

b. **What was your average cleanup time?** Less than 10 minutes.

7. **Other comments:** The equipment performed up to expectations. It was very user friendly. Would be beneficial during inspections is used in conjunction with equipment capable of determining volume and in conjunction with a method of determining type of agent fill.

QUESTIONNAIRE FOR EQUIPMENT EVALUATION

NDE SYSTEM: ARS

OPERATOR: 2 **Date:** 25 Aug. 1992

1. **Was the training time and instruction adequate? What recommendations do you have?** Training time was sufficient to learn operation of the equipment and collection of data. More time could be spent on understanding how to tell if one is collecting the best data.

2. **What equipment or equipment operation problems did you have?** Minor problems with cables were experienced.

3. **Estimate how long the equipment would last in the test environment before it would have to be repaired/replaced.** N/A. This equipment would be "toughened up" before deployment.

4. **How could the equipment be made to operate better in the field?** Longer cables.

5. **How could the equipment be made more user friendly?** Making the program WINDOWS compatible will make it more versatile and adaptable to use in the inspection regime.

6. **What was your average setup time?** 5 minutes

a. **What was your average operation time per munition?** 20 seconds

b. **What was your average cleanup time?** 5 minutes

7. **Other comments:** The Los Alamos personnel took an active interest in preparing the OSIA personnel, even to the extent of customizing the data-collection program to meet our needs. All their efforts were greatly appreciated.

QUESTIONNAIRE FOR EQUIPMENT EVALUATION

NDE SYSTEM: PINS

OPERATOR: 3 **Date:** 24 Aug 92

1. **Was the training time and instruction adequate? What recommendations do you have?** Total training time of 18 hours was adequate. A more substantial discussion of health physics would be appropriate.

2. **What equipment or equipment operation problems did you have?** No particular problems were noted with OSIA personnel. The P.I.s MCA exhibited an electronic malfunction which shut down the high voltage.

3. **Estimate how long the equipment would last in the test environment before it would have to be repaired/replaced.** The equipment performed well for 80+ hours of data collection. There's no reason to believe the equipment wouldn't last for many months before repair is required.

4. **How could the equipment be made to operate better in the field?** The reliance upon H and Fe peaks may not be appropriate for all agents. Find other lines as appropriate or include a Fe calculation slug for configurations w/o Fe.

5. **How could the equipment be made more user friendly?** The equipment is about as user-friendly as it can get. A computer with a screen that can be seen in the sun would help.

6. **What was your average setup time?** ~15 mins

a. **What was your average operation time per munition?** ~30 mins

b. **What was your average cleanup time?** ~10 mins

7. **Other comments:** The counting technique relies heavily upon geometry, as does any gamma spectroscopy endeavor. This can introduce a slot of variability into the data. This subject should be explored in more depth in the training. Also, the auto analysis routine needs a lot of work.

TABLE 3

QUESTIONNAIRE FOR EQUIPMENT EVALUATION

NDE SYSTEM: PINS

OPERATOR: 4 **Date:** 25 Aug 92

1. **Was the training time and instruction adequate? What recommendations do you have?** Yes, some of the training could be automated. I'd like to see a self-paced software tutorial on reading spectra.

2. **What equipment or equipment operation problems did you have?** Coax connectors used in cabling were threaded. These came loose occasionally and should be replaced with the crimp type.

3. **Estimate how long the equipment would last in the test environment before it would have to be repaired/replaced.** I have no clue. At least a year.

4. **How could the equipment be made to operate better in the field?** The set-up table for the source and shadow blocks is unnecessarily large and complicated. Holes in the poly block for the should be tapered. The computer screen is difficult to read in the sun and should be replaced.

5. **How could the equipment be made more user friendly?** The Maestro software (Ortec) needs work. Besides bug fixes the "soft" controls for the MCA are very easy to unintentionally disturb. This can result in wasted operator time.

6. **What was your average setup time?** 5 min.

a. **What was your average operation time per munition?** 40 min.

b. **What was your average cleanup time?** 5 min.

7. **Other comments:** Do no oversimplify PINS. While the auto-analysis software is one of the most attractive features, its not as good as a skilled operator. I would like to see a strong operator training program.

QUESTIONNAIRE FOR EQUIPMENT EVALUATION

NDE SYSTEM: UPE

OPERATOR: 5 **Date:**

1. **Was the training time and instruction adequate? What recommendations do you have?** Training was adequate in that it was similar to the amount of time we would have to train inspectors intending to use the equipment in Russia. The training showed us that the equipment is not user friendly enough and training demands much more time than allowed. Recommendation--try training people on the equipment package PNL says they'll have ready in approximately one year or drop the funding.

2. **What equipment or equipment operation problems did you have?**

   a. Psion computer's software doesn't allow operator to go back and correct or change data after screen has been changed. No new data can be added to an existing file after data acquisition and data cannot be recomputed; e.g., operator acquires waveform and TOFs for munition and later discovers munition diameter was slightly off. Information cannot be amended. The computer should also be much more automated so the operator doesn't have to input repetitive info for each acquisition file (name, munition, origin, team, etc.). Computer must also be shut off after each data acquisition which is time consuming and operators may not input changes to USD10 while Psion is taking data from it. Hitting USD10 buttons causes Psion to crash - time consuming and annoying. Many buttons are too small, operator has to use a pen to push buttons when in gloves.

   b. USD10 o'scope seems designed to be set up and used for long-term data acquisition without changing amp gain, display width, etc. Operator must toggle through many fields to make changes which is time consuming and a hassle with gloves on. This could be made easier if all commonly used buttons showed on the screen, but they are interspersed with displays which remain constant (language-English). Our PI told us the USD10 software cannot be changed as item was bought "off the rack."

   c. Transducers work quite well individually but bands to place around small munitions are difficult to manage. Operator must fiddle with transducers to get readings and must be able to view o'scope while adjusting band. Bands currently in use bend easily, cannot be used for munitions lying horizontally. When using bands, fill level is registered only as being to point where munition begins to form nose cone. When using only one transducer to measure fill level of large tanks, measurement is rough because distance from fill line to top of munition is measured with tape measure.

3. **Estimate how long the equipment would last in the test environment before it would have to be repaired/replaced.** Psion, USD10, and cable would last a long time. Bands to hold transducers get bent out of shape easily - 3 days to 2 weeks.

4. **How could the equipment be made to operate better in the field?** Using a flexible, expandable holder for transducers would make receiving a signal easier. Magnets might work, a wrap-around transducer is very awkward. Streamline software to header info is automatically repeated. Combine equipment components of Psion and o'scope. Allow for data corrections.

5. **How could the equipment be made more user friendly?** Require fewer buttons to be pushed on Psion. Keep frequently adjusted variables (dB, freeze on/off, display width) together to lessen toggling. Fix the transducer problem.

6. **What was your average setup time?** 10 minutes to check USD10 inputs, start up Psion, and calibrate system.

a. **What was your average operation time per munition?** Varies widely; 5-30 minutes

b. **What was your average cleanup time?** Very brief; 2-3 minutes

7. **Other comments:**

QUESTIONNAIRE FOR EQUIPMENT EVALUATION

NDE SYSTEM: UPE

OPERATOR: 6 **Date:**

1. **Was the training time and instruction adequate? What recommendations do you have?** No - the instruction was good but there are a lot of factors to take into consideration when operating the system. For the most part, we were trained on 155-mm surrogates so it was trial and error when operating on spray tanks or MCIs and 105 mm. I would recommend that after seeing the storage configuration of the different types of chemical weapons, training should encompass all types and not just 155 mm because it is different to operate for each kind.

2. **What equipment or equipment operation problems did you have?** The screen on the USD10 is really hard to read when exposed to sunlight.

   In order to save data, you have to reboot the system each time and if you want to review your data, you have to go into DOS. Seems like you should be able to do that from the main menu. Also if you make a mistake on the keyboard and you go on to the next screen, you can't go back and change it so now that whole data sheet is useless.

   We found out that the cart has to be really close to the person operating the transducers. I think the cables for the transducers need to be longer.

3. **Estimate how long the equipment would last in the test environment before it would have to be repaired/replaced.** I think it would last for quite some time in a test environment, providing it is shielded from sunlight and rain.

4. **How could the equipment be made to operate better in the field?** It needs a better screen. You can't see the USD10 screen outside.

5. **How could the equipment be made more user friendly?** There needs to be a help key so if you run into problems during operation you could press the help key. Should also be able to go back and change data in case of mistakes. Right now if you read the wrong peak and punch that into the computer and then realize it was wrong, you can't go back to change it so that means you have bad data. Should also be able to bring up all your data from the menu instead of having to go into DOS. Should also be able to operator the USD10 and the Psion at the same time.

6. **What was your average setup time?** 5-10 minutes

a. **What was your average operation time per munition?** It depends on the type of munition. 1 ton containers only took a couple of minutes.

because there is less involved in obtaining data, but the 105-mm took 10-15 min because it was more trial and error due to storage configuration.

b. **What was your average cleanup time?** Clean up is easy and it doesn't take very long at all. Only a couple of minutes.

7. **Other comments:** The UPE is a system that the more I used it, the more I liked it. It got easier the more time you spent with it. There is the problem of interpretation. But I think if I spent more time training with it, then that problem could be solved. The fixtures for the different munitions need to be changed. it is too hard to play with the fixture to figure out what is a good peak and what is a bad peak. I think this is a system that could be very useful in the future with continued development. I think the PIs have a better view of how munitions are stored and can develop from there rather than just training on 155-mm surrogates. I also think that training with the equipment should be in gloves to get a better feel of how the equipment would actually be used. I don't think the UPE is ready to be fielded. There were problems in getting readings with 155 mustard, 8 in VX, 105 GB, etc but the PIs saw the problems and should be able to develop from there.

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