UCRL-50007-83
Distribution Category UC-41

UCRL--50007-83

DE85 001434

Hazards Control Department Annual Technology Review 1983

Scientific Editor: R. V. Griffith

Manuscript date: June 15, 1984

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

LAWRENCE LIVERMORE NATIONAL LABORATORY
University of California • Livermore, California • 94550

Available from: National Technical Information Service • U.S. Department of Commerce
285 Port Royal Road • Springfield, VA 22161 • \$10.00 per copy • (Microfiche \$4.50)

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

cb

Foreword

This report, which covers the period from October 1982 to September 1983, is divided into three major sections. The first section, Progress Reports, covers the status of activities undertaken or continuing during the period; additional reports or separate publications will cover the final results of these activities. The second section, Technical Notes, contains reports on interesting activities of a more limited scope on which further reporting is not anticipated. The third section lists recent publications.

Readers who are interested in more detail may contact the authors of the reports.

Contents

FOREWORD	ii
PROGRESS REPORTS	
Industrial Hygiene	
Field Testing of Carbon Adsorber Beds—II	3
Protection of Self-Contained Breathing Apparatus During High Work Rates and Low Operating Pressures	6
Radiation Protection	
Calculating Spectra and Dose Rates in the ⁶⁰ Co Pool	9
Measuring Pu in a Glove Box Using Portable NaI and Germanium Detectors	21
Fire Safety	
Evaluation of Personal Alarm Devices for Firefighters	28
Evaluating Electrical Cables by the LLNL Ease-of-Ignition Apparatus	35
Zone-Model Correlations with Experimental Enclosure Fires	43
Definition of the Concentration Gradient Above Flammable Liquids	48
TECHNICAL NOTES	
Industrial Hygiene	
Impact and Vibration Testing of Firefighters' Self-Contained Breathing Apparatus	57
Instrument Development	
Measurement of Aerosol Concentration as a Function of Size and Charge	61
Radiation Protection	
Comparison of Calculated Neutron Spectrum and Dose Equivalent from NBS and LLNL 15-cm D ₂ O Spheres	68
Programs for Calculating Beta Spectra	73
CAM Particle Deposition Evaluation	79
Mercury Scrubber for the Ostlund Tritium Monitor	83
PUBLICATION ABSTRACTS	89

Progress Reports

Field Testing of Carbon Adsorber Beds—II

Peter M. Swearengen, James S. Johnson, Charles A. Harder, and Cynthia A. Cadena-Fix

We studied activated-carbon-adsorber beds used for air-cleaning to measure service life. We used ethane gas in a pulse test to determine the residual adsorption capacity (RAC) of the carbon. Small cartridges were placed in a manifold parallel to the main bed with the air flow closely matching that of the main bed. The cartridges were moved periodically and tested in the laboratory for the RAC.

Introduction

Activated carbon adsorbers are used at LLNL for air-cleaning of both large and small ventilation systems. We know that carbon adsorber beds lose the capacity for organic vapors during their lifetimes. At some point during this decline, the carbon should be removed and a fresh batch installed. The high cost of replacement, however, dictates that such maintenance be done only when necessary. The purpose of our project is to follow the service life of several adsorber beds and to measure the remaining effective adsorption capacity (i.e., residual adsorption capacity or RAC).

Previous work has shown that ethane gas could be used to measure the RAC of a carbon bed.¹ Subsequent work in our laboratory has corroborated this, and a testing manifold has been fabricated that samples in parallel with a large carbon adsorber bed. This manifold will contain multiple cartridges of activated carbon. Our rationale for this particular system is that changes observed in the test cartridge carbon will reflect conditions in the main bed.

Experimental Description

We calibrated the removable carbon cartridges within the test manifold for their retention time of ethane gas under controlled flow conditions. At periodic intervals, the cartridges will be removed from the manifold and tested in the laboratory to observe any change in response to the ethane test. A variable uptake of water can occur

on carbon with fluctuating relative humidity in the air passing through the filter. This uptake will be accounted for by an equilibration period for the cartridge using very dry (< 5% RH) air. The flow of dry air will remove water adsorbed on the carbon.

A schematic diagram of the carbon test manifold is shown in Fig. 1. We designed the system to be modular, allowing access to one cartridge without affecting the rest of the system. Valves isolate the cartridge of interest from the system flow, and the removal or installation of a single unit is possible in a matter of minutes. Individual cartridges are protected from dust or particulate attrition by HEPA filters installed upstream. The in-line HEPA filters downstream from the cartridges protect the pump from particles that might escape from the carbon bed. The pressure drop across the carbon system can be monitored during operation by the magnehelic gauge. Finally, we installed a control valve on the downstream (exhaust) manifold to allow the total vacuum seen by the pump to be held within manufacturer's specifications. If the vacuum becomes too large, outside air can compensate for the flow.

We also installed a critical orifice in the system downstream from each cartridge to ensure constant and uniform flow. Flow through each orifice was determined using an NBS traceable spirometer. The pressure drop across each orifice was held to a vacuum greater than 38 cm Hg during calibration to ensure operation in the critical range.

For our air-cleaning system, residence times across the bed vary depending upon the fume-hood sash opening. Values can range from 0.16 to

Figure 1. Schematic of carbon test manifold.

0.22 sec. Since a long residence time would tend to optimize adsorption (and most rapidly deplete the bed capacity), the test cartridges should represent only the worst case of the bed condition, and, therefore, we set the flows for the longer residence time.

The charcoal for each test sample was placed in a 5.08-cm diameter cylindrical cartridge 5.08 cm in height. With a cross sectional area of 20.27 cm², the linear flow velocity through the bed was 1397 cm·min⁻¹, assuming a mean flow of 28.3 lpm. The residence time in the carbon bed is 0.218 sec. This value can be compared with a typical industry standard of 0.1–0.2 sec for air-cleaning of organic vapors.² This figure can also be compared to nuclear applications where a minimum residence time of 0.25 sec is required for removal of organic radioiodine compounds.³

Results

Table 1 summarizes the ethane-pulse testing of individual carbon cartridges. Five ml volumes of the gas were injected into a flowing air stream via a gas-tight syringe. The air flow in the cartridge test system was controlled by a Tylan mass-flow controller. The flow was split downstream from the cartridge, with part of the exhaust going to a flame ionization detector (FID) in a Varian 1520A gas chromatograph. A valve was placed below the split to adjust the flow to the detector. All remaining flow was exhausted. A schematic of this test system is shown in Fig. 2.

We measured the time for the ethane to flow to the detector without adsorption effects by filling a test cartridge with a mixture of glass beads 1 mm and 3 mm in diameter. The 1-mm beads were added to the larger beads in the cartridge until the pressure drop across the cartridge was equal to that of a typical carbon-filled cartridge

Table 1. Ethane retention times.

Cartridge	Wt carbon ^a (g)	Retention time ^b (min)
M1	45.92	5.96 ± 0.03
M2	50.49	5.93 ± 0.06
M3	44.42	6.27 ± 0.37
M4	46.56	5.51 ± 0.05
M5	52.84	4.17 ± 0.25
M6	52.03	5.56 ± 0.09

Flow velocity: 8.22 cm·sec⁻¹ based on 10 slpm flow from mass-flow controller through a 2" diameter carbon cartridge.

Space time: 0.3089 min

^a Sutcliffe-Speakman 208C Carbon, 8 × 16 mesh.

^b Average of 6 measured values.

Figure 2. Carbon-adsorber-bed test system.

($\sim 0.20''$ H_2O on a Dwyer manometer). We injected ethane across the blank cartridge to obtain a base time for ethane travelling to the FID. This retention time is often referred to as "space time." Subtraction of the space time from a measured retention time across a carbon-filled cartridge should give a retention time due only to the adsorption effects from the carbon. We also give a listing of the retention times for six carbon cartridges of Manifold I in Table 1.

Future Work

Future work will involve several refinements to the current testing scheme and the analysis of the cartridges already in service. A blank cartridge will be installed in the laboratory where the main air flow is entering the fume hood under study. This cartridge will then be analyzed to measure background contributions from sources other than the chemical vapor fumes contained within the

fume hood. Such data will measure the decline of RAC from fume-hood activities compared to the decline due only to other air pollution sources. Finally, a second carbon manifold is under construction to study a different air-cleaning system in a separate facility.

References

1. P. M. Swearingen, J. S. Johnson, R. A. da Roza, and C. A. Harder, *Hazards Control Annual Technology Review*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-50007-82 (1983).
2. David Ainsworth, Sutcliffe Speakman Inc., private communication, October, 1981.
3. American Association for Contamination Control (AACC), *Tentative Standard for High-Efficiency Gas-Phase Adsorber Cells (AACC designation: CS-8T)*, Amendment 1, Appendix C, October 1973.

Protection of Self-Contained Breathing Apparatus During High Work Rates and Low Operating Pressures

Jerry W. Stengel and Roberta A. Rodrigues

Our previous investigation of firefighters' self-contained breathing apparatus (SCBA) at high work rates had indicated that only one-third of the SCBA tested could maintain the necessary pressure. SCBA must maintain positive facepiece pressure during high work rates at low cylinder pressures. During firefighting use, the most critical need for SCBA protection may occur at the time the low pressure alarm sounds, and the firefighter exits or conducts a rescue operation. We performed follow-up investigations on available SCBA at high work rates and low operating pressures, showing that current SCBA can maintain positive facepiece pressure, even though only one SCBA actually did it at the alarm point.

Methods

The testing equipment and procedures described in our previous report¹ were used again (Fig. 1). We measured peak and minimum facepiece pressures at full cylinder pressure, repeated at several decrements, and stopped at the low-pressure alarm point. Measurements were recorded for a minimum of ten successive breaths. The breathing machine parameters were 100 liters/minute ventilation rate, 2.06 L tidal volume, and 49 respirations/minute. We estimated this to cause peak flows of between 300 and 400 liters/minute.

A significant question concerns the validity of the typical pressure-monitoring location in the breathing zone, between the upper lip and nose of the head form (Fig. 2). While this is the appropriate place for measuring maximum breathing resistance, it does not necessarily represent pressures

at the outer sealing surfaces of the facepiece. Pressures at the sealing surfaces are more directly related to protection against inward leakage of contaminated air.

Theoretically, the breathing-zone pressure could go negative during inhalation, while pressures at the sealing surfaces remain positive. Breathing-zone monitoring would produce a false indication of loss of protection. This is especially true when the facepieces have nose cups that isolate an area surrounding the breathing zone from the rest of the facepiece. Comparisons of pressures measured at seven locations on two different facepieces with nose cups showed no noticeable difference in pressure tracings. Monitoring locations appear valid within the limits of sensitivity of the equipment used—estimated to be ± 0.1 inch (0.25 cm) of water pressure.

Figure 1. Diagram of SCBA testing apparatus.

Figure 2. Pressure map of various test locations within facepiece.

Results

One out of the six SCBA we tested maintained positive facepiece pressure. Although more facepiece pressures fell with decreasing cylinder pressures, some remained relatively constant and one actually increased facepiece pressure (Figs. 3a and 3b). As operating pressures decreased, breathing resistances (maximum facepiece pressure) generally increased. Pressures beyond 4 inches (10 cm) of water are considered excessive and pressure beyond 9 inches (22.5 cm) are intolerable to most wearers.

Varying performance is attributed to different demand-valve-design characteristics. The shapes of the breath-waveform pressure tracings are also characteristic "signatures" of differing designs. In general, SCBAs with facepiece-mounted demand valves performed well, presumably due to the elimination of frictional losses of rapidly flowing,

low-pressure air through a 0.5-m length of corrugated hose from belt-mounted demand valves.

Conclusions

Adding the criteria that SCBA must maintain positive-facepiece pressure at or below the alarm point makes the high-work-rate test severe in that only one SCBA tested did it. Our results imply that firefighters performing strenuous work are losing protection (protection factors < 10,000) at low operating pressures. However, our results also demonstrate that high performance (maintaining positive facepiece pressure at low operating pressures) is achievable with current technology. Therefore, this test is strongly recommended as a baseline test against which effects of the firefighting environment (e.g., temperature, corrosion, etc.) should be evaluated. The National Fire Protection Agency is currently developing such tests.²

Figure 3a. Positive facepiece pressure as a function of a compressed-air, cylinder-operating pressure (VE = 100 liters/minute).

Figure 3b. Negative facepiece pressure as a function of a compressed-air, cylinder-operating pressure (VE = 100 liters/minute).

References

1. J. W. Stengel, "Self-Contained Breathing Apparatus Protection at High Work Rates," *Hazards Control Department Annual Technology Review-1982*, UCRL-50007-82 (1983).
2. NFPA Committee for Revision NFPA 1981 Standards on SCBA and NFPA Committee on Protective Equipment for Firefighters, *Draft on Standard for Self-Contained Breathing Apparatus for Firefighters*, National Fire Protection Association (1981).

RADIATION PROTECTION

Calculating Spectra and Dose Rates in the ^{60}Co Pool

Charles T. Prevot

We have calculated the spectra and dose rates at various locations in the Hazards Control ^{60}Co irradiation pool. The calculations were performed using the radiation transport code, MORSE76L.

Introduction

The Standards and Calibrations Laboratory (Bldg. 255) is part of the Radiation Dosimetry Group of the Hazards Control Department's Radiation and Environmental Safety Division. Its purpose is to maintain radiation standards for LLNL; the Standards and Calibrations Lab also offers radioactive sources that provide gamma, neutron, beta, and x rays for calibrating instruments, irradiating various materials for LLNL researchers, and performing routine calibrations for the LLNL Personnel Dosimetry Program.

One such facility is the ^{60}Co irradiation pool that provides a high-intensity gamma field for radiation-damage studies and dosimetry development programs. The ^{60}Co irradiation pool is 2 m in diameter and 6 m deep. The intense source that lies at the bottom of the pool consists of 72 pencil-shaped, encapsulated ^{60}Co rods (20,000 Ci) arranged vertically in a wire-mesh basket so that they form a circle 25 cm in diameter.

The Waste Package Project has been studying the effects of radiation on corrosion and leaching of materials at the Tuft Repository in Nevada. To support this study, we have characterized the radiation field from these ^{60}Co rods using the radiation transport code, MORSE76L. Gamma-fluence

spectra and dose rates were calculated at various positions in the pool.

Results

We calculated the spectra and dose rates under two sets of conditions. One, the source holder and geometry (Fig. 1) shows the source holder or "basket" sitting on a stainless-steel plate 1.905 cm thick (3/4 inch). The top of this plate is 16.510 cm (6-1/2 inches) off the pool bottom. The plate diameter is 1.54 m. Location A is 12.159 cm above the top of this plate and on the axis of the holder. Location B, also on the axis, is 21.159 cm above the plate. Locations C and D are at the same height as A, but off-axis 15.2 and 47 cm, respectively.

For the second case, the samples to be irradiated were placed in an assembly depicted in Fig. 2 (also shown in Fig. 2 are the locations of interest). The composition of the sample is given in Table 1. Calculations of spectra and dose rates were made at locations, A, B, C, D, E, F, G, J, and K. The dose rates for all nine positions are given in Table 2. Measurements of the dose rates have not been completed; however, a preliminary measurement at position A was within 5% of the calculated value. The spectra are given in Tables 3 through 11 and are shown in Figs. 3 through 11.

Figure 1. Locations of positions A, B, C, and D relative to the source holder.

Table 1. Isotopic composition of the irradiated sample.

Element	Isotopic composition (atoms/cm ² -barn)
H	0.0155
O	0.0401
Al	0.0029
Si	0.0128
Fe	0.0084

Figure 2. Sketch showing locations of positions E, F, G, J, and K.

Table 2. Dose rates for various positions in C Cell.

Position	D (rem/sec)
A	1150
B	642
C	150
D	38
E	20.6
F	15.8
G	8.74
J	0.239
K	0.198

Table 3. Energy-dependent fluence at position A in C Cell.

Lower-energy bound (MeV) ^a	$\gamma/\text{cm}^2\text{-MeV}$	Fractional standard deviation ^b	γ/cm^2
0.1250	4.426(-3)	0.045	7.391(-5)
0.1417	4.785(-3)	0.139	9.044(-5)
0.1606	4.324(-3)	0.108	9.253(-5)
0.1820	3.734(-3)	0.097	9.074(-5)
0.2063	3.537(-3)	0.030	9.727(-5)
0.2338	3.002(-3)	0.061	9.336(-5)
0.2649	2.532(-3)	0.071	8.963(-5)
0.3003	1.860(-3)	0.050	7.440(-5)
0.3403	1.416(-3)	0.065	6.429(-5)
0.3857	1.007(-3)	0.053	5.186(-5)
0.4372	8.533(-4)	0.074	4.975(-5)
0.4955	9.661(-4)	0.113	6.386(-5)
0.5616	6.225(-4)	0.080	4.663(-5)
0.6365	5.506(-4)	0.049	4.669(-5)
0.7213	4.939(-4)	0.047	4.756(-5)
0.8176	6.124(-4)	0.209	6.675(-5)
0.9266	4.525(-4)	0.043	5.584(-5)
1.050	3.406(-3)	0.022	4.768(-4)
1.190	2.896(-3)	0.009	4.584(-4)
1.349			

^a Henceforth abbreviated LEB.

^b Henceforth abbreviated fsd.

Figure 3. Spectra calculation for position A (C Cell), energy-dependent fluence for detector 1.

Table 4. Energy-dependent fluence at position B in C Cell.

LEB (MeV)	$\gamma/\text{cm}^2\cdot\text{MeV}$	t_{ad}	γ/cm^2
0.1250	3.397(-3)	0.192	5.673(-5)
0.1417	3.328(-3)	0.054	4.400(-5)
0.1606	2.599(-3)	0.243	5.562(-5)
0.1820	1.956(-3)	0.054	4.753(-5)
0.2063	2.028(-3)	0.038	5.577(-5)
0.2339	1.673(-3)	0.051	5.203(-5)
0.2649	1.185(-3)	0.031	4.195(-5)
0.3003	1.095(-3)	0.126	4.380(-5)
0.3403	7.598(-4)	0.044	3.449(-5)
0.3857	5.839(-4)	0.056	3.007(-5)
0.4372	5.365(-4)	0.088	3.128(-5)
0.4955	4.413(-4)	0.039	2.917(-5)
0.5616	4.101(-4)	0.072	3.072(-5)
0.6365	2.951(-4)	0.048	2.502(-5)
0.7213	2.871(-4)	0.065	2.765(-5)
0.8176	3.427(-4)	0.049	3.735(-5)
0.9266	2.727(-4)	0.068	3.365(-5)
1.050	1.830(-3)	0.007	2.562(-4)
1.190	1.648(-3)	0.015	2.620(-4)
1.349

Figure 4. Spectra calculation for position B (C Cell), energy-dependent fluence for detector 1.

Table 5. Energy-dependent fluence at position C in C Cell.

LEB (MeV)	$\gamma/\text{cm}^2\cdot\text{MeV}$	fsd	γ/cm^2
0.1250	1.228(-3)	0.115	2.051(-5)
0.1417	9.202(-4)	0.083	1.739(-5)
0.1606	7.001(-4)	0.055	1.498(-5)
0.1820	6.675(-4)	0.061	1.510(-5)
0.2053	6.213(-4)	0.073	1.709(-5)
0.2338	7.415(-4)	0.283	2.306(-5)
0.2649	5.335(-4)	0.163	1.889(-5)
0.3003	3.068(-4)	0.061	1.050(-5)
0.3403	2.646(-4)	0.121	1.291(-5)
0.3857	1.816(-4)	0.065	9.352(-6)
0.4372	1.589(-4)	0.078	9.264(-6)
0.4955	1.290(-4)	0.032	8.527(-6)
0.5616	1.209(-4)	0.076	9.055(-6)
0.6365	1.079(-4)	0.065	9.150(-6)
0.7213	1.126(-4)	0.086	1.084(-5)
0.8176	1.074(-4)	0.144	1.171(-5)
0.9266	1.108(-4)	0.180	1.367(-5)
1.050	3.329(-4)	0.014	4.661(-5)
1.190	2.813(-4)	0.018	4.473(-5)
1.349

Figure 5. Spectra calculation for position C (C Cell), energy-dependent fluence for detector 1.

Table 6. Energy-dependent fluence at position D in C Cell.

LEB (MeV)	$\gamma/\text{cm}^2\cdot\text{MeV}$	fad	γ/cm^2
0.1250	4.795(-5)	0.223	8.008(-7)
0.1417	2.424(-5)	0.141	4.581(-7)
0.1606	2.414(-5)	0.156	5.166(-7)
0.1820	1.620(-5)	0.266	3.937(-7)
0.2063	2.273(-5)	0.144	6.251(-7)
0.2338	1.965(-5)	0.318	6.111(-7)
0.2649	1.509(-5)	0.207	5.342(-7)
0.3003	1.206(-5)	0.374	4.824(-7)
0.3403	1.347(-5)	0.361	6.115(-7)
0.3857	8.118(-6)	0.134	4.181(-7)
0.4372	7.616(-6)	0.135	4.440(-7)
0.4955	6.989(-6)	0.447	4.620(-7)
0.5616	4.076(-6)	0.087	3.053(-7)
0.6365	4.109(-6)	0.082	3.484(-7)
0.7213	3.556(-6)	0.144	3.424(-7)
0.8176	2.965(-6)	0.103	3.232(-7)
0.9266	3.348(-6)	0.151	4.131(-7)
1.050	5.544(-6)	0.024	7.762(-7)
1.190	4.240(-6)	0.023	6.742(-7)
1.349

Figure 6. Spectra calculation for position D (C Cell), energy-dependent fluence for detector 1.

Table 7. Energy-dependent fluence at position E in C Cell.

LEB (MeV)	$\gamma/\text{cm}^2\text{-MeV}$	fsd	γ/cm^2
0.1250	1.458(-4)	0.066	2.43(-6)
0.1417	2.755(-4)	0.531	5.21(-6)
0.1606	9.850(-5)	0.133	2.11(-6)
0.1820	1.068(-4)	0.136	2.60(-6)
0.2063	1.184(-4)	0.270	3.26(-6)
0.2338	7.072(-5)	9.080	2.20(-6)
0.2649	5.780(-5)	0.150	2.05(-6)
0.3003	4.344(-5)	0.072	1.74(-6)
0.3403	6.094(-5)	0.198	2.77(-6)
0.3857	3.380(-5)	0.111	1.74(-6)
0.4372	4.427(-5)	0.258	2.58(-6)
0.4955	2.919(-5)	0.090	1.93(-6)
0.5616	2.106(-5)	0.069	1.58(-6)
0.6365	2.277(-5)	0.136	1.93(-6)
0.7213	2.497(-5)	0.193	2.40(-6)
0.8176	1.829(-5)	0.142	1.99(-6)
0.9266	1.765(-5)	0.159	2.18(-6)
1.050	2.943(-5)	0.030	4.12(-6)
1.190	2.851(-5)	0.105	4.53(-6)
1.349

Figure 7. Spectra calculation for position E (C Cell), energy-dependent fluence for detector 1.

Table 8. Energy-dependent fluence at position F in C Cell.

LEB (MeV)	$\gamma/\text{cm}^2\text{-MeV}$	fsd	γ/cm^2
0.1250	1.242(-4)	0.270	2.07(-6)
0.1417	7.701(-5)	0.189	1.46(-6)
0.1606	9.894(-5)	0.185	2.12(-6)
0.1820	8.520(-5)	0.225	2.07(-6)
0.2063	5.834(-5)	0.144	1.60(-6)
0.2338	5.114(-5)	0.274	1.59(-6)
0.2649	5.755(-5)	0.289	2.04(-6)
0.3003	3.767(-5)	0.187	1.51(-6)
0.3403	8.430(-5)	0.655	3.83(-6)
0.3857	3.177(-5)	0.160	1.64(-6)
0.4372	4.234(-5)	0.328	2.47(-6)
0.4955	2.094(-5)	0.096	1.38(-6)
0.5616	1.277(-5)	0.103	9.56(-7)
0.6365	1.423(-5)	0.149	1.21(-6)
0.7213	1.058(-5)	0.108	1.02(-6)
0.8176	1.313(-5)	0.083	1.43(-6)
0.9266	1.688(-5)	0.181	2.08(-6)
1.050	2.340(-5)	0.067	3.28(-6)
1.190	2.091(-5)	0.116	3.32(-6)
1.365

Figure 8. Spectra calculation for position F (C Cell), energy-dependent fluence for detector 1.

Table 9. Energy-dependent fluence at position G in C Cell.

LEB (MeV)	$\gamma/\text{cm}^2\text{-MeV}$	fsd	γ/cm^2
0.1250	5.959(-5)	0.138	9.95(-7)
0.1417	1.089(-4)	0.578	2.06(-6)
0.1606	5.213(-5)	0.168	1.12(-6)
0.1820	1.088(-4)	0.498	2.64(-6)
0.2063	3.322(-5)	0.148	9.14(-7)
0.2338	3.779(-5)	0.185	1.18(-6)
0.2649	3.276(-5)	0.210	1.16(-6)
0.3003	2.336(-5)	0.226	9.30(-7)
0.3403	1.942(-5)	0.113	8.82(-7)
0.3857	2.158(-5)	0.215	1.11(-6)
0.4372	2.329(-5)	0.388	1.36(-6)
0.4955	1.121(-5)	0.148	7.41(-7)
0.5616	8.191(-6)	0.123	6.14(-7)
0.6365	9.035(-6)	0.130	7.66(-7)
0.7213	9.020(-6)	0.169	8.69(-7)
0.8176	8.470(-6)	0.316	9.23(-7)
0.9266	6.947(-6)	0.150	8.57(-7)
1.050	1.203(-5)	0.038	1.68(-6)
1.190	1.030(-5)	0.044	1.64(-6)
1.349

Figure 9. Spectra calculation for position G (C Cell), energy-dependent fluence for detector 1.

Table 13. Energy-dependent fluence at position J in C Cell.

LEB (MeV)	γ/cm^2-MeV	fad	γ/cm^2
0.1250	2.574(-6)	0.558	4.30(-8)
0.1417	2.044(-6)	0.343	3.87(-8)
0.1606	1.534(-6)	0.259	3.28(-8)
0.1820	1.674(-6)	0.329	4.08(-8)
0.2063	1.584(-6)	0.268	4.37(-8)
0.2338	8.767(-7)	0.279	2.73(-8)
0.2649	7.504(-7)	0.213	2.66(-8)
0.3003	7.700(-7)	0.147	3.08(-8)
0.3403	1.643(-6)	0.547	7.46(-8)
0.3857	5.937(-7)	0.192	3.06(-8)
0.4372	5.990(-7)	0.256	3.48(-8)
0.4955	2.991(-7)	0.128	1.98(-8)
0.5516	7.110(-7)	0.246	5.40(-8)
0.6365	2.469(-7)	0.061	2.09(-8)
0.7213	2.446(-7)	0.096	2.36(-8)
0.8176	2.565(-7)	0.231	2.80(-8)
0.9266	2.337(-7)	0.276	2.88(-8)
1.050	1.846(-7)	0.092	2.58(-8)
1.190	1.321(-7)	0.033	2.10(-8)
1.349

Figure 10. Spectra calculation for position J (C Cell), energy-dependent fluence for detector 1.

Table 11. Energy-dependent fluence at position K in C Cell.

LEB (MeV)	$\gamma/\text{cm}^2\text{-MeV}$	fsd	γ/cm^2
0.1250	2.072(-6)	0.289	3.35(-8)
0.1417	2.277(-6)	0.414	4.20(-8)
0.1606	9.782(-7)	0.331	2.09(-8)
0.1820	1.386(-6)	0.258	3.37(-8)
0.2063	7.345(-7)	0.291	2.01(-8)
0.2338	1.052(-6)	0.369	3.27(-8)
0.2649	1.274(-6)	0.332	4.51(-8)
0.3003	1.914(-6)	0.707	7.66(-8)
0.3403	8.575(-7)	0.427	3.89(-8)
0.3857	3.891(-7)	0.134	2.00(-8)
0.4372	5.876(-7)	0.341	3.43(-8)
0.4955	2.822(-7)	0.113	1.87(-8)
0.5616	2.954(-7)	0.112	2.21(-8)
0.6365	2.646(-7)	0.183	2.24(-8)
0.7213	1.545(-7)	0.076	1.49(-8)
0.8176	2.493(-7)	0.326	2.72(-8)
0.9266	1.299(-7)	0.155	1.60(-8)
1.050	1.352(-7)	0.092	1.89(-8)
1.190	1.267(-7)	0.164	2.01(-8)
1.349

Figure 11. Spectra calculation for position K (C Cell), energy-dependent fluence for detector 1.

Measuring Pu in a Glove Box Using Portable NaI and Germanium Detectors

Dale E. Hankins

A NaI crystal or germanium detector inside a portable lead shield can determine the amount of plutonium in a glove box. We define the number of counts required and the locations outside the box where the detector needs to be positioned. The calculated accuracy for measuring the Pu when our locations are used is within $\pm 30\%$ for most glove boxes. We also discuss other factors that may affect this accuracy, such as gamma-ray absorption by glove-box materials, self-absorption by Pu, absorption by equipment in the glove box, and the limits of the counting equipment.

Introduction

Measuring the Pu present in a glove box is required for inventory and process control, criticality safety, and before removal of a glove box for disposal. In the past, we used a 2×2 NaI crystal with a portable multichannel analyzer. These measurements had several errors: our goal was eliminating or evaluating these errors. The inverse square relationship and absorption of gamma rays make an absolute evaluation of residual Pu in a glove box impossible using a NaI crystal for counting the 380 keV photon complex from Pu. However, strict accuracy is not required for most purposes; errors of $\pm 50\%$ to 100% are often considered adequate. In this study, we modified the lead shield used with the NaI crystal. We then determined the counting positions around glove boxes of various sizes that would give the best estimate of the Pu remaining in the glove box. We also evaluated the problem of gamma-ray absorption by glove-box materials, self-absorption by Pu, absorption by equipment in the glove box, and the limits of equipment sensitivity.

We developed a procedure for measuring Pu in glove boxes up to $4 \times 4 \times 8$ ft. This procedure evaluated the amounts of Pu within an error calculated to be $< \pm 30\%$. Gamma-ray absorption by the glove-box materials was measured and used to estimate the averaged absorption.

Limited studies with the germanium detector indicated that it was superior to the NaI detector in discriminating between other isotopes that may be present in a glove box, suggesting that we should replace our current setup with a germanium detector.

Lead Shield for the NaI Crystal

We had placed the NaI crystal inside a 1-in.-thick lead shield because it could be transported easily and positioned conveniently near a glove box. The lead shield was used to (1) decrease the detector background and the associated detection limit for Pu in a glove box, (2) shield the crystal from Pu located elsewhere in the room, and (3) act as a collimator to locate the Pu, or other isotopes, within a glove box.

We first determined the directional response of the shielded NaI crystal to Pu gamma rays around 380 keV. We were surprised to find that the detected area was much smaller than we had believed, and that only a small, well-collimated area was being detected. This was caused, in part, by the crystal face being recessed 3.25 cm (1-1/4 in.) inside the crystal mount. We had assumed the crystal face was very near the front face of the mount, and we usually recessed the crystal face an inch or two inside the lead shield. This resulted in a very well-collimated beam which missed measuring a large part of the Pu in the glove box.

The lead shield is made of several rings that make it easier to move. One of the end lead rings was modified by cutting a 45° bevel on the inside of the ring to increase and define the angle that gamma rays could reach the crystal. When the NaI crystal is inserted backwards in the shield, it still provides an excellent collimator for locating sources inside a box, especially if the crystal is recessed two or more inches in the shield.

The 60-keV gamma ray from the ever-present ^{241}Am can be a problem. If it is too abundant, it

causes excessive dead time and peak energy shift in the analyzer. We investigated the use of a copper or cadmium filter over the end of the lead shield to reduce the effect of this gamma ray. Both copper and cadmium have large absorption cross-sections at 60 keV and small cross-sections at 280 keV. We found that 32-mil-thick cadmium was much more effective than 42-mil-thick copper in reducing the 60-keV gamma rays, while both materials reduced the count rate at 380 keV by the same amount. We installed the 32-mil-thick cadmium over the end of the lead shield.

A large and well-defined detection angle for the crystal and shield combination is important for measurements. Therefore, we moved the crystal forward in the lead shield until the front of the crystal mount touched the cadmium filter. This provided accurate reproduction of the measurement geometry. The directional response of this configuration was determined using a Pu source

(Fig. 1). Although the resolution is not sharp, the detection angle is approximately 90° (45° to either side of center). This modification of the lead shield increased the crystal background which increased the minimum detectable mass of Pu. The increased angle of detection also allowed more of the Pu from other glove boxes in the room to be detected. These adverse effects must be accepted, however, since the original shield-detector configuration was so narrowly collimated that the whole glove box could not be viewed.

Initial Field Evaluation

Determining the amount of Pu at any location in a glove box to within $\pm 30\%$ was our objective. We began by measuring a typical glove box (Fig. 2). Important features of the box are its sloping sides and the varying absorption of the

Figure 1. Directional response of NaI crystal to the gamma rays from Pu in the 380 keV complex. The detector efficiency is given as a function of angle.

Figure 2. Schematic of a typical glove box.

380-keV x rays by the glove-box materials (Lucite, stainless steel, aluminum, gloves, glove port covers). The sloping sides cause wall contamination at varying distances from the detector location, depending on whether the contamination is near the bottom or top of the glove box.

We measured Pu at eight locations in a glove box similar to the one illustrated in Fig. 2: three along each side, and one at each end. The detector

was one meter from the center of the glove box. Pu metal in a small paint can was placed at selected, well-defined positions inside the glove box.

We did not find any combination of measurements that could determine the source quantity to within $\pm 30\%$ when the Pu was located in the corners of the glove box (low readings), or at the center or ends of the glove box (high readings). It

appeared that the problem of low responses in the corner could be solved if the detector were positioned at the corners of the glove box.

Response Calculations

Our HP-85 computer program calculated the effects of geometry and directional response of the detector for a geometry similar in size and shape to the glove box used experimentally. These calculations were intended to guide the optimum selection of detector positions. The separation between detector and glove box is an important parameter in these calculations. If the separation is too small, the inverse-square relationship causes large variations in detector response for sources located at different positions in the box. If the separation is too large, inverse-square errors become less severe, but the detector count rate is significantly reduced. This, in turn, increases the minimum detectable level of Pu accordingly. Large separations also increase the likelihood that Pu in other glove boxes will be detected.

We calculated the Pu with the detector in six different positions (each of four corners and each of the two sides). The detector-glove box separation was varied until the sum of responses for the

six measurement points was as independent as possible from the position of the source in the glove box. We found that the corners, the center of each side, and the middle of the glove box were the most difficult source positions to evaluate accurately.

Results

Calculations using the $3 \times 3 \times 6$ ft glove box showed that we could obtain an acceptable evaluation if the detector-to-glove box distances were 2.5 ft from the glove box side and 2.0 ft from the glove box corner. When the six counts (2 from the side and 4 from the corners) using a single point source were averaged and compared to the average for 33 sources located throughout the box, the single source count rate was within $\pm 30\%$, independent of source location. If each of the measurement distances was 2.0 ft, the errors ranged from $+45\%$ (which is unacceptable) to -28% .

We repeated these calculations for a number of typical glove-box sizes. In Table 1, the results of these calculations are given for the geometries that meet the error criterion $\pm 30\%$. The exception is a $4 \times 4 \times 4$ ft box, where only four counts

Table 1. Measurement error and counting efficiency obtained for various sizes of glove boxes.

Size of Box (width-height-length)	Number of measurements			Measurement distance			% Relative counting efficiency	Measurement error and Pu location in box	
	side	corner	end	side	corner	end		% high reading	% low reading
$3 \times 3 \times 3^a$	4			2			0.84	22 side, midplane	22 corner, bottom
$3 \times 3 \times 3$	4			2.5			0.71	15 side, midplane	16 center, top or bottom
$3 \times 3 \times 6^a$	2	4		2.5	2		0.50	27 side, midplane	25 end, bottom
$3 \times 3 \times 6$	2	4		2.5	2		0.51	24 side, midplane	27 end, bottom
$3 \times 3 \times 9$	4	4		2.5	2.5		0.38	25 side, midplane	23 end, top or bottom
$3 \times 3 \times 12$	6	4		2	2		0.37	28 side, midplane	27 end, top or bottom
$4 \times 4 \times 4$	4			2.5			0.54	34 side, midplane	30 corner, top or bottom
$4 \times 4 \times 4$	4	4		2.5	2.5		0.47	28 corner, midplane	18 center, top or bottom
$4 \times 4 \times 6$	2	4		2.5	2		0.44	29 side, midplane	23 end, top or bottom
$4 \times 4 \times 8$		2	3	3		3	0.33	24 side, in front of detector, midplane	21 corner, top or bottom
$4 \times 4 \times 7$	4		2	3		3	0.34	30 side in front of detector, midplane	20 corner, top or bottom

^a These boxes had sloped sides. All others were straight.

were used and the errors range from +34% to -30%. The error range could be reduced to meet our criterion only if 8 counts were made (+28% to -18%). The improved accuracy does not justify doubling the counting effort.

We show schematically in Fig. 3 acceptable counting locations and distances. To avoid cluttering the figure, we have shown simply the distance and direction from the glove box for only one of each symmetric location.

Also given in Table 1 are the relative counting efficiencies. This is the average counting efficiency for one gram of Pu placed uniformly throughout the glove box. We approximated this distribution by calculating the efficiency from sources placed on a one-foot matrix within each of the glove boxes. The calculated counting efficiency is relative to that obtained from a one-gram Pu source at one meter from the face of the detector shield. The counting efficiency decreases as the glove box size increases, which is the result expected from inverse-square considerations. The sensitivity of this counting procedure is considerably less for the larger glove boxes, and, consequently, more Pu goes undetected in the larger glove boxes.

As an aside, a glove box that is smaller than the ones shown in Fig. 2 can be counted by assuming it has the dimensions of one of the sizes shown in Fig. 2. The detectors could be positioned at the locations shown. The smaller glove box could be placed in the center of this area, and a series of counts could be obtained and evaluated as if it were the larger glove box.

Accuracy of Measurements

The measurement error in percent is the largest error that we obtained (Table 1). This required that all the Pu in the glove box was located in the worst possible location. In practice, this would never occur, and most measurements would have less error, probably within $\sim \pm 10\%$ (without glove-box attenuation and self-absorption).

Absorption by Glove-Box Materials

The absorption of the 380-keV complex gamma rays by the materials used in glove box is significant, and a correction for absorption must be made. We measured the decreased response caused by these materials using the 2×2 NaI crystal and our one-gram Pu calibration source

(Table 2). Fortunately, the differences in the response caused by absorption of the glove-box materials are not large. The greatest error would come from gamma rays exiting through the glove ports where the 15-mil glove absorption is negligible but the glove port cover absorbs 21% of the gamma rays. When assaying a glove box, the glove ports should all be the same, either all open or covered. An average correction for glove-box absorption can be made based on the materials used in the glove box and the coverings over the glove ports. The use of an average absorption will introduce an error but its magnitude is small.

Absorption by Plutonium

We had used a 27.2-gram piece of Pu metal as a source. We selected this large piece to provide a high count rate, and thereby reduce the count times required to attain reasonable counting statistics. The Pu was scrap material and it was not symmetric. It was slightly elongated, and when rotated, we observed a variation in the counting rate of 20% caused by self-absorption of the 380-keV complex gamma rays in the Pu. The averaged count from this source was only 29% of the expected count rate based on the count rate from our one-gram Pu calibration source. (The calibration source is a disk oriented with the flat side facing the detector.)

Most surveys of glove boxes being sent for salvage would not involve a large mass of Pu metal. Self-absorption in these boxes should be small and can be ignored. For operational glove boxes, this may not be true, and the glove-box contents should be inspected for large pieces of

Table 2. Decrease in detector count rate caused by absorption of 380-keV complex gamma rays via glove-box construction materials.

Material	Decreased count rate (%)
3/8 in. thick Lucite	9
1/16 in. stainless steel	14
1/4 in. Al end-port plate	12
Glove port cover	21
Steel shipping glove box	16
Plywood (3/4 in.) shipping glove box	6
15-mil glove	0

Figure 3. Detector distances from several sizes of glove boxes.

Pu before an estimate is made of the glove-box contents based on count rate.

Absorption by Materials in the Glove Box

By far, the largest error expected is caused by absorption of the gamma rays by other items in the glove box. Equipment commonly present in glove boxes includes drill presses, lathes, planers, bandsaws, and other large steel equipment. Any plutonium located behind one of these pieces of equipment will not be detected at a single detector location. Our detector positions allowed the detection of Pu behind such items. In some cases, the equipment has holes, crevices, or other recesses that can hide Pu. Occasionally, we have measured above or below the glove box to ensure this did not occur.

When the glove box contains materials that absorb the 380-keV complex gamma rays, the experimenter should estimate the extent of this absorption. This estimate will normally be the largest error. Little guidance can be given for these situations since each is unique.

The Germanium Detector and Its Advantages

Following the experimental procedure we have discussed so far will provide accurate counts. However, placing a cadmium shield over the face of the detector reduces the intensity of the 60-keV gamma rays from ^{241}Am , but does not reduce its higher energy gamma rays. When large amounts of ^{241}Am or other isotopes are present in a glove box, it becomes impossible to evaluate the Pu with the NaI detector because it cannot distinguish between photons due to Pu and those due to other isotopes, and thus, the amount of Pu will be overestimated. The spectrum viewed on the multichannel analyzer display will be distorted, usually at the low energy end of the channels being summed.

We recently measured boxes that contained ^{239}Pu , ^{241}Am , ^{238}Np , and other heavy elements. We used the NaI crystal discussed previously and an Ortec GMX series, Gamma-X, HPGe coaxial germanium detector (45.4 mm diam by 36.5 mm length). We could, in all cases, determine the presence of Pu using the germanium detector, but we could not evaluate the Pu with the NaI crystal. The germanium-detector results for one of the boxes that contained considerable quantities of the other isotopes had ^{239}Pu peaks at 375 and 414 keV located on top of a significant Compton continuum. Corrections for the added counts in

the peaks were made using the continuum on either side of the peak. Many of the new analyzers have features that will perform this subtraction.

The detection efficiency of the germanium detector gave us a count rate of 0.37 cts/sec and 0.21 cts/sec for the 375 and 415 keV peaks, respectively, from our one-gram calibration source at a source-to-detector-face distance of 1 meter. The sensitivity limit for Pu in a glove box would be between 0.5 and 1.0 g for count times of ~5 minutes at each counting location. This sensitivity is similar to that obtained previously with the NaI crystal. This limit for the germanium detector would increase for boxes containing other isotopes in significant quantities, but it would be superior to the NaI crystal which could not be used to evaluate the Pu.

Our limited comparison study with the germanium and NaI crystals indicates that the germanium should be considered for future use. Its high resolution gives it the advantage of being able to discriminate other isotopes from Pu and has essentially the same sensitivity as the 2×2 in. NaI crystal. A lead shield would have to be made, the directional dependence measured, and the detector sensitivity calculated for sources at various locations in different size boxes similar to those described previously.

Limit of Sensitivity

For measurements made under various field conditions, the limit of sensitivity for small quantities of Pu in a glove box is difficult to establish. The background count in a room containing little Pu is about 160 cpm with our counting equipment and an analyzer window set to detect gamma energies between 330 and 430 keV. If the count is made in a room which has other glove boxes containing Pu, the background will be higher and variable throughout the room. At any given location, the background will be dependent on the orientation of the lead shield. In the past, we have pointed the lead shield toward a wall to obtain a background count.

The count rate of the NaI detector from our one-gram Pu source at one meter from the source is ~730 cpm. If one assumes that a counting rate of twice background is valid, the smallest quantity of Pu that can be detected is about 0.2 gram. This assumes ideal counting conditions. In most field applications, it would be difficult to detect 0.2 gram with any degree of confidence. Based on our past experiences, values of 1.0 gram are probably more realistic.

FIRE SAFETY

Evaluation of Personal Alarm Devices for Firefighters

John Sharry and Robert A. da Roza

Although three of the models of the personal alarm devices (PAD) tested had received letters of acceptability and compliance from the State of California/Occupational Safety and Health Administration (Cal/OSHA), we found that none of the models met *all* of the Cal/OSHA specifications. Additional tests showed other deficiencies in the PADs' design. This points out the need for the purchaser or user of such devices to specify acceptance criteria and perform his own tests.

Introduction

The Standards Board of the State of California/Occupational Safety and Health Administration (Cal/OSHA) recently developed and passed a standard that requires firefighters engaged in interior-structure fires use a personal alarm device, or PAD, with a self-contained breathing apparatus (SCBA). The PADs will summon aid in the event of an emergency involving the firefighter so equipped. The specifications for the PADs are given in the General Industrial Safety Orders from Cal/OSHA (Title 8, General Industry Safety Orders, Article 10.1). Implementation of these orders was originally scheduled for March 31, 1983, but this was extended to September 30, 1983.

The LLNL Fire Department and Hazards Control's Safety Science Group conducted tests of the four available devices to determine the best device to purchase. The tests determined if the devices complied with the specifications given by Cal/OSHA and also if such a device were useful, i.e., that it accomplish its purpose of aiding rescuer firefighters to find another firefighter who is immobilized (Table 1).

Although three of the models tested had received letters of acceptability and compliance from Cal/OSHA, our tests showed that none met all of the Cal/OSHA specifications. Also, we revealed other deficiencies in the PADs by some additional tests to which we subjected the units. Our "water-on-the-speaker" test showed that water

collected on the diaphragm speakers prevents sound transmission. The "cold-salt-water" test shows how severely some of the units leaked. The "interfering-sounds" test only scratched the surface of this large problem and points out that sound frequency, pulsation rates, and tone changes must be considered as part of a PAD specification. Information gained from a signal-attenuation experiment and a field trial show the need for a louder alarm: the 95 dBA alarm was clearly the more desirable alarm.

Results

At first, we tested four units of each manufacturer's model (Table 2) following the test parameters specified in Table 1. Due to the importance of the water intrusion and 80°C tests, a second group of units was purchased and tested; two units were tested in a special oven and all of them were subjected to sea water.

Table 3 summarizes our results. In addition to a pass/fail result, a notation is included to indicate performance. Weak performance means that the unit was emitting an audible sound, but it was below the specified 85 dBA. A fail notation without indication of weak performance means that the unit did not emit any sound. We describe specific performance results as against the Cal/OSHA specifications in the following section.

Table 1. Specifications required by the Cal/OSHA standard and the tests performed to verify PADs.

Specification (2)(A):

Controls shall be incorporated in alarm devices for manual activation and reset, and shall be protected against accidental deactivation. Such controls shall be designed to be operated by a gloved hand.

Specification (2)(B):

Alarm devices shall contain a motion detector which will activate the alarm if the firefighter is motionless for not less than twenty (20) seconds nor more than forty (40) seconds. The alarm shall also include a pre-warning device to signal the firefighter that the alarm is approaching the point of activation.

Specification (3)(A):

Alarm devices shall emit a signal with a sound pressure level of not less than 85 dba measured at a distance of three (3) meters for not less than one (1) hour using an eighty percent (80%) charged battery. Signal frequency used shall not be less than 2000 Hz nor more than 4000 Hz.

Specification (3)(B):

The alarm shall operate in a temperature range of -10° to 80°C and for a period of two minutes at 140°C .

Specification (3)(C):

Alarm devices shall be designed to withstand damage created by deterioration of the type of battery recommended by the manufacturer for use in such devices.

Specification (3)(D):

Alarm devices shall remain operable after being submerged in sea water for at least one hour at a depth of two meters. Upon examination, the interior shell shall show no signs of water intrusion or corrosion. Effective May 12, 1983, this regulation was amended to remove the second sentence.

Specification (3)(E):

Alarm devices shall be impact and shock resistant, and shall be designed to remain operable after being dropped six (6) successive times from random positions onto a concrete floor from a height of not less than two meters.

Specification (3)(F):

Alarm devices shall not weigh more than 350 grams, including batteries.

Specification (4)(A):

Alarm devices shall be equipped with a visual or audible device to indicate when the battery has been discharged to not less than 80 percent of its rated capacity.

Discussion

Spec. (2)(A) Manual Activation

The switch on the Life Gard Model R-100A, hereafter called Life Gard I, did not always function properly when moved gently to the ON position, but it did when snapped over hard. Manually activating the Securus S-O-S switch in either the ON or OFF position is difficult, especially with a gloved hand. It must be pressed very hard and held until the alarm starts. The PAL switch was so tricky and difficult to use that the firefighters using the PAL asked to have it removed from the tests.

Spec. (2)(B) Motionless Activation

All devices signaled correct warnings after the proper period of stillness by the firefighter. However, a common complaint was that the de-

Table 2. Manufacturer's models tested according to Cal/OSHA specifications.

1. Life Gard Personal Distress Device	Model R-100A
2. Life Gard II Personal Distress Device	Model R-200
3. Securus S-O-S Personal Distress Locator	Model PDL-3
4. PAL	

vice may sound off while the firefighter was moving. After the first warning sound, a sharp rap is needed to keep it from sending the actual alarm. In the lab, the devices were swung on a pendulum with a two-second period. All devices activated themselves while moving thusly. It would be useful to have an engineering standard for defining motionlessness as applied to PADs.

Table 3. Pass/Fail summary results for the four PADs tested.

Cal/OSHA Specification	Life Gard I	Life Gard II	Securus S-O-S	PAL
2(A) Manual activation	switch failed	OK	Hard to use reliably	could not tell position
2(B) Motionless activation	OK	OK	OK	OK
3(A) Sound level @ 22°C	2P ^a	3P	4P, 1F ^b	2P, 1F
Sound frequency	2P	2P	4P	3P
Battery life	Pass	Pass	Pass	Pass
3(B) Temperature -10°C	1F(W) ^c	3F(W)	1F(W), 3F	3F(W)
80°C	2F(W)	2P, 3F(W)	3F(W), 2F	4F(W)
140°C	1P	1P	1P	1P
3(C) Damage by battery leakage	Fail	Pass	Fail	Pass
3(D) Water intrusion deionized water	2F	2P, 2F	2P, 2F	4F
sea water		10P, 5F	6P, 2F	2P, 4F
3(E) Impact resistance		1P, 2F	2P, 1F	3P
3(F) Weight	Pass	Pass	Pass	Pass
4(A) 90% Battery capacity indicator	No	Yes	No	No

^aP = passed specification.

^bF = failed specification.

^cW = weaker than specification.

Spec. (3)(A) and (B) Sound Level and Frequency at Temperature of Use

All measurements were made at three meters. Each device was tested for the performance described in (3)(A) at the three extreme temperatures given in (3)(B) plus room temperature (22°C).

We assumed that the -10°C temperature simulated the cold soaking of a PAD on the outside of a fire truck in cold weather and its subsequent use (automatic mode for the PAD). Therefore, after we checked the PADs' operation, we placed several in a freezer at -10°C for one hour to chill them. Upon removal from the freezer, we checked the manual mode (where the firefighter can signal an alarm on his own) and listened for the sound.

The tests at 22°C were run for over one hour and then the current drain was measured to estimate the remaining lifetime of an 80%-charged battery. The minimum voltage required to obtain an audible signal was also measured.

The upper end of the temperature range over which a PAD might be used is given as 80°C. The PAD should produce the signal given in (3)(A) for one hour at 80°C. For the test, we turned the switch to its automatic position while at room

temperature then set it in an oven preheated to 80°C. The sound level was checked immediately and every 15 minutes by opening the oven door. The decrease in sound-pressure level relative to the starting measurement is noted in Table 4.

The U.S. Testing Company, an independent testing agency, had expressed concern that our sound-level measurements with the PADs in an oven might be inaccurate due to reflections from the oven surfaces. We, therefore, designed and built a special oven that could be quickly removed from the PAD whenever a sound measurement was made (Fig. 1). The results from this new test oven agree well with previous results from the old test oven. The two tests run with the new oven are the last entries shown for Life Gard II and Securus SOS at 80°C in Table 4.

The test at 140°C simulated a short period of high temperature to assess possible damage. We placed a room-temperature PAD in an oven preheated to 140°C for two minutes. After removing the PAD from the oven, we checked its manual mode of operation.

Table 4 also shows the sound-pressure level at 22°C for several units of each make of PAD. A range is given for each unit because the loudness

Figure 1. Test oven (a) closed and (b) open, showing PAD.

Table 4. Sound-pressure level and frequency response of the PADs tested.

PAD	Signal frequency db @ kHz	Sound level at 3 m, dBA slow response				Pulse rate (pulses/s)
		-10°C	22°C	80°C	140°C	
Life Gard I		1P(W)		2F	1P	2.4
	76 @ 2		84-85	-37.5		
	84 @ 4		85-86	-11		
	76 @ 8					
Life Gard II		3P(W)		2F, 3F	1P	2.0
	95 @ 2		94-96	-11.5		
	87 @ 4		94-95	-12		
				-4		
				-19		
			94-95	-10		
Securus S-O-S		3F		5F	1P	1.8
	81 @ 2	1P(W)	84-90	fail, 25 min		
	90 @ 4		80-84	-27		
			86-90	-14		
			88-89	fail, 30 min		
			85-86	-16		
PAL		3P(W)		4F	1P	1.2
	81 @ 2		84-88	-5		
	88 @ 4		82-84	-12		
	77 @ 8		82-86	-10		
				-5		

drifted up and down during the two-minute observation. This varying amplitude is in addition to the intentional pulsing of each model. The approximate pulse rate is also given in Table 4. The signal frequencies were measured with an octa-band analyzer, so they are rather coarse. Entries of P(W) for the -10°C test meant that the alarm was a little weak—no measurements were taken. An entry of F at -10°C meant that no alarm could be heard. The entries of F for the 80°C test meant that the sound pressure level was below 85 dBA at 3 meters at the end of one hour. The negative numbers indicate in decibels how far it was below its sound level at 22°C . Only one unit, a Life Gard II, had a sound level above 85 dBA after one hour at 80°C . Exposing the PADs to a temperature of 140°C for 2 minutes had no noticeable effect. They were just as loud afterwards and suffered no physical damage.

Spec. (3)(C) Damage by Battery Leakage

The Life Gard I has a large opening between the battery compartment and the electronics compartment, measuring 4 by 11 mm. The Securus S-O-S has a long (2.5 by 52 mm) open slot connecting the two compartments, plus a 6 by 15 mm opening at one side. The openings in these two devices are large enough so that any corrosive liquids formed by the battery could damage the electronics. The Life Gard II and PAL have small holes in the compartment divider just large enough for the battery connector wires. Also some sealant is placed where the wires go through the holes. It is unlikely that liquid would go from one compartment to the other.

Spec. (3)(D) Water Intrusion

The first group of devices we tested were submerged under two meters of deionized water for one hour. Upon removal, they were dried externally, checked for operation, then opened to see any water leakage. We did not use sea water on this first batch so we could save units from being severely damaged. A second group of units was tested by the revised Cal/OSHA spec; i.e., sea water was used and only operation of the unit after submergence was checked.

The battery in each unit of the first group had been changed at least once before the water intrusion test. All gaskets and seals were inspected before the test to assure that they were as the manufacturer intended. Even though deionized water was used for this group, about half of these units that leaked never operated properly after being dried out. In the second group of submerged

PADs, the cover on the electronics compartment of the Life Gard II was not touched. These were all brand new units. The results of these tests are shown in Table 3.

Spec. (3)(E) Impact Resistance

Three units of each model were drop-tested except the Life Gard I. Only two Life Gard I were available and both were inoperable after the water submergence test. The speaker diaphragms were dislodged from one of the Life Gard II units on the fourth drop and the sound stopped after the fifth drop of the other unit. The yellow part of the case broke on the second drop of the Securus S-O-S unit; the break was in an unlikely place and was probably due to a rare flaw in the plastic.

Spec. (3)(F) Weight

All devices weighed less than the 350 grams allowed.

Spec. (4)(A) 80% Battery Capacity Indicator

For this test, the battery was replaced by a variable voltage dc power supply capable of supplying sufficient current to operate the PAD. Only the Life Gard II gave a clear and accurate indication of when the battery was discharged to 80% of its rated capacity. Its LED flashed brightly until the 80% voltage was reached then it quit flashing. On the Life Gard I, the LED just gradually decreased in brightness until the battery was almost dead. On the PAL originally tested, serial number 4027, the LED noticeably dims too soon. Batteries would be replaced too often. More recent PAL units operate like the Life Gard II. The Securus S-O-S has no LED. Below 80% voltage, it emits a constant tone instead of the pulsing alarm tone to indicate low voltage. However, the sound-pressure level is so low that the tone cannot be heard in a moderately noisy environment.

Special Tests

To evaluate the usefulness of the PADs, we also evaluated several additional conditions:

(1) We poured a few milliliters of water on the PAD as it lay with its speaker aimed upward. The Life Gard II and Securus S-O-S units, with vibrating disk speakers, completely stopped producing sound during this test. They recovered as soon as the water was poured off. The two PADs with cone-shaped speakers protected by a thin plastic sheet continued to sound during this test but the sound level was too low to be useful.

(2) The PAD was allowed to float in a tub of water, salt, and ice for one and one-half hours at a temperature of $\sim 6^{\circ}\text{C}$. This was actually our first attempt to test the PADS at -10°C . None of the PADS worked properly when first removed from this cold bath. When warmed up, the Securus S-O-S worked properly and was dry inside. The other three models had leaked severely resulting in corroded electronics. Even after washing in de-ionized water and drying thoroughly, none recovered.

(3) A firefighter might encounter noises that would mask the alarm of the PAD or that might sound the same as or similar to a PAD alarm. These two situations could hamper the rescue of an immobile firefighter. In a residential fire, it is very likely that a residential-type smoke detector would be sounding continuously during a fire (the national standards on residential smoke detectors are ANSI/UL 217-1979 and ANSI/NFPA 74). The specification for the sound-pressure level is 85 dBA at 10 feet with no mention of sound frequency. We measured the sound-pressure level and frequency on seven residential smoke detectors. Most smoke-detector alarms were louder than the standard and the sound is almost all in the 2000 and 4000 Hz frequency range. This is the same frequency range specified for PADS. All gave a continuous signal except the First Alert which had a pulse overlaying a continuous signal. It would be very hard to detect a PAD signal when near any smoke detector, especially a First Alert.

The signal from the Securus S-O-S was attenuated by 11 dBA by an interior stud and plasterboard wall. In a quiet hallway with a background noise level of 58 dBA, this is readily discernable at 10 feet. In a lab with equipment and a operating fume hood, it was barely detectable at 10 feet.

(4) We combined some of these effects in a field trial in a large equipment penthouse that contained several rooms and contained two boilers, several compressors and many blowers. The sound level in the penthouse varied from 72 dBA at the entry door to 91 dBA in a far room. The dividing walls were made of sheet metal and all the doors were open. An alarming PAD was placed somewhere in the penthouse and an alarming smoke detector, Semhart Smoke Alarm, was placed about in the center of the complex of rooms.

A firefighter using an SCBA entered the penthouse and searched for the alarming PAD. The PADS emitting an 85 dBA signal could not be

heard until the searcher was past the smoke detector and within about 20 feet of the PAD. The PAD emitting a 95 dBA signal could be heard as soon as the searcher entered the penthouse unless the PAD was in the furthest corner. A firefighter on the outside of the penthouse with the outside doors closed did not hear the alarming PAD.

Specific Unit Faults

Life Gard I

- The switch failed to operate properly.
- The sound level was too low at 80°C .
- It leaked badly and the electronics are not protected from a leaking battery.
- It has no weak battery indicator.
- This unit is not certified to meet Cal/ OSHA specs.

Life Gard II

- The sound level at 80°C was too low on one of the five units tested, slightly low on two units and satisfactory on two units.
- Seven of the nineteen units leaked.
- Two out of three units were damaged in the drop test.

Securus S-O-S

- The switch is hard to use for the manual ON operation.
- Three out of four units tested would not work at -10°C .
- At 80°C two units quit alarming after one-half hour and the other three were too quiet after one hour.
- Four out of twelve units failed the water intrusion test, and one out of three failed the impact test.

PAL

- The switch is difficult to use and was disliked during both field testing by the firefighters and lab testing by the experimenters.
- One of three units was a little quiet at 22°C , and all four tested at 80°C were too quiet.
- The battery drain while alarming is twice that of other models.
- Eight out of the ten failed the water intrusion test.

Conclusions

It is obvious from our work that a redesign effort is needed on all devices as well as better design and quality control standards established. While the authors agree with NFPA President Robert Grant's call for such devices (See *Fire Command*, October 1979), the devices currently on the market do not meet the demands of the fire service and the expenditure of funds on such devices would be a waste. Although each fire department that purchases PADs cannot put their devices through all the Cal/OSHA specification tests, they should do the water-intrusion test at least and return to the vendor all units that fail. The need for such devices is obvious; however, the devices, to serve a useful purpose, must be

reliable, easy to use, and sound an alarm of sufficient loudness to be heard in the firefighting environment.

Our test results have been shared with Cal/OSHA and the PAD manufacturers. It is expected that the manufacturers will make improvements in their products. The results reported here are on units purchased on the open market between May and October, 1983.

Acknowledgments

The authors wish to acknowledge the assistance of Laboratory Technician Beverly Lum who conducted most of the tests, and LLNL Firefighters Wade Diebner, Gary Linney and Dave Galloway who coordinated field testing and served as an advisory committee for the tests.

Evaluating Electrical Cables by the LLNL Ease-of-Ignition Apparatus

H. K. Hasegawa, S. Van Bommel,* and R. White*

Using the LLNL Ease-of-Ignition apparatus, we examined three physical characteristics of cables commonly used at LLNL: (1) mass per unit length of cable, (2) the outside diameter, and (3) the percentage of conductor material. We observed trends in tests determining times-to-ignition that larger conductor diameters and ratios of conductor-to-outside diameter have ignition times dependent on the chemical composition of the jacket material.

Introduction

Our fuel-load surveys of DOE fusion facilities have identified a variety of wire and cable insulations as dominant potential fuels. In terms of fire performance, one very important characteristic of these cables is how resistive they are to ignition. The LLNL Ease-of-Ignition apparatus is a small-scale experiment that ranks materials as a function of their times to ignition. These results also identify relative ignition energies of materials which can indicate what sources pose ignition threats around such materials. For fire-modeling purposes, ignition information could add a data point for stochastic ignition predictions and initial-fire-growth calculations.

One of the obvious problems with our previous small-scale tests of cables was the wide variation of physical characteristics as well as insulation types, the combination of which made any realistic comparison of performance impossible. Therefore, we opted to evaluate the individual effects of cable size, geometry, composition, and materials on a matrix of several commonly used cable types. In order to determine changes in performance due to the jacket material or to the conductor configuration (i.e., whether they were multiconductor, stranded, solid, etc.), we identified and tested cable types all the same size but made of different jacket materials. To determine the effect of cable size alone (diameter, jacket thickness, etc.), we kept the cable material and composition constant but varied the sizes.

Experimental Design

Since our objective was to establish a correlation between a cable's physical characteristics and its time-to-ignition, we identified a matrix of cable types available in several different sizes. Our previous studies identified polyvinylchloride (PVC), Neoprene, and rubber as the most commonly used cable-jacketing materials at LLNL (Table 1). To ensure uniformity of jacket composition for each of the insulating materials, we analyzed chemically the different cable sizes.

Ease-of-Ignition Test Method

Figures 1 and 2 show the test apparatus and related instrumentation. The only sensors used in this series were the thermopile and water temperature thermocouple (abbreviated T.C.). Two parallel vertical specimens, 140 wide and 152 mm high, face each other at a separation of 53 mm. The facing surfaces of both specimens are exposed to a methane diffusion flame supplied from a multiported burner located below the lower edge of the specimens. The gas flow rate through each of the independently controlled burners is set to 100 ml/s (12.5 SCFH) of technical-grade methane, producing a heat flux of $3.2 \text{ W/cm}^2 \pm 0.2 \text{ W/cm}^2$ from a total gas flow of $200 \text{ ml/s} \pm 10 \text{ ml/s}$ (25 SCFH ± 1.3 SCFH) resulting in an energy release of 7 kJ/s. The reason for having the two specimens face each other was simulating the reinforcement that would occur in a worst-case fire situation.

The time-to-ignition is the time at which flame attaches to a specimen surface and when

* Cogswell College, San Francisco, California.

Table 1. Commonly used cable-jacketing materials at LNL.

Cable	Jacket/ dielectric materials	Jacket thickness (mm)	o.d. (mm)	Mass of jacket (g/cm)	Mass of dielectric (g/cm)	Total cable mass (g/cm)	No. of conductors	Conductor(s) size (mm)	% insulation material
RG 213 A/U	PVC/P.E.	1	10	0.369	—	1.57	1	—	23.5
RG 59 B/U	PVC/P.E.	1.02	6	0.22	0.0925	0.56	1	—	56
RG 58 C/U	PVC/P.E.	0.14	4.95	0.14	0.05	0.38	1	0.9	52
Telephone cable	PVC/P.E.	0.3	7.62	0.561	—	4.37	4	—	56.6
Welding cable AWG 6	Neoprene	2.54	10.24	0.68	—	1.94	1	5.3	36
Welding AWG 4/0	Neoprene/ rubber	3.5	23	4.195	—	14	1	14	29.96
Power cord	Neoprene/ Neoprene	—	15.2	0.135	conductor jacket 0.085	0.315	4	—	72
Test prod.	rubber/ rubber	2	4.75	0.13	—	0.20	1	—	65
Welding 2/0	rubber/ rubber	2.7	19.05	1.22	—	7.85	1	3325 strands	20.9
Welding AWG 2	rubber/ rubber	0.3	14.2	1.07	—	4.14	1	1666 strands	25.8
Audio cable	rubber/ rubber	0.26	1.1	0.29	—	0.78	3	—	37

the specimen begins to contribute a significant quantity of fuel, as indicated by a rise in voltage of a thermopile. The thermopile consists of a bank of thermocouples located 6.4 mm above the top edge of each specimen and 6.4 mm out from the plane of their surface.

Test Specimens

We tested eight, rectangular cable-array samples, 140 wide and 152 mm high. Two arrays were required for each test, and four replicate tests were conducted. The specially designed specimen holders gripped cable samples at their ends (Fig. 3), and this provided sufficient tension to prevent large deformation of the individual cables due to heating, which ensured reasonable reproducibility among the samples.

Test Procedure

At the beginning of each test day, cooling water was set to a predetermined flow rate and the hood draft was turned on. Two pieces of noncombustible miranite were mounted in the test flame. We started the data acquisition system, energized the electrical spark igniter, and opened the gas solenoid valves. This procedure provided a baseline trace and also brought the cooling water tempera-

ture within the range prescribed in our standard. After this initialization, the burners were shut off, the miranite boards were replaced by actual samples, and we started the formal testing.

The time to flame attachment (visual) was noted with an event marker on a strip-chart recorder. Generally, just before the flame attachment was noted, the thermopile voltage increased, indicating the onset of fuel contribution (time-to-ignition). We took the time to fuel contribution from the recorder trace as the time at which the trace began to rise above the baseline. This was determined by a straight-line projection of the rising part of the thermopile trace back to the baseline. Small increases in voltage (less than 10% of the baseline) were ignored.

We terminated the test three seconds or more after (1) the trace either exceeded the baseline by 30% or a maximum temperature had been reached, and (2) flame attachment had occurred. Otherwise, the test ran for 5 minutes. We conducted four tests of each cable type listed in Table 1.

Results

We intended to establish a correlation between a cable's physical characteristics and its

Figure 1. Actual experimental setup of Ease-of-Ignition apparatus.

Figure 2. Schematic detailing experimental setup and sampling ports.

Figure 3. Specially designed specimen holders.

time to fuel contribution. We considered the outside diameter, the total mass (grams) per centimeter, and the percentage of insulating material as the cables' physical characteristics. These properties were then plotted against their respective times to fuel contribution. We also determined the change in performance from a single conductor to a multiconductor. PVC, Neoprene, and rubber were analyzed separately, and our conclusions are based on a comparison of the performance of all three materials.

PVC Analysis

As shown in Fig. 4, the PVC cables tested, with the exception of the multiconductor, were

Figure 4. Cross sections of (a) single conductor cables and (b) multiconductor cables.

coaxial types using polyethylene as the dielectric material. Of the three insulating materials tested, PVC was the only one to exhibit a near linear relationship between its physical characteristics and its time-to-ignition. Figures 5(a) through (c) show the following relationships:

- Decreasing the outside diameter reduces the time-to-ignition [Fig. 5(a)].
- Although it is not a linear relationship, it appears that decreasing the mass also reduces the time-to-ignition [Fig. 5(b)].
- There is no correlation between the percentage of insulating material and the time-to-ignition [Fig. 5(c)].

Although a larger sample of cables must be evaluated to verify these relationships conclusively, our preliminary findings seem logical, based on heat-transfer principles. In order to achieve ignition of cable insulations, they must be heated to their ignition temperature. The greater the mass, the more energy, or in this case, the more time is needed to bring the jacket material to its critical temperature. Conversely, reducing the mass reduces the heating time.

Testing the multiconductor seemed to confirm this relationship between physical characteristics and time-to-ignition. The four conductor telephone cables were loosely wrapped with a PVC jacket which resulted in substantial air space between the outer jacket and the conductors. This elliptical cable had a major axis diameter of 0.76 cm and a time-to-ignition of 10.75 sec. By comparison, the RG 59 B/U cable (single conductor) with an outside diameter of 0.6 cm had a time-to-ignition of 78.75 sec. The greatly reduced ignition time for the multiconductor cable can be directly attributed to the air space that allowed the outer jacket material to heat up rapidly (i.e., only the mass of the jacket absorbs the heat as opposed to heating up the jacket and insulator in the coaxial). It appears that we may roughly predict the times-to-ignition of PVC-jacketed coaxial cables with respect to the scale of the Ease-of-Ignition apparatus.

Neoprene Analysis

Due to limited availability, only three of the four planned Neoprene-insulated cables were tested and one of these was a multiconductor. Unfortunately, since multiconductors are not plotted, we had to use just two data points. This degraded the quality of our analysis so that we could draw no clear conclusion. However, the two data points shown in Figs. 6(a) and (b) seem to indicate that Neoprene has a time-to-fuel contribution inde-

Figure 5. Times to fuel contribution for PVC as a function of (a) decrease in outside diameter, (b) decrease in mass, and (c) percentage of insulating material and the time to ignition.

pendent of the cables' physical properties. Both plots show that cables with vastly different outside diameters and masses had almost identical times-to-ignition. Yet, like PVC, the larger diameter Neoprene multiconductor displayed a time-to-ignition of nearly half that of the single conductor: 47s and 85s, respectively.

This indicates that, in our choice of single conductor cable sizes, we have exceeded a size threshold where the conductor absorbs most of the thermal energy. This makes the ignition time solely dependent on the chemical composition of the jacket. Again, the energy dissipation in the

Figure 6. Times to fuel contribution to Neoprene showing (a) the outside diameter and (b) decreasing mass.

multiconductor is not as pronounced as in the single conductor. Further experiments will have to substantiate this hypothesis.

Rubber Analysis

Preliminary examination of the rubber-insulated cables shows no correlation between its physical characteristics and the time to fuel contribution [see Figs. 7(a) and (b)]. The AWG 2 cable, with an outside diameter of 1.37 cm, had an average time-to-ignition of 146.35 sec, while the larger AWG 2/0 cable, with an outside diameter of 1.9 cm, had an average ignition time of 120 sec. Our third data point was an 0.495-cm wire with a short time to fuel contribution of 67.35 sec. And like the previous cables, the rubber multiconductor had a reduced time-to-ignition of 69.4 sec.

Conclusions

Because of the insufficient number of cable sizes for each cable type and the choice of sizes (i.e., not a wide enough spread among sizes), we cannot say anything definite about the relation-

ship between a cable's physical characteristics and its time-to-ignition. However, we have enough information to indicate performance trends that could be applied to a larger and more comprehensive research effort.

It is apparent that the Ease-of-Ignition apparatus, in its present form, cannot be used to proceed with this more comprehensive effort. A major problem is that the fire exposure fluctuates a great deal because it is a diffusion flame. Since the times to fuel contribution, in most cases, differ by only seconds, the nonuniform exposure can produce illogical and anomalous results. Furthermore, the ignition time is calculated as the average of four runs. If one or more times-to-ignition are extreme, the average time-to-ignition can be very inaccurate. Although we took great pains to ensure uniformity among the specimens before and during testing, it is highly probable that individual cables deformed during the fire. This would change the amount of surface area exposed to the flame, which would alter its time-to-ignition.

We believe that the combination of the above variables is significant enough to cause the seemingly illogical results obtained from the rubber-jacketed cable tests; the larger and more massive AWG 2/0 cable had a time to fuel contribution 26 sec less than the smaller AWG 2 cable. The following times-to-ignition for each of the burns for

Figure 7. Rubber test result showing (a) increasing outside diameter and (b) decreasing cable mass.

the two cable types illustrates the wide variation in times:

	AWG 2	AWG 2/0
Burn 1	135.0 sec	95 sec
Burn 2	119.0 sec	145 sec
Burn 3	172.0 sec	105 sec
Burn 4	159.4 sec	135 sec

Both sets of data have a spread of about 50 sec from the shortest to the longest time-to-ignition. Substituting a radiant panel (the same size as a specimen) for one of the specimens and eliminating all existing burner ports except for one under the sample to serve as a pilot flame is a possible improvement. The radiant panel would provide a uniform and steady thermal flux on the specimen and should provide more reproducible results.

Although not proven in this study, we feel that the three major physical characteristics that govern a cable's time-to-ignition are the mass per unit length, the outside diameter, and the percent-

age of conductor material. Based on our results, it appears that cables with a conductor diameter of approximately 0.8 cm and greater, and a ratio of conductor-to-outside diameter of 60% or more will have times-to-ignition dependent primarily on the chemical composition of the jacket material. In other words, if the conductor's mass dominates the cable composition, it is as if the jacket material is attached to an infinitely insulating slab. Cables containing smaller conductor sizes will probably perform according to relationships derived from a cable's chemical composition, physical makeup, and physical dimensions, as was indicated by the PVC coaxials we tested in this study. Similarly, PVC four-wire multiconductors would perform according to one relationship, triaxials to another, and so on.

After modifications to the Ease-of-Ignition apparatus have been completed, more extensive research should be carried out to confirm or disprove the above hypotheses. More runs of each cable type should be done to improve the accuracy of the data and to eliminate or smooth out extremes.

Zone-Model Correlations with Experimental Enclosure Fires

N. Alvares and K. Foote

We are developing risk analyses for fires in enclosures where mathematical models provide the initial conditions of fire damage to facilities at risk. The several models we surveyed for this purpose are zone models that are essentially analytical descriptions of control volumes having uniform properties within defined, time-dependent boundaries. We describe some model-validation studies using our experimental data from FY-82 work. We also include results from FY-83 experiments, showing data for conditions where the fire source is moved to different sites in the test cell.

Model-Validation Studies from FY 82

We compare model output to results from FY-82 experiments in the LLNL fire-test cell, where ventilation rates, fire strengths, and fire-source positions were controlled and changed within the test-cell volume. To date, all experiments have had air introduced at floor level and air extracted in a wall near the ceiling to approximate standard ventilation geometry (Fig. 1). Figures 2(a) and (b) show data from two tests used to validate enclosure-fire models. Both fires are somewhat ventilation-controlled, as indicated by the hydrocarbon (CH_4) and carbon monoxide (CO) production. However, Test 27B is much closer to having adequate ventilation because the oxygen consumption and formation of combustion gas reach a constant level; in Test 9A, though, gas data is continuously increasing until the fire is terminated. Also, the shape of the inlet and extraction flow shows a decreasing trend through Test 9A that does not appear in Test 27B, indicating the relative difference in ventilation control between the tests.

Table 1 describes characteristics of several enclosure-fire models we are considering for enclosure-fire risk analysis, and Table 2 compares experimental results from Tests 9A and 27B to model predictions at specified times. Each of these models have some parameters that they predict well, and others that appear to be far off target. We wished to gain experience in applying model results to unique conditions and experimental fire variations. To this end, we chose the single-zone model developed by Professor E. E. Zukoski at California Institute of Technology. This model

(Cal Tech 1) is easy to apply and adapt, and it gives reasonable predictions of our experimental results.

Comparison of Models and Test Data

Figure 3 compares Cal Tech 1 predictions with oxygen consumption data for Tests 27B and 9A. The shape of these predicted curves are encouraging, but it does not constitute a direct correlation with measured data, i.e., at no time in the modeled O_2 consumption would the prediction match real conditions. Cal Tech 1 predicts less available oxygen than was actually measured for the two tests. Even though this model inaccurately predicts the oxygen concentration, it is still a valuable tool for risk assessment in that it consistently gives a pessimistic prediction.

Figure 4 compares gas-temperature predictions with test data that indicate too low a temperature rise early on, and too great a rise when the fire approaches equilibrium. This model comes to temperature equilibrium too slowly. Thus, it is not very useful for predicting gas temperature.

Examples of Results from FY-83 Tests

FY-83 experiments focused on the characteristics of room geometry such as ventilation duct locations, fire elevation and position, whereas, the FY-82 work explored the effects of changes in the fire itself.

Figure 5 shows the floor plan's horizontal fire-source positions for three FY-83 tests. Here,

fire output is modified by the proximity of the wall and corner to the fire plume. All these fires were ventilated at 250 liters/sec with a fire strength of 400 kW, and only the horizontal position was changed. Figures 6(a)-(d) shows O_2 depletion and product gases (CO , CO_2 , and CH_4) for three tests (11, 2B, and 9). Except for the CH_4 curves, the correspondence of the data to the Cal Tech I model is remarkable, making the task of modelers who have good chemistry algorithms much easier. The more interesting CH_4 curves probably demonstrate flame-quenching effects of surface proximity, e.g., Test 11 consistently puts out less CH_4 than do either Test 2B or 9. Test 9 is quite noisy because of the fire proximity to the extraction duct, which may also be the reason for the greater CH_4 production. We believe this increased production is caused by pyrolyzing gases

entering the exit duct which stops the hydrocarbon conversion to CO and H_2O . Note that the discontinuities in the CH_4 curves past 1400 sec are due to condensation in the sample lines to the analyzer.

Summary

In the next fiscal year, we will apply all of the models to our data. We should be able to discern (after enough experience with model manipulation and data analysis) the correct physical parameters to create "general" adjustments to model algorithms for fires in our enclosures. From these comparisons, we will then select the modeling procedure that can best be employed as the starting point of our risk analysis.

Figure 1. Section view of the LLNL fire-test cell.

Figure 2(a). Test 27B at 400 kW and 250 liters/sec.

Figure 2(b). Test 9A at 800 kW and 500 liters/sec.

Figure 3. Comparison of Cal Tech I oxygen depletion predictions for Tests 9A and 27B.

Table 1. Enclosure-fire parameters of the 6 models tested for risk analysis.

Harvard	LANL	PNL	Cal Tech I	Cal Tech II	LLNL
Two layer Ambient lower	Two layer Heated lower	Two layers Ambient lower	One layer No lower	Two-layer Ambient lower	Two-layer Ambient lower
O ₂ depletion Fixed mass		O ₂ depletion Fixed mass			
Multiple rooms	Single room	Single room	Single room	Multiple rooms	Single room
Complicated Large	Complicated Large	Complicated Large	Simple Small	Complicated Large	Simple Small

Table 2. Model parameters.

Test 27B

Parameters	Data	Harvard	Cal Tech I	PNL	LANL	Cal Tech II	LLNL
Time (sec)	2200	2200	2200	2200	1800	800	300
Ambient temp (°C)	18	18	22	18	18	18	18
Hot layer temp (°C)	252	158	287	222	282	287	287
Cold layer temp (°C)	136	18	287	18	111	18	18
Wall temp (°C)	—	123	206	—	—	—	—
Heat loss to wall (kW)	270	15	329	164	313	320	320
Fire strength (kW)	330	341	399	259	391	400	400
O ₂ (% vol)	11.0	6.8	9.4	11.3	9.6	—	—
CO ₂ (% vol)	7.5	9.1	—	5.4	5.9	—	—
CO (% vol)	0.1	0.02	—	0	0.1	—	—
Flow reversal peak (g/sec)	—200	—210	—300	—410	—210	34	—
Time of peak	15 sec	2 sec	20 sec	20 sec	20 sec	30 sec	—

Test 9A

Parameters	Data	Harvard	Cal Tech I	PNL	LANL	Cal Tech II	LLNL
Time (sec)	600	600	600	600	630	800	300
Ambient temp (°C)	34	34	22	34	34	34	34
Hot layer temp (°C)	299	175	351	267	329	304	388
Cold layer temp (°C)	146	34	351	34	136	34	34
Wall temp (°C)	—	126	215	—	—	—	—
Heat loss to wall (kW)	600	231	682	327	629	640	640
Fire strength (kW)	700	484	801	556	786	800	800
O ₂ (% vol)	6.5	7.6	4.0	10.8	7.9	—	—
CO ₂ (% vol)	8.5	10.9	—	5.7	6.8	—	—
CO (% vol)	2.8	0.03	—	0.01	0.8	—	—
Flow reversal peak (g/sec)	—420	—550	—570	—180	—400	117	—
Time of peak	15 sec	2 sec	20 sec	20 sec	11 sec	30 sec	—

Figure 4. Comparison of Cal Tech I gas-temperature predictions for Tests 9A and 27B.

Figure 5. Closeup of fire-test-cell showing floor positions.

Figure 6. Tests 9, 2B, and 11 showing curves for (a) oxygen, (b) CO_2 , (c) CO, and (d) CH_4 .

Definition of the Concentration Gradient Above Flammable Liquids

Rafael Munoz-Candelario* and Norman J. Alvares

Areas where the potential for spill of flammable fluids is finite are defined as hazardous locations, and are subject to code restrictions regarding location and protection from potential ignition sources. These locations require a specific separation distance between the potential spill plain and the ignition sources. This distance is universally accepted to be 18 inches for most U.S.A. codes. We found that acceptable separation distances have increased over the years, intuitively in the name of safety, although we found no data to support this. We surveyed the literature and performed experiments to find a quantitative basis for the increasing distances. The literature revealed a case for evaporating fluids with boundary conditions for the volatile vapor diffusing through a stagnant gas film. In containers with open tops, the calculated vapor-concentration gradients are monotonic and directly proportional to the vapor pressure of the fluid. We confirmed the validity of these calculated values by performing experiments to determine the elevations at which flammable mixtures formed above the surfaces of low-volatility, high-vapor-density liquids.

Introduction

When the vapor density of flammable liquids or gases is greater than the air density, released vapors tend to collect in tight enclosures and in the depressions of horizontal surfaces. For spilled fluids, the concentration gradient above the liquid surface is driven by vapor pressure at the bulk fluid temperature. In a completely closed container, we expect that the partial pressure of flammable gas in air will come to equilibrium with the vapor pressure at times long past the original spill (assuming enough fluid was spilled to provide this concentration). In open containers or in normal rooms with leaks, a concentration gradient is formed above the liquid surface. This gradient is dependent upon the rate of evaporation of the liquid and on the geometry and porosity of the container.

Current regulations require that appliances with ignition sources (open flame, sparking devices, glow coils, switches, etc.) be placed with the ignition source at least 18 inches above the potential spill surface.¹ In the past, this height varied from 6 to 24 inches. We could find no documented reason for these choices of regulation heights. Therefore, to establish a technical basis for defin-

ing a "safe" height, we believed a quantitative investigation was necessary, including analytical and theoretical analysis of gradient formation.

A proper perspective of the wide range of practical situations requiring an adequate understanding of this problem can be gained from a brief review of the literature. Baum and Rockett² developed equations to predict the vapor concentration of spilled volatile materials assumed to lie at the bottoms of container-ship holds. Wing did an equivalent study of accidental releases of toxic vapors in nuclear-reactor control rooms.³ Foerster et al. analyzed the formation of explosive gasoline-vapor clouds after major spills in road tunnels.⁴ Theoretical studies have also been made by Georgakis⁵ on the development and decay of liquid-fuel spills in large tankers, and by Zeman⁶ on the dynamics and modeling of heavier-than-air releases of cold gas. McKay and Matsugu measured wind-induced evaporation rates of liquid hydrocarbon spills on land and water, and developed equations to predict such rates.⁷

The most fundamental and comprehensive study on fuel and hydrocarbon vaporization was reported by Gauss in 1973.⁸ Starting from the basic diffusional equations for steady- and unsteady-state vaporization, and using experimental data on evaporation from flat disks under low-velocity winds, Gauss developed a semi-empirical expression to predict evaporation rates

* University of Puerto Rico at Mayaguez, Puerto Rico.

of pure liquid hydrocarbons over a wide range of conditions. Analyses of the flammable envelopes surrounding pools of pure hydrocarbons and other fuels were also performed.

We found no experimental or theoretical study on the determination of the concentration of heavier-than-air vapors above the surfaces of low-volatility liquids in the absence of convection currents. The work reported below was aimed at defining the fundamental mechanisms governing such evaporation processes and at developing methods to estimate possible hazardous concentrations.

Applicable Theory

The rates at which pure liquids vaporize depend on factors such as air velocity across the liquid surface, air and liquid temperature, liquid vapor pressure and mass diffusivity, and geometry factors. If the air above the surface of the liquid is stagnant, evaporation occurs solely by molecular diffusion. The driving force for this process is the difference between vapor concentration at the gas-liquid interface and at other points in the gas column in the direction of transport. Assuming an isothermal environment, conditions at the interface correspond to equilibrium. The partial pressure of the evaporating substance is therefore equal to its vapor pressure at the temperature involved. The equilibrium vapor concentration at the liquid surface is then a function only of temperature, since this in turn fixes the vapor pressure.

The diffusional equations have been solved for the simple case of a liquid in a container with an open top vaporizing into air. The liquid surface is totally bounded by the walls of the container, allowing diffusion to occur in only the vertical direction. The liquid level is maintained at constant temperature and pressure, and we assume the vapor and air form an ideal-gas mixture.

Bird, Steward and Lightfoot discuss this specific evaporation problem and present solutions to the applicable diffusional equations for both unsteady- and steady-state conditions.⁹ For the case of steady-state diffusion in the system shown in Fig. 1, concentration profiles in the gas phase are determined by solution of the molar flux equation:

$$N_{AZ} = -cD_{AB} \frac{\partial X_A}{\partial Z} + X_A(N_{AZ} + N_{BZ}) \quad (1)$$

where N_{AZ} , N_{BZ} = molar fluxes with respect to fixed axis,

c = molar density,
 D_{AB} = diffusion coefficient of gas A
 into gas B, and
 X_A = mole fraction of A.

For A vaporizing into B, $N_{BZ} = 0$, and Eq. (1) reduces to

$$N_{AZ} = -\frac{cD_{AB}}{1 - X_A} \frac{\partial X_A}{\partial Z} \quad (2)$$

for the limit, $\Delta Z \rightarrow 0$, and steady-state conditions,

$$-\frac{dN_{AZ}}{dZ} = 0 \quad (3)$$

Substituting Eq. (2) into (3) gives

$$\frac{d}{dZ} \left(\frac{cD_{AB}}{1 - X_A} \frac{dX_A}{dZ} \right) = 0 \quad (4)$$

For ideal gases at constant pressure and temperature, c is constant and D_{AB} is very close to constant, giving a second-order equation for concentration profiles in terms of X_A :

$$\frac{d}{dZ} \left(\frac{1}{1 - X_A} \frac{dX_A}{dZ} \right) = 0 \quad (5)$$

The solution of Eq. (5) for concentration profile is

$$\frac{1 - X_A}{1 - X_{A0}} = \left(\frac{1 - X_{A2}}{1 - X_{A0}} \right)^{\frac{Z - Z_0}{Z_2 - Z_0}} \quad (6)$$

The subscripts 0 and 2 in Eq. (6) refer to the elevations at the surface of the liquid and the top of the enclosure, respectively. If the stagnant air column is assumed to be infinitely high, the value of X_{A2} is zero. Taking the datum plane for the elevations right at the liquid surface makes the value for Z_0 also zero, and the equation simplifies to the following form:

$$\left(\frac{1 - X_A}{1 - X_{A0}} \right) = \left(\frac{1}{1 - X_{A0}} \right)^{Z/Z_2} \quad (7)$$

This permits calculation of the gas-phase concentration as a function of fractional height above the liquid's surface for long enclosures of known height. The equilibrium gas-phase concentration for Eq. (7) can be calculated from the vapor pressure of the liquid at the temperature of the system.

Figure 1. Diffusion of A through B in steady state with B not in motion. Graph shows how concentration profile for B is distorted because of diffusion of A.

Procedure and Results

Our work was aimed at confirming the applicability of Eq. (3) for predicting the concentration of heavier-than-air vapors above the surfaces of low-volatility, flammable liquids. Rather than attempting to measure the concentrations at different heights, our approach was to determine only those heights corresponding to the lower flammable limit (LFL) of the vapors. The values obtained in this way were compared with the heights predicted by Eq. (3).

We used long, open-ended glass tubes of different diameters as enclosures, then immersed the lower portions of the tubes in a vessel of water. The setup was placed in a large, closed chamber to eliminate convection currents and to provide semi-isothermal conditions.

The liquids tested were hydrocarbons immiscible with water. We then pipetted the hydrocarbons into the tubes to form a floating layer on the water surface. We calculated the time when the steady-state concentration gradient would be established in the tube.¹⁰ After the predetermined

time had elapsed, we measured the LFL height using a very-small-capacitance spark probe inserted into the gas column from the top of the tube. Figure 2 shows this apparatus.

Table 1 lists experimental parameters for this series. In all experiments, the liquids were within 1 degree C of the ambient air temperatures in the experimental chamber.

Table 2 summarizes our experimental data and results. Values of fractional height above the liquid surface (corresponding to the LFL) are presented and compared with corresponding values predicted by theory. These were obtained from

Table 1. Experimental parameters.

Parameter	
Tube inner diameters	1.05, 2.2, and 10.3 cm
Tube lengths above the liquid surface	25 to 35.7 cm
Hydrocarbons under tests	normal heptane and octane
Liquid temperatures	room (20°C to 24°C)
Diameter of the spark probe	2 mm

Figs. 2 and 3 for n-heptane and n-octane, respectively.

Conclusions

Our results show that the concentration profiles of low-volatility liquids vaporizing into stagnant atmospheres can be closely approximated by the basic diffusional equation for steady-state vaporization. The data presented in Table 2 show good agreement between the observed and the calculated concentrations at LFL: within 4.4% in the n-heptane experiments, and within 10.7% in the n-octane experiment. This is remarkably good, considering that experimental deviations did not permit attaining true equilibrium at the gas-liquid interface. Small convection currents may have been generated by temperature variations between the gas and liquid.

Some of the tests described in Table 2 involved determining the position of the lower flammable concentrations near the walls of the large-diameter tube rather than at its center. This was done to establish if radial concentration gradients occurred in addition to the expected vertical ones. The possibility of radial gradients arises because, at the wall, the rate of evaporation is zero,

Figure 2. Change in concentration of heptane vapors with fractional height above surface of liquid.

Table 2. Experimental data and results.

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Tube i.d. (cm)	1.05	1.05	1.05	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	2.2	1.05	2.2	10.3	10.3	10.3	10.3	1.05
Hydrocarbon	normal heptane (nC ₇)	nC ₇	nC ₇	nC ₇	nC ₇	nC ₇	nC ₇	nC ₇	nC ₇	nC ₇	nC ₇	normal octane (nC ₈)	nC ₈	nC ₈	nC ₈	nC ₈	nC ₈	nC ₈	nC ₈
T _{liquid} (°C)	21	22	20.5	21	21	20	19	19	20	20	20	22	22	21	21	21	21	24	24
T _{vapor} (°C)	21	22	21	21	23	21	21	21	21	22	22	22	22	22	21	14	27	24	24
Tube height above liquid surface cm (Z ₂)	35.4	35.4	35.7	25	25	25	25	25	25	25	25	25	25	25	26.8	26.8	26.8	27.7	25
Height where flaming occurred (cm) (Z)	27.7	27.9	27.1	18.4	18.8	18.6	17.5	17.7	18.3	17.8	18.1	9.7	8.3	8.7	8.2	8.2	8.5	11.2	9.0
Z/Z ₂ (observed)	0.782	0.788	0.759	0.736	0.752	0.744	0.700	0.708	0.732	0.712	0.724	0.388	0.332	0.348	0.306	0.306	0.317	0.404	0.360
Z/Z ₂ (theoretical)	0.782	0.793	0.776	0.782	0.782	0.770	0.760	0.760	0.770	0.770	0.770	0.390	0.390	0.352	0.352	0.352	0.352	0.460	0.460
% deviation from theory	0	-0.6	-2.2	-5.9	-3.8	-3.4	-7.9	-6.8	-4.9	-7.5	-6.0	0	-14.9	-1.1	-13.0	-13.0	-9.9	-12.1	-21.8
Sparker position		center of tube				1/4 diameter from wall		1 mm from wall	3 mm from wall	7 mm from wall	1 cm from wall		center of tube				1 mm from wall	center of tube

Figure 3. Change in concentration of octane vapors with fractional height above surface of liquid.

and it increases toward the center. We were unable to provide conclusive evidence for either the presence or absence of radial gradients.

We note that the density gradient in the gas column above the surface of the liquids appears monotonic from bottom to top, as predicted by Eq. (6) and shown in Figs. 2 and 3. However, stratification, or gravity settling of the vapors heavier than air, may be indicated by the negative deviation between calculated and experimental data, especially apparent in the n-octane results.

References

1. National Electric Code, NFPA 70, Chapter 5, 1983.
2. Howard Baum and John Rockett, *An Investigation of the Forced Ventilation in Container-ship Holds*, U.S. Department of Commerce, NBSIR 83-2665 (1983).
3. James Wing, *Toxic Vapor Concentrations in the Control Room Following a Postulated Accidental Release*, U.S. Nuclear Regulatory Commission, Washington, D.C. (1979).
4. H. Foerster, H. Kraemer, and G. Schoen, "Dispersion of Gasoline in Road Tunnels After Release of Major Quantities," *Heavy-Gas Risk Assessment Symposium Proceedings*, edited by Hartwig Sylvius, Reidel, Neith, (1980).
5. C. Georgakis, J. Congalidis, and G. Williams, "Model for Non-Instantaneous LNG and Gasoline Spills," *Fuel* 58, 113 (1979).
6. Otto Zeman, "The Dynamics and Modeling of Heavier-Than-Air Cold Gas Releases," *Atmospheric Environment* 16, 741 (1982).
7. D. McKay, and R. S. Matsugu, "Evaporation Rates of Liquid Hydrocarbon Spills on Land and Water," *The Canadian Journal of Chemical Engineering* 51, 434 (1973).
8. Arthur Gauss, *Fuel and Hydrocarbon Vaporization*, U.S. Department of Defense, BRL Report No. 1661 (1982).
9. R. B. Bird, W. E. Steward, E. L. Lightfoot, *Transport Phenomena*, John Wiley & Sons, New York (1960).
10. B. J. Zwolinski and R. C. Wilhoit, *Handbook of Vapor Pressures and Heats of Vaporization of Hydrocarbons and Related Compounds*, Publications in Science and Engineering, Texas A & M University, Texas, API 44-TRC (1971).

Technical Notes

INDUSTRIAL HYGIENE

Impact and Vibration Testing of Firefighters' Self-Contained Breathing Apparatus

J. Stengel

I conducted impact and vibration tests on two types of self-contained breathing apparatus (SCBA) used by Lawrence Livermore National Laboratory (LLNL) firefighters in an attempt to analyze the environmental effects of routine transport to and handling at the fire scene. The purpose of these tests was to evaluate the ruggedness and reliability of this life-support equipment. Although high-pressure fittings were found somewhat vulnerable to impacts, SCBA generally withstood testing at ambient temperatures. High- and low-temperature extremes are likely to produce more severe damage.

Introduction

Impact tests are being proposed separately by the National Fire Protection Association (NFPA) and the National Institute of Occupational Safety and Health (NIOSH) to determine self-contained breathing apparatus' (SCBA) ability to withstand rough handling characteristic of their harsh use during firefighting. The proposed NIOSH test requires three 1-meter drops, once on each axis (Figs. 1 and 2). The proposed NFPA test procedure calls for pressurized SCBA to be functional following 12 1-meter drops and to have no catastrophic failure when dropped once from a 2-meter height.

Impact

Experimental Description

Our LLNL testing was performed using two types of compressed air cylinders: a 4500-psi, aluminum-fiber-wound composite cylinder (Survivair) and a heavier, 2200-psi, steel cylinder (Scott Air Pak II).^{*} Individual cylinders were dropped unpressurized once from a 2-meter height and twelve times from a 1-meter height.

^{*} The steel cylinder is representative of several older SCBA models. The Scott model was previously used by LLNL and is currently used by the Fire Department of Livermore, California, and others in the Bay Area where LLNL firefighters may be involved in "mutual-aid" responses.

I used test stands to drop composite and steel SCBA cylinders. A regulator was dropped once from 2 meters. Another regulator was dropped from 1 meter twelve times. A single facepiece was dropped once from 2 meters, then twelve times from 1 meter. Finally, a complete SCBA assembly was dropped a total of 36 times, 12 times per axis to study the effect of all drops on one axis as would be allowed by the NFPA test.

Results

Results of the impact testing are summarized in Table 1 and Fig. 3. The facepiece was tested for leakage and proper operation of the exhalation valve using test fixtures normally used for this purpose, and no serious damage was found. Regulators passed the machine test per NIOSH testing procedures and proper operation was observed. Cylinders passed hydrostatic testing per DOT requirements and were serviceable. No visible cracks were observed in the threaded neck of the composite cylinders. Cylinder valves and gauges were damaged and rendered inoperable, but they did not fail in a way likely to release pressure. A high-pressure fitting was severed when the complete SCBA assembly was dropped by hand. This damage was found to be easily reproduced in a single attempt and was not the result of cumulative damage.

Figure 1. Stand for 1-meter drop test.

Figure 2. Stand for 2-meter drop test.

Discussion

Drop test stands are not as useful as "free drops" by hand in discovering SCBA weaknesses. Free drops represent a more realistic handling condition. Because of cumulative damage from repeated drops, the 1-meter drops are more severe than the 2-meter drops. *Therefore, the 2-meter drop test is considered unnecessary.*

I concluded that most NIOSH-approved SCBA would pass the 1-meter drop test except for weakness in the area of high-pressure connections to the SCBA cylinder and valve assembly. Most other SCBA designs are similar in this respect and damage can be expected to be similar (or worse). A redesign to strengthen and protect this area of the SCBA will be required for most SCBA to pass. Since these tests were performed only at ambient temperatures, damage from high- and low-temperature drop tests is likely to be more severe than noted. Nonetheless, I concluded the NFPA 1-meter drop should be adopted as the SCBA impact test.

Vibration

The SCBA (Survivair Mk. I) currently in use at LLNL was placed inside the protective case supplied by the manufacturer, and subjected to a Military Standard 810-C vibration test simulating ground transportation by a rubber-tire vehicle.¹ This vibration test is currently proposed by NIOSH and NFPA for SCBA testing.

Prior to installation on the vibration table, the SCBA was tested for proper function on a breathing machine similar to that used by the NIOSH in their certification testing of the apparatus. The protective case was placed inside a plywood box and secured to the vibration table with tie-downs.

Accelerometers were fixed to the vibration table, the SCBA container, and the SCBA to ensure that the required acceleration levels would be attained. The SCBA cylinder was fully charged with

¹ Military Standard 810-C, Method 514.2.

Table 1. Results of unpressurized impact testing.

Test	Total impacts	Component dropped	Remarks	Pass/Fail
2 meters	1	Facepiece	Functional, minor abrasion	P
	1	Regulator	Functional, minor abrasion	P
	3	Steel Cylinder	1 drop/axis, serviceable, paint abraded	P
	3	Composite Cylinder	1 drop/axis, serviceable, surfaces slightly abraded	P
1 meter	12	Facepiece	4 drops/axis, functional, minor abrasion, passed leak test	P
	12	Regulator	functional, by-pass valve opened 1/4, selector valve bent	P
	36	Steel Cylinder	12 drops/axis, serviceable, passed DOT hydrostatic test, valve inoperable	P
	36	Complete SCBA assembly (composite cylinder)	12 drops/axis, serviceable, alarm assembly severed from high-pressure line causing SCBA to be inoperable	F

compressed air prior to the test. Testing was performed at ambient temperature.

Vibration was applied along each of three mutually perpendicular axes according to the plot in Fig. 4. The sine-wave sweep from 5 to 500 to 5 Hz requires 15 minutes, and was done for one hour per axis. Prior to the test, a resonance search was done using a 1-g input, cycling from 7.5 to 2000 to 7.5 Hz in 15 minutes. No significant resonances were located.

Results

Visual inspection of the vibrated SCBA revealed a slight pressure loss (decrease from 4200 to 3900 psi), which, upon routine inspection by firefighters, would have resulted in the unit being removed from service. It is likely that no leak actually occurred. I believe that the pressure gauge indication was changed by the vibration. Two areas of minor abrasion were noted on the

facepiece lens and high-pressure hose. Upon inspecting the fittings and hardware for tightness, the bypass valve and the locking ring on the mainline valve backed open. Significant air flow from the bypass should be detected and corrected as a well-trained wearer dons the SCBA.

Discussion

The facepiece assembly was successfully leak-tested. A post-vibration breathing machine test produced a tracing comparable to pre-vibration testing, and I concluded that the vibration environment had no significant adverse affect on the SCBA's ability to function and protect if given a proper inspection before use. At ambient temperature this test is considered mild, but would be potentially severe if performed at high and low temperatures. This standard vibration test is considered appropriate for NIOSH and NFPA use in SCBA testing.

Figure 3. Selected damage photos of test runs.

Figure 4. Profile of vibration test.

INSTRUMENT DEVELOPMENT

Measurement of Aerosol Concentration as a Function of Size and Charge

Arthur Biermann and Werner Bergman

We have developed an aerosol diagnostic system that measures the number concentration of aerosols as a function of particle size and electronic charge. Size-charge analysis was accomplished by first fractionating the aerosol according to the electrical mobility of the particle, then determining the particle-size distribution of each mobility fraction using either a Climet optical counter or an ASASX-P laser spectrometer. By accumulating a particle-size distribution of each mobility fraction, we could determine by mathematical techniques the aerosol number concentration as a function of both particle charge and size. We are currently using this system to determine the aerosol number concentration as a function of particle size from 0.1 to 3.0 μm in diameter and as a function of particle charge from -1000 to $+1000$ electronic charges.

Introduction

The behavior of charged aerosol particles can significantly affect particle deposition and coagulation. Applications of charged aerosols include aerosol capture involving such methods as filtration and electrostatic precipitation, and charged-spraying techniques. The charge carried by aerosol particles has been measured by a variety of techniques including first- and second-order mobility spectrometers, aerosol electrometers, and variations on the Millikan oil-droplet apparatus. These previous methods have generally been applied to only the analysis of monodisperse aerosols, whereas our charge measurement technique is valuable for heterodisperse aerosols. Modifications to the mobility analyzer and computer data acquisition system will be discussed. We will also illustrate results for several types of latex aerosols.

Instrumentation

We show the instrumentation configuration, including our modifications, for particle-size and charge analysis in Fig. 1. The aerosol is first sampled by a Thermo Systems, Inc. electrostatic classifier (Model-3071). The Model 3071 is a differen-

tial mobility analyzer (DMA), as opposed to the cumulative type or first-order, in that it extracts particles in a specific electric mobility range as determined by the electric field and air-flow rates. The instrument is commercially available with a negative high voltage applied to the central rod of the cylindrical column. At a given voltage or electric field, charged particles experience a force tangential to their direction of flow due to the radially directed electric field. Negatively charged particles are repelled outward to be deposited on the outer cylinder. Positively charged particles are attracted to the center rod. Positively charged particles, in a certain mobility range, pass through the center-rod aerosol exit, forming the charged-particle sample outlet, q_+ .

The positively charged particles exiting in this airstream are analyzed by a detector for size. In the case of monodisperse aerosols, the detection of particle size is not necessary. However, in the case of heterodisperse aerosols, the size distribution and concentration of particles in the sample is determined by an optical particle counter. As the voltage is increased successively, the size distributions corresponding to lower and lower constant mobilities are measured until the entire mobility spectrum of the positively charged particles has been determined.

Figure 1. Instrumentation configuration for size-charge analysis.

In order to also measure the mobility spectrum of particles carrying negative charges, we incorporated a positive high-voltage power supply and high voltage relay into the DMA (Fig. 1). When the positive high voltage is applied to the center rod, negatively charged particles, rather than positively ones, are collected through the mobility-fractionated sample outlet.

For a complete charge-distribution analysis, it is also necessary to determine the size distribution of particles without charge. For this, the optical counter sampling configuration was changed to sample a portion of the excess air. While in this mode, the greatest voltage is selected in an attempt to remove all charged particles from the excess air outlet.

We used either a Climet 208 particle analyzer or a Particle Measurement Systems ASASX-P laser spectrometer for the optical counter to determine particle size. With the Climet, the particle-size spectrum, ranging from 0.3 to 10 μm in diameter, can be accumulated in 128 channels. The laser spectrometer, having a size range of 0.1 to 3.0 μm in diameter over 32 channels, has the advantage of detecting a lower particle size than the Climet.

Since 15 to 60 pre-selected mobility intervals might be necessary for a complete charge-distribution measurement, a 30- to 50-channel size distribution is accumulated for each mobility interval, generating an inordinate amount of data to be processed. Because of this, we interfaced an LSI-11/23 computer with the instruments for control, data acquisition, data processing, storage, retrieval and three-dimensional graphical representations. The manner in which the instrumentation is interfaced to the computer has previously been reported.¹ Using a FORTRAN program code, the experimenter is prompted for changes in default values for the DMA flow rates, optical-counter parameters, and sample time. The program proceeds to set a DMA voltage, wait for a certain equilibrium time period, and then accumulate a size spectrum with the specified optical particle counter. The mobility of particles sampled by the optical particle counter is determined according to Liu and Pui.² Particle charge is given by the ratio of this mobility to the mobility for a single-charged particle. This process is repeated until the entire range of pre-selected voltages, or mobilities, have been scanned.

Results

First, we obtained results of aerosol concentration as a function of both particle size and charge for only particles carrying positive charges. And, to further simplify the distribution, we used only monodisperse aerosols. Figure 2 is a three-dimensional representation of the size-charge distribution for the 0.797- μm latex aerosol. Grid lines for both the charge and diameter axes are positioned at equal-logarithmic spacings. Viewing the peak from the diameter axis, the peak is extremely narrow because of the monodisperse latex. But, viewing the peak from the charge axis, the peak is much broader, with some particles having as many as 1000 charge units. The highest particle concentration occurs at 14 charge units. The peak in the center rear of the graph is the background particles occurring from the evaporation of water droplets without a latex particle in them. Note that most of these smaller particles have little charge. The distribution spacing seems rather coarse with respect to charge because only 14 mobility intervals were scanned.

The combined positive- and negative-charge distribution for the 0.797- μm latex atomized at 25 psi is shown in Fig. 3. Equal-log intervals were still being used along both axes, however, on the charge axis, the "zero" grid line was added between the negative and positive distributions using the same spacing. Here, we have two peaks for the 0.797- μm latex corresponding to particles carrying negative and positive charges. Peak counts occur at ± 12 charge units. A greater concentration of particles carry positive charges. For the background aerosol particles at 0.2 μm diameter, the majority of particles are uncharged.

To further test the overall behavior of the size and charge distribution analysis, the 0.797- μm atomized latex aerosol was passed through a unipolar charger prior to sampling by the DMA and laser spectrometer. Ideally, this unipolar charger should place equal positive charges on particles of the same size by diffusion charging. The result, shown in Fig. 4, was a very narrow concentration distribution with respect to both the size and charge. A very small peak next to the major peak corresponds to doublets. The geometric mean charge for the 0.797- μm latex particles is +33 units with a corresponding geometric standard deviation of 1.45. The relative standard deviation, or

Figure 2. Three-dimensional surface representation for the atomized 0.797-μm latex, positive portion only.

Figure 3. Normalized counts for the combined positive, zero, and negative size-charge surface representation for the atomized 0.797-μm latex aerosol.

Figure 4. The size-charge distribution for the unipolar charge 0.797- μ m latex aerosol.

the arithmetic standard deviation/mean charge, is 25.8%. Both the mean and standard deviation agree with what other investigators have found for the mobility spectrum from this unipolar charger.³

The final test case using a monodisperse aerosol involved passing the aerosol through a neutralizer prior to sampling. Theoretically, the neutralizer reduces the aerosol charge to the Boltzman equilibrium charge distribution. The result, illustrated in Fig. 5, indicated the maximum particle concentration occurred at about "zero" charge. Comparing the atomized-only case in Fig. 3, the positive and negative charge peaks have been eliminated and merged toward zero charge. The peak concentration for the latex actually occurred at slightly less than zero charge at -3 units.

Summarizing the various treatments for the latex aerosols, Fig. 6 compares the corresponding contour graphical representations for the atomized only, unipolar-charged, and neutralized cases

previously shown in Figs. 3, 4, and 5. The contour lines corresponding to equal-normalized concentrations are 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9. This provided a more quantitative presentation of the data than the three-dimensional surface figures.

Conclusions

The aerosol diagnostic system we described can measure the number concentration of particles as a function of both size and electronic charge. Instrumental to our system is an LSI-11/23 computer that controls, accepts, and processes large quantities of information. Accumulation of a complete size-charge distribution requires 30 to 90 minutes depending upon the desired charge resolution and the optical-counter sampling time. In any case, the sampling time necessitates a constant aerosol for a significant period of time.

Figure 5. The combined size-charge distribution for the neutralized 0.797- μm latex aerosol.

Figure 6. Three-dimensional contour representations for the 0.707- μ m latex aerosol—atomized only, unipolar-charged, and neutralized.

References

1. A. Biermann and W. Bergman, *Measurement of Aerosol Concentration as a Function of Size and Charge*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-88417 (1983).
2. B. Y. H. Liu and D. Y. H. Fui, "A Submicron Aerosol Standard and the Primary Absolute Calibration of the Condensation Nuclei Counter," *J. of Colloid and Interf. Sci.* **47**, 155-171 (1974).
3. B. Y. H. Liu, K. T. Whitby, and D. Y. H. Fui, "A Possible Electrical Analyzer for Size-Distribution Measurement of Submicron Aerosols," *APCA Journal* **24**, 1067-1072 (1974).

RADIATION PROTECTION

Comparison of Calculated Neutron Spectrum and Dose Equivalent from NBS and LLNL 15-cm D₂O Spheres

Charles T. Prevost

We compared calculated neutron spectra and dose-equivalent for National Bureau of Standards (NBS) and Lawrence Livermore National Laboratory (LLNL) 15-cm D₂O spheres. First, MORSE calculations of the NBS sphere were compared to O5R calculations. Second, MORSE calculations of the LLNL sphere were compared to MORSE calculations of the NBS sphere.

Introduction

Unless the shape of the neutron spectrum of the source being measured is the same as that used for calibration, there will be some error in the measurement of the neutron dose rate with any instrument or dosimeter. To minimize these errors due to spectral differences, the experimenter must have a variety of neutron spectra when calibrating or evaluating instruments or dosimeters. This allows the experimenter to select a spectrum that most nearly represents the desired measurement.

Since neutron spectra at power reactors are much softer (low average energy) than those from the fast neutron sources (²⁵²Cf, PuBe, etc.) normally used for calibration, the National Bureau of Standards (NBS) designed a moderated ²⁵²Cf calibration source using a D₂O-filled sphere with a radius of 15 cm. The sphere is covered with a 0.05-cm thick cadmium shell. This sphere is based on a similar sphere developed at the Lawrence Livermore National Laboratory (LLNL).¹ Although the neutron spectrum does not duplicate reactor spectra, it is much closer than that from fast neutron sources.

Experimental Description

The 15-cm D₂O sphere and source encapsulation used by LLNL is significantly different from that used at NBS. In order to make a comparison of the two spheres, we first performed calculations using the NBS geometry to see how well our results compared with those done for the NBS.

Ing and Cross used the radiation-transport code O5R to perform the calculations on the NBS sphere in free space without cadmium.² They also investigated the significance of various parameters such as the encapsulation and the material in the tube used for inserting the source into the sphere. They concluded that most of these had an insignificant effect on dose equivalent and came up with the simplified model shown in Fig. 1. The results for this model are given in Table 1.² The fluence given at an energy, E_i , represents the quantity $4\pi R^2 E_i \phi(E)$ for the histogram interval defined by E_i and E_{i+1} . This convention follows that used by Ing and Makra.³ These spectra are in the form of $4\pi R^2$ times the fluence per unit lethargy (i.e., $\Delta N/\Delta \ln E$). The values in Table 1 were for 256,000 neutrons and have not been normalized. The 1-meter fluence in the third column was obtained by dividing the second column by $4\pi R^2$, multiplying by $\ln(E_i/E_{i+1})$, and dividing by $(E_i - E_{i+1}) \times 256,000$.

Calculation Basis

We used the LLNL version of the radiation-transport code, MORSE, for all our calculations. The first model we used was the one from Ing and Cross. The second was a much more detailed model of the description given by Schwartz and Eisenhaur.⁴ Both models gave 2.37×10^{-7} and 2.42×10^{-7} (mrem/hr)/(n/sec), respectively, at 1 meter from the center of the sphere. Both of

Figure 1. Ing and Cross model of NBS 15-cm D_2O sphere.

these calculations used a modified Maxwellian fission spectrum, with a temperature of 1.42 MeV as an input spectrum. The spectrum for the detailed model is given in Table 2.

The NBS 15-cm sphere is wrapped with cadmium, so Schwartz used Ing and Cross' free-space spectrum, cadmium cross sections, and ICRP fluence-to-dose-equivalent conversion factors, and arrived at 2.29×10^{-7} (mrem/hr)/(n/sec) at 1 meter from the center of the sphere.⁵ For the MORSE calculation, we included cadmium in the model and repeated the calculation. The result was 2.33×10^{-7} (mrem/hr)/(n/sec). Despite this excellent agreement in the dose equivalent rate, Fig. 2 shows the differences in the spectra.

Since the O5R and MORSE codes produced results that agreed with the NBS 15-cm sphere results, we chose MORSE for the LLNL-sphere calculations. The source-insertion hole in the LLNL sphere is much larger in diameter than that in the NBS sphere (3.387 cm vs 0.64 cm). As a result, the outer radius of the D_2O is also larger (18.364 cm). Moreover, the encapsulation of the LLNL ^{252}Cf source is different than that of the NBS ^{252}Cf source. The model used for the calculation is shown in Figs. 3 and 4. The calculated spectrum for the LLNL sphere is given in Table 3 and is compared with the NBS sphere in Fig. 5. The dose

Table 1. Leakage spectrum from NBS D_2O -moderated ^{252}Cf source at 1 meter (256,000 neutrons).

Energy (MeV)	$4\pi R^2 E_{eff}$ (EY)	n/cm^2 (MeV)
1.00E-05	7.02E+03	5.50E-02
5.00E-05	9.59E+03	1.20E-02
1.00E-04	1.17E+04	5.04E-03
2.00E-04	1.26E+04	2.71E-03
4.00E-04	1.41E+04	1.52E-03
7.00E-04	1.50E+04	8.70E-04
1.00E-03	1.61E+04	5.95E-04
3.00E-03	1.76E+04	3.01E-04
6.00E-03	1.88E+04	1.35E-04
1.00E-02	1.90E+04	7.54E-05
2.00E-02	2.02E+04	4.35E-05
4.00E-02	1.89E+04	2.04E-05
6.00E-02	1.87E+04	1.18E-05
8.00E-02	1.78E+04	7.96E-06
1.00E-01	1.67E+04	5.79E-06
1.50E-01	1.56E+04	3.39E-06
2.00E-01	1.42E+04	2.54E-06
2.50E-01	1.31E+04	1.82E-06
3.00E-01	1.25E+04	1.42E-06
3.50E-01	1.09E+04	1.04E-06
4.00E-01	9.37E+03	7.78E-07
4.50E-01	5.77E+03	4.23E-07
5.00E-01	7.62E+03	4.99E-07
5.50E-01	1.13E+04	6.70E-07
6.00E-01	1.21E+04	6.55E-07
7.00E-01	1.30E+04	6.23E-07
8.00E-01	1.30E+04	5.40E-07
9.00E-01	1.25E+04	4.58E-07
1.00E+00	8.67E+03	2.84E-07
1.20E+00	1.05E+04	2.98E-07
1.40E+00	1.40E+04	3.35E-07
1.60E+00	1.75E+04	3.63E-07
1.80E+00	1.86E+04	3.40E-07
2.00E+00	1.96E+04	3.21E-07
2.30E+00	2.45E+04	3.55E-07
2.60E+00	3.02E+04	3.84E-07
3.00E+00	2.67E+04	2.97E-07
3.50E+00	2.05E+00	1.95E-07
4.00E+00	1.57E+04	1.30E-07
4.50E+00	1.76E+04	1.29E-07
5.00E+00	1.59E+04	1.04E-07
6.00E+00	1.22E+04	6.91E-08
7.00E+00	8.0E+03	3.93E-08
8.00E+00	6.64E+03	1.93E-08
9.00E+00	2.82E+03	1.03E-08
1.00E+01	1.86E+03	6.09E-09
1.10E+01	1.19E+03	3.53E-09
1.20E+01	4.76E+02	1.29E-09
1.30E+01	3.97E+02	9.88E-10
1.40E+01	2.06E+02	4.75E-10
1.50E+01	1.06E+02	2.27E-10

^a From Ing and Cross.

Table 2. LLNL-calculated differential leakage spectrum from NBS D₂O-moderated ²⁵²Cf source at 1 meter.

Energy (MeV)	n/cm ² (MeV)
1.000E-10	2.005E+00
4.000E-07	1.398E-01
3.180E-06	2.392E-02
2.520E-05	4.194E-03
2.000E-04	5.799E-04
1.590E-03	9.364E-05
1.261E-02	1.107E-05
1.000E-01	3.146E-06
2.236E-01	9.142E-07
5.000E-01	7.264E-07
5.946E-01	6.103E-07
7.071E-01	5.405E-07
8.409E-01	3.438E-07
1.000E+00	2.801E-07
1.257E+00	3.482E-07
1.581E+00	3.626E-07
1.988E+00	3.821E-07
2.500E+00	3.046E-07
2.973E+00	2.129E-07
3.535E+00	1.547E-07
4.204E+00	1.084E-07
5.000E+00	7.132E-08
5.765E+00	4.409E-08
6.646E+00	2.297E-08
7.663E+00	1.116E-08
8.835E+00	5.714E-09
1.019E+01	2.055E-09
1.174E+01	6.700E-10
1.354E+01	1.790E-10
1.561E+01	4.784E-11
1.800E+01	

Table 3. LLNL-calculated differential leakage spectrum from LLNL D₂O-moderated ²⁵²Cf source at 1 meter.

Energy (MeV)	n/cm ² MeV ^a	n/cm ² MeV ^b
1.000E-10	8.960E-04	1.778E+01
4.000E-09	1.257E-01	2.042E-01
3.180E-06	2.612E-02	3.250E-02
2.520E-05	4.200E-03	5.107E-03
2.000E-04	4.911E-04	5.956E-04
1.590E-03	7.909E-05	9.371E-05
1.261E-02	1.150E-05	1.319E-05
1.000E-01	2.741E-06	3.191E-06
2.236E-01	7.949E-07	9.476E-07
5.000E-07	8.512E-03	7.404E-07
5.946E-01	5.027E-07	6.009E-07
7.071E-01	4.510E-07	5.580E-07
8.409E-01	3.053E-07	3.618E-07
1.000E+00	2.257E-07	2.769E-07
1.257E+00	2.562E-07	3.118E-07
1.581E+00	2.704E-07	2.752E-07
1.988E+00	3.347E-07	3.374E-07
2.500E+00	2.819E-07	2.804E-07
2.973E+00	1.672E-07	1.624E-07
3.535E+00	1.259E-07	1.092E-07
4.204E+00	9.863E-08	8.267E-08
5.000E+00	6.182E-08	5.933E-08
5.765E+00	3.926E-08	3.897E-08
6.646E+00	2.057E-08	1.966E-08
7.663E+00	1.030E-08	9.885E-09
8.835E+00	4.803E-09	4.025E-09
1.019E+01	1.779E-09	1.755E-09
1.174E+01	6.478E-10	5.241E-10
1.354E+01	1.572E-10	1.613E-10
1.561E+01	4.461E-11	4.001E-11
1.800E+00		

^a Without walls, floor, and air.

^b With walls, floor, and air.

equivalent at 1 meter is 2.02×10^{-7} (mrem/hr)/(n/sec). This is 11.8% lower than that for the NBS sphere. Next, the walls, floor, and air were included in the model to determine the effects of scatter. The spectrum is given in Table 3. The scatter raised the dose-equivalent rate to 2.16×10^{-7} (mrem/hr)/(n/sec) at 1 meter.

In the near future, we will make a comparison between the MORSE results and that from the radiation-transport code, TART. Also, we will try to resolve the spectra differences in the codes O5R and MORSE.

Figure 2. NBS sphere vs NBS sphere with LLNL calculation.

Figure 3. Model of LLNL 15-cm D₂O sphere.

Figure 4. Source encapsulation and rabbit for LLNL model.

Figure 5. LLNL sphere vs NBS sphere calculation.

References

1. R. V. Griffith, D. R. Slaughter, H. W. Patterson, J. L. Beach, E. G. Frank, D. W. Rueppel, and J. C. Fisher, "Multi-Technique Characterization of Neutron Fields from Moderated ^{252}Cf and $^{238}\text{PuBe}$ Sources," *Proc. National and International Standardization of Radiation Dosimetry*, Atlanta, GA, Vol. II, p. 167 (Dec. 5-9, 1977).
2. H. Ing and W. G. Cross, "Spectral and Dosimetric Characteristics of a D_2O -Moderated ^{252}Cf Calibration Facility," *Health Physics* 46, 1 (1984).
3. H. Ing and S. Makra, *IAEA Compendium of Neutron Spectra in Criticality Accident Dosimetry*, International Atomic Energy Agency, Vienna, Austria, Technical Report Series No. 180 (1978).
4. R. B. Schwartz and C. M. Eisenhaur, *The Design and Construction of a D_2O -Moderated ^{252}Cf Source for Calibrating Neutron Personnel Dosimeters Used at Nuclear Power Reactors*, National Bureau of Standards, Gaithersburg, MD, NUREG/CR-1204 (1980).
5. R. B. Schwartz, private communication, National Bureau of Standards, Gaithersburg, MD (August 1983).

Programs for Calculating Beta Spectra

Charles T. Prevost

Several programs have been written to calculate beta spectra given the atomic number of the daughter and the transition energy. We discuss and compare two methods of obtaining Fermi function values.

Introduction

With the recent increased interest in beta dosimetry by the nuclear industry, a need exists to have beta spectra available for theoretical analyses such as radiation transport. The calculation of detector response functions requires the use of a gamma, Γ , function with a complex argument. This function cannot be readily evaluated, but it has been tabulated; Wilkinson has developed analytical approximations.^{1,2} Mantel has reported beta spectra³; unfortunately, he does not include tables of intensity versus energy, so the data is difficult to use. So, we wrote several codes for the HP-85 which will calculate any beta spectrum of interest.

Fermi Function

Beta particles of either sign (positive or negative electrons) may be ejected in the course of spontaneous transformation of atomic nuclei. The statistical distribution of the electrons ejected covers all energies from zero up to a maximum energy, E_0 , characteristic of the transformation. This distribution of electron energies reflect the relative probability of the various possible ways in which the total energy, E_0 , released by a nucleus, can be shared between an electron and a neutrino.

The probability of emission of an electron is proportional to the Fermi function, which is defined as the ratio of the electron density at the daughter nucleus to the density at infinity (outside the atom):

$$f(Z, E) = f(Z, \eta) = \frac{|\phi e(0)|}{\delta e(\infty)_Z} \\ = \eta^{2s} e^{-\pi\eta} (1 + s + i\delta) \quad (1)$$

where

$\Gamma(z)$ = complex gamma function,
 Z = atomic number of daughter,

η = momentum of electron after its ejection from the atom (in units of mc),

m_0 = mass of the electron,

c = 2.99776×10^8 m/sec,

v = velocity of electron (m/sec),

$\beta = v/c = \eta/\sqrt{1 + \eta^2}$,

$\epsilon = w = \sqrt{1 + \eta^2}$ = total energy of electron (in units of mc^2)

$T = mc^2(w - 1)$ = kinetic energy of electron (in units of mc^2)

$\gamma = Z/137$,

$s = \sqrt{1 - \gamma^2} - 1$,

$\delta = \gamma/\beta = Z \sqrt{1 + \eta^2} / 137\eta$,
 $= (4\pi mcR/h)^{2s} [\Gamma(3)/\Gamma(3 + 2s)]^2$
 $(1 + s/2)$,

R = nuclear radius = $1.37 A^{1/3} 10^{-15}$ (m),

h = 6.62×10^{-34} J - s, and

A = atomic weight.

The Fermi function depends on the atomic number of the daughter and electron energy, but not of the maximum energy.

Beta Spectrum

The beta spectrum is related to the Fermi function by the relation

$$N(E) = f_c(Z, E) (E_0 - E)^2 \\ \times (E + 1)(E^2 + 2E)^{-1/2} \quad (2)$$

where E is in units of m_0c^2 , and f_c is the Fermi function multiplied by a screening correction and a shape factor. Since the screening correction rarely has more than a 2-3% effect, it was ignored for these calculations.

Shape Factor. The transition probability is proportional to the product of the electron and neutrino wave functions. Consecutive terms in the expansion for these wave functions decrease rapidly. The first term in the expansion generates the

allowed transition, and successive terms refer to the forbidden transitions of increasing order. These forbidden transitions have diminishing, but nonvanishing probability.

Allowed transitions are characterized by the absence of a change in nuclear spin and parity ($\Delta J = 0$, $\Delta \pi = \text{no}$). Forbidden transitions are hindered by the involvement of a change in nuclear spin and parity ($\Delta J = 1$, $\Delta \pi = \text{yes}$). Unique transitions are associated with those forbidden transitions governed by a single moment, as against parity-forbidden transitions which are governed by a combination of several beta moments. Presently, it is impossible to calculate the shape for non-unique forbidden spectra. However, it has been shown empirically that the non-unique, first-forbidden spectra have a shape similar to unique, allowed transitions,⁴ and the non-unique, second-forbidden spectra have a shape similar to unique, first-forbidden transitions.⁵ Table 1 shows the shape-correction type for various transition classifications. The type of transition is given by Mantel for a large number of transitions.³ The shape-correction factor for unique spectra is given by

$$S_n = \sum_{r=0}^n \frac{(2\nu + 1)!}{4^r (\nu!)^2 (2n - 2\nu + 1)!} q^{2(n-r)} L_r, \quad (3)$$

where

- n = degree of forbiddenness,
- q = neutrino momentum in units of $m_0 c$,
and
- L = tabulated function.^{5,6}

For unique, forbidden spectra, the correction factor, S_n , simplifies to

$$\begin{aligned} S_1 &= (w^2 - 1) + (w_0 - w)^2 \\ S_2 &= (w^2 - 1)^2 + (w_0 - w)^4 \\ &\quad + 10/3 (w^2 - 1) (w_0 - w)^2 \end{aligned}$$

$$\begin{aligned} S_3 &= (w^2 - 1)^3 + (w_0 - w)^6 + \\ &\quad 7(w^2 - 1) (w_0 - w)^2 [(w^2 - 1) \\ &\quad + (w_0 - w)^2] \end{aligned} \quad (4)$$

Since we are really interested in the shape and not the magnitude of these corrections, the correction factors were all normalized to their value at zero kinetic energy ($w = 1$). Thus, S_1 was divided by $S_1(1) = (w_0 - 1)^2$; S_2 by $S_2(1) = (w_0 - 1)^4$; S_3 by $S_3(1) = (w_0 - 1)^6$. The shape-correction factor for allowed spectra is 1.

Evaluating the Fermi Function

There are two ways of obtaining values of the Fermi function. The first is to interpolate between values tabulated in the NBS tables, and the second is to use Wilkinson's approximation for the complex gamma function to derive an analytical expression for the Fermi function.

The program NBSTAB was written to take 80 pairs of energy and Fermi function values from the NBS tables and create a data file which can be read by the program that then calculates the beta spectrum (called BETAS). This was done so that the table values would only have to be entered once. They are then saved in a data file for subsequent use. BETAS reads the energy and Fermi function data from the file created by NBSTAB and interpolates to obtain Fermi function values at energies of interest, which are integer multiples of $E_0/20$. For energies greater than 3.1018 MeV ($\eta = 7$), the following expression is used:

$$f(Z, \eta) = \eta^2 F(Z, \eta) = \eta^{2+2s} (A + B/\eta + C/\eta^2) \quad (5)$$

The values of A , B , and C are tabulated in the NBS tables for each Z . This program also calculates the spectral correction factors which vary for allowed and forbidden transitions. The corrected spectrum is written out on the printer as a function of energy, and is written to a data file that can be plotted with the program DPLOTM, which is a modified version of HP's DPLOT.

Table 1. Shape-correction type for various transition classifications.

Mantel type	Classification	Nuclear spin change	Nuclear parity change	Shape type
0	Allowed	0, ± 1 (not 0 $\rightarrow$ 0)	No	0
1'	Non-unique, first-forbidden	0, ± 1	Yes	0
1	Unique, first-forbidden	± 2	Yes	1
2'	Non-unique, forbidden	± 2	No	1
2	Unique, second-forbidden	± 3	No	2

The code WLKFF uses a Wilkinson approximation for the complex gamma function to calculate the Fermi function and create a data file which can be read by BETAS. For this case,

$$F(Z, w) = 2(1 + \gamma)(2pR)^{2(\gamma-1)} e^{\frac{-\pi\alpha Z w}{p}} \times [\Gamma(2\gamma + 1)]^{-2} (\Gamma(\gamma + i\alpha Z w/p))^2, \quad (6)$$

where

$$\begin{aligned} \ln \Gamma(z) &\approx (z-1/2)\ln z - z + 1/2\ln(2\pi) \\ &\quad + 1/12z + \dots, \\ \ln(x + iy) &\approx (x-1/2)\ln(x^2 + y^2) \\ &\quad - 2y \operatorname{Arctan}(y/x) - 2x \\ &\quad + \ln(2\pi) + x/[6(x^2 + y^2)] + \dots, \\ w &= \text{total electron energy in } m_0c^2 \text{ units,} \\ p &= [w^2 - 1]^{1/2}, \\ s &= (E - 2)/(E + 2), \\ &= e^2/\hbar c = 1/137, \text{ and} \\ &= [1 - (\alpha Z)^2]^{1/2}. \end{aligned}$$

The function, $\Gamma(2\gamma + 1)$, depends on Z , and since it has no effect on the shape, it does not need to be included in the calculation.

Figure 1, a flow chart illustrating the use of the codes, shows two methods of obtaining the spectra. The first involves the use of NBSTAB, BETAS, and DPLOTM. After the initial use of NBSTAB for a given Z , only BETAS and DPLOTM are required for subsequent calculations for that Z . The second method requires only WLKFF and DPLOTM.

Results

Both BETAS and WLKFF were used to calculate spectra for ^{147}Pm , ^{204}Tl , and ^{90}Sr . Although

different in magnitude, the shape determined by the two methods are within 1% at all energies and within a tenth of a percent, except near the ends of the spectra. Thus, the Wilkinson approximation is more than adequate and is easier to use than entering the NBS values from tables. Our results are given in Tables 2, 3, and 4, and also shown in Figs. 2, 3, and 4. Both uncorrected and corrected spectra are shown to illustrate the effect of the shape-correction factor.

References

1. U.S. Department of Commerce, *Tables for the Analysis of Beta Spectra*, National Bureau of Standards, Applied Mathematics Series 13.
2. D. H. Wilkinson, "Evaluation of the Fermi Function," *Nuclear Instruments and Methods* **82**, 122-124 (1970).
3. J. Mantel, "The Beta Ray Spectrum and the Average Beta Energy of Several Isotopes of Interest," *Journal of Applied Radiation and Isotopes* **23**, 407-413 (1972).
4. L. T. Dillman, "Radionuclide Decay Schemes and Nuclear Parameters for Use in Radiation-Dose Estimation," *J. Nucl. Med.* **10**, Suppl. 2 (1969).
5. K. Siegbahn, *Beta- and Gamma-Ray Spectroscopy* (North-Holland Publishing Co., Amsterdam 1955), p. 328.
6. M. E. Rose, *Tables for the Analysis of Allowed and Forbidden Beta Transitions*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-1459 (1953).

Figure 1. Flowchart for calculation of the beta spectrum.

Table 2. ^{147}Pm beta spectrum.

$E(\text{MeV})$	$N(E)$	C	$S(E)$
0.0006	0.650	1.000	0.650
0.0112	0.607	1.000	0.608
0.0225	0.567	1.000	0.567
0.0337	0.523	1.000	0.523
0.0449	0.479	1.000	0.479
0.0561	0.436	1.000	0.436
0.0674	0.393	1.000	0.392
0.0786	0.350	1.000	0.350
0.0896	0.308	1.000	0.308
0.1010	0.267	1.000	0.267
0.1123	0.228	1.000	0.228
0.1235	0.190	1.000	0.190
0.1347	0.155	1.000	0.155
0.1459	0.122	1.000	0.122
0.1572	0.093	1.000	0.093
0.1684	0.066	1.000	0.066
0.1796	0.044	1.000	0.044
0.1908	0.025	1.000	0.025
0.2021	0.012	1.000	0.012
0.2133	0.003	1.000	0.003
0.2245	0.000	1.000	0.000

Figure 2. ^{147}Pm beta spectrum.

Table 3. ^{204}Tl beta spectrum.

$E(\text{MeV})$	$N(E)$	C	$S(E)$
0.0006	10.31	0.999	10.31
0.0382	10.36	0.972	10.07
0.0764	10.30	0.954	9.82
0.1145	10.12	0.946	9.57
0.1527	9.81	0.948	9.30
0.1909	9.40	0.960	9.02
0.2291	8.89	0.982	8.73
0.2672	8.29	1.013	8.40
0.3056	7.61	1.055	8.03
0.3436	6.87	1.107	7.61
0.3818	6.08	1.169	7.11
0.4199	5.26	1.241	6.53
0.4581	4.43	1.323	5.86
0.4963	3.61	1.415	5.10
0.5345	2.81	1.517	4.26
0.5726	2.07	1.629	3.37
0.6108	1.40	1.751	2.45
0.6490	0.83	1.883	1.56
0.6872	0.39	2.025	0.78
0.7253	0.10	2.176	0.22
0.7635	0.00	2.338	0.00

Figure 3. ^{204}Tl beta spectrum.

Table 4. ^{90}Sr beta spectrum.

$E(\text{MeV})$	$N(E)$	C	$S(E)$
0.0006	40.7	1.000	40.7
0.1135	54.1	0.928	50.2
0.2270	68.8	0.865	59.5
0.3405	82.1	0.813	66.7
0.4540	93.5	0.770	72.0
0.5675	102.5	0.738	75.6
0.6810	108.8	0.715	77.8
0.7945	112.1	0.703	78.8
0.9080	112.4	0.700	78.7
1.0215	109.7	0.708	77.6
1.1350	104.2	0.725	75.5
1.2485	96.0	0.753	72.3
1.3620	85.6	0.790	67.7
1.4755	73.5	0.838	61.5
1.5890	60.1	0.895	53.8
1.7025	46.2	0.963	44.5
1.8160	32.5	1.040	33.8
1.9295	20.1	1.128	22.6
2.0430	9.7	1.223	11.9
2.1565	2.6	1.333	3.5
2.2700	0.0	1.450	0.0

Figure 4. ^{90}Sr beta spectrum.

CAM Particle Deposition Evaluation

Arthur Biermann and Steve Velen

We assessed particle deposition and loss occurring in an Eberline Alpha-3 Continuous Air Monitor (CAM) using monodisperse test aerosols. Our study also included the investigation of detection loss due to deposition of nonuniform particles on the collection filter. Results indicate that particle losses were a strong function of aerosol size, with a 44% loss occurring for 6- μm diameter aerosols and a 0.3% loss for the 0.6- μm diameter aerosols.

Introduction

We investigated the deposition and loss of laboratory-generated aerosols in an Eberline Alpha-3 Continuous Air Monitor (CAM). CAMs are used at LLNL in radiation alarm systems; they contain 47-mm-diameter particulate collection filters and 25-mm alpha detectors. We determined the distribution of different aerosol sizes on the particulate-collection filter in order to investigate the effectiveness of the CAM's sampling and detector configuration. We also assessed the dependence of aerosol losses in the sampling inlet, filter housing, and other locations in the CAM detector and filter chamber as a function of particle size. This information, along with a spatial calibration of the alpha detector, result in a more quantitative determination of alarm points for the CAM.

Experimental Procedure

Monodisperse aerosols of dioctylsebacate (DOS) and methylene blue (MB) were generated using a Berlund-Liu aerosol generator.¹ This generator uses a vibrating orifice to produce uniformly sized droplets from a pressurized liquid solution. We added dispersion air to the particles, and added additional air to evaporate the droplets leaving the solute as either a solid or nonvolatile liquid particle. The concentration of the solution and the size of the orifice determined the final aerosol particle size. We generated three different sized aerosols. A solution of 0.01% MB in isopropanol resulted in a 0.56- μm -diameter solid

aerosol. Solutions of 0.01 and 0.1% DOS produced, respectively, 2.78- and 6.24- μm -diameter liquid aerosols. Trace amounts of MB were also added to the DOS solutions for subsequent spectrophotometric analysis. After generation, the aerosol particles were passed vertically upward through a ⁸⁵Kr ionizing aerosol neutralizer, and then directed downward toward the CAM inlet sample port.

The size distributions of the aerosols were monitored using a Climet 208 optical-particle analyzer. The Climet had been calibrated for particle sizes from 0.3- to 10.0- μm in diameter using aerosols of uniform latex spheres. Before each CAM-sampling period, we used the optical counter to verify the uniformity of the aerosol distribution. If any doublet or triplet particles appeared, the aerosol generator was readjusted to eliminate them. For each test aerosol, several Climet size distributions were taken during the CAM-sampling periods. The size values we report are the average of the geometric mean diameters from the Climet distributions.

The CAM contained a 47-mm diameter, cellulose membrane filter with a pore diameter of 5.0 μm . The sampling flow rate for the three aerosol tests was 11 lpm (or 30 lpm as measured by the CAM rotometer). We used sampling times from 60 to 90 min depending on the particular aerosol size.

Aerosol particles that were deposited on the surfaces of the CAM sample chamber walls or inlet probe were removed by repeated swipes using Q-tips soaked in acetone. Each swipe was rinsed in 5 or 10 cc of acetone. Aerosol particles collected by the filter were removed by dissolving portions of the filter in acetone. A DK-11 spectrophotometer was used to measure the absorbance of MB in the solutions.

¹ R. N. Berglund and B. Y. H. Liu, "Generation of Monodisperse Aerosol Standards," *Env. Sci. and Tech.* 7 147-152 (1973).

Results

We measured the amount of particle deposition for eight different portions of the CAM chamber, including the collection filter. A schematic depicting the location of these areas is shown in Fig. 1. The deposition occurring in these areas is listed in Table 1 for the three test aerosols. Diameters of the test aerosols are reported as the optical particle diameters and calculated aerodynamic diameters. Deposition values are given as percentages relative to the total mass of MB retrieved from all CAM surfaces and the filter. The filter was the major collection area for the smaller particle sizes, with 96.0 and 99.7% of the particle deposits retrieved for the 2.7- and 0.6- μm -diameter aerosols, respectively. However, for the largest

Table 1. CAM aerosol deposition at 30 lpm (CAM rotameter) for three monodisperse aerosols.

	1	2	3
Optical diameter (μm)	6.23	2.76	0.56
Aerodynamic diameter (μm)	5.95	2.65	0.64
Location	% of total deposits		
Inlet tube	0.61	0.42	0.055
Inlet tube, bottom	2.06	1.84	0.071
Area above detector	44.0	0.48	0.056
Rest of area around detector	1.90	0.11	0.038
Rest of chamber, back, outside	4.67	0.55	0.046
Filter holder ring	0.50	0.46	0.026
Detector	0.05	0.11	0.025
Filter	46.2	96.0	99.7

Figure 1. CAM chamber and collection areas.

size, the $6.0\text{-}\mu\text{m}$ -diameter, only 46.2% was collected by the filter. Areas of significant collection occurred in aerosol inlet regions of the CAM. In the case of the $6.0\text{-}\mu\text{m}$ aerosol, the area above the detector and opposite the inlet collected 44% of the particles, nearly as much as the filter itself. Obviously, the larger particles deviate from the air streamlines as they approach the filter and hit this localized area above the detector.

Secondary collection areas for the larger-sized particles are the outside edge and back of the chamber and the inlet tube itself. Combined, these areas captured 7.2% of the $6.0\text{-}\mu\text{m}$ particles, but only 1.1% of the $2.6\text{-}\mu\text{m}$ particles.

The deposition patterns of the particles captured on the filter surface are illustrated in Fig. 2 for the 0.6- , 2.7- , and $6.0\text{-}\mu\text{m}$ -diameter cases. The

most uniform collection is that for the $0.6\text{-}\mu\text{m}$ diameter particles, while the 2.7- and $6.0\text{-}\mu\text{m}$ diameter particles show marked high concentrations in an area of the filter which is opposite the chamber from the inlet. With these patterns in mind, filters from actual tests were divided into four concentric areas. The subdivided area boundaries are illustrated on the clean filter in Fig. 2. The percentage of particle deposition in the subdivided areas relative to the total collected on the filter is presented in Table 2. The values confirm quantitatively that particle collection is extremely nonuniform on the filter surface. For all test aerosols, deposition decreases toward the center of the filter.

Since the detector itself is only 25 mm in diameter, it is important to ascertain the detection efficiency for areas of the filter lying outside its

Figure 2. Particle deposition on the collection filter for (a) a clean filter showing subdivided areas, (b) $0.6\text{ }\mu\text{m}$, (c) $2.7\text{ }\mu\text{m}$, and (d) $6.0\text{ }\mu\text{m}$ aerosols. The CAM outlet is at the top.

Table 2. Aerosol deposition on the CAM filter for the three test aerosols.

	1	2	3
Optical diameter (μm)	6.23	2.78	0.56
Aerodynamic diameter (μm)	5.95	2.65	0.64
Concentric area (radius, μm)	% of total filter deposits		
15-23.5, top 1/3 ^a	17.5	18.4	16.5
15-23.5, remainder 2/3	25.1	31.4	33.9
10-15, top 1/3 ^a	34.0	15.7	10.5
10-15, remainder 2/3	9.4	15.5	17.8
5-10	12.9	14.9	16.9
0-5	1.2	4.0	4.4

^a Top 1/3 is the area of filter directly opposite the CAM inlet.

projected area onto the filter. For this reason, a spatial calibration was performed using a ^{239}Pu source having a 3-mm effective diameter. We can estimate what fraction of particles collected by the filter are actually detected by integrating the product of the spatial calibration and particle collection over the filter area. The percentage of particles actually detected are 32, 34, and 35% for the 6.0-, 2.7-, and 0.6- μm diameter aerosols, respectively.

Thus, many of the nonhomogeneities in particle deposits seen on the filter are cancelled by the detector integration. Relative to the percentages to the total deposition throughout the CAM, the fractions detected are 15, 32, and 34% for the 6.0-, 2.7-, and 0.6- μm diameter aerosols. The lower value for the larger aerosol test case resulted from the significant particle losses in other areas of the CAM.

Conclusions

Particle loss in the CAM is extremely sensitive to the aerosol size distribution in the 0.6- to 6.0- μm diameter range. Using monodisperse aerosols, losses ranged from 0.3% for 0.6- μm diameter to over 50% for particles as large as 6- μm in diameter. Particle collection on the 47-mm diameter filter was nonhomogeneous for all particle sizes, but especially so for 2 μm and above. For the largest particle size we considered, it was estimated that only 15% of the aerosol would actually be detected. For smaller aerosols, filter collection approaches 100% and the amount detected approaches 35%.

Mercury Scrubber for the Ostlund Tritium Monitor

Peter M. Swearingen, James S. Johnson, Charles A. Harder, and Lisa M. Caldwell

We describe a mercury scrubber that will be placed in an air stream containing tritium. The device removes mercury by amalgamation on a gold surface. We observed an inlet-to-outlet removal of mercury ratio of 5000. The scrubber will be placed in a flow system to protect an Ostlund Tritium Monitor.

Introduction

The Ostlund tritium monitor in Building 331 at LLNL uses a palladium catalyst on molecular sieve material to trap tritiated hydrogen gas. The monitor is in continuous use for stack-effluent observation. Future decontamination operations in the building will release mercury vapor into the effluent. Since mercury poisons the palladium catalyst, a scrubbing system will be necessary to clean mercury vapor from the $250 \text{ ml} \cdot \text{min}^{-1}$ gas-sampling stream passing through the Ostlund device.

Device Description

The tendency of elemental mercury to combine with certain other metals to form amalgams is well-known.¹ Gold readily amalgamates with mercury, and this combination is used as the basis for the scrubber design. To enhance amalgamation, it seemed desirable to provide a large surface area of gold.

We chose stainless-steel wool material* for its high surface area and electroplated it with gold. Approximately 225 g of the gold-plated wool material was divided into four sections and compressed into the individual compartments of the flow device shown in Fig. 1. Each compartment module is individually threaded and the sub-units are screwed together in series for the complete assembly. With this construction, disassembly for cleaning or replacement of the element is simple and rapid.

To further enhance the scrubbing efficiency of this unit, we chose a convoluted flow path. Air enters the cylindrical system through a 0.6350-cm central port and must then exit to the next cham-

ber through four 0.3175-cm ports equally spaced near the circumference of a circular baffle disk. Flow from the second chamber then passes through another 0.6350-cm opening centered in a third circular disk. This variation of flow exits is repeated in successive chambers to force a highly dispersed flow of air around the gold plated scrubbing surface of each compartment.

Device Performance

We tested the scrubber by challenging the assembled unit with a known concentration of mercury vapor in air. Test atmospheres were generated with a system previously discussed by Nelson.² In the Nelson procedure, calculations based on volumetric considerations and the temperature of heated-air flow across a mercury-pool surface are used to determine the flow settings on mercury generator rotameters. We measured mercury-vapor concentrations with a Bacharach Mercury Sniffer (Bacharach Instruments Co., AMBAC Industries, Model MVZ) and our measurements closely agreed with the mercury concentrations calculated for the Nelson system.

Flow in the Ostlund monitor's sampling line is predetermined at $250 \text{ ml} \cdot \text{min}^{-1}$ (air). Our system was assembled to control flow through the scrubber to this amount. A schematic of the apparatus is shown in Fig. 2. Flow was set by a mass-flow controller (Control Unit FM360, Tylan, Inc.), and the mercury was monitored by passing the exhaust air through an impinger containing a solution of KMnO_4 and H_2SO_4 . Subsequent to each period of testing, the permanganate solution was analyzed for mercury content by atomic absorption spectrophotometry (cold-vapor-generation technique). No mercury was detected by this procedure. In addition, valves allowed the upstream or downstream flow to be diverted to the mercury sniffer for periodic instrumental monitoring. Results of the quantitative testing are shown in Table 1.

* Elephant Brand Metallic Wool, #430 stainless steel, medium grade (1), International Steel Wool Corp., Springfield, Ohio.

Figure 1. Flow device showing stainless-steelwool inside.

(impinger for Table 1,
instrumental for Table 2)

Figure 2. Schematic of experimental apparatus.

Table 1. Quantitative testing results.

Day	Time of flow ^a	Challenge concentration (mg Hg·m ⁻³)	Total mercury (mg)
1	5:57:00	0.62	0.0553
2	5:59:00	0.75	0.0673
3	6:04:00	0.78	0.0710
4	6:06:00	0.92	0.0846
5	5:58:00	0.79	0.070
6	6:04:00	0.75	0.0683
7	6:12:00	0.73	0.0679

Total testing time: 42:22:00 Total mercury uptake: 0.4851 mg

^aElapsed time of flow through each KMnO₄ solution before a fresh solution was installed.

A second test of the mercury scrubber was performed at higher mercury concentrations. For this challenge, we used both the Bacharach MV2 and a Jerome Model 411 mercury-vapor analyzer (Jerome Instrument Corp., Jerome, Arizona 86331). The Model 411 can detect mercury concentrations as low as 10⁻³ mg·m⁻³. We tested for mercury-vapor penetration through the scrubber and found no measurable mercury downstream. Since only a fraction of the mercury-laden air from the generator was drawn through the scrubber, the excess flow was exhausted into a fume hood. The exhaust flow was diluted with clean air from a mass-flow controller, and the diluted mixture was monitored regularly with the Bacharach device. Results from this second test are shown in Table 2.

Conclusions

The potential source of mercury contamination is from diffusion pumps that have undergone an initial cleaning process. There is no measurable mercury (by volume) in these pumps after this cleaning. The pumps will then be baked in a large oven that exhausts to the stack at a volumetric flow of 140 cfm. The stack flow itself is nominally 13,000 cfm. A worst-case mercury concentration was arbitrarily chosen as the addition of 100 g·hr⁻¹ (7 ml) of mercury from the oven to the main stack. This hypothetical example assumes seven pumps are heated in the oven at one time, with a total residue of 1 ml of mercury per pump. In this situation, the maximum concentration seen

Table 2. Second test results.

Day	Time of flow	Challenge concentration (mg·m ⁻³)	Total mercury (mg)
1	6:00:00	3.89	5.45
2	6:00:00	3.89	5.45
3	5:00:00	3.89	4.54
4	5:30:00	3.89	5.00
5	7:00:00	3.89	6.31
Total testing time: 29:30:00		Total mercury uptake: 26.75 mg	

by the scrubber is 5 mg·m⁻³. Several times during the second phase of testing, the challenge concentration rose to this amount before being adjusted back to the indicated average concentration. Each time this excursion occurred, the penetrating flow was measured and no mercury was detected by the Jerome Model 411 instrument.

A more complete characterization of this scrubber would require the following questions to be answered:

- What is the total mercury capacity of the scrubber before breakthrough?
- What higher concentrations of mercury vapor could the scrubber effectively remove from air?
- Is it possible to regenerate the scrubber to restore its original cleaning capacity?

The answers to these questions would provide a more thorough characterization of the scrubber for an ideal operational use. Since our application of this scrubber is for a specialized case, the data we obtained is adequate for this application. We feel that the gold wool scrubber described here will protect the Ostlund monitor from mercury-vapor poisoning.

References

1. F. A. Cotton and G. Wilkinson, *Advanced Inorganic Chemistry*, 2nd Ed. (Wiley, 1962), p. 604.
2. G. O. Nelson, "Simplified Method for Generating Known Concentrations of Mercury Vapor in Air," *Rev. Sci. Instr.* 41(5), 776 (1970).

Publication Abstracts

PUBLICATION ABSTRACTS

B. Baptiste, *The Prevention of Back Injuries and Pain*, presented at the 70th Annual National Safety Congress and Exposition, October 19, 1982, Chicago, Illinois; Lawrence Livermore National Laboratory, Livermore, CA, UCRL-88242 (1982).

J. H. Elliott, *The Use of Radiation Damage to Match the Sensitivity of LiF TLD Dosimeters*, presented at the Health Physics Annual Meeting, Baltimore, Maryland, 19-23 June, 1983.

Radiation damage has been used to reduce the sensitivity of unmatched LiF TLDs to match that of the working stock in our dosimetry laboratory. Three thousand new TLD ribbon dosimeters, whose mean sensitivity was about 10% greater than our dosimeter working stock, were grouped by sensitivity. After some groups were exposed to different doses to determine the rate of sensitivity loss, S/S_0 vs rads, the remaining groups were exposed to doses obtained from the sensitivity loss plot to obtain a match to the working stock. The shapes of the glow curves obtained before and after irradiation did not change, and the use of our ultraviolet second-read dose-estimation method was still viable. The altered sensitivities fell within the plus or minus 10% limits of the working stock and remained unchanged after a 20-hour anneal at 400°C. This method might be useful in producing a large quantity of matched TLDs.

C. L. Graham and J. H. Elliott, *A Source of Monoenergetic Electrons for Beta Dosimetry*, presented at the International Beta Dosimetry Symposium, February 15-18, 1983, Washington, D.C.; Lawrence Livermore National Laboratory, Livermore, CA, UCRL-88022 (1983).

We have developed an electron spectrometer which can produce a continuous beam of monoenergetic electrons. The spectrometer uses 20 millicuries of ^{137}Cs as a source of electrons which can be magnetically focused at the exit port. Various electron energies can be selected by changing the magnetic field. The maximum electron energy and dose rate for the present design are approximately 630 keV and 1.5 rad/hr, respectively.

R. V. Griffith, T. A. McMahon, and Guillermo Espinosa, *A Commercial Bacterial Colony Counter for Semiautomatic Track Counting*, presented at the

10th International DOE Neutron Dosimetry Workshop, August 30-September 2, 1983, Aca-pulco, Mexico.

The information one must obtain from a solid-state track detector depends on the specific application. The most common information need is the measurement of track density. The number of tracks per unit area is commonly needed by those performing neutron and alpha dosimetry, for example, to determine radiation dose. In recent years, a class of semi-automatic counting systems has become available for under \$15,000. These systems, usually developed for bacterial colony counting, are capable of measuring track density. The basic instrument is designed to count relatively large objects ($>100\text{ }\mu\text{m}$) with low magnification using an illuminated stage. However, track counting can be done with an accessory television camera coupled to an optical microscope. Tracks from electrochemical etching can be counted easily with objectives as low as 2X.

R. V. Griffith and T. A. McMahon, *A Multi-component Personnel Neutron Dosimeter-DOSPEC*, presented at the Health Physics Society Annual Meeting, June 19-23, 1983, Baltimore, Maryland; Lawrence Livermore National Laboratory, Livermore, CA, UCRL-88591 (1983) [Abstract only].

A small, passive multicomponent neutron dosimeter has been developed that overcomes many of the disadvantages of traditional single-component dosimeters—TLD albedo, NTA film, track-etch, etc. The DOSPEC concept combines the sensitivity and ease of processing of TLD with the fast neutron response characteristics of up to three track-etch materials—CR39, polycarbonate, and cellulose nitrate (LR115). The amount of effort to process multicomponent dosimeters does not have to scale with the number of detectors, if the TLD is used to screen out the large proportion of negligible exposures. However, when needed, the additional detectors can increase the accuracy of the dosimetry. The DOSPEC detectors provide spectral and body orientation information that is valuable to interpretation of dosimeter response and eventual dose assessment. In addition, the interpretation of detector responses can be easily adapted to a hand-held, programmable calculator. Results from intercomparison and field exposures

illustrate the advantages and limitations of the DOSPEC concept.

D. E. Hankins, "Beta- and Gamma-Dose Measurements of the Godiva IV Critical Assembly," *Health Physics*; Lawrence Livermore National Laboratory, Livermore, CA, UCRL-88284 (1982).

To aid in the re-evaluation of an exposure that occurred in 1963, information was required on the response of film badges to the beta- and gamma-ray doses from a critical assembly. Of particular interest was the beta spectra from the assembly. The techniques used and the results obtained in this study are of interest to health physicists at facilities where exposures to betas are occurring.

We measured the dose rates from the Los Alamos National Laboratory Godiva IV Critical Assembly at numerous distances from the assembly 4 and 12 days following a burst. We obtained information on the beta-particle spectra using absorption curve studies. The beta/gamma dose rate ratio as a function of distance from the assembly was determined. We measured the shielding provided by various metals, gloves, and clothing. We compared the beta- and gamma-ray doses measured with a film packet used in the past at the Nevada Test Site with two types of current TLD personnel badges. Measurements made with a commercial thin-window ion chamber instrument are compared with the dose rates obtained using other dosimeters.

D. E. Hankins, "Beta Dosimetry Studies at LLNL," *Proc. of the International Beta Dosimetry Symposium*, Washington, D.C., 15-18 February, 1983; Lawrence Livermore National Laboratory, Livermore, CA, UCRL-88041 (1983).

This paper summarizes three beta dosimetry studies made recently at the Lawrence Livermore National Laboratory. The first study was to determine the beta-gamma exposure rates at the Los Alamos Godiva IV Critical Assembly. The beta spectra from the assembly were evaluated using absorption curves, and the beta-gamma dose rates ratios were determined at various distances from the assembly. A comparison was made of the doses determined using two types of TLD personnel dosimeters and a film badge. The readings of an Eberline R0-7 instrument and the dose rates determined by TLDs were compared. Shielding provided by various metals, gloves, and clothing were measured. The second study was to deter-

mine the beta-energy response of the Eberline R0-7 instrument based on measurements made with the PTB beta sources. This study required additional calibration points for the PTB sources which were made using extrapolation chamber measurements. The third study resulted in two techniques to determine the beta energy ($E_{\max}$) from the readings of thin-window portable survey instruments. Both techniques are based on the readings obtained using aluminum filters. One technique is for field application, requires one filter, and provides a quick estimate of the beta energy in three energy groups: <0.5 MeV, $0.5-1.5$ MeV, and >1.5 MeV. The second technique is more complex, requiring measurements with two or three filters, but gives the beta energy and the approximate shape of the beta spectrum.

D. E. Hankins, Beta-Energy-Response Determination of the Eberline R0-7 Survey Instrument, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19484 (August, 1982).

D. E. Hankins, "Evaluation of Beta Energy ($E_{\max}$) and Spectral Type Using Survey Instruments," *Health Physics*; Lawrence Livermore National Laboratory, Livermore, CA, UCRL-88275 (October, 1982).

We describe two techniques for determining the maximum beta energy ($E_{\max}$) from a source by using thin-window survey instruments. The first technique is a simple field procedure involving the use of a single absorber. The other technique requires three absorbers. The first technique gives beta energy in three divisions: <0.5 MeV, >1.5 MeV, and between 0.5 and 1.5 MeV. The second technique, which is more accurate, gives $E_{\max}$ and information on the spectrum shape of the source.

D. E. Hankins, Neutron and Gamma-Ray Measurements on the LANL Little Boy Comet Assembly, presented at the Little Boy Comet Assembly Measurements Meeting, Los Alamos, New Mexico, 13-14 September, 1983; Lawrence Livermore National Laboratory, Livermore, CA, UCRL-89797 (1983).

We measured neutron and gamma-ray dose rates at various distances from the Little Boy Comet Assembly at Los Alamos National Laboratory (LANL) in April of 1983. The Little Boy Comet Assembly is a replica of the atomic weapon detonated over Hiroshima. The assembly

was designed to be operated at various steady-state power levels. The distances selected ranged from 107 to 567 m. The latter point was on the edge of a mesa overlooking the Critical Assembly Facility in Pajarito Canyon, LANL, New Mexico. Gamma-ray measurements were made with a Reuter-Stokes environmental ionization chamber that has a sensitivity of 1.0 μ R/hour. Neutron measurements were made with a pulsed-source remmeter, designed and built at Lawrence Livermore National Laboratory (LLNL), that has a sensitivity of 0.1 μ rem/hr. Our measurements, as well as those made by other experimenters, were intended to verify recent neutron and gamma kerma calculations made with radiation transport computer codes. Preliminary comparisons with other measurements are in good agreement with our work.

D. E. Hankins, *A New Method for Evaluating Albedo Neutron Dosimeters and a Technique to Determine the Energy of Betas (E_{max}) Using Survey Instruments*, presented at the Health Physics Annual Meeting, Baltimore, Maryland, 19-23 June, 1983; also in the *Proceedings of the International Beta Dosimetry Symposium*, published by the U.S. Nuclear Regulatory Commission, Washington, D.C., 15-18 February, 1983.

This report summarizes the results from two studies at the Lawrence Livermore National Laboratory. The first was the development of an improved technique for the evaluation of our albedo neutron dosimeters. The second was a method to evaluate the beta energy (E_{max}) and spectral type using portable survey instruments.

The albedo dosimeter study originated from a review of five years of personnel data. A new evaluation method was developed which is based on the ratio of the readings from the TLD 600 in the albedo neutron dosimeter and the thermal response of the TLD 100 or 600 in the personnel badge. Calibration factors are obtained which vary depending on this ratio. The variation in these factors is the same within a particular facility, but are not the same at all facilities. Limits are set on the calibration factors based on survey instrument results of the thermal neutron dose rate and the 9- to 3-inch sphere ratio. Significant improvements in the accuracy of doses determined from albedo neutron dosimeters can be obtained by using this technique.

The second part of this paper describes two techniques for determining the maximum beta energy (E_{max}) from a source by using thin-window

survey instruments. The first technique is a simple field procedure involving the use of a single absorber and gives beta energy in three divisions: <0.5 MeV, 0.5 to 1.5 MeV and >1.5 MeV. The second technique requires three absorbers, but is more accurate, gives E_{max} and information on the spectrum shape of the source.

D. E. Hankins, *A Wrist Albedo Neutron Dosimeter*, presented at the 10th International DOE Neutron Dosimetry Workshop/EURATOM-CENDOS, Acapulco, Mexico, 30 August-2 September, 1983.

We are developing a wrist dosimeter that can be used to measure the exposure at the wrist to x rays, gamma rays, beta particles, thermal neutrons, and fast neutrons. It consists of a "Hankins-type" albedo neutron dosimeter that was modified to make it more wearable on the wrist. ABS plastic in the form of an elongated hemisphere provides the beta and low-energy x-ray shielding necessary to meet the requirement of depth dose measurements at 1 cm. The dosimeter has a beta window located in the side of the hemisphere oriented toward an object being held in the hand. A TLD 600 is positioned under the 1-cm thick ABS plastic and is used to measure the thermal neutron dose. At present, we are using Velcro straps to hold the dosimeter on the inside of the wrist. We are studying the directional response and energy dependence of the albedo dosimeter to fast neutrons; preliminary results indicate no serious problems exist with either.

C. J. Huntzinger, J. L. Cate, Jr., M. Dreicer, and D. E. Hankins, *A Sensitive Real-Time Waste Water Monitor*, presented at the Health Physics Annual Meeting, Baltimore, Maryland, 19-23 June, 1983.

An automatic, on-line tritium monitoring system for a combined industrial/sanitary waste water stream has been developed. It provides early detection of either chronic or acute tritium spills to the sewer.

Two major tasks were identified: to provide a relatively pure sample, and a reliable sensitive tritium detector. A prototype cross-flow filtration unit is used to clarify the sample stream. Teflon and Dacron filter disks (2" diam) with pore sizes ranging from 10 μ m down to 0.5 μ m have been tested. With a sample flow rate of 0.1 milliliter per minute, the 0.5 μ m and 1.0 μ m filters were found to be best, lasting over eight days before plugging. Tests were made with a liquid scintillation flow

cell detector. The detector element is a thin-wall Teflon tube coiled flat and sandwiched between two matched photomultiplier tubes operating in the coincidence mode. Preliminary measurements have shown a static minimum detectable activity (MDA) of 50 pCi (1.85 Bq) per milliliter. A combined flow of 0.5 milliliter per minute limits scintillator consumption to 1 gallon (3.8 liters) per week.

An improved, second-generation flow-cell detector is under development. It incorporates an external source for quench correction and will be connected to an emergency warning system microcomputer that will calculate specific activity, and, if necessary, send an alarm to a central dispatch center.

J. L. Morse, *System Safety-A Reality at a National Laboratory*, presented at the 6th International System Safety Conference, Houston, Texas, 26-30 September, 1983; Lawrence Livermore National Laboratory, Livermore, CA, UCRL-89089 (1983).

Intensive system safety efforts during the past several years at the Lawrence Livermore National Laboratory (LLNL) have brought health and safety considerations into the earliest planning of major new projects. These efforts included organizational changes with fundamental top management philosophical changes, better integration of health and safety disciplines into the design team, and routine use of system safety analysis techniques. Tangible benefits include more harmony between the Safety Department and project management, earlier and higher quality safety inputs, plus documentation of safety design rationale. Specific system safety techniques used at LLNL are preliminary hazards analysis, failure mode and effects analysis, fault-tree analysis, operational hazards analysis, and various MORT techniques, including occupancy-use readiness trees. The Department of Energy (DOE) has recognized the merit of this approach with the recent DOE Order 5481.1 which requires department-wide application of system safety principles.

J. A. Mosovsky, *Laser Dyes: Their Hazards and Controls*, presented at the Annual American Industrial Hygiene Conference, Philadelphia, Pennsylvania, 22-27 May, 1983.

Dye lasers utilize a lasting solution which normally contains a complex fluorescent organic dye in solution with an organic solvent. Toxicity information on these laser dyes is scarce, and manufacturers offer little or no help in describing associated hazards on labels or in Material Safety Data Sheets. Due to the increasing popularity of dye lasers, dye and solution hazards needs to be defined in order to protect operating personnel by properly instituting dye solution preparation and dye laser controls.

Literature searches were conducted on the most common laser dyes: xanthenes (rhodamines and fluoresceins), polymethines (cyanines and carboxyanines), coumarins, and stilbenes. Manufacturers and users were contacted and dyes were subjected to the Ames Mutagenicity Test.

Toxicity of dyes and their solutions were found to vary greatly. Some dyes are reported to be carcinogenic, others relatively harmless. LD_{50} s range from 2 mg/kg to greater than 15 g/kg. Tested routes of exposure are unlikely to be represented in work areas where dye lasers operate or where dye solution preparation takes place. Ames Test results have not been finalized, but preliminary data show variability in mutagenicity for different dyes.

Engineering, administrative, and personnel protective equipment controls are recommended for handling dyes, preparing dye solutions, and operating dye lasers. Toxic waste controls are also defined.

B. Odell, *Old Explosive Facilities Need Love (Safety Analyses) Too*, presented at the 6th International System Safety Conference, Houston, Texas, 26-30 September, 1983; Lawrence Livermore National Laboratory, Livermore, CA, UCRL-89089 Draft (1983).

The paper gives several reasons why existing explosive test facilities need current safety analyses and how these analyses are performed. Included is a history of the test site, a discussion of a typical explosives experiment, and a summary of the various hazards involved, plus major concerns and findings. This is followed by a discussion on how the safety analyses reports are written and approved and how the recommendations are incorporated.

P. M. Swearengen, *Desorption of Organic Vapors from Activated Carbon Adsorber Beds*, presented at the Annual American Industrial Hygiene Conference, Philadelphia, Pennsylvania, 22-27 May, 1983.

The effect of intermittent use on activated carbon adsorber beds is being studied for a variety of solvents under dynamic flow conditions. Adsorption and desorption rate constants are determined and compared to obtain a "retentivity" index for different solvents. The techniques of gas chromatography and infrared analysis are employed for the analysis of vapor streams above and below a carbon bed. Kinetic expressions can be employed to analyse the resulting data. The results obtained can be interpreted in terms of adsorber bed performance in a variety of industrial hygiene situations.

K. C. Young, *Charged Particle Beam: A Safety Mandate*, presented at the 6th International System Safety Conference, Houston, Texas, 26-30 September, 1983.

The Advanced Test Accelerator (ATA) is a recent development in the field of charged-particle

beam research at Lawrence Livermore National Laboratory (LLNL). With this experimental apparatus, researchers will characterize intense pulses of electron beams propagated through air.

Inherent with the ATA concept was the potential for exposure to hazards, such as high radiation levels and hostile breathing atmospheres. The need for a comprehensive safety program was mandated; a formal system safety program was implemented during the project's conceptual phase.

A project staff position was created for a safety analyst who would act as a liaison between the project staff and the safety department. Additionally, the safety analyst would be responsible for compiling various hazards analyses reports, which formed the basis of the project's Safety Analysis Report. Recommendations for safety features from the hazards analysis reports were incorporated as necessary at appropriate phases in project development, rather than adding features afterwards.

The safety program established for the ATA project facilitated in controlling losses and in achieving a low level of acceptable risk.