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Hazards Control Department

Annual Technology Review 1985

Scientific Editor:
Richard V. Griffith

General Editor:
Kevin J. Anderson

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Cover Photographs (counterclockwise from front)

**Electron micrograph of a HEPA filter fiber,
showing particle loading.**

**Use of laser eye protection with a copper-vapor
laser.**

**HOT SPOT Health Physics codes can be taken into
the field for rapid initial assessment of nuclear
accidents.**

**Explosives safety allows for safe, successful tests
at LLNL's Site 300.**

**Self-Contained Breathing Apparatus research is
conducted in the respirator test facility.**

**Cover Design:
Duane Hoepker**

**Composition:
Sharon Kerst**

**Layout:
Kenneth Chinn**

**Proofreading:
Delores Mason
Mary Pineda**

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Foreword

The *Annual Technology Review* highlights some of the research performed in the LLNL Hazards Control Department from October 1984 to September 1985. The seven major sections in the *Annual* cover scientific concerns in the areas of Industrial Hygiene, Aerosol Physics, Health Physics, Fire Science, Dosimetry, Criticality Safety, and Safety Analysis. For a broader overview of the types of work performed in the Hazards Control Department, we have compiled the abstracts of other recent publications by Department members.

Readers interested in more detail on any of the papers in the *Annual* may contact the authors directly.

Acknowledgment

We would like to thank B. Elaine Bosserman for her assistance in preparing and revising many of the manuscripts in this publication.

Exposure Guidelines for Steady Magnetic Fields

Gordon Miller

The powerful magnetic fields produced by many DOE energy-research experiments, including the Mirror Fusion Test Facility-B (MFTF-B) experiment at LLNL, necessitate the development of personnel-exposure guidelines for steady magnetic fields. A literature search and conversations with active researchers show that it is currently possible to develop preliminary exposure guidelines for steady magnetic fields. Further research is needed, however, to develop definitive exposure standards. This paper gives an overview of the results of past research into the bioeffects of magnetic fields, discusses hazards that may be encountered by people with sickle-cell anemia or medical electronic and prosthetic implants, and presents the LLNL steady magnetic-field exposure guidelines.

Introduction

Extremely powerful magnetic fields will be used for plasma confinement in the Mirror Fusion Test Facility-B (MFTF-B) controlled thermonuclear fusion experiment. Peak fields, generated by superconducting magnets in a vacuum vessel, will reach 12 T (1 T = 10,000 Gauss). Fields in areas actually occupied by personnel could reach up to 140 mT.

During the planning stages of the MFTF-B experiment, I found that no magnetic-field exposure standards existed, and extant guidelines were not well founded. It thus became necessary to develop magnetic-field exposure guidelines before operating the MFTF-B experiment.

History

Research into the bioeffects of magnetic fields dates back to at least 1892.¹ Much of this early research is, however, of dubious value, as characterized by St. Laurent "...the biological aspects of the experiment are presented with meticulous care, while the physical parameters, such as magnetic field intensity, are ignored completely."² Researchers realized this in the 1970s, and a quality-control revolution occurred. One result of this was the creation of the interdisciplinary science of bioelectromagnetics, which combines physics, biology, and occasionally other sciences such as behavioral psychology.

In 1970, before the results of upgraded research became available, the Stanford Linear Accelerator Center (SLAC) had been obliged to develop magnetic-field exposure guidelines. In 1981 a DOE working group reviewed the state of knowledge about magnetic fields and developed DOE magnetic-field exposure guidelines,³ which are listed in Table 1 along with the SLAC guidelines. Recent animal research has demonstrated that these guidelines are extremely conservative.

Table 1. Previous DOE magnetic-field exposure guidelines and guidelines used by the Stanford Linear Accelerator Center (SLAC).

	Day-Long Average (mT)		Short Periods (mT) (a few minutes)	
	SLAC	DOE	SLAC	DOE
Whole Body Exposure Limits	20	10	200	100
Exposure Limits for Extremities	200	100	2000	1000

Steady and Time-Varying Fields

The SLAC, DOE, and LLNL magnetic-field exposure guidelines all pertain to *steady* magnetic fields. In a steady magnetic field, the flux does not change with time; such a non-varying (steady) flux will not cause current to flow in a fixed object. The superconducting magnets in MFTF-B generate a steady magnetic field.

If, however, the magnetic flux changes with time, this is a time-varying field; such a field will cause an electrical current to flow in conductive objects (in-

cluding living organisms) even when the polarity of the field does not change.

Electrical current flow can also be induced if a conductor moves in a steady magnetic field, such as in the case of the rotor of a dc dynamo or even blood flowing in the body. The LLNL magnetic-field exposure guidelines are based on limiting the voltage induced when blood moves in a steady magnetic field.

Bioeffects

Table 2 summarizes the results of recent bioeffects research. The functioning of the heart is manifested by voltages that can be routinely measured by the tracings on an electrocardiogram (ECG). A typical ECG consists of a series of waves that repeat with every heartbeat; each such wave has been designated by a specific letter (see Fig. 1). The "P wave" results from the electrical activity that accompanies the contraction of the smaller pump chambers on the top of the heart, the atria, which force blood into the larger pump chambers below, the ventricles. The ventricles contract to deliver blood to the lungs or the entire balance of the body; the electrical activity that accompanies this is manifested by the "QRS" complex. The atria relax while the ventricles contract, but this relaxation is masked by the electrical activity of the ventricles. The recovery of the ventricles is manifested by the "T wave" on the ECG.

The blood flow from the left ventricle is delivered to the body by the arterial system. The entire output of the left ventricle is briefly confined to one

large artery just above the heart, the aorta. Blood, an ionized fluid, flows through this large vessel at high speed.

An ionized fluid will generate a "magnetohydrodynamic" (MHD) voltage proportional to the vessel diameter, the speed of the fluid, and the field strength. The fluid speed and vessel diameter are larger in the aorta than in any other place in the body, so an aortic MHD voltage is predictable and noticeable on ECGs made while animals are in magnetic fields. Since blood flows through the aorta when the ventricles are recovering, the aortic voltage appears on an ECG as an enlarged T wave. Tenforde et al. at the Lawrence Berkeley Laboratory (LBL) have studied this additional MHD voltage as found on animal electrocardiograms.^{9,27,37-39} The results of research to date show that this phenomenon is not harmful, and the enlarged T wave disappears as soon as the animal is removed from the magnetic field. Further tests are under way at LBL to conclude whether this phenomenon is potentially hazardous or not.

Table 2. Summary of the results of recent research into the bioeffects of steady magnetic fields.

Field Strength (mT)	Effect	Reference
1-10	Electroretinograms were influenced in nonhibernating turtles (<i>Pseudemys scripta elegans</i> and <i>Chelydra serpentina</i>) in a light-controlled environment, if exposed to magnetic field immediately after the offset of ambient lighting.	4
70-1,300	Cytochrome C oxidase activity <i>in vitro</i> increased or decreased, depending on whether sample was moved in field (1-h exposures).	5
1,500	Behavior of mice not affected.	6
1,500	Immune responses of mice not affected.	7
<60	Growth of tumors <i>in vitro</i> checked in concert with hypothermia. Magnets attached to test rats for 2-24 h per day, hypothermia induced once every 4-5 days. Speculation that effect is due to binding of paramagnetic oxygen to magnet, away from bulk of tumor, that deprives tumor of oxygen.	8
1,500	T wave increase noted; blood pressure changes not evident in cynomolgus macaques. Predict no adverse effects in men exposed to fields as strong as 2 T.	9
5.2 average	Weak correlation with hypertension in employees of aluminum and chlor-alkali plants.	10
93 and 140	Gestation and lag times of growth of <i>Staphylococcus aureus</i> 812 affected, as well as activity of infecting virions.	11
600	Non-heritable damage found in <i>Drosophila melanogaster</i> after about 48 h exposure.	12
1,600	Mice developed transient reticulocyte count and enduring leukocyte count changes, effects noticed one day after start of 30-day exposure. Corticosterone levels fluctuated during experiment, catecholamines rose for about 20 days. Spermatozooids fluctuated throughout experiment.	13
2,000	Blood parameters of rhesus monkeys exposed for 40-67 h not affected. Problems encountered with experimental protocol.	14
105	Aneurysm clips remained on artery of test rat at 2 mT/cm field gradient.	15
220	Aneurysm clips twisted off of artery of test rat at 21 mT/cm field gradient.	15
1,600	Sizes of red blood cells increased in mice during 30-day test. Reticulocytes increased, then fell below normal.	16
40×10^{-6}	Modification of Earth's field by listed amount changed circadian rhythms of sparrows (<i>Passer domesticus</i>) in light-controlled environment. Experimenters call magnetic fields a weak time referent in comparison to light.	17
705	Frog (<i>Rana pipiens</i>) eggs and sperm not affected by exposures in NMR equipment for 20 min.	18
100	Implanted Co5Sm permanent magnets in rats had no effect.	19
40	Follow up of 181 medical NMR patients revealed no effect.	20
2,000	Function of excised frog (<i>Rana pipiens</i>) sciatic nerves unaffected after 17 h.	21
1,000	Retinal rods moved by field.	22
350	Sickled red blood cells moved by field.	22
5,000-20,000	Enzyme reactions not affected.	22
2-3,700	No statistically significant mutations in <i>Tradescantia</i> ; some increase in one type of mutation (not statistically significant) noted.	23
20-120	No blood changes in rats; possible weight increases in young rats.	24
880-1,400	No changes in growth rates or blood of mice.	25
500-1,200	Increase in the mortality of the ciliate <i>Spirostomum ambigua</i> challenged with PDS after exposure to magnetic fields.	26
2,000	Rat heart and breathing rates unaffected after 5-h exposure.	27
2,150	Bacteriophage OX-174 DNA unaffected by 1-h <i>in vitro</i> exposure.	28
15-30	Hypotosterolemia noted in chlor-alkali plant workers.	29

Table 2. (Continued.)

Field Strength (mT)	Effect	Reference
60	Water intake and urination increased in rabbits after three weeks.	30
300	Water intake and urination increased in rabbits after 48 h.	30
600	Water intake and urination increased in rabbits after 16 h.	30
352	No effect in Chinese hamster ovary cells placed in a medical NMR unit for 13.7 h.	31
1,500	No behavioral changes that could reflect altered circadian rhythms in mice exposed for five days all day or for ten days, 16 h off and 8 h on (simulating occupational exposures).	32
0.05	Circadian rhythms affected in guinea pigs in light-controlled environment.	33
0.001-0.06	Pineal cells of pigeons responded to gradual or rapid realignments of Earth's magnetic field.	34
0.052-0.123	Serotonin n-acetyltransferase and melatonin levels in pineal glands of rats in light-controlled environment affected.	35
1,000	Mice showed no evidence of ill effects after two years of continuing exposure. No reproductive effects found.	36

Figure 1. The functioning of the heart is apparent as voltages on a routine electrocardiogram. Note how exposure to a steady magnetic field can increase the T wave.

The MHD interaction between moving blood and a steady magnetic field could also elevate blood pressure.³⁹ The magnitude of this elevation should be pro-

portional to the square of the field strength. Predicted increases in blood pressure are listed in Table 3. It can be seen that a 5% elevation will occur at exposure to a magnetic field of about 4 T.

Other bioeffects, including effects on the reproductive systems, have been reported, particularly in Eastern European literature; however the results of rigorously controlled Western research do not support the Eastern European findings. The results of Kelman, who conducted lifetime exposure tests of mice, are particularly important in that reproduction factors and a variety of physiological criteria were evaluated without finding evidence of ill-effects.³⁶ Nakagawa did find that rabbits increase water retention and urination after sustained exposure to magnetic fields of 60 μ T or more.³⁰

I reviewed two articles-reporting the results of epidemiological studies of workers exposed to magnetic fields on the job. One report found a weak correlation between magnetic-field exposures and elevated blood pressure in blacks,¹⁰ the other reported a correlation between magnetic fields and hypotesterolemia.²⁹ The industrial processes involved, however, also involve exposing the workers to high temperatures. Heat is a well-known stressor of the circulatory system and also influences male reproduction. The effects these studies attributed to magnetic fields could also be attributed to excessive heat in the workplace.

Table 3. Predicted blood-pressure elevations caused by MHD interaction. Note that a 5% elevation will occur at exposure to a magnetic field of about 4 T.

Field strength (T)	Percent BP elevation
2	1
3	3
4	5
5	7
6	10

Other animal test data tend to support the conclusion that steady magnetic fields are not particularly hazardous. This may help to explain why early bioeffects data did not seem highly significant: the effects of steady magnetic fields are so subtle that the routine control procedures followed in early biological experiments allowed spurious experimental variables to mask the true presence or absence of bioeffects.

Artificial Cardiac Pacemakers

Artificial cardiac pacemakers are vulnerable to steady magnetic fields because they use magnetically activated reed switches. These reed switches change from one operating mode (where the switches sense and amplify the output of the heart's natural pacemaker) to a safety backup mode (where they send out pulses at a steady, fixed rate). In a physician's office, the backup mode is tested by placing a magnet over the patient's chest, which causes the reed switch inside to change the mode of the pacemaker. If this were to happen accidentally, the backup mode's fixed-frequency signal could fall into a potentially destructive competition with the signal from the heart's natural pacemaker. It has been coarsely estimated that 3-4% of pacemaker users could be threatened by these competing signals if the pacemaker inadvertently changed to the backup mode.¹⁶

Pavlicek et al. checked the operation of several pacemakers, as did the Siemens Corporation, which sells both pacemakers and medical devices for nuclear magnetic resonance (NMR) imaging.^{41,42} This research reveals that the reed switches in some artificial pacemakers can switch into the backup mode in magnetic fields as low as 1.4 mT (the reed switches relax again at lower field strengths, some-

times as low as 0.8 mT). The Food and Drug Administration now advises the manufacturers of medical NMR units to use warning labels for users to avoid places where the field exceeds 0.5 mT.⁴³ Reed switches are also used in a variety of other medical electronic devices, such as nerve stimulators.

Prosthetic Devices

A variety of non-electronic prosthetic devices implanted in patients might also cause problems if the patient is exposed to a powerful magnetic field. Such devices can be small, such as aneurysm clips or orthopedic pins of various sizes, or they can be large items such as artificial hips. The movement of an aneurysm clip could gravely threaten the user and can occur with little or no warning. The movement of larger implants would be accompanied by discomfort or pain before a permanently destructive movement occurred. The force acting on a magnetizable object, such as a metallic prosthetic device, is related to properties of the field (namely the field strength and the field gradient) and the properties of the object (namely its magnetic susceptibility and the volume of magnetizable material).³⁷

New et al. did pioneering research on the hazards associated with aneurysm clips and medical NMR units.¹⁵ He found that an aneurysm clip rotated, but did not pull off, the femoral artery of a rat when the field strength was 0.105 T and the field gradient was 0.2 T/m, while a similar test clip came off in a field of 0.22 T with a field gradient of about 2.1 T/m. These data show that aneurysm clips are not critically affected when the product of the field strength and field gradient is about $2.1 \times 10^{-2} \text{ T}^2/\text{m}$. It is, however, reasonable to wonder if aneurysm clips subjected to repeated substantial rotations will remain useful.

It will be necessary to know the materials and volumes of a host of prosthetic devices before good guidelines can be written to safeguard the users of such devices. At present, I am canvassing the trade associations that represent the manufacturers of medical prosthetic devices in order to obtain such information.

Sickle-Cell Anemia

Budinger noted that sickled cells rotate in a magnetic field of 0.35 T.²² This rotation occurs in a strong steady magnetic field because the hemoglobin

in a sickled red blood cell exhibits a magnetic anisotropy that causes a torque when the molecule is in a steady magnetic field. The hemoglobin molecules of a sickled cell are stacked in a manner that combines the torques created by individual molecules, so even a magnetic field below 2 T could create a significant aggregate torque. Further research is needed to show the specific physical consequences of this magnetically induced torque.

Circadian Rhythms

Western European researchers have found that the pineal gland, an organ that plays a major role in the timekeeping of vertebrates, responds to magnetic fields.⁴³⁻⁴⁵ Even minor alterations of the Earth's steady magnetic field (~ 0.05 mT) can cause the day/night cycle of an organism to fall out of adjustment if the organism has no other visual cues. Tenforde, however, subjected mice to 1.5-T fields while maintaining regular day/night light cycles and observed no changes in their behavior during the exposure.³² This suggests that even strong magnetic fields do not disrupt an organism's timekeeping if visual cues of light and dark are maintained.

I contacted the National Aeronautics and Space Administration, which calls upon astronauts

to work in very harsh environments of constantly changing magnetic fields and 90-minute light/dark cycles. Astronauts continue to function when 24-hour cycles are maintained by the simple expedient of blocking off cabin windows and shutting off lights during night cycles.⁴¹ It is advisable, however, that people should not be allowed to work in magnetic fields for several shifts without a break.

Tools

A strong magnetic field can move a magnetizable (or compressed-gas cylinder, possibly even making it a dangerous missile if the force acting on it is strong enough. MFTF-B engineers have predicted that the field strength and gradient would be hazardous where the field exceeded 100 mT, such as around the locations of ferrous construction features (i.e., cat walks). Such conditions could induce a sideways force on a wrench equivalent to that of gravity.⁴⁵ Users of equipment that generates strong magnetic fields would be advised to conduct trials with representative tools tied to the belt (or otherwise secured) to see where magnetic force on the tools causes them to become unmanageable.

LLNL Magnetic-Field Exposure Guidelines

The LLNL magnetic-field exposure guidelines, summarized in Table 4, apply only to steady magnetic fields. These are written as typical industrial hygiene standards that establish time-weighted average (TWA) and short-term exposure criteria. The averaging interval for the time-weighted average, however, is not the eight-hour day, as will be seen.

The TWA criterion is based on limiting the average MHD voltage to 1-2 mV, as advised by Budinger, a physician and leading researcher on the bioeffects of magnetic fields.⁴⁶

The TWA criterion would limit the induced voltage to 1 mV (as an average) in an obese person doing moderately heavy work. The underlying assumptions of moderately heavy work and an obese person make this limit conservative: obese people have a larger volume of blood (estimated to be about 1.18 times more than people of average

Table 4. Summary of the LLNL magnetic-field exposure guidelines.

Field Strength (mT)	Action
1	Exclusionary warning for pace-maker users; cautionary warning for those with prosthetic implants.
50	Action limit: Training and medical surveillance required. Persons with sickle-cell anemia (not merely the trait) prohibited.
60	TWA limit for the trunk.
500	Definition of a "strong magnetic field" used to change TWA averaging interval from 40-h workweek to an 8-h day.
600	TWA limit for the extremities.
2000	Peak exposure criterion.

build), and work increases the cardiac output (moderate sustained work would cause approximately a doubling of cardiac output). Increased blood volumes raise the blood velocity in the aorta which in turn increases the MHD voltage. It is also noted that test animals have been subjected to MHD voltages of around 1 mV without any evidence of ill-effects.

The peak exposure criterion, 2 T, is based on the patient-exposure recommendation of Budinger.⁴⁷ His recommendation was based on concern about possible elevation of the blood pressure. The United Kingdom allows patient exposures to fields as strong as 2.5 T in medical NMR imaging.⁴⁸

The time interval over which the TWA exposure is computed changes from the 40-h workweek to the 8-h workday when the peak exposure exceeds 500 mT. This additional restriction was added due to present uncertainty about the effects of sustained exposures to strong fields, per the advice of Tenforde⁴⁹ and the results of Nakagawa.³⁰

Both limits apply to fields measured at the trunk of the body instead of at the extremities because the target organ for magnetic-field exposure is the heart. (Average exposures up to 600 mT are acceptable for the extremities, although the peak exposure criterion for the extremities is 2000 mT, the same as for the trunk.)

Other Actions

Persons with pacemakers and other medical electronic implants are warned to stay out of places where fields exceed 1 mT. Adherence to the FDA warning criterion of 0.5 mT would have meant blocking off a major roadway on the LLNL site. I found no evidence that the reed switches in pacemakers would switch below 1.4 mT; I also discov-

ered that the quality controls for reed switches are unusually strict.³⁰

Persons with small prosthetic implants are also warned to avoid areas where fields exceed 1 mT. People with mid-sized implants are treated on a case-by-case basis. Persons with large implants are advised to carefully enter places where fields exceed 1 mT and to report where they begin to feel their implants, so that field strengths and gradients can be surveyed there.

Persons with sickle-cell anemia are excluded from places where field strengths exceed 50 mT.

Action Level

LLNL has set the medical-surveillance/training action level at 50 mT. The action level could have been set at other field strengths, but it is reasonable to believe that the TWA limit will be raised when the results of further research become available.

Access to areas where fields exceed 50 mT is restricted to authorized personnel, and physical examinations are required if people must work in magnetic fields above 50 mT for more than one shift.

Special training for workers where magnetic fields exceed 50 mT includes:

- Describing the anticipated or measured exposures.
- Describing the bioeffects of magnetic fields.
- Discussing limitations on people with pacemakers, other medical electronic implants, prosthetic devices, and sickle-cell anemia.
- Advising personnel not to work multiple shifts without a break.
- Warning people about tools and compressed-gas cylinders.

Conclusion

This paper introduced the LLNL magnetic-field exposure guidelines and presented a rationale for the exposure limits. The history and difficulties associated with biomagnetics research were described along with the results of recent bioeffects

research. Supplemental controls to protect users of cardiac pacemakers, other medical electronic implants, or prosthetic devices, and those with sickle-cell anemia were also discussed.

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The Effect of Organic Vapor Mixtures on the Service Life of Respirator Cartridges

Peter M. Swearengen and S. Catherine Weaver

We challenged pairs of MSA respirator cartridges with two compounds, isopropyl alcohol and methyl ethyl ketone, to study the effects of organic vapor mixtures on respirator cartridge performance. Each cartridge was challenged at three concentrations: low concentrations of the single compounds, a mixture of the two compounds, and high concentrations of the single compound. Each experiment was conducted at 20% and at 85% relative humidity. We experimentally observed 1 and 10% breakthrough times in every case; we found that the breakthrough times for the mixture agreed with the single high-concentration challenge. Our experimental data were matched to a theoretical model derived from modified Wheeler-Robell equations and showed close correlations between adsorption rate constants for the mixture and for the individual compounds. Based on these first experiments, we feel that an accurate mathematical model for determining the kinetics of organic vapor mixtures is possible. We plan further experiments to verify this.

Introduction

A significant amount of data is available concerning the efficiency of respirator cartridges against the single-compound challenge of many classes of organic vapors.¹⁻⁴ Respirators, however, are often used in an environment that contains more than one organic vapor at a time. (A common example of this is spray painting.) The response of respirator cartridges to mixtures of organic vapors, as in spray paint, has not been well-documented.

We challenged pairs of respirator cartridges with two common solvents, isopropyl alcohol (IPA) and methyl ethyl ketone (MEK), to see if mixtures of organic vapors affected the cartridges' performance. We chose these compounds because they have similar molecular weight and physical parameters (Table 1). The cartridges were challenged under three separate conditions: low concentration of the single compounds, each at ten times the Threshold Limit Value (TLV)*; a mixture of the two

compounds; and high concentration of the single compounds. Each challenge condition was conducted at two separate relative humidities (RH), 20 and 85%.

In this paper, we show times for 1 and 10% breakthrough of the single compounds and the mixtures, and we compare the experimental results to a kinetic analysis to provide insight into respirator-cartridge performance under the described conditions.

Table 1. Molecular properties of IPA and MEK.

	Isopropyl alcohol	Methyl ethyl ketone
Molecular weight	60.11	72.12
Boiling point	82.4	79.6
Vapor pressure ^a	44 mm Hg at 25°C	99 mm Hg at 25°C
Dipole moment	1.66 ^b	2.77 ^c

^a Ref. 5.

^b Ref. 6.

^c Ref. 7.

* The Threshold Limit Value is defined by the American Council of Governmental Industrial Hygienists (ACGIH) as "the time-weighted average concentration for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect."

Experimental Apparatus and Methodology

The experiments were conducted within a flow system that allowed precise control and measurement of all operating parameters (Fig. 1). The airstream was generated using a Miller-Nelson Research device (Model HCS-301) that provides control of flow, temperature, and relative humidity.⁸ Solvent concentrations of IPA and MEK were carefully added to the airstream from a syringe driven by a syringe pump; multiple syringe pumps were employed during injection of the mixtures. An infrared analyzer monitored the solvent concentration upstream from the respirator cartridges. For the mixtures, calibration of the infrared analyzer for one compound was performed in the presence of the second compound; in this manner, optical-signal contributions from the second compound were taken into account over the concentration ranges used in the study.

The respirator cartridges used throughout this work were MSA Chemical Cartridges (PN 459315). A small chamber was designed so that the airstream would flow through both cartridges simultaneously. The parallel exhaust flows were then combined downstream from the chamber, and this airstream was monitored for solvent concentrations. The downstream airflow was analyzed by gas chromatography using a data system; a glass-packed

column, 3 m $\times$ 2 mm i.d., was used with a flame-ionization detector in the chromatograph. Injections into the chromatograph were made from a gas-sampling valve. The valve and the chromatography data system were controlled by a digital valve-sequence programmer. The bulk of the airstream was then exhausted into a fume hood. Each solvent was tested on the MSA cartridges at a low (20%) and a high (85%) relative humidity. In each case, the cartridges were prehumidified by placing them in the desired airstream for 16 h. This conditioning resulted in an uptake of water to a constant weight for the 85% RH cartridges and no change (or an occasional slight weight loss) for the 20% RH cartridges. One cartridge pair was tested at low solvent concentrations (approximately ten times the TLV concentration of each solvent) at each of the two separate RH values. Another cartridge pair was tested with a mixture of IPA and MEK, where the concentration of each component was at (or near) a value of ten times the TLV. And finally, cartridges were tested at high concentrations of the single solvents, where the concentration was close to the sum of ten times the TLV of each component (IPA and MEK separately at about 7500 ppm). We repeated each of these tests six times.

Figure 1. The experiments with organic vapor mixtures were conducted in a flow system that allowed precise control and measurement of all operating parameters.

Experimental Results and Discussion

Our goal is to characterize the performance of respirator cartridges when challenged by multiple organic vapors as accurately as conventional equations describe single-compound challenges. Using modified Wheeler-Robell equations,⁹ we were able to determine adsorption and desorption constants for MEK and IPA (see Tables 2 and 3). The results given are the mean of six values, and 1 σ values are reported for the observed deviations in the results.

Several important trends appear from these data. First, with a single compound, a larger adsorption rate constant correlates with a longer breakthrough time (where the time is determined empirically). This follows logically, if one assumes that a higher adsorption rate corresponds to a greater affinity of the carbon for the chemical, and thus a longer time for the challenge compound to move through the carbon and appear on the downstream side. Second, under similar challenge concentrations, a smaller rate constant and a shorter break-

through time always occur at the higher RH. This is consistent with the idea of water covering available adsorption sites and hindering the maximum possible uptake of chemical by the carbon surface.

Finally, similar rate constants (and similar breakthrough times) occur when only the total challenge concentration alone is considered. That is, regardless of whether the total challenge vapor concentration is a mixture of IPA and MEK or is composed of only IPA or MEK, the rate constants and breakthrough times are very similar. For these two compounds, a principle of superposition appears to occur; conversely, for this situation and these molecules, there does not appear to be any observable synergism. This fact may be valuable in creating a model that predicts breakthrough times for respirator cartridges. Once the model is validated, an industrial hygienist will be able to select cartridges appropriate to particular field conditions without going through laboratory tests.

Table 2. Experimental breakthrough times for MEK at various concentrations.^a All values are $\pm 1 \sigma$.

	RH (%)	Concentration (ppm _v)	k_{ads} (min ⁻¹)	k_{des} (min ⁻¹)	K_L	W_e (g/g)	$t_b(1\%)$ (min)	$t_b(10\%)$ (min)
MEK mixture total conc.	20	2500 (± 200) 7500 (± 200)	4400 ± 800	2.2 ± 0.7	2100 ± 570	0.13 ± 0.03	29.0 ± 3.0	33.0 ± 3.0
MEK mixture total conc.	85	2500 (± 100) 7600 (± 200)	2800 ± 400	4.2 ± 2.3	1100 ± 900	0.10 ± 0.02	18.0 ± 2.0	23.0 ± 2.0
MEK single low conc.	20	2500 ± 200	5300 ± 600	0.31 ± 0.13	16000 ± 6600	0.33 ± 0.04	65.0 ± 2.0	73.0 ± 1.5
MEK single low conc.	85	2400 ± 100	2900 ± 700	1.3 ± 0.5	3000 ± 2100	0.20 ± 0.02	35.0 ± 2.0	45.0 ± 3.0
MEK high conc.	20	7400 ± 100	4700 ± 400	2.6 ± 1.0	2000 ± 600	0.33 ± 0.02	25.0 ± 1.5	29.0 ± 1.5
MEK high conc.	85	7500 ± 100	2600 ± 400	5.1 ± 1.7	600 ± 200	0.27 ± 0.01	16.0 ± 1.0	20.0 ± 0.4

^a The K_L s reported are an average of all six runs with their corresponding sigma value. This does not correspond to values obtained by using average k_{ads}/k_{des} from this table.

Table 3. Experimental breakthrough times for IPA at various concentrations.^a The experimental values are $\pm 1 \sigma$.

	RH (%)	Concentration (ppm _v)	k_{ads} (min ⁻¹)	k_{des} (min ⁻¹)	K_L	W_c (g/g)	$t_b(1\%)$ (min)	$t_b(10\%)$ (min)
IPA mixture total conc.	20	5000 ± 100 7500 ± 200	3700 ± 200	2.8 ± 0.9	1500 ± 600	0.21 ± 0.03	27.0 ± 2.0	31.0 ± 1.5
IPA mixture total conc.	85	5100 ± 200 7600 ± 200	2500 ± 400	2.0 ± 0.6	1500 ± 800	0.18 ± 0.03	19.0 ± 2.0	25.0 ± 1.5
IPA single low conc.	20	4400 ± 300	4200 ± 400	0.90 ± 0.20	5200 ± 1500	0.28 ± 0.02	41.0 ± 4.0	46.0 ± 2.0
IPA single low conc.	85	4600 ± 100	3700 ± 400	2.9 ± 0.3	1300 ± 100	0.24 ± 0.03	31.0 ± 4.0	39.0 ± 2.0
IPA high conc.	20	7500 ± 200	3900 ± 400	2.1 ± 0.7	1800 ± 400	0.32 ± 0.02	27.0 ± 2.0	31.0 ± 2.0
IPA high conc.	85	7500 ± 100	2800 ± 500	1.6 ± 0.8	1800 ± 600	0.26 ± 0.02	19.0 ± 2.0	25.0 ± 2.0

^a The K_L s reported are an average of all six runs with their corresponding sigma value. This does not correspond to values obtained by using average k_{ads}/k_{des} from this table.

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Alarm Points for Oxygen Monitors Used in the MFTF-B Facility

Gordon Miller

Oxygen concentration monitors were installed in a vault where numerous pipes carried inert cryogens and gases to the Mirror Fusion Test Facility (MFTF-B) experimental vessel. We reviewed the problems associated with oxygen-monitoring systems and the reasons why such monitors are installed. As a result of this review, the MFTF-B monitors were set to sound an evacuation alarm when the oxygen concentration fell below 18%. We chose the 18% alarm criterion to minimize false alarms and to allow time for personnel to escape in an oxygen-deficient environment.

Introduction

An "oxygen-deficient atmosphere" contains less than 19.5% oxygen, as stated in the standard for open surface tanks promulgated by the Department of Labor under the Occupational Safety and Health Act (OSHA) of 1970.¹ While planning the installation of oxygen-deficiency sensors and alarms in a large vault housing the MFTF-B magnetic-confinement fusion experiment, the question arose as to whether 19.5%

oxygen was suitable as the level to sound evacuation alarms. Thousands of gallons of liquid nitrogen and liquid helium were to flow from nearby liquefaction plants into and out of the vessel to cool superconducting magnets. The considerations that went into deciding the oxygen level at which an evacuation alarm should sound are discussed below.

Physiological Considerations

The partial pressure of oxygen in a gas mixture—the actual number of oxygen molecules present in the gas—can be calculated by multiplying the barometric pressure of the mixture by the volumetric percentage of oxygen in it. In the case of air at sea level the partial pressure of oxygen is 20.9% of atmospheric pressure (760 mm Hg), or 159 mm Hg. Deep-sea divers rely on the distinction between the partial pressure of oxygen and the percentage of oxygen in their breathing air; a diver's air tank holds gas mixtures at elevated pressures that contain very small volumetric percentages of oxygen.

It is well reported that people can tolerate breathing air in which the volumetric oxygen concentration exceeds 16% without ill effects.^{2,3} As can be seen in Table 1, people develop progressively more serious symptoms as the oxygen concentra-

tion decreases below 16% until death occurs when the oxygen concentration reaches 6%. The alveolar partial pressure gives a measure of how much oxygen is actually available to the body. The alveolar partial pressure of oxygen can be estimated using the following formula⁴:

$$P_a = F_i(P_b - 47) - P_c \left(F_i + \frac{1 - F_i}{0.85} \right)$$

where

F_i = Volumetric oxygen percentage in the air being breathed.

P_b = Barometric pressure of the atmosphere being breathed.

P_c = Alveolar partial pressure of CO₂ (about 40 mm Hg).

Table 1. The effects of oxygen deficiency.³

Sea-level volumetric oxygen concentration (%)	Physiological effect
16-12	Increased breathing volume; Accelerated heartbeat; Impaired attention and thinking; Impaired coordination.
14-10	Very faulty judgment; Very poor muscular coordination; Muscular exertion causes rapid fatigue that may cause permanent heart damage; Intermittent respiration.
10-6	Nausea and vomiting; Inability to perform vigorous movement or loss of all movement; Unconsciousness, followed by death.
Less than 6	Spasmodic breathing; Convulsive movements; Death in minutes.

It can be shown that the alveolar partial pressure of oxygen at a high altitude, such as in Denver, from air with an oxygen concentration of 19.5% is *below* the alveolar partial pressure at sea level, such

as in San Francisco, from air with an oxygen concentration of only 16%.² It should be noted that people do acclimate to altitudes up to 6000 feet.²

Oxygen Monitoring

While a variety of methods are available for measuring oxygen concentrations in air,⁵ only electrochemical sensors are commonly used to measure the oxygen content of breathing air. In an electrochemical sensor, a pair of electrodes is immersed in an electrolyte in a chamber, as shown in Fig. 1. One end of the chamber is open, but covered with a membrane through which oxygen can diffuse into the electrolyte. Oxygen dissolved in the electrolyte drives a chemical reaction that generates a current proportional to the volumetric concentration of oxygen in the air. Oxygen in the cell is expended to drive the reaction, thereby reducing the oxygen concentration in the electrolyte. This creates a diffusion gradient that causes more oxygen to pass through the membrane. In order to operate the detector, it is necessary only to connect this electrochemical cell to a meter and ensure that fresh air always flows over the membrane. The concentra-

tion of oxygen in fresh air is always 20.9% by volume, so the instrument is calibrated by drawing fresh air past the sensor, and the output is adjusted to read 20.9%. While there are variations in cell design and chemistry, the description given above applies to virtually every electrochemical oxygen instrument.⁶

Unfortunately, changes in barometric pressure and temperature can cause false alarms, as discussed by Swarengen et al.⁷ These results suggest why the LLNL Fire Department received false alarms when weather fronts passed by the Livermore site.

Meteorological conditions can be regarded as variables fluctuating about mean values that change over time; then it can be seen that reducing the volumetric oxygen concentration at which an electrochemical monitor sounds an alarm should also reduce the number of false alarms.

Figure 1. A typical electrochemical fuel cell used in oxygen-deficiency monitors.

Regulatory Considerations

OSHA states in 29CFR 1910.94 (d) (1): "When, during emergencies as described in paragraph (d)(11)(v) of this section, workers must be in areas where concentrations of air contaminants are greater than the limit set by paragraph (d)(2)(iii) of this section, or oxygen concentrations are less than 19.5%, they shall be required to wear respirators adequate to reduce their exposure to a level below these limits, or to provide adequate oxygen."¹

This paragraph specifies the minimum oxygen content of breathing air as a volumetric percentage. It is not a specification of when monitoring devices are to warn of insufficient (or excessive) oxygen content. This is important because many fixed-point oxygen-monitoring systems, including the one considered here, are not installed to assure that local breathing air has more than 19.5% oxygen; instead, these systems sound alarms warning people to leave places where the air is becoming dangerously deficient in oxygen due to an unusual occurrence (such as a cryogen spill or a leak of inert gas). It is assumed that the oxygen concentration will remain close to 20.9% until an unusual incident occurs, and the chance is insignificant that biological/chemical

processes will gradually reduce oxygen concentrations below 19.5%.

The strict OSHA specification for oxygen deficiency has an important aspect when considering where to set an alarm level. Many oxygen deficiencies, including those that could occur in the MFTF-B vault, will probably develop quickly. The volumetric percentage (and partial pressure) of oxygen will rapidly drop from 20.9% and 159 mm Hg (at sea level) to much lower levels when a leak or vapor cloud creates an expanding volume of oxygen-deficient gas. The level at which an alarm is set will influence the time in which people can escape before the atmosphere becomes hazardous. An alarm point set closer to the normal atmospheric content of oxygen will sound the alarm earlier and give more escape time than an alarm point set further away from the normal atmospheric content of oxygen. An alarm point set close to atmospheric content will also, however, be more prone to false alarms.

It is noted that the effects of altitude are not explicitly mentioned in the regulations. This is not the only oxygen-concentration limit specified in Federal and other standards, including OSHA regulations. Some of the other oxygen-deficiency limits are specified in Table 2.

Table 2. Definitions of oxygen deficiency. Note that even the Code of Federal Regulations has not agreed to a consistent definition.

Source	Volumetric oxygen concentration (%)	Conditions for determination	Sea-level partial pressure of oxygen (mm Hg)
29CFR 1910.94	19.5	—	148
29CFR 1910.134	16.0	—	122
29CFR 1915.81	16.5	—	125
30CFR 11	19.5	"By volume at sea level"	148
NIOSH Criteria Document for Working in Confined Spaces	19.5	At sea level (Class C space)	148
	16.1-19.4	At sea level (Class B space)	122-147
	16 or less	At sea level (Class C IDLH space)	122 or less
ANSI Z117.1-1977	18	—	137

Behavioral Considerations

False alarms are not just an annoyance for a fire department or maintenance personnel; they are a technological case of "the boy who cried wolf." Too-frequent false alarms can cause workers to pay less attention to an oxygen-deficiency alarm and ei-

ther evacuate slowly or not bother to evacuate at all (as has happened in at least one case away from LLNL). Serious consequences could occur from this attitude if the alarm is real.

Conclusions

We drew the following conclusions for the purposes of installing oxygen monitors in the MFTF-B vault:

1. This system is intended to warn people of dangerous oxygen deficiencies, not to monitor compliance with the 19.5% OSHA definition of "oxygen deficiency."

2. Permanently installed oxygen monitors are prone to false alarms. Swearingen's data objectively confirm theoretical predictions that barometric and temperature changes will cause the indications of oxygen meters to change.

3. LLNL is at a low altitude, and it is therefore not necessary to have a volumetric oxygen concentration of 19.5% to sustain life, or even to maintain productivity or avoid any type of ill-effect.

4. If the system experienced a high false-alarm rate, we found a real danger that persons working in the MFTF-B vault would not react to

oxygen-deficiency alarms in a timely manner, or would ignore them.

5. Setting the alarm point at a volumetric oxygen percentage of 19.5% will increase the probability of false alarms; conversely, setting the alarm point at a lower concentration decreases the escape time in an emergency. The alarm point for the MFTF-B oxygen monitors needed to be set at a level that balanced a longer escape time against the probability of false alarms.

It was recommended that oxygen-deficiency monitors be installed and that alarm points be set at a volumetric oxygen concentration of 18%. This concentration is used as the minimum-oxygen-content criterion in the widely respected Threshold Limit Value lists,⁸ and represents the best compromise between minimizing false alarms and maximizing the time for escape.

Open Issues

The most commonly used definition of oxygen deficiency, 19.5% by volume, is not well suited for use as an alarm point and also warrants reconsideration as the definition of an oxygen-deficient atmosphere.

The evaluation described in this paper suggests that the following matters need further consideration:

1. What is a "safe" oxygen concentration for acclimated and unacclimated people at various altitudes? This matter is well addressed in the contexts of aviation, astronautics, and aquanautics, and should also be investigated in the contexts of average working populations and industrial workers who may also encounter oxygen-depriving substances such as carbon monoxide, methylene chloride, or aromatic nitrates and amines. It may be possible to set better standards for oxygen deficiencies and action limits for evacuation.

2. How much do meteorological conditions (namely, the rates of temperature and pressure

change) vary in different geographic areas? These two variables will influence how adequately a reduced alarm point will prevent false alarms.

3. Can electrochemical oxygen monitors be modified or replaced by a different operating system so such monitors will measure volume percentages instead of partial pressures? Such instruments should be intrinsically more resistant to false alarms. City Tech of London has developed a sensor with a capillary section that makes it far less sensitive to barometric pressure fluctuations than conventional sensing. Since the Bureau of Mines evaluation was very favorable,⁵ LLNL has purchased a portable instrument from Neotronics that contains this sensor. Another manufacturer replaced a conventional sensor and automatic barometric pressure compensation with a City Tech sensor.

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Aerosol Physics

Assessment and Characterization of Aerosols Generated from a Dual-Beam High-Speed Flow Cytometer

J. Kwan

Since material processed through a flow cytometer may include various mutagenic chemicals and pathogenic microorganisms, the potential for aerosolization of this material and subsequent personnel exposure are issues of concern. To assess and characterize the aerosol-generation potential of a dual-beam high-speed flow cytometer, I processed a test solution (10^8 particles/ml) of lambda phages in a buffer solution) through the cytometer. Aerosolized particles were then captured by an Anderson air sampler on agar plates seeded with *Escherichia coli*. I found that this flow cytometer did indeed generate significant amounts of aerosolized particles in the respirable range. Further work needs to be done to determine the effectiveness of an enclosure surrounding the cytometer to trap such aerosols.

Introduction

The technology of flow cytometry has become an important tool for modern biotechnologies. Flow cytometry is capable of isolating and counting cells or subcellular particles at a rate of 20,000 particles per second with high resolution and efficiency.¹ Samples to be sorted are suspended in an aqueous buffer solution, stained with a DNA-specific fluorescent dye, and then processed by a fluorescent-activated cell sorter. A schematic of the operation is illustrated in Fig. 1.

The potential aerosolization of hazardous chemical and biological materials when processed through the flow cytometer is an issue of concern. Some of these chemical agents are possible mutagens or carcinogens (DNA-specific dyes such as bis-

benzimidazole and chromomycin, and anti-neoplastic agents such as cytosine-araboside and bromodeoxyuridine) or pathogenic microorganisms (various transformed human cell lines that harbor oncogenic viruses, such as Epstein-Barr virus, and human body-fluid samples that may contain Hepatitis B virus and Human T-Lymphotropic virus type III).

This study aims at characterizing the aerosol-generation potential of the flow-cytometry operation used at LLNL. I intended to determine whether a high-speed flow cytometer did generate aerosols and, if so, what the particle-size distribution is. A sampling method for the collection, counting, and aerodynamic sizing of viable airborne particles will be discussed.

Experimental Procedures

Using a motor-driven syringe, we delivered into the flow system 30 ml of "SM" phage culture me-

dium containing 3.3×10^{10} lambda bacteriophages. The sample ran through the quartz flow

Figure 1. Schematic of the dual-beam high-speed flow cytometry system.

chamber and the grounding collar into the waste-collection vessel. The area between the flow chamber and the waste-collection vessel was surrounded partially by a plexiglass enclosure, but the front of the enclosure remained open during the survey.

Bacteriophages infect bacteria in much the same way as some microorganisms can infect human cells. Lambda bacteriophages are highly specific and infect only *Escherichia coli*. To capture settling airborne phage particles aerosolized by the flow-cytometry process, we placed a set of agar plates seeded with *Escherichia coli* in an open-face configuration at various locations within the plexiglass enclosure, as shown in Fig. 2.

Another set of agar plates was used in conjunction with an Anderson microbial air sampler for the collection, counting, and aerodynamic sizing of the viable particles. The Anderson air sampler (Fig. 3) is a multi-stage, multi-orifice cascade impactor which is used to measure the size distribution and total concentration of particles in air. Each stage in the sampler separates an agar plate by a metal disk perforated with holes; these holes decrease in size from stage to stage. Hence, only the smallest particles reach the final stage in the Anderson sampler as air is drawn through the apparatus. The Anderson sampler was operating at a flow rate of 1 ft³/min for ten minutes.

Figure 2. The sampling dishes were spaced in five different locations within the plexiglass enclosure of the flow cytometer.

Figure 3. The Anderson air sampler consists of six stages, allowing progressively smaller particles to pass from stage to stage.

Table 1. Response of agar plates to lambda bacteriophages aerosolized by the flow cytometer. These plates were open-faced samples dispersed around the enclosure.

Sample #	# of plaques
A1	230
A2	147
A3	Too numerous to count
A4	Too numerous to count
A5	223

Results

After the sampling, I incubated the agar plates at 35°C for 24 hours. As the lambda bacteriophages infect the *Escherichia coli*, clearings called "plaques" form on the agar surface. At the end of the incubation period, the phage particles aerosolized by the flow cytometer and subsequently captured on the plates were then visible as plaques. I recorded the number of plaques observed on the open-face samples (A1-A5) (see Table 1).

Due to the overcrowding of plaques on the plates used in conjunction with the Anderson sampler (B1-B6), I estimated the number of viable phage particles collected by applying the positive-hole conversion method.² This method is a statistical estimation of the actual number of organisms present, based on the number of positive impaction sites ("holes") on the agar surface. Table 2 gives the results from the Anderson air sampler and the

Table 2. Results of the Anderson sampler test to determine the particle-size distribution of aerosolized particles from the flow cytometer. Note that most of the particles were in the respirable range ($< 5 \mu\text{m}$).

Sample #	Cut-off size (μm)	Positive holes	Viable part. estimated
B1	7	68	75
B2	4.7-7.0	54	58
B3	3.3-4.7	Agar plate broke, unable to count	
B4	2.1-3.3	326	675
B5	1.1-2.1	368	1010
B6	0.65-1.1	223	326

rough size distribution estimated from the number of stages the particles were able to penetrate. Note that the largest numbers of particles are in the respirable range (smaller than 5- μ m diameter).

Unfortunately, the agar plate broke in the third stage of the Anderson sampler, and the tight scheduling of the flow cytometer did not allow me to make a second test run.

Discussion

The bacteriophage-bacteria aerosol detection system is highly specific. Lambda bacteriophages infect only *Escherichia coli* bacteria; it is reasonable to assume, then, that the plaques I found on the agar plates had been caused by the phages escaping from the flow cytometer, and not from other background sources.

As can be seen in Tables 1 and 2, under its normal operation mode the high-speed cell sorter

did generate droplet aerosols mostly in the respirable range ($< 5 \mu$ m). Considering the potentially hazardous nature of materials being processed through the system, containment of this aerosol is necessary. Further effort is needed to study the existing local exhaust system and to establish performance criteria of such a system to assure proper personnel protection.

Acknowledgments

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Fabricating Micro Air Filters Using Lithographic Techniques

W. Bergman and D. Ciarlo

We have developed a method for manufacturing very precise micro air filters using lithographic techniques, similar to the way in which computer chips are made. These small filters are readily used for filtration studies and experiments. One of our new techniques uses gold fibers formed by electroplating gold on a template; our other technique uses boron diffusion to define the fibers. While these two methods show a great deal of promise, the major drawback is that the fibers themselves are not round, but rectangular (in the case of the gold fibers) or elliptical (in the case of the boron fibers).

Introduction

Quantitative comparisons between theoretical and experimental filters require an accurate knowledge of microscopic filter structure. This structure is poorly defined for common air filters, which have wide and random distributions of fiber diameters, fiber orientations, and various interfiber spacing. To avoid these large uncertainties associated with the structure of real filters, experimentalists often fabricate model filters with controlled geometry.

The approach used by previous researchers to fabricate model filters is to string a series of parallel wires on a support frame. The wire sizes and spacings between neighboring wires are varied to simulate fiber-size distributions and nonhomogeneities in fiber-packing fractions. Models of deep-

bed filters are made by stacking several frames together. The major problem with this approach is the large fiber diameter, typically 20 μm or larger, and the inability to accurately control interfiber spacing due to machine inaccuracy, especially for more complex filter structures.

These problems can be overcome by using lithographic techniques to manufacture individual filter frames. As in the fabrication of computer micro chips, we can make "micro air filters" that may have fiber diameters as low as 2 μm and may have complex, yet precisely controlled, filter structures. In addition, these micro air filters can be economically produced in large quantities, thus making it an attractive technique for filtration studies.

Fabrication of Micro Air Filters

We have investigated two lithographic techniques for fabricating micro air filters. In one technique, fibers are formed by electroplating gold on a template or pattern. The other technique uses boron diffusion through a template to define the silicon fibers. Each process consists of a series of alternating deposition and etching steps.

Figure 1 illustrates the sequence of steps used to form a silicon-fiber filter. After forming an oxide layer on both sides of a thin silicon wafer, a photo-

resist pattern (a pattern transferred photographically to the surface) is placed on one side and the exposed oxide layer is etched away with hydrogen fluoride. Boron is then driven into the silicon wafer by diffusion through the etched oxide layer to define the fiber diameter. The diffusion process forms a fiber having an elliptical cross section. Another photo-resist pattern is then placed on the back side of the wafer, and the oxide layer is etched away with hydrogen fluoride. The silicon is then etched

Figure 1. The sequence of steps used to form a silicon-fiber micro air filter.

back using an ethylenediamine pyrocatechol solution. Since this solution can only etch away the silicon and not the boron-doped silicon, this step forms the fibers themselves. The oxide is removed in the final step.

Figure 2 shows electron micrographs of the cross section of the silicon fiber filter produced by this process. The dimensions of the elliptical fibers in Fig. 2 are $5 \times 13 \mu\text{m}$.

A separate but analogous series of steps involving a template, deposition, and etching will fabricate a gold-fiber filter. Figure 3 shows an electron micrograph of a portion of the gold filter frame. Note the rough surface and rectangular cross section of the gold fibers. The gold fibers are $4 \times 10 \mu\text{m}$.

Figure 2. Electron micrographs of silicon-fiber micro air filters.

Figure 3. This electron micrograph of electroplated gold fibers shows the rough surface and the rectangular shape of the fibers.

Figure 4. Optical micrograph of a 1-mm-diameter filter disk.

Figure 5. A depth filter can be made from these test micro air filters by stacking several filter disks on top of each other.

An optical micrograph of a typical filter frame fabricated by the lithographic technique is shown in Fig. 4. The fibers span across a circular opening of 1-mm diameter. Several of these filter disks can be

stacked together to form a depth filter, as shown in Fig. 5. By stacking together filter disks with varying fiber diameters and fiber spacings, many different model filters can be formed.

Conclusions

Micro air filters fabricated by lithographic techniques are promising candidates for filtration studies. Because of the precision of the lithographic technique, it is possible to fabricate extremely com-

plex filter structures that simulate the complexities of commercial air filters. The cost of these micro filters should also be low because they are readily mass-produced. The only drawback is that the filter

fibers produced by these two techniques are not round. The boron-diffusion method yields elliptical fibers, while the electroplating method yields rect-

angular fibers. We are currently exploring methods for minimizing this problem.

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Development of a High-Efficiency, High-Performance Air Filter Medium

*W. Bergman, A. H. Biermann,
S. R. Sawyer, and O. T. Martin*

A unique high-efficiency particulate air (HEPA) filter medium has been developed for applications in high temperature and high pressure environments. This filter medium is a composite made from quartz and stainless-steel fibers that have been sintered together. The composite medium has the same efficiency and pressure drop as standard HEPA glass media, but has four times the tensile strength and can operate continuously at temperatures up to 550°C. In a conventional HEPA, the binder burns out above 250°C, and the medium loses its strength; our composite filter medium has no comparable loss of strength even at 550°C.

Introduction

High-efficiency particulate air (HEPA) filters are universally used to protect workers and the environment from hazardous airborne material. These filters were designed for applications having relatively low particle loadings at essentially ambient temperature and pressure conditions. Although commercial HEPA filters have proven to be very satisfactory for such routine applications, they are prone to failure at high temperatures, high pressures, and high humidities.¹⁻⁴ In many cases, these extreme environments can destroy the filter element, thereby allowing contaminated air to escape. A number of credible accident scenarios have been proposed in nuclear reactors involving high temperatures, pressures, and humidities that may damage existing HEPA filters and subsequently allow contamination of workers and the environment.¹⁻⁴

Several different solutions have been proposed to address the problems of HEPA failure under credible accident conditions. A HEPA filter made from polypropylene and polycarbonate fibers was developed to withstand structural failure under high pressure, high humidity, and high acid conditions; unfortunately, this filter's efficiency degrades above 90°C, and above 150°C the medium is completely destroyed.⁵

Another approach to the problem is to fabricate high-efficiency filters from a fibrous stainless-

steel medium.^{6,7} Although these stainless-steel filters are able to withstand the adverse environments of high temperature, pressure, and humidity, they do not have efficiencies comparable to HEPA filters (the stainless-steel filter has only a 60% efficiency at its minimum).

The development of a HEPA filter that can withstand high temperature, high pressure, and high humidity conditions requires a careful selection of filtering materials, optimum construction design, and submicrometer size of the fibers or other filtering elements. The primary reason for using glass microfibers in ordinary HEPA filters is that bulk fibers having diameters as small as 0.3 μm (which are responsible for the high efficiency of HEPA filters) are easily available. Unfortunately, these microfibers cannot be formed into a high-strength filter medium using conventional adhesives. The prospects for finding a better adhesive are not very good because all organic adhesives and even silicon glues degrade at high temperatures.

It appears that a filter medium made from a single component cannot simultaneously meet the requirements of high strength, high temperature resistance, and high efficiency.

Composite Filter Medium of Sintered Quartz and Stainless Steel Fibers

Conventional HEPA filters cannot withstand temperatures above 250°C due to the burning of the adhesive that bonds the glass fibers together. We reasoned that if a substitute method for bonding glass microfibers could be found, then the resulting filter medium would have the desired resistance to high temperatures. Moreover, if this alternative bonding method could provide the tensile strength of a sintered stainless-steel medium, then the resulting filter would also have the desired strength.

Our reasoning led us to the development of a composite sintered filter medium made from a mixture of stainless-steel and quartz fibers. Quartz microfibers with an average diameter of 0.5 μm would provide the high efficiency, while stainless-steel fibers with an average diameter of 2 μm would provide the bonding mechanism for the quartz fibers and give the composite medium its high strength. Sintering the composite filter medium fuses the metal fibers together and mechanically holds the quartz fibers in a random three-dimensional cage structure. We used quartz fibers rather than glass fibers because glass would have melted during the initial high-temperature sintering operation.

We prepared a series of composite filter media in which we varied the volumetric fractions of quartz in ten-percent increments from 0% quartz to 100% quartz. The filter media were prepared by first blending the steel and quartz fibers in a water suspension; the water suspension was then drained through a screen, thereby forming a filter mat. Finally, we sintered the composite filter mats in a hydrogen furnace at 1100°C for two hours.

Electron micrographs were taken of the composite filter samples to examine how well the glass and stainless steel fibers are dispersed. Figures 1 and 2 are electron micrographs of the medium containing 40% quartz by volume at a magnification of 200 $\times$ and 1000 $\times$, respectively. We found this medium to have a filter efficiency and pressure drop comparable to standard HEPA media. The stainless-steel fibers have a uniform diameter of 2 μm , while the quartz fibers have a distribution of diameters around 0.5 μm .

This size difference allows the steel fibers to be distinguished from the quartz fibers in Fig. 1(a) at 200 $\times$ and 2(a) at 1000 $\times$. To show a clearer distinction between the steel and quartz fibers, we

(a)

(b)

Figure 1. Scanning electron micrographs of 40% quartz, 60% steel fibers at 200 $\times$ magnification. (a) Image using secondary emission electrons, showing only the quartz fibers. (b) Image using backscattered primary electrons, showing both quartz and stainless-steel fibers.

(a)

(b)

Figure 2. Scanning electron micrographs of 40% quartz, 60% steel fibers at 1000 $\times$ magnification. (a) Image using secondary emission electrons, showing only the quartz fibers. (b) Image using backscattered primary electrons, showing both quartz and stainless-steel fibers.

have also taken electron micrographs using the backscattered electrons in Figs. 1(b) and 2(b). In the backscattered mode, the higher Z fibers (steel) appear white. The conventional electron micro-

graphs [Figs. 1(a) and 2(a)] are obtained from the emission of secondary electrons, which are independent of Z number, and show both steel and quartz fibers as white images. Since each set of electron micrographs in Figs. 1 and 2 was taken of the same viewing area of the filter, by comparing the *a* figures (showing both stainless-steel and quartz fibers) and the *b* figures (showing only the stainless-steel fibers) we can readily see how well the quartz fibers are dispersed in the supporting cage network of steel fibers, as intended.

Filter-Efficiency Tests of the New Medium

Sample sheets containing different percentages of quartz fiber were evaluated in our filter test laboratory to determine the fraction of quartz fibers required to yield a filter efficiency and pressure drop comparable to standard HEPA filters. Each of the filters was tested at a face velocity of 2 cm/s to simulate the flow through a standard HEPA filter. In these tests we used a heterodisperse dioctyl sebacate (DOS) aerosol generated with a Laskin nozzle. Particle concentration as a function of particle size was determined before and after the filter using a differential mobility analyzer coupled to a condensation nuclei counter and a LAS-X laser spectrometer. For the high-efficiency filters, we used a diluter operating at about 1200 to 1 dilution to dilute the upstream aerosols; the filter-penetration curves were corrected for the particle losses in the diluter. Details of our filter-efficiency tests are presented more thoroughly elsewhere.⁸

Figures 3-5 show penetration as a function of DOS particle diameter for composite filter media with increasing volume fractions of quartz fibers from 0% to 50% in ten-percent increments. For comparison with commercially available filters, we have also included the filter penetration as a function of particle size for standard HEPA filter media (Fig. 4) and for the Bekaert sintered-steel fiber filter (Fig. 3). Several trends can be seen in these figures. The most apparent trend is the decrease in filter penetration (i.e., higher efficiency) with increasing quartz volume fraction. In addition, as the volume fraction of quartz increases, the width of the penetration curve decreases and the particle size of maximum penetration shifts to smaller sizes. This can be seen quantitatively in Table 1. These observations are in agreement with filtration theory.

Figure 3. Filter penetration as a function of particle diameter for filters, including one containing 100% stainless-steel fibers, 10% and 20% quartz, and a Bekaert stainless-steel medium for comparison.

Figure 5. Filter penetration as a function of particle diameter for composite filter having 50% quartz and 50% stainless-steel fibers.

Figure 4. Filter penetration as a function of particle diameter for composite filters having 30% quartz, 40% quartz, and a commercial HEPA filter for comparison.

Table 1. Particle size of maximum penetration and width of penetration curve for the new composite filter media.

% Quartz	Width (μm)	Particle size (μm)
0	0.77	0.27
10	0.30	0.22
20	0.26	0.22
30	0.14	0.19
40	0.13	0.17
50	0.10	0.17

the penetration curve for 0.3-μm diameter particles because that curve corresponds to the current certification test for standard HEPA filters.) According to Fig. 4, the HEPA filter has a penetration of 0.005% for 0.3-μm diameter particles (the standard certification test using 0.3-μm particles measured 0.006%, which shows our tests are in close agreement). Referring to Fig. 6, we see that this penetration would correspond to one of our composite filters having 36% quartz by volume.

The penetration data for the composite filters for 0.3-μm diameter particles has also been plotted in Fig. 7 as a function of the filter pressure drop. As expected, the filters having a lower penetration due

In Fig. 6, we have compiled the data from Figs. 3-5 into two curves showing the percent filter penetration as a function of percent quartz by volume. The dashed curve represents the maximum penetration while the solid curve represents the penetration at 0.3-μm diameter. (We have included

Figure 6. These curves show filter penetration as a function of quartz percentage in the composite medium. Note the quartz percentage that yields comparable results to a standard HEPA medium (from Fig. 4) is 36% quartz.

to the greater fraction of quartz fibers also have a higher pressure drop. On this curve we have included the data point for HEPA filters. Note that the point falls on the same curve, which suggests that the average fiber diameter of the HEPA filter is also the same as our 36% quartz composite medium. From Figs. 6 and 7, it is clear that we can make composite sintered filters having the same efficiency and the same pressure drop as a standard HEPA filter.

Filter-Strength Tests

One of the primary reasons for developing our composite sintered medium is to achieve a much

Figure 7. Filter penetration as a function of pressure drop for 3- μ m diameter particles. A standard HEPA filter has been included, showing that our composite filters are comparable.

stronger filter medium than a current HEPA filter. We conducted a series of tensile-strength tests on uniformly cut samples of the same media tested for aerosol penetration above. Each sample was attached to an Instron tensile-strength tester operated at a constant rate of elongation. Figure 8 shows the force at which each sample failed as a function of the percent quartz in the sample. In general, we see that the filter becomes easier to tear as the percentage of quartz increases; however, comparing the tear strength of the standard HEPA medium (170 g) to the comparable composite medium (36% quartz), we see that the composite medium requires four times the tearing force.

Figure 8. The composite filters become easier to tear as the percentage of quartz fiber increases. However, the tear strength of a comparable composite filter is about four times greater than a standard HEPA filter.

Conclusions

We have demonstrated the feasibility of constructing a metallic HEPA filter medium, that is resistant to high temperatures as a composite of sintered quartz and stainless-steel fibers. This medium has a comparable efficiency (99.995%) and pressure drop (0.7") to the standard HEPA glass me-

dium but can be operated continuously at temperatures up to 550°C instead of 250°C and can withstand four times the tearing force. We plan to optimize the fabrication of this filter medium and incorporate it into a HEPA filter design.

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WOTAMS: A Transuranic-Aerosol Measurement System for Workplace, Stack, or Fence-Line Air Monitoring

C. T. Prevo, A. H. Biermann, R. C. Kaifer, S. R. Sawyer, D. W. Rueppel, R. M. del Vasto, T. J. Merrill, D. L. Sawyer, and R. E. Salbeck

We have developed a compact *W*orking-area *T*ransuranic-Aerosol *M*onitoring System (WOTAMS) with a sensitivity of better than 0.5 MPC-h for ^{239}Pu , using alpha spectroscopy. A detector, mounted in the inlet pipe to monitor a filter paper during the collection, responds immediately if it senses a release of radioactivity; then, after a time specified by the operator, the filter is moved to the vacuum chamber for more-sensitive offline analysis. A microcomputer controls the filter transport, operates as a 256-channel PHA, performs calculations, checks calibration, and drives a matrix display. We assessed the particle deposition and loss occurring in WOTAMS by investigating the dependence of losses in the sampling inlet and real-time alpha detector areas with respect to particle size. Further, we determined the uniformity of particle deposition on the collection filter to ascertain the effectiveness of the detector and collection filter configuration. Results indicate that particle losses in the WOTAMS are less than 0.5% for particle diameters in the 1-7 μm range.

Introduction

The *W*orking-area *T*ransuranic *A*erosol *M*onitoring System (WOTAMS) is an online monitoring system currently under development to detect particles containing long-lived alpha emitters. The most common online method for measuring transuranic aerosols is to draw a large sample of air through a filter paper and simultaneously use a solid-state detector to count the alpha activity on the filter paper. WOTAMS has a higher sensitivity than existing monitors and is applicable to both stack and ambient air monitoring. The system we have developed is compact and very efficient for detecting particles as large as 10 μm in diameter.

An online monitoring system must be able to function in the presence of radon (^{222}Rn) and thoron (^{220}Rn) and their daughter particles.¹⁻³ Although radon and thoron are gases that pass through the filter medium, their charged daughter particles readily attach to particles collected along

with the transuranic aerosols. Figure 1 shows the decay schemes of radon and thoron. The daughter particles that can interfere with the measurement of transuranic aerosols using alpha particles are RaA (^{218}Po), ThC (^{212}Bi), RaC' (^{214}Po), and ThC' (^{212}Po), which emit alphas at 5.99, 6.05, 7.68, and 8.78 MeV, respectively. Under normal conditions, radon and thoron concentrations range from 0.04 to 0.4 pCi/liter at locations at one meter above ground level.⁴ This represents an alpha-emitter concentration that is 20-200 times the 40-h occupational MPC of soluble ^{239}Pu . The energy degradation of the 5.99-, 6.05-, and 7.68-MeV alphas due to the filter medium and air can result in these readings appearing in the same portion of the spectrum as the ^{239}Pu (alpha-particle energies of 5.15, 5.13, and 5.10 MeV). This results in an increased background, thereby reducing the sensitivity of the instrument for measurement of ^{239}Pu .

(a) radon (^{222}Rn) (b) thoron (^{220}Rn)

Figure 1. The decay schemes of radon and thoron. Some of these daughter products can interfere with transuranic-aerosol measurement.

A continuous air monitor (CAM) is widely used for such measurements. Because the counting is done in air and uses a short-time-constant integrating circuit, the CAM has a limited sensitivity of 10 MPC/hr for ^{239}Pu . Also, losses of particles to the walls are strongly dependent on particle size, increasing drastically as the particle size decreases.⁵ The concentration distribution of the particles on the filter also becomes less scattered as the particle size decreases.

Due to these limitations of the CAM, we set out to develop a new instrument that would have greatly improved sensitivity. The approach we adopted for WOTAMS was to collect the sample on a filter paper and then move the filter paper into a vacuum-spectroscopy system for analysis while we collected a second sample. In the meantime, the first sample could be monitored using an in-air spectroscopy system.

Description of WOTAMS

The WOTAMS includes an inline detector that views the filter as the sample is being collected.

This detector will quickly give an alarm if a release should occur while the previous filter medium is

(a)

(b)

Figure 2. (a) Side view of the WOTAMS inlet probe. (b) Inside of the probe, looking downward from the inlet.

being analyzed offline in the vacuum-spectroscopy system. The air-sampling inlet of the WOTAMS consists of a 15.4-cm-long, 5.25-cm-diameter probe that sits on the collection filter. Inside the probe is a conical flow divider to divert the airstream flow lines around the alpha detector. A three-pronged holder is used to support the detector and flow divider in the center of the probe and above the filter. Figure 2(a) is a side view of the inlet probe and Fig. 2(b) is a photograph of the inside, looking downward from the inlet. Figure 3 is a cross-sectional view of the inlet probe assembly.

House vacuum or an external pump pulls the monitored air through the filter medium. A vacuum pump is included to pump the spectroscopy detector chamber rapidly down to the operating pressure. A dual-purpose shutter protects the detector during vacuum-chamber venting and allows for pe-

riodic detector calibration by means of a source mounted on its top side. At the time the aerosol is monitored, very tight seals exist on the inline filter medium where a sample is being collected and around the vacuum-spectroscopy chamber where the previous sample is being analyzed. Before the filter medium can be advanced, it is necessary to close the sample-line vacuum valve, vent the vacuum chamber, and release the lower pressure plate. It takes 20 seconds after a count to start the next inline count, and an additional 30 seconds to pump down the vacuum chamber so the high-resolution analysis can be started. Figure 4 shows the inline and vacuum-spectroscopy detectors along with the air-monitoring and filter-transport system. The WOTAMS data-acquisition and NSC-800 computer systems have been described elsewhere.⁶

Figure 3. Cross-sectional view of the inlet probe assembly.

Figure 4. Schematic of the WOTAMS system, showing the inline and vacuum-spectroscopy detectors along with the air-monitoring and filter-transport system.

Particle-Deposition Evaluation

In a previous study we found that significant particle losses can occur in the sampling systems of other CAMs.¹ In the WOTAMS, we assessed the dependence of particle losses in both the sampling inlet and the real-time alpha detector areas as a function of particle size. To investigate the effectiveness of the detector configuration, we determined the uniformity of particle collection on the WOTAMS filter for different aerosol sizes. Two different detector sizes at varying spacings above the aerosol collection filter were studied.

A Berglund-Liu aerosol generator was used to produce monodisperse test aerosols of dioctylsebacate (DOS) and methylene blue (MB). This

generator uses a vibrating orifice to produce uniformly sized droplets from a pressurized liquid solution. Clean, filtered air is introduced for proper droplet dispersal and evaporation of the solvent, leaving the solute, either a solid or nonvolatile liquid, as the aerosol particle. The concentration of the solution and the size of the orifice determine the final aerosol particle size. Aerosols were monitored for particle size with a TSI Model 3300 aerodynamic particle-size analyzer.

We chose to study aerosols in the 1–10 μm range because we expect aerosol impaction to be the dominant mechanism for particle loss. Also, previous studies involving another continuous air

monitor have indicated significant losses in this size range.⁵ The three general aerosol size categories we studied were 1.5, 3, and 6–8 μm diameters. The exact values we report are the averages of geometric-mean aerodynamic diameters from several samplings throughout a test period.

For this investigation, the WOTAMS unit was operated at volumetric flow rates of 2 and 4–5 cfm.

Filter Performance

Performance of the WOTAMS depends strongly on the type of filter medium used. We evaluated two types of filter media for WOTAMS use: Millipore Fluoropore and Gelman Acropor, both having pore diameters of 1.2 μm . Both types of filter media possess a relatively smooth surface compared to typical fibrous media, so that we expect most particle collection to be on the surface. In the case of the Acropor medium, liquid particles, after collection by the filter, diffused across its surface so quickly that our attempts to measure the uniformity of collection across the surface were not successful. Therefore, we chose the Fluoropore medium for most of our particle-loss experiments.

Aerosol particles deposited on the surfaces of the WOTAMS inlet probe assembly were removed by washing with isopropanol or by swiping and dissolving the swipes in acetone. We analyzed the washings for the amount of methylene blue by measuring the absorbance using a Bausch and Lomb Spectronic 88 spectrophotometer. To analyze for uniformity of particle collection on the filter, the

Flow rates were set according to a calibrated venturi prior to an experiment; pressure loss across the filter was monitored throughout the test period. Two sizes of detectors—1.7- and 3.4-cm diameter—were used in the experiments. The position of the detector above the collection filter could be varied from 0.5 to 2 cm.

collection filter was cut into several concentric rings; washings from these sections were also analyzed spectrophotometrically. To prevent filter loading, we used several filters in any given experiment.

We measured the amount of particle deposition for five different areas of the WOTAMS sampling inlet probe and collection filter, shown in Fig. 3, including the inlet-tube walls, the flow-stream divider cone above the detector (incident to the incoming aerosol), the walls of the flow divider (parallel to the aerosol flow), a simulated detector, and the detector and flow divider support. Our results using the 6- to 7- μm diameter liquid aerosol are presented in Table 1. Total depositions are expressed in percentages relative to the particle collection on all surfaces and the sum of all collection filters used throughout the experiment. Total deposition in the inlet assembly varies from 0.1 to 0.4%. No losses were detected on the probe walls. Highest losses occurred for the detector support and flow divider. The smallest wall loss occurred using

Table 1. Particle deposition in the WOTAMS sample inlet for large particles.

Aerosol diameter (μm)	Experimental parameters				
	6	6	7	6	6.8
Volumetric flow (cfm)	4	2	5	5	5
Detector	Large	Large	Large	Small	Small
Distance to filter (mm)	0.5	0.5	2	2	0.5
	Percentage deposition				
1. Probe wall	0.0	0.0	0.0	0.0	0.0
2. Detector support	0.06	0.0	0.1	0.0	0.25
3. Flow divider, front	0.11	0.1	0.1	0.06	0.0
4. Flow divider, sides	0.07	0.04	0.14	0.04	0.01
5. Detector face	0.03	0.0	0.0	0.0	0.0
Total losses	0.27	0.13	0.34	0.10	0.27

the smaller diameter detector at the lower flow. On the other hand, the largest particle losses occurred using the larger detector at 5 cfm.

The concentration profile across the filter surface for the experiments involving large-particle aerosols is shown in Fig. 5. The amount collected on each concentric ring has been paired with a radius which corresponds to the area-weighted average of the inner and outer ring diameters. The profiles indicate a decreased concentration toward the center of the filter beneath the detector. As would be anticipated, the lowest concentration values occur for the case where the detector is closest to the filter. The lower concentration toward the center, though, is not altogether the result of the detector itself masking the flow-stream line. Visual examination of the lower concentrated areas actually indicates an unresolved outline of the detector and flow divider support upstream of the filter. These reduced levels of concentration become a more significant portion of the area of a given concentric ring for smaller rings. Thus, decreased concentrations in the center of the filter are attributed to both the detector and the detector flow-divider support. Areas of higher particle concentration occur outside the detector's projected area on the filter. The effect of these non-uniform particle deposits on the performance of the WOTAMS real-time detector

was found to be small because of the good detector geometry.⁷ In a worst case scenario, with all particles collected in an annulus encompassing the outer half of the filter, the radiation flux seen by the detector was 90% of the ideal. Particle-loss results for the smaller aerosol-size distributions are shown in Table 2. Total losses in these experiments range from 0.04 to 0.4%.

Investigation of Tailing Effects

Energy degradation of the alpha particles as they pass through the filter medium causes the same type of peak tailing as seen in air, thereby reducing the sensitivity of the system. We investigated four types of filter media to determine their contribution to tailing effects: TF Teflon and Versapor (from Gelman), and Fluoropore and Durapore (from Millipore). Versapor and Millipore had a 1.2- μm pore size, TF Teflon had a 1.0- μm pore size, and Durapore had a pore size of 0.45- μm .

A 1-h air sample at a flow rate of 60 lpm (except for Durapore at 30 lpm, as limited by its pore size) was simultaneously taken through each filter, and these samples were then counted in separate vacuum chambers for one hour. The spectra were very similar for the TF Teflon and the Fluoropore

Figure 5. Concentration profile across the WOTAMS filter surface.

Table 2. Particle deposition in the WOTAMS sample inlet for smaller particles.

Aerosol diameter (μm)	Experimental parameters				
	3	3	3	1.5	1.5
Volumetric flow (cfm)	4	4	5	5	5
Detector	Large	Large	Large	Large	Small
Distance to filter (mm)	0.5	1	2	0.5	2
	Percentage deposition				
	0.08	0.0	0.11	0.0	0.0
1. Probe wall	0.08	0.0	0.11	0.0	0.0
2. Detector support	0.01	0.0	0.0	0.0	0.0
3. Flow divider, front	0.01	0.0	0.02	0.0	0.13
4. Flow divider, sides	0.0	0.04	0.01	0.43	0.10
5. Detector face	0.01	0.0	0.0	0.0	0.07
Total losses	0.11	0.04	0.14	0.43	0.30

with approximately 0.5% of the total background counts in the ^{239}Pu - ^{241}Am window. Durapore was also good with 1%, but Versapor was not quite as good with 3% of the counts in the window. These results are preliminary and further tests will be performed.

Another practical consideration in choosing a filter for the WOTAMS is how well it operates in the

transport. Of the three media with low degradation, Durapore appears to be the best, TF Teflon is satisfactory, but Fluoropore is not recommended because of its tendency for the edges to curl. Durapore is also much less expensive than either of the Teflon filters.

Sensitivity Calculations

To illustrate how various parameters affect the sensitivity of the system, we calculated sensitivities for different radon and thoron air concentrations with both in-vacuum and inline counting geometries. For the purpose of these calculations, we assumed uniform deposition of activity on the filter paper. This is a reasonable assumption as illustrated by calculations and by aerosol measurements on the system.^{6,8} We calculated the backgrounds occurring in the plutonium-counting window for three radon and thoron air concentrations and three detector sizes. These calculations were based on an analysis of the activity of the daughter products on the filter medium as a function of time after collection and on the background measurements discussed earlier for Teflon and Durapore. The calculated backgrounds are given in Table 3. Using these backgrounds, minimum detectable MPC-h were calculated using Pasternak's equation for the minimum detectable counts,⁹ also shown in Table 3. We regard these results as preliminary, since they were not made with the WOTAMS itself.

Table 3. Backgrounds in the plutonium counting window and calculated minimum MPC-h for various radon and thoron air concentrations and detectors.

^{222}Rn - ^{220}Rn Concentrations (pCi/l)	Detector Area (mm^2)		
	500 In-air	800 In-vacuum	1700 In-vacuum
Background			
0.04	82	6.8	13
0.1	203	17	32
0.4	809	68	130
MPC-h			
0.04	0.67	0.07	0.05
0.1	1.0	0.11	0.07
0.4	2.0	0.20	0.14

Conclusions

We are developing an instrument that should significantly improve the state of the art for transuranic aerosol measurement in the workplace, in stacks, and at the fence line. This new instrument should have a sensitivity of better than 0.5 MPC-h.

We found that particle losses in the inlet sample probe assembly of the WOTAMS aerosol monitor were minimal (less than 0.5%) over an aerodynamic aerosol range of 1.5-7 μm diameter and volumetric flows of 2-5 cfm. Because of the low particle losses, we recommend that any future particle-loss studies on this inlet assembly should be done using a fluorescein tracer to gain increased sensitivity. Most aerosol losses occurred on the detector and

flow-divider support. It is likely that losses on the detector and flow-divider support (which are already low) could be further reduced by a smaller and more aerodynamic design. Concentration profiles across the surface of the collection filter ranged from 20-100% at the center to 100-120% on the outer section, depending on aerosol size, detector position, and flow. It is possible that the uniformity of particle collection on the surface could also be somewhat improved by a better design. Finally, these concentration profiles may be used to assess which detector size might prove optimum for the detection of particles collected on the filter.

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New Test Methods for Ultra-Low Penetration Aerosol (ULPA) Filters

W. Bergman, A. H. Biermann, and S. R. Sawyer

Ultra-Low Penetration Aerosol (ULPA) filters have many uses in clean-room applications. However, existing ULPA test methods are not adequate to measure the filter efficiency because the filter becomes loaded to capacity before a meaningful measurement can be made. We have developed a new test method that uses particle spectrometers and a sampling bag downstream of the filter. By capturing all of the air downstream of the filter rather than just a small sample, the bag allows for much shorter sampling times. This eliminates the filter-loading problems experienced with the previous test method.

Introduction

The semiconductor and electronics industries require Ultra-Low Penetration Aerosol (ULPA) filters for use in their clean-room applications. These filters have penetrations even lower than 0.001%, which is the limit of the present U.S. certification test for High Efficiency Particulate Air (HEPA) filters. Considering the large quantity of ULPA filters planned and already in use in clean rooms, the lack of an adequate test procedure represents a major problem. To address this problem, a large number of companies and organizations are investigating new test methods for determining the penetration of these filters. The most notable of these organizations is the Institute of Environmental Sciences that has formed a working group to establish a recommended practice for ULPA filtration. This group is currently conducting a round-robin test on various low-penetration filter media using only laser particle counters. Several filter manufacturers are also advertising the efficiency of their ULPA filters for 0.12- μm diameter particles as measured by a laser particle counter. However, 0.12- μm is the smallest particle size the laser counter can measure.

These various efforts to establish an ULPA filter test method are all based on using a laser particle

counter as a substitute for the current photometer test with 0.3- μm dioctyl phthalate (DOP) aerosols. The implicit assumption in these new laser tests, as well as in the current DOP photometer test, is that the penetration of any filter can be represented by the penetration measurement for a single particle size. Unfortunately, this is not true, since all filters have a maximum penetration at a specific particle size and a lower penetration for other particle sizes. Moreover, the particle size of maximum penetration can shift to smaller or larger sizes depending on the filter parameters, such as the diameter of the fibers in the filter mat (smaller fiber yields a smaller particle diameter of maximum penetration; a larger fiber yields a larger particle diameter of maximum penetration), and the test conditions, such as the air flow (higher flow rate yields a smaller particle size of maximum penetration, and a lower flow yields a larger particle diameter).¹ For ULPA filters, however, the particle size of maximum penetration is typically below even the smallest detectable particle size of a laser counter. Therefore, we have developed a test method that is able to measure filter penetration over a wide range of particle sizes in order to determine the maximum penetration.

Previous Test Methods

Figure 1 shows a schematic of our standard test method for evaluating HEPA filters. The method uses particle-size spectrometers to measure

the particle concentrations as a function of size before and after the test filter. The ratio of the downstream to upstream concentration yields the filter

penetration as a function of particle size. Since the concentration of the challenge aerosol typically exceeds the limits of the particle-size spectrometer, it is necessary to dilute the challenge aerosol before making the upstream measurement. The particle size spectrometer in our studies consists of a differential mobility analyzer (DMA) coupled to a con-

Figure 1. Schematic of existing filter-test method for measuring filter penetration of HEPA and ULPA filters as a function of particle size.

densation nuclei counter (CNC) for measuring particle sizes from 0.01- to 0.5- μm diameter and a LAS-X laser counter for measuring particle sizes from 0.12- to 3.0- μm diameter. The complexity of this system requires a computerized data-acquisition and instrument control.³ Figure 2 shows the penetration as a function of particle size for a HEPA filter having a DOP photometer penetration of 0.005%. Note that the limiting size of the laser counter falls on the peak filter penetration.

For extremely low penetration ULPA filters, this HEPA filter test method is no longer adequate. The filters are so efficient that the medium becomes completely clogged before an appreciable number of particles can penetrate, which leads to a very small working sample. The downstream spectrometer is unable to measure the very low particle concentrations. The largest factor contributing to this instrument limitation is the small sample volume passing through the instrument. The sample flow rates of the LAS-X and the CNC are 90 and 300 cm^3/min , respectively. Because of this small sampling rate, it is necessary to sample for long times in order to accumulate sufficient particle counts. The sampling time itself can be reduced by increasing the challenge aerosol concentration up to the limit

Figure 2. Experimental penetration of a HEPA filter as a function of DOS particle diameter. The LAS-X counter measures particles greater than 0.12 μm diameter.

Figure 3. Experimental penetration of an ULPA filter as a function of DOS particle diameter. During the 12-minute test, five repeat measurements were made with the LAS-X particle counter for particles greater than $0.12 \mu\text{m}$ and a single measurement with the DMA-CNC analyzer for particles smaller than $0.12 \mu\text{m}$.

of rapid particle coagulation; however, the increased challenge concentration also loads the filter faster. If solid particles are used in the sampling, the primary effect of the filter loading will be a reduced filter life and an underestimation of the filter penetration. This is caused by the buildup of solid particles trapped on the filter mat, which helps to capture other challenge particles, thereby yielding an erroneously high efficiency. The solid particles remain in the filter and cannot be removed by drying the filter, as is possible with liquid particles; this leads to a reduced filter life.

If liquid particles are used, then the filter loading can cause an overestimation of filter penetration. The liquid particles trapped on the filter fibers

will coalesce and travel toward the back of the filter because of the air flow; once the liquid reaches the downstream side it can spray out, implying an anomalously high penetration. In a real environment, however, a concentration so high would never occur that such problems as liquid spraying and solid-particle loading would be a concern. The liquid particles can also cause potential problems in clean-room applications due to liquid evaporation.

Figure 3 shows the penetration of dioctyl sebacate (DOS) aerosols through a Matheson filter Model 6134-P8FF. The increasing filter penetration seen in the repeat measurements is due to particle spraying from the rear side of the filter.

New Test Procedure

We have developed a new procedure for testing ULPA filters that avoids the problem of filter clogging. Figure 4 shows that we have replaced the downstream particle spectrometer with a sample bag. By trapping all or a large fraction of the filter exhaust in an inflatable Tedlar bag, we can significantly reduce the exposure time of the ULPA filter. Previous instruments measured only a small sample

of the downstream air, requiring a long time before a large enough specimen could be obtained. Our sampling bag collects a large amount of the exit air, allowing a measurement from the total sample, rather than a proportionate sample. The challenge aerosol is removed once the bag is sufficiently full.

We then measure the particle-size distribution in the bag using the particle-size spectrometers;

Figure 4. The new filter-test method for measuring filter penetration of ULPA filters, using a bag sampler.

Figure 5. The new bag method yields essentially the same results as the direct method.

from this we can determine the total number of penetrating particles in each size increment, and also the particle diameter of maximum penetration.

This new filter test method effectively saves the downstream aerosol sample to accommodate the

small sampling rate of the particle-size spectrometer. Our tests show that the particle losses in the bag are negligible. Figure 5 shows that the bag method yields essentially the same penetration as the direct method.

Conclusions

New test methods for determining the penetration of ULPA filters must be able to measure filter penetration as a function of particle size from 0.01- to 0.5- μm diameter. This range of particle sizes is needed to guarantee that the maximum filter penetration is measured. The particle-size spectrometers used in these test methods consist of a differential mobility analyzer coupled to a condensation nuclei

counter and a laser particle counter. The limitations of these instruments require the dilution of the upstream measurement and a bag sample for accumulating the downstream sample. Based on several preliminary tests, we expect that these new methods will extend the range of detectable filter penetration from 0.001% in the present photometer tests to less than 0.000001% at a particle diameter of 0.3- μm .

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Health Physics

HOT SPOT Health Physics Codes

Steven G. Homann

The newly developed HOT SPOT Health Physics codes allow fast assessment of accidents involving radioactive materials. These codes run on the Hewlett-Packard HP-41 family of hand-held computers, and the software resides on a single 128K minicassette. This compact system is intended for easy field use of the HOT SPOT codes. At present, 13 separate programs exist, ranging from general programs for downwind assessment following the release of radioactive material to more specific programs dealing with the release of plutonium, uranium, or tritium. Other programs estimate the dose commitment from the inhalation of various radionuclides, and estimate the effects of a surface-burst nuclear weapon.

Introduction

HOT SPOT is part of the Department of Energy's Accident Response Group. The HOT SPOT computer programs described in this article were created to provide Health Physics personnel with a fast field-portable calculational aid for evaluating accidents involving radioactive materials. The HOT SPOT codes provide a first-order approximation of the radiation effects associated with the atmospheric release of

radionuclides. Although significant errors are possible, the HOT SPOT programs will provide a reasonable level of accuracy for a timely initial assessment. More importantly, the HOT SPOT codes will produce a consistent output for the same input assumptions, thus minimizing the errors of reading a graph incorrectly, for instance, or scaling a universal nomogram during an emergency situation.

Equipment

To provide an inexpensive and portable tool, I developed the codes for the Hewlett Packard HP-41 family of hand-held computers. Figure 1 shows the equipment required to use the HOT SPOT codes, and Fig. 2 shows how the HOT SPOT equipment can easily fit within its padded aluminum suitcase for field use. The hardware is robust and has survived a multitude of emergency exercises. A small user shell allows easy access and operation of all the codes. Once this shell is loaded, it remains in the HP-41 until the user resets the memory or until the batteries are depleted. The code residing in the computer at any one time can be displayed by

pushing the RCL key. The output is in an engineering format to three significant figures. This option results in useful output for units specified in multiples of 1000 (such as micrometer, millirem, etc.).

HOT SPOT software resides on a single 128K minicassette. Operating instructions and information are contained in LLNL Manual-161 *HOT SPOT Health Physics Codes* (April 1985), available from the author. The manual is designed for users of the codes and therefore does not contain detailed descriptions of algorithms used in the codes; however, key assumptions (e.g., particle distribution, release fraction, etc.) are noted as appropriate.

Figure 1. The equipment required for running the HOT SPOT Health Physics codes includes an HP-41, 128K minicassette, manual, printer, and power source.

Figure 2. All components of the HOT SPOT codes fit easily into a steel carrying case.

Background

The dosimetric methods of *ICRP Publication 30* have been used throughout the HOT SPOT programs. Individual organ dose values (unweighted) are produced, along with the committed dose equivalent (weighted, equivalent whole-body dose commitment). Programs involving the atmospheric transport of radionuclides employ a Gaussian plume-dispersion model. Initial radionuclide distribution is

modeled using virtual source terms as needed, e.g., modeling the initial distribution associated with an explosive release, or areal resuspension source term. Owing to the large uncertainties associated with the source term, diffusion coefficients, etc., additional fine tuning of the model with plume-rise algorithms and similar modifications was deemed unwarranted.

HOT SPOT Programs

Table 1 is a summary of the programs contained in the *HOT SPOT Health Physics Codes* manual. Three general programs—PLUME, EXPLUME, and RESUS—allow for downwind dose assessment following the release of radioactive material as a result of a continuous or puff release, explosive release, or an area contamination event. These three programs interact with a database containing 75 radionuclides selected from *ICRP Publication 30* (see Table 2 for a complete listing). The source term can contain any or all of the radionuclides in the database, each with its independent release fraction, activity, and mitigation factor if applicable. Should a desired radionuclide not reside in the database, a dose-conversion factor can be input. Other specific programs deal with the release of plutonium, uranium, and tritium to expedite the initial assessment of accidents involving nuclear weapons. Additional programs estimate the dose com-

mitment from inhalation of any one of the radionuclides listed in the database, and estimate the effects of a surface-burst nuclear weapon.

Figure 3 is an example output of the PUEXP program, which estimates the downwind plume-centerline dose commitment and ground deposition resulting from the explosive release of plutonium. The default output is shown; output options exist for off-axis locations, time-integrated air concentration, and user-selectable downwind distances.

The author will provide copies of the *HOT SPOT Health Physics Codes* manual to any interested parties. Copies of the 128K minicassette containing the codes themselves are also available from the author.

An IBM PC-compatible version of the HOT SPOT codes is currently in progress. The HOT SPOT codes will be an executable program with a source code written in Turbo Pascal.

Table 1. Programs contained in the HOT SPOT Health Physics codes.

Program Name	Description
PUEXP	Downwind dose commitment and ground deposition estimates resulting from an explosive release of plutonium.
PUFIRE	Downwind dose commitment estimates resulting from a fire involving plutonium.
PURES	Downwind dose commitment estimates resulting from the resuspension of plutonium.
FIDLER	FIDLER calibration and data reduction. Also contains a subroutine for the determination of radionuclide weight fractions as a function of mix age.
TRIT	Downwind dose commitment estimates resulting from a tritium release.
UFIRE	Downwind dose commitment estimates resulting from a fire involving natural uranium or any enrichment of ^{235}U .
LUNG	Lung screening for plutonium using a FIDLER detector.
BOMB	Effects of a surface-burst fission weapon.
RADWORK	Determination of recommended workplaces for the handling of radioactive materials.
PLUME	General Gaussian plume dispersion model, using ICRP-30 Library.
EXPLUME	General explosive release dispersion model, using ICRP-30 Library.
RESUS	General resuspension model, using ICRP-30 Library.
DOSE	Inhalation dose commitment, using ICRP-30 Library.

Table 2. Radionuclides contained in the HOT SPOT database selected from ICRP Publication 30.

Nuclide	Options (class)	Default form	Nuclide	Options (class)	Default form
H-3 (oxide only)		Class D	I-133		Class D
C-14		Class D	I-134		Class D
C-14G (carbon dioxide)		Class D	I-135		Class D
Na-22		Class D	Xe-133		N/A
Na-24		Class D	Xe-135		N/A
P-32	D W	Class W	Cs-134		Class D
S-35		Class W	Cs-136		Class D
Ar-41		N/A	Cs-137		Class D
Ca-45		Class W	Ba-140		Class D
Cr-51		Class Y	La-140	D W	Class W
Mn-54		Class W	Ce-144	W Y	Class Y
Fe-55		Class W	Pr-144		Class Y
Fe-59		Class W	Pm-147		Class Y
Co-57		Class Y	Ta-182		Class Y
Co-58	W Y	Class Y	Ir-192	W Y	Class Y
Co-60	W Y	Class Y	Au-198		Class Y
Zn-65		Class Y	Tl-204		Class D
As-76		Class W	Po-210		Class W
Se-75		Class W	Ra-226		Class W
Kr-85		N/A	Th-232		Class Y
Kr-85M		N/A	U-232		Class Y
Kr-87		N/A	U-233		Class Y
Kr-88		N/A	U-234		Class Y
Rb-86		Class D	U-235	W Y	Class Y
Sr-89	D Y	Class Y	U-236		Class Y
Sr-90	D Y	Class Y	U-237		Class Y
Y-91	W Y	Class Y	U-238	D W Y	Class Y
Zr-95	D W Y	Class Y	Np-239		Class W
Nb-95	W Y	Class Y	Pu-238	W Y	Class W
Mo-99		Class D	Pu-239	W Y	Class Y
Tc-99M		Class W	Pu-240	W Y	Class Y
Ru-103		Class Y	Pu-241	W Y	Class Y
Ru-106		Class Y	Pu-242	W Y	Class Y
Cd-109		Class Y	Am-241		Class W
Te-132	D W	Class W	Am-243		Class W
I-125		Class D	Cm-242		Class W
I-131		Class D	Cm-244		Class W
I-132		Class D	Cf-252		Class Y

US

PLUTONIUM
H.E. RELEASE

PUEXP

REV-4/30/85

TOTAL PLUTONIUM: 3.0 KG

HIGH EXPLOSIVE: 150. LB

STABILITY = B

WIND SPEED = 1.5 M/S

CLOUD TOP = 266 M

CLOUD RADIUS = 23 M

D=0.1 KM

DEP = 8.01 $\mu\text{Ci}/\text{m}^2$

50-YR DOSE COMMITMENT:

LUNG***** 133.00 REM

SURFACE BONE 396.00 REM

RED MARROW** 30.900 REM

LIVER***** 86.300 REM

EQUIVALENT

WHOLE-BODY** 36.500 REM

D=0.2 KM

DEP = 8.01 $\mu\text{Ci}/\text{m}^2$

50-YR DOSE COMMITMENT:

LUNG***** 139.00 REM

SURFACE BONE 418.00 REM

RED MARROW** 32.400 REM

LIVER***** 90.600 REM

EQUIVALENT

WHOLE-BODY** 38.300 REM

D=0.5 KM

DEP = 4.01 $\mu\text{Ci}/\text{m}^2$

50-YR DOSE COMMITMENT:

LUNG***** 68.000 REM

SURFACE BONE 204.000 REM

RED MARROW** 15.000 REM

LIVER***** 44.200 REM

EQUIVALENT

WHOLE-BODY** 18.700 REM

D=1.0 KM

DEP = 2.01 $\mu\text{Ci}/\text{m}^2$

50-YR DOSE COMMITMENT:

LUNG***** 38.100 REM

SURFACE BONE 114.000 REM

RED MARROW** 8.8600 REM

LIVER***** 24.800 REM

EQUIVALENT

WHOLE-BODY** 18.500 REM

D=2.0 KM

DEP = 1.01 $\mu\text{Ci}/\text{m}^2$

50-YR DOSE COMMITMENT:

LUNG***** 21.300 REM

SURFACE BONE 63.800 REM

RED MARROW** 4.9400 REM

LIVER***** 13.800 REM

EQUIVALENT

WHOLE-BODY** 5.8500 REM

D=5.0 KM

DEP = 4 $\mu\text{Ci}/\text{m}^2$

50-YR DOSE COMMITMENT:

LUNG***** 7.9700 REM

SURFACE BONE 23.900 REM

RED MARROW** 1.8500 REM

LIVER***** 5.1800 REM

EQUIVALENT

WHOLE-BODY** 2.1900 REM

D=10.0 KM

DEP = 1 $\mu\text{Ci}/\text{m}^2$

50-YR DOSE COMMITMENT:

LUNG***** 2.3400 REM

SURFACE BONE 7.8300 REM

RED MARROW** 545.-03 REM

LIVER***** 1.5200 REM

EQUIVALENT

WHOLE-BODY** 645.-03 REM

D=20.0 KM

DEP = 0.2 $\mu\text{Ci}/\text{m}^2$

50-YR DOSE COMMITMENT:

LUNG***** 595.-03 REM

SURFACE BONE 1.7800 REM

RED MARROW** 138.-03 REM

LIVER***** 386.-03 REM

EQUIVALENT

WHOLE-BODY** 163.-03 REM

D=50.0 KM

DEP = < 0.2 $\mu\text{Ci}/\text{m}^2$

50-YR DOSE COMMITMENT:

LUNG***** 89.3-03 REM

SURFACE BONE 260.-03 REM

RED MARROW** 28.8-03 REM

LIVER***** 58.1-03 REM

EQUIVALENT

WHOLE-BODY** 24.6-03 REM

D=100.0 KM

DEP = < 0.2 $\mu\text{Ci}/\text{m}^2$

50-YR DOSE COMMITMENT:

LUNG***** 28.6-03 REM

SURFACE BONE 61.7-03 REM

RED MARROW** 4.79-03 REM

LIVER***** 13.4-03 REM

EQUIVALENT

WHOLE-BODY** 5.66-03 REM

Figure 3. Example: Three kilograms of weapons-grade plutonium are involved in a one-point detonation (150 pounds of high explosive). The sun is low and the wind speed is 1.5 m/s. Estimate the ground contamination and dose commitments due to cloud passage for locations downwind (centerline of plume) from the event.

Thermal Degradation of Welding Blankets

Anne E. Lipska-Quinn and Stephen J. Priante

We investigated the thermal-degradation mode of a number of non-asbestos welding blankets. Twenty-five samples representing the products of major blanket distributors were subjected to thermogravimetric analysis in air to determine the onset and the extent of thermal degradation. Samples with the least amount of weight loss were also studied for production of toxic products during thermal degradation (carbon monoxide, carbon dioxide, hydrogen cyanide, hydrogen chloride, and formaldehyde). We then subjected the most thermally stable blanket exhibiting the least amount of toxic-product formation during degradation to a large-scale test. The sample for the large-scale test was 3- x 3-ft in size, exposed to 3500°C from an oxyacetylene torch and tested for toxic products approximately one foot away from the cloth. Results of our study indicate that unless welding blankets are composed of silica cloth, they will lose a considerable amount of weight when exposed to temperatures as low as 300°C and will form substantial amounts of toxic products. Blankets made of silica cloth are extremely resistant to high temperatures, produce minimal amounts of toxic products, and are, therefore, the best substitute for the previously used asbestos blankets.

Introduction

Since asbestos fibers can no longer be used because of the health hazards involved, alternative heat-resistant materials have been employed in the manufacture of welding blankets. As the result of an incident involving thermal failure of a non-asbestos welding blanket, where welders accidentally exposed the blanket to high temperature and were overcome by toxic fumes, we were asked to conduct an extensive study investigating the thermal properties of currently available non-asbestos welding blankets. We were particularly interested in determining the heat resistance and the amount of toxic-product generation from these materials at temperatures attained in routine welding and cutting operations. Our experimental approach consisted of the following steps:

1. We conducted a literature search on available non-asbestos blankets to find the temperature needed for onset of degradation, the formation of

toxic products during the thermal degradation, and test results from Underwriter's Laboratory (UL).

2. We performed thermogravimetric analysis (TGA) on various blanket samples to determine the temperature responsible for the onset of degradation, the rate of weight loss, and the total weight loss at the completion of each thermal analysis.

3. We tested those blankets with the smallest weight loss and/or highest heat resistance, as obtained from the TGA runs, for toxic-product formation.

4. We performed additional in-depth testing of the best blanket in terms of thermal resistance and toxic-product formation. We exposed a representative 3- x 3-ft blanket sample to an oxyacetylene torch and tested for the presence of toxic products approximately one foot away from the cloth.

Experimental Procedure and Observations

The results of our literature search revealed that most of the heat-resistant fabric used in welding blankets is made of fiberglass or silica. In many of the fiberglass formulations, the cloth is coated with silicon rubber, hypalon, neoprene, or an acrylic fiber; many of the silica-based blankets are covered with a proprietary coating. Little information is available in the open literature on thermal behavior of the various welding blankets, so we obtained representative samples from various distributors and submitted the samples to a series of laboratory tests. Our thermogravimetric analysis was conducted in air at a heating rate of 20°C/min from ambient temperature to 900°C. We monitored the weight of the sample and its rate of change as a function of temperature. An example of this data is shown in Fig. 1. Results of our TGA runs are summarized in Table 1.

Table 1 shows that the temperature required for the initial degradation of the samples varied between 40 and 689°C. The total weight loss also differed considerably from sample to sample. Note that the silica fabrics display a large amount of moisture loss, followed by a slow weight loss at higher temperatures.

Based on the TGA results, we chose a number of samples for analysis of toxic-product formation at elevated temperatures. We eliminated the first eight samples listed in the table because these samples degrade at low temperatures, they lose too

much overall weight to be considered heat resistant, and they are coated either with neoprene or hypalon which evolve large amounts of HCl upon degradation. In the next group of eight samples, we tested Thermonol cloth because of its relative resistance to heat; and we tested Siltemp, Silica fabric #2-3700, and Thermoglass cloth because of their low overall weight loss. Out of the next 15 samples, we tested one LLNL Stores stock blanket, and the last six samples listed in the table. Because of non-uniform coating with a binder on the fiberglass base of the LLNL stock welding blanket, thermograms produced from this material are different, as indicated by the temperature needed for initial weight loss (see Table 1).

To avoid this problem, some manufacturers heat the fibers to a high temperature to remove the excess binder prior to distribution. It appears that this particular manufacturer did not do this, resulting in an initial non-uniform degradation pattern of the fiberglass blanket. We eliminated sample #21 from further testing since it is coated with neoprene, which could give off large amounts of HCl at elevated temperatures. Samples #22-25 were also not tested for toxic products because they either started to degrade at low temperatures or had lost too much overall weight to be considered heat resistant.

Our screening tests for toxic-product formation were done with Draeger tubes. We heated the samples to 500°C and tested the resulting smoke for CO, CO₂, HCN, HCl, and NO_x. Two grams of each sample were used for each determination. Results of the screening tests are given in Table 2.

The above materials were not treated with a special organic finish; thus the HCN and NO_x are degradation products from an organic binder used during the fiber-manufacturing process. If at the end of the process, the fibers are not subjected to high temperature to remove excess binder from the cloth, both HCN and NO_x will be formed when the fabric is subsequently subjected to high temperatures. Various manufacturers told us that both silica and fiberglass cloths are acid washed after they are woven, and although most of the acid is washed off, some residue is left on the cloth. The amount of residue will depend on how thoroughly the cloth was washed with water at the end of the processing.

In order to compare small-scale results with a more realistic situation, we chose the Siltemp cloth

Figure 1. Sample of the thermogravimetric test data, showing the rate of a welding blanket's weight loss as a function of temperature.

Table 1. Thermogravimetric analysis of non-asbestos welding blankets.

Sample identification	Temperature leading to initial weight loss (°C)	Total weight loss (%)
1. Duck heavy-weight hard finish CFM approved	311	94.30
2. Weld Tex vinyl-coated fabric	276	97.60
3. Fro-Prene nylon fabric coated with Hypalon	266	84.00
4. Armor-Pleated heavy-duty Hypalon fabric	285	92.07
5. Fro-Lon #1 fiberglass cloth with Hypalon coating	277	30.18
6. Fro-Lon #2 fiberglass cloth with Neoprene coating	220	19.06
7. Fro-Sil fiberglass cloth with rubber coating	220	7.96
8. Jaxcolite glass cloth	289	40.36
9. Thermonol cloth	569	71.26
10. Weld flex	205	41.07
11. Weld-O-Glass #2300 (fiberglass)	289	44.60
12. Fro-Flex special fiber blend	291	43.20
13. Fromelt, silica fabric	328	19.64 (9.81)*
14. Siltemp, silica fabric	182	15.33 (9.92)*
15. Silica fabric #2-3700	182	18.29 (9.89)*
16. Thermoglass cloth	40	5.25
17. LLNL Stores stock welding blanket, Sample #1	307	3.46
18. LLNL Stores stock welding blanket, Sample #2	218	17.95
19. LLNL Stores stock welding blanket, Sample #3	207	10.38
20. Weld-O-Glass #2-1900 (same as Silica #2-3700)	182	18.29 (9.89)*
21. Weld-O-Glass #3000R	452	13.22
22. Weld-O-Glass #2000G	274	21.75
23. Nor-Fab material	689	61.05
24. Thermo-Sil Style #1550	299	22.61
25. West Mac Co. #HR100-96	324	22.03
26. Weld-O-Glass #900FC	346	2.85
27. Weld-O-Glass #1000FC	380	2.54
28. Weld-O-Glass #2650	381	0.82
29. Weld-O-Glass #1850	503	0.63
30. Zetex 1100	245	3.42
31. Zetex 1200	313	2.39

* Percent moisture loss.

as our candidate for large-scale testing. Inside the large-scale test cell, we exposed a 3- x 3-ft sample to a cutting torch and tested for the presence of CO, CO₂, HCN, HCl, and NO_x approximately one foot away from the cloth. This test represented the worst possible situation to which a welding blanket might be subjected. Results showed negative readings for all gases except NO_x, which registered 10 ppm; this is not in agreement with our laboratory small-scale test. However, the results from our small-scale lab

test were obtained from products generated at 500°C and sampled directly from the smoke stream. We feel that the 1 ppm of HCN would be diluted at one foot away from the blanket to concentrations below the detection limits of the Draeger tube. We attribute the absence of HCl to its dissociation to Cl₂ and H₂ by the 3500°C flame. The higher NO_x reading results from the interference of Cl₂ with the active chemical diphenylbenzidine in the NO_x Draeger tube.

Table 2. Toxic-product formation from welding blanket samples heated in air at 500°C.

Sample identification	Toxic products and amounts				
	CO (%)	CO ₂ (%)	H ₂ N (ppm)	HCl (ppm)	NO _x (ppm)
1. Thermonol	0.5	5	150	<50	N.A. ^a
2. Siltemp	0	0	2	>20	1
3. Silica fabric #2-3700	0.25	0	9	>20	6
4. Thermoglass	0	0	10	0	3
5. LLNL Stores stock blanket sample	0.5	5.0	30	>50	10
6. Weld-O-Glass #900FC	0.5	2.5	75	10	7
7. Weld-O-Glass #1000FC	0.5	2.6	75	100	0
8. Weld-O-Glass #2650	0.1	0	15	10	7
9. Weld-O-Glass #1850	0.1	0	30	10	15
10. Zetex-1100	0.5	trace	50	0	trace
11. Zetex-1200	0.4	trace	25	10 ^b	0.5
Threshold Limit Value	50 ppm	5000 ppm	3 ppm	5 ppm	5 ppm

^a Too much interference by other compounds; cannot interpret results.

^b Color change is due more to Cl₂ than to HCl.

Conclusions

The results of our tests provide a database to be used for selecting welding blankets that can be expected to produce the minimum amount of toxic materials when exposed to the high temperature

from a welding torch flame. Care must be taken, however, in predicting the specific operational performance of a given blanket on the results of our small-scale laboratory tests.

Acknowledgment

We would like to thank Donald Beason for conducting the large-scale oxyacetylene test on the Siltemp sample.

Fire Endurance of Sprinklered Glass Walls

Donald Beason

The National Fire Protection Association (NFPA) code allows the use of tempered glass walls as fire and smoke barriers in the construction of atriums. The LLNL Fire Science Group conducted tests to determine if fires would be likely to shatter these glass barriers and allow smoke and flame penetration into adjoining rooms. We used both a large (250 kW) and a small (40 kW) fire source to test tempered glass, ordinary plate glass, and laminated safety glass. While the tempered glass allowed by the NFPA code showed no damage from the large fire which was sufficient to initiate the room sprinkler, the glass did shatter when directly exposed to the 40-kW fire. The plate glass cracked with the 250-kW fire and allowed smoke penetration. The best candidate was the laminated safety glass, which cracked upon exposure to the 250-kW fire, but maintained its integrity and did not allow the passage of smoke or flames.

Introduction

The National Fire Protection Association (NFPA) *Code for Safety to Life from Fires in Buildings and Structures* describes guidelines for constructing atriums. The NFPA code requires that atriums be separated from adjacent spaces by fire barriers with at least a 1-h fire-resistance rating. An exception to this, though, is the use of sprinklered glass walls.

"Glass walls may be used in lieu of the fire barriers where automatic sprinklers are spaced 6 ft (182.88 cm) apart or less along both sides of the glass wall, not more than 1 ft (30.48 cm) from the glass, and with the automatic sprinklers located so that the surface of the glass is wet upon operation of the sprinklers. The glass shall be tempered glass held in place by a gasket system which permits the glass framing system to deflect without loading the glass before the sprinklers operate."¹

Because this procedure is allowed by the NFPA, LLNL has adopted the use of tempered glass as a smoke barrier for enclosed atrium spaces. This procedure will almost certainly work for fires that initiate and spread at some distance from the glass separation; however, fires directly adjacent to the tempered glass could create conditions of intolerable stress in the glass during either the fire exposure or the subsequent thermal shock during the initial water-spray sequence.

Because of this concern, the Fire Science Group conducted experiments using commercially installed tempered-glass panes exposed to large and small fires. The object of these tests was to assess the validity of the NFPA recommendation that tempered glass may be used as a safe and effective fire and smoke barrier in DOE atrium buildings.

Experimental Procedure

The tests were conducted in the LLNL fire-test cell. Within the cell, we constructed a simulated office space protected by the tempered-glass atrium

barrier. Two fire sizes were selected to simulate a range of conditions for initiating fires. The larger fire was an isopropyl pool fire of 0.425 m² with a

Figure 1. The large fire source used in these tests, an isopropyl pool fire with a strength of about 250 kW.

Figure 2. The small fire source, 40-kW natural-gas diffusion flame.

Figure 3. Heat-transfer pattern of the large test fire cast on a sheetrock inset.

fire strength of about 250 kW. The small fire source consisted of a gas pipe burner 2.54 cm in diameter and 30 cm long; a 40-kW natural-gas diffusion flame was produced from holes drilled symmetrically along the length of the pipe. Figures 1 and 2 show the large and small fire sources, respectively, as viewed through a glass atrium barrier. Figure 3 shows the heat-transfer pattern cast by the 250-kW fire on a sheetrock inset for the window. We used this pattern to select positions for thermocouples on the atrium window. Two standard 160°F fire-protection sprinklers were installed according to the NFPA code, and are shown in Fig. 4. Figure 5 is a schematic of the test room showing the appropriate dimensions and relative locations of the sprinklers and thermocouples.

Figure 4. Sprinkler system installed according to NFPA specifications.

Figure 5. The test room used in these experiments. Note the locations of the sprinklers and the thermocouples.

Results

Table 1 summarizes the test parameters and observations from our five tests. The first test was on tempered glass with the 250-kW fire source. The glass remained intact throughout the test and showed no signs of thermal damage. The temperature on the fire side of the glass just before the sprinklers fused was 230°C, as shown in Fig. 6. We

inspected the glass pane after the test with a polariscope to determine if there had been any thermal degradation of the glass. We found no indications of such damage.

In Test 2, the same glass panel used in Test 1 was exposed to the flame of the 40-kW gas burner. In this test, however, after only 80 s (and before the

Table 1. Summary of tests conducted on sprinklered glass panels.

Test	Fire strength (kW)	Type of glass	Maximum glass temp. before failure (°C)	Time to glass failure (s)	Upper-layer room temp. at glass failure (°C)	Upper-layer room temp. at sprinkler fusing (°C)	Observations
1	250	Tempered	No failure	~	—	204	Sprinkler fused: 46 s
2	40	Tempered	39	80	36	—	No sprinkler
3	250	Plate	458	34	200	198	Sprinkler fused: 45 s
4	250	Laminated	385	30	200	210	Sprinkler fused: 37 s
5	40	Tempered	960	216	35	—	Glass fractured and fell out of frame. Thermocouple relocated to give flame temperature.

Figure 6. Temperature curve for the first test, which used tempered glass with the 250-kW fire source.

sprinklers could fuse) the tempered glass broke into small pieces ($\sim 3/8$ -in.²). Figure 7 shows the glass wall after the fire was put out and before the glass fell from the frame.

Our third test was conducted on a pane of standard plate glass exposed to the 250-kW fire. The glass cracked 11 s before the sprinkler head fused. The glass remained in the frame, but a large crack at the base of the glass would have allowed smoke to penetrate into the next space in a real office environment.

In the fourth test, a pane of laminated safety glass was installed in the frame and exposed to the 250-kW fire. The laminated glass cracked, but maintained its integrity (i.e., the crack would not have allowed smoke penetration). The safety glass is approximately 30% more expensive, but may be worth the extra cost where the smoke boundary must be maintained. We expect that the safety glass would

also crack when exposed to the 40-kW fire, because of the high stress generated by direct exposure to the flames before sufficient heat could be generated to fuse a sprinkler; but we expect that, because of the vinyl film in the laminated glass, this glass should still maintain its integrity. The manufacturer states that this type of glass can withstand a ΔT up to 50°C without fracturing, depending upon the thickness and the actual temperature.²

In the fifth test, we repeated the small fire exposure of tempered glass, as in Test 2. We repeated this setup because of the possible thermal damage to the glass during exposure to the 250-kW fire in Test 1. As expected, the glass fractured after 216 s of exposure. The sprinkler system did not fuse. Figure 8 shows a time vs temperature curve for the exposed glass surface during this test. The maximum temperature at the time of glass fracture was 950°C.

Figure 7. In the second test, the glass panel directly exposed to the smaller fire shattered and fell from the frame.

Figure 8. Time vs temperature curve for Test 5. The glass panel shattered when directly exposed to the 40-kW fire before the sprinkler system could fuse.

Conclusion

These tests show that tempered glass performs adequately when exposed to relatively large fires that create a temperature rise in the room fast enough to fuse sprinklers before high stresses can

be generated in the glass. However, if the fire is concentrated in a small area on the glass surface and is not large enough to generate a rapid temperature rise in the room, sufficient stresses can be

generated to shatter the glass. Such fires would negate the effectiveness of the smoke and fire barriers as required by the NFPA code. Laminated safety glass appeared to provide the best protection, even

though the glass cracked during the fire exposure. In this case, the panel remained intact and in place, and the smoke boundary was not breached.

Reference

1. National Fire Protection Association, Boston, MA, *Code for Safety to Life from Fires in Buildings and Structures*, NFPA 101-1981, Section 6-2, "Construction and Compartmentation," subsection 6.2.2.3, paragraph 6.2.2.3.1.h, 1981.
2. Pat Brennan, Habenicht-Howlett, San Francisco, CA, private communication (1986).

Sensitivity of Fire and Smoke Detectors to Environmental Conditions: RF and Microwave Exposure

Kirk J. Staggs

Certain extreme environmental conditions can affect the performance of fire and smoke detectors, either with false alarms or with decreased sensitivity. We surveyed the types and placement of smoke detectors in areas of extreme environmental conditions at the Lawrence Livermore National Laboratory. To determine the effect of exposure to radiofrequency or microwaves, we tested some types of smoke detectors with a small transmitter and a microwave generator. With the low power levels available to our test instruments, we found no change in the smoke detector performance.

Introduction

We began work on this project to define thresholds for fire- and smoke-detector failures resulting from extremes in environmental conditions. These conditions include:

- Unusually high or low temperature.
- Unusually high or low humidity levels.
- Pressure variations.
- Microwave or radiofrequency (rf) energies.
- Ionizing radiation.
- The presence of volatile fluids and outgassing solids such as solvents, extracts, plastics, and other similar elements.
- Other undefined phenomena within LLNL.

These studies may be used to aid designers in the selection of components for fire-management systems.

This work was conducted in phases to examine different environmental conditions. The test procedure for each subsequent phase was determined by the results of the previous phase or phases. The recently completed first phase was divided into five tasks:

1. Conduct a survey of detector types used at LLNL.
2. Inspect LLNL facilities to determine extreme environmental exposure conditions.
3. Develop a procedure and experimental apparatus for studies of detector exposure to rf and microwave exposure.
4. Conduct first phase testing of rf and microwave exposure.
5. Summarize findings in an interim report.

The purpose of this interim report is to present a critical review of our surveys and testing to determine the effects of rf or microwave exposure on detectors.

Detectors

Several different types of fire or smoke detectors are used at LLNL. Most of these detectors are designed to sense the presence of either convected energies (heat) or radiant energies of aerosols and gases. Convected energy detectors, or heat detectors, respond to the thermal energy generated in a fire. These detectors operate either on the fixed-

temperature or the rate-of-rise method of detection. The fixed-temperature units respond when their operating element reaches a preset temperature; the rate-of-rise units respond when the rate of temperature change exceeds their preset value (usually around 15°F/min).

Radiant energy detectors, or optical detectors, respond to the infrared and/or ultraviolet light produced in a fire. Of the several different types of aerosol and gas detectors, photoelectric and ionization detectors are the most common. The photoelectric detectors respond when aerosols or gases generated during a fire enter the detector and affect the propagation of light passing between a light source and a sensor. Ionization detectors respond when aerosols or gases enter the sensing chamber

and reduce the electrical current (generated by a radioactive material) to the current-sensing circuitry.

An ionization smoke detector might be affected by rf energies coupling to the leads of the components within the detector. At very high frequencies, the short leads of the components act like small antennae absorbing more and more energy as the rf or microwave frequency reaches their resonant frequency.¹

Literature Search and Facility Survey

Many detector manufacturers place warning labels on their products, advising that the detectors should not be used in certain adverse environments. This warning is suitable for routine use in offices and other commercial buildings; however, the nature of work at a research laboratory leads to many extreme environmental conditions. In such cases, the LLNL fire-management system must still provide fire and smoke detectors, and we often need to know the exact operational limits for individual detectors. Unfortunately, manufacturers rarely release this type of information, and we were forced to search the literature to see if we could find the reported results of any performance tests on the fire- and smoke-detector types used at LLNL.

Information obtained from the Plant Engineering Department at LLNL indicates that heat detectors, flow alarms, and ionization smoke detectors are predominantly used throughout LLNL. For the facility survey, we toured the various laboratory buildings on site, taking photographs of the fire and

smoke detector installations. Our survey was mainly directed at chemistry and electronics labs, fabrication shops, high bays, and other similar areas where extreme environmental conditions might exist. During the survey we recorded the type of room, its geometry, its construction materials, and the type of ventilation system servicing the room. In addition, we noted the type of fire or smoke detector used and environmental factors that might influence the detector's operation.

We learned of false alarms that occurred near a microwave capacitor in a vault room of the Physics Research Building. It appears that during operation of the microwave generator, reflected microwave energy stimulated the detectors and activated the alarm system. To shield the detectors from reflected microwaves, each detector was covered with aluminum foil, as shown in Fig. 1. Unfortunately, this foil impedes the air flow, thus making operation of the detectors unreliable.

Figure 1. In the case of false alarms near a microwave capacitor in a vault room, each detector was covered with aluminum foil to shield it from reflected microwaves.

Test

We conducted tests by exposing several different smoke detectors to varying degrees of rf and microwave energies to see how often such false alarms could be generated. The tests were conducted using a hand-held radio transmitter as a fixed-frequency microwave source and a microwave generator as a variable-frequency source. The hand-held transmitter is the Motorola MX350 FM unit with a 6-W output, one of the most powerful transceiver units used on site and the same type as used by the LLNL Fire Department; we were concerned that nearby operation of such transceivers could activate the alarms. The microwave generator, model HP350, operates at an intensity of 10-mW continuous wave, while most normal background sources are at levels less than 1 mW. The apparatus that supported the detectors during testing consisted of a wood panel with three detector bases and a control panel (Fig. 2). A wood panel was used because it is non-conductive and would not reflect the microwave energy. The control panel supplied the necessary power to operate the detec-

tors, an indicating light, and a meter to monitor detector firing.

In the first part of our testing, we used the hand-held transmitter. We placed its antenna approximately six inches from the detector under test and closed the transmit switch. We then repeated this procedure with an actual voice transmission through the transmitter. The detector did not respond to either transmission. Near the end of each test, a standard test gas (used by maintenance personnel to provide a detectable aerosol) was sprayed on the detectors to determine their response. We found no difference from the previous detector response.

The second part of our testing used the microwave generator. In preparing each test, a detector was placed against the output wave-guide tube of the generator. The generator output was then stepped up at 1 GHz per second between 1 and 26 GHz. We repeated this procedure while test gas was sprayed at the detector. Again, we saw no measurable change in detector response.

Figure 2. The apparatus supporting the detectors being tested consisted of a wood panel with three detector bases and a control panel.

Conclusion

Our survey of detector placements indicates that smoke detectors are seldom located in areas of extreme environmental conditions at LLNL. Such areas are generally serviced with heat detectors and/or sprinkler systems with flow alarms. The false alarms caused by operation of a microwave generator probably resulted from reflected microwave energies several orders of magnitude above the levels

of our tests; the low power levels available with our test equipment—the type of routine equipment found near smoke alarms on site—were insufficient to stimulate the detector. The incorporation of an interlock system in microwave vault rooms, which would deactivate the fire and smoke detectors before operating the microwave generator, should alleviate this problem.

Reference

1. Peter Davis, Electrical Engineering Department, Lawrence Livermore National Laboratory, Livermore, CA, private communication (1985).

Shock Hazards Resulting from the Inadvertent Release of Water from Fire-Protection Sprinkler Systems

N. J. Alvares and K. J. Staggs

The inadvertent release of water from fire-protection sprinkler systems could increase the risk of shock to workers in areas where high-voltage electrical equipment is in operation. We conducted two types of experiments to survey the extent of this risk: (1) to assess electrical conduction through water films on floor surfaces such as could result from sprinkler release, and (2) to define the potential of electrical discharge from surfaces of high electrical potential to a person in the area. For the latter series of tests, we used selected water-spray distributions and concentrations, and a grounded resistance probe of the same average resistivity as the human body. Our findings show that water film conductivity provides the most direct electrical coupling between high-potential conductors and ground. The pattern of the voltage gradient indicates significant importance of position and proximity of electrodes to the ground point. Water-spray discharge studies show no increase in current flow between the high-voltage grid and the grounded electrode, which is not dependent on water conductivity.

Introduction

With the increased use of very high power sources (power supplies, capacitor banks, etc.) in laser and magnetic fusion energy research, nuclear power plants, and other high-energy areas, the concern has been raised that the inadvertent spraying of water on high-voltage electrical equipment could increase the risk of electrical shock to operating personnel. Electrical engineers tend to perceive fire-protection sprinkler systems as an extraordinary hazard in areas where high-energy circuits, appliances, and systems are present; because of this perception, wet-pipe sprinkler systems are often excluded from certain areas.

However, statistics show that the death rate caused by fires (26 in 1000) is more than five times that caused by electrical accidents (5 in 1000). Furthermore, analyses indicate that the probability of an inadvertent release of water from properly designed sprinkler systems is very small (approx-

mately 1 in 1,000,000). Non-engineered equipment cooling systems do have a high probability of inadvertent water releases, however; and excluding wet-pipe sprinkler systems in areas already containing non-engineered cooling systems because of the supposed increased risk of water-induced shock is not a valid argument. Conversely, wet-pipe sprinkler systems will certainly reduce the consequences of fires.

A literature search reveals several data sources related to an actual electrical conductivity measurement in water spills, sprays, or hose streams. One report sets qualitative distance limits between the hose nozzle and the high-voltage electrical source in terms of voltage levels and water flow rate.¹ However, we could find little applicable research relating to the electrical-shock potential when both equipment and personnel are exposed to a contiguous spray. Because of our inability to find data or

theoretical information to help us define water-related shock hazards, we designed a set of experiments to investigate the issue.

The experiments were limited to two specific areas: (1) the condition of water-layer formation from water leaks in and around high-voltage equip-

ment, and (2) the hazard of electrical discharge carried on water droplets during inadvertent operation of the fire-protection sprinklers or failure of the water cooling lines. Note that in both of these scenarios, ground-fault systems should operate before any dangerous conditions can develop.²

Water-Layer Test

To determine water-layer formation, we constructed and instrumented an acrylic rectangular chamber, as shown schematically in Fig. 1. A standard test probe was used as a source electrode, and a copper plate located at a horizontal distance of 46 cm (18 in.) was used as a ground plane. Instrumentation consisted of a megometer for a power source, and a digital multimeter to measure the volt-

age drop along the water surface between the source electrode and the ground. The containment chamber was filled with tap water to levels varying between 6.25 cm (2.5 in.) to 17.8 cm (7 in.). At each selected level, we made voltage measurements across the water source in 2.5 cm (1 in.) increments between the source electrode and the ground plane.

Figure 1. Test chamber to determine shock hazards from the formation of water layers caused by fire-protection sprinkler systems.

Test Results and Discussion

Results from these tests are plotted in Fig. 2. Note how the gradient is very steep at distances near 0 and 70 cm, the locations of the source and ground points. Since water has a linear resistance, we believe this is due to the configuration of the

source electrode and ground plate; an extrapolation of these gradients indicates increased gradients as water levels decrease until direct contact is no longer possible. Further analysis indicates that at low water levels, most of the voltage drop between the source and ground will occur within a few centimeters of the source; inversely, in high water levels

Figure 2. Results of the water-layer test. Note the steep gradients near 0 and 70 cm, the locations of the source and ground points.

most of the voltage drop will occur near the ground. Figure 3 is a curve comparing the linear slope portion of the voltage gradient with water-layer thickness. As water-layer thickness increases, the voltage gradient approaches an asymptote at about 0.25 V/cm. We can extrapolate the gradient for thin layers, assuming that the layer is contiguous and of uniform thickness.

These results are representative of our experimental apparatus. Changes in electrode shape, cross-sectional area of conduction path, water conductivity, and solid-suspension ratio would change the magnitude, but not the trend of these data.

Figure 3 The linear portion of the voltage gradient from Fig. 2, plotted as a function of water depth.

Water-Spray Test

We designed an experimental system to address the concern that water spray from fire-protection sprinklers could decrease the dielectric properties of the air between a grounded person and a high-voltage electrical apparatus. If the dielectric properties of a water-spray/air mixture are lower than air alone (highly unlikely, since air at high humidity is more resistant to electrical breakdown than dry air), we need to define the parameters of a potential difference and water spray that will allow the break-

down phenomenon. The test system must have features that simulate the range of these conditions. To this end, we constructed a large chamber from non-conducting materials and equipped it with a water-spraying system, a high-voltage grid, a grounded coil with electrical resistance similar to that of an average human being, computer-controlled timing and diagnostic circuits, and appropriate safety interlocks for protection both of operator and equipment. Figure 4 shows schematically our test apparatus.

Figure 4. Schematic of the apparatus used in the water-spray test.

The inside dimensions of the test chamber are 1.2 m² in floor area and 1.85 m high. Figures 5 and 6 show the chamber schematically and photographically, illustrating the three major components of the apparatus:

- The high-voltage grid.
- The "Man-Equivalent Resistance Probe" (MERP).
- The water-spray nozzles.

The door is clear acrylic, and the rest of the chamber is made of construction gray PVC. A thin copper sheet with a drain hole in its center covers the bottom surface. Collected water drains through

a plastic pipe to a grounded building drain. A grounded copper screen covers all exterior chamber surfaces except for the door.

The high-voltage grid was suspended on an aluminum frame (0.76 × 0.76 m). Grid spacing (0.12 × 0.12 m) was given by bare copper wires attached to the frame. The frame was suspended from the test chamber top by adjustable hangers; grid-position changes are relative to the top of the MERP, where minimum and maximum separation is 2.5 and 22.5 cm, respectively. Grid potential up to 12 kV ac was provided by a high-voltage transformer controlled by a Variac.

Figure 5. Test chamber for the water-spray test, showing the three main components: the high-voltage grid, the "Man Equivalent Resistance Probe" (MERP), and the water-spray nozzles.

Figure 6. Photograph of the test chamber.

The MERP consisted of an acrylic rod 3 cm in diameter and 1 m high. The top 0.82 m of the acrylic rod was wound with stainless-steel wire (total resistance = 1000 Ω). This resistance is essentially similar to the bulk resistance of an average human being.³ Current flow induced in the MERP by any discharge phenomenon between the MERP and the high-voltage grid is sensed and recorded by an Apple II+ computer through an optical isolator system. The MERP is positively grounded to the central ground for the system.

The water-spray system conveyed water from a pressurized tank through a throttling valve and solenoid valve to a composite nozzle station containing three separate nozzles that would allow water flow through one or all nozzles simultaneously. While we made a provision for a variable water-flow rate, we conducted all of our tests with the water flow set to

6.1 l/min·m² (the water supply recommended for each sprinkler in ordinary hazards).*

Our experimental procedure for the water-spray tests was quite simple; however, because of the high voltage, we were required to provide stringent and fast-acting safety interlocks. The Apple computer controlled the safety interlock system as well as the diagnostic system. Once we had pre-selected and established the experimental conditions, we needed to actuate only three control switches to initiate the experimental sequence. The sequence is outlined below:

1. Safety circuits established and confirmed.
2. Power to grid established.
3. Water spray initiated.
4. Data-sequence cycle.
5. Power terminated.
6. Safety circuit confirmed test termination.
7. Apparatus reset.
8. Data reduced, displayed, recorded on disk.

Experimental Results

The experimental plan called for a sequential series of tests where the control variables were: (1) the separation distance between the MERP and the high-voltage grid ($2.5 \text{ cm} < \delta < 22.5 \text{ cm}$); (2) the potential difference between the high-voltage grid and ground ($\text{emf} < 12 \text{ kV-A}$); (3) the water-spray rate ($\dot{V}_{\text{water}} \leq 6.1 \text{ l/min}\cdot\text{m}^2$); and (4) the water quality (ranges from distilled water to water from sprinkler pipes that were undrained for several months. The dependent variable for these tests would be the presence of current elevation or spikes across the MERP.

Preliminary tests in dry air showed no variation in MERP current at the extremes in separation distance between the grid and the MERP, or for variation in the grid voltage level at any separation distances. Because of these observations, we decided to abandon our original test protocol and initiated all subsequent tests at the position providing the maximum chance for interaction between the high-voltage grid and the MERP. Table 1 lists data for the tests conducted at these conditions, and Fig. 7 shows examples of our data output for the four most severe test conditions with and without water spray.

* The NFPA Group 2 rating.

Table 1. Parameters of the different water-spray tests conducted in this study. Grid voltage of 12 kV ac was used in every test.

Test number	Grid position (cm above MERP)	Water type	MERP current (μA)
KV12MCA	22.5	City	8
KV12LDA	2.5	Deionized	20
KV12LCA	2.5	City	19
KV12LSA	2.5	Sprinkler	27

The maximum MERP current for these tests was 27 μA , which is more than two orders of magnitude below the 1 mA perception threshold, sometimes used as a maximum safe current level.

The perceptible elevation of current flow when the grid is energized can be attributed to the grid acting as a transmission antenna that induces current in the MERP windings. The magnitude of current elevation is consistent with this phenomenon.

In preliminary test, the water-spray sequence was terminated before the MERP sensing circuit was shut down. A small, continuous stream

Figure 7. Samples of data output for the most severe test conditions with and without water spray.

Figure 8. Maximum MERP current levels for the dry test at two grid positions.

Figure 9. Maximum MERP current levels for the tap water test, extrapolated beyond 30 kV for two different grid positions.

of water trickled down from the energized grid to the MERP, allowing high current flow to ground through the MERP. This accidental current was detected by the measurement system (in fact, it overpowered one component); therefore, our system has the capability to sense such discharges when they occur. The major variations of the water-spray test data are attributed to water conduction between the windings of MERP. (Nevertheless, these differences are only on the order of 7–8 μA .) Consequently, we need only contrast the “no water spray” test to any of the “water spray” tests.

Dry Test

Evaluation of the maximum current levels, using no water and with grid positions at 2.5 and 22.5 cm above the MERP, indicates MERP current levels of 1.4 $\mu\text{A}/\text{kV}$ at 2.5 cm and 0.61 $\mu\text{A}/\text{kV}$ at 22.5 cm at grid potentials of 1 to 12 kV ac. A plot of these current levels extrapolated out beyond 30 kV is shown in Fig. 8.

Tap Water Test

Tests conducted using tap water with the grid again placed at 2.5 and 22.5 cm above the MERP indicate maximum MERP current levels of 1.6 $\mu\text{A}/\text{kV}$ at 2.5 cm and 0.75 $\mu\text{A}/\text{kV}$ ac. This 1–2 μA increase in current flow over the dry runs is due to water collecting on the MERP and decreasing its resistance. Figure 9 gives an extrapolation of these results.

Deionized and Sprinkler Water

We also conducted tests using deionized and sprinkler water with the grid at 2.5 cm and voltage levels set at 12 kV ac. (We ignored the 22.5 cm position because the tap-water test results at that position gave no indication of current change.) Our results with the deionized and sprinkler water were similar to the tap-water results, and any differences were inconclusive.

Conclusions

An analysis of our water-film and spray test data resulted in the following conclusions:

- The relative locations of the electrode and the grounding point to the water affected the voltage gradient.
- An increase in the thickness of the water layer inversely reduces the voltage gradient between the high voltage and the ground electrode.

- At the smallest possible distance between the electrode and MERP, the water-spray test gave minimal indications of current flow (12 kV, 60 Hz).

- Measurably small changes in current flow occurred with different types of water (tap, sprinkler, deionized) and electrode spacing.

All indications are that for a standard 60-Hz system, risk of an electrical discharge sufficient to

create a shock hazard is negligible. Our tests did not investigate the shock hazard involving capacitor systems and dc power sources, which have substantially different current flows. Also, our water-spray

tests used only one electrode configuration; other configurations may yield substantially different results.

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Dosimetry

Use of CR-39 Foils for Personnel Neutron Dosimetry: Improved Electrochemical Etching Chambers and Procedures

Dale E. Hankins, Steven G. Homann, and Joane Westermarck

We have improved the electrochemical etching procedures for our new dosimetry system that uses foils of CR-39 plastic. During 1985 we modified our etching chambers to correct several problems, and we also investigated changes to the etching procedures, which gave us a more uniform track density and size. The currently recommended etch parameters are given in this report. A new generation of CR-39 material from the manufacturer proved to have a considerably lower background track density and a higher sensitivity; the new foils are also more uniform in thickness, which eliminates the need to numerically compensate for thickness variations. We have also determined the energy dependence of the CR-39 using monoenergetic neutrons from accelerators at Battelle Northwest Laboratories and at Los Alamos National Laboratory. We found some variation in the energy dependence, but we believe this was caused by changes in the etching procedures and by uncertainties in the fluences of the neutrons from the accelerators. We have also suggested a means by which the counting of CR-39 tracks may be automated; this would be very useful in adapting the CR-39 dosimetry system to large-scale use.

Introduction

We have previously reported on the development of a personnel neutron dosimetry system using CR-39 plastic.¹ This new dosimetry system was designed to permit its large-scale use, such that one full-time technician could process 2000 track-etch dosimeters per month. In order to improve the energy dependence of CR-39, the foils are etched in

an oven at 60°C. We have redesigned the etch chambers described in our previous report and have made a number of changes and improvements in etching procedures and evaluation techniques. In this report we describe these improvements and their effects on the dosimetry system.

Etch Chambers

During the past year, we have redesigned our etch chambers to correct several problems, such as deterioration of the glue joints, leakage of the KOH around the stainless-steel electrode, and a gradual bending of the chambers. Other problems in track uniformity caused apparently by a non-uniform

electric field strength throughout the etch chamber were corrected by increasing the KOH reservoir on all sides. Figure 1 shows the 8-cell etch chamber. Engineering drawings of the 8-cell etch chambers and sketches of the 24-cell etch chamber are available from the authors.

Figure 1. Drawing of the redesigned 8-cell etch chamber.

Etching Procedures

We have considerably changed our etching procedures from those recommended earlier.¹ Our currently recommended etching parameters are shown in Table 1.

Etching Times

One of the unsolved problems from the previous report was a difference in the size and number of tracks between foils etched in our 8- and 24-cell chambers, with the smaller chambers consistently

giving us more tracks and requiring a shorter blow-up time to provide tracks of the same size. (The "blow up" step is a final stage in the etching process which greatly enlarges the smaller tracks, thereby reducing the large variations in track sizes.) Because the 8-cell chambers have thinner walls, the temperature of the KOH inside the smaller chambers increases faster than in the 24-cell chambers. We determined that this difference in heating rate was responsible for the differences.

To correct this problem, we now place the etch chambers loaded with the CR-39 foils and the

Table 1. New recommended etching parameters for CR-39 foils.

	Etching	Blow-up	Post etch
High voltage	3000 V	2700 V	0
Frequency	60 Hz	2.0 kHz	0
Temperature	60°C ^a	60°C	60°C
Time	5 h	23 min ^b	about 15 min
KOH normality	6.5 N	6.5 N	6.5 N

^a The etch chambers and KOH must be kept in the oven overnight (or over the weekend).

^b No adjustment for foil thickness is required if the foils are within ± 3 of 25 mils.

KOH (in a separate plastic dispensing bottle) in the oven overnight or longer to warm up. The KOH is added to the cell when the etch is started. This change in procedure increases the track density by about 70%, reduces the required blow-up time, and (apparently) changes the neutron energy dependence of the foils (discussed below). The background track density also increases by about 70%. This revised procedure eliminates the differences in track densities between the 8- and 24-cell chambers and allows the same blow-up times to be used with both chambers. We recommend that all etchings be performed with both the chambers and the KOH preheated to 60°C.

A study of etching time indicated that a one-hour etch yields an abundance of very small tracks that are not yet properly blown up, even though the larger tracks are of proper size. Therefore, we recommend etch times of longer than two hours. On the other hand, etching for longer than the standard eight-hour workday is not considered practical for a dosimetry program; etching for 16 hours (overnight) gives a large increase in the number of background tracks and is not acceptable.

We found that the track density as a function of etching time was linear. The etching time is the sum of the etch and blow-up time (but does not include the post-etch time, as described below). Our revised etching procedures resulted in reducing the blow-up times recommended previously.¹ Figure 2 shows our current blow-up times vs etching times.

We studied the effect of leaving the foils in the oven for a period of time after the high voltage is turned off. We tried to determine if this post-etching would alter the appearance and number of tracks. Post etches of 10, 20, and 30 minutes were performed by leaving the chambers in the oven after the high-voltage etch was complete. The effect on track appearance is significant. With no post etch, the tracks are ragged and rough. As the post-etch time is increased, the tracks become smoother and rounder. However, at 30 minutes, the larger tracks seem to collapse and take on a "bullseye" appearance. The actual number of tracks counted on the Biotran reader remained the same within 3%. We had hoped that the rounding of the small tracks would make them easier for the Biotran reader to detect, but this did not occur.

We can conclude then that removing the chambers from the oven immediately at the end of the etch time is not critical. Although we noticed no change in track density at 30 minutes post etch, the change in the appearance of the tracks indicates

Figure 2. Blow-up time as a function of etching time, using 6.5 N KOH.

that the post etch should be limited to no more than 20 minutes. This allows the staff member some flexibility in removing the chambers from the oven when the cycle is complete. We recommend that a routine post etch of about 15 minutes be used.

We performed several etches during the year, which included 30- and 60-minute pre-etches by adding the KOH to the cell before applying the high voltage. Other researchers report that their one-hour pre-etched step reduces the number of background tracks.^{2,3} Our experience, however, has been that the pre-etch always increases the number of background tracks. In one study with no pre-etch, the background was 1.37% of the track density obtained from 700 mrem of ²⁵²Cf neutron exposure; a 30-minute pre-etch gave 1.54%, and the 60-minute pre-etch gave 1.82%. We used 14 foils for the background and five foils exposed to the ²⁵²Cf source. These results again confirm that a pre-etch, using our etching procedures, increases the background track density and should not be used.

Variations in Foil Thickness

An unexpected advantage of the new etching procedure is that the previous correction for foil thickness (about 2% per mil) is required. We are not certain why this correction is no longer necessary,

but it could be that at 60°C the chemical etching becomes more important than the electrochemical etching process. In our earlier procedures, our etching temperature changed during the etch from room temperature to 60°C.

We made a study to determine the change in blow-up time required for foil thicknesses other than our standard thickness of 25 mil. Each mil deviation from 25 requires about a 1.7-minute change in blow-up time (less for thinner foils, more for thicker foils). Small differences of ± 3 mil from 25 mil can be ignored, but if the foils average more than three mils thicker or thinner than 25, a corrected blow-up time should be applied.

As mentioned above, care should be taken to avoid inadequate blow-up time, which results in a

larger variation in track size and a decrease in track density. Too long a blow-up time is less serious.

The most recent CR-39 material from American Acrylics has been uniformly close to 25 mils in thickness and requires no change in our etching procedure. Because the foil thicknesses are close to 25 mils, we no longer sort the CR-39 foils for thickness before they are used. This greatly simplifies the handling of CR-39 foils for large-scale application in a personnel dosimetry program.

KOH Normality

We studied the effect of variations in the KOH normality on the track density by etching with

Figure 3. Track density as a function of oven temperature (5-hour etching cycles using 6.5 N KOH).

normalities between 5 and 9 N. We found that a KOH normality of about 6.5 maximizes the number of tracks obtained; small changes in the KOH normality around 6.5 N will not cause significant changes in the track density. We recommend that 6.5 N KOH be used for all etchings.

We also investigated the aging of the KOH itself, and found that KOH solution should not be used more than five times. A gradual decrease in the track density occurs at a rate of about 1% per day. We recommend that the KOH solution be changed on a regular basis, at least weekly.

Oven Temperature Variations

The laboratory oven we had been using to etch the foils at 60°C did not have a good temperature

regulator. When the room temperature began to fluctuate, the oven temperature also varied. The effect of temperature variations on the track density is shown in Fig. 3, which indicates that at 60°C, a temperature change of 1° causes ~7% change in track density. Therefore, the temperature of the oven must be closely regulated. We purchased a digital controller that controls the oven temperature to within $\pm 0.1^\circ\text{C}$ at the measurement point. Recently, we found that the temperature of the etch chamber located at the bottom of the oven is hotter than the chamber at the top of the oven. This is apparently caused by radiant heating from the aluminum plate over the heating coils at the bottom of the oven. To solve this problem, we placed a plywood baffle in the oven. Ideally, an oven used for etching should have its heat source isolated from the oven chamber.

Power Supplies

We received three power supplies from Homann-Bell,⁴ the first of which was placed into service in June. Several small problems developed, and the manufacturer made a number of changes in the power supply. To protect our etch chambers from damage if the chamber happened to leak KOH, changes were also made in the program for the HP-41C computer that controls the power supply. The changes in the program included a procedure that brings the high voltage up in steps instead of all at once, and also has a more frequent test of

the system to detect possible shorting that could result in a failure.

The power supplies have a variable output with frequency between 50 and 2500 Hz and voltages between 0 and 3500 V (RMS). The units are capable of powering four of the 24-cell units. The cost of each of these power supplies is now \$6,700.00. The power supply we have been using has been very reliable and has withstood at least two etch failures without sustaining damage.

CR-39 Material

The new CR-39 material from American Acrylics is considerably better than our earlier batch. The sensitivity has been increased, and the thickness of the sheets is much more uniform.

The background tracks on the foils remain our only major problem with the CR-39 material. From our observations and studies, we have learned that the background tracks on the bottom side of the foil during casting are more numerous by a factor of 15. The background is not affected by multiple cleaning of the molds and is apparently independent of various batches of the monomer supplied by Pittsburgh Plate Glass.

Over time, the background increases rapidly at first, then apparently slows or stops. The background track density of the CR-39 foils increases by

about 60% over a nine-month period. As the CR-39 foils age, some foils develop a large background track density that was not present in the original material. We have been able to delay the increases in background tracks and the occurrence of outliers by storing the foils in a deep freeze and in the dark. We do not know at this time whether the low temperature or the darkness is responsible for the delay.

Our studies found that the addition of the anti-oxidant, Nougard 445, did not change the background track density. We also noticed that the newer CR-39 material exhibited some fading (~12%) over a three-month period when kept on a laboratory shelf. An earlier study with the previous CR-39 material over a seven-month period showed no fading.

but we caution that this study was not started until the CR-39 foils were already nine months old, with the foils kept in a desk drawer. The new material also exhibited a decrease in its sensitivity to neutrons during the three-month period, but this decrease in sensitivity did not occur for foils kept in a deep freeze. Additional studies of aging are being made.

The background for new CR-39 material using our etching techniques is approximately eight mrem.

If the quality factor (QF) for neutrons is increased by a factor of 2 or 2.5, this background will be 16 to 20 mrem. This is too high a background to allow personnel dosimetry at the low dose values most workers exposed to neutrons receive each month. This could have a serious impact on the usefulness of the CR-39 dosimetry system. During the next fiscal year we will study this problem.

Linearity

We recently repeated an earlier linearity study¹ because we have made several significant changes in our etching procedures and because we are now using high-sensitivity CR-39 foils. In addition, we observed a bias in the results from the quality-control badges that are used in our personnel dosimetry program. One explanation for this bias was a nonlinear response of the CR-39 foils at 700 mrem, the dose used for calibration. The results we obtained from

the current linearity study are shown in Fig. 4, indicating a departure from a linear response at about 400 mrem. This is appreciably lower than the 1.5 rem found in our earlier study.

The change in the linearity of the high-sensitivity foils was caused by an increase in the number of tracks at a given dose. (Linearity is a function of track density, and nonlinearity above 400 mrem would not normally be a problem, since personnel

Figure 4. Results of the current linearity study, indicating a departure from linear response at about 400 mrem (CR-39 foils purchased in October 1985).

exposures rarely exceed 400 mrem.) An occasional test of the nonlinearity should be included in the dosimetry program.

Reproducibility

Our current precision has greatly improved over the precision attainable last year. We use 4-6 foils that have been exposed to 700 mrem of ^{252}Cf neutrons as standard foils in each etch chamber. These foils provide a continuing measure of the precision of our etching procedure. The standard foils have an average track density of about 4500 tracks/cm². Recently the standard deviation of these foils has ranged from 1.6 to 6.3%, averaging 3.2%. These results are from the most recent etchings and represent a significant improvement over the standard deviation of 6.8% previously reported.¹ This improvement resulted in part from the changes made in the etch chamber design and etching procedures, but also from improvement in the CR-39 foils themselves. The background of the present foils does not have the outliers that we observed in the past. The standard deviation of the background foils averages 22% and ranges from 17 to 31%.

Energy Dependence

The energy dependence of the CR-39 foils was determined using monoenergetic neutrons from accelerators at Battelle Northwest Laboratories and at Los Alamos National Laboratory (LANL). A styro-foam holder was made to hold the badges during the exposures to monoenergetic neutrons. Rather than use one or two neutron energies per run, we could mount the bare CR-39 foils and one of our LLNL badges in five-degree steps at a distance of 50 cm from the source. We measured 31 different neutron energies per run over an angle of 150°.

At Battelle, the badges were exposed to 106 different neutron energies ranging from 10 keV to 16.6 MeV. At each energy, three foils were exposed in our LLNL badge holder and three foils were exposed in glassine envelopes, both with no backscattering material. At LANL the neutron energies ranged from 49 keV to 4.0 MeV. The Battelle exposures were made at angles from 0 to 150°, while at LANL the angles varied from 0 to 80°. A single tritium gas target was used at LANL, while at Battelle targets of tritium, deuterium, and ^{12}C were used.

The data from these studies are shown in Fig. 5, which makes apparent some significant differences in the results. The fine structure of the Battelle results is not present in the LANL results. Some of these differences could have been caused by errors in the dose estimates at angles from about 75 to 90° where considerable absorption or scattering in the target assembly may have occurred. The LANL results indicate a low-energy threshold of around 0.08 MeV compared to ~0.15 MeV for the Battelle curve. The LANL results show an upper energy cut-off beginning at about 3 MeV compared to 4 MeV for the Battelle results.

Our practice of placing the loaded etch chamber and the bottles of KOH in the oven overnight could have had some effect on the energy response. The entire etch cycle is at 60°C instead of the lower and non-uniform temperatures occurring when the etch was started with both the KOH and the etch chambers at room temperature. This initial increase in etch temperature apparently lowered the low-energy threshold. The change in the upper neutron energy cut-off may also have been caused by the new etching procedure, or may have been experimental error in the dose evaluation at the various angles.

The differences in the curves from LANL and Battelle are not serious. Both curves indicate that the energy response is relatively flat from about 0.1 to 3 MeV, which is far superior to that of any other personnel neutron dosimeter.

The response of our badge at 14 MeV is lower than the response found by others.^{3,5,6} It is possible that our etching techniques enhance the response to protons but not to recoil carbon and oxygen. We hope to repeat the test of the 14-MeV response of the badge in the near future.

Foils were sent to the National Bureau of Standards to be exposed to the 2-, 24-, and 144-keV reactor beams. At 144 keV, the response was 8.1 tracks/mrem, which agrees very well with our results from Battelle and LANL. At 24 keV, we found 1.12 tracks/mrem, which can be accounted for by neutrons with energies of 135, 280, and 364 keV that comprise 2.8% of the neutrons in the beam. When the appropriate QF values are applied to these higher-energy neutrons, a track density of 1.1 tracks/mrem is expected, which matches well with our observed tracks. At 2 keV we found 2.4 tracks/mrem, which cannot be accounted for by higher-energy neutrons in the beam at this time.

CR-39 foils were exposed to thermal neutrons at the Omega West Reactor at LANL. The results

Figure 5. Results of the energy-dependence tests of CR-39 performed at Los Alamos National Laboratory and at Battelle Northwest. Note the slight differences in response from the two sets of tests.

indicate that the foils have no significant response to thermal neutrons.

The Battelle results indicated that when the back of the foil (the side opposite from the incident neutrons) is etched, the readings are reduced by 25% except for the 13- to 16-MeV neutrons, where

no difference was observed. In a similar study using ^{252}Cf , we found a 23% reduction. Both of these agree with the results of Tommasino.⁶ The Battelle results indicated that placing the foils on a phantom increases all readings by 7%. A phantom should be used for all calibrations of CR-39 foils.

Automation of Track Counting and Data Handling

In order to automate the counting of tracks on the CR-39 foils, we have connected the Biotran reader to our HP-85 computer. The computer records the results from each of six fields and performs calculations to determine the track density or the dose. The reading procedure requires changing the focus of the microscope until the largest count

is obtained for each field of view. This procedure can be automated using a commercially available auto-focusing device made by Nikon, which could significantly reduce the reading time for each foil. We suggest that this type of auto-focusing device be considered for use by other dosimetry groups that have a large number of foils to read.

Foil Identification

For identification of the top or bottom of the foil, our most recent sheets of CR-39 were cut into foils that had one corner of the foil cut off at a 45° angle. This also provides a method to assure that the foils are oriented properly in the dosimeter badge.

We still need a better method of marking each foil to identify the wearer. Other researchers are considering a binary system with holes laser cut through the foils.² This would be compatible with their present binary coding system for personnel badges. One foreseeable problem would be if the holes were to be plugged with melted polyethylene

or CR-39 plastic. Another problem could be to assure that the computer control for the laser cutter is operating properly.

A different technique Harrison and others are investigating is the use of a bar code.² They have found a plastic label and adhesive that will apparently withstand KOH or NaOH solutions. They believe these labels could be made with a bar code. To use this technique, we would probably have to increase the size of our CR-39 foils. A bar-coding procedure would be a significant improvement over present marking methods and would be useful for dosimetry groups with large numbers of foils to identify and read.

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Study of Environmental Effects on CR-39

Dale E. Hankins, Michael Salamon (University of California, Berkeley), and Joane Westermarck

We have just completed a study of environmental effects on foils of CR-39 plastic used in our new personnel neutron dosimetry system. The results from the study show that the decreasing sensitivity of CR-39 foils to neutrons and the fading of latent tracks are accelerated by exposure to elevated temperatures and oxygen levels, and UV light. Moisture variations have no effect on the fading of tracks or the sensitivity of the foils. Our results indicate that CR-39 foils should be stored in a dark area near 0°C. When worn as a personnel neutron dosimeter, the CR-39 should be packaged to keep it from being exposed to light, and the wearer should be instructed to avoid subjecting the dosimeter to high temperatures.

Introduction

In order to make effective use of CR-39 foils in a personnel neutron dosimetry program, we must know the effects of various environmental factors on CR-39 material. In a joint University of California, Berkeley, and LLNL study, we subjected CR-39 foils to various temperatures, relative humidities, light levels, and atmospheres. The temperatures studied were -16°, 6.8°, 19°, and 40°C; relative humidity

(RH) levels ranged from dry (desiccated), ambient, or wet (100% RH); the light levels consisted of ultraviolet (UV) or no light (dark); and the atmospheres were air, oxygen, and argon. Eighteen combinations of 12 variables were selected for the study. A majority of the combinations included dry air in darkness. The combinations selected are given in Table 1.

Procedure

The foils were placed in glassine envelopes, taped to a phantom, and then exposed to 700 mrem of neutrons from a bare ²⁵²Cf source at a source-to-foil distance of 1 m. This exposure was made at the Hazards Control Standards and Calibration Facility using source #595. To determine the sensitivity of the foils when we began this study in October 1984, we exposed and etched additional foils. Unfortunately, these results cannot be used to detect any small changes in sensitivity that may have occurred because we have subsequently redesigned our etch chambers, improved the etching procedures, and changed the normality of the KOH solution.

One-third of the foils used in this study were exposed to neutrons prior to sending them to U.C. Berkeley where they were exposed to various envi-

ronmental conditions. We refer to these as "pre-exposed" foils. After the foils were returned to LLNL, another third of the foils was exposed to neutrons, and these are referred to as "post-exposed." We used the remaining third to study the background track density of the CR-39. We used the pre-exposed foils to evaluate neutron track fading, and the post-exposed foils to evaluate changes in the neutron sensitivity of the CR-39. We placed nine foils in each environmental category: three unexposed, three pre-exposed, and three post-exposed. Control foils in each category were kept together in a small box in a desk drawer in our laboratory.

The foils were electrochemically etched in an oven at 60°C with 0.5 N KOH starting with 5 h at 3000 V and 60 Hz, followed by 38 min at 2700 V

Table 1. The track density of pre- and post-etched foils as a function of environmental variables.

Foil #	Temperature (°C)	Moisture	Light	Atmosphere	Track density (tracks/cm ²)		Deviation post-exp pre-exp
					pre-exp 10/11/85	post-exp 5/13/85	
1	6.8	dry	dark	air	2752	2876	+4.5
2	6.8	dry	dark	argon	2773	2975	+7.2
3	6.8	dry	dark	oxygen	2704	2750	+1.7
4	6.8	ambient	dark	air	2722	2815	+3.4
5	6.8	wet	dark	air	2810	2908	+3.5
6	-16	ambient	UV	air	2676	2516	+5.9
7	19	dry	dark	air	2590	2714	+4.8
8	19	dry	dark	argon	2720	3278	+20.1
9	19	dry	dark	oxygen	2568	2521	-1.8
10	19	ambient	dark	air	2324	2235	-3.5
11	19	wet	dark	air	2452	2335	-4.7
12	19	ambient	UV	air	— ^a	— ^a	—
13	40	dry	dark	air	1833 ^b	2168 ^b	+18.3
14	40	dry	dark	argon	2069 ^c	2972 ^c	+43.6
15	40	dry	dark	oxygen	138 ^d	167 ^d	+21.1
16	40	ambient	dark	air	1629 ^b	2297 ^b	+41.0
17	40	wet	dark	air	1780 ^b	1896 ^b	+6.5
18	40	dry	UV	air	2744 ^e	3151 ^e	+14.8
19 ^f	19	ambient	dark	air	2608	2682	
20 ^f	19	ambient	dark	air			

^a Cloudy, uneven appearance with large number of tracks.^b Track sizes are smaller than normal, with many small uncounted tracks.^c Track sizes slightly larger than normal.^d Tracks are very small.^e Some extremely large tracks and many small tracks.^f Control.

and 2.0 kHz, subsequently followed by a 15-min post etch at 60°C. The foils were read on a Biotran III reader with each field of view having an area of 3 × 3 mm. We read a total of six fields on each foil and averaged the results. Corrections were made to the track density for individual foil thickness. The results shown in Tables 1 and 2 are the average of the three foils in each category except for the control conditions, where six foils were used.

Table 2. The effects of temperature on the average background of CR-39 foils.

Temperature (°C)	Average background (tracks/cm ²)
-16	43
6.8	46
19	56
40	varied (see Table 2a)
controls	59

Results

The average background track densities show the effects of different temperatures, as illustrated in Table 2. The foils kept at 6.8° and -16°C have an average track density of 43 tracks/cm², those at 19°C average 56 tracks/cm², while those at 40°C

varied, as shown in Table 2a. The background of the controls was 59 tracks/cm². These results show a smaller background for the foils kept at the lower temperatures. This is in agreement with recent findings of a similar study we have in progress, which

Table 2a. Background track density of foils kept at 40°C.

Foil #	Atmosphere	Light	Moisture track density (tracks/cm ²)	Background
13	air	dark	dry	62
14	argon	dark	dry	50
15	oxygen	dark	dry	23 ^a
16	air	dark	ambient	64
17	air	dark	wet	54
18	air	UV	ambient	1218 ^b

^a Tracks are very small.

^b Some extremely large tracks and many small tracks.

found that keeping the foils at low temperatures slows the increase in background tracks with time. The background of the foils at the time we started this study was about 34 tracks/cm².

Foils kept in oxygen at 40°C had low backgrounds (23 tracks/cm²) and foils exposed to UV light at 40°C had very large backgrounds (1218 tracks/cm²); see Table 2a. The UV light also made the results from Foils #12 at 19°C unreadable. These foils had numerous small tracks that gave the foils a cloudy appearance in the areas where the polyethylene was not in contact with the foil. This did not occur for the UV light exposure at 40°C (possibly because the polyethylene adhered better to the CR-39 foils at the elevated temperature).

The track densities on the pre-exposed and post-exposed foils shown in Table 1 are essentially the same (within $\pm 6\%$) for temperatures of -16° , 6.8° , and 19°C with the exception of the foils kept in the argon atmosphere. The post-exposed track foils kept in argon had significantly higher track densities.

At 40°C, the post-exposed track densities are all higher than the pre-exposed track densities. The tracks from the pre-exposed and post-exposed foils kept at 40°C in an argon atmosphere are slightly

larger than those found on the control foils. Apparently, the argon protects the surface of the foil, which keeps the foil from losing sensitivity to neutrons. However, argon does not prevent the latent tracks from fading.

We observed that the determination of the track density on foils exposed at 40°C was less precise (a larger standard deviation) because the track sizes were reduced. Apparently, heating the foils causes a change in the foil surface, resulting in smaller tracks from both pre-exposed and post-exposed foils.

Although we found no effect at lower temperatures, oxygen caused most of the tracks to be too small for reading at 40°C. UV light caused the opposite effect, making some of the tracks several times larger than normal but also causing numerous very small tracks to appear (as discussed above).

Increasing the temperature causes a definite increase in fading and a decrease in sensitivity of the foils. The fading was 10% at 19°C and 36% at 40°C, and the sensitivity decreased by 12% at 19°C and 24% at 40°C. Our control foils had track densities midway between the values obtained for foils kept at 6.8° and 19°C .

Discussion

Exposure to environmental background neutrons causes part of the increase in the CR-39 background track density. At Livermore this environmental background is about 6 mrem per year. Our study extended over a six-month period with an additional one month total handling time prior to and following the environmental exposures. During this seven months, the environmental background contributed about 3.5 mrem, which would increase the

background track density by about 14 tracks/cm². When we started this study, the background of the foils was 34 tracks/cm²; therefore, we expected 48 tracks/cm² ($34 + 14$) at the end of the study. We observed 43 tracks/cm² for the foils kept at -16° or 6.8°C , 56 tracks/cm² for foils at 19°C , and we observed varying results at 40°C, but if the two outliers (oxygen and UV exposed) are removed, a result of 58 tracks/cm² is obtained.

These results indicate that storing the foils at low temperature may actually reduce the effect of background neutrons on the track density, or perhaps this low reading could have been caused by a reduced neutron background in the building and the refrigerator. However, note that the foils kept at room temperature (19°C) had a background track-density increase larger than expected from environmental background neutrons alone.

This study shows that temperature and light can adversely affect the accuracy of a personnel dosimeter. The CR-39 foils must be protected from light; our present badge, with a colored beta filter,

will provide a light-free package. Heat will affect the readings, but this effect should be small for a one-month exchange cycle. For badges kept at room temperature, the monthly fading and decrease in sensitivity would be about 2%, and at 40°C (104°F), we would expect a 6% fading and a 4% decrease in sensitivity. These values do not indicate a significant problem for the routine use of CR-39 as a personnel dosimeter. No fading or change in sensitivity was found in an investigation where badges were left in the glove compartment of a sealed automobile for one month during the summer.

Conclusions

We have identified three environmental conditions that can affect the results obtained from CR-39 personnel neutron dosimeters: an oxygen-rich atmosphere, high temperatures, and UV light. We found that the moisture content of the air has no effect on the dosimeter readings; an argon atmosphere apparently prevents the CR-39 foils from losing sensitivity and could be considered along with refrigeration for the long-term storage of CR-39 foils.

To slow the background increase and the loss of neutron sensitivity, new CR-39 foils should be stored in a refrigerator at near freezing temperature. If possible, the refrigerator should be located in a low neutron background area (such as the basement of a large concrete building). While being worn as a personnel dosimeter, the CR-39 foils must be packaged to protect them from light, and the wearer should be instructed to avoid subjecting his badge to prolonged high temperatures.

Criticality Safety

Development of a Neutron Detector for Criticality Alarm Systems

Austin A. O'Dell and John H. Thorngate

We have investigated three potential neutron detectors to evaluate for use in criticality alarm systems. The counting elements in all three detector types are based on thermal-neutron interactions in ^6Li . Each detector must be small ($\sim$ few cm), must operate at a low bias voltage (~ 10 V), and must have high detection sensitivity. Since the counting element in each detector is enclosed by a 10-in.-diameter spherical polyethylene moderator, the detector responds proportionally to the *biological* hazard in a neutron radiation environment rather than to the incident neutron flux. In addition to acting as a criticality alarm, such a neutron detector can serve the functions of continuous and historical monitoring of operational radiation levels, acting as a reliable criticality accident alarm, and monitoring post-accident radiation levels. We have tested these three detector types at the Los Alamos National Laboratory SHEBA and GODIVA assemblies, using steady-state runs to calibrate the detectors at selected high rates and using long-period reactor excursions to check for detector linearity and saturation effects. With the results of these irradiation tests, we have identified promising ways to improve these designs to produce more sensitive and reliable neutron detectors for criticality safety applications.

Introduction

In consultation with the DOE Office of Nuclear Safety, we identified a need in the DOE community for a reliable, well-characterized neutron detector for use in criticality alarm systems. This new neutron detector should be applicable for any DOE research or production nuclear facility where fissionable materials are processed or stored, but would be particularly useful in a facility where:

- The gamma radiation background is high.
- The fissionable materials are in metallic form.
- The facility contains large or massive structures that might significantly attenuate gamma radiation emitted in a criticality accident.

Our primary purpose was to develop a compact, highly reliable neutron detector that operates at a low-voltage bias and can be readily adaptable

with conventional digital instrumentation and computer systems.

In addition to its main purpose of sounding an evacuation alarm within one second of a minimum credible criticality accident,* we have chosen to design this neutron detector to respond proportionally to the *biological* hazard of the extant radiation rather than simply to the incident neutron flux, thereby providing a measure of the actual danger to personnel. This was accomplished by tailoring the detector response to be linear with the neutron dose-equivalent, within practical limits ($\pm 20\%$).

* As defined in ANSI/ANS Standard 8.3-1979 and DOE Order 5480.1A, Chapter V (1981).

Continuous remote monitoring with a high-sensitivity neutron detector also facilitates the detection of abnormal deviations in normal operational radiation levels. This information can be very valuable to supervisors for identifying and responding to potentially dangerous work procedures. In the event of a critically accident, remote monitoring would also permit continuous evaluation of the radiation levels at the accident site, allowing observations of possible secondary criticalities. The detector could also aid in the evaluation of reentry

conditions and thus reduce the need to send in personnel with hand-held monitors.

Finally, such in-place neutron detectors will continuously monitor work-area background radiation levels, detect increases in operational radiation levels, and monitor long-term changes in such levels. Archival storage of such data could be accomplished on computer-based media for rapid retrieval, display, and further analysis. Such archival records could be useful for reconstructing accident histories or personnel radiation exposures.

Detectors and Instrumentation

We have developed three prototype neutron detectors that could be used in the manner described above. These three detector types use thermal neutron interactions in ^6Li and are deployed within 10-in.-diameter spherical polyethylene moderators. Detector Type A, shown in Fig. 1, is composed of an external 0.030-in.-thick ^6LiF disk converter coupled to a silicon charged-particle detector. The detector bias is approximately 9 V. This design is similar to a smaller detector developed by W. Tyree at the Rocky Flats Plant.^{1,2} This detector and the associated electronics package

was developed by Eberline Instruments Inc., in collaboration with LLNL.

Detector Type B (Fig. 2) is an upgrade of Type A, where specially designed surface-barrier charged-particle detectors are used to monitor *both* sides of

Figure 1. Detector Type A is composed of an external 0.030-in.-thick ^6LiF disk converter coupled to a silicon charged particle detector.

Figure 2. Detector Type B is an upgrade of Type A. Note that the surface-barrier charged-particle detectors are used to monitor both sides of the external ^6LiF converter.

the external ${}^6\text{LiF}$ converter. We took special care to minimize all metal components in order to reduce gamma sensitivity. The converter spacing was reduced to approximately 0.005 in. to improve charged-particle collection. The entire detector housing is composed of polystyrene and has overall dimensions of approximately 2 in. diameter by 1.5 in. long. This detector was built by Tennelec Inc., in collaboration with LLNL.

Detector Type C is a scintillation detector that uses a 10-mm cube ${}^6\text{LiF}(\text{eu})$ fluor mounted directly to a high-speed PIN silicon photocell, as shown in Fig. 3. This detector was built by Harshaw in collaboration with LLNL.

Figure 3. Detector Type C is a scintillation detector that uses a 10-mm cube ${}^6\text{LiF}(\text{eu})$ fluor mounted to a high-speed silicon photocell.

Tests of the Three Detector Types

We first tested the three detector designs using radioisotopic neutron sources at LLNL. The main irradiation tests were performed at the Los Alamos National Laboratory (LANL) to test and calibrate these detectors in high steady-state fields, in slowly-varying fields, and in fast-burst (e.g., 0.05–1 ms) reactor excursions. For this purpose, we used the SHEBA and the GODIVA critical assemblies at LANL, which provided mixed neutron and gamma radiation fields.

SHEBA and GODIVA Assemblies

The SHEBA critical assembly is composed of a cylindrical stainless-steel tank as shown in Fig. 4, containing a 5%-enriched aqueous uranyl nitrate solution. The uranyl nitrate solution is transported between storage and dump reservoirs by a combination of air pressure and vacuum lines controlled by an arrangement of binary valves. In this assembly, a critical configuration is obtained by transferring an appropriate quantity of solution into the cylindrical

Figure 4. The SHEBA critical assembly.

tank. No control rods are required to operate this assembly.

The SHEBA assembly is mounted in a low-scatter (thin metal) building near Kiva 1 at the LANL Pajarito Site. Operation and monitoring of the assembly is performed remotely at the central Control Room approximately 370 m from the SHEBA assembly; patch panels in the SHEBA building and in Kiva 1 are provided to attach user instrumentation to the existing cabling between the SHEBA assembly and the Control Room. The SHEBA assembly can be operated in four modes: steady state, positive-period ramp, slow burst, and free evolution.

The GODIVA assembly is a bare (hence the name) cylindrical metal reactor, as shown in Fig. 5. The six fuel rings are made of 93.5%-enriched uranium alloy, held together by three steel clamps. The total fuel mass is approximately 66 kg. Three insertable control rods are used to regulate the assembly, and a cylindrical stainless-steel safety block is used for fast-burst operation.

GODIVA is housed in Kiva 3 and is also operated and monitored at the central Control Room approximately 250 m away. GODIVA has similar patch panels for user instrumentation cables, allowing many experimenter functions to be performed in the Control Room. The GODIVA assembly can be operated in three major modes: steady state, positive-period ramp, and fast burst.

Test Methods

A total of three Type A neutron detectors, two Type B neutron detectors, one Type C neutron detector, and three Eberline gamma detectors were included in these LANL tests. The three Type A detectors and three Eberline gamma detectors were instrumented using commercial microprocessor-based criticality instrumentation supplied by Eberline Instrument Corporation. Eberline personnel assisted us in obtaining data for these detectors in both the SHEBA and GODIVA irradiation tests. We monitored the tests of detector Types B and C using conventional laboratory electronics with a Tennelec TC171 preamplifier attached directly to the silicon detectors. A bias voltage of 50 V was applied to the Type B detectors and 12 V to the Type C detector. Each preamp output was routed to a linear main-amplifier, to a single-channel pulse-height discriminator, and finally to a digital scaler positioned in an automatically sequenced daisy-chain connected to a buffered serial printer. This

Figure 5. The GODIVA critical assembly.

instrumentation chain recorded the ID number, the Julian date, the time of day (HH:MM:SS), the counting time (in 0.1-s units), and the five detector counts for contiguous time intervals during steady-state runs, positive-period ramps, and free-evolution runs.

We attempted to use a new fast-burst monitor circuit in the GODIVA tests, but the circuit did not work satisfactorily. For several GODIVA runs, the Type C detector was operated as an unbiased current-mode detector. In this case, the detector output was routed to the Control Room via a coaxial cable that was terminated at a single-sweep oscilloscope. The radiation/time history obtained from the sweep photograph was in good agreement with the Control Room monitor. However, we observed some

saturation effects at high radiation levels due to the lack of proper detector bias.

We used the LLNL-developed Neutron Remmeter II to monitor the neutron dose equivalent for all tests. A Pu-Be neutron source was used at selected intervals to recalibrate the detectors and to determine whether any permanent damage had occurred.

SHEBA Experiments

All detectors and the remmeter monitor were arranged in an approximately 100° circular arc 2.82 m from the center of the SHEBA tank at approximately 1 m above the concrete floor. Table 1 lists the runs performed at SHEBA, including Pu-Be calibrations. Runs #1, 2, 4, and 6 were steady-state runs used primarily to calibrate the detectors at high rates. Runs #3, 5, 8, and 9 were long-period reactor excursions used primarily to check for detector linearity and saturation effects. Run #7 was a

shutdown decay from the high-level Run #6. Run #10 was a free-evolution excursion carried out to demonstrate the runaway and eventual shutdown of a highly moderated system. (This run, although interesting from a reactor physics viewpoint, was not particularly useful for our calibration and, in fact, resulted in unnecessary exposure to the detectors and the associated electronics instrumentation.) These SHEBA runs were concluded with a recalibration of all detectors with a Pu-Be neutron source.

We have summarized the results of the SHEBA steady-state runs in Table 2. For each Type B detector, the two charged-particle detector outputs have been summed to give the total detector sensitivity. The notation "N.A." indicates that no data was available for entries. As can be seen, the sensitivities of the three detector types, in units of counts-per-minute per millirem-per-hour, are approximately 10, 35, and 700 for Types A, B, and C, respectively. The sensitivity of the Type C detector appears to decrease (saturate) slightly at high radiation levels.

Table 1. Outline of the SHEBA runs, including Pu-Be calibrations.

Run	Date	Run Type	Neutron (mrem/h)	Gamma (mr/h)
1	8/30/83	Steady state	94	10
2	8/30/83	Steady state	91	10
3	8/30/83	Ramp (~200 s)	91-280	10-30
4	8/30/83	Steady state	278	30
5	8/30/83	Ramp	270-1230	30-125
6	8/30/83	Steady state	1230	125
7	8/30/83	Decay shutdown	N.A.*	N.A.
8	8/31/83	Ramp (~56 s)	N.A.	N.A.
9	8/31/83	Ramp (~120 s)	N.A.	N.A.
10	8/31/83	Free-evolution	N.A.	N.A.
Pu-Be	8/31/83	Calibration	21.2	N.A.

* N.A. = not available.

Table 2. Summary of SHEBA steady-state experiments. Measured sensitivity is in cpm/(mrem/h).

Neutron detector	Run 1 94. mrem/h	Run 2 91. mrem/h	Run 4 278. mrem/h	Run 6 1320. mrem/h	Pu-Be 21.1 mrem/h
A2	N.A.*	12.0	11.1	11.2	N.A.
A4	N.A.	11.3	10.9	11.4	9.38
A6	N.A.	10.7	9.14	10.3	N.A.
B1	34.8	35.2	34.9	34.7	30.0
B2	36.5	36.3	36.0	36.4	30.1
C	706.	716.	706.	637.	626.

* N.A. = not available

GODIVA Experiments

The detectors were arranged in an approximately 100° circular arc at 4.0-m from the center of the GODIVA assembly, approximately 1-m above the concrete floor. The runs performed at GODIVA, including the Pu-Be calibrations, are listed in Table 3. After the initial Pu-Be calibration, four steady-state GODIVA runs were performed primarily to calibrate the detectors for the GODIVA neutron spectrum.

The GODIVA bursts were originally planned to test the fast-burst capabilities of the three prototype detectors. The interval-times between GODIVA burst and alarm trip were monitored with high resolution using the microcomputers and specially designed software supplied by Eberline. In the case of Types B and C, we had designed a preliminary current-sensing circuit for fast-burst detection, but this circuit did not perform reliably during our tests. A large part of

the problem was an unexpected polarity reversal, and the difficult logistics for circuit adjustment and reset between bursts. We have completely reworked this design and hope to have a reliable, remotely adjustable, and remotely resettable current-sensing circuit for the next series of offsite tests using fast-burst radiation.

The measured sensitivities of the Type B and C detectors are summarized in Table 4. Note that the sensitivities for the GODIVA spectrum appear to be slightly higher than for SHEBA. However, the Type C detector partially "blinds-out" at high radiation levels (above about 1500 mrem/h) such that its effective sensitivity is greatly reduced. Again, this problem may be largely due to the non-optimized electronics and detector bias used in these experiments. No data is available for the Type A detectors in the steady-state runs.

The measured interval time between the GODIVA burst and the registration of high-alarm in

Table 3. Summary of GODIVA runs for calibrating the criticality neutron detector prototypes.

Run type	Date	Parameters and comments
Calibration	9/1/83	Pu-Be 18.3 mrem/h
Steady state #1	9/1/83	13.0 mrem/h
Steady state #2	9/1/83	174. mrem/h
Steady state #3	9/1/83	1620. mrem/h
Steady state #4	9/1/83	16650. mrem/h (detector C paralyzed)
Burst #1	9/1/83	No LANL trigger
Calibration	9/2/83	Pu-Be 19.3 mrem/h
Steady state #5	9/2/83	2000. mrem/h (detector C disconnected)
Burst #2	9/2/83	No trigger, $\Delta T \approx 68^\circ\text{C}$ (detector C to scope)
Burst #3	9/2/83	No trigger, $\Delta T \approx 50^\circ\text{C}$, $\tau \approx 160 \mu\text{s}$
Burst #4	9/2/83	$\Delta T = 45^\circ\text{C}$, 8.3×10^{15} fiss., $\gamma = 3$ rad, $n = 18$ rad, $\tau \approx 195 \mu\text{s}$
Burst #5	9/2/83	$\Delta T = 51^\circ\text{C}$, 9.4×10^{15} fiss., $\gamma = 3$ rad, $n = 20$ rad, $\tau \approx 175 \mu\text{s}$
Burst #6	9/2/83	$\Delta T = 35^\circ\text{C}$, 6.5×10^{15} fiss., $\gamma = 2$ rad, $n = 14$ rad, $\tau \approx 270 \mu\text{s}$
Burst #7	9/2/83	$\Delta T = 30^\circ\text{C}$, 5.6×10^{15} fiss., $\gamma = 2$ rad, $n = 12$ rad, $\tau \approx 450 \mu\text{s}$
Burst #8	9/2/83	$\Delta T = 223^\circ\text{C}$, 4.1×10^{16} fiss., $\gamma = 15$ rad, $n = 90$ rad, $\tau \approx 240 \mu\text{s}$

Table 4. Summary of GODIVA steady-state experiments. Measured sensitivity is in cpm/(mrem/h).

Neutron detector	Pu-Be 18.3 mrem/h	GODIVA 13.0 mrem/h	GODIVA 174. mrem/h	GODIVA 1620. mrem/h	Pu-Be 19.3 mrem/h	GODIVA 2000. mrem/h
B1	41.7	49.3	38.4	36.2	95.9 ^a	33.7
B2	34.5	37.3	36.5	36.0	43.2 ^a	32.9
C	682	754	815	319 ^b	N.A.	N.A.

^a High residual background radiation level.

^b Temporary blind-out at high radiation levels.

each of the three Type A detectors tested was determined. This interval time varied from approximately 50 to 500 ms, depending on the burst size and the overall pulse width. As indicated above, we were not successful in obtaining similar information for the Type B and C detectors due to the failure of our preliminary current-sensing circuit.

However, for several of the final GODIVA bursts, the Type C detector was connected directly to a fast oscilloscope in the Control Room via a terminated coaxial cable. In this manner we were able to record the GODIVA radiation bursts by photographing the scope sweep. The output of the Type C detector varied with burst size, nominally 0.5 V in magnitude with a FWHM of 2 ms. This

procedure provided time histories of the GODIVA bursts that roughly matched those provided by LANL, but did not provide burst-to-alarm interval times.

Since the Type C detector was unbiased during the fast-burst tests, we did note some saturation effects at high radiation rates. The detector signals were quite usable as burst indicators for our purpose. With some improvement of the electronics and the appropriate use of a bias voltage, we expect to solve this problem and provide a reliable burst sensor for the Type C detector. This fact, coupled with its high sensitivity at low radiation levels, make this detector very attractive for this project.

Conclusions

The steady-state and slow-ramp runs on SHEBA were very useful in characterizing the three types of detectors tested. The free-evolution run, although interesting from a physics viewpoint, contributed little to our knowledge of detector performance and resulted in unnecessarily high radiation exposure to the detectors and to the associated electronics. The steady-state and burst runs on GODIVA were also useful to our tests of the detectors. However, we were able to obtain useable burst data only for detector Types A and C. The maximum GODIVA burst (#8, 223°C) was useful for timing purposes, but was

so short in duration (approximately 50 μ s) that it did not realistically simulate a criticality accident. Furthermore, the high radiation intensity of this burst also resulted in unnecessarily high exposure to the detectors and to the associated electronics.

Overall, these tests generated important data and valuable feedback that will aid in our next series of offsite tests with respect to detector redesign, irradiation procedures, and operational logistics. These tests will help us to finalize our design and eventually to make available a neutron detector for criticality alarm systems.

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Calculations to Assess Nuclear Criticality Safety: Power-History Calculations of Nuclear Excursions

Harry F. Lutz

We have begun to develop and document a set of four computer codes that are useful in many aspects of criticality safety practice. These codes will be made available to run on small personal computers for comparison with the results of more comprehensive calculations running on large mainframe machines. Calculations using the smaller codes are easier and less expensive to run, and also allow field calculations. The first of the four Nuclear Criticality Safety Assessment Codes—for calculating the power histories of nuclear excursions—has been completed. In this paper I describe the development of the point-reactor model, a lumped-parameter model that allows us to exploit several useful approximations. I describe the assumptions made, the means of obtaining effective values of kinetic parameters in the chain-reacting system, and we give the range of validity of the model. Refinements of the point-reactor model allow us to take into account reactivity feedback and yield-enhancing mechanisms. The second code, criticality calculations of arrays of fissile material, is currently being documented; the other two codes—criticality calculations of single units of fissile material, and consequence models—will be produced at six-month intervals. Copies of the first code and its documentation are available from the author.

Introduction

We have undertaken a project sponsored by the DOE Office of Nuclear Safety to develop a suite of well-documented and useful calculational tools, Nuclear Criticality Safety Assessment Calculations. The calculational tools are carefully explained, keeping in mind the special needs of the nuclear criticality safety specialist. As part of the project, we are also developing computer codes that will run on personal computers.

The project is divided into four sections. Each section is covered in a separate publication. The four important aspects of nuclear criticality safety covered in the project are:

1. *Power-history calculations of nuclear excursions.* The power-history, or the number of fissions as a function of time, of a nuclear excursion depends on both the nuclear properties of the fissile fuel and the thermodynamic properties of the material involved. The criticality safety specialist

needs to assess the potential yield of an unplanned nuclear excursion and its behavior over time. The duration of a nuclear excursion can vary from a few seconds to many minutes. By understanding the sensitivity of the power history to certain parameters, the criticality safety specialist can concentrate on effective control measures.

2. *Criticality calculations of arrays of fissile material.* An obvious application of criticality calculations of arrays of fissile material is to assure the safe and efficient operation of storage vaults for fissile material. An operational vault usually contains a variety of materials and sizes. Hence the criticality safety specialist has a need for a rapid calculational tool to assess normal and unusual operations of a real storage vault.

3. *Criticality calculations of single units of fissile material.* These criticality calculations answer such questions as how the critical mass varies

with the shape of the unit, with the presence of reflectors around the unit or diluents in the fissile material, and density. Knowing the sensitivity to certain parameters, one can provide safe, efficient control measures.

4. *Consequence models.* Consequence models refer to calculating the radiation output, pressure, and kinetic energy of a potential nuclear excursion as a function of time. The applications of these models are in the placement of detectors for alarm systems, personnel protection, and mitigation factors.

The first part of the project, calculating power histories of nuclear excursions, has been completed and will be described in more detail below. The computer program that we have developed for this part of the project uses the LIVERMORE SOLVER OF DIFFERENTIAL EQUATIONS software package adapted to personal computers. The computer program is available on diskette and has been distributed to interested parties in the DOE community.

Basic Concepts

Reactivity

One of the basic parameters used in describing the kinetics of a system with fissionable material is a dimensionless number called the reactivity, ρ , which describes the rate of change of the number of neutrons in the system. Since the number of neutrons in the system is proportional to the power produced by neutron-induced fission, the reactivity also describes the rate of change of the power.

$$\rho = \frac{\text{production rate} - \text{removal rate}}{\text{production rate}} \quad (\text{definition of } \rho).$$

Note that $\rho < 1$. When the neutron production rate equals the neutron removal rate, $\rho = 0$ and the number of neutrons in a system with no external sources does not change. The state in which $\rho = 0$ is called *critical*, with exactly the same number of neutrons removed as are produced by the system. When $\rho > 0$, we have a *supercritical* system; when $\rho < 0$, we have a *subcritical* system.

A related factor is the effective reproduction factor, k :

$$k = \frac{\text{production rate}}{\text{removal rate}} \quad (\text{definition of } k).$$

In a critical system, $k = 1$.

Delayed Neutrons

The physical phenomenon that usually dominates the dynamics of a system containing fissionable material (and, indeed, makes possible a controllable nuclear reactor) is the presence of delayed neutrons. Delayed neutrons arise from the decay of certain kinds of fission fragments. About 40 of the radioactive species produced in neutron-induced fission yield delayed neutrons. Figure 1 shows the origin of delayed neutrons in ^{87}Br and ^{137}I . In nuclear kinetics, the 40 radioactive species fall into six aggregate groups whose mean lifetimes vary from a few tenths of a second to about 80 seconds. These times are much greater than those for prompt neutron emission (10^{-14} s) or neutron reproduction (10^{-3} to 10^{-8} s).

Delayed neutron precursors are produced at a much lower rate than prompt neutrons (typically over 100 prompt neutrons are produced for each radioactive fission fragment that decays by delayed-neutron emission). Yet, since the neutron precursors live longer than the neutrons, the number of neutron precursors is usually greater than the number of neutrons.

Often, the reactivity ρ is divided by the delayed neutron fraction, β . We call $\rho/\beta = 1$ a "dollar" (\$) of reactivity.

Figure 1. Level diagram showing the origin of delayed neutrons in ^{87}Br and ^{137}I . The lifetime of the delayed neutron emission is controlled by the beta decay of the parent nuclide, which produces a neutron in events going to an excited state of the daughter nuclide.

Power-History Calculations of Nuclear Excursions

For our first set of Nuclear Criticality Safety Assessment Codes, we used a "lumped-parameter" model for nuclear kinetics and exploited certain useful approximations of that model. The lumped-parameter model, which eliminates detailed properties of the system by means of an averaging process, is usually called the point-reactor model. As we will see, the equations that describe the point-reactor model depend only on the time variable. Effects produced by geometry or neutron energy are contained in the parameters of the point-reactor model. This model is satisfactory only when the system of fissile material is close to critical; this restriction allows us to treat most cases of practical interest, however.

Our purpose in describing the point-reactor model is twofold. First, we want to give the reader an understanding of the phenomena involved in an accidental nuclear excursion. How much energy is likely to be produced during an accident? What is the time behavior of the energy released? What properties of the system determine the shutdown mechanism of the nuclear excursion? Second, we want to give the criticality safety specialist some computational tools for estimating the behavior of an accidental nuclear excursion when the parameters describing the chain-reacting system are not precisely known.

The rate at which energy is produced in a chain-reacting system is proportional to the number of neutrons present in the system. Hence, we need to know how the neutron population changes with time.

Neutrons can be added to the system in several ways: first, an external source not related to the fission process can add neutrons; second, a neutron-induced fission can emit between 0 and 5 neutrons promptly (in about 10^{-14} s); and third, delayed neutrons are a result of the radioactive decay of some fission fragments produced during fission. The neutron population is decreased by absorption, which leads either to fission or to capture without fission, or by the leakage of neutrons from the system. The time that a neutron survives between birth (as a prompt or delayed neutron) and death (from capture or leakage) varies between 10^{-3} and 10^{-8} s.

Obtaining Effective Values of Kinetic Parameters

The parameters that appear in the point-reactor model are integral properties of the chain-reacting system. The effective values of these parameters must be obtained by averaging over space and over

the energy spectrum of the neutrons. We can show that, for a system containing a single neutron energy, the effective weighting function used in the spatial average energy is the flux of an unperturbed critical steady-state reference system. For the single-neutron-energy system, the effect of a neutron at the center counts more than the effect of a neutron on the edge, where leaking is likely.

The form of the point-reactor differential equations is the same in both methods of averaging. The parameters refer to weighted averages. Usually, we have accurate values for these parameters only when we are working on a well-designed system based on detailed computer calculations and experimental studies. We can, however, make reasonable estimates of these parameters based on known critical chain-reacting systems and calculate with a range of values.

Range of Validity of the Point-Reactor Model for Calculating Power Histories

The point-reactor model assumes that the neutron density increases or falls as a whole when the reactivity changes. It does not assume, however, that the neutron density is uniform throughout the chain-reacting system.

We are interested in calculating power histories of an entire chain-reacting system that is close to critical. In general, we are not interested in the detailed spatial behavior of neutron density. Heterogeneous details of the system affect the computation of the effective values of the kinetic parameters used in the point-reactor model, but such parameters are integral properties of the system. The neutron energy spectrum of the system may shift during an excursion and also affect the kinetic parameters. If necessary, we can employ a quasi-static scheme, using the point-reactor model to calculate changes in the neutron density and thermodynamic properties between snapshots of the chain-reacting system. With the snapshots, we determine the shape of the neutron density and the effective kinetic parameters of the static system.

The point-reactor model cannot describe spatially dependent dynamic effects. In large reactors,

these effects may result from time lags in the propagation of local perturbations. Large departures from critical can produce spatial effects in both large and small chain-reacting systems. These effects are transient and are more evident in computer studies than in real systems because the computer studies can change properties discontinuously. Real systems need some interval of time to accomplish change.

The equations of the point-reactor model describe the behavior of the mean values of the neutron and precursor populations. If the populations are small, then the fluctuations about the mean can be significant, and we need to consider the underlying stochastic processes. One application that we have considered is the assembly of fissile material in the presence of a weak neutron source.

The best indicator of the range of a model's validity in calculating power histories of nuclear excursions is its successful application to fast, slow, bare, and reflected chain-reacting systems. Our point-reactor model has been successfully applied to the following different types of chain-reacting systems:

TREAT (transient reactor test facility). A graphite-moderated, air-cooled reactor with a graphite-uranium oxide fuel mixture.

SPERT (special power excursion reactor test). A water-moderated, water-cooled reactor with either highly enriched metal fuel or low-enriched oxide fuel.

TRIGA. A light water-cooled, zirconium-hydride-moderated reactor with a 20% enriched ^{235}U fuel impregnated into zirconium hydride.

KEWB (kinetic experiment water boiler). A small homogeneous reactor, with its solution of uranium sulfate in water contained by a 1-ft-diameter stainless-steel vessel surrounded by a graphite reflector.

KIWI-TNT. A destructive test of a nuclear-rocket thermal reactor with uranium fuel in a graphite moderator; the rocket was propelled by hydrogen.

GODIVA. A bare sphere of about 53 kg of 93.5% ^{235}U .

Elementary Solutions of the Point-Reactor Model at Low Power

We used a set of seven coupled nonlinear differential equations for the point-reactor model. To make the solution of this system undaunting, we re-

stricted the solutions of the model to low power levels. With this restriction, reactivity does not depend on the power history of the system, and we

have an artificial condition of no reactivity feedback. We relax the restriction as we gain competence and have to address real-life problems.

We start by considering a system in equilibrium. Next, we consider the response of the point-reactor model to an impulse of source neutrons and then to a step insertion of reactivity. This analysis is similar to that used in electrical circuit analysis. We use Laplace transform theory to solve the set of differential equations and to gain an understanding of the dynamical system.

Adiabatic Point-Reactor Models with Reactivity Feedback

Our previous discussions have been limited to low power levels in the chain-reacting system. We are now ready to make our models more realistic by allowing the reactivity to depend on the power history of the chain-reacting system. We introduce a feedback term in the reactivity, and we assume that only an insignificant amount of heat generated in the system is transferred to the surroundings. The latter assumption gives us the adiabatic model. Reactivity feedback and an adiabatic model give us the tools to discuss self-limiting excursions.

The adiabatic model has more applications to real systems than we might realize. Most fission-produced thermal energy is made by slowing down

After treating the impulse of source neutrons and the step insertion of reactivity, we develop an approximation that uses only one group of delayed neutrons instead of six. The effective parameters in the one-group system can be chosen to describe either a rapid or slow increase in the neutron population. Finally, we develop the constant precursor model for situations above prompt critical, and the prompt-jump model for situations below prompt critical. Both of these models have analytic solutions when reactivity feedback is neglected.

highly charged, massive fission fragments. The range of these fragments is less than a millimeter in solids and liquids. Hence, the relevant heat capacity is the heat capacity of the fuel mass. After the fuel mass heats up, a dynamic process transfers the heat to the surroundings of the fuel. In a nuclear excursion, that first pulse or first several pulses of power may be described quite accurately by the adiabatic model. After the initial phase, we may have to model a heat-transfer process. As the energy increases, we must also consider changes of state, such as melting and vaporization or even explosive disassembly of the system.

Yield-Enhancing Mechanisms

Now we will consider two mechanisms that can enhance the yield: a time delay in reactivity feedback and the assembly of the system in the presence of a weak neutron source.

If the chain-reacting system is superprompt critical and the reproduction time is short, the rate at which energy is deposited into the system can be very high. As a result, the system will require a significant amount of time to adjust and lower the reactivity. In an all-metal system such as GODIVA, inertial effects provide this delay in reactivity feedback, which is roughly the time it takes an acoustic wave to travel from the center to the surface of the system.

Time delays usually concern us only in fast metal systems. Some numbers can help explain why. In metals, the speed of sound is about 5000 m/s, and in water it is about 1500 m/s. The delay associ-

ated with a 10-cm-radius metal system is 2×10^{-5} s. The delay associated with a 50-cm-radius water system is 3×10^{-4} s.

If the chain-reacting system is assembled in the presence of a weak neutron source and a small number of delayed neutron precursors,* no reactivity feedback will occur until a sustained chain reaction is initiated. The reactivity feedback models we have employed thus far assume that there are enough neutrons to start producing energy when the reactivity of the system reaches a value of zero. This assumption is not always valid. When the neutron and precursor populations are small, we have

* A uranium system is likely to be assembled in the presence of a weak neutron source. A plutonium system usually contains ^{240}Pu , which acts as a neutron source.

to consider statistical fluctuations in the values predicted by the point-reactor model. A metallic uranium system can assemble to a superprompt critical configuration in the presence of a weak neutron source before a persistent chain reaction starts to generate significant amounts of energy to shut down the excursion.

When the neutron and precursor populations become large enough, we can use the equations of the point-reactor model to calculate the behavior of the system. When the neutron source is weak, the initial conditions for the point-reactor model have a spread of values that we calculate with a statistical model.

Use of NCSAC Codes with Personal Computers

The end result of this project is to develop a series of criticality safety calculational tools that are able to run on small personal computers. The ability to run the codes on small computers offers many definite advantages, even though the same computational capability is available via large, sophisticated codes running on mainframe machines. Results of the more comprehensive calculations can be compared with NCSAC results, and discrepancies might identify input errors common in the larger codes because of the complexity of input data. Calculations using the smaller codes are easier and less expensive, and allow field calculations.

All NCSAC codes will be made available directly through the Nuclear Criticality Information System (NCIS) computer network, for use by all criticality safety specialists. The codes can be downloaded from NCIS onto smaller computers, or a separate diskette is available directly from the author. At present the fully documented code for calculating power histories in nuclear excursions is available, and documentation has recently been completed for the criticality calculations of arrays of fissile material. We expect that the remaining two modules will be produced at six-month intervals.

An Experimental Study of Neutron Noise with Criticality Safety Applications in Mind

C. S. Barnett

In order to explore the feasibility of developing a criticality warning system, I studied the statistics of detected neutrons that leaked from four subcritical reflected enriched-uranium assemblies. I considered three possible signatures that might be used to discriminate among assemblies of various multiplications. They are (1) variance-to-mean (V/M) ratio of the counts in a time bin, (2) covariance-to-mean (C/M) ratio of the counts in a common time bin from two different detectors, and (3) covariance-to-mean ratio of the counts from a single detector in two adjacent time bins of equal length, which I call the serial covariance-to-mean (SC/M) ratio. For my purposes, the performances of the three discriminators were not greatly different, but in general SC/M was more effective than V/M, which in turn was more effective than C/M. The noise-analysis techniques performed well enough in deeply subcritical situations to deserve testing in an applications environment. They have a good chance of detecting potentially dangerous changes in reactivity. One can expect the sharpest results when comparing two records, one taken in the past under circumstances known to be normal and one taken at present to search for a change.

Introduction

Currently, nuclear criticality safety practitioners employ two basic tools to ensure safety in a facility that handles fissile material: (1) administrative and mechanical controls of material, and (2) criticality alarm systems. The administrative and mechanical controls place limits on the amount of fissile material allowed in any one place, as well as limiting its shape, position, and movement. These controls are developed before any operations are begun in a facility. The second control, a criticality alarm system, sounds an alarm *as an accident is taking place*. If the administrative controls are effective, there is no possibility of a nuclear criticality accident; if the criticality alarm is activated, it is already too late to avoid a catastrophic situation. Note the wide gap between these two circumstances. Can we develop instruments and methods to warn operators who work with fissile materials of undesired but less-than-catastrophic increases in neutron multiplication?

Suppose a flexible criticality warning system (CWS) of instruments and methods were developed

to sense changes in reactivity. Possible safety applications of a CWS are (1) monitoring reactivity changes at various points in a fuel-fabrication facility or a chemical-processing line where an excess mass of fissile material might accumulate and possibly lead to near-critical configurations, and (2) helping to minimize the probability of inducing a criticality event during recovery from accident situations, such as fire, flood, earthquake, or criticality.

Tied to the safety implication of a CWS is an economic one. The reactivities of process configurations are often difficult to calculate reliably; hence, design and operational safety limits must be set at quite conservative levels, levels that might unnecessarily constrain production rates. Perhaps a CWS would safely allow some relaxation of limits imposed for criticality safety reasons.

I undertook the work reported here to explore the feasibility of developing such a criticality warning system by using neutron-noise analysis.

A Game

To set the scene, consider the following imaginary situation: in a laboratory I have set up a fixed-geometry neutron counting arrangement. This counting apparatus records the time at which a detection occurs and the identity of the specific detector (if more than one is used). Meanwhile, in the stockroom you have available n subcritical assemblies of fissile material. The multiplications of these subcritical assemblies are $M_1 > M_2 > \dots > M_n$, and each assembly contains a source of neutrons. Roughly speaking, the multiplication of an assembly that contains fissile material and a neutron source is: (mean neutron population in the assembly) $\div$ (mean neutron population in the assembly if the fissile material is removed but all other materials are left in place). All are packaged in identical containers. You have adjusted the neutron-source strengths in each assembly so that all assemblies give a common mean count rate when placed in our fixed-geometry counting apparatus.

We play a game as follows: in the stockroom, you use some kind of device, a roulette wheel perhaps, to randomly choose an assembly from the stockroom and place it into the counting apparatus. In the laboratory, I turn on the counter until K counts, say, are recorded. You spin your roulette wheel again and select another (or the same) assembly and place it into the counting apparatus. Again, I record K counts.

Now I must try to decide, from the two records I have in the laboratory, whether or not you placed *different* assemblies into the apparatus. Observe that the problem is constructed so that I cannot use neutron-count rate as a discriminator, since all of the sample sources have the same strengths. If any useful information is available, it is stored in the way the detections are spread along the time line—and useful

information is indeed stored in such records. The statistical properties of a high-multiplication record are different from those of a low-multiplication record.

One way I might proceed is to select a statistical parameter that tends to be high in high-multiplication records and low in low-multiplication records, and then design a processor to estimate that parameter. I then apply this processor to the two records and announce "different assemblies" if the two estimates are sufficiently far apart and "same assembly" otherwise. The more I know about your random selection scheme (your roulette wheel) and about the different multiplications of the assemblies, the better I am able to determine what "sufficiently far apart" should be. Also, what I decide to be "sufficiently far apart" will depend upon the reward or penalty for a correct or incorrect answer. Because of the inherent statistical nature of the source emission and fission processes, my decision procedure can never be perfect.

The game just described is an idealization of the problem of detecting changes in reactivity at fissile-material work stations or processing points. The roulette wheel and the set of subcritical assemblies of various multiplications simulate the uncertainties that always accompany machine and human interaction. The requirement that count rate cannot be used as a discriminator corresponds to the fact that neutron source strengths at the workplace will vary in ways not controllable by the observer. For example, increased count rate does not necessarily imply increased reactivity; it may just mean that a stronger source of neutrons has entered the area of interest or that the extraneous background rate has increased because of additional neutron emitters brought into the vicinity of the workplace.

The Work Done

I assembled enriched uranium subcritical units of different multiplications, drove them with a neutron source, and recorded the detection times of leaked neutrons. I used four assemblies, the most reactive having a multiplication of about 10, and two neutron sources, one nonfission and one fission. Sixteen detectors were placed near the assem-

bly, and each time a detection was recorded the identity of the firing detector was also recorded.

All these records were stored on a medium accessible to a CDC 7600 computer. I then subjected the records to various algorithms designed to extract statistical signatures that could be tested for their ability to discriminate among various levels of

multiplication. In accord with the restrictions mentioned above, count rate was not used as a discriminator in any of the algorithms.

I concentrated my effort on three different discriminators. They are (1) the variance-to-mean (V/M) ratio of the counts in a time bin, (2) the covariance-to-mean (C/M) ratio of the counts in a common time bin from two different detectors, and (3) the covariance-to-mean ratio of the counts from a single detector in two adjacent time bins of equal length [which I call the serial-covariance-to-mean ratio (SC/M)]. With the software I could arrange for any subset of the 16 detectors to act as a single detector.

The performances of the three discriminators were not greatly different, but a fairly consistent hierarchy did emerge: SC/M was more effective than V/M, which in turn was more effective than C/M. That the variance-to-mean discriminator performed slightly better than the covariance-to-mean dis-

criminator is inconsistent with the lore that C/M techniques should be better than V/M techniques because C/M techniques avoid estimating the contribution of the Poisson component of the sample. This result suggests that for a given set of assets (a given number of detectors and associated electronics) it is better to lump the detectors into one unit and perform V/M measurements than to split the detectors into a pair of symmetric units and perform C/M measurements. Apparently, the reduction in detector efficiency that is a consequence of the splitting eliminates whatever advantage might otherwise accrue to C/M measurements.

The newly introduced SC/M discriminator performed slightly better than either of the other two, perhaps because it embodies the advantages of both: detection efficiency of the V/M discriminator and avoidance of the estimation of the Poisson component that is a property of the C/M discriminator.

Experimental Description

The fuel for the subcritical assembly consisted of eight enriched (93.2%) uranium shells, four sets of twins. Inside diameter of the smallest pair is 11.8 cm; outside diameter of the largest pair is 15.9 cm. The shells nest snugly, making it convenient to assemble, starting from smallest to largest, a sequence of one-shell, two-shell, three-shell, and four-shell configurations. The apparatus is shown in Fig. 1. The corresponding sequence of uranium masses was 5.49, 11.67, 16.31, and 22.64 kg. Each assembly was reflected internally by an 11.8-cm-o.d., 1.9-cm-thick spherical shell of acrylic resin and reflected externally by a 16.0-cm-i.d., 10-cm-thick spherical shell of acrylic resin. The 8-cm-diameter central void accommodated the driving neutron sources. The calculated reproduction factors (k) for the four assemblies were 0.59, 0.74, 0.82, and 0.92. Calculated median energies of neutrons inducing fission varied from 0.4 keV for the one-shell assembly to 100 keV for the four-shell assembly.

Leaking neutrons were detected by two identical planar arrays of ^3He detectors, eight detectors per bank. Detectors were 2-in. diameter by 36-in. long, backed by a 2-in.-thick block of polyethylene. The solid angle subtended at the center of the assembly by a single detector averaged 1.2%.

The detection-time and detector-number data pairs were recorded on floppy disks. For any given assembly configuration, a single run terminated when one floppy disk was full of data. Typically, about 120,000 counts were recorded per run. The sum of the count rates from all 16 detectors varied in the neighborhood of a few kilohertz when assemblies were driven by either of two neutron sources, fission or nonfission, each emitting about 10^4 neutrons per second. For each major configuration of interest, I made 20 runs, yielding 20 disks of data.

Discriminator Comparisons

Focus attention on one discriminator, V/M for instance. Pick an assembly configuration, pick one data disk for that configuration, and decide on a detector subset (all 16, for example). Calculate V/M ratios for several different time-bin-widths, e.g.,

250 μs , 500 μs Perform a two-parameter, least-squares fit of these data to the theoretical V/M vs time-bin-width curve. One of the parameters is our V/M estimator; the other is the assembly decay time constant. Repeat the process for the remaining 19

Figure 1. The subcritical assembly used in this work. Top hemispheres are sectioned to show detail.

disks of data taken under identical circumstances. I now have 20 samples of the V/M estimator, generally all different because of the randomness inherent in the processes from which the data were extracted. Finally, fit a cumulative probability distribution function to these 20 samples.

Repeat the process outlined in the previous paragraph for the other three assembly configurations. We now have cumulative distribution functions for the four assemblies with fuel masses of 5.49, 11.67, 16.31, and 22.64 kg of uranium. Interpolate between these four mass points and get a recipe that assigns a V/M cumulative distribution for any fuel mass between 5.49 and 22.64 kg (hence a recipe for any calculated reproduction factor between 0.59 and 0.92, the range of reproduction factors for these assemblies).

I now have sufficient information to predict the performance of a V/M threshold decision proce-

dure. Suppose I wish to find out how well I can discriminate between a 6.0- and a 6.5-kg mass assembly with my apparatus placed as it was when all the data were collected. I generate the V/M distribution functions for both the 6.0-kg and the 6.5-kg cases. Then, by moving the V/M threshold from low to high values, I generate a curve of true vs false high decision probability. That is, I can compute, for any threshold setting, two important conditional probabilities: (1) the probability that a disk of data from a 6.5-kg assembly, when processed as described above, will yield a V/M value greater than that threshold (true high decision probability), and (2) the probability that a disk of data from a 6.0-kg assembly, when so processed, will yield a V/M value greater than that threshold (false high decision probability). A set of such pairs generates a curve inside the unit square, which curve I call the "decision-rule performance characteristic" (DRPC).

From that curve I can determine the false high decision probability that I must accept for any desired true high decision probability.

I constructed DRPCs for the V/M discriminator for three sets of detectors (all 16, a subset of 8, and a subset of 4) for fuel mass pairs in the neighborhood of 6.0 kg and 16.0 kg, and for two neutron sources (fission and nonfission). Similarly, I generated corresponding DRPCs for the C/M and SC/M discriminators. Since the C/M and SC/M discriminators use covariance techniques, two detector subsets are required. The sets chosen were symmetric halves of the sets used for the V/M case. Also, each of the C/M and SC/M techniques requires least-squares fits to unique theoretical functions that have time-bin width for domain and discriminator value for range.

It was by using the DRPCs as measures of effectiveness that I arrived at the performance order mentioned earlier: SC/M > V/M > C/M. The sample size on which each DRPC is based is not large (20 samples), so there is uncertainty in each. Nevertheless, I find it convincing that the stated order emerges in case after case. Here are two quantitative examples of relative performances of discriminators: Case I, nonfission source, 16 detectors—task is to discriminate between 16.0-kg and 16.4-kg assemblies, 5% false high decision probability accepted. Corresponding true high decision probabilities for SC/M, V/M, and C/M discriminators are 97, 86, and 81%. Case II: same as Case I, except assemblies are driven by a fission source. Corresponding true high decision probabilities for SC/M, V/M, and C/M discriminators are 86, 75, and 75%.

I chose two operating points for discussion in this report: 6.0- and 16.0-kg fuel mass. These masses correspond to calculated reproduction factors of 0.6 and 0.8. In the neighborhood of $k = 0.6$, the Δk required for satisfactory discrimination by the best of the three discriminators varies from about 0.03 to 0.07 as the number of active detectors varies from 16 down to 4. In the neighborhood of $k = 0.8$, the corresponding Δk s are 0.01 and 0.02. By "satisfactory discrimination" I mean that the Δk that separates the two assemblies to be discriminated must be greater than or equal to the quoted numbers if the true high decision probability is to be essentially one and the corresponding false high decision probability is to be essentially zero.

The discriminators whose properties I investigated exploit the stochastic nature of the fission process and the stochastic nature of neutron emis-

sion from nonfission and fission neutron sources. Hence an interpretive probabilistic model is required. For the fast spectrum systems I studied, the point model with no delayed neutrons seemed to be adequate. Starting with the assumptions of that model, I did a derivation of the relations needed for interpretation of the experiments. In the model I allow for two neutron detectors, a mixed neutron source (nonfission plus fission), and extraneous background flux on the detectors. The details of the derivation are too lengthy to display here, but an outline of the steps involved is appropriate:

1. Write probability balance relations for the three-dimensional state space (one dimension for the neutron population and one dimension each for the two detectors).

2. Pass to the limit of small time increment and obtain a triply infinite set of ordinary differential equations for the probability mass function that assigns probability to elements of the state space.

3. Collapse that array of ordinary differential equations to one partial differential equation for the probability generating function.

4. Extract from that partial differential equation a system of ordinary differential equations for selected low-order moments.

5. Solve the system derived in step 4.

Finally, selected members of that solution set are combined to yield the theoretical expressions for the three discriminators: variance-to-mean ratio, covariance-to-mean ratio, and serial-covariance-to-mean ratio.

Figure 2 and Tables 1 and 2 display a sample of some experimental results. The relative performances of the three different discriminators is apparent from the figure after noting that the effectiveness of the decision rule is measured by the closeness of the DRPC to the upper left-hand corner of the unit square.

Table 1 summarizes the increments in fuel mass that are required for satisfactory discrimination between low-mass and high-mass situations. For example, the entry in row 1, column 1 (1.0 kg) says that with 16 detectors and a nonfission source, 6.0 and 7.0 kg ($6.0 + 1.0$) of fuel can be satisfactorily distinguished but greater resolutions cannot be obtained. For only 8 detectors, the best we can achieve is to distinguish between 6.0 and 7.4 kg ($6.0 + 1.4$). Table 2 summarizes the same information for the reproduction factor, k . Entries display the value of Δk that must be added to low k if the best of the three discriminators is to satisfactorily

Figure 2. The relative performances of the three discriminators—variance to mean (V), covariance to mean (C), and serial covariance to mean (S)—can be seen by how close the curves approach the upper left corner of the unit square.

Table 1. Increment in fuel mass, in kilograms, required to obtain satisfactory discrimination.

No. of detectors \ Low mass (kg)	Nonfission source		Fission source	
	6.0	16.0	6.0	16.0
16	1.0	0.5	1.0	0.6
8	1.4	0.6	1.6	0.7
4	2.8	1.2	2.8	1.0

Table 2. Increment in multiplication factor (k), required to obtain satisfactory discrimination.

No. of detectors \ Low k	Nonfission source		Fission source	
	0.605	0.819	0.605	0.819
16	0.025	0.009	0.025	0.010
8	0.035	0.010	0.040	0.012
4	0.068	0.020	0.068	0.017

separate the low k and the high k situations. We see from Table 2 that in the neighborhood of $k = 0.6$, the Δk required for satisfactory discrimination varies from about 0.03 to about 0.07 as the number of active

detectors varies from 16 to 4. In the neighborhood of $k = 0.8$, the Δk required for satisfactory discrimination varies from about 0.01 to about 0.02 as the number of active detectors varies from 16 to 4.

Implications

Work done in laboratory situations approaches an ideal not found in the world of applications, however. What are some of the implications of this work for the global picture of criticality safety? The ground now gets a bit shaky, but I think a few statements can be supported.

The noise-analysis techniques studied performed well enough in deeply subcritical situations to deserve testing in an applications environment. They have a good chance of detecting changes in reactivity that are potentially dangerous. One can expect sharpest results when comparing two records, one taken in the past under circumstances known to be normal and one taken at present to search for change. Further, to be most effective, the geometry of the past and present arrangements should be as nearly identical as possible. In particular, the detector positions relative to the center of the zone being surveyed should be faithfully reproduced if possible. The situation is analogous to that of a physician

reading two electrocardiograms, one taken when the patient was known to possess normal health and one taken later to try to detect a change.

I have avoided discussion of the possibility of the direct measurement of the reproduction factor, k . If we possessed the ideal machine, we could wheel it into the vicinity of any assembly containing fissile material, turn it on for a specified time, and it would announce the value of k . I know of no avenue that leads toward that ideal. The methods I examined could be calibrated in terms of k for use in production testing and inspection applications but do not seem to lend themselves to direct measurement of k unless one knows or assumes additional information about the assembly being inspected and the efficiency of the detector.

The gap between criticality controls may not have closed, but I think it is perhaps a fraction smaller.

Safety Analysis

LLNL Risk Assessment of Competing Construction Projects

James L. Morse, James J. Bloedorn, and Rice T. Trolan

Each year, LLNL reviews all facility and utility upgrade projects to determine their relative ranking in terms of safety benefit vs cost. This process begins when a team of health and safety professionals screens the proposed upgrade projects. A personal computer is used to record, display, and print risk data about each competing project. This information, including a computer-generated cost-benefit graph, assists line management to reach decisions concerning the relative merit of each project. The spreadsheet formatting used to perform the risk scoring and the cost-benefit analysis is included with this paper.

The Risk-Assessment Process at LLNL

LLNL's risk-assessment methodology is a refinement of a necessary risk-management function, the ranking of safety-upgrade projects in a logical way. With frequently limited funds, a rationale for this ranking is important.

Our risk-assessment process begins with a small committee of experts who review each proposed facility and utility upgrade project for its safety, health, and environmental merit. The current committee consists of a fire-protection engineer, a health physicist, an industrial hygienist, an industrial safety engineer, an environmental engineer, and a safety analyst as chairman.

The review commences with each member of the committee becoming familiar with the proposed upgrade by inspecting the detailed proposals, along with their accompanying justification information. These proposals originate from the program or department managers who have responsibility for each respective facility. The members of the com-

mittee are encouraged to discuss the merits of a project with the operational managers and safety people involved with each facility.

When the information gathering is complete, the committee meets to perform the risk scoring (described below). Generally, the committee achieves reasonable agreement on the risk scores, since extreme views or biases tend to be dampened.

To conduct the risk analysis, a personal computer (PC) with a spreadsheet program is used to calculate and record the data with integrated graphics. The ease of entering and manipulating data on the spreadsheet format makes sensitivity analysis especially easy: various consequences and probability factors can be changed to see their impact on the risk score instantly, and the graphical cost-benefit information can be displayed on the PC.

Following this risk-scoring activity, the data is printed and forwarded to the responsible LLNL Associate Director for final LLNL approval.

The Risk-Scoring Analysis

Our risk-scoring analysis is a variation of a system developed in the early 1970s by William T. Fine, then of the Naval Ordnance Laboratory (NOL).¹ Our risk-scoring formula is:

$$\text{Risk Score} = \text{Consequences} \times \text{Exposure} \times \text{Likelihood} \quad (1)$$

Let us discuss Eq. (1) and its concepts. A "consequence" is the undesired result of a sequence of events starting with the initiating event. Consequences may include fatalities, serious or minor injuries or illness, dollar loss, work delays, and adverse public reaction. Table 1 lists some consequence factors and their accompanying risk scores. A particular hazard may have more than one consequence, each at a different probability level. However, as the seriousness of a consequence goes up, its probability of occurring generally goes down. It is important for the team members to select the consequence and its related probability that will result in the greatest risk score.

The last two terms of Eq. (1), exposure and likelihood, are probability factors and are defined as:

Exposure Probability that an initiating event will occur which may or may not result in an undesired consequence. "Exposure" is the number of times in a given period that the hazard presents it-

self. For example, a busy intersection has a greater probability of an accident than a quiet intersection, provided that the "hazard" of each is the same. For this reason, one of the ways to estimate the probability of the initiating event is to look at the exposure, or amount of time the threat is present.

Likelihood Probability that the specified consequences will occur, given that the initiating event occurs.

These probability factors are given in whole numbers (contrary to actual probabilities, which are fractions). Although more than two factors may be identified in making up the total probability, it is usually simplest to break down the total probability into "exposure" and "likelihood" as mentioned above.

The risk score is calculated using the values selected from Tables 1-3 and inserting them into Eq. (1) above. One could stop the risk assessment here; however, a more complete assessment is possible with the justification analysis.

Table 1. Factors used to estimate the risk score of a given consequence.

Description	Risk score
Catastrophe	
Numerous fatalities	
Extensive damage (> \$25 million)	
Major disruption of work	
Off-site health affected	100
Several fatalities	
Property damage (\$1 to \$25 million)	
Serious programmatic interruption	50
Fatality, serious illness (e.g., cancer)	
Property loss (\$500,000 to \$1 million)	
Work interruption	25
Permanent disability, chronic irreversible disease (amputation, loss of eye, etc.)	
Property damage (\$100,000 to \$500,000)	
No significant off-site threat, but public involved with adverse publicity	15
Serious injuries, illness (without permanent disability)	
Property damage (\$10,000 to \$100,000)	
No significant off-site threat, public not involved	5
Minor injuries, illness (i.e., no disability)	
Property loss (< \$10,000)	
No work effect	1

Table 2. Probability factors for the occurrence of the initiating event. This is referred to as "exposure."

Description	Risk score
Continuous threat	
Very likely to occur	
95% probability	10
Frequent threat	
50% probability	6
Occasional threat	
1% probability	3
Unusual threat	
0.001 probability	2
Rare threat	
0.00001 probability	1
Very rare threat, only remotely possible	
10^{-7} probability or smaller	0.5

Table 3. Use the following to establish the probability factor of the initiating event resulting in the consequences specified. This is called "likelihood."

Description	Risk score
Most likely and expected result	
95% probability	10
Quite possible, not unusual	
50% probability	6
Unusual sequence of coincidences	
1% probability	3
Remotely possible coincidence	
0.001 probability	2
Extremely remote possibility	
0.00001 probability	1
Practically impossible	
10^{-7} probability or smaller	0.5

The Justification Analysis

Once a project has been determined to pose a safety, health, or environmental problem, appropriate corrective actions must be tentatively decided upon and their costs estimated. Using the risk score discussed above, we can now use two operative elements—the cost and the degree of correction—to determine an index of justification.

$$\text{Justification} = \frac{\text{Risk Score}}{\text{Cost} \times \text{Degree of Correction}} \quad (2)$$

The cost is the estimated dollar cost of the proposed corrective action. The dollar unit is dropped to create a pure number for comparison. The degree of correction is an estimate of how much the proposed corrective action will reduce the identi-

fied risk. (A safety-improvement project may attempt the containment of a consequence, the elimination or mitigation of a hazard, the interruption of an accident sequence, or a combination of these approaches.) Degree of correction values are given in Table 4.

Values are substituted into the formula to determine a numerical value for justification. Projects can then be ranked by justification for management action. Notice that if cost is removed from the justification formula, then another useful value, benefit, can be obtained:

$$\text{Benefit} = \frac{\text{Risk Score}}{\text{Degree of Correction}} \quad (3)$$

Table 4. Degree of correction values and their associated risk scores.

Identified risk	Risk score
100% eliminated	1
Reduced to at least 75%	2
Reduced by 50 to 75%	3
Reduced by 25 to 50%	4
Reduced by less than 25%	6

Example Calculations

A hypothetical example of the spreadsheet format is shown in Fig. 1. Cost and benefit may be plotted on the X and Y axes to give a smooth computer-generated curve showing benefit vs cost (see Fig. 2). Projects are plotted in order of justification by cumulative cost (X axis) and cumulative benefit (Y axis). In Figure 2, notice that the more cost-effective projects fall on the left side and steeper part of the curve where great benefit is derived from modest cost. The use of cumulative cost on the X axis allows the manager to conveniently see his budget

limit for all upgrade projects. A vertical line may be drawn through the budget limit, intersecting the cost-benefit curve; this intersection then is a cut-off point for competing projects.

The relative effectiveness of eliminating or mitigating the risk, based on the proposed cost, can be compared to other proposed projects. This will assist management in allocating resources to the projects presenting the highest risks, after assuring that cost effectiveness has been considered.

Fac	Hazard	Risk score	Consequence	Exposure	Likelihood	Corrective action	Deg. of correct.	Just.	Cost (\$1000s)	Cumul. cost (\$1000s)	Benefit	Cumul. benefit
A3	Toxic waste storage	900	15	10	6	Upgrade storage area	2	75.0	6	6	450.0	456.0
B5	Oxygen deficiency alarms	900	50	3	6	Install two sensors	3	15.8	19	25	300.0	750.0
C2	Pigeons	30	1	10	3	Remove pigeons	1	10.0	3	28	30.0	780.0
A1	HEPA filters	450	50	3	3	Upgrade sys.	2	4.5	50	78	225.0	1005.0
B1	Catwalk	135	15	3	3	Repair catwalk	3	3.2	14	92	45.0	1050.0
B2	30-ton crane	300	50	3	2	Certify crane	2	3.2	47	139	150.0	1200.0
B3	Remote air monitors	135	15	3	3	Install two monitors	3	2.6	17	156	45.0	1245.0
C1	Parking lot	500	5	10	10	Resurface parking lot	3	1.7	100	256	166.7	1411.7
B4	Hand and foot counter	90	5	6	3	Install one	4	0.9	26	282	22.5	1434.2
A2	Roadway	45	5	3	3	Construct roadway	2	0.3	65	347	22.5	1456.7

Risk Score = Consequences × Exposure × Likelihood Factor												
Justification = $\frac{\text{Risk Score}}{\text{Cost} \times \text{Degree of Correction}}$												
Benefit = $\frac{\text{Risk Score}}{\text{Degree of Correction}}$												

Figure 1. Typical spreadsheet format for a hypothetical example, used to derive risk score, justification, and benefit.

Figure 2. A typical cost/benefit curve, showing where the budget limit removes the upper portion of the curve.

Conclusions

We feel our modified NOL risk-assessment method can be used satisfactorily by most organizations. However, the assessment system has some limitations. First, the scores derived should be used only for *relative* positioning of projects. The system is ultimately a qualitative methodology, and the numbers derived by the process have no intrinsic value. (For example, scores within 20 percent of each other can be considered as *essentially* indicating similar importance). This is due to the subjectivity involved in group assignment of consequence, probability, and degree-of-correction values.

A second limitation is the lack of consistency of scores between groups of evaluators charged

with ranking projects. For example, group A will not score consequences and probability factors in the same manner as group B. This is due to the unique biases of each group. Similarly, it is unreasonable to expect the *same* group to be completely consistent in scoring the same projects over a period of time.

With these limitations, the risk-assessment method described is superior to the purely intuitive methods commonly practiced today. The added dimension of using a personal computer and spreadsheet give the safety staff an additional tool to effectively communicate cost-benefit analysis to management.

Reference

1. William T. Fine, *Mathematical Evaluations for Controlling Hazards*, Naval Ordnance Laboratory Report, White Oak, MD, NOLTR-71-3 (1971).

Publication Abstracts

N. J. Alvares, "Fire Damage to Polymeric Materials in the Three Mile Island-Unit 2 Reactor Building," Lawrence Livermore National Laboratory, Livermore, CA; presented at American Chemical Society meeting, Miami Beach, FL, April 28-May 3, 1985.

Thermal damage to susceptible material in accessible regions of the reactor building was distributed in nonuniform patterns. No clear explanation for nonuniformity was found in examined evidence, e.g., burned materials were adjacent to materials that appear similar but were not burned. Because these items were in proximity to vertical openings that extend the height of the reactor building, we assume the unburned materials preferentially absorbed water vapor during periods of high, local steam concentration. Simple hydrogen-fire-exposure tests and heat-transfer calculations duplicate the degree of damage found on inspected materials from the containment building. These data support estimated 8% pre-fire hydrogen concentration predictions based on various hydrogen production mechanisms.

Charles S. Barnett, *A Study of Neutron Noise from Reflected, Metal Assemblies with Criticality Safety Applications in Mind*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53657, presented at the Workshop on Subcritical Reactivity Measurements, Albuquerque, NM, August 26-29, 1985.

I studied the statistics of detected neutrons that leaked from four subcritical reflected, enriched-uranium assemblies, to explore the feasibility of developing a criticality warning system based on neutron noise analysis. The calculated multiplication factors of the assemblies are 0.59, 0.74, 0.83, and 0.92. I studied three possible discriminators; i.e., three signatures that might be used to discriminate among assemblies of various multiplications. They are (1) variance-to-mean ratio of the counts in a time bin (V/M), (2) covariance-to-mean ratio of the counts in a common time bin from two different detectors (C/M), (3) covariance-to-mean ratio of the counters from a single detector in two adjacent time bins of equal length, which I call the serial-covariance-to-mean ratio (SC/M). The perfor-

mances of the three discriminators were not greatly different, but a hierarchy did emerge: $SC/M \geq V/M \geq C/M$. An example of some results: in the neighborhood of $k = 0.6$ the Δk required for satisfactory discrimination varies from about 3 to 7% as the detector solid angle varies from 19 to 5%. In the neighborhood of $k = 0.8$ the corresponding Δk s are 1% and 2%. The noise analysis technique studies performed well enough in deeply subcritical situations to deserve testing in an applications environment. They have a good chance of detecting changes in reactivity that are potentially dangerous. One can expect sharpest results when doing comparisons; i.e., when comparing two records, one taken in the past under circumstances known to be normal and one taken now to search for change.

W. Bergman, A. Biermann, and S. Sawyer, *New Test Methods for Ultra-Low Penetration Air (ULPA) Filters*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-92476 (1985); presented at the 16th Annual Meeting of Fine Particle Society, Miami Beach, FL, April 22-26, 1985.

Ultra-low penetration aerosol (ULPA) filters have many uses in clean-room applications. However, existing ULPA test methods are not adequate to measure the filter efficiency because the filter becomes loaded to capacity before a meaningful measurement can be made. We have developed a new test method that uses particle spectrometers and a sampling bag downstream of the filter. By capturing all of the air downstream of the filter rather than just a small sample, the bag allows for much shorter sampling times. This eliminates the filter-loading problems experienced with the previous test method.

W. Bergman and D. Chiarlo, *Fabricating Micro Air Filters Using Lithographic Techniques*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-92474 (1985); presented at the 16th Annual Meeting of Fine Particle Society, Miami Beach, FL, April 22-26, 1985.

We have developed a method for manufacturing very precise micro air filters using lithographic techniques, similar to the way in which computer chips are made. These small filters are readily used

for filtration studies and experiments. One of our new techniques uses gold fibers formed by electroplating gold on a template; our other technique uses boron diffusion to define the fibers. While these two methods show a great deal of promise, the major drawback is that the fibers themselves are not round, but rectangular (in the case of the gold fibers) or elliptical (in the case of the boron fibers).

W. Bergman and W. Kuhl, *High Temperature, High Efficiency Electric Air Filter Using a Stacked-Disk Design*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-92476 (1985); presented at the 16th Annual Meeting of Fine Particle Society, Miami Beach, FL, April 22-26, 1985.

We have developed a high temperature, high efficiency air filter by using stainless steel and alumina fibrous filter media. The filter proved to be highly efficient as a result of the applied electric field, and our stacked-disk design allowed the easy removal of particle deposits. The stacked-disk design also allows the capacity of the filter unit to be changed by adding or removing individual disks. Further research on this filter design is still needed to establish filter loading and filter cleaning characteristics.

M. D. Cable, W. R. Graves, S. M. Lane, R. A. Lerche, S. G. Prussin, M. S. Singh, D. R. Slaughter, and C. L. Wang, *Report of Time-Resolved Neutron Measurement Working Group*, Lawrence Livermore National Laboratory, Livermore, CA, informal report.

Last year the "time-resolved neutron measurement working group" was formed to study and develop ideas for fusion burn width measurements at Nova. The group held six half-day workshops and extensively discussed three possibilities: (1) neutron streak camera, (2) scintillator fiber-optics streak chamber (SFS), and (3) gated transmission-line neutron diode. A fourth possibility using U-scintillator sandwich streak camera was proposed following the workshops.

The study was continued informally for several months. These meetings led to an optimized SFS (Scintillator-Streak Camera), a simple neutron streak camera, and the suggested possibility of using semiconductor detectors.

In Section II, we describe each scheme. In Section III, each scheme is discussed and we make recommendations for future actions and directions.

Robert A. da Roza, Arthur H. Biermann, and Cynthia A. Cadena-Fix, *The New LLNL Test Facility for QNFF*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-92896 (1985); presented at the Second ISRP Conference, York, England, September 1-5, 1985.

A new facility for studying the factors affecting the protection provided by respirators has been assembled at the Lawrence Livermore National Laboratory (LLNL). A test chamber and its ancillary instrumentation incorporate several unique features. Quantitative fit factors (QNFF) can be determined by two separate methods: (1) by aerosol as a function of particle size (0.03-3 μm), and (2) by gas (dichlorodifluoromethane) for air-supplying respirators, achieving QNFFs as great as 10^6 . The challenge concentration of the gas is measured by an infrared spectrophotometer, whereas the concentration of the gas leaking into the facepiece is measured by a gas chromatograph. The results of both of these methods can be compared to the results obtained simultaneously from the standard, forward-light-scattering photometer method. The differential air pressure in the facepiece and the inhaled air flow rate is recorded as a function of time. We can test the protection capability of a respirator under heavy work or emergency conditions, using an exercise protocol that slowly brings the subject up to a work rate such that the subject's heart is beating at 80% of its maximum capacity. We will first study the effect of facial hair growth on the QNFF for self-contained breathing apparatus.

R. A. da Roza and C. A. Cadena-Fix, Lawrence Livermore National Laboratory, Livermore, CA, and C. T. Bien, U.S. Department of Labor OSHA, Washington, D.C., *How Respiratory Protection Factors are Affected by Facial Hair*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-91702 (1985); presented at the American Industrial Hygiene Conference, Las Vegas, NV, May 19-24, 1985.

The effect of facial hair growth on the protection provided by a respirator was studied. In recent years there has been a continuing conflict between the various regulatory agencies and workers who must wear respirators for proper respiratory protection, yet for any of a variety of reasons do not want to shave daily. The workers cite civil rights, religious freedom, vanity, and skin conditions as reasons. The regulators cite other regulators, but very little data. There has not been much data published. This

study provides substantially more data on which reasonable decisions can be based. The protection factors were measured quantitatively over a two-month span while the ten subjects let their facial hair grow. Curves are presented that show the change in obtained protection factor versus time for each individual. Replicate fittings were made to show the variability in protection factor with a given amount of beard growth. This variability is compared with that obtained from clean-shaven subjects. The data from all subjects are grouped and changes in protection factor are analyzed for statistical significance. The MSA Ultra-Vue full facepiece was used in this study, both in the positive pressure SCBA configuration and in the negative pressure air purifying Ultra-Twin configuration.

Robert A. da Roza and S. Catherine Weaver, *Is it Safe to Wear Contact Lenses While Using a Full-Facepiece Respirator?*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53653 (1985); presented at the Second ISRP Conference, York, England, September 1-5, 1985.

The Federal OSHA regulation that prohibits the wearing of contact lenses while using a respirator is being challenged by users. We surveyed 9100 fire fighters around the U.S. and Canada to determine if the wearing of contacts while using a self-contained breathing apparatus (SCBA) had caused any serious problems to warrant this strict regulation. Of the 1405 questionnaires returned, 403 fire fighters do wear contact lenses with SCBA, despite the regulation. Of these, only six responded that contact-lens related problems had caused them to remove the facepiece in an environment in which the facepiece would normally be worn. In contrast, the safety-related problems caused by eyeglasses in SCBA—which are legal—are proportionately higher. Over half of the supervisors returning the questionnaire admitted that some of their employees wear contacts with SCBA; however, these supervisors knew of only eight cases when contact-lens problems had caused the facepiece to be removed when it should not have been. Our investigation has indicated that these problems were not significantly hazardous. We believe that the use of contacts with a respirator should not be prohibited.

K. S. Griggs, D. S. Myers, and R. W. Buddemeier, *Environmental Monitoring at the Lawrence Livermore National Laboratory: 1984 Annual Report,*

Lawrence Livermore National Laboratory, Livermore, CA, UCRL-50027-84 (1985).

Dale E. Hankins, *Effect of Air-Scattered Beta Particles on Instrument and Dosimeter Readings,* Lawrence Livermore National Laboratory, Livermore, CA, UCRL-90534 (1984); published in *Health Physics*, 49(3), pp. 435-441, 1985.

Air-scattered beta particles are responsible for many of the inaccuracies encountered when readings are obtained with many types of beta survey instruments and personnel dosimeters.

The ratio of beta particles scattered at various angles to betas coming directly from the source increases as the distance from the source increases. This ratio, at a given distance from the source, is also a function of the beta energy, becoming larger for lower-energy beta sources. Changes in this ratio cause the response of beta instruments to have an apparent change in the directional response. These air-scattered beta particles are also responsible, in many cases, for a part of the apparent decrease in the efficiency of beta survey instruments when detecting low-energy beta sources. Air-scattered betas also cause personnel dosimeters, which are not properly designed to detect them, to have responses that are low.

Experimental results are given to confirm the above effects. Design changes to survey instruments and dosimeters are suggested that would eliminate the errors created by the failure of the instruments to detect these air-scattered beta particles.

Dale E. Hankins, *Evaluation of Hand Exposure in Shielded Glove Boxes Using Wrist Albedo Neutron Dosimeters,* Lawrence Livermore National Laboratory, Livermore, CA, UCRL-90659 (1984); presented at the Personnel Radiation Dosimetry Symposium, Knoxville, TN, October 15-18, 1984.

We studied the response of wrist albedo neutron dosimeters inside simulated glove boxes. Three boxes measuring $3 \times 3 \times 5$ ft were made with 1/2, 1-1/2, and 3-3/4 in.-thick polyethylene walls; port holes were cut into the sides and end of the box to permit the placement of arm phantoms inside the box. We placed a ^{252}Cf neutron source at four different locations in the box. The albedo dosimeters were placed on the arm phantoms, which were inserted into the port holes. Thus, we measured the exposure at various angles around the arm. We

measured the neutron dose rate using the 9-in. sphere remmeter, and determined the 9/3 in. sphere ratio and the thermal neutron dose using the same instrument. Differences exist in the readings of the dosimeters at various source locations in the glove box; distances from the source, angles around the arm, and for each of the three polyethylene glove box thicknesses. We developed a procedure for evaluating the albedo readings and estimated the agreement obtainable between the readings of the 9-in. sphere dose and the albedo dosimeter readings for a real exposure situation.

Dale E. Hankins and Steven G. Homann, *Improvements in the Etching of CR-39 for Large-Scale Personnel Neutron Dosimetry*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-90660 (1984); presented at the Personnel Radiation Dosimetry Symposium, Knoxville, TN, October 15-18, 1984.

We have made application of CR-39 as a personnel neutron dosimeter more practical by simplifying the etching procedure and by using a new etch chamber and power supply. The new etching procedure developed by Tommasino (Laboratory Dosimetria e Biofisica-ENEA-Casaccia, Rome, Italy), which uses an elevated temperature ($\sim 60^{\circ}\text{C}$), and eliminates the previously required five-hour pre-etch cycle. Electrochemical etching is performed at 60 Hz rather than at ~ 2 to 10 kHz. This greatly improves, or flattens, the neutron energy dependence of the CR-39. We developed new etch chambers capable of handling 25 or more foils simultaneously and having only one liquid electrode. To make the tracks larger and more uniform in size, we used a high-frequency power supply in the final etching step. Because the track sizes are uniform in size, the track-counting results are more reproducible when this step is used. The high-frequency electrical parameters are produced and controlled via a parallel-resonant RLC circuit in which the etch chamber represents the capacitor.

Dale E. Hankins, Steven G. Homann, and Joane M. Davis, *Personnel Neutron Dosimetry Using Hot, Low-Frequency Electrochemical Etching*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-92652 (1985); presented at the 13th International Conference on Solid-State Nuclear Track Detectors, Rome, Italy, September 23-27, 1985.

At the Lawrence Livermore National Laboratory (LLNL), we have developed a technique for the electrochemical etching of CR-39 for large-scale application as a personnel neutron dosimeter. We have designed etch chambers that can etch up to 24 foils. Several of these chambers can be used simultaneously with a single power supply. Our etching is done at 60 Hz, 3000 V for 5 hours in a 60°C oven using 6.5 N KOH. This is followed by an additional 43-minute etch at 60°C , 2.0 kHz, and 2700 V, which increases the track size and makes the tracks relatively uniform in size. A 15-minute post-etch at 60°C gives the tracks a smoother appearance.

The sensitivity of the system is 6 tracks/mrem with a background of 8 mrem, giving a lower limit of sensitivity of approximately 10 mrem for the dosimeter (when three foils are used). At 700 mrem, the Biotran reader reproducibility is about 1%, and the precision of the foil results has a standard deviation that averages about 5%. The dosimetry system is linear up to 1.5 rem and can be corrected for doses up to 10 rem. The energy dependence was recently determined using ~ 100 monoenergetic neutron energies from 10 keV to 16.4 MeV. The energy response is fairly flat from ~ 150 keV to 4.5 MeV, but drops by about a factor of three in the range 13-16 MeV. The dosimeter has been tested at a power reactor and its response is low by 20-30%.

A seven-month study indicated no fading of tracks. The dosimeter has a significant variation in directional response, dropping to about 20% at 90° . Several etching parameters were studied, including KOH normality, high voltage, frequency, etch time, blow-up time, oven temperature, and pre- and post-etching procedures. We have been using this dosimeter at LLNL as our personnel neutron dosimeter since January, 1985.

Dale E. Hankins, Steven G. Homann, and Joane M. Davis, *Personnel Neutron Dosimetry Using an Improved Technique for Electrochemical Etching of CR-39 Plastic*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-91964 (1985); presented at 1985 Health Physics Society Meeting, Chicago, IL, May 26-30, 1985.

In January 1985, the Lawrence Livermore National Laboratory changed to electrochemically etched CR-39 foils as its primary personnel neutron dosimeter. Recently developed etching chambers and a new procedure have made feasible the large-scale use of CR-39. We have developed chambers

capable of etching 24 foils at a time; several of these chambers can be used simultaneously with a single power supply. The energy response of CR-39 is relatively uniform for neutron energies from 20 keV to 15 MeV when etched in a lab oven at 60°C and using a two-stage etching procedure. We show the effect of variations in the etching parameters (high voltage, frequency, etch time, KOH normality, and temperature).

W. R. Harper and H. F. Lutz, *Criticality Safety Audits: A Manual for LLNL*, Lawrence Livermore National Laboratory, Livermore, CA, M-179 (1986).

Avoiding an accidental nuclear excursion overrides all other considerations when experiments and operations involving fissile material are conducted at the Lawrence Livermore National Laboratory (LLNL). The probability of such an accident can be reduced by strict adherence to material handling standards and procedures, and by continued training of the involved personnel.

The Criticality Safety Group of the Hazards Control Department at LLNL has the responsibility for developing and monitoring criticality safety-related procedures. Monitoring these procedures includes conducting periodic audits of operating components and facilities to ensure their conformance to standards set by the U.S. Department of Energy (DOE), the American Nuclear Society (ANS), and in-house safety directives.

This Manual provides step-by-step instructions, procedures, guidance, and references for use by the members of a criticality safety audit team.

James S. Johnson and Robert A. da Roza, *Variability of Respirator In-Facepiece Sampling Data*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-93005 (1985); presented at the International Society for Respiratory Protection Conference, York, England, September 2-6, 1985.

The detection of test-aerosol penetration through a respirator face seal may vary depending on the location of in-facepiece sampling probes. By comparing the concentration of test aerosol within the cylinders of a breathing machine to the concentration at various sampling-probe locations within the mask, a measure of penetration variability has been obtained. Recent preliminary mannequin data from W. R. Myers and J. R. Allender of NIOSH has indicated significant variability; R. A. Bentley et al. of the U.K. Health and Safety Executive, Research

and Laboratory Services Division, have also observed substantial variability. However, preliminary data from testing done at the Lawrence Livermore National Laboratory (LLNL) does not show as significant a variability as these other findings. The LLNL respirator-fit data related to sampling-probe location varied from 0-33% when compared to the breathing-machine reference concentrations. We observed no significant difference however, when the sampling probe was located in the standard nose/mouth sampling area. Results from a new mass-balance sampling technique will be used to determine the effects of probe placement on the standard respirator fit-test method. Since existing respirator-performance standards are based on this fit-test method, it is important to understand and resolve the possible variability due to probe locations.

Brian L. Koponen, Kevin J. Anderson, Tina D. McGowan, and Elsa V. Galtan, *International Directory of Nuclear Criticality Safety Personnel*, Lawrence Livermore National Laboratory, Livermore, CA, UCAR-10105-85 (1985).

This Directory lists the names, addresses and special interests of over 500 people interested in nuclear criticality safety. About 150 of these are also users of the Nuclear Criticality Information System (NCIS), an online computer information system with several extensive databases of nuclear criticality information. The Directory contains a description of NCIS, and arranges the several categories of personnel information in color-coded sections. The Directory will be updated regularly.

Harry F. Lutz, *Nuclear Criticality Safety Assessment Calculations: Part I. Calculating Power Histories in Nuclear Excursions*, Lawrence Livermore National Laboratory, Livermore, CA, M-164 (1985).

We will develop the lumped-parameter model for nuclear kinetics and exploit certain useful approximations of that model. The lumped-parameter model, which eliminates detailed properties of the system by means of some averaging process, is usually called the point-reactor model. As we will see, the equations that describe the point-reactor model depend only on the time variable. Effects produced by geometry or energy of the neutron are contained in the parameters of the point-reactor model.

The point-reactor model is satisfactory only when the chain-reacting system is close to critical. This restriction allows us to treat most cases of

practical interest. For example, we want to describe how energy is generated during an excursion. Below critical, the power of a chain-reacting system decreases; above critical, it increases. It is difficult to increase the reactivity of a chain-reacting system very much above critical because the energy deposited in the system by the fission process shuts down the excursion. Hence, we only need a dynamic model that is valid near critical. The point-reactor model, of course, cannot describe spatially dependent dynamic effects.

Our purpose in describing the point-reactor model is twofold. First, we want to give the reader an understanding of the phenomena involved in an accidental nuclear excursion. How much energy is likely to be produced during an accident? What is the behavior in time of the energy released? What properties of the system determine the shutdown mechanisms of the nuclear excursion? Second, we want to give the criticality safety specialist some computational tools for estimating the behavior of an accidental nuclear excursion when the parameters describing the chain-reacting system are not precisely known.

The rate at which energy is produced in a chain-reacting system is proportional to the number of neutrons present in the system. Hence, we need to know how the neutron population changes. Neutrons can be added to the system in several ways. First, an external source not related to the fission process can add neutrons. Second, a neutron-induced fission can emit a number of neutrons between 0 and 5 promptly, that is, in about 10^{-14} s. Third, delayed neutrons are a result of the radioactive decay of some fission fragments produced during fission. Customarily, we fit delayed neutron data by considering six groups of precursors with mean lifetimes from a few tenths of a second to about 80 s. A level and rate diagram for neutrons and precursor atoms in a chain-reacting system illustrates the relationships among the various production and destruction mechanisms for neutrons and delayed neutron precursors.

The neutron population is decreased by absorption, which either leads to fission or capture without fission, or by the leakage of neutrons from the system. The time that a neutron survives between birth as a prompt or delayed neutron and death from capture or leakage varies between 10^{-3} and 10^{-8} s.

Because the neutron population and the precursor population have such different characteristic times, the chain-reacting system is an example of a

stiff system. Such systems present a challenge to those who attempt to create an accurate numerical solution because the time steps called for by one population are so much smaller than those called for by the other population. On the other hand, we can exploit the stiffness of these systems to develop useful approximations, if we recognize their ranges of validity.

James L. Morse, Rice T. Trolan, and James J. Bloedorn, *Risk Assessment with a Personal Computer*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20440 (1985); presented at the 7th International System Safety Conference, San Jose, CA, July 25-29, 1985

Each year, the Lawrence Livermore National Laboratory (LLNL) reviews all facility and utility upgrade projects to determine their relative ranking in terms of safety benefit vs cost. The process begins when a team of health and safety professionals screens these proposed projects. Using a variation of William Fine's Naval Ordnance Laboratory (NOL) risk scoring system, a microcomputer is used to record, display, and print risk data about each competing project. This information, including a cost-benefit graph, assists line management to reach decisions concerning the relative merit of each project. The spreadsheet formatting to perform the risk scoring and cost-benefit analysis is included with this paper.

Rafael Munoz-Candelario, University of Puerto Rico at Mayaguez, Puerto Rico, and **Norman J. Alvares**, Lawrence Livermore National Laboratory, Livermore, CA. "Definition of the Concentration Gradient Above Flammable Liquids," published in *Special Technical Testing Publication 882* (American Society for Testing and Materials (ASTM), Philadelphia, 1985).

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 in. for most U.S. 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 volatile, high-vapor-density liquids.

Austin A. O'Dell, *A New Criticality Alarm at LLNL*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-91982 (1985); presented at the Health Physics Society meeting, Chicago, IL, May 26-31, 1985.

An extended function criticality alarm system (CAS) has been developed at the Lawrence Livermore National Laboratory (LLNL). Primary emphasis was placed on compliance with established ANS/ANSI and USDOE standards which were implemented by integration of high-reliability hardware, uninterruptible power sources, regular system maintenance and calibration, rigorous evacuation training and drills, and carefully developed accident-response planning. Data acquisition and processing is performed by a commercial microprocessor-based monitoring system which provides both continuous supervision of system status and distributed processing to preserve priority functions of the CAS. Of course, the primary task of any CAS is to promptly activate an evacuation alarm in the event of a nuclear criticality accident. In addition, however, the new LLNL system also provides capabilities for monitoring normal operational radiation levels, for monitoring anomalously high or variable levels, for monitoring the extremely high levels which follow a criticality accident, and for facilitating a remote assessment of reentry into an accident area. The system also provides buffer-memory from which accumulated radiation-level data can be transferred to an off-line computer system for archival storage, additional processing, and/or graphics display. Several types of "conventional" gamma-ray and/or neutron detectors can be interfaced with the system after minor modification. In a related LLNL research project, a new CAS neutron detector is under development which will provide a well-verified response to simulated criticality accidents and will directly interface with the new LLNL CAS.

Gerald T. Schweickert, *Berylliosis—A Disease of the Past?* Lawrence Livermore National Laboratory, Livermore, CA, UCRL-90661 (1985).

The natural history of berylliosis remains a toxicological puzzle despite 40 years of investigation. In this paper, I review current theories on the mechanisms of the disease, most of which are based on hypersensitivity of an individual's immune system to Be. I examine over-response as a critical factor using the updated Be case registry, carcinogenicity evidence, and experimental animal data. Comments are presented on the efficacy of industrial hygiene controls, implemented during the 1940's, that have reduced the incidence of beryllium-related disease in the U.S. to nearly zero.

Gerald Schweickert and Constance De Grange, *Identifying and Managing Indoor Air Pollution at LLNL: A Status Report 1980-1984*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20286 (1984).

We discuss indoor air pollution from the perspective of LLNL's experience between 1980 and 1984. Background information is presented covering the nature of reported complaints, possible causes, and suggested methods of improvement. Tobacco smoke, long-curing glues, adhesives, and polymers (as in particle board and furniture) are the most likely sources of pollutants. Nearly all instances have been relieved by increasing the percentage of outside air in building ventilation systems. We present an approach to prevent future episodes that involves engineering design and usage inventory. Reviews by engineers, designers, future occupants, and industrial hygienists are recommended. Existing problems have been tedious to resolve; a prompt, direct method of control, i.e., increased ventilation, may be just as successful as a prolonged investigation involving comprehensive air-sampling in search of pollution sources.

M. S. Singh, "10-MJ Laser Target Chamber Operations," in *Laser Program Annual Report*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-50021-84 (1985).

The next step beyond Nova will be to produce high gain in a fusion fuel pellet. We estimate that 1 to 10 MJ of driver energy will be required to produce the requisite high gain. Such a facility, if upscaled from

Nova, could be very expensive. Our efforts, then, are to minimize costs of each component.

We present three options for a low-cost target chamber. Each option is based on a target with high gain (~ 100), which would yield a total energy of 1 GJ. Environmental effects can be substantial when fusion yields of this magnitude are involved, and many options (including some presented here) may be rejected for this reason.

Peter M. Swarengen and S. Catherine Weaver, *The Effect of Solvent Vapor Mixtures on Respirator Cartridge Service Life*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-91757 (1984); presented at the 1985 American Industrial Hygiene Conference, Las Vegas, NV, May 19-24, 1985.

We studied the effect of two organic vapors on respirator cartridge adsorption characteristics. Two compounds found in paints used at LLNL, isopropyl alcohol (IPA) and methyl ethyl ketone (MEK), were added to a flowing airstream (40 SLPM) that passed through a pair of MSA NIOSH-certified organic vapor respirator cartridges. The compounds were injected into the air stream singly at a concentration close to 10x the respective TLV value, and together as a mixture, at a concentration nearly equal to the sum of the two single concentrations (i.e., 10x TLV). In addition, each compound was injected alone at a high concentration equal to the total mixture challenge concentration (i.e., the sum of both compounds, each at 10x the TLV, respectively). All experiments were repeated at two different humidity values, 20 and 85% RH. 1 and 10% breakthrough times were observed in each case and the breakthrough times of the mixture challenge agreed closely with those of the high concentration challenge. The results were also analyzed by modified Wheeler-Robell kinetic techniques. Close correlations were observed between adsorption rate constant values for the mixture case and adsorption rate constants measured for the individual components. Parameters from the kinetic analysis are reported for each compound tested at the different experimental conditions.

C. L. Wang, R. Kalibjian, M. S. Singh, J. D. Wiedwald, D. E. Campbell, E. M. Campbell, M. D. Cable, W. R. Graves, S. M. Lane, R. A. Lerche, R. H. Price, and D. G. Stearns, Lawrence Livermore National Laboratory, **G. A. Mourou,** University of Rochester, and **S. G. Prusslin,** University of California, *Approaches to Ultrafast Neutron De-*

tectors, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-91317 (1984); presented at the 5th Topical Conference on High Temperature Plasma Diagnostics, Tahoe City, CA, September 16-20, 1984.

We discuss two approaches to obtain neutron detectors of very high temporal resolution. In the first approach, a uranium-coated cathode is used in a streak tube configuration. Secondary electrons accompanying the fission fragments from a neutron-uranium reaction are accelerated, focused and energy analyzed through a pinhole and streaked. Calculations show that a 20-ps time-resolution can be obtained. In the second approach, a uranium-coated cathode is integrated into a transmission line. State-of-the-art technology indicates that time resolution of 20 ps can be obtained by gating the cathode with a fast electric pulse.

Ross L. Wilson, *The Psychological Aspects of Personnel Contamination*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-92501 (1985); presented at the Hazardous Materials Management Conference and Exposition, Oakland, CA, April 23-25, 1985.

Accidents involving exposure to radioactive or other toxic materials may involve an unusual degree of emotional trauma, particularly when members of the general public are involved. Methods that have been employed in dealing with such trauma in relation to occupational accidents in which personnel were contaminated with radioactive materials are discussed. Techniques for extending these methods to members of the general public are also discussed.

Kenneth C. Young, "Transuranic Waste—Long-Term Planning," Lawrence Livermore National Laboratory, Livermore, CA, presented at the 7th International System Safety Conference, San Jose, CA, July 25-29, 1985.

Societal concerns for the safe handling and disposal of toxic waste are behind many of the regulations and control measures in effect today. Transuranic waste, a specific category of toxic (radioactive) waste, serves as a good example of how regulations and controls impact changes in waste processing—and vice versa. As problems would arise with waste processing, changes would be instituted. These changes improved techniques for handling and disposal of transuranic waste, reduced

the risk of breached containment, and were usually linked with regulatory changes. Today, however, we face a greater public awareness of and concern for toxic waste control; thus, we must anticipate *potential* problems and work on resolving them before they can become *real* problems.

System safety analyses are valuable aids in long-term planning for operations involving trans-

uranic as well as other toxic materials. Examples of specific system safety analytical methods demonstrate how problems can be anticipated and resolution initiated in a timely manner having minimal impact upon allocation of resource and operational goals.