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Emergency Protection from Aerosols

G. A. Cristy
C. V. Chester

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EMERGENCY PROTECTION FROM AEROSOLS

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Solar and Special Studies Section
Energy Division

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EMERGENCY PROTECTION FROM AEROSOLS

G. A. Cristy
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ABSTRACT

Expedient methods were developed that could be used by an average person, using only materials readily available, to protect himself and his family from injury by toxic (e.g., radioactive) aerosols. The most effective means of protection was the use of a household vacuum cleaner to maintain a small positive pressure on a closed house during passage of the aerosol cloud. Protection factors of 800 and above were achieved.

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1. INTRODUCTION

1.1 Purpose

A long-range program to develop the emergency response capabilities of nuclear power plant operators and those of the surrounding civil authorities has been sponsored by the U.S. Department of Energy (DOE) and its predecessors through the Division of Biomedical and Environmental Research. The objective of the program is to develop and test expedient methods of protecting persons and buildings from the airborne radioactive aerosols likely to be produced during the hypothetical meltdown of a water-cooled nuclear reactor. A meltdown with an accompanying breach in reactor containment caused by sabotage or terrorist action is presumed. The measures considered are limited to those that could be performed in emergencies by individuals using materials and/or equipment that are already in existence or that could be made available by prior planning.

1.2 Historical Perspective

In 1972, the Clinch Valley Study[1] reviewed the status of existing regulations and the plans for emergency response capabilities at

nuclear plants in the event of accidental releases of radioactive materials. Recommendations for improvements in regulations and response capabilities contained in the study included the following:

1. establish regional Emergency Operations Control Centers to assist in handling crises,

2. establish emergency plans for monitoring and predicting the movements of radioactive clouds during (unlikely) accidental releases,

3. plan warning systems to allow for the timely evacuation of populations at risk from accidental releases of radioactivity,

4. develop expedient means of protecting individuals who must remain in areas at risk during the passage of radioactive clouds, and

5. distribute nonradioactive potassium iodate pills before emergencies for use by the population in preventing or reducing the uptake of radioactive iodine from radioactive clouds.

Previous studies of the problem of protecting water-cooled nuclear reactors from actions by saboteurs or from coordinated terrorist attacks have shown[2,3] that it is possible, although extremely difficult, for a highly coordinated, well-disciplined group of terrorists--aided by a cooperating nuclear power plant employee (or ex-employee)--to cause a meltdown of the power plant reactor and a consequent release of radioactivity from the containment vessel. The Three Mile Island (TMI) experience has, however, raised doubts that it is really possible for a saboteur to facilitate a meltdown in the available time even with a quasi-military operation. Studies of the TMI accident also suggest that the amount of radiation that could be released is far less (by a factor of about 10^3 to 10^5)[4] than that assumed in previous studies.[2,3] The consequences of a hypothetical release have been studied[5] using historical meteorological data to establish the range of possible dispersal sequences. The radioactive material that would be released would be in the form of radioactive gases of krypton, xenon, and iodine, and in the form of a mixture of very finely divided oxides of various fission products. The gases would tend to disperse rapidly and to be diluted.

The particulate material would be about 1 to 3 μ in diameter and would be deposited slowly as the radioactive cloud moved downwind. In all the scenarios examined, lethal inhaled doses could be prevented by evacuating the people downwind of the release; the people could be evacuated on foot by moving in a crosswind direction at a rate of 3.2 km/h. Such a plan requires an effective system for informing the public in the vicinity of the reactor of the imminent danger and of the best evacuation routes based on existing and predicted wind conditions.

It is clear from the previous studies that the major threat to the population at risk is the inhaled dose. The prophylactic iodine countermeasures suggested by the Clinch Valley Study would make a major contribution to the protection of the population during a reactor meltdown. However, in addition to the crosswind evacuation and the prophylactic iodine treatment, other expedient countermeasures would be needed if some of the people downwind of a damaged reactor could not be evacuated immediately (e.g., handicapped persons, patients in hospitals or nursing homes).

The major problem is providing protection against inhalation and ingestion of toxic particles. The obvious solution is to breathe filtered air. In industrial practice, dust-filter respirators or gas masks are normally used. For the general public, this equipment usually is not available.

Experiments[6] carried out at Fort Detrick in 1958 provide some valuable information on improvised masks. Either a bath towel (folded to provide two layers) or a man's handkerchief (folded to provide eight layers) can be held over the nose and mouth to reduce aerosol inhalation by 85 to 90% (a PF* of 7 to 10). Both these devices produce a pressure drop, which could be tolerated by an adult. Wetting of the filter medium increases the pressure drop without significant improvement in filtration efficiency. To keep the hands free, the filter could be tied directly over the mouth. Inhaling through the mouth and exhaling through the

---

*PF = protection factor, which is defined as the ratio of the dose that a person would receive without the protective device to the dose he would receive with the device.

nose minimize the dead-air volume and the amount of salivation on the filter. These methods are cumbersome at their best; at their worst, with children, they might not suffice. Therefore, other methods of reducing inhalation and ingestion are needed.

To develop and test methods of protecting people and the living spaces within buildings from radioactive particles, it was decided to experiment with aerosols of Bacillus globegii (BG) spores, thereby avoiding the experimental difficulties of working with radioisotopes. As stated previously, the radioactive particles are expected to range from 1 to 3 μ in size. The average diameter of monodispersed BG spores is about 2 μ. Therefore, the diffusion properties of BG spores should be quite similar to those of the radioactive particles they simulate. Bacillius globegii are nonpathogenic organisms that grow readily in nutrient agar and form very hardy spores that can be handled quite safely.

Personnel of the Oak Ridge National Laboratory's (ORNL) Biology Division prepared concentrated spores ("mud") by growing the BG from a strain of BG spores obtained from Edgewood Arsenal. The mud was analyzed by growing colonies from serial dilutions and was found to contain about 2×10^{11} spores/g. (Note that the methods developed for protection against radioactive aerosols should be equally effective against attacks by terrorists using biological organisms.)

2. EXPERIMENTAL EQUIPMENT AND TECHNIQUES

2.1 Development of Aerosol Generators

2.1.1 Modified Lauterbach generator

A modified Lauterbach generator that could produce large quantities of aerosols containing viable BG spores was developed. The generator produced aerosols at the rate of from 10^9 to 10^{10} spores/min from a suspension of the mud in denatured alcohol. Water slurries were tried, but they gave less consistent results than the alcohol slurry because of the clumping of the spores in water. The aerosol from the alcohol slurry consists of predominantly monodispersed spores. The airborne particles have an average diameter of about 2 μ and show a deposition velocity of about 3×10^{-4} m/s.

The aerosol generator is shown in Fig. 1. The 3-ℓ, 3-neck flask holds the suspension of BG spores in alcohol maintained at a constant level by a supply line that enters at the bottom and an overflow line on the side. The 1-ℓ flask is used as a supply reservoir to which the overflow is pumped by means of an air lift. The two 1.27-cm-OD (0.5-in.-OD) stainless steel tubes each have eight 0.343-mm (0.0135-in.) No. 80 drill holes equally spaced around their circumferences. The aerosol is generated by the action of compressed air at 2×10^5 Pa (30 psig) being discharged through the 16 holes across the surface of the liquid.

2.1.2 New nozzle

The generation rate achieved by the Lauterbach generator was adequate for most of our tests, but it was not high enough to simulate some of the conditions desired. Therefore, a new nozzle was designed, built, and tested. Generation rates as high as 1.3×10^{13} monodispersed spores/min were obtained.

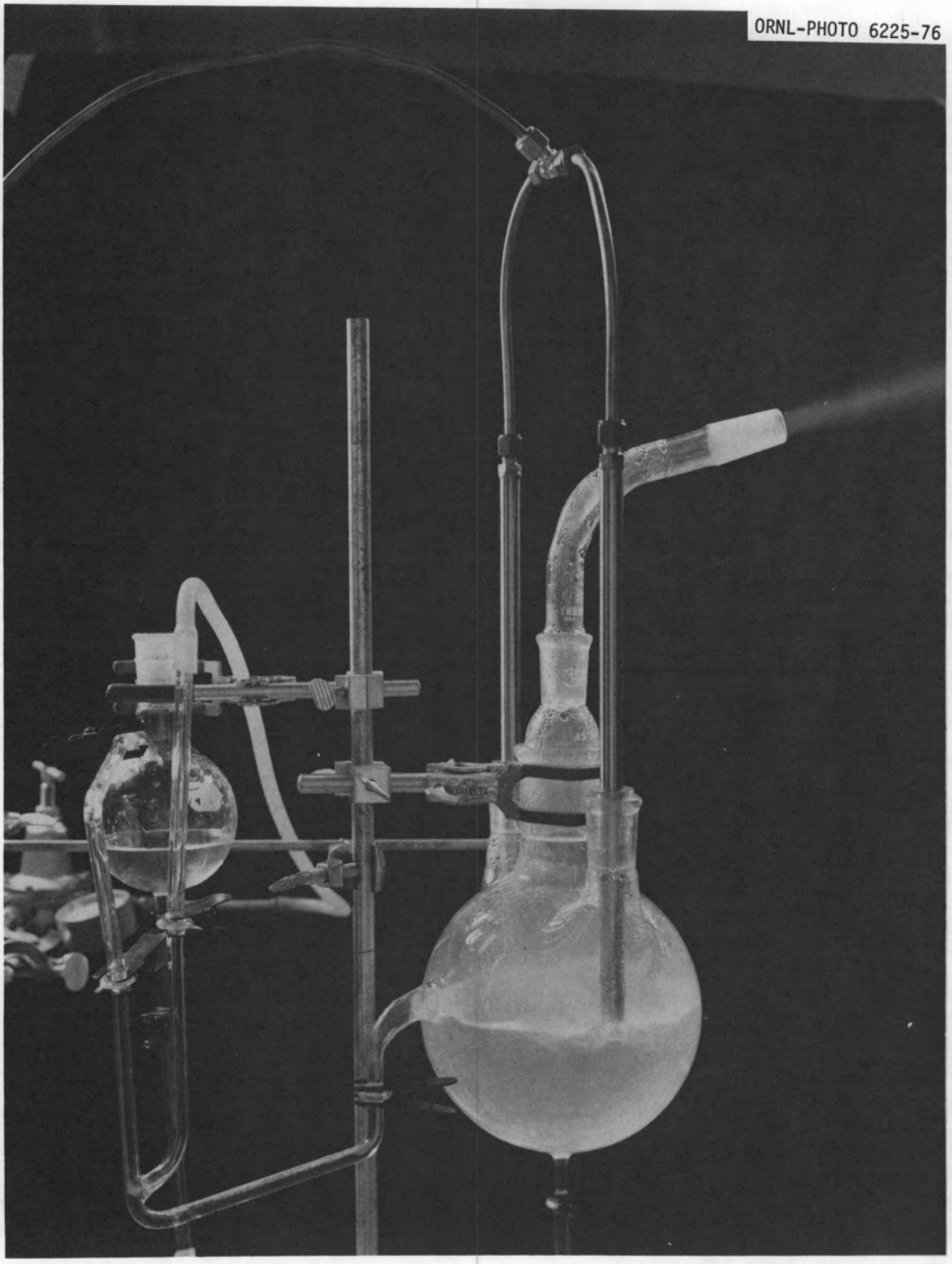

Fig. 1. Modified Lautenbach generator

2.2 Aerosol Collection Techniques

2.2.1 Aerosol enclosures

Two types of enclosures were designed and constructed for use in preliminary experiments to hold the generated aerosols long enough to establish rates of generation, average particle size, and deposition velocities.

Two units of the first type, called expandable glove boxes, are shown in Fig. 2. Each box holds 0.028 m^3 (1 ft^3) of air in its collapsed position and can be expanded to hold 0.056 m^3 (2 ft^3) when air is blown into it. Each box has a rubber glove installed in each of two of its nonexpanding sides.

The second type, shown in Fig. 3, is a single plastic enclosure 6 m wide, 12 m long, and 3 m high (20 x 40 x 10 ft). It is inflated by an air blower.

2.2.2 Aerosol sampling techniques

Several sampling techniques were tested and evaluated. The major method used all-glass impingers of the type manufactured by Ace Glass, Inc., Vineland, New Jersey (see Fig. 4). The aerosol particles from a measured volume of air (actually a known constant flow rate and a measured time) were collected by drawing the air through two all-glass impingers in series. The first impinger contained water, but the second was kept dry to serve as a water tap to protect the vacuum pump from spillover. This arrangement gave reproducible results. Tests showed that the loss of spores from this type of sampler was about 3%.* When extremely accurate recovery was desired, two sets of impingers (of two each) were used in series. This arrangement gave a leakage rate of less than 1 in 1000. BG spores can remain viable and will not become inactive when kept for several days in the demineralized water in which they are collected.

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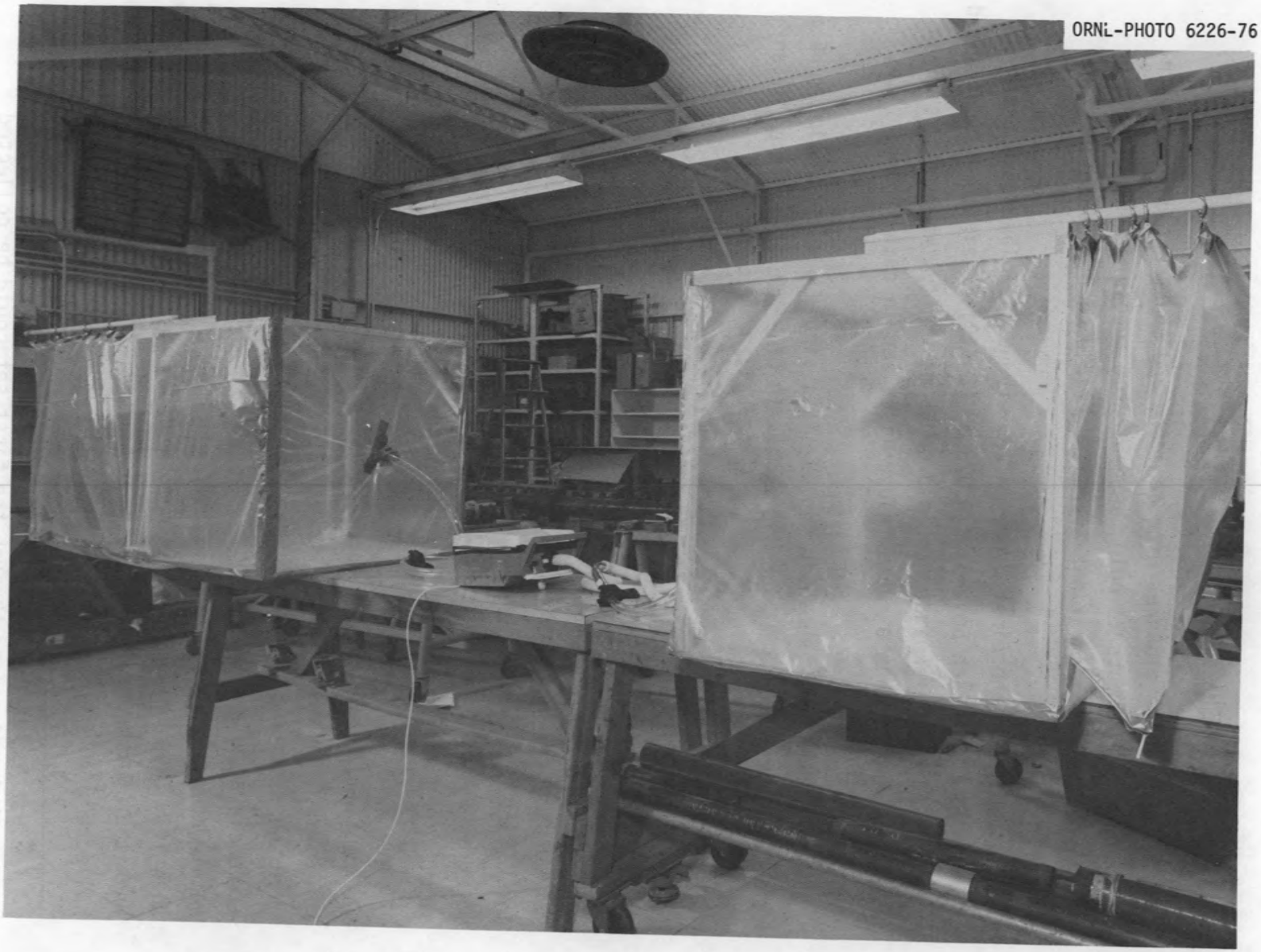
*That is, by adding another set of impingers in series, additional spores that had passed through the first set could be collected.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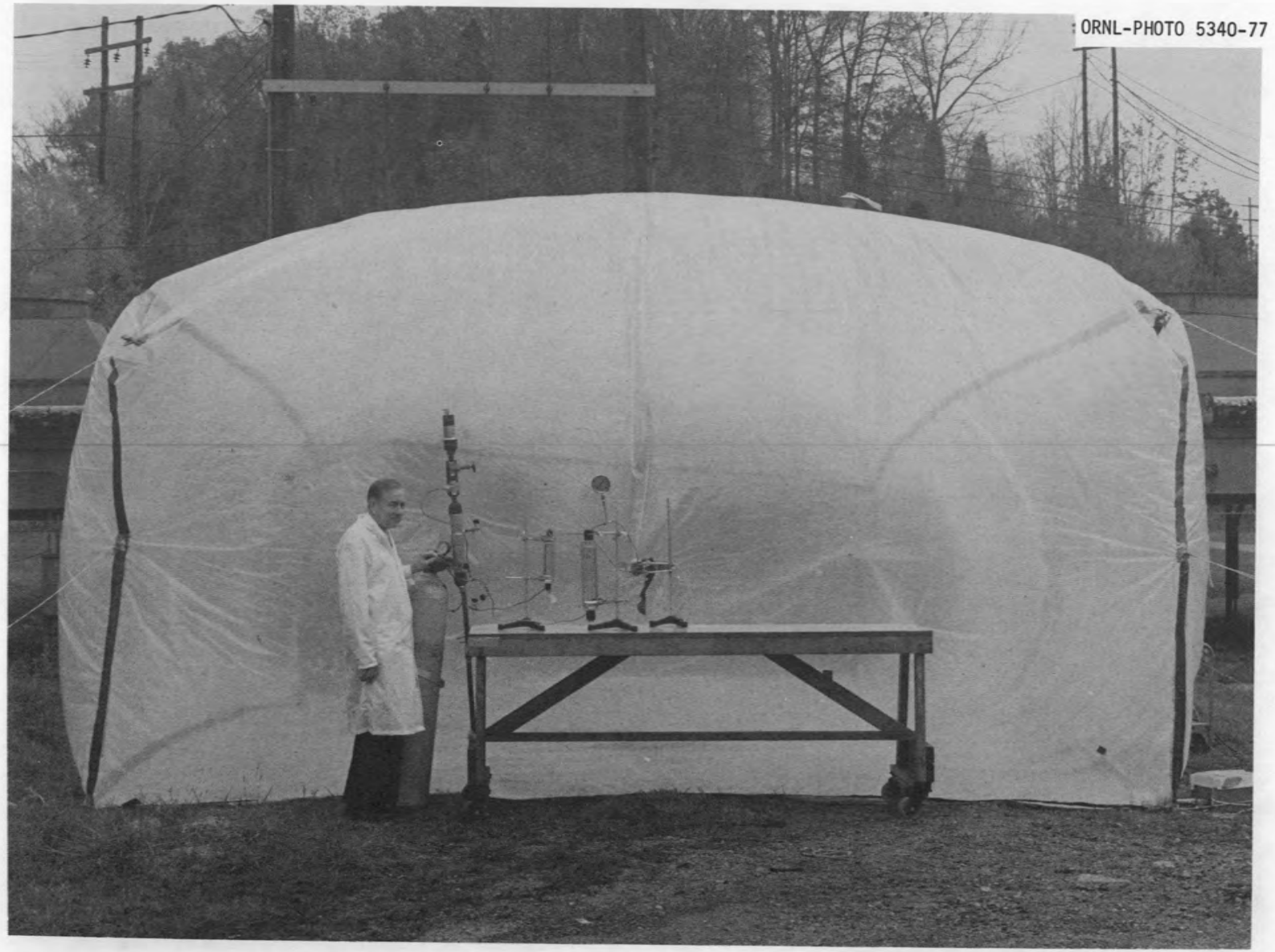

Fig. 3. Large plastic enclosure (inflated)

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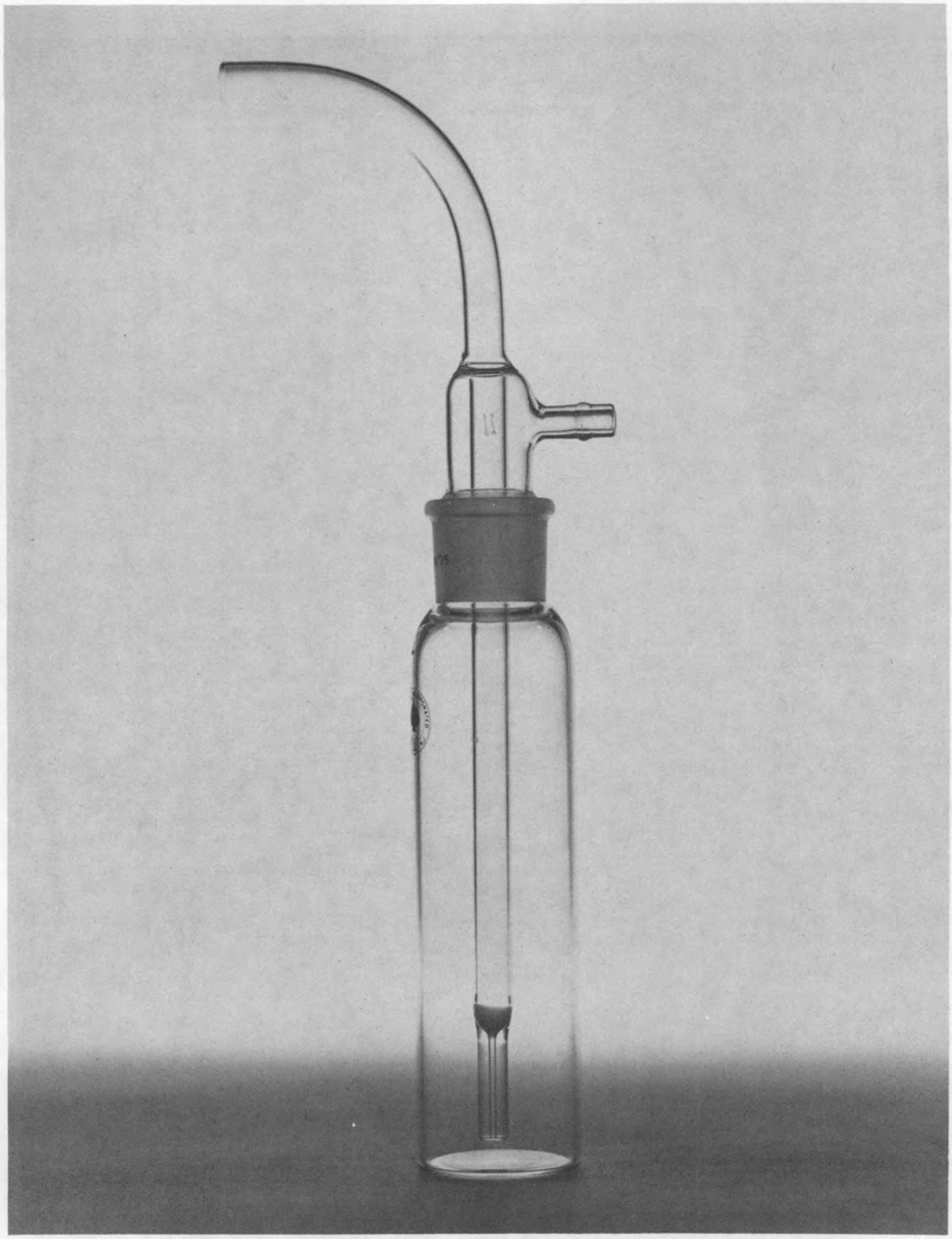

Another sampling method used filter paper. A known amount of air was drawn through a sampling device that held a special type of filter paper. The filter paper was chosen on the basis of two criteria--a pore size small enough to trap 1-μ particles and the ability to disintegrate readily when shaken up in a bottle of water. The filter papers were then transferred (using sterile tweezers) to an "8-oz" bottle containing 100 ml of water. Vigorous shaking of the bottle broke up the paper and resulted in the suspension of the BG spores. Aliquot samples of the water suspensions (or serial dilutions of the suspensions) were cultured on nutrient agar surfaces to determine the number of spores collected.

A third sampling method used slit samplers of the type manufactured by Reyonier and Sons, 3806 N. Ashland Avenue, Chicago, Illinois. Slit samplers have a clock mechanism that slowly rotates an agar plate under a slit in the lid. A vacuum pump draws air through the slit at a constant rate (measured at 9.4 ℓ/min). Any spores in the air are trapped and retained on the agar. The agar plates were incubated for 12 h to develop the colonies for counting. Because this method was more difficult to assess than the impinger method, it was used only for spot checking the impinger results.

A fourth sampling method, used only on the first two outdoor tests, was the Partichrome analyzer being developed by Chemical Systems Laboratory (CSL). Because the development was not complete at the time of our tests, the analyzer was operated by CSL personnel. The Partichrome analyzer gave results generally comparable to those of the other sampling methods. However, it was somewhat difficult to use because it detected other airborne organic materials in the particle size range of 0.5 to 10 μ. In the outdoor tests the background of other organic materials was often of the same order of magnitude as that of the BG samples. The Partichrome analyzer does have one tremendous advantage over the other methods; however, the results are available within minutes rather than within a day or two.*

---

*At the time these tests were run, the Partichrome analyzer was classified. Therefore, the method of analysis cannot be given here.

2.3 Infiltration Rate for Closed Houses

The rate of infiltration of air into closed houses was estimated by two different methods: (1) CO_2 diffusion and (2) equilibrium pressure.

2.3.1 Carbon dioxide diffusion method

A weighed amount of CO_2 was released into the closed space, and the air in the space was analyzed continuously using a Wilks Miran-101 portable CO_2 analyzer. The infiltration rate was calculated by the equation

$$R = \frac{1}{T} \ln C_T/C_i \quad , \tag{1}$$

where

R = rate of change of air (changes/h),
T = time from start (h),
C_i = CO_2 concentration at start (m^3 CO_2/m^3 air),
C_T = CO_2 concentration at time T.

Note that this infiltration rate depends on the t velocity during the test and on the difference in inside and outside temperatures. Under most of the test conditions, the wind velocity and temperature differences remained fairly constant.

2.3.2 Equilibrium pressure method

The large house (final test) was not tight enough to use the CO_2 diffusion method for the entire structure. The method used consisted of blowing air into the closed house until a pressure equilibrium was reached. The air flow and the house pressure at equilibrium were measured. From these measurements the rate of change was calculated.

$$R = \nu/V \quad , \tag{2}$$

where

ν = V rate of air blowing into the house (m^3/h),
V = volume of the house (m^3).

From the equilibrium pressure, an equivalent wind velocity was calculated by using the stagnation pressure generated on the side of a building by the wind.

3. RESULTS

3.1 Laboratory Evaluations

3.1.1 Establishing average particle size

To ensure that the particle size of the aerosol approximated was that of the radioactive particles it simulated, the average size of the aerosol particles was estimated by two different methods. The first method measured the optical size of the particles. Spores were allowed to settle out on microscope slides on the bottom of the plastic box. After 1 d of settling time, the slides were examined under a microscope equipped with a measured grating. The average size of the particles was estimated to be 1.75 μ.

The other method was based on a modified Stokes law calculation, developed at Fort Detrick,[7] which measures the aerodynamic size of the particles. The method requires measuring the rate of decrease of the aerosol concentration in an enclosed space. The mathematical development is shown in Appendix A. By using the modified Lauterbach generator and the 1-m^3 glove boxes, the diameter was established at ∿2 μ (Table 1). By using the pressure nozzle and the large polyethylene bag ("tent"), the average diameter was calculated to be 2.2 μ.

3.1.2 Calculation of deposition velocity

The deposition velocity was calculated from the rate of settling of spores in a plastic glove box. Petri dishes containing nutrient agar were placed uncovered in the bottom of the glove box. Aerosol containing BG spores was discharged into the box for 1 min. The covers were placed on the petri dishes at the rate of one each minute for the first 15 min, then one every 15 min for 2 h; All dishes were incubated overnight. The data for the first 15 min from one such experiment are plotted in Fig. 5. The straight line shown on Fig. 5 was obtained from a fit of the best straight line drawn through the data points as determined by the least-squares method.

Table 1. Calculation of average particle diameter[a]

T (h)	Observed data C (spores/ml)	Observed data c_0/c_t	Calculations c_0/c_t	Calculations D (μ)
0	6700			
1	4000	1.68	0.519	1.99
2	2250	2.98	1.092	2.04
5	420	15.95	2.769	2.06

[a]Constants in Eq. (A.6), Appendix A, are:

$\frac{V}{A}$ = 100 cm,

n = 0.018 centipoise = 1.8×10^{-4} g/s·cm,

g = 980.7 cm/s^2,

p' = 1.29×10^{-3} g/cm^2 (negligible),

p = 1.2 g/cm^2.

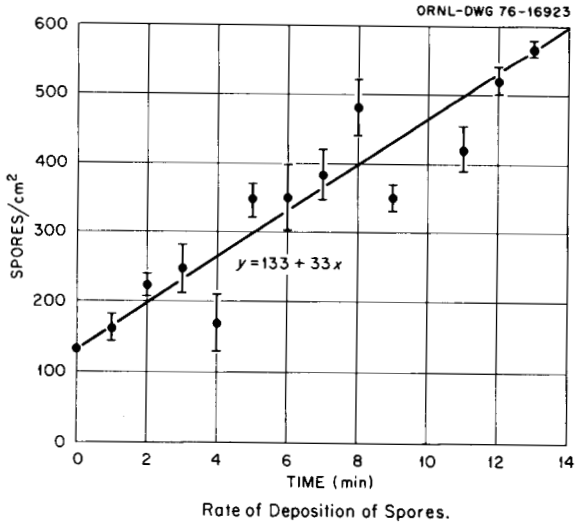

Fig. 5. Rate of deposition of spores

The deposition velocity is calculated as follows:

$$V = R/c,$$

where

V = deposition velocity in cm/s,

R = rate of deposition in spores/cm^2·s,

c = initial concentration in spores/cm^3 (in this experiment c was 23 spores/cm^3).

The slope of the graph in Fig. 5 is 33 spores/cm·min. Therefore,

$$R = 33/60 = 0.55 \text{ spores/cm}^2\cdot\text{s},$$

$$V = 0.55/23 = 0.0239 \text{ cm/s} = 2.4 \times 10^{-4} \text{ m/s}.$$

3.1.3 Viability of spores

Tests made to determine the viability of the spores showed that keeping the spores in water or alcohol suspensions for as long as a week caused no detectable loss of concentration of viable spores. The procedures used during the aerosol tests never required holding the spores in either liquid for more than 3 or 4 d.

3.1.4 Protection factors using vacuum cleaner

Experiments were performed to evaluate the feasibility of using an ordinary home vacuum cleaner as a filter for removing aerosol particles from the air, thereby serving as the basis of the system to protect living spaces from the intrusion of radioactive particles. Specifically, an occupied house could be closed before a radioactive cloud arrived. The home vacuum cleaner could be adapted to filter outside air and discharge it into the house to maintain a very small positive pressure that would reduce the infiltration of radioactive particles. Duplicate tests were performed using the five following experimental setups:

1. one clean bag in the vacuum cleaner,

2. a double bag in the vacuum cleaner (one clean bag was opened at the bottom, and another clean bag was placed inside; the first bag was resealed with duct tape),

3. flour in a clean bag (the first test used 5 lb of flour, and the second test used only 1 cup,

4. clean bag in the sweeper cannister with another clean bag on the exhaust, and

5. dirty bag in the sweeper (bags were loaded with a normal three-month accumulation for an ordinary household).

Tests were performed by generating aerosol for 10 min a closed, collapsible plastic box containing 2 m^3 of air (see the box on the left in Fig. 2). The sweeper was then used to transfer and filter 1 m^3 of the contaminated air into a second cloud-expandable plastic box that already contained 1 m^3 of essentially clean air. By analyzing the concentration of spores in both boxes before and after the transfer, the PF was calculated as follows:

$$PF = \frac{\text{number of spores removed from box 1}}{\text{increase in spores in box 2}} \quad . \tag{3}$$

The PF is defined as

$$PF = \frac{\text{concentration in air before filtration}}{\text{concentration in air after filtration}}$$

or

$$PF = \frac{V_{11}C_{11} - V_{12}C_{12}}{V_{22}C_{22} - V_{21}C_{21}} \quad ,$$

where

C_{11} = concentration of spores in box 1 before transfer,
C_{12} = concentration of spores in box 1 after transfer (normally equal to C_{11}),
C_{21} = concentration of spores in box 2 before transfer,
C_{22} = concentration of spores in box 2 after transfer,
V_{11} = volume of air in box 1 before transfer,
V_{12} = volume of air in box 1 after transfer,
V_{21} = volume of air in box 2 before transfer,
V_{22} = volume of air in box 2 after transfer.

Although the two sets of duplicate tests were performed under conditions as nearly the same as possible, the second experiment generally gave

higher PFs than did the first experiments; results are given in Table 2. The most significant finding of these tests is the fact that the best filtration can be obtained by using a sweeper bag that has a normal collection of household dirt in it.

Table 2. Protection factor limits (by error analysis)

Filtering method	Protection Factor	
	First experiment	Second experiment
1. One clean bag	40-100	78-176
2. Double clean bag	65-146	333-750
3. Flour in one clean bag	187-420	427-600
4. Clean bag in sweeper & clean bag	67-150	190-421
5. Dirty bag in sweeper	933-2100	1133-2550

3.2 Preliminary Field Test

As a check on experimental techniques and to compare actual results with expected values, a preliminary field test was run. The generator was set up and operated for 10 min discharging into a 1-m^3, closed plastic box. Samples were taken to determine the rate of generation of the aerosol. The generator was then operated for 30 min discharging into the air at a height of 1 m above ground. Open petri dishes were placed downwind of the generator at intervals of 3 m. One dish was placed as close to the direction the wind was blowing as possible and one dish was placed on either side at a distance of 1 m. An impinger sample was taken continuously at a point 15 m downwind and at a height of 1 m above ground. Wind velocity was measured every 5 min with a Hastings air meter. Velocity varied from 1 to 2.5 m/s (2.2 to 5.6 mph); there was some gusting of up to 5 m/s (11 mph). Average wind velocity was estimated to be 2.0 m/s (4.4 mph).

Expected fallout and expected concentration (15 m downwind of a point source) were calculated by using published correlations.[7]

Comparisons between calculated and observed values are given in Table 3. The observed and calculated concentrations in the air were reasonably close, but the observed fallout (on the plates) was at least a factor of 10 lower than that calculated.

Table 3. Comparison of calculated and experimental values of fallout and downwind concentration

Distance from generator (m)	Fallout (spores/cm^2)		Average concentration (spores/ℓ)	
	Calculated	Observed	Calculated	Observed
3	83.7	6.9		
6	58.2	3.6		
9	36.8	2.9		
12	24.8	3.2		
15			172	123

Fallout was based on a deposition velocity of 3×10^{-4} m/s. The fact that the observed values were so low suggests that either the deposition velocity may be about 3×10^{-5} m/s or that the correlation does not work well near the ground over such short distances. The latter is the more likely explanation.

3.3 Field Tests on Closed Houses

Two series of experiments were performed. Each series had somewhat different objectives. The modified Lauterbach generator was used in the first series of tests, and the high pressure nozzle was used for the other series. An attempt was made to determine whether a closed house would serve as a filter for the aerosol particles. See Appendix B for mathematical calculations in support of this effort.

3.3.1 First series of tests

Five separate experiments were conducted on three houses. One house was tested for leakage rate only. In each of the other cases, the aerosol generator was set up and operated for several hours on the windward side of the house being tested. At the beginning of the test, CO_2 from a fire extinguisher was released into the closed house. A Wilks Miran-101 portable specific vapor analyzer was used to record the concentration of CO_2 during the experiment. A set of impingers was used to collect a continuous sample of air just outside the house. Various methods of analysis were used to measure the buildup of spore concentrations inside the house. A sensitive anemometer and a recording wind-direction instrument were erected on a 2-m pole outside the building. The data from the five tests are summarized in Table 4.

Table 4. Tests on closed houses (first series)

	Tool shed		Private home	Trailer home	
	Test 1	Test 2	Test 3	Test 4	Test 5
Leakage rate (R), changes/h	0.20	0.25	0.130	0.163	0.44
Average wind velocity, m/s	2.1	1.3	1.3	0.7	1.5
Average concentration outside building (from impinger sample), spores/ℓ	150	165		514	540
Calculated concentration outside building, spores/ℓ				376	560
Duration of experiment, min	150	120	250	180	180
Concentration inside house at end of experiment, spores/ℓ	105			111	470
P_F (calc)	0.56			1.8	1.84

During test 4, samples taken inside the building to determine the rate of buildup of BG were 30-min samples. Figure 6 shows that the measured rate of buildup compared rather well with the buildup calculated on the basis of the measured diffusion rate.

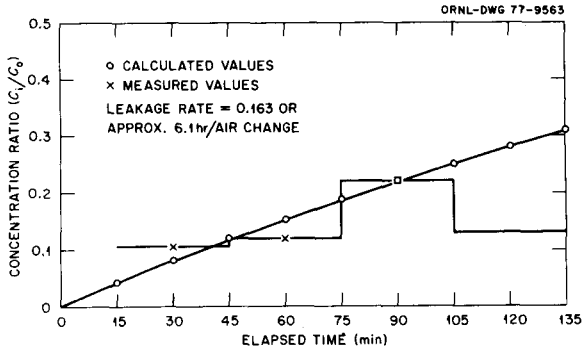

Fig. 6. Buildup of BG concentration (test 4)

Figure 7 shows the results of similar samples taken during test 5. Samples were taken at 5-min intervals during the first half hour and each 10 min thereafter. With the exception of three samples, measured and calculated rates were essentially the same.

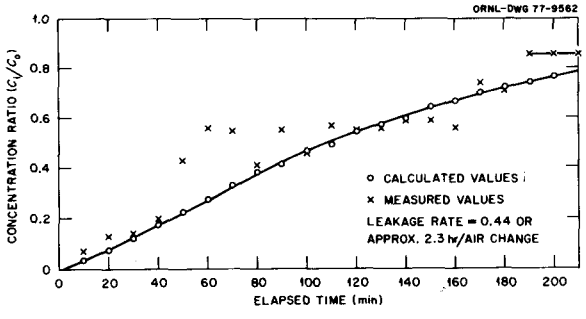

Fig. 7. Buildup of BG concentration (test 5)

Results of these tests suggest that there is no effective filtration of the aerosol during passage of the air through the walls of a building.

If there is no improvement in filtration PF, a building will provide significant protection from inhaled dose only during the time required for one air change. For example, from Table B.1 (Appendix B), it can be seen that the PF is reduced to less than 3 when T = 1/R. The buildings tested are believed to be at least as tight as most residences. Therefore, with only the closed building as defense against intrusion of contamination, people in such houses will have protection for only 3 to 5 h.

3.3.2 Second series of tests

The second series of tests was designed primarily to evaluate the use of a vacuum cleaner to supply filtered air to an occupied space to maintain a slight positive pressure, thus improving the PF of the space. The tests were performed on an old house in a semiremote area. The second floor of the house was sealed off by a trap door and polyethylene plastic to reduce the volume being tested. The first-floor plan of the house is shown in Fig. 8. In preparation for the tests, rooms 1 and 2 were sealed with plastic, and room 2 was fitted with a home vacuum cleaner for filtered makeup air as shown in Fig. 9. The intake to the cleaner pulled outside air in through a hole in a board installed in a window. The other holes were fitted with tubes so that samples of the air in the room could be taken from outside the house. Infiltration rate tests were run on rooms 1 and 2 using the CO_2 diffusion technique. The remainder of the house was closed up and tested for tightness by blowing air into the closed house until equilibrium was reached. The flow rate into the house was measured by a Pitot tube in a 3.66-m-long (12-ft-long), 0.3-m-diam (12-in.-diam) tube installed on the intake side of the blower (Fig. 10). Equilibrium pressure was measured by an inclined tube manometer. Using data obtained from this test, the infiltration rate during a 1.4-m/s (3-mph) wind was calculated in order to simulate the meteorological conditions existing during subsequent tests. Infiltration rates of the three spaces are tabulated in Table 5.

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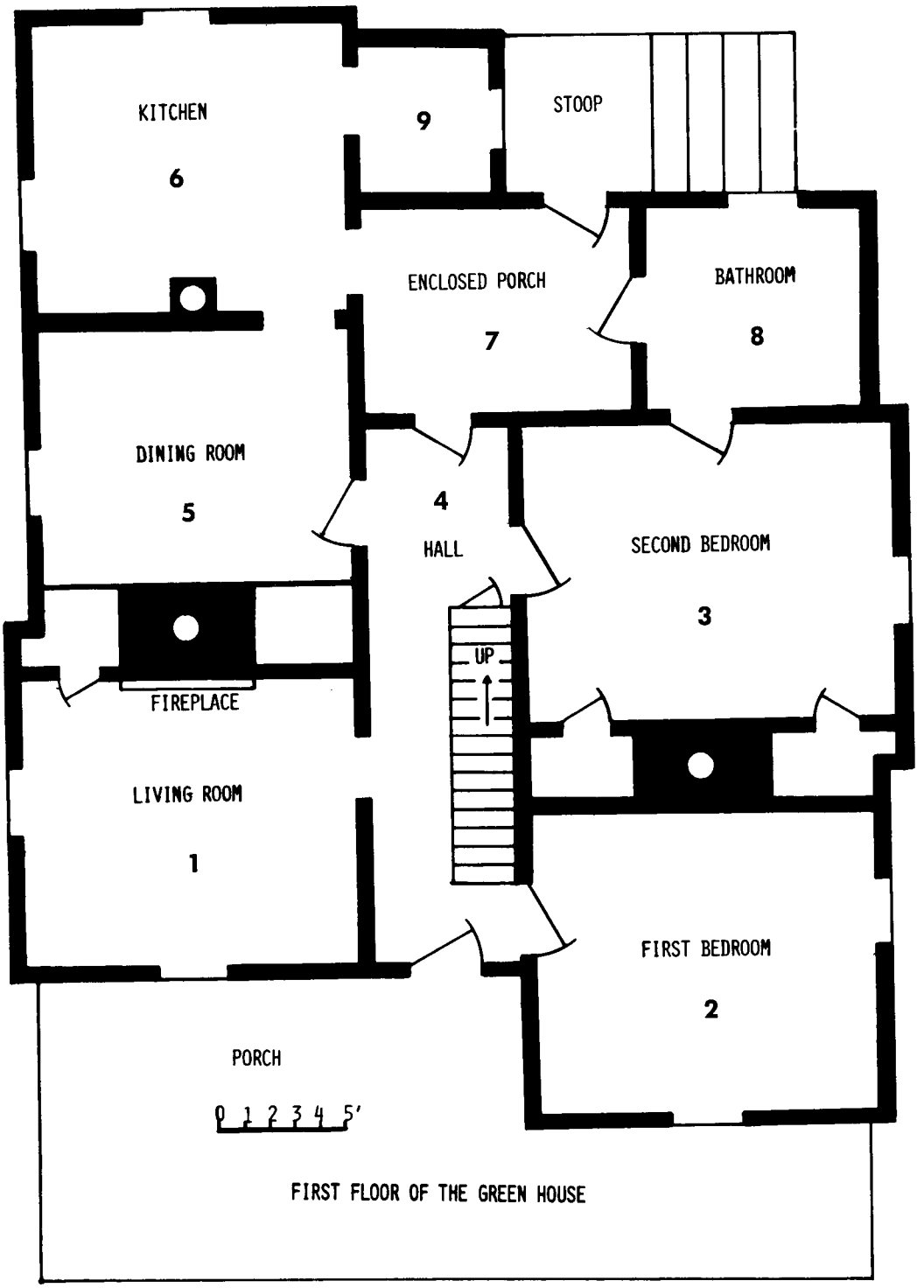

Fig. 8. First-floor plan

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Fig. 9. Vacuum cleaner installation (room 2)

Fig. 10. Measuring inlet air

Table 5. Infiltration rates (second series)

Room	Volume (m^3)	Infiltration rate (m^3/h)	Infiltration rate (changes/h)	Turnover time (h)
2	36	78[a]	2.2	0.26
1	37	4.6	0.12	8.1
3-9	186	477	2.6	0.39

[a]This rate was calculated from the infiltration (CO_2) test, it compares quite favorably with the cleaner-rated capacity of 70 m^3/h.

Two separate 4-h tests were performed. The house was subjected to an aerosol cloud generated by the high-pressure nozzle (Fig. 11). Samples of air outside the house were taken to establish the concentration of the cloud as it passed the house. Samples were taken of the air in the three enclosed spaces for the duration of the test. Results of the two tests are shown in Table 6. Table 7 gives the calculated dose rates that a person would receive either inside or outside the house and the PF provided by the closed house. Data given in Table 7 show that higher PFs could be obtained if a reasonably accurate prediction of the time at which the cloud passed could be made. The house could then be opened to clear out the contamination at an appropriate time. For example, if the house were opened 20 min after cloud passage, the PFs would be higher by factors ranging from 13 to 7000.

Fig. 11. Aerosol generator in operation

Table 6. Spore concentrations (second series)

Duration of tests (min)	Test 1[a]		Test 2[b]		
	Rooms[c]		Rooms		
	1	3-9	1	3[c]	4-9
0-10	0	66	10	700	2.1×10^5
10-20	4	87	100	400	4.2×10^5
20-30	17	43	140	460	2.4×10^5
30-60	0	48	790	210	0.9×10^5
60-90	6	41	860	410	3.3×10^5
90-120	0	23	980	420	
120-150	6	19	880	430	18×10^3
150-180	8	22	540	440	11×10^3
180-210	1	23	270	410	7×10^3
210-240			240	760	3×10^3

[a]5.1×10^{13} spores were released over a 2-min period; cloud concentration was 1.9×10^4 spores/ℓ.

[b]2.7×10^{14} spores were released over a 4-min period; cloud concentration was 2×10^6 spores/ℓ.

[c]An experimental error resulted in contamination of room 2 before the first test, so the data obtained are meaningless. To avoid recurrence of the error and to avoid an extensive decontamination operation, room 3 was equipped with a sweeper makeup and sealed off from the rest of the house for test 2. Although the rate of release of spores was about the same in the two cases, variations in the wind and distance from the house caused a factor of 100 difference in the measured cloud concentration.

Table 7. Calculation of dose rates and protection factors[a]
(All doses are in thousands of spores)

Duration of tests (min)	Test 1[b]				Test 2[c]					
	Sealed room		Closed house		Sealed room		Room with sweeper		Closed house	
	Increment	Sum	Increment	Sum	Increment	Sum	Increment	Sum	Increment	Sum
0-10	0	0	6.6	6.6	1	1	70	70	2100	2100
10-20	0.4	0.4	8.7	15.3	10	11	40	110	4200	6300
20-30	1.7	2.1	4.3	19.6	14	25	46	156	2400	8700
30-60	0	2.1	14.4	34.0	237	262	63	219	2700	11400
60-90	1.8	3.9	12.3	46.3	258	520	123	342	9900	21300
90-120	0	3.9	6.9	53.2	294	814	126	468	540	21840
120-150	1.8	5.7	5.7	58.9	264	1078	129	597	540	22380
150-180	2.4	8.1	6.6	65.5	162	1240	132	729	330	22710
180-210	0.3	8.4	6.9	72.4	81	1321	123	852	210	22920
210-240					72	1393	228	1080	90	23010
Protection factors (PFs)	45		5.2		57		74		3.5	
PFs if house has been opened after 20 min	950		25		7000		700		13	

[a]Doses were calculated on the basis of an average of inhalation rate of 10 liters of air/min.

[b]Outside dose is 380.

[c]Outside dose is 80,000.

4 DISCUSSION AND CONCLUSIONS

4.1 Diffusion Protection Factor vs Filtration Protection Factor

It has been postulated that closing a house before passage of a cloud of aerosol particles provides protection to persons inside the house in two ways. One, entry of the toxic particles can be delayed in the same way that a closed house delays the entry of uncontaminated air (restricting its movement to small openings into and out of the building and slowing the process by which the entering air is diffused into the contained air). Second, aerosol particles cling to the sides of the very small openings (cracks) through which air enters the house; the cracks can be said to "filter" the air. The mathematical development of a method for calculating the two PFs is contained in Appendix B. Unfortunately, there seems to be no evidence of the second method working on the 2-μ BG particles.

Figures 6 and 7 compare the measured buildup rate with a buildup rate calculated on the diffusion PF only. If any filtration PF had been obtained, it would have reduced the actual buildup rate below the diffusion buildup rate.

The fact that no filtration was detected may be attributable to the physical nature of the particles. Radioactive aerosols in the form of metallic oxides have a tendency to plate out on the surfaces they contact. The tests should be repeated using some type of finely divided metal oxide.

4.2 Significance of Results

4.2.1 Types of threats

Two distinctly different types of potential threats may be considered: (1) the continuous release of toxic aerosols or (2) the sudden release of toxic aerosols. [A sudden release forms a cloud that becomes increasingly larger as it moves downwind; such a cloud passes a specific structure within a finite period (up to 1 h).]

4.2.2 Closed buildings

The degree of air-tightness obtained by simply closing the buildings varied considerably: the air change rate varied from 0.12 air change/h for the tightly sealed room (equivalent to the very tightest of new constructions) to 2.6 changes/h for a very old, drafty house. By simply closing a building as tightly as possible before the arrival of a continuous radioactive aerosol, occupants could reduce their expected dose by a factor of 3--if the duration of the exposure were more than the time required for 1 air change (20 min to 8 h, depending on the air-tightness of the house).

On the other hand, if the threat is a short-duration cloud of radioactivity that is being monitored by an emergency team such as that of the airborne monitoring system operated by EG&G for the U.S. Department of Energy, the house could be closed before the cloud arrived, then opened and aired out as soon as the cloud had passed. Under such conditions, PFs of 10 to 200 might be obtained. (See results from the second series tests on the closed house and the sealed room.)

4.2.3 Closed building with filtered air

The PF obtained from closing a house during exposure to a toxic aerosol can be improved by using a household vacuum cleaner to provide an emergency filtered-air supply (Fig. 9). By maintaining a slight positive air pressure in the house during the cloud's passage and opening up as soon as the cloud had passed, a PF of about 800 could be obtained.

There are many high-performance filters (known in the nuclear industry as HEPA or absolute filters) that might be used to improve the PF provided by the vacuum cleaner used in these tests. This approach should be investigated in future work.

These conclusions are based on only a few tests and should be verified by more extensive tests on other buildings.

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APPENDIX A
CALCULATION OF AVERAGE PARTICLE SIZE*

Let

f_v = force applied to cause a particle of radius r to move with a constant velocity u through a medium with viscosity n (viscous flow),

f_g = force caused by gravity on a particle of radius r and a density p falling through a medium of density p'.

Then, from Stokes law,

$$f_v = 6\pi rnu \quad . \tag{A.1}$$

From gravitational considerations,

$$f_g = \frac{4}{3} g\pi r^3(p - p') \quad . \tag{A.2}$$

Combine Eqs. (A.1) and (A.2) by assuming $f_v = f_g$:

$$u = \frac{(4/3)g\pi r^3 (p - p')}{6r\pi n} = \frac{gD^2(p - p')}{18n} \quad . \tag{A.3}$$

On the assumption that convection currents preclude tranquil settling, the decrease in concentration c can be expressed by

$$\frac{dc}{dt} = \frac{-c}{T} = \frac{-u'cA}{V} \quad , \tag{A.4}$$

where

u' = deposition velocity,

t = variable time,

T = total time,

A = horizontal area on which spores are being deposited,

H = height spores have to fall to be removed.

---

*Adapted from Special Report No. 36, Camp Detrick, Maryland, November 15, 1945.

Rearrange Eq. (A.4) integrate, and solve for u'--:

$$u' = \frac{V}{AT} \ln\left(\frac{c_o}{c_t}\right) \quad . \tag{A.5}$$

If we assume that in the vicinity of surface A, turbulence is sufficiently mild that u' = u, we can combine Eqs. (A.3) and (A.5) and solve for an effective diameter D:

$$D = \left[\frac{18nV \ln(c_o/c_t)}{ATg(p - p')}\right]^{1/2} \quad . \tag{A.6}$$

APPENDIX B
METHOD OF CALCULATING PROTECTION FACTORS OF CLOSED HOUSES

B.1 Definitions

The protection afforded by a building consists of two parts. The first is time dependent and occurs because a closed building delays the entry of outside air. The second is not time dependent and will occur only if the passage through the walls removes some of the contaminant. If the radioactive cloud passes rather quickly compared with the time it takes for equilibrium to be established between outside and inside air, the total inhaled dose received by persons in the house will be reduced. The amount of reduction is strongly dependent on the rate of in-leakage and the length of time it takes for the cloud of radioactive particles to pass.

Protection factors are defined as the ratio of the dose one would receive if he were outside to the dose one would receive if he were inside. In our case, we will consider PF as the product of two protection factors--one PF attributable to diffusion, which we know exists, and one PF attributable to postulated removal of the contaminant as the air passes through the wall, which we will try to discover with our experiments. Let

$$PF = P_D \cdot P_F \quad ,$$

where

PF = total protection factor,

P_D = protection factor provided by diffusion,

P_F = protection factor provided by filtration.

In the case of toxic aerosols, the rate of accumulation of inhaled dose commitment will be proportional to the concentration of toxic particles in the air. It is assumed that the decay of the toxic particles is small enough to be neglected during the period of exposure. That is,

we assume that the rate of accumulation of inhaled dose commitment is proportional to the concentration of the simulant.

B.2 Calculation of the Diffusion Protection Factor (P_D)

Carbon dioxide was used to measure the infiltration rate of air into the house. A measured amount of CO_2 was released into the closed house, and the air inside was analyzed for CO_2 at periodic intervals (e.g., every half hour for 4 h).

The first step in calculating P_D is to calculate the rate of diffusion of air into the house, which should be essentially the same as the rate of diffusion of CO_2 out.

Let

C = concentration of CO_2 inside house (m^3 CO_2/m^3 air),
C_i = C at time zero,
C_T = C at time T (h),
v = rate of influx of air into the house (m^3 air/h),
V = volume of the house (m^3 air), and
R = v/V = rate of change of air in the house (change/h).

The material balance equation is rate of increase = rate of influx - rate of outflow:

$$V \frac{dC}{dt} = 0 - Cv \qquad (B.1)$$

This equation can be solved for the infiltration rate R:

$$R = -\frac{1}{T} \ln\left(C_T/C_i\right) \qquad (B.2)$$

The value of R depends on the wind velocity around the house, the temperature difference between inside and outside, and the design of the house. With steady wind velocity and constant temperature difference, the value of R for any one house should be a constant.

The P_D is then calculated as follows.

Let

D_o = inhaled dose commitment (either thyroid or whole body) a person would receive outside (R),

D = inhaled dose commitment a person would receive inside (if there were no loss of particles because of walls),

$P_D = D_o/D_i$,

k = proportionality factor between particle concentration and inhaled dose commitment accumulation rate (R/min particles/ℓ),

T = time the cloud takes to pass (h),

E = concentration of the toxic particles inside the house at time t (particles/ℓ),

E_o = concentration of the toxic particles outside the house, assumed constant from t = 0 to t = T (particles/ℓ).

Then

$$D_o = k \int_o^T E_o \, dt = kE_oT \tag{B.3}$$

and

$$\frac{D_i}{k} = \int_o^\infty E \, dt = \int_o^T E \, dt + \int_T^\infty E \, dt \tag{B.4}$$

Let

$$A = \int_o^T E_t \, dt \tag{B.5a}$$

and

$$B = \int_T^\infty E_t \, dt \quad , \tag{B.5b}$$

where A is proportional to the dose commitment accumulated during cloud passage and B is proportional to the dose commitment accumulated after cloud passage. The material balance during cloud passage is

$$V \frac{dE}{dt} = (E_o \cdot v) - (E \cdot v) \quad , \tag{B.6}$$

from which

$$\frac{d(E_o - E)}{E_o - E} = -Rdt \quad , \tag{B.7}$$

Therefore, at any time t (less than T)

$$\ln\left(\frac{E_o - E_t}{E_o - E_i}\right) = -Rt \quad , \tag{B.8}$$

where E_i is the initial concentration of the contaminant inside the house. Since $E_i = 0$, we can write

$$E_t = E_o(1 - e^{-Rt}) \quad . \tag{B.9}$$

Substituting into Eq. (B.5a) and integrating over the range $0 \leq t \leq T$ gives

$$\frac{A}{E_o} = T - \frac{1}{R} + \frac{e^{-RT}}{R} \quad . \tag{B.10}$$

Examples of accumulated dose commitments for various cloud passage times are shown in Table B.1; R = 1 (i.e., 1 air change/h) is assumed. Comparison of the last two columns indicates how the inside inhaled dose commitment A approaches the outside inhaled dose commitment D_o/k as T increases.

If the length of time of cloud passage is short compared with the time for one air change and if the occupants of a house could open up the house immediately after cloud passage, the accumulated dose inside would be less than what would have been received outside; but, when the length of time that it takes for the cloud to pass is long compared with the time for one air change, the dose inside would be very nearly the same as the dose outside.

Table B.1. Calculated accumulated dose commitment inside house for various cloud passage times[a] (R = 1 assumed)

T (h)	T - 1/R	e^{-RT}/R	A	$D_0/k = E_0T$
0.5	-0.5	0.61	0.11 E_0	0.5 E_0
1.0	0	0.37	0.37 E_0	1.0 E_0
2.0	1	0.14	1.14 E_0	2.0 E_0
4.0	3	0.02	3.02 E_0	4.0 E_0
10.0	9	0.00	9.00 E_0	10.0 E_0

[a]$PF = E_0/A$.

B.3. Calculation of the Contamination Protection Factor Due to Filtration

An attempt was made to estimate this protection by subjecting the house to a cloud of BG aerosol of known concentration F_0 for a specific time T. The infiltration rate R was determined at the same time to ensure that wind conditions were identical for both calculations.

Let

G = concentration of BG spores in the house (spores/m^3),

G_0 = concentration of BG spores outside the house (spores/m^3),

P_F = protection factor provided by the house,

R = v/V = rate of change of air in the house,

G_0/P_F = concentration of BG spores actually entering the house.

The material balance is given by

$$V \frac{dG}{dt} = \frac{G_o}{P_F} v - Gv \quad , \tag{B.11}$$

$$\frac{dG}{dt} = \frac{R}{P_F} (G_o - G \cdot P_F) \quad , \tag{B.12}$$

$$\frac{d(G_o - G \cdot P_F)}{(G_o - G \cdot P_F)} = -RT \quad , \tag{B.13}$$

$$\ln\left(\frac{G_o - G_T \cdot P_F}{G_o - G_i \cdot P_F}\right) = -RT \quad . \tag{B.14}$$

But $G_i = 0$, therefore,

$$R = -\frac{1}{T} \ln\left[\frac{G_o - G_T \cdot P_F}{G_o}\right] \quad . \tag{B.15}$$

Combining Eqs. (B.15) and Eq. (B.2) gives

$$\frac{G_o - G_T \cdot P_F}{G_o} = C_T/C_i \quad . \tag{B.16}$$

Solve for P_F:

$$P_F = \left[G_o/G_T\right] \left[1 - C_T/C_i\right] \quad .$$

This equation can be used to calculate the contamination protection factor afforded by the house because of filtration through the walls using the measurements of CO_2 concentrations and BG concentrations at each time T. (Note: BG concentrations are indicated by G; CO_2 concentrations, by C.)

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