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An Assessment of Radiation Doses from Residential Smoke Detectors that Contain Americium-241

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HEALTH AND SAFETY RESEARCH DIVISION

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ABSTRACT

External dose equivalents and internal dose commitments were estimated for individuals and populations from annual distribution, use, and disposal of 10 million ionization chamber smoke detectors that contain 110 kBq (3 μCi) americium-241 each. Under exposure scenarios developed for normal distribution, use, and disposal using the best available information, annual external dose equivalents to average individuals were estimated to range from 4 fSv (0.4 prem) to 20 nSv (2 μrem) for total body and from 7 fSv to 40 nSv for bone. Internal dose commitments to individuals under post disposal scenarios were estimated to range from 0.006 to 80 μSv (0.0006 to 8 mrem) to total body and from 0.06 to 800 μSv to bone.

The total collective dose (the sum of external dose equivalents and 50-year internal dose commitments) for all individuals involved with distribution, use, or disposal of 10 million smoke detectors was estimated to be about 0.38 person-Sv (38 person-rem) to total body and 1.3 bone-Sv (130 bone-rem).

SUMMARY

Ionization chamber smoke detectors contain small amounts, typically 110 kBq (3 μCi), of the radioactive material, ^{241}Am. Therefore, they are potential sources of radiation exposure to the general public. This report presents estimates of external radiation dose equivalents and internal 50-year dose commitments that might be received by individuals and the population of the United States from annual distribution, use, and disposal of 10 million ionization chamber smoke detectors. Although considerable uncertainty exists in these estimates, they indicate typical and maximum radiological impacts of smoke detectors on various population groups (distribution workers, store customers, residential users, etc.).

Persons who might be exposed to the smoke detectors were divided into functionally related groups. An exposure scenario was constructed for a representative individual from each group. The scenarios were then used to calculate doses (external dose equivalents or internal 50-year dose commitments) to the group members. Individual doses were summed to obtain population doses.

Exposure scenarios were constructed from information on domestic smoke detector use obtained from the literature and U. S. Nuclear Regulatory Commission's licensing files. These scenarios represented groups of persons involved in transport, distribution, use, and disposal of smoke detectors. In addition, consideration was given to persons who could be exposed to the radiation from smoke detectors incidentally and accidentally during transport, distribution, disposal, and unusual circumstances.

Table 1 is a summary of potential external dose equivalents and internal dose commitments to total body and bone (the critical organ) of the individuals and population groups considered in this assessment. Under normal conditions, average external dose equivalents to individuals were estimated to range from 4 fSv (0.4 prem) to 20 nSv (2 μrem) to total body, and from 7 fSv to 40 nSv to bone. Highest total-body dose equivalents (80 nSv) were calculated for 14 local delivery truck drivers. These same individuals could receive dose equivalents of 160

Table 1. Summary of potential radiation doses to individuals and the population from distribution, use, disposal, and unusual events involving 10 million ionization chamber smoke detectors

	Number of persons	To total body		To bone	
		Individual, Sv Average	Collective, person-Sv	Individual, Sv Average	Collective, bone-Sv
Normal events:					
Transport workers	5E+3[a]	1E-8	6E-5	2E-8	1E-4
Distribution workers	7E+5	2E-8	1E-2	3E-8	2E-2
Store customers	2E+8	5E-10	1E-1	1E-9	2E-1
Persons on truck routes	2E+8	7E-15	2E-6	1E-14	3E-6
Residential users:					
Homeowner	5E+6	1E-8	6E-2	2E-8	1E-1
Mate	5E+6	2E-8	1E-1	4E-8	2E-1
Others	5E+6	9E-9	5E-2	2E-8	9E-2
Waste collection	2E+5	1E-9	2E-4	2E-9	4E-4
Persons near incinerators	2E+8	6E-12[b]	9E-4[b]	7E-11[b]	1E-2[b]
Unusual events:					
Drinking contaminated water	5E+5	1E-7[b]	6E-2[b]	2E-6[b]	7E-1[b]
Eating crops:					
Irrigated with contaminated water	2E+8	9E-12[b]	2E-3[b]	1E-10[b]	2E-2[b]
Grown near landfill	2E+8	2E-10[b]	5E-2[b]	3E-9[b]	6E-1[b]
Grown on landfill	2E+7	3E-10[b]	6E-3[b]	3E-9[b]	7E-2[b]

Table 1. (continued)

	Number of persons	To total body		To bone	
		Individual, Sv Average	Collective, person-Sv	Individual, Sv Average	Collective, bone-Sv
Warehouse fire	[c]	8E-5[b]	[c]	8E-4[b]	[c]
Home fire	7E+3	3E-7[b]	2E-3[b]	3E-6[b]	2E-2[b]
Cleanup after fire	[c]	6E-9[b]	[c]	6E-8[b]	[c]
Foil ingestion	[c]	5E-4[b]	[c]	6E-3[b]	[c]

[a]Read as 5×10^3. This notation is used in other tables in this report.

[b]50-year dose commitments from ingestion or inhalation of ^{241}Am during one year.

[c]Not estimated.

nSv to bone. Residential users of smoke detectors were estimated to receive slightly lower dose equivalents: 9 to 50 nSv (0.9 to 5 μrem) to total body, and from 20 to 100 nSv (2 to 10 μrem) to bone.

Internal dose commitments to individuals under post disposal and unusual scenarios (excluding foil ingestion) were estimated to range from 6 pSv to 80 μSv (0.6 nrem to 8 μrem) to total body and from 70 pSv to 800 μSv (7 nrem to 80 mrem) to bone. The highest individual internal dose commitments in this group were for firefighters at warehouse fires.

Total annual collective doses (the sum of external dose equivalents and 50-year internal dose commitments) for all individuals involved with distribution, use, or disposal of 10 million smoke detectors was estimated to be about 0.38 person-Sv (38 person-rem) to total body and 1.3 bone-Sv (130 bone-rem).

When compared with typical annual radiation doses from other sources of exposure (Table 2), the doses potentially associated with transport, distribution, use, and disposal of ICSDs are quite low. The estimated annual collective dose associated with 10 million ICSDs appears to be six orders of magnitude lower than that from natural radiation. Individual doses from normal exposures to ICSDs range from 4 to 12 orders of magnitude lower than doses from the other sources.

Table 2. Summary of annual total-body radiation doses from various sources in the United States

Source	Average individual dose equivalents (Sv)	Population dose equivalents (person-Sv)
Environmental		
Natural	1.0E-3	2.1E+5
Global fallout	4.0E-5	8.2E+3
Nuclear power	3.0E-8	7.0
Subtotal	1.1E-3	2.2E+5
Medical		
Diagnostic	7.2E-4	1.5E+5
Radiopharmaceuticals	1.0E-5	2.0E+3
Subtotal	7.3E-4	1.5E+5
Occupational	8.0E-6	1.6E+3
Miscellaneous	2.0E-5	5.0E+3
Total	1.8E-3	3.7E+5
ICSDs (normal events)	4.0E-15 to 7.0E-8	3.8E-1

Source: National Academy of Sciences, National Research Council, The Effects on Population of Exposure to Low Levels of Ionizing Radiation, Report of the Advisory Committee on the Biological Effects of Ionizing Radiations, Washington, D.C. 20006 (November 1972).

1. INTRODUCTION

Residential fires rank as the second most frequent cause of accidental death in the home in the U. S. Early detection of home fires can be a key element in reducing this toll on life and the associated property losses. Since 1969, over 25 million ionization chamber smoke detectors (ICSDs) have been distributed in the United States. Almost all of these ICSDs contained small amounts of the radioactive material americium-241 (^{241}Am), thus making ICSDs potential sources of exposure to the general public from ionizing radiation.

Because ^{241}Am is classified as a "byproduct material," its use is regulated by the U. S. Nuclear Regulatory Commission (NRC). Current (1980) regulations require that manufacture and import of ICSDs be licensed, but place no restrictions on their receipt, possession, use, transfer, and acquisition (i.e., these actions are exempt from regulation and requirements for a license) (Code of Federal Regulations, 1980).

This report was prepared with funds supplied by the NRC under Interagency Agreement No. DOE 40-543-75. Support was provided by the Office of Engineering Standards, Division of Engineering Standards, which was transferred during April 1981 to the Office of Nuclear Regulatory Research, Division of Risk Analysis. This report contains estimates of radiation dose equivalents that might be received by the population of the United States during unrestricted transport, distribution, use, and disposal of 10 million ICSDs that contain 110 kBq (3 μCi) of ^{241}Am each. It complements, adds to, and supports other published smoke detector studies (Wrenn and Cohen, 1979; Belanger, Buckley, and Swenson, 1979).

Information concerning manufacture, transport, and distribution of ICSDs was obtained from the NRC's licensing files. This information and that gleaned from available literature was used to construct representative scenarios (sets of exposure conditions) for transport, distribution, use, and disposal of smoke detectors. The resultant sets of conditions were the bases for calculating radiation doses to exposed persons.

Section 2 of this report contains a description of ICSDs and an explanation of their operation. Section 3 contains a discussion of the strategy and methods used to estimate radiation doses to man. Section 4 contains estimates of radiation dose equivalents to persons from exposures that may occur during transport, distribution, use, and disposal of (including fires and unusual events). Each of these sections contains specifications of the exposure conditions used to make the dose estimates. This done in recognition of the fact that we selected for use in this assessment a small, representative (neither worst nor best) sample of the infinitely large number of possible scenarios.

In compliance with the official policy of the Oak Ridge National Laboratory, this report uses the International System of Units (SI). The relationship between the new SI units and the previously used units for the radiation quantities found in this report are given in Table 3. For convenience, the numerical values of prefix symbols used in this report are given in Table 4.

2. PRODUCT INFORMATION

Information obtained from the NRC indicates that approximately 25 million ICSDs were distributed throughout the United States between 1969 and 1978 (Table 5). These detectors are designed to protect life or property by sounding an alarm when airborne products of combustion from a fire reach a predetermined concentration. The relative merits of available smoke detector types (ICSDs and others) are not of concern in this report. They have been discussed amply elsewhere (Belanger, Buckley, and Swenson, 1979; Organization for Economic Cooperation and Development, 1977; USNRC, 1978; Wrenn and Cohen, 1979; and the many references cited in these reports). These studies find that the various detector types complement each other, and are all beneficial under certain conditions. (Most fire prevention experts recommend installation of both an ICSD and a photoelectric detector in the home.)

An ICSD consists essentially of an ionization chamber, electronic circuitry, an AC power supply or battery, an alarm, and an outer case.

Table 3. Relationships between some SI units and previously used units

Quantity	SI unit and symbol	Previous unit and symbol	Conversion factor
Activity	becquerel, Bq	curie, Ci	1 Bq = 2.7E-11 Ci
Dose equivalent	sievert, Sv	rem	1 Sv = 100 rem
Energy	joule, J	electron volt, eV	1 J = 6.2E+18 eV

Table 4. Values of prefix symbols used in this report

Prefix	Value	Prefix	Value
a	10^{-18}	m	10^{-3}
f	10^{-15}	k	10^{3}
p	10^{-12}	M	10^{6}
n	10^{-9}	G	10^{9}
μ	10^{-6}	T	10^{12}

Table 5. Domestic distribution of ^{241}Am in smoke detectors[a]

Year	Number of units distributed	Total ^{241}Am activity distributed (GBq)	^{241}Am activity per unit (MBq)		Number of distributors
			Average	Range	
1969	30	0.037	1.2	[b]	1
1970	59,000	174	2.9	[b]	1
1971	65,000	191	2.9	0.037-2.9	3
1972	121,000	310	2.6	0.037-2.9	3
1973	254,000	411	1.6	0.030-2.5	4
1974	390,000	340	0.87	0.015-1.7	7
1975	703,000	399	0.57	0.011-1.3	10
1976	3,352,000	801	0.24	0.011-0.7	14
1977	7,928,000	1590	0.20	0.015-1.9	17
1978[c]	14,200,000	1690	0.12	0.0074-1.1	34

[a] Derived from data supplied by the U. S. Nuclear Regulatory Commission.

[b] Values unavailable.

[c] Belanger et al., 1979.

The ionization chamber is the central component. It contains a source of ionizing radiation (^{241}Am) positioned between two oppositely charged electrodes. Alpha particles emitted during radioactive decay of the ^{241}Am interact with neutral air molecules flowing through the chamber and ionize them positively by ejecting an electron. The ejected electrons form negative ions by attachment to neutral air molecules. The resulting ions are attracted toward the oppositely charged electrode, thus establishing a small, reasonably steady electric current between the electrodes. The electronic circuitry monitors this current and, when the current changes by more than a predetermined amount, triggers the alarm.

Under normal conditions, ion production and removal are in equilibrium. However, if the air entering the ionization chamber contains particles (viz., combustion products) that are much more massive than the air molecules, this equilibrium will be disturbed. The more massive particles capture some of the ions and electrons in the chamber. Because they are more massive, the resulting charged particles move toward the electrodes more slowly than do the ions. This allows some of the particle-ion pairs to be swept out of the chamber by the airflow before reaching the appropriate electrode. The net effect is a reduction in the ionization chamber current. When the current drops below a predetermined level, the alarm will sound.

Some ICSDs contain two ionization chambers. One chamber acts as a reference, the other as a measurement chamber. The reference chamber is constructed to prevent entry of combustion products and, thus, monitors only ambient air. The measurement chamber acts as the single unit described above. In this design, the electronic circuitry senses differences between the current flows in the two chambers. If the current in the measurement chamber drops below that in the reference chamber by a predetermined amount, the alarm will sound.

Table 5 is a summary of ^{241}Am-containing ICSD distribution in the United States. Since becoming generally available during 1969, the number of ICSDs distributed each year has increased rapidly, and surpassed 14 million in 1978. The average ^{241}Am contents of the detectors has decreased from 2.9 MBq (79 μCi) in 1970 to 0.12 MBq (3.2 μCi) in

1978. Manufacturers' project that the numerical distribution will level off below the 1978 value, and that the average ^{241}Am content of ICSDs will continue to decrease (Belanger, Buckley, and Swenson, 1979). The number of licensed distributors has also increased significantly since 1975.

The sources of ionizing radiation used in ICSDs consist of 1- to 3-mm wide strips or 5-mm diameter discs that are cut or punched from a 0.2-mm thick composite. The composite consists of a 0.002-mm-thick mixture of gold and ^{241}Am that is hot-forged onto a 0.2-mm-thick silver backing and covered by a 0.001- to 0.002-mm-thick gold foil.

We did not assess, at our sponsor's (the NRC's) request, manufacture of ICSDs or the americium-containing foils. (See U. S. Nuclear Regulatory Commission, 1978, for an assessment.) Finished ICSDs are packaged and distributed as ordinary consumer products. Wrapped in a plastic bag, each detector is boxed singly, three boxes to a carton. Most smoke detectors are purchased from retail stores and installed in homes. All smoke detectors are mounted manually on ceilings or walls – usually one or two per home in halls or bedrooms. Once installed, the smoke detectors should be maintained by replacing batteries (for those which require batteries), testing the alarm, and cleaning air intakes. Manufacturers estimate that properly maintained smoke detectors should have a useful life of ten years. At the end of their useful life, most detectors are discarded as domestic solid waste, and may be replaced with new detectors.

3. ASSESSMENT STRATEGY

The purpose of this study was to provide a basis for estimating potential radiation dose equivalents to individuals and the population of the United States from ICSDs. To do this, average dose equivalents (hereafter simply called doses) to total body, bone (skeleton), and, in some cases, lungs were calculated with the aid of the CONDOS methodology and computer code (O'Donnell et al., 1981) for annual transport, distribution, use, and disposal of 10 million ICSDs that contain 3 μCi of ^{241}Am each. As prescribed by the methodology, the population was divided into functionally related groups of persons. Each group was represented by a typical individual who was assumed to be exposed to ICSDs under a set of exposure events described in Sect. 4 and Appendix A. The computer code and the exposure conditions were used to: (1) calculate external dose equivalents and internal dose commitments to individual group members; (2) sum individual doses to give group population doses; and (3) sum group doses to give overall population doses.

Population groups considered include: (1) truck drivers, truck-terminal workers, and persons along truck routes who could be exposed during transport of ICSDs from 7 suppliers to 70 large retail store warehouses and 700 wholesale-distribution warehouses; (2) warehouse workers, truck drivers, retail stock and sales clerks, store customers, and persons along truck routes who could be exposed during handling of ICSDs in the warehouses, transport from the warehouses to 21,000 large chain stores and 210,000 small retail stores, and handling and sale in the retail stores; (3) persons who could be exposed during use of ICSDs in residences; (4) persons who could be exposed during and after disposal of broken ICSDs; and (5) persons exposed during a residential or warehouse fire. Section 4 contains descriptions of each group considered and listings of the exposure conditions assumed for each group.

External doses are the result of exposures to photons emitted during radioactive decay of the ^{241}Am contained in sources (viz., ICSDs and air) external to the bodies of exposed individuals. External dose equivalents given in this report are the sums of doses received during one year of such exposures. Internal dose commitments are the result of exposures to all radiations (photons, alpha, beta particles) emitted by nuclides taken into the bodies of exposed persons via inhalation and ingestion. Internal doses given in this report are 50-year dose commitments, that is, the sums of doses received over the succeeding 50 years from radionuclides inhaled and ingested during the year considered.

All doses were calculated using the CONDOS II computer code (O'Donnell et al., 1981). CONDOS calculates external doses from direct exposures to physical objects (e.g., ICSDs) and immersion in contaminated air, and internal doses from inhalation and ingestion of radionuclides released from ICSDs. In all cases, the dose calculations are based on appropriate input data.

CONDOS solves standard source geometry equations to calculate doses from physical objects. Dose-rate conversion factors (Kocher, 1980) are used to calculate doses from immersion in contaminated air. All organ doses from external exposures are based on factors derived from estimates by Poston and Snyder (1974) of absorbed dose rates in the organs for monoenergetic photons emitted by radionuclides dispersed uniformly in a semiinfinite air space. All radionuclide decay data used in the dose calculations were taken from Kocher (1977).

CONDOS II uses a breathing rate of 0.9 m^3/h and organ-specific 50-year dose-conversion factors from Dunning et al. (1979) to calculate internal doses from inhalation of radionuclides. Ingestion doses are calculated using input-specified quantities of ingested radionuclides and organ-specific 50-year dose-conversion factors from Dunning et al. (1979). Both sets of internal dose-conversion factors were derived using a quality factor of 10 for alpha particles. Table 6 is a listing for ^{241}Am of its radioactive half-life, photon and beta-particle spectra, and immersion, inhalation, and ingestion dose-conversion factors for nine body organs and tissues. (The inhalation and ingestion dose-conversion factors for endosteal bone cells are ~2-3 times higher than those for bone, which were used in this assessment.)

Americium-241 has a radioactive half-life of 433 years and decays by emission of alpha particles and gamma and x-ray photons to ^{237}Np which has a half-life of about 2×10^6 years. Neptunium-237 has a lengthy decay chain but, due to its long half-life, would not appreciably affect the dose estimates in this report. Therefore, it was not included in this assessment.

Once inhaled or ingested, ^{241}Am deposited in the lung or the gastrointestinal tract may be absorbed into the blood and distributed to different body organs, principally bone and liver. In ICRP-19 (ICRP, 1972), it is assumed that 45% of ^{241}Am is deposited on bone surfaces, 45% in the liver, and 10% in other tissues. Based on animal studies,

Table 6. Data for Am-241 (Radioactive half-life = 4.33E+02 Y).

Photon		Beta particle		Dose-conversion factors			
Energy (pJ)	Intensity	Energy (pJ)	Intensity	Organ	Ingestion (Sv/Bq)	Inhalation (Sv/Bq)	Immersion (Sv/Y PER Bq/cm^3)
0.16	.0000	1.60	.0000	Total body	4.32E-07	2.40E-05	2.81E-02
0.24	.2800	3.20	.0000	Skin	0.00E+00	0.00E+00	3.70E-02
0.32	.0000	4.81	.0000	Bone	5.13E-06	2.55E-04	5.13E-02
0.48	.0269	6.41	.0000	Testes	1.16E-07	5.67E-06	2.42E-02
0.64	.0000	8.01	.0000	Ovaries	1.16E-07	5.67E-06	1.48E-02
0.80	.0000	9.61	.0000	Liver	2.30E-06	1.13E-04	1.69E-02
0.96	.3630	11.21	.0000	Kidneys	2.97E-07	1.46E-05	1.75E-02
1.12	.0017	12.82	.0000	Lungs	3.43E-11	8.45E-05	2.06E-02
1.28	.0000	14.42	.0000	GI Tract	2.97E-09	1.76E-08	1.70E-02
1.44	.0000	16.02	.0000				
1.60	.0000	17.62	.0000				
2.40	.0000	19.22	.0000				
3.20	.0000	20.83	.0000				
4.81	.0000	22.43	.0000				
6.41	.0000	24.03	.0000				
8.01	.0000	25.63	.0000				
9.61	.0000	27.23	.0000				
11.21	.0000	28.84	.0000				
12.82	.0000	30.44	.0000				
14.42	.0000	32.04	.0000				
16.02	.0000	33.64	.0000				
24.03	.0000	35.24	.0000				
32.04	.0000	36.85	.0000				
48.06	.0000	38.45	.0000				
64.08	.0000	40.05	.0000				

^{241}Am is expected to remain in body organs with half-times ranging between 40 and 100 years.

The inhalation dose-conversion factors were derived (Dunning et al., 1979) using the International Commission on Radiological Protection (ICRP) task group lung model (Morrow et al., 1966) and parameters from ICRP Publication 19 (ICRP, 1972). Retention of radionuclides in organs other than the respiratory tract was modeled by linear combinations of up to five decaying exponential functions. The factors used in this assessment correspond to those for particles having activity median aerodynamic diameters of 1.0 μm and the y solubility classification which has the highest lung dose-conversion factor.

The ingestion dose-conversion factors were derived (Dunning et al., 1979) using a four-segment catenary model of the gastrointestinal (GI) tract (Bernard, 1968) with mean transit times suggested by Eve (1966). Retention of radionuclides in organs other than the GI tract was modeled using the above mentioned linear combinations of decaying exponential functions.

The source foils used in ICSDs were modeled as 0.5-cm-diam × 0.0002-cm-thick cylinders of a gold plus ^{241}Am mixture covered by a 0.00015-cm-thick gold foil. The matrix contains 2 mg/cm^3 of ^{241}Am (2.8 kBq/cm^2) or a total activity of 110 kBq (3 μCi). The foils were assumed to be enclosed in a 0.254-cm-thick iron housing.

Arrays of detectors (cartons and pallets) were modeled as homogeneous cylinders of a composite material containing 0.28 ng/cm^3 of ^{241}Am (35 Bq/cm^3). The composite was a homogeneous mixture of ^{241}Am, plastic, cellulose, iron, carbon, and lead that was chosen to approximate exposure rates from an array of point-source detectors in cartons and pallets. The effective density of the composite material was 1.4 g/cm^3.

4. DOSE ESTIMATES

Radiation doses were estimated for annual transport, distribution, use, and disposal of 10 million ICSDs that contain 110 kBq (3 μCi) of ^{241}Am each. We did not estimate doses to workers or the general public during manufacture of the smoke detectors. Rather, we assumed all smoke detectors to originate from suppliers (seven would be required to distribute 10 million detectors under our assumptions) who are defined as individuals licensed to manufacture, import, or make initial distribution for sale of ^{241}Am-containing smoke detectors. In this section, we summarize the dose estimates and discuss the more important exposure assumptions used to calculate the doses. External dose equivalents are given for total body. Dose equivalents to other organs may be estimated by multiplying the values for total body by the following factors:

bone	- 1.93
lungs	- 0.73
kidneys	- 0.63
liver	- 0.60
maximum segment of GI tract	- 0.63
testes	- 0.87
ovaries	- 0.61

Appendix A contains detailed tabulations of the exposure conditions. Appendix B contains corresponding tabulations of the dose estimates.

4.1 Transport of Smoke Detectors

The transport and distribution schemes used in this study were constructed from information supplied to the NRC by ICSD manufacturers and a summary of procedures and exposure conditions for transport and distribution of consumer products (Etnier and O'Donnell, 1979). We attempted to make relatively simple schemes that encompass a wide range of exposure conditions. Local truck delivery (LD) was assumed to include all deliveries made within 32 km (20 miles) of the origin. Regional deliveries (RD) were assumed to span 400 km (250 miles – a 5-hour drive); over-the-road deliveries (OTRD) were assumed to span distances greater than 400 km and to consist of two or more successive regional deliveries. Most OTRD and RD trucks were assumed to contain complete shipments that were loaded at the origin and delivered to their destinations with no intermittent handling at terminals. Less-than-truckload (LTL) shipments were modeled as composites of unrelated items and were assumed to stop at truck terminals every 400 km where they are unloaded and loaded onto other trucks before reaching their final destinations.

To estimate doses to workers and the general public during bulk transportation of smoke detectors from suppliers to warehouses, we assumed seven suppliers who distribute a total of 10 million ICSDs per year. Each supplier was assumed to ship 720,000 smoke detectors to ten chain store warehouses and 720,000 smoke detectors to 100 wholesale warehouses (see Fig. 1). Transportation and distribution schemes differ depending upon the final destination. Each supplier was assumed to send ten shipments per year (7,200 detectors per shipment) to each of ten warehouses (see Fig. 2). Each shipment was assumed to consist of 50 pallets, each containing 48 cartons (three smoke detectors per carton). These shipments were assumed made as OTRDs and to span average total distances of 1,200 km (750 miles). Three drivers (one for each 400-km leg) were assumed for each trip (30 drivers per warehouse); each driver was assumed to make ten 400-km trips a year.

The transportation of smoke detectors to wholesale warehouses is outlined in Fig. 3. Each of the seven suppliers was assumed to service 100 wholesalers, making five shipments per year (1,440 detectors per shipment) to each warehouse. In all cases a local pickup driver was assumed to carry LD shipments to a local truck terminal where shipments are handled and loaded on regional LTL delivery trucks. The trucks were assumed to travel 400 km (250 miles) to regional terminals where shipments are handled and reloaded onto other regional delivery trucks. This process was assumed to occur three times per shipment. At the

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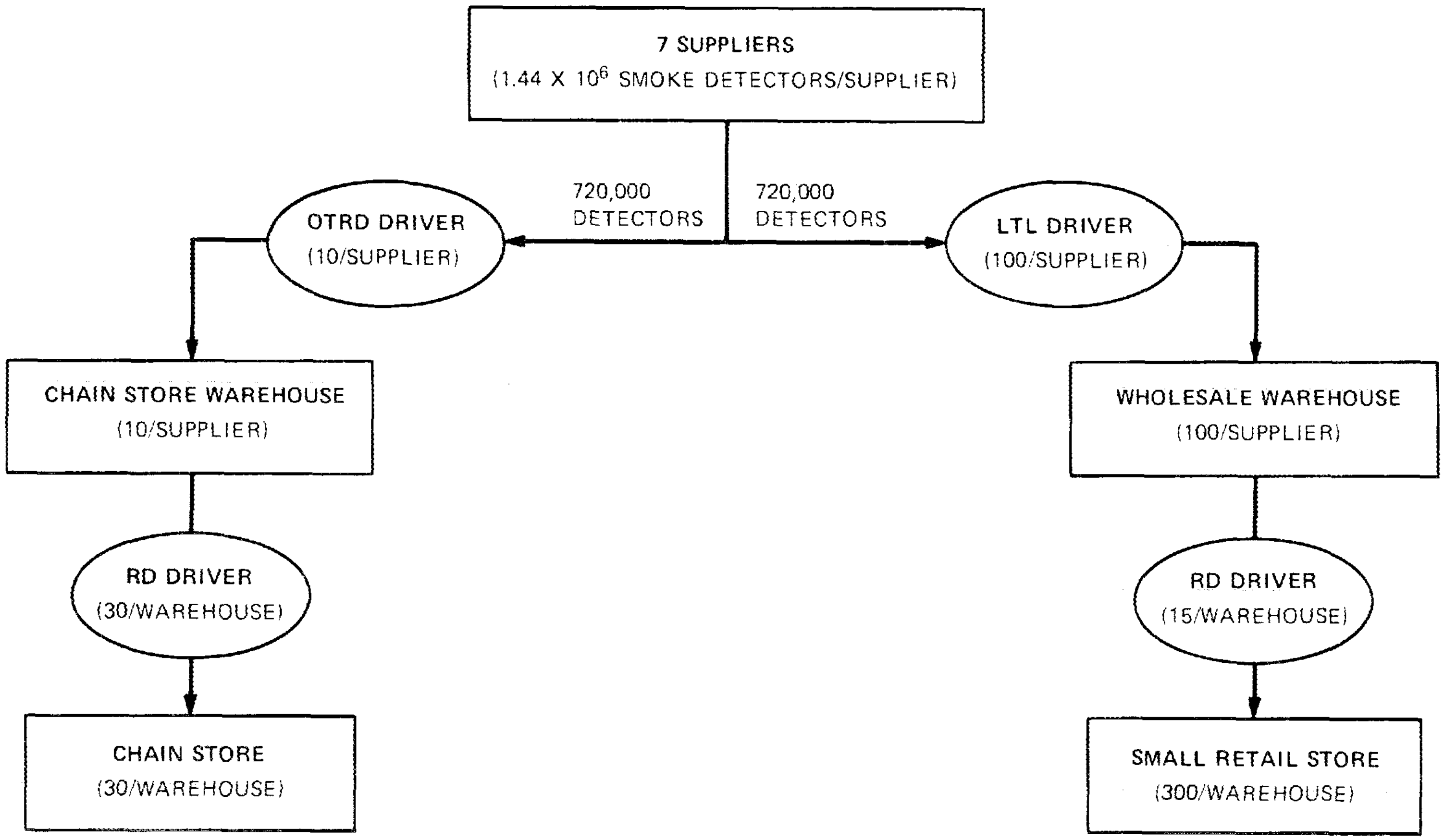

Fig. 1. General view of the transport and distribution of smoke detectors from supplier to destination.

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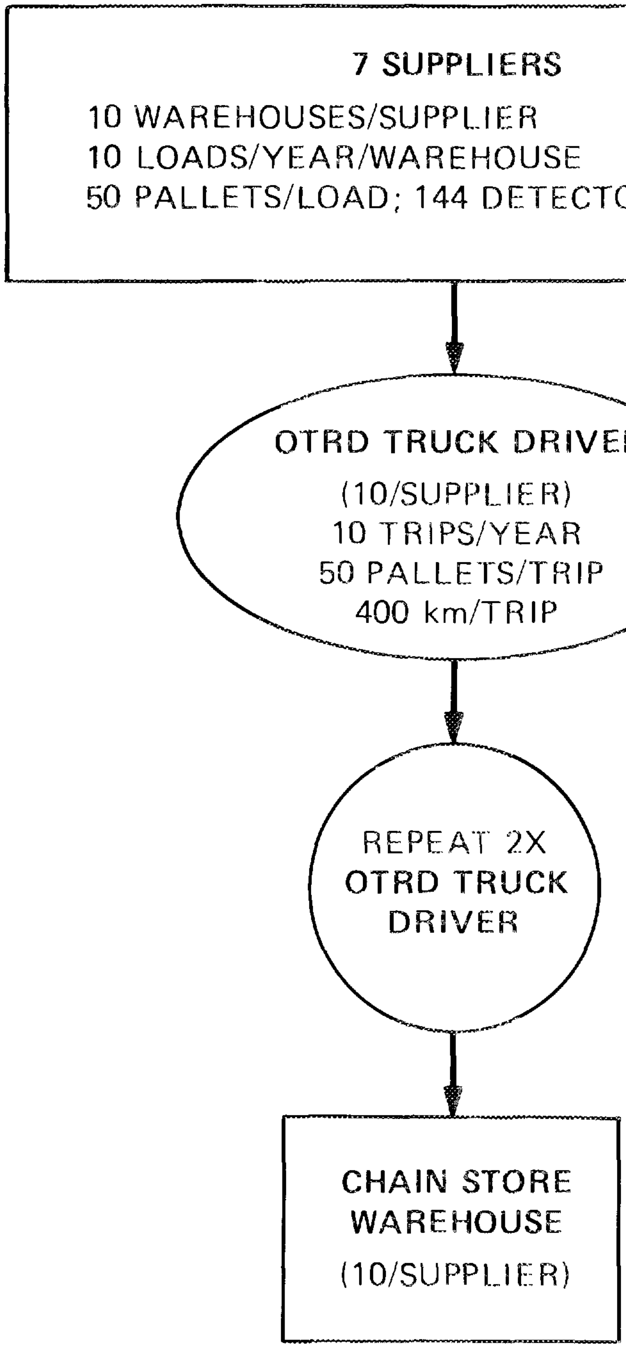

Fig. 2. Flow chart for the transport of 5 million smoke detectors from the supplier to a chain store warehouse.

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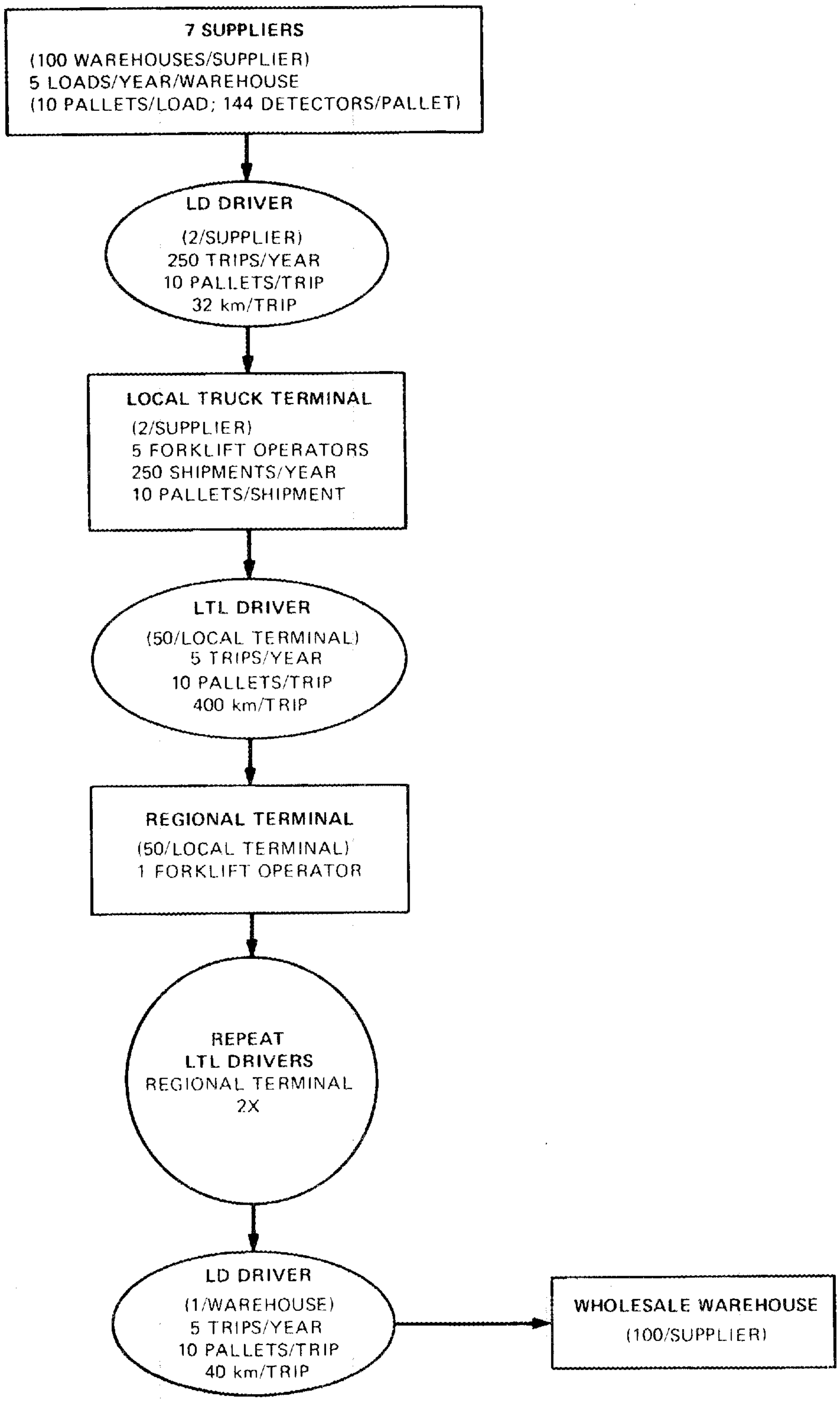

Fig. 3. Flow chart for the transport of 5 million smoke detectors from the supplier to a wholesale warehouse.

destination terminals, the shipments were assumed loaded onto LD trucks which transport them to the wholesale warehouses (700 warehouses).

Tables A.1 and A.2 list the exposure conditions assumed for transport of 5 million smoke detectors from suppliers to chain store warehouses, and 5 million detectors from suppliers to wholesale warehouses. Tables B.1 and B.2 give the estimated radiation doses that might be received by truck drivers, terminal workers and the general public during the two modes of transport considered. Table 7 is a summary of potential radiation doses to the total body of the various population groups involved in these modes. The 14 local delivery drivers who carry smoke detectors to local truck terminals prior to transport to wholesale warehouses could receive the highest total-body dose equivalents, 83 nSv (8.3 μrem), and bone dose equivalents, 160 nSv (16 μrem). The average total-body dose to all transport workers could be about 12 nSv (1.2 μrem). The total collective dose to all transport workers could be 60 person-μSv (0.006 person-rem).

4.2 Distribution of Smoke Detectors

The distribution scheme used for this study complements the transportation scheme. We considered: (1) distribution of 5 million ICSDs from 70 chain store warehouses to 21,000 chain stores and subsequent sale in the stores (Fig. 4), and (2) distribution of 5 million detectors from 700 wholesale warehouses to 210,000 small retail stores and subsequent sale in the stores (see Fig. 5).

In both cases, warehouse workers were assumed to handle and work near ICSDs awaiting distribution and to load local or regional delivery trucks that transport the detectors to stores. Stock clerks were assumed to handle and sell detectors from floor displays. Store customers were assumed to be exposed to the displays.

Tables A.3-A.4 list the exposure conditions assumed for distribution of the smoke detectors via the two modes discussed. Tables B.3-B.4 present radiation doses to total body of individuals and the various groups of persons involved in the two distribution schemes.

Table 7. Summary of total-body doses due to transport of smoke detectors

Population group	Individual doses, Sv			Number of persons	Population doses, person-Sv
	Average	Lowest	Highest		
Truck drivers	1.7E-8	1.3E-8	8.3E-8	3.0E+3	5.2E-5
Truck terminal workers	3.8E-9	2.9E-9	3.1E-8	2.2E+3	8.1E-6
Public on truck routes	4.5E-15	8.3E-16	2.1E-12	2.1E+8	9.5E-7

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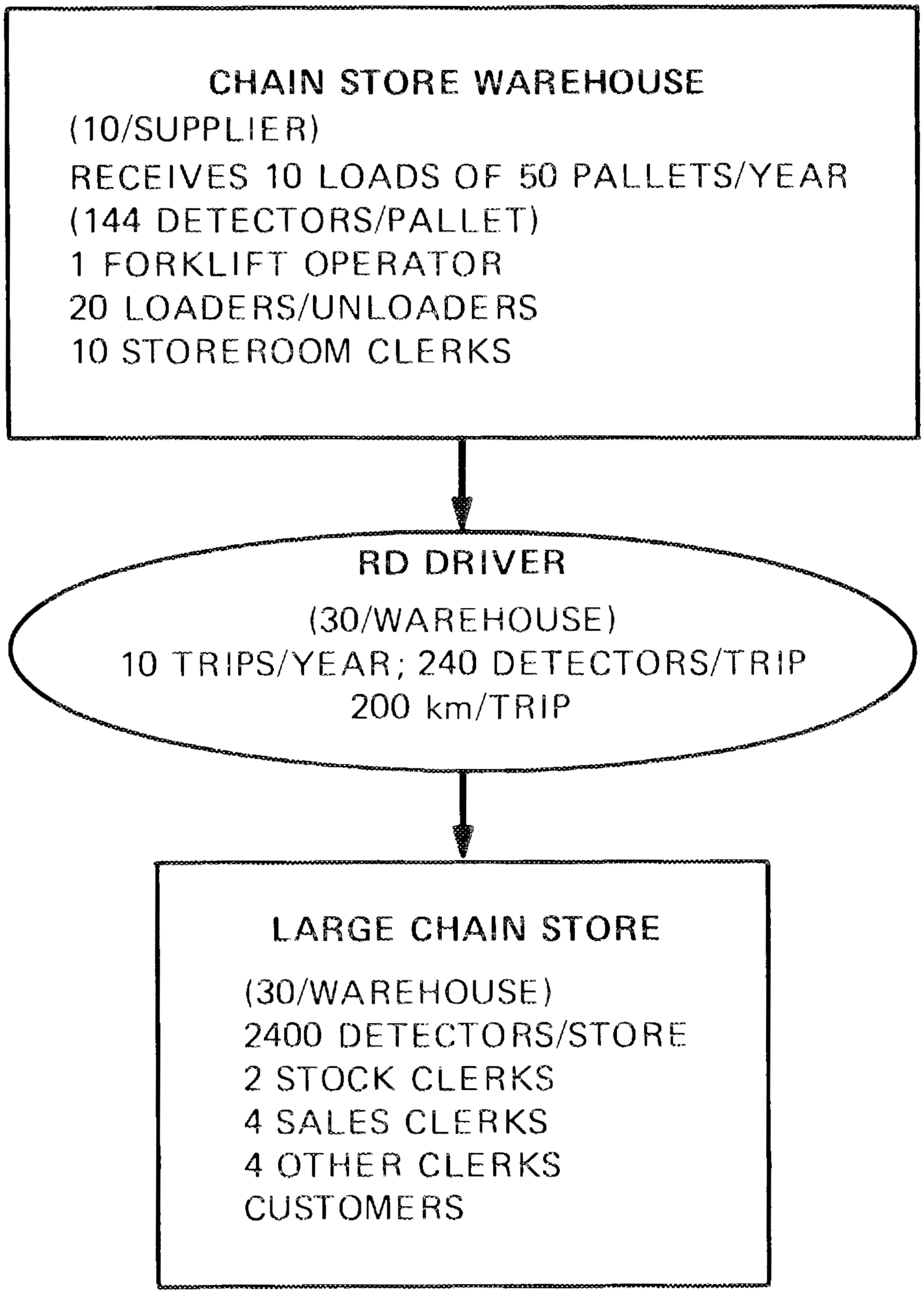

Fig. 4. Flow chart for the distribution of smoke detectors from a chain store warehouse to a large chain store.

ORNL–DWG 81-6440

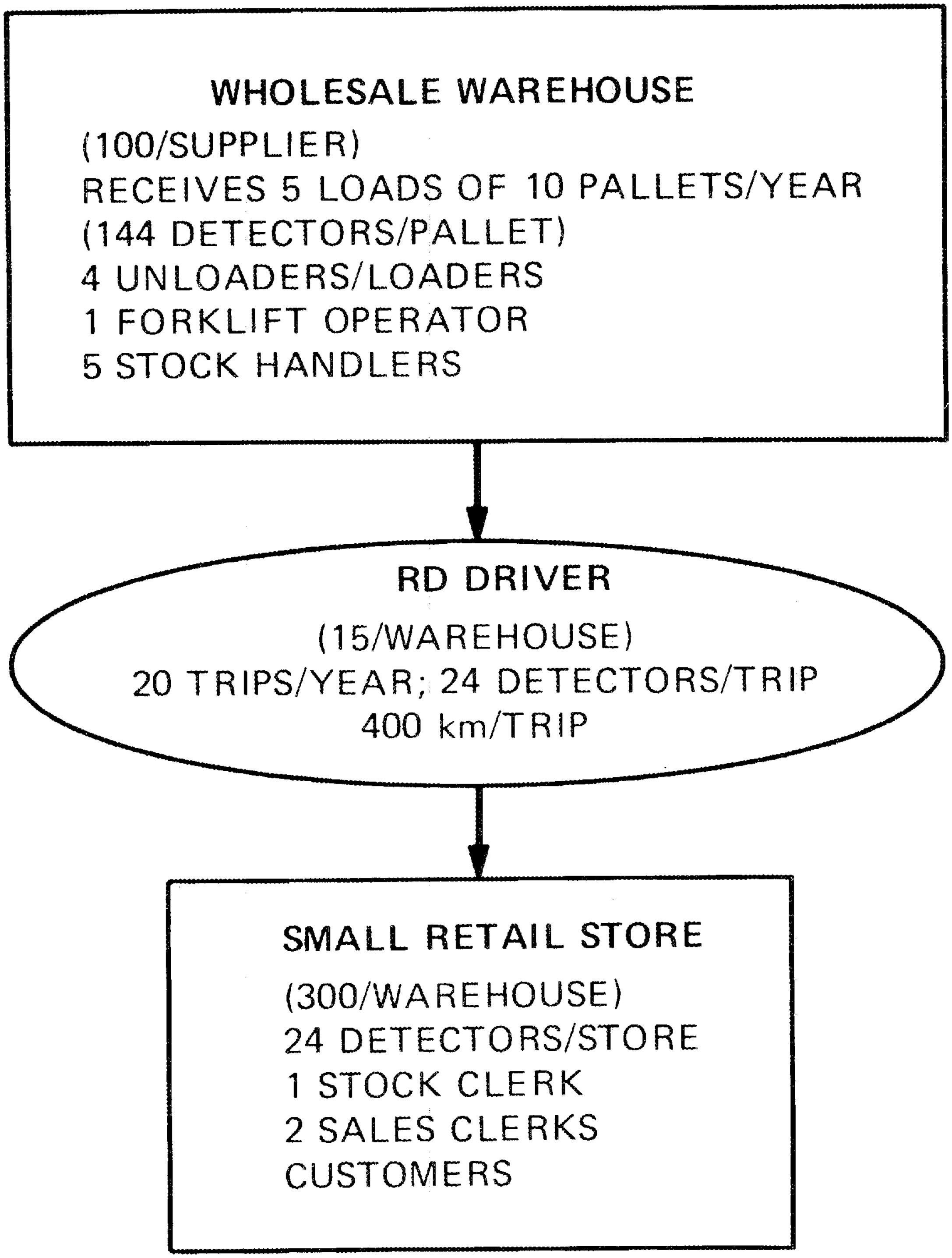

Fig. 5. Flow chart for the distribution of smoke detectors from a wholesale warehouse to small retail stores.

Table 8 summarizes the radiation doses to the various groups of individuals.

The individuals who could receive the highest doses to total body during the distribution of smoke detectors were found to be stock handlers working in the wholesale warehouses. These individuals, who handle cartons of packaged smoke detectors and work near stored cartons, could receive annual total-body doses of 70 nSv (7 μrem). The highest group dose (0.11 person-Sv) could be received by store customers even though the average individual dose to these customers was found to be relatively low (0.5 nSv). Each customer was assumed to shop 12 h/year in a large department store, and 50 h/year in a small retail store.

4.3 Use of Smoke Detectors

For this assessment, we assumed that 10 million ICSDs, each containing 110 kBq (3 μCi) of ^{241}Am, are distributed to 5 million households, and calculated doses for one year of use and a one-time purchase and installation. If the ICSDs have a 10-year useful life (as claimed by manufacturers), this set of smoke detectors could deliver the estimated doses for 10 years. Purchase, installation, removal, and disposal occur only once during the 10-year lifetime of an ICSD. Doses from these exposures were found insignificant with respect to doses during use.

Two ICSDs were assumed to be installed in each home, 10% in bedrooms and 90% in halls (Wrenn and Cohen, 1979; Belanger et al., 1979). Table 9 lists the exposure conditions and radiation doses from use in the home of two ICSDs that contain 110 kBq of ^{241}Am each.

A homeowner who purchases, installs, and maintains two smoke detectors in his home, sleeps 8 h/day, and spends 4 h/day at other activities in the home could receive an annual dose equivalent to total body of 39 nSv (3.9 μrem). A mate, who was assumed to spend 8 h/day in the home sleeping and 8 h at other activities, could receive a dose equivalent to total body of 50 nSv/year. Other members of the household could receive 9 nSv/year to total body.

Table 8. Summary of total-body doses due to distribution of smoke detectors

Population group	Individual doses, Sv			Number of persons	Population doses, person-Sv
	Average	Lowest	Highest		
Warehouse workers	3.4E-8	1.3E-9	7.0E-8	9.1E+3	3.0E-4
Truck drivers	2.2E-9	1.9E-9	3.8E-9	1.3E+4	2.7E-5
Store workers	1.5E-8	2.5E-10	4.0E-8	6.5E+5	9.7E-3
Store customers	5.0E-10	1.5E-10	5.0E-10	2.1E+8	1.1E-1
Public on truck route	3.6E-15	7.5E-16	3.3E-14	2.1E+8	7.6E-7

Table 9. Exposure conditions and radiation doses from use of two smoke detectors each containing 110 kBq of ^{241}Am

Exposed person	Exposure activity	Source	Duration of exposure, h/year	Distance from source, cm	Dose equivalent to total body, nSv/year
Homeowner	Purchase	2 detectors	0.5	30	0.4
			0.5	90	0.05
	Install	1 detector	0.5	30	0.2
	Maintain	1 detector	2	90	0.09
	Sleep	1 detector	2920	180	32
		1 detector	2920	600	3
	Other	2 detectors	1460	600	3
	Total				39
Mate	Sleep	1 detector	2920	180	32
		1 detector	2920	600	3
	Other	1 detector	2920	300	12
		1 detector	2920	600	3
	Total				50
Other individual	Sleep	2 detectors	2920	600	6
	Other	2 detectors	1460	600	3
	Total				9

If both ICSDs are located in halls (none in the bedroom), the doses given in Table 9 would change as follows:

Homeowner - from 39 nSv to 10 nSv
Mate - from 50 nSv to 21 nSv
Other - unchanged at 9 nSv.

To estimate an annual population dose from use of 10 million ICSDs, the following assumptions were made: (1) 10% of five million homes (500 thousand homes) have one detector in the bedroom and one in the hall, as represented by Table 9; and (2) 90% of the homes (4.5 million homes) have both detectors in halls, as represented above. This would give an annual collective total-body dose of 0.23 person-Sv (23 person-rem).

A total, annual, steady-state, collective dose may be estimated by using the above assumptions and assuming 100 million smoke detectors to be in use (this represents a steady state of 10 million distributed annually, 100 million in use, and 10 million discarded each year). The resulting steady-state collective dose to total body from use would be 2.3 person-Sv for 5 million households.

4.4 Disposal

To assess the impact of the disposal of 10 million ICSDs per year, we made several assumptions:

1) a local population group consists of one million persons in 333,333 home units, each housing a family of three;
2) each home unit contains two ICSDs;
3) under steady-state conditions, 10% of the ICSDs in use will be discarded each year, thus, each set of one million persons will discard 66,666 detectors annually (150 local population groups are required for annual disposal of 10 million ICSDs);

4) of the discarded ICSDs, 90% (60,000) go directly to land disposal and 10% (6,666) are incinerated and the incinerator residue going to a land disposal site (Brinkerhoff, 1973).

4.4.1 Waste collection

Waste collection crews were assumed to consist of two collectors and one driver. Each crew was assumed to service 960 homes per week and collect 192 detectors/year. Approximately 347 collection crews would be required to service one million persons, and 104,000 collectors and 52,000 drivers would be required to dispose of 10 million ICSDs. Doses to collectors and drivers are summarized in Table 10. Collectors could receive individual dose equivalents of 2 nSv/year (0.2 μrem) to total body and a collective dose equivalent of 200 person-μSv (0.02 person-rem) to total body. Drivers could receive 0.006 nSv/year, and the collective dose to drivers could be 0.3 person-μSv/year.

4.4.2 Land disposal

Several assessments have been made of possible doses from land disposal of ICSDs (Belanger et al., 1979; Wrenn and Cohen, 1979). These assessments consider leaching into ground water and ingestion of the contaminated water, leaching into ground water and use of the water to irrigate crops which are subsequently ingested, and uptake of ^{241}Am by crops planted on old burial sites, dusting of crops with ^{241}Am, etc. All of these assessments, and those that follow, are highly speculative in that they use conservative assumptions based on extrapolated data.

Belanger et al. (1979) made the following assumptions to estimate dose commitments from drinking contaminated ground water:

"1. Ten million ICSDs are disposed of in one year with an average source activity of 3 μCi (110 kBq).

2. Ten percent of ICSDs disposed of in landfills have been previously incinerated and these sources can lose up to ten percent of their initial activity in one year.

Table 10. Exposure conditions and external radiation doses to municipal solid waste collectors from disposal of 10 million smoke detectors containing 110 kBq of ^{241}Am each

Exposed person	Number of individuals	Exposure activity	Duration of exposure, h/year	Distance from source, cm	Dose equivalent to total body, nSv/year	Collective dose equivalent person-Sv
Collectors	1.0E+5	Pick up waste	4.8	30	1.9	2.0E-4
		Near truck	500	180	2.3E-2	2.4E-6
Total					1.9	2.0E-4
Drivers	5.0E+4	Driving	2000	180	5.7E-3	3.0E-7

3. The remaining 90 percent of ICSDs lose up to 0.01 percent of source activity in one year.
4. One-half of the total activity leached from americium sources in one year eventually enters the ground water during a similar interval.
5. The volume of leachate generated per year is 90 billion gallons, all of which enters the ground water system and is available for withdrawal. (This assumption is predicated on the fact that 70 percent of 18,500 solid waste landfill sites in the U. S. are in ground water supply areas, and that the average infiltration of precipitation is 10 inches per year.)
6. There is no significant dilution of the zone of contamination from surrounding ground water.
7. One percent of the contaminated water is withdrawn for domestic water supply and five percent of that amount is consumed as drinking water."

We believe assumption 4 to be unrealistically conservative. Cline (1966) studied the leaching of ^{241}Am in soils under varying conditions of soil pH. His results indicate that after leaching with 100 inches of water (the equivalent of ten-years infiltration of precipitation at ten inches per year) only 2% of the ^{241}Am was leached from the top one centimeter of acid (pH = 4.5) soil and only 24% was leached from the top centimeter of basic (pH = 7.5) soil. The maximum americium penetration of the soil was observed to be 20 centimeters in the basic soil and five centimeters in the acid soil. Using this study (which was based on the equivalent of 10 years infiltration of precipitation) as indicative of americium behavior in soil, we concluded that 2.5% of the total activity leached from americium sources in one year might enter the ground water during that year. Even this is a conservative estimate since Cline's study shows that the maximum americium penetration during the equivalent of 10 years infiltration of precipitation was 20 centimeters. Presumably, most aquifers lie much deeper than 20 centimeters below ground surface.

The results of Belanger et al. (1979) were scaled to match our assumptions (i.e., 10 million ICSDs discarded per year in land fills and 2.5% of the total americium activity leached into ground water during that year). The resulting 50-year dose commitments from drinking 370 ℓ of contaminated water per year (and those calculated using the assumptions of Belanger et al. and our dose-conversion factors) are given in Table 11. The individual estimated to receive the highest dose commitments (under the assumptions of Belanger et al.) could receive 2.6 μSv (0.26 mrem) to total body and 30 μSv to bone. The average individual (under our modifications to the assumptions of Belanger et al.) could receive 0.13 μSv to total body and 1.6 μSv to bone. Ingestion of contaminated ground water could yield collective doses of 0.061 person-Sv (6.1 person-rem) and 0.72 bone-Sv.

Using the assumptions of Belanger et al. (1979) for ingestion of crops irrigated with contaminated water and our 2.5% leach assumption, we estimated annual individual dose commitments of 0.009 nSv (0.9 μrem) to total body and 0.1 nSv to bone (Table 11). Corresponding collective dose commitments were 0.002 person-Sv (0.2 person-rem) and 0.02 bone-Sv.

If the fraction of environmentally dispersed ^{241}Am that is ultimately ingested by man is 10^{6} (Wrenn and Cohen, 1979) and 10% of the annually disposed ^{241}Am (0.11 TBq) is so dispersed, about 110 kBq could be ingested. This could produce collective dose commitments of 0.05 person-Sv and 0.6 bone-Sv. The average individual could receive 0.2 nSv to total body and 3 nSv to bone (Table 11).

To estimate potential doses from ingestion of crops grown directly on landfills, we assumed all the discarded ^{241}Am (1.1 TBq) to be uniformly dispersed within the top 20 cm of soil (density = 1.5 g/cm^3) of the 2000 km^2 (500 thousand acres) of currently used landfill (Belanger et al., 1979). The resulting concentration of ^{241}Am in the soil would be 1.8 mBq/g. Assuming the ^{241}Am content of plants to be 0.0001 that of soil and an annual dietary plant intake of 3650 g (Wrenn and Cohen, 1979), a person eating plants grown on old landfills could ingest 0.67 mBq of ^{241}Am. Such a person was estimated to receive 50-year dose commitments of 0.29 nSv to total body and 3.4 nSv to bone (Table 11). To estimate a population dose from ingestion of plants grown on old

Table 11. Radiation doses to individuals and populations from land disposal of 10 million ^{241}Am-containing smoke detectors

Exposure pathway	Intake per year (mBq)	Individual dose commitment (nSv)		Intake per year (kBq)	Collective dose commitment (person-Sv)		References
		Total body	Bone		Total body	Bone	
Ingestion							
leach water							
- highest	5920	2600	30,000				Belanger
- typical	3.04	130	1,600	140	0.061	0.72	Belanger, modified
irrigated crops	0.020	0.0086	0.10	4.2	0.0018	0.022	Belanger, modified
crops, general	0.52	0.22	2.7	110	0.048	0.57	Wrenn and Cohen
crops grown on landfill	0.67	0.29	3.4	14	0.0061	0.072	Wrenn and Cohen
burning	*a*	0.0015	0.018	*a*	0.00023	0.0027	See text
Inhalation							
resuspended particles	2.4	60	610	*a*	*a*	*a*	Wrenn and Cohen
burning	*a*	0.0013	0.014	*a*	0.00020	0.0021	See text

[a]Not estimated.

landfills, we assumed 10% of the population (21 million persons) to behave as the above individual. This yielded population dose commitments of 0.0061 person-Sv and 0.072 bone-Sv from ingestion of 14 kBq of ^{241}Am.

Another potential exposure pathway near landfills is resuspension of uncovered ^{241}Am. Johnson finds the average concentration of uranium resuspended in air above soil that contains 1 Bq of uranium/g of soil to range between 3.5 and 540 μBq/m^3 (as reported in Wrenn and Cohen, 1979, and Belanger et al., 1979). Assuming that resuspension of americium and uranium are similar and that landfill soils contain 1.8 mBq/g of ^{241}Am, we estimated the average, steady-state concentration of resuspended ^{241}Am to range between 0.0064 and 1.0 μBq/m^3. Using the higher value and assuming a breathing rate of 1.2 m^3/h and exposures during 250 eight-hour days, we estimated an annual intake (via inhalation) of 2.4 mBq/year. Such exposures could yield individual 50-year dose commitments via inhalation of approximately 60 nSv to total body, 610 nSv to bone, and 200 nSv to lungs (Table 11). We did not estimate potential collective doses from resuspension because we felt that very few persons would be at a landfill for 8 h of each workday.

Since only 6% of the 12,000 land disposal sites operating in the United States during 1967 were classified as sanitary landfills (General Electric Company, 1975), another potential source of public exposure is airborne ^{241}Am released by burning at landfills. To estimate potential doses via this pathway, we assumed 66,666 ICSDs containing 7.4 GBq of ^{241}Am to be discarded during one year at one landfill. We further assumed 0.001% of the discarded ^{241}Am (74 kBq) to become airborne during burning (Cutshall et al., 1978, find typical releases of 0.01% at 1200°C and about an order of magnitude lower releases at 600-900°C). Using the same assumptions regarding dispersion and intake of the released material as were used for incinerators (see Sect. 4.4.3), we estimated that the average individual could receive 1.3 pSv to total body, 14 pSv to bone, and 4.7 pSv to lungs via inhalation; 1.5 pSv to total body, 18 pSv to bone, and 0.00012 pSv to lungs via ingestion. Population doses from burning 10 million ICSDs were estimated to be 0.00020 person-Sv (total body), 0.0021 bone-Sv, and 0.00071 lung-Sv via inhalation; 0.00023 person-Sv, 0.0027 bone-Sv, and 0.18 lung-nSv via ingestion (Table 11).

4.4.3 Incineration

To estimate potential radiation doses from incineration of ICSDs, we assumed incineration of 6666 ICSDs per year in one incinerator that services one million persons. (Approximately 150 such incinerators would be required to incinerate 10 million ICSDs per year.) The incinerator was assumed to have a 15-m-high stack and an 15-m/s effluent release velocity. Inhalation and ingestion doses were calculated with the AIRDOS-II computer code (Moore, 1977) using average meteorological conditions (USAEC, 1974) and internal radiation dose conversion factors from Killough et al. (1978). A 10% release of particulates out the stack was assumed. Cutshall et al. (1978); EAD Metallurgical (1977); Hall and Hunt (1975 and 1978); and Niemeyer (1969) have measured the release of ^{241}Am from source foils and whole ICSDs during high temperature tests. The range of reported values is:

foils only: 0.006 - 0.3%;
whole detectors: 0.003 - 0.2%.

For this assessment we assumed 0.2% of the 110 kBq (3 μCi) per detector to become airborne and 10% of this to be released from the stack. This resulted in a postulated release of 140 kBq (4 μCi) of ^{241}Am from each incinerator stack per year.

Collective dose estimates to total body, bone, and lungs from inhalation and ingestion are listed in Table 12. These doses were calculated assuming each person to remain near the incinerator and to eat food raised within 80 km (50 mi) during the entire year. The average individual could receive 5.8 pSv (0.58 nrem) to total body, 65 pSv to bone, and 9.5 pSv to lungs. The maximally exposed individual could receive 3.8 nSv (0.38 μrem) to total body, 43 nSv to bone, and 7.0 nSv to lungs. Total collective doses to a population of 150 million persons around 150 incinerators was estimated to be 0.87 person-mSv (0.087 person-rem), 9.7 bone-mSv, and 1.4 lung-mSv.

Table 12. Population dose estimates for airborne release of 140 kBq of ^{241}Am from an incinerator stack (1 million persons)

Organ	Exposure pathway	Collective dose (person-Sv)
Total Body	Inhalation	2.7E-6
	Ingestion	3.1E-6
	Total	5.8E-6
Bone	Inhalation	2.8E-5
	Ingestion	3.7E-5
	Total	6.5E-5
Lungs	Inhalation	9.5E-6
	Ingestion	2.4E-10
	Total	9.5E-6

4.5 Fires

To estimate 50-year dose commitments to firefighters from combating residential and warehouse fires, we made the following assumptions:

1. During a fire, 0.2% of the ^{241}Am present in the building becomes airborne as 1-μm-diam particles. This assumption maximizes the calculated dose commitments because it uses the highest total ^{241}Am release fraction found during temperature testing at 1200°C (Cutshall et al., 1978).
2. All firemen who enter a burning building use self-contained breathing apparatus (Oak Ridge Fire Department, 1981). These apparatus allow no more than 1% of the air breathed by firemen to come from the air in the burning building.
3. The air intake rate for firemen is 1.2 m^3/h (U. S. Department of Health, Education, and Welfare, 1970).
4. The burning buildings have a ventilation rate of one building volume per hour, an undoubtedly low ventilation rate.
5. Firefighters enter the burning buildings at the instant that the ^{241}Am is released and remain in the building for 8 h. This is a conservative assumption because it is rare that a firefighter would remain in a burning building during a continuous 8-h period and because potential dose commitments from being in a burning building are time dependent (see Table 13). Delayed entry into the building could reduce the calculated dose commitments significantly (e.g., a 1-h delay could reduce doses to 37% of those given; a 2-h delay, to 14%).

4.5.1 Residential fires

Under the preceding assumptions, a firefighter combating a fire in a residence containing two ICSDs and having a volume of 450 m^3 could inhale 0.012 Bq (0.32 pCi) of ^{241}Am. The corresponding 50-year dose

Table 13. Time-dependent fraction of 8-hour dose commitment received by individuals during fire

Hour	Fraction of 8-h dose delivered
0-1	0.63
1-2	0.23
2-3	0.086
3-4	0.032
4-5	0.012
5-6	0.0043
6-7	0.0016
7-8	0.00058

commitments would be 0.28 μSv (0.028 mrem) to total body, 3.0 μSv to bone, and 1.0 μSv to lungs. If the firefighter enters the residence after the fire has progressed for 1 h and remains for 7 h, he would receive only 37% of the 8-h dose commitments given above.

It has been estimated that there could be 7000 fires per year that might involve release of ^{241}Am from smoke detectors (USNRC, 1978). Assuming 7000 firefighters (one near the burning ICSDs in each home), we estimated population doses of 0.0020 person-Sv (0.20 person-rem) to total body, 0.021 bone-Sv (2.1 bone-rem), and 0.0070 lung-Sv (0.70 lung-rem).

4.5.2 Warehouse fires

Warehouse fires are not common, and we believe the probability is very low that a warehouse containing a large quantity of ICSDs will burn. Therefore, although we made individual dose estimates for firefighters, we did not make a population dose estimate.

A chain warehouse was assumed to have a volume of 3000 m^3 and to contain 3600 ICSDs (see Sects. 4.1 and 4.2) which could release 800 kBq of ^{241}Am during a fire that burned all of them. Using the assumptions and conditions mentioned above, we estimated a firefighter to inhale 3.2 Bq of ^{241}Am. Such a firefighter could receive a total-body dose commitment of 75 μSv (7.5 mrem), a bone dose commitment of 800 μSv (80 mrem), and a lung dose commitment of 270 μSv (27 mrem). As before, these estimates may be reduced depending on the time and duration of building entry.

4.5.3 Cleanup after fire

Cleanup after a fire in a residence or a warehouse was assumed to require 8 h, and cleanup personnel were assumed to wear no respiratory equipment. Cutshall et al. (1978) measured the powdery (transportable) residue (32 g) from heating an ICSD to 1200°C, and find that the activity contained in particles with diameters less than or equal to 10 μm to be ~0.0014 of the source activity. We assumed 1 wt % of the particles in the residue to have a diameter of 1 μm. Therefore, the average content of 1-μm-dia particles in the transportable residue left by burned ICSDs would be 0.048 Bq/g (110 kBq × 0.0014 × 0.01/32.1 g).

We estimated potential dose commitments from cleanup by using the findings of Johnson and Cutshall et al. (1978). Johnson estimates airborne concentrations of uranium resuspended from soils to range between 3.5 and 540 $\mu Bq/m^3$ per becquerel per gram of soil (see Sect. 4.4.2). From Cutshall, we estimated the transportable residue from burned ICSDs to contain 0.048 Bq of ^{241}Am/g. Using Johnson's higher estimate, the airborne concentration of respirable ^{241}Am could be 26 $\mu Bq/m^3$. Breathing at a rate of 1.2 m^3/h for 8 h could result in an intake of 0.25 mBq of ^{241}Am. The resulting 50-year dose commitments due to inhalation could be 6.0 nSv (0.60 μrem) to total body, 64 nSv (6.4 μrem) to bone, and 21 nSv (2.1 μrem) to lung. Since it is highly unlikely that an individual would remain near the rubble of burned ICSDs for 8 h and Johnson's assumptions apply to a large contaminated-surface area (here we have relatively small contaminated surface areas), doses from cleanup would most likely be much lower than the above estimates. This would be especially true for cleanup after residential fires.

Collective dose estimates from cleanup after 7000 residential fires under the preceding assumptions were 42 person-μSv (4.2 person-mrem) to total body, 450 bone-μSv (45 bone-mrem), and 150 lung-μSv (15 lung-mrem).

4.6 Ingestion of Source Foils

Under normal conditions of distribution, use, and disposal of ICSDs, the ^{241}Am-containing source foils are inaccessible. However, a determined individual could remove the foils (probably by destroying the ICSD) and subsequently ingest them. To estimate potential dose commitments from such an event, we used data obtained from a study of an ICSD assembler who swallowed two foils which contained ~70 and 90 kBq (1.9 and 2.4 μCi) of ^{241}Am (Rundo et al., 1977). This study concludes that, despite unusually long durations in the GI tract (16 and 24 d), the foils lost <1% of their original activities and <1.5% of the lost activity entered the blood and body organs.

To estimate potential 50-year dose commitments from ingestion of foils containing 110 kBq (3 μCi) of ^{241}Am, we assumed 1% of the activity to escape from the foils. This would be equivalent to ingestion of ~1.1 kBq of ^{241}Am. This could give 50-year dose commitments of 0.48 mSv (48 mrem) to total body and 5.7 mSv (570 mrem) to bone.

REFERENCES

Belanger, R., D. W. Buckley, and J. B. Swenson. 1979. *Environmental Assessment of Ionization Chamber Smoke Detectors Containing Am-241.* NUREG/CR-1156.

Brinkerhoff, R. J. 1973. Inventory of intermediate-size incinerators in the United States — 1972. *Pollution Eng.* 5(11):33-38.

Cline, J. F. 1966. *Uptake of Am-241 and Pu-239 by Plants.* BNWL-CC-925.

Code of Federal Regulations. 1980. Title 10 — Energy. Chapter I — Nuclear Regulatory Commission. Part 30 — Rules of General Applicability fo Domestic Licensing of Byproduct Material. Section 30.20 — Gas and Aerosol Detectors Containing Byproduct Material.

Cutshall, N. H., I. L. Larsen, and F. N. Case. 1978. *High Temperature Testing of Smoke Detector Sources.* NUREG/CR-0403 (ORNL/NUREG/TM-246).

Dunning, D. E., Jr., S. R. Bernard, P. J. Walsh, G. G. Killough, and J. C. Pleasant. 1979. *Estimates of Internal Dose Equivalent to 22 Target Organs for Radionuclides Occurring in Routine Releases from Nuclear Fuel-Cycle Facilities, Vol. II.* NUREG/CR-0150, Vol. 2; ORNL/NUREG/TM-190/V2.

EAD Metallurgical. 1977. "Test Results for Foil Integrity." Attachment to letter to U.S. Nuclear Regulatory Commission. November 10, 1977.

Etnier, E. L., and F. R. O'Donnell. 1979. *A Summary of Procedures Used to Transport and Distribute Consumer Products.* ORNL/TM-6675.

General Electric Company. 1975. *Solid Waste Management Technology Assessment.* VanNostrand Reinhold Company. New York.

Hall, E. G., and D. G. Hunt. 1975. *A Summary of an Integrity Testing Programme on Alpha Foils Used in Ionization Smoke Detectors.* TRC Report No. 378. Amersham. The Radiochemical Centre, Ltd.

Hall, E. G., and D. G. Hunt. 1978. Integrity testing of radioactive sources used in consumer products. In *Radioactivity in Consumer Products,* ed. A. A. Moghissi et al., pp. 398-422. NUREG/CP-0001.

ICRP Committee 2 Task Group. 1972. The metabolism of compounds of plutonium and other actinides. *ICRP Publication 19*, Pergamon Press, Oxford.

ICRP Committee 2 Task Group. 1967. Deposition and retention models for internal dosimetry of the human respiratory tract. Errata and revisions to report. *Health Phys.* 13:1251.

Killough, G. G., D. E. Dunning, Jr., S. R. Bernard, and J. C. Pleasant. 1978. *Estimates of Internal Dose Equivalent to 22 Target Organs for Radionuclides Occurring in Routine Releases from Nuclear Fuel-Cycle Facilities*, Vol. II. NUREG/CR-0150 (ORNL/NUREG/TM-190).

Kocher, D. C. 1977. *Nuclear Decay Data for Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities*. ORNL/NUREG/TM-102.

Kocher, D. C. 1980. Dose-rate conversion factors for external exposure to photon and electron radiation from radionuclides occurring in routine releases from nuclear fuel cycle facilities. *Health Phys.* 38(4):543-621.

Moore, R. E. 1977. *The AIRDOS-II Computer Code for Estimating Radiation Doses to Man from Airborne Radionuclides in Areas Surrounding Nuclear Facilities*. ORNL-5245.

Morrow, P. E., D. V. Bates, B. R. Fish, T. F. Hatch, and T. T. Mercer. 1966. Deposition and retention models for internal dosimetry of the human respiratory tract. *Health Phys.* 12:173-207.

Niemeyer, R. G. 1969. *Containment Integrity of* ^{226}*Ra and* ^{241}*Am Foils Employed in Smoke Detectors*. ORNL/TM-2684.

Oak Ridge Fire Department. 1981. Telephone conversation between Chief McMahon and F. R. O'Donnell which revealed that almost all firemen, when entering or working near a burning building, wear self-contained breathing apparatus which are at least 99% effective in excluding ambient air from breathing air.

O'Donnell, F. R. 1978. Assessment of Radiation Doses from Radioactive Materials in Consumer Products — Methods, Problems and Results. In *Radioactivity in Consumer Products*, ed. A. A. Moghissi, et al., pp. 241-52. NUREG/CP-0001. U. S. Nuclear Regulatory Commission, Washington, D.C.

O'Donnell, F. R., D. C. Kocher, O. W. Burke, and F. H. Clark. 1981. *CONDOS-II — A Tool for Estimating Radiation Doses from Radionuclide-Containing Consumer Products.* NUREG/CR-2068; ORNL/NUREG/TM-454.

Organization for Economic Cooperation and Development. Nuclear Energy Agency. 1977. *Recommendations for Ionization Chamber Smoke Detectors in Implementation of Radiation Protection Standards.*

Poston, J. W., and W. S. Snyder. 1974. A model for exposure to a semi-infinite cloud of a photon emitter. *Health Phys.* 26(4):287-293.

Rundo, J., W. D. Fairman, M. Essling, and P. R. Huff. 1977. Ingestion of ^{241}Am sources intended for domestic smoke detectors: report of a case. *Health Phys.* 33(6):561-566.

U.S. Atomic Energy Commission (USAEC). 1974. Appendix II.I: Assumptions and Models Used to Assess Environmental Effects. In *Environmental Statement on Liquid Metal Fast Breeder Reactor Program,* Vol. 2. WASH-1535.

U.S. Department of Health, Education, and Welfare. 1981. *Radiological Health Handbook.* Rockville, Maryland.

U.S. Nuclear Regulatory Commission. 1978. "An Interim Staff Analysis of the Environmental Effects of Ionization Type Smoke Detectors." Unpublished staff report by Transportation and Product Standards Branch. Contact D. A. Smith.

Wrenn, M. E., and N. Cohen. 1979. *Assessment of Risks and Benefits of Home Ionization-Type Smoke Detectors.* Draft report prepared for the Ionization Smoke Detector Bureau of the National Electrical Manufacturers' Association.

APPENDIX A

DETAILED TABULATIONS OF EXPOSURE CONDITIONS

DETAILED TABULATIONS OF EXPOSURE CONDITIONS

The following definitions will be useful for interpreting the headings of Tables A.1-A-4:

TIME — duration (h/y) of exposure,

AIR:

- CONC — airborne concentration (g/cm^3) of radionuclides,
- RADIUS — radius (cm) of the air space,

AMT ING — mass (g) of ingested radionulides,

SOURCE:

- DESCRIPTION — source description,
- G — source geometry index number (1 indicates a point source; 11 indicates a cylindrical source),
- M — source material index number (14 = composite material used to represent cartons and pallets of smoke detectors),
- MASS — mass of thorium in the source (in g if G = 1; g/cm^3 if G = 11),
- LENGTH — length (cm) of a cylindrical source,
- RADIUS — radius (cm) of a cylindrical source,
- DISTANCE — distance (cm) between source and exposed persons,

ABSORBER:

- DESCRIPTION — absorber description,
- M — absorbing material index number (1 = aluminum and 13 = air), and
- THICK — thickness (cm) of the absorber.

TABLE A.1. EXPOSURE CONDITIONS FOR TRANSPORT OF 5 MILLION ICSD'S
FROM SUPPLIERS TO CHAIN STORE WAREHOUSES

		AIR:			SOURCE:							ABSORBER:		
	TIME (H/Y)	CONC (G /CM**3)	RADIUS (CM)	AMT ING (G)	DESCRIPTION	G, NO	M, NO	MASS (G)	LENGTH (CM)	RADIUS (CM)	DISTANC (CM)	DESCRIPTION	M, NO	THICK (CM)
					TRUCK DRIVERS									
OVER THE ROAD (2.0800E 02 MEMBERS) DRIVING	5.0E 01	0.0	0.0	0.0	50 PALLETS	11	14	1.4E-10	7.3E 02	1.5E 02	1.4E 02	TRUCK PARTS	1	5.0E-01
*					*							AIR	13	1.4E 02
					GENERAL PUBLIC, AVG.									
ON RURAL ROUTES (3.3310E 06 MEMBERS) ON ROUTES	4.5E-02	0.0	0.0	0.0	50 PALLETS	11	14	1.4E-10	1.8E 02	2.9E 02	1.8E 04	TRAILER WALL	1	1.8E-01
*					*							AIR	13	1.8E 04
ON BUSINESS ROUTES (1.9952E 07 MEMBERS) ON ROUTES	1.0E-01	0.0	0.0	0.0	50 PALLETS	11	14	1.4E-10	1.8E 02	2.9E 02	1.8E 04	TRAILER WALL	1	1.8E-01
*					*							AIR	13	1.8E 04
					GENERAL PUBLIC, MAX.									
ON BUSINESS ROUTES (1.0000E 00 MEMBERS) ON ROUTES	2.0E-02	0.0	0.0	0.0	50 PALLETS	11	14	1.4E-10	1.8E 02	2.9E 02	3.1E 03	TRAILER WALL	1	1.8E-01
*					*							AIR	13	3.0E 03

TABLE A.2. EXPOSURE CONDITIONS FOR TRANSPORT OF 5 MILLION ICSD'S
FROM SUPPLIERS TO WHOLESALE WAREHOUSES

	TIME (H/Y)	AIR: CONC (G /CM**3)	AIR: RADIUS (CM)	AMT ING (G)	SOURCE: DESCRIPTION	G, NO	M, NO	MASS (G)	LENGTH (CM)	RADIUS (CM)	DISTANC (CM)	ABSORBER: DESCRIPTION	M, NO	THICK (CM)
					TRUCK DRIVERS									
LOCAL PICKUP (1.4000E 01 MEMBERS)														
DRIVING	1.3E 02	0.0	0.0	0.0	10 PALLETS	11	14	1.4E-10	1.6E 02	1.5E 02	1.4E 02	TRUCK PARTS	1	5.0E-01
*					*							AIR	13	1.4E 02
REGIONAL (2.0820E 03 MEMBERS)														
DRIVING	2.5E 01	0.0	0.0	0.0	10 PALLETS	11	14	1.4E-10	1.6E 02	1.5E 02	1.4E 02	TRUCK PARTS	1	5.0E-01
*					*							AIR	13	1.4E 02
DELIVERY (6.9400E 02 MEMBERS)														
DRIVING	5.0E 00	0.0	0.0	0.0	10 PALLETS	11	14	1.4E-10	1.6E 02	1.5E 02	1.4E 02	TRUCK PARTS	1	5.0E-01
*					*							AIR	13	1.4E 02
HANDLE CARGO	2.0E 01	0.0	0.0	0.0	1 CARTON	11	14	2.8E-10	2.0E 01	1.2E 01	3.0E 01	AIR	13	3.0E 01
NEAR CARGO	1.3E 00	0.0	0.0	0.0	6 PALLETS	11	14	1.4E-10	8.1E 01	1.5E 02	9.0E 01	AIR	13	9.0E 01
AT DOCK	3.8E 00	0.0	0.0	0.0	6 PALLETS	11	14	1.4E-10	8.1E 01	1.5E 02	3.0E 02	AIR	13	3.0E 02
					TRUCK TERM. WORKERS									
LOCAL TERM. WORKERS (6.9000E 01 MEMBERS)														
LOAD AND UNLOAD	1.7E 01	0.0	0.0	0.0	1 PALLET	11	14	2.8E-10	8.1E 01	4.2E 01	1.2E 02	AIR	13	1.2E 02
NEAR CARGO	1.0E 02	0.0	0.0	0.0	6 PALLETS	11	14	1.4E-10	8.1E 01	1.5E 02	3.1E 02	AIR	13	3.1E 02
REG. TERM. WORKERS (2.0820E 03 MEMBERS)														
LOAD AND UNLOAD	8.5E-01	0.0	0.0	0.0	1 PALLET	11	14	2.8E-10	8.1E 01	4.2E 01	1.2E 02	AIR	13	1.2E 02
NEAR CARGO	1.0E 01	0.0	0.0	0.0	6 PALLETS	11	14	1.4E-10	8.1E 01	1.5E 02	3.1E 02	AIR	13	3.1E 02
					GENERAL PUBLIC, AVG.									
ON LOCAL PICKUP RTES (8.0500E 05 MEMBERS)														
ON ROUTES	4.2E 00	0.0	0.0	0.0	10 PALLETS	11	14	1.4E-10	1.8E 02	1.4E 02	1.8E 04	TRUCK WALL	1	1.8E-01
*					*							AIR	13	1.8E 04

TABLE A.2. (CONTINUED)

		AIR:			SOURCE:						ABSORBER:		
	TIME (H/Y)	CONC (G /CM**3)	RADIUS (CM)	AMT ING (G)	DESCRIPTION	G, M, NO NO	MASS (G)	LENGTH (CM)	RADIUS (CM)	DISTANC (CM)	DESCRIPTION	M, NO	THICK (CM)
ON BUSINESS ROUTES (1.9952E 08 MEMBERS) ON ROUTES *	5.0E-02	0.0	0.0	0.0	10 PALLETS *	11 14	1.4E-10	1.8E 02	1.4E 02	1.8E 04	TRUCK WALL AIR	1 13	1.8E-01 1.8E 04
ON RURAL ROUTES (3.3310E 06 MEMBERS) ON ROUTES *	2.3E-02	0.0	0.0	0.0	10 PALLETS *	11 14	1.4E-10	1.8E 02	1.4E 02	1.8E 04	TRUCK WALL AIR	1 13	1.8E-01 1.8E 04
ON DELIVERY ROUTES (3.9905E 07 MEMBERS) ON ROUTES *	8.3E-02	0.0	0.0	0.0	10 PALLETS *	11 14	1.4E-10	1.8E 02	1.4E 02	1.8E 04	TRUCK WALL AIR	1 13	1.8E-01 1.8E 04
					GENERAL PUBLIC, MAX.								
ON LOCAL PICKUP RTES (1.0000E 00 MEMBERS) ON ROUTES *	8.3E-01	0.0	0.0	0.0	10 PALLETS *	11 14	1.4E-10	1.8E 02	1.4E 02	3.1E 03	TRUCK WALL AIR	1 13	1.8E-01 3.0E 03

TABLE A.3. EXPOSURE CONDITIONS FOR DISTRIBUTION OF 5 MILLION ICSD'S FROM CHAIN STORE WAREHOUSES AND CHAIN STORES

	AIR:				SOURCE:							ABSORBER:		
	TIME (H/Y)	CONC (G /CM**3)	RADIUS (CM)	AMT ING (G)	DESCRIPTION	G, NO	M, NO	MASS (G)	LENGTH (CM)	RADIUS (CM)	DISTANC (CM)	DESCRIPTION	M, NO	THICK (CM)
					WAREHOUSE WORKERS									
FORKLIFT OPERATOR (6.9000E 01 MEMBERS)														
UNLOAD	4.2E 01	0.0	0.0	0.0	1 PALLET	11	14	2.8E-10	8.1E 01	4.2E 01	1.2E 02	AIR	13	1.2E 02
LOAD	2.5E 01	0.0	0.0	0.0	1 PALLET	11	14	2.8E-10	8.1E 01	4.2E 01	1.2E 02	AIR	13	1.2E 02
*					2/3 PALLET	11	14	2.8E-10	8.1E 01	3.4E 01	1.2E 02	AIR	13	1.2E 02
OTHER UNLOADERS (6.9400E 02 MEMBERS)														
NEAR TRUCKS	5.0E 01	0.0	0.0	0.0	24 PALLETS	11	14	1.4E-10	3.7E 02	1.5E 02	6.1E 02	AIR	13	6.1E 02
STOCK HANDLERS (6.9400E 02 MEMBERS)														
HANDLE CARTONS	8.3E-01	0.0	0.0	0.0	1 CARTON	11	14	2.8E-10	2.0E 01	1.2E 01	3.0E 01	AIR	13	3.0E 01
NEAR STORED PALLETS	2.5E 02	0.0	0.0	0.0	24 PALLETS	11	14	1.4E-10	3.7E 02	1.5E 02	3.0E 02	AIR	13	3.0E 02
LOADERS (6.9400E 02 MEMBERS)														
LOADING TRUCKS	2.0E 01	0.0	0.0	0.0	1 PALLET	11	14	2.8E-10	8.1E 01	4.2E 01	3.0E 02	AIR	13	3.0E 02
*					2/3 PALLET	11	14	2.8E-10	8.1E 01	3.4E 01	3.0E 02	AIR	13	3.0E 02
					TRUCK DRIVERS									
DELIVERY DRIVERS (2.0830E 03 MEMBERS)														
DRIVING	2.5E 01	0.0	0.0	0.0	1.67 PALLETS	11	14	2.8E-10	8.1E 01	5.4E 01	6.1E 02	TRUCK PARTS	1	5.0E-01
*					*							AIR	13	6.1E 02
HANDLING CARTONS	6.7E 00	0.0	0.0	0.0	1 CARTON	11	14	2.8E-10	2.0E 01	1.2E 01	3.0E 01	AIR	13	3.0E 01
NEAR CARGO	1.0E 01	0.0	0.0	0.0	.83 PALLET	11	14	2.8E-10	4.1E 01	5.4E 01	3.0E 02	AIR	13	3.0E 02
					LARGE STORE WORKERS									
STOCK CLERKS (4.1670E 03 MEMBERS)														
CHECK SHIPMENT	4.2E-01	0.0	0.0	0.0	1.67 PALLETS	11	14	2.8E-10	8.1E 01	5.4E 01	9.0E 01	AIR	13	9.0E 01
HANDLE CARTONS	6.7E 00	0.0	0.0	0.0	1 CARTON	11	14	2.8E-10	2.0E 01	1.2E 01	3.0E 01	AIR	13	3.0E 01
NEAR CARTONS	5.0E 02	0.0	0.0	0.0	1.67 PALLETS	11	14	2.8E-10	8.1E 01	5.4E 01	4.5E 02	AIR	13	4.5E 02

TABLE A.3. (CONTINUED)

		AIR:			SOURCE:							ABSORBER:		
	TIME (H/Y)	CONC (G /CM**3)	RADIUS (CM)	AMT ING (G)	DESCRIPTION	G, NO	M, NO	MASS (G)	LENGTH (CM)	RADIUS (CM)	DISTANC (CM)	DESCRIPTION	M, NO	THICK (CM)
SALES CLERKS (8.3330E 03 MEMBERS)														
HANDLE BOXED DETECT.	1.0E 01	0.0	0.0	0.0	1 BOX	11	14	2.8E-10	7.6E 00	1.2E 01	3.0E 01	AIR	13	3.0E 01
HANDLE CARTONS	3.3E 00	0.0	0.0	0.0	1 CARTON	11	14	2.8E-10	2.0E 01	1.2E 01	3.0E 01	AIR	13	3.0E 01
NEAR DISPLAY	2.5E 02	0.0	0.0	0.0	144 DETECTOR	11	14	2.8E-10	8.1E 01	4.2E 01	3.0E 02	AIR	13	3.0E 02
OTHER WORK	1.8E 03	0.0	0.0	0.0	144 DETECTOR	11	14	2.8E-10	8.1E 01	4.2E 01	6.0E 02	AIR	13	6.0E 02
OTHER CLERKS (8.3330E 03 MEMBERS)														
IN SALES AREA	1.0E 03	0.0	0.0	0.0	144 DETECTOR	11	14	2.8E-10	8.1E 01	4.2E 01	1.5E 03	AIR	13	1.5E 03
					GENERAL PUBLIC, AVG.									
STORE CUSTOMERS (2.1000E 08 MEMBERS)														
IN STORE	1.2E 01	0.0	0.0	0.0	144 DETECTOR	11	14	2.8E-10	8.1E 01	4.2E 01	6.0E 02	AIR	13	6.0E 02
ON RURAL TRUCK RTES. (1.8000E 08 MEMBERS)														
ON ROUTES	1.0E-01	0.0	0.0	0.0	1.67 PALLETS	11	14	2.8E-10	8.1E 01	5.4E 01	1.8E 04	TRUCK WALL	1	1.8E-01
*					*							AIR	13	1.8E 04
ON CITY TRUCK RTES. (2.1000E 08 MEMBERS)														
ON ROUTES	1.7E-01	0.0	0.0	0.0	1.67 PALLETS	11	14	2.8E-10	8.1E 01	5.4E 01	1.8E 04	TRUCK WALL	1	1.8E-01
*					*							AIR	13	1.8E 04
					GENERAL PUBLIC, MAX.									
ON CITY TRUCK RTES. (1.0000E 00 MEMBERS)														
ON ROUTES	3.3E-02	0.0	0.0	0.0	1.67 PALLETS	11	14	2.8E-10	8.1E 01	5.4E 01	3.1E 03	TRUCK WALL	1	1.8E-01
*					*							AIR	13	3.0E 03

TABLE A.4. EXPOSURE CONDITIONS FOR DISTRIBUTION OF 5 MILLION ICSD'S FROM WHOLESALE WAREHOUSES AND SMALL RETAIL STORES

		AIR:			SOURCE:							ABSORBER:		
	TIME (H/Y)	CONC (G /CM**3)	RADIUS (CM)	AMT ING (G)	DESCRIPTION	G, NO	M, NO	MASS (G)	LENGTH (CM)	RADIUS (CM)	DISTANC (CM)	DESCRIPTION	M, NO	THICK (CM)
					WAREHOUSE WORKERS									
RECEIVERS (6.9400E 02 MEMBERS)														
NEAR SHIPMENTS	5.0E 00	0.0	0.0	0.0	10 PALLETS	11	14	1.4E-10	1.6E 02	1.5E 02	3.0E 02	AIR	13	3.0E 02
FORKLIFT OPERATORS (6.9400E 02 MEMBERS)														
MOVE PALLETS	4.2E 00	0.0	0.0	0.0	1 PALLET	11	14	2.8E-10	8.1E 01	4.2E 01	1.2E 02	AIR	13	1.2E 02
STOCK HANDLERS (3.4700E 03 MEMBERS)														
HANDLE CARTONS	2.0E 00	0.0	0.0	0.0	1 CARTON	11	14	2.8E-10	2.0E 01	1.2E 01	3.0E 01	AIR	13	3.0E 01
NEAR STORED CARTONS	2.5E 02	0.0	0.0	0.0	6 PALLETS	11	14	1.4E-10	8.1E 01	1.5E 02	3.0E 02	AIR	13	3.0E 02
MOVE SHIPMENTS	1.5E 01	0.0	0.0	0.0	8 CARTONS	11	14	2.8E-10	4.1E 01	2.4E 01	1.2E 02	AIR	13	1.2E 02
LOADERS (2.0820E 03 MEMBERS)														
HANDLE CARTONS	6.7E 00	0.0	0.0	0.0	1 CARTON	11	14	2.8E-10	2.0E 01	1.2E 01	3.0E 01	AIR	13	3.0E 01
NEAR SHIPMENTS	1.0E 02	0.0	0.0	0.0	8 CARTONS	11	14	2.8E-10	4.1E 01	2.4E 01	3.0E 02	AIR	13	3.0E 02
					TRUCK DRIVERS									
DELIVERY DRIVERS (1.0410E 04 MEMBERS)														
DRIVING	1.0E 02	0.0	0.0	0.0	8 CARTONS	11	14	2.8E-10	4.1E 01	2.4E 01	1.8E 02	TRUCK PARTS	1	5.0E 00
*					*							AIR	13	1.8E 02
UNLOADING CARTONS	1.3E 00	0.0	0.0	0.0	1 CARTON	11	14	2.8E-10	2.0E 01	1.2E 01	3.0E 01	AIR	13	3.0E 01
NEAR SHIPMENT	2.0E 01	0.0	0.0	0.0	4 CARTONS	11	14	2.8E-10	2.0E 01	2.4E 01	3.0E 02	AIR	13	3.0E 02
					SMALL STORE WORKERS									
STOCK CLERKS (2.0820E 05 MEMBERS)														
HANDLE CARTONS	6.7E-01	0.0	0.0	0.0	1 CARTON	11	14	2.8E-10	2.0E 01	1.2E 01	3.0E 01	AIR	13	3.0E 01

TABLE A.4. (CONTINUED)

		AIR:			SOURCE:							ABSORBER:		
	TIME (H/Y)	CONC (G /CM**3)	RADIUS (CM)	AMT ING (G)	DESCRIPTION	G, NO	M, NO	MASS (G)	LENGTH (CM)	RADIUS (CM)	DISTANC (CM)	DESCRIPTION	M, NO	THICK (CM)
SALES CLERKS (4.1640E 05 MEMBERS)														
HANDLE BOXED DETECT.	1.0E 00	0.0	0.0	0.0	1 DETECTOR	11	14	2.8E-10	7.6E 00	1.2E 01	3.0E 01	AIR	13	3.0E 01
NEAR DISPLAY	1.0E 03	0.0	0.0	0.0	12 DETECTORS	11	14	2.8E-10	2.0E 01	2.4E 01	3.0E 02	AIR	13	3.0E 02
OTHER WORK	1.0E 03	0.0	0.0	0.0	12 DETECTORS	11	14	2.8E-10	2.0E 01	2.4E 01	6.0E 02	AIR	13	6.0E 02
					GENERAL PUBLIC, AVG.									
STORE CUSTOMERS (2.1000E 08 MEMBERS)														
IN STORE	4.0E 01	0.0	0.0	0.0	12 DETECTORS	11	14	2.8E-10	2.0E 01	2.4E 01	6.0E 02	AIR	13	6.0E 02
NEAR DISPLAY	1.0E 01	0.0	0.0	0.0	12 DETECTORS	11	14	2.8E-10	2.0E 01	2.4E 01	3.0E 02	AIR	13	3.0E 02
ON TRUCK ROUTES (2.1000E 08 MEMBERS)														
ON ROUTES	3.3E-01	0.0	0.0	0.0	8 CARTONS	11	14	2.8E-10	4.1E 01	2.4E 01	1.8E 04	TRUCK WALL	1	1.8E-01
*					*							AIR	13	1.8E 04
					GENERAL PUBLIC, MAX.									
ON TRUCK ROUTES (1.0000E 00 MEMBERS)														
ON ROUTES	6.7E-02	0.0	0.0	0.0	8 CARTONS	11	14	2.8E-10	4.1E 01	2.4E 01	3.1E 03	TRUCK WALL	1	1.8E-01
*					*							AIR	13	3.0E 03

APPENDIX B

DETAILED TABULATIONS OF RADIATION DOSES

TABLE B.1. RADIATION DOSES FROM TRANSPORT OF 5 MILLION ICSD'S FROM SUPPLIERS TO CHAIN STORE WAREHOUSES

DOSES TO WHOLE BODY

	INDIVIDUAL DOSE EQUIVALENT, SV			POPULATION DOSE EQUIVALENT, PERSON-SV
	EXTERNAL	INTERNAL	TOTAL	
	TRUCK DRIVERS			
OVER THE ROAD (2.080E 02 MEMBERS) DRIVING	3.33E-08	0.0	3.33E-08	6.92E-06
DOSE TO OVER THE ROAD	3.33E-08	0.0	3.33E-08	6.92E-06
SUMMARY OF DOSES FOR TRUCK DRIVERS		: LOWEST	3.33E-08	
		HIGHEST	3.33E-08	
		TOTAL		6.92E-06
	GENERAL PUBLIC, AVG.			
ON RURAL ROUTES (3.331E 06 MEMBERS) ON ROUTES	7.36E-15	0.0	7.36E-15	2.45E-08
DOSE TO ON RURAL ROUTES	7.36E-15	0.0	7.36E-15	2.45E-08
ON BUSINESS ROUTES (1.995E 07 MEMBERS) ON ROUTES	1.62E-14	0.0	1.62E-14	3.23E-07
DOSE TO ON BUSINESS ROUTES	1.62E-14	0.0	1.62E-14	3.23E-07
SUMMARY OF DOSES FOR GENERAL PUBLIC, AVG.		: LOWEST	7.36E-15	
		HIGHEST	1.62E-14	
		TOTAL		3.47E-07
	GENERAL PUBLIC, MAX.			
ON BUSINESS ROUTES (1.000E 00 MEMBERS) ON ROUTES	2.03E-13	0.0	2.03E-13	0.0
DOSE TO ON BUSINESS ROUTES	2.03E-13	0.0	2.03E-13	0.0
SUMMARY OF DOSES FOR GENERAL PUBLIC, MAX.		: LOWEST	2.03E-13	
		HIGHEST	2.03E-13	
		TOTAL		0.0
SUMMARY OF DOSES FOR TRANSPORT		: LOWEST	7.36E-15	
		HIGHEST	3.33E-08	
		TOTAL		7.27E-06

TABLE B.2. RADIATION DOSES FROM TRANSPORT OF 5 MILLION ICSD'S FROM SUPPLIERS TO WHOLESALE WAREHOUSES

DOSES TO WHOLE BODY

	INDIVIDUAL DOSE EQUIVALENT, SV			POPULATION DOSE EQUIVALENT, PERSON-SV
	EXTERNAL	INTERNAL	TOTAL	
TRUCK DRIVERS				
LOCAL PICKUP (1.400E 01 MEMBERS)				
DRIVING	8.32E-08	0.0	8.32E-08	1.17E-06
DOSE TO LOCAL PICKUP	8.32E-08	0.0	8.32E-08	1.17E-06
REGIONAL (2.082E 03 MEMBERS)				
DRIVING	1.66E-08	0.0	1.66E-08	3.47E-05
DOSE TO REGIONAL	1.66E-08	0.0	1.66E-08	3.47E-05
DELIVERY (6.940E 02 MEMBERS)				
DRIVING	3.33E-09	0.0	3.33E-09	2.31E-06
HANDLE CARGO	7.47E-09	0.0	7.47E-09	5.18E-06
NEAR CARGO	1.60E-09	0.0	1.60E-09	1.11E-06
AT DOCK	1.01E-09	0.0	1.01E-09	6.99E-07
DOSE TO DELIVERY	1.34E-08	0.0	1.34E-08	9.30E-06
SUMMARY OF DOSES FOR TRUCK DRIVERS		: LOWEST	1.34E-08	
		HIGHEST	8.32E-08	
		TOTAL		4.51E-05
TRUCK TERM. WORKERS				
LOCAL TERM. WORKERS (6.900E 01 MEMBERS)				
LOAD AND UNLOAD	5.12E-09	0.0	5.12E-09	3.53E-07
NEAR CARGO	2.61E-08	0.0	2.61E-08	1.80E-06
DOSE TO LOCAL TERM. WORKERS	3.12E-08	0.0	3.12E-08	2.15E-06
REG. TERM. WORKERS (2.082E 03 MEMBERS)				
LOAD AND UNLOAD	2.56E-10	0.0	2.56E-10	5.32E-07
NEAR CARGO	2.61E-09	0.0	2.61E-09	5.43E-06
DOSE TO REG. TERM. WORKERS	2.87E-09	0.0	2.87E-09	5.97E-06
SUMMARY OF DOSES FOR TRUCK TERM. WORKERS		: LOWEST	2.87E-09	
		HIGHEST	3.12E-08	
		TOTAL		8.12E-06

TABLE B.2. (CONTINUED)

	INDIVIDUAL DOSE EQUIVALENT, SV			POPULATION DOSE EQUIVALENT, PERSON-SV
	EXTERNAL	INTERNAL	TOTAL	
	GENERAL PUBLIC, AVG.			
ON LOCAL PICKUP RTES (8.050E 05 MEMBERS)				
ON ROUTES	1.52E-13	0.0	1.52E-13	1.22E-07
DOSE TO ON LOCAL PICKUP RTES	1.52E-13	0.0	1.52E-13	1.22E-07
ON BUSINESS ROUTES (1.995E 08 MEMBERS)				
ON ROUTES	1.81E-15	0.0	1.81E-15	3.61E-07
DOSE TO ON BUSINESS ROUTES	1.81E-15	0.0	1.81E-15	3.61E-07
ON RURAL ROUTES (3.331E 06 MEMBERS)				
ON ROUTES	8.32E-16	0.0	8.32E-16	2.77E-09
DOSE TO ON RURAL ROUTES	8.32E-16	0.0	8.32E-16	2.77E-09
ON DELIVERY ROUTES (3.990E 07 MEMBERS)				
ON ROUTES	3.00E-15	0.0	3.00E-15	1.20E-07
DOSE TO ON DELIVERY ROUTES	3.00E-15	0.0	3.00E-15	1.20E-07
SUMMARY OF DOSES FOR GENERAL PUBLIC, AVG.:		LOWEST	8.32E-16	
		HIGHEST	1.52E-13	
		TOTAL		6.05E-07
	GENERAL PUBLIC, MAX.			
ON LOCAL PICKUP RTES (1.000E 00 MEMBERS)				
ON ROUTES	1.90E-12	0.0	1.90E-12	0.0
DOSE TO ON LOCAL PICKUP RTES	1.90E-12	0.0	1.90E-12	0.0
SUMMARY OF DOSES FOR GENERAL PUBLIC, MAX.:		LOWEST	1.90E-12	
		HIGHEST	1.90E-12	
		TOTAL		0.0
SUMMARY OF DOSES FOR TRANSPORT :		LOWEST	8.32E-16	
		HIGHEST	8.32E-08	
		TOTAL		5.39E-05

TABLE B.3. RADIATION DOSES FROM DISTRIBUTION OF 5 MILLION ICSD'S
FROM CHAIN STORE WAREHOUSES AND CHAIN STORES

DOSES TO WHOLE BODY

	INDIVIDUAL DOSE EQUIVALENT, SV			POPULATION DOSE EQUIVALENT, PERSON-SV
	EXTERNAL	INTERNAL	TOTAL	
	WAREHOUSE WORKERS			
FORKLIFT OPERATOR (6.900E 01 MEMBERS)				
UNLOAD	1.25E-08	0.0	1.25E-08	8.66E-07
LOAD	1.27E-08	0.0	1.27E-08	8.75E-07
DOSE TO FORKLIFT OPERATOR	2.52E-08	0.0	2.52E-08	1.74E-06
OTHER UNLOADERS (6.940E 02 MEMBERS)				
NEAR TRUCKS	3.60E-09	0.0	3.60E-09	2.50E-06
DOSE TO OTHER UNLOADERS	3.60E-09	0.0	3.60E-09	2.50E-06
STOCK HANDLERS (6.940E 02 MEMBERS)				
HANDLE CARTONS	3.13E-10	0.0	3.13E-10	2.17E-07
NEAR STORED PALLETS	6.71E-08	0.0	6.71E-08	4.66E-05
DOSE TO STOCK HANDLERS	6.74E-08	0.0	6.74E-08	4.68E-05
LOADERS (6.940E 02 MEMBERS)				
LOADING TRUCKS	1.73E-09	0.0	1.73E-09	1.20E-06
DOSE TO LOADERS	1.73E-09	0.0	1.73E-09	1.20E-06
SUMMARY OF DOSES FOR WAREHOUSE WORKERS		: LOWEST	1.73E-09	
		HIGHEST	6.74E-08	
		TOTAL		5.22E-05
	TRUCK DRIVERS			
DELIVERY DRIVERS (2.083E 03 MEMBERS)				
DRIVING	4.36E-10	0.0	4.36E-10	9.08E-07
HANDLING CARTONS	2.50E-09	0.0	2.50E-09	5.21E-06
NEAR CARGO	8.55E-10	0.0	8.55E-10	1.78E-06
DOSE TO DELIVERY DRIVERS	3.79E-09	0.0	3.79E-09	7.89E-06
SUMMARY OF DOSES FOR TRUCK DRIVERS		: LOWEST	3.79E-09	
		HIGHEST	3.79E-09	
		TOTAL		7.89E-06
	LARGE STORE WORKERS			
STOCK CLERKS (4.167E 03 MEMBERS)				
CHECK SHIPMENT	3.21E-10	0.0	3.21E-10	1.34E-06
HANDLE CARTONS	2.51E-09	0.0	2.51E-09	1.04E-05
NEAR CARTONS	1.91E-08	0.0	1.91E-08	7.96E-05
DOSE TO STOCK CLERKS	2.19E-08	0.0	2.19E-08	9.14E-05

TABLE B.3. (CONTINUED)

	INDIVIDUAL DOSE EQUIVALENT, SV			POPULATION DOSE EQUIVALENT, PERSON-SV
	EXTERNAL	INTERNAL	TOTAL	
SALES CLERKS (8.333E 03 MEMBERS)				
HANDLE BOXED DETECT.	3.37E-09	0.0	3.37E-09	2.81E-05
HANDLE CARTONS	1.25E-09	0.0	1.25E-09	1.04E-05
NEAR DISPLAY	1.29E-08	0.0	1.29E-08	1.08E-04
OTHER WORK	2.25E-08	0.0	2.25E-08	1.88E-04
DOSE TO SALES CLERKS	4.01E-08	0.0	4.01E-08	3.34E-04
OTHER CLERKS (8.333E 03 MEMBERS)				
IN SALES AREA	1.98E-09	0.0	1.98E-09	1.65E-05
DOSE TO OTHER CLERKS	1.98E-09	0.0	1.98E-09	1.65E-05
SUMMARY OF DOSES FOR LARGE STORE WORKERS :		LOWEST	1.98E-09	
		HIGHEST	4.01E-08	
		TOTAL		4.42E-04
	GENERAL PUBLIC, AVG.			
STORE CUSTOMERS (2.100E 08 MEMBERS)				
IN STORE	1.54E-10	0.0	1.54E-10	3.24E-02
DOSE TO STORE CUSTOMERS	1.54E-10	0.0	1.54E-10	3.24E-02
ON RURAL TRUCK RTES. (1.800E 08 MEMBERS)				
ON ROUTES	1.12E-15	0.0	1.12E-15	2.02E-07
DOSE TO ON RURAL TRUCK RTES.	1.12E-15	0.0	1.12E-15	2.02E-07
ON CITY TRUCK RTES. (2.100E 08 MEMBERS)				
ON ROUTES	1.91E-15	0.0	1.91E-15	4.01E-07
DOSE TO ON CITY TRUCK RTES.	1.91E-15	0.0	1.91E-15	4.01E-07
SUMMARY OF DOSES FOR GENERAL PUBLIC, AVG.:		LOWEST	1.12E-15	
		HIGHEST	1.54E-10	
		TOTAL		3.24E-02
	GENERAL PUBLIC, MAX.			
ON CITY TRUCK RTES. (1.000E 00 MEMBERS)				
ON ROUTES	2.34E-14	0.0	2.34E-14	0.0
DOSE TO ON CITY TRUCK RTES.	2.34E-14	0.0	2.34E-14	0.0
SUMMARY OF DOSES FOR GENERAL PUBLIC, MAX.:		LOWEST	2.34E-14	
		HIGHEST	2.34E-14	
		TOTAL		0.0
SUMMARY OF DOSES FOR DISTRIBUTION :		LOWEST	1.12E-15	
		HIGHEST	6.74E-08	
		TOTAL		3.29E-02

TABLE B.4. RADIATION DOSES FROM DISTRIBUTION OF 5 MILLION ICSD'S FROM WHOLESALE WAREHOUSES AND SMALL RETAIL STORES

DOSES TO WHOLE BODY

	INDIVIDUAL DOSE EQUIVALENT, SV			POPULATION DOSE EQUIVALENT, PERSON-SV
	EXTERNAL	INTERNAL	TOTAL	
	WAREHOUSE WORKERS			
RECEIVERS (6.940E 02 MEMBERS)				
NEAR SHIPMENTS	1.34E-09	0.0	1.34E-09	9.32E-07
DOSE TO RECEIVERS	1.34E-09	0.0	1.34E-09	9.32E-07
FORKLIFT OPERATORS (6.940E 02 MEMBERS)				
MOVE PALLETS	1.25E-09	0.0	1.25E-09	8.71E-07
DOSE TO FORKLIFT OPERATORS	1.25E-09	0.0	1.25E-09	8.71E-07
STOCK HANDLERS (3.470E 03 MEMBERS)				
HANDLE CARTONS	7.51E-10	0.0	7.51E-10	2.60E-06
NEAR STORED CARTONS	6.71E-08	0.0	6.71E-08	2.33E-04
MOVE SHIPMENTS	1.59E-09	0.0	1.59E-09	5.52E-06
DOSE TO STOCK HANDLERS	6.95E-08	0.0	6.95E-08	2.41E-04
LOADERS (2.082E 03 MEMBERS)				
HANDLE CARTONS	2.50E-09	0.0	2.50E-09	5.21E-06
NEAR SHIPMENTS	1.74E-09	0.0	1.74E-09	3.62E-06
DOSE TO LOADERS	4.24E-09	0.0	4.24E-09	8.83E-06
SUMMARY OF DOSES FOR WAREHOUSE WORKERS		: LOWEST	1.25E-09	
		HIGHEST	6.95E-08	
		TOTAL		2.52E-04
	TRUCK DRIVERS			
DELIVERY DRIVERS (1.041E 04 MEMBERS)				
DRIVING	1.03E-09	0.0	1.03E-09	1.07E-05
UNLOADING CARTONS	4.99E-10	0.0	4.99E-10	5.20E-06
NEAR SHIPMENT	3.48E-10	0.0	3.48E-10	3.62E-06
DOSE TO DELIVERY DRIVERS	1.87E-09	0.0	1.87E-09	1.95E-05
SUMMARY OF DOSES FOR TRUCK DRIVERS		: LOWEST	1.87E-09	
		HIGHEST	1.87E-09	
		TOTAL		1.95E-05
	SMALL STORE WORKERS			
STOCK CLERKS (2.082E 05 MEMBERS)				
HANDLE CARTONS	2.50E-10	0.0	2.50E-10	5.20E-05
DOSE TO STOCK CLERKS	2.50E-10	0.0	2.50E-10	5.20E-05

TABLE B.4. (CONTINUED)

	INDIVIDUAL DOSE EQUIVALENT, SV			POPULATION DOSE EQUIVALENT, PERSON-SV
	EXTERNAL	INTERNAL	TOTAL	
SALES CLERKS (4.164E 05 MEMBERS)				
HANDLE BOXED DETECT.	3.37E-10	0.0	3.37E-10	1.40E-04
NEAR DISPLAY	1.74E-08	0.0	1.74E-08	7.24E-03
OTHER WORK	4.30E-09	0.0	4.30E-09	1.79E-03
DOSE TO SALES CLERKS	2.20E-08	0.0	2.20E-08	9.17E-03
SUMMARY OF DOSES FOR SMALL STORE WORKERS :		LOWEST	2.50E-10	
		HIGHEST	2.20E-08	
		TOTAL		9.22E-03
	GENERAL PUBLIC, AVG.			
STORE CUSTOMERS (2.100E 08 MEMBERS)				
IN STORE	1.72E-10	0.0	1.72E-10	3.61E-02
NEAR DISPLAY	1.74E-10	0.0	1.74E-10	3.65E-02
DOSE TO STORE CUSTOMERS	3.46E-10	0.0	3.46E-10	7.26E-02
ON TRUCK ROUTES (2.100E 08 MEMBERS)				
ON ROUTES	7.47E-16	0.0	7.47E-16	1.57E-07
DOSE TO ON TRUCK ROUTES	7.47E-16	0.0	7.47E-16	1.57E-07
SUMMARY OF DOSES FOR GENERAL PUBLIC, AVG.:		LOWEST	7.47E-16	
		HIGHEST	3.46E-10	
		TOTAL		7.26E-02
	GENERAL PUBLIC, MAX.			
ON TRUCK ROUTES (1.000E 00 MEMBERS)				
ON ROUTES	9.46E-15	0.0	9.46E-15	0.0
DOSE TO ON TRUCK ROUTES	9.46E-15	0.0	9.46E-15	0.0
SUMMARY OF DOSES FOR GENERAL PUBLIC, MAX.:		LOWEST	9.46E-15	
		HIGHEST	9.46E-15	
		TOTAL		0.0
SUMMARY OF DOSES FOR DISTRIBUTION :		LOWEST	7.47E-16	
		HIGHEST	6.95E-08	
		TOTAL		8.21E-02

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