NUREG/CR-1156

Environmental Assessment of Ionization Chamber Smoke Detectors Containing Am-241

Prepared by R. Belanger, D. W. Buckley and J. B. Swensen

Science Applications, Inc.

Prepared for
U. S. Nuclear Regulatory
Commission

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GPO Sales Program
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U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

and

National Technical Information Service
Springfield, Virginia 22161

NUREG/CR-1156
SAI 01379-729LJ

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Manuscript Completed: October 1979
Date Published: November 1979

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Washington, D.C. 20555
NRC-02-78-045

EXECUTIVE SUMMARY

Residential fires continue to pose a major problem in the United States, ranking as the second most frequent cause of accidental death in the home. Between 7,500 and 12,000 lives are lost in fires every year with 70 percent of these occurring in residential fires. Residential property loss due to fires is over one billion dollars annually. A key element in reducing loss of life and property is early detection of fires. Various devices are available that detect flames, heat, or products of combustion. In recent years devices that detect products of combustion have been introduced to the consumer market and their sales have increased dramatically. These so-called "smoke" detectors are of two types. The majority have been of the ionization chamber smoke detector (ICSD) type which contains small amounts of radioactive material. The remainder have been of the photoelectric type which contains no radioactive material. A combination detector has been recently marketed that contains both an ICSD and a photoelectric detector. Based on theoretical studies and case histories, the estimated percent of residential fire-related deaths that smoke detectors could save is between 41 and 89 percent.

Most ionization chamber smoke detectors contain americium-241 (Am-241), a radioactive substance that emits ionizing radiation. Other radionuclides could be used in place of Am-241. In the past, radium-226 (Ra-226) has been used in detectors, but at present it is not employed in the consumer product. Nickel-63 (Ni-63) is presently being studied for use in consumer smoke detectors, having already been used in commercial applications such as in large warehouses. The user of an Am-241 ICSD is exempt from regulations, but the manufacturer must apply for and obtain a specific license from the Nuclear Regulatory Commission to distribute the product. The license is granted only after the applicant has demonstrated that the product is designed and will be manufactured in a manner such that specific requirements and safety criteria are met.

Since 1972-1973, the residential market for Am-241 ICSD's has increased rapidly. Fourteen million units containing a total of 41 curies of Am-241 were distributed in 1978 and 26 million units have been distributed since 1972. Based

upon present projections, about 90 million units will be distributed by 1986. The peak year of distribution should be 1978. The average activity per unit in 1978 was 3 uCi and projections indicate this will become lower in the future.

The distribution of photoelectric detectors has been minimal compared to ICSD's. Early photoelectric units were not as reliable as comparable ICSD's because of various reasons, in particular, the use of incandescent bulbs. The introduction of low-power light emitting diodes has improved their reliability considerably. The cost of photoelectric units is greater than the cost of comparable Am-241 ICSD's, basically because of slightly more complex circuitry. The photoelectric units have been found to react quicker to smoldering or slow-burning fires while the ICSD's react quicker to fast-burning fires. Both appear to have responses comparable in terms of saving lives. However, it is felt the ICSD units may have a slight edge over the photoelectric units since response is more critical to fast-burning fires.

The nonradiological impacts due to use of both ICSD's and photoelectric detectors have been determined to be slight and indistinguishable from one another. For a typical residential installation, the risk of an occupant being exposed to nonradiological toxic products, due to burning for example, is judged to be extremely small.

The use of Am-241 ICSD's does result in exposure of people to low levels of radiation. Analysis shows that the manufacture, distribution, normal use, and disposal of 14 million Am-241 ICSD's each containing 3 uCi of Am-241 will result in a collective total body dose of 1100 person-rem. The useful life is assumed to be ten years. Disposal is by either sanitary landfill or incineration. Fourteen million ICSD's will service about 21 million people. Analysis also shows the risk to the exposed population is about 0.1 fatal cancer. The normally-occurring cancer mortality rate for the total population of the United States is about 370,000 per year or about 35,000 per year for a group of 21 million people.

A comparison of these numbers illustrates the relatively small risk involved in using an Am-241 ICSD. It should be noted the 370,000 cancer deaths per year are actual deaths while the 0.1 fatal cancer over ten years of ICSD use was calculated using conservative assumptions. The ratio of the potential lives saved to the possible fatal cancers due to use of ICSD's ranges from 15,000 to 51,000.

Analysis of potential accidents with Am-241 ICSD's showed the dose commitments received by maximally exposed individuals to be significantly within the safety criteria standards required by the Nuclear Regulatory Commission.

Comparative analyses based upon cost, risk, and benefits, found present day Am-241 ICSD's to be preferable to ICSD's with other radionuclides and preferable to present day photoelectric detectors. The best available unit for fire protection was found to be the recently marketed combination detector. The cost of a combination unit is considerably more than the Am-241 ICSD and data is lacking on how much more sensitive it is. Therefore, the cost-effectiveness of combination units compared to Am-241 ICSD's is unknown.

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1. SUMMARY

1.1 OBJECTIVE

Since the issuance of the National Environmental Policy Act (NEPA) of 1969, all agencies of the Federal Government are required to prepare detailed environmental impact statements (EIS) on proposals for legislation and other major Federal actions significantly affecting the quality of the human environment. The main objective of these studies is the careful consideration of environmental aspects of proposed actions. Licensing and regulatory policy and procedures for environmental protection as related to the NRC are stated in the Code of Federal Regulations, Title 10, Part 51 (10CFR51).

At present, the Nuclear Regulatory Commission (NRC) is reevaluating the adequacy of existing policy dealing with the distribution of consumer products containing radioactive material. One such consumer product is the ionization chamber smoke detector (ICSD), which in recent years has become widely distributed.

The objective of this report is the assessment of the impact of ICSD's on people and the environment. An assessment of benefits and risks is made for presently-distributed ICSD's and possible alternatives. The work should prove to be an important source of information for a generic environmental impact statement (GEIS) on consumer products containing radioactive material which will be written in the future.

1.2 APPROACH

The approach to be followed in this report is to cover all topics necessary to arrive at a comprehensive assessment of ionization chamber smoke detectors. First a general overview or background information on ionization chamber smoke detectors and fire detection is given. A discussion of types of ICSD's, possible radionuclides used, regulations and guidelines, distribution, and description of life span activities is included.

A discussion of the environmental impact of the use of ICSD's follows. The benefits derived from ICSD usage include the saving of lives and property due to early detection of fires. The adverse impacts include both radiological and nonradiological aspects. The radiological impacts are expressed in terms of health effects from exposures and dose commitments acquired during the life span of the ICSD's. Included in the discussion of radiological impacts is the disposal of ICSD's at the end of their useful life. The resulting exposures and dose commitments are estimated for various disposal scenarios including landfill and incineration. Possible accidents or misuses of ICSD's are discussed as potential environmental impacts. Calculated dose and dose commitments are compared to NRC safety criteria as found in the Code of Federal Regulations under Title 10, Energy.

The next section deals with alternatives to present day ICSD's. The discussion includes reduction of activity in detectors, use of different radionuclides, and various alternatives such as photoelectric detectors that do not contain radioactive material.

Having discussed both the benefits and impacts of ICSD's and various alternatives, a cost-and-risk-benefit analysis is performed to assess the Am-241 ICSD's and the different options available. The assessment is both quantitative and qualitive in nature.

As a final section, a discussion of future products and trends is given. Such a discussion is, by nature, qualitative and represents little more than an educated guess as to future trends and products.

1.3 DISCUSSION

Residential fires continue to pose a major problem in the United States, ranking as the second most frequent cause of accidental death in the home. Between 7,500 and 12,000 lives are lost in fires every year with 70 percent of these occurring in residential fires. Residential property loss due to fires is over one billion dollars annually. A key element in reducing loss of life and property is early detection of fires. Various devices are available that detect flames, heat, or products of combustion. In recent years devices that detect products of combustion have been introduced to the consumer market and their sales have increased dramatically. These so-called "smoke" detectors are of two types. The majority have been of the ionization chamber smoke detector (ICSD) type which contains small amounts of radioactive material. The remainder have been of the photoelectric type which contains no radioactive material. A combination detector has been recently marketed that contains both an ICSD and a photoelectric detector. Based on theoretical studies and case histories, the estimated percent of residential fire-related deaths that smoke detectors could save is between 41 and 89 percent.

Most ionization chamber smoke detectors contain americium-241 (Am-241), a radioactive substance that emits ionizing radiation. Other radionuclides could be used in place of Am-241. In the past, radium-226 (Ra-226) has been used in detectors, but at present it is not employed in the consumer product. Nickel-63 (Ni-63) is presently being studied for use in consumer smoke detectors, having already been used in commercial applications such as in large warehouses. The user of an Am-241 ICSD is exempt from regulations, but the manufacturer must apply for and obtain a specific license from the Nuclear Regulatory Commission to distribute the product. The license is granted only after the applicant has demonstrated that the product is designed and will be manufactured in a manner such that specific requirements and safety criteria are met.

Since 1972-1973, the residential market for Am-241 ICSD's has increased rapidly. Fourteen million units containing a total of 41 curies of Am-241 were distributed in 1978 and 26 million units have been distributed since 1972. Based upon present projections, about 90 million units will be distributed by 1986. The peak year of distribution should be 1978. The average activity per unit in 1978 was 3 uCi and projections indicate this will become lower in the future.

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The use of Am-241 ICSD's does result in exposure of people to low levels of radiation. Analysis shows that the manufacture, distribution, normal use, and disposal of 14 million Am-241 ICSD's each containing 3 uCi of Am-241 will result in a collective total body dose of 1100 person-rem. The useful life is assumed to be ten years. Disposal is by either sanitary landfill or incineration. Fourteen million ICSD's will service about 21 million people. Analysis also shows the risk to the exposed population is about 0.1 fatal cancer. The normally-occurring cancer mortality rate for the total population of the United States is about 370,000 per year or about 35,000 per year for a group of 21 million people.

A comparison of these numbers illustrates the relatively small risk involved in using an Am-241 ICSD. It should be noted the 370,000 cancer deaths per year are actual deaths while the 0.1 fatal cancer over ten years of ICSD use was calculated using conservative assumptions. The ratio of the potential lives saved to the possible fatal cancers due to use of ICSD's ranges from 15,000 to 51,000.

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Comparative analyses based upon cost, risk, and benefits, found present day Am-241 ICSD's to be preferable to ICSD's with other radionuclides and preferable to present day photoelectric detectors. The best available unit for fire protection was found to be the recently marketed combination detector. The cost of a combination unit is considerably more than the Am-241 ICSD and data is lacking on how much more sensitive it is. Therefore, the cost-effectiveness of combination units compared to Am-241 ICSD's is unknown.

1.4 CONCLUSIONS

Based upon the results of this study, a number of conclusions regarding ICSD's are stated below.

1. A significant amount of uncertainty exists with respect to the total

population dose and resultant health effects as determined by this study. Due to the inclusion of conservatism, however, the results of these assessments are of value in delineating the upper bound of radiological impact. These assessments also serve to identify the relative importance of the various activities associated with ICSD use and disposal as sources of exposure.

2. The sum of doses to the population from the annual production, distribution, use, and disposal of 14 million Am-241 ICSD's is estimated to be lower than that which would be expected to result in one cancer death or one serious genetic effect.

3. The environmental assessment of presently-distributed Am-241 ICSD's indicates dose commitments much lower than the safety criteria found in 10CFR32 for gas and aerosal detectors.

4. The estimated percent of residential fire-related deaths that smoke detectors could save is between 41 and 89 percent.

5. The use of Am-241 ICSD's is justifiable as a means to detect fires and prevent loss of life and property. The estimated benefit-to-risk ratio for units containing 3 uCi is between 15,000 and 51,000.

6. The use of Ra-226 in ICSD's is not recommended because of a longer half-life compared to the half-life of Am-241 and because of the emanation of small amounts of Rn-222.

7. The use of Ni-63 in ICSD's instead of Am-241 is recommended if the cost and sensitivity of Ni-63 ICSD's can be made comparable to Am-241 ICSD's. They are not recommended if their cost is higher.

8. Am-241 ICSD's are cost-effective compared to presently-distributed photoelectric detectors.

9. The best available unit for fire protection is the combination detector containing both an ICSD and a photoelectric detector. However, data is lacking as to whether it is cost-effective compared to Am-241 ICSD's.

2. BACKGROUND INFORMATION ON ICSD'S

2.1 GENERAL DISCUSSION

Residential fires continue to pose a major problem in the United States. They remain the second most frequent cause of accidental death in the home. The rate per capita is greater in the United States than in any other industrialized nation. Though fire data is often incomplete and inaccurate it is estimated between 7,500 and 12,000 people die in fires annually. Another 300,000 fire injuries are incurred and four to five billion dollars in property is destroyed(1). Residential fires have been found to contribute significantly to the loss of life due to fires. The main causes of loss of life are burns and smoke inhalation. Both burns and smoke inhalation can be avoided if early detection of fires is practiced. Such detection can be made by the use of various devices to detect flames, heat, or products of combustion. In recent years detectors that detect products of combustion have been introduced in the market place and the sale of such devices has increased dramatically. The majority of the "smoke" detectors have been of the ionization chamber smoke detector (ICSD) type, while the remainder have been of the photoelectric type. Both types detect combustion products and hence are given the name "smoke detectors."

The most widely distributed ICSD contains americium-241 (Am-241). Because of its dominance on the market place, detectors with Am-241 are considered in this report as the reference ICSD. Other ICSD's are and have been manufactured. In particular, units containing radium-226 (Ra-226) have been available to consumers. At present in the United States the only other alternative radionuclide being considered is nickel-63 (Ni-63). As in the cases of Am-241 and Ra-226 units, Ni-63 has been used in commercially available units. However, Ni-63 ICSD's have not been sold on the residential market as of this time. For analysis in this report, Am-241 ICSD's will be considered the primary detector. All other ICSD's will be considered as alternatives with radioactive material.

2.2 DESCRIPTION OF ICSD'S

2.2.1 General Operation

Ionization chamber smoke detectors operate in the following simplified manner. A source of ionizing radiation is positioned between two electrodes with an electric potential between them. For present day ICSD's the radiation source emits ionizing radiation in the form of alpha or beta particles depending upon the radionuclide used in the detector. The emitted particles create positive ions by removing electrons from gas molecules along their path. Released electrons attach to neutral gas molecules forming negative ions. The produced ions flow toward the appropriate electrodes depending upon whether their charge is negative or positive. The result is a small current through the gap between the electrodes. The ICSD electronics detect the level of the current that normally flows in the circuit. Should a change in current develop it will be detected by a discriminate portion of the ICSD circuitry, causing an alarm or warning signal to be sounded.

The current in the ICSD can be lowered or hindered by two mechanisms: (1) ionized particles recombining before reaching the electrodes and (2) transfer of ionized particles out of the space between the electrodes by air flow. Air flow through ICSD's is normally not limiting and does not affect the detector current significantly. The basic hindrance of the current is from recombination of the ions. Normally the recombination rate in the chamber is at an equilibrium condition. The recombination rate and ion density between the electrodes is constant.

Introduction of foreign particles such as products of combustion into the chamber results in ion capture by the foreign particles. The increased mass of the particles to the ions results in a significantly reduced velocity (the particle-ion pair compared to the ion alone) and some of the pairs are carried by air flow out of the chamber before reaching the electrodes, whereby the electrode current is reduced because of a reduction in charge transfer. When the current drops to the discriminate level, the alarm is sounded indicating the presence of foreign particles between the electrodes.

2.2.2 Radionuclides in ICSD's

Essentially any source of ionizing radiation can be used in an ionization chamber smoke detector. The selection of a radionuclide for use in an ICSD by a manufacturer requires considerations of both economics and safety. As will be outlined in Section 2.3, certain regulations and guidelines govern the manufacture and distribution of ICSD's. Particular radiation safety standards must be met. Important considerations in selecting a radionuclide for use in an ICSD are:

1. Radioactive half-life,
2. Ionization potential,
3. Radiological consequences, and
4. Cost or availability.

The radioactive half-life is important in establishing the useful lifetime of an ICSD. Radionuclides with extremely short half-lives cannot be effectively used. The ionization potential refers to the effective current which might be generated in an ICSD. Here the problem of using an alpha- or beta-emitter must be addressed. Am-241 is an alpha-emitter while Ni-63 is a beta-emitter. The third item considered in radionuclide selection is the possible radiological consequences during use or misuse. The consequences are essentially external exposure or internal exposure due to inhalation or ingestion of the radionuclide. Table 2.1 gives important radiological information on the radionuclides so far identified as possible sources in ICSD's: Am-241, Ra-226, and Ni-63. Maximum Permissible Concentrations (MPC) as defined in 10CFR20 are included for comparison sake. The cost or availability of radionuclides in an appropriate form and enclosure will, of course, greatly affect its selection.

2.2.3 ICSD Design and Construction

The design of ICSD's includes variations in the design of the major components such as the ionization chamber. Am-241 alpha particles have a mean range in air at STP of approximately four centimeters. Therefore, within four centimeters of the Am-241 source, approximately the same number of positive and negative ions will be created. This will be the case between the electrodes for Am-241 ICSD's with electrode spacing of four centimeters or less. Such a chamber

Table 2.1. Radiological Data for Ni-63, Ra-226 and Am-241.

Radionuclide	Half Life (Years)	Specific Activity (Ci/g)	Energy of Emission, MeV(%)			Other Radiations	Most Restrictive MPC (μCi/ml)	
			Alpha	Beta	Gamma		Air	Water
Ni-63	92	62	-	0.067(100)	-	-	2E-9	3E-5
Ra-226	1620	1.0	4.78(95) 4.60(5)	0.09,0.17 (both e^-)	Rn x-rays 0.19(4), trace others to 0.6	daughter radiations from Rn-222, Po-218, Pb-214, Bi-214, Po-214	2E-12	3E-8
Am-241	458	3.3	5.49(85) 5.44(13)	0.02,0.04 0.05(all e^-)	Np L x-rays 0.06(36), trace others to 0.07	daughter radiations from Pu-241	2E-13	4E-6

is referred to as a bipolar chamber. When electrode spacing is greater than four centimeters, two regions will exist in the ionization chamber. The region within four centimeters of the Am-241 source will be similar to the bipolar chamber. The region beyond four centimeters will essentially have ions of only one polarity present. A space charge region will separate the two regions and act to stabilize the ion concentration in the unipolar chamber. Figures 2.1 and 2.2 illustrate the two types of chambers(2).

ICSD's can also vary according to the number of chambers. Dual chamber devices essentially have a reference chamber and a measurement chamber. The reference chamber establishes a current based only on the ambient air (no foreign material). The measurement chamber establishes the current based on the ambient air plus any foreign material such as combustion products that may be in the chamber. A triple chamber ICSD (not presently available on the market) is designed to obtain the best working point for a detector while compensating for nonfire conditions. Though designed for beta sources, in particular Ni-63, triple chamber smoke detectors can be made using Am-241.

The remainder of the ICSD consists of the electronics, power source or battery, alarm horn, and enclosure. The electronics and power source designs are fairly standard. The enclosure design is important to the successful functioning of an ICSD. The design of the enclosure may be based on the following factors:

1. Velocity effects on entry and exit from the unit.
2. Current leakage paths on high impedence components or insulators in the sensing chamber.
3. Adhesion of aerosol particles to plastic pieces that have acquired a static charge.

2.3 REGULATIONS AND GUIDELINES

Smoke detectors that contain Am-241 are subject to regulation by the U. S. Nuclear Regulatory Commission (NRC). The NRC regulates the distribution of Am-241 smoke detectors in both Agreement and Non-Agreement States. The extent of regulation is stated in the Code of Federal Regulations under Title 10, Energy. Am-241 is considered to be a byproduct material, which is defined as "any radioactive material (except special nuclear material) yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing special nuclear material." Part 30 of Title 10 (10CFR30) states the

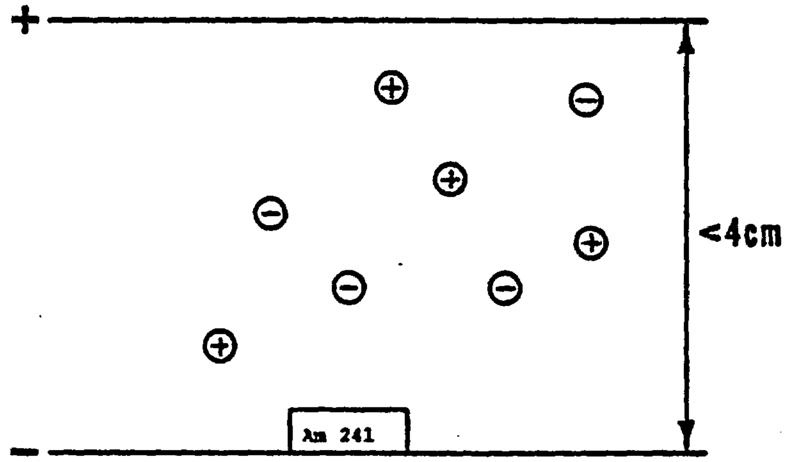


Figure 2.1. Bipolar Ionization Chamber[2].

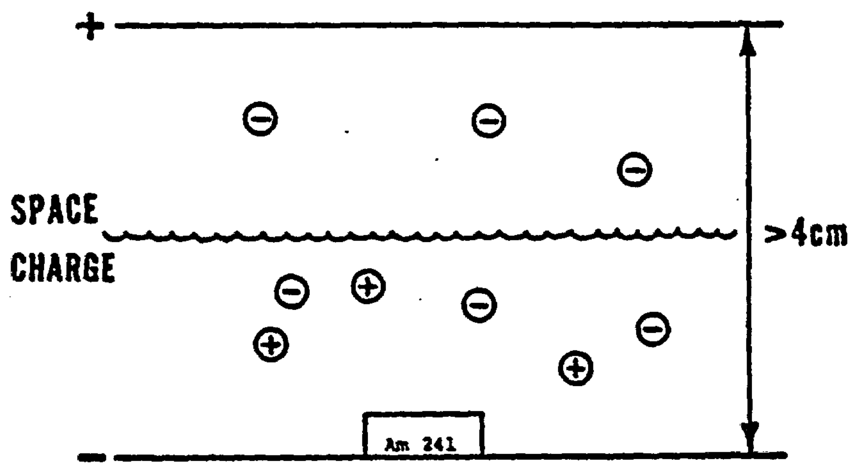


Figure 2.2. Unipolar Ionization Chamber[2].

rules applicable to all persons in the United States governing domestic licensing of byproduct material under the Atomic Energy Act of 1954, as amended, and exemptions from domestic licensing requirements permitted by Section 81 of the Act.

10CFR30.20 deals explicitly with gas and aerosol detectors containing byproduct material. It states "except for persons who manufacture, process, produce, or initially transfer for sale or distribution gas and aerosol detectors containing byproduct material, any person is exempt from the requirements for a license set forth in Section 81 of the Act . . . to the extent that such person receives, possesses, uses, transfers, owns, or acquires byproduct material in gas and aerosol detectors designed to protect life or property from fires and airborne hazards, and manufactured, processed, produced, or initially transferred in accordance with a specific license issued..."

In order to manufacture, process, produce, or initially transfer gas and aerosol detectors, a license is required. 10CFR32 covers specific domestic licenses to manufacture or transfer certain items containing byproduct material. Gas and aerosol detectors are covered in Section 32.26. The requirements for application for a license are outlined including information that must be supplied by the applicant.

The safety criteria for gas and aerosol detectors are covered in Section 32.27. An applicant for a license is required to demonstrate that a product is designed and will be manufactured in a manner such that certain criteria are met. The criteria are as follows:

1. The external radiation dose in any one year or the dose commitment resulting from the intake of radioactive material in any one year to a suitable sample of the group of individuals expected to be most highly exposed due to the normal use and disposal of a single exempt unit and to normal handling and storage of expected quantities of exempt units accumulated in one location during marketing, distribution, installation, and servicing of the product will not exceed the organ doses specified in Column I of Table 2.2.

2. Wear and abuse of a product due to normal handling and use during its useful life will not result in a significant reduction in the effectiveness of safety features such as containment and shielding.

3. The probability should be low that safety features of the product would fail under use outlined in criterion 1 such that a person would receive an external dose or dose commitment in excess of the organ doses specified in Column II of Table 2.2. Low probability is stated to be

Table 2.2. Organ Doses for Safety Criteria Evaluation (10CFR32.28).

Part of Body	Column I (rem)	Column II (rem)	Column III (rem)
Whole body; head and and trunk; active blood-forming organs; gonads; or lens of eye	0.005	0.5	15
Hands and forearms; feet and ankles; localized areas of skin averaged over areas no larger than 1 square centimeter	0.075	7.5	200
Other organs	0.015	1.5	50

not more than one such failure per year per 10,000 exempt units distributed.

4. The probability should be negligible that safety features of the product would fail under use outlined in criterion 1 such that a person would receive an external dose or dose commitment in excess of the organ doses specified in Column III of Table 2.2. Negligible probability is stated to be not more than one such failure per year per one million exempt units distributed.

Smoke detectors which may be produced in the future containing byproduct material other than Am-241 would have to meet the same requirements and regulations as given above. Detectors with Ni-63 would fall into this category since Ni-63 is considered a byproduct material.

Smoke detectors which contain Ra-226 are not regulated by the NRC since Ra-226 is not byproduct, source, or special nuclear material. Ra-226 is considered to be a naturally-occurring material and as such is not under regulation by the NRC or comprehensively controlled by any other federal agency. The regulation of Ra-226 and other naturally-occurring or accelerator-produced radioactive materials (NARM) on a state level is non-uniform and incomplete. The Conference of Radiation Control Directors, which is an organization whose membership is comprised of all directors of radiation control programs in the 50 states, the territories, and some large municipal agencies, established a Task Force to develop guidance for the individual state's evaluation of NARM products. Representatives from State Radiation Control Programs, the Bureau of Radiological Health (BRH), the NRC, and the U. S. Environmental Protection Agency (EPA) were on the Task Force. The major output of the Task Force was a set of guides for NARM materials[3]. NARM Guide 3 deals with gas and aerosol detectors and "provides criteria for the evaluation of gas and aerosol detectors containing radioactive material which are to be distributed to persons exempt . . ." NARM Guide 3 applies essentially the same standards to Ra-226 smoke detectors as the NRC applies to smoke detectors with byproduct material.

2.4 DISTRIBUTION OF ICSD's

Ionization chamber smoke detectors have been used in the United States since 1951[4]. The first detectors used foils containing approximately 20 uCi of Ra-226 in the form of radium sulphate. In 1963 Am-241 was introduced into the manufacture of ICSD's. The first specific license to distribute ICSD's was issued by the Atomic Energy Commission (AEC) on September 17, 1963. The first license granting exemption was issued September 5, 1969. The ICSD in this case contained approximately 80 uCi of Am-241.

Nearly all distributed ICSD's in the early years were used in commercial installations such as factories, public buildings, and warehouses. Because of the success of ICSD's in commercial installations and the large number of fires in home residences, authorities began to study the potential benefits that ICSD's might have in the home residence. For example, one study by the National Research Council of Canada, Division of Building Research, researched a series of dwelling fires in Ontario Province and concluded that 41 percent of the deaths could have been prevented by installation of ICSD's[5]. Cost was the basic limiting factor for use of commercial ICSD units in homes. Commercial units were basically too expensive for use by most homeowners.

Manufacturers were able to bring ICSD's into the consumer product market by developing single station self-contained units, some battery operated, and by cutting the cost via mass production. In the past years, the advances in electronic state-of-the-art and competition among manufacturers and distributors has lowered prices considerably and ICSD's are essentially affordable by nearly all consumers. Since about 1972-73, the home or residential market for ICSD's has increased rapidly. This can be attributed to the above reasons, to promotion by such groups as the National Fire Prevention and Control Administration, and by vigorous promotion campaigns by the manufacturers.

The distribution of ICSD's with Am-241 is by far the greatest part of the market today. Few Ra-226 units are still manufactured. No Ni-63 units have been marketed in the home or residential market. Based on data supplied to the NRC by manufacturers and distributors, Table 2.3 illustrates the dramatic rise in the use of Am-241 ICSD's in the consumer area. Because all the data reported to the NRC is not clearly divided into commercial and consumer products, the information in Table 2.3 was developed by talking to various manufacturers to determine what products might have been commercial. Table 2.4 illustrates the total distribution of all (commercial plus residential) Am-241 ICSD's for the same time frame used in Table 2.3. Included in the data is the number of firms licensed by NRC to distribute each year. The total activity for all units, the average activity for all units, the average activity per unit, and the range of activity per unit are included in both Tables 2.3 and 2.4.

The past distribution of Ra-226 ICSD's is not as easily quantified as the Am-241 ICSD's. This is a function of the regulation of products containing NARM. As discussed in Section 2.3, the regulation of NARM materials is not comprehensively controlled by any Federal agency and is at the option of the individual states. For this reason no central reporting agency has compiled data on Ra-226 ICSD distribution. Contact with agencies such as the Bureau of Radiological Health and identified manufacturers and distributors of Ra-226 ICSD's resulted in the compilation of a list of Ra-226 ICSD distribution that can only be considered a best effort, and not a complete list. Table 2.5 illustrates the compilation of identified Ra-226 ICSD distribution.

2.5 DESCRIPTION OF ICSD LIFE SPAN

The manufacture, distribution, use, and disposal of ionization chamber smoke detectors will introduce various segments of the population to ICSD's at various times and places. No all-encompassing description of ICSD life span can be made in a manner which is easily used. For this reason, it is necessary to model the life span by grouping similar events or occurrences. The life span of ICSD's can be divided into the following basic phases:

1. Manufacture,
2. Storage,
3. Distribution, including sale and display,
4. Installation,
5. Consumer use, and
6. Disposal or abandonment.

The consideration of accidents and ICSD misuse will be made for all phases of the ICSD life span. The detailed description of each ICSD life span phase is included in Section 3.

Table 2.3. Distribution of Residential Am-241 Ionization Chamber Smoke Detectors[a].

Year	No. Units Distributed	Total Activity (mCi)	Activity (μCi) Per Unit	
			Average	Range
1969-71	393	0.39	1.0	--
1972	12,800	12.8	1.0	--
1973	92,000	92.1	1.0	0.8-1.0
1974	198,000	247	1.2	0.4-12.2
1975	580,000	3,980	6.9	0.3-12.8
1976	3,040,000	15,600	5.1	0.3-13.7
1977	7,900,000	31,000	3.9	0.3-9.8
1978	14,100,000	40,700	2.9	0.2-8.6
Total	25,900,000	91,600	3.5	0.2-13.7

[a]Data estimated on best available information (NRC distribution data files as of May 1, 1979, conversations with manufacturers, etc.)

Table 2.4. Distribution of Am-241 Ionization Chamber Smoke Detectors[a].

Year	No. Distributors	No. Units Distributed	Total Activity (mCi)	Activity (μCi) Per Unit	
				Average	Range
1969	1	30	1	35.0	--
1970	1	60,000(est.)	4,690	80(est.)	--
1971	3	65,400	5,160	78.9	1.0-79.4
1972	3	121,000	8,380	69.3	1.0-77.6
1973	4	254,000	11,100	43.7	0.8-68.0
1974	7	390,000	9,160	23.5	0.4-46.8
1975	10	821,000	12,200	14.9	0.3-34.2
1976	17	3,360,000	21,700	6.4	0.3-19.0
1977	21	8,060,000	37,300	4.6	0.3-40.2
1978	34	14,200,000	45,600	3.2	0.2-29.5
Total	49	27,300,000	155,000	5.7	0.2-79.4

[a]Data includes smoke detectors used for residential, industrial, commercial, and military application.

Table 2.5. Distribution of Residential Ra-226 Ionization Chamber Smoke Detectors.

Company	No. Units Distributed	Activity (μCi) Per Unit	Total Activity (mCi)	Distribution Period
1	12,237	0.15	< 2	1968-1974
2	1,000,000	0.05	50	1974-1978
3	10,000	1.00	10	1967-1971
4	1,000	0.75	< 1	1974-1976
5	15,000-20,000	0.5-0.75	7.5-15	Before 1977
6	10,000	1.5	15.0	1972-1975
7	22,000	0.5	11.0	1970-1973
8	804,000	0.05	40.2	1975-1978
9	214,000	0.05	10.7	1970-1976
Total Activity			155	

3. ENVIRONMENTAL IMPACT

3.1 BENEFITS

3.1.1 Saving of Life

Occupants of residences in which an uncontrolled fire commences are exposed to at least three specific life threatening parameters: toxic gases, smoke particles, and burning fire (for a discussion of each of these parameters see Appendix A).

In the United States, between 7,500 and 12,000 lives are lost in fires each year[1]. In 1976 the death toll to victims of residential fires amounted to approximately 70 percent of the total fire deaths that year. Residential smoke detectors are presently designed to detect smoke particles in the atmosphere and warn the building occupants of potential danger. An attempt to estimate the reduction of residential fire deaths due to the presence of smoke detectors is a difficult task which must reduce to some form of subjective analysis with large uncertainties to the final probabilities.

The State Fire Marshall's Office in the State of California has developed the California Fire Incident Reporting System (CFIRS) to which all fires are reported that have been attended to by a local fire fighting unit[6]. An example of part of the fire incident report form is illustrated in Figure 3.1. As information is developed from these forms it goes on to computer data tapes for annual analysis of all reported fires within the State. At present, not enough reports have been completed to the point that sufficient information can be gathered to accurately appraise the effectiveness of residential smoke detectors. There does appear to be some impact apparently due to smoke detectors and the State Fire Marshall has included the following pertinent statement in the 1978 CFIRS annual report:

> "The most notable (positive signs) relates to residential building fires. In spite of a continuing increase in the number of housing units in the State, residential building

Entries contained in this report are intended for the sole use of the State Fire Marshal. Estimations and evaluations made herein represent "most likely" and "most probable" cause and effect. Any representation as to the validity or accuracy of reported conditions outside the State Fire Marshal's office, is neither intended nor implied.

STATE OF CALIFORNIA
OFFICE OF THE STATE FIRE MARSHAL

FIRE INCIDENT REPORT

INCIDENT NO.

DEL 1 ☐ CORR 2 ☐

________________ FIRE DEPARTMENT
(DEPARTMENTAL USE)

1 OCCUPANT NAME	RELATIONSHIP	ALARM SOURCE: TEL. ☐ BOX ☐ PFAS ☐ VERBAL ☐ RADIO ☐ OTHER ☐	1
2 ADDRESS / ROOM / APT. NO.	CITY / ZIP	TELEPHONE NO. (CALL BACK)	2
3 OWNER NAME	ADDRESS / CITY / ZIP	CENSUS/PARCEL NO.	3
4 MANAGER NAME	ADDRESS / CITY / ZIP	TELEPHONE NO.	4

A. INFORMATION (PAGE 17)

1 FIRE DEPT. ID | INCIDENT NO. | EXPOSURE NO. | TIME | MONTH | DAY | YEAR | DAY CODE | COUNTY OF FIRE | DIST-CITY | OUT OF JURISDICTION CHECK IF YES ☐

B. PROPERTY CLASSIFICATION (PAGE 19)

1 CODE "TYPE OF INCIDENT" — CONSTR DATE: PRE 72 1 ☐ POST 72 2 ☐
2 CODE PROPERTY CLASSIFICATION (COMPLEX)
3 CODE PROPERTY CLASSIFICATION (INDIVIDUAL)

C. PROPERTY TYPE (PAGE 41)

1 PROPERTY MANAGEMENT: PVT 1 ☐ FED 2 ☐ STATE 3 ☐ COUNTY 4 ☐ CITY 5 ☐ DISTRICT 6 ☐ FOREIGN 7 ☐ OTHER 8 ☐
2 CODE STRUCTURE, BUILDING OR VEHICLE - PROPERTY TYPE — BUILDING NO. STORIES
3 STRUCTURE, BUILDING OR VEHICLE - CONSTRUCTION TYPE: EXT. WALL N/C 1 ☐ COMB 2 ☐ | INT. WALL N/C 3 ☐ COMB 4 ☐ | FLOOR - ROOF N/C 5 ☐ COMB 6 ☐ | FIRE RATED YES 7 ☐ NO 8 ☐

D. EXTENT OF DAMAGE (PAGE 45)

1 CODE EXTENT OF DAMAGE – FIRE
2 CODE EXTENT OF DAMAGE – SMOKE
CODE EXTENT OF DAMAGE – WATER
4 ESTIMATED LOSS - PROPERTY | ESTIMATED LOSS - CONTENTS

E. LOCATION & CAUSE (PAGE 49)

1 CODE LEVEL OF ORIGIN
2 CODE SOURCE OF HEAT CAUSING IGNITION
3 CODE FORM OF HEAT CAUSING IGNITION
4 CODE ACT OR OMISSION CAUSING IGNITION

F. AREA, MATERIALS & SMOKE SPREAD (PAGE 63)

1 CODE AREA OF ORIGIN
2 CODE TYPE OF MATERIAL FIRST IGNITED
3 CODE FORM OF MATERIAL FIRST IGNITED
4 CODE MAIN AVENUES SMOKE SPREAD

G. SPREAD OF FIRE (PAGE 77)

1 CODE MAIN AVENUES FIRE SPREAD
2 CODE TYPE MATERIAL CAUSING SPREAD
3 CODE FORM MATERIAL CAUSING SPREAD
4 CODE ACT OR OMISSION CAUSING SPREAD

H. PROTECTION FACILITIES (PAGE 91)

1 CODE SPRINKLERS – TYPE
2 CODE SPRINKLERS – EFFECTIVENESS
3 CODE STANDPIPES – TYPE
4 CODE STANDPIPES – EFFECTIVENESS
5 CODE PORTABLE EXTINGUISHERS – TYPE
6 CODE PORTABLE EXTINGUISHERS – EFFECTIVENESS

I. PROTECTION FACILITIES (PAGE 97)

1 CODE PRIVATE BRIGADE – TYPE
2 CODE PRIVATE BRIGADE – EFFECTIVENESS
3 CODE SPECIAL HAZARD PROTECTION – TYPE
4 CODE SPECIAL HAZARD PROTECTION – EFFECTIVENESS
5 CODE SIGNAL OR WARNING SYSTEM TYPE | CODE EFFECTIVENESS
6 CODE SIGNAL WARNING SYSTEM - MEANS OF ACTIVATION
7 CODE SIGNAL-WARNING SYSTEM – TYPE DETECTORS
8 CODE WATCHMAN EFFECTIVENESS | CODE OTHER FACILITIES EFFECTIVENESS

J. MISCELLANEOUS (PAGE 109)

1 FIREFIGHTER: NO. INJURED | NO. OF DEATHS — CIVILIANS: NO. INJURED | NO. OF DEATHS
2 SFM FORM 60-1 SUBMITTED FOR EACH DEATH (CHECK BOX IF YES) ☐

SFM Form GO-60 (REV 7-74) SPECIAL

OSP

Figure 3.1. Fire Incident Report.

> fires have declined for the third year in a row. This, coupled with 19 percent fewer residential fire deaths (deaths at the scene), leads us to believe we may be witnessing the first long range benefits of smoke detectors in California houses."[7]

A feeling for the impact that residential fires have on the overall fire fatality picture can be acquired from the CFIRS data. Table 3.1 is a comparison of injuries and deaths related to fires in dwellings and apartments in California during 1977 and 1978. During these two years the most significant change for civilians was the reduction in fire-related deaths. For dwellings and apartments the number of deaths dropped 22 percent (this differs from the Fire Marshall statement in that dwellings such as mobile homes, hotels, and such are not included in Table 3.1). Should this decline in residential fire-related deaths continue it could be a significant factor for smoke detectors. In California the number of residences and apartments equipped with smoke detectors is estimated to be 20 percent[8]. From this it would appear that as more houses are equipped with some form of smoke detector the reduction in civilian fire-related deaths should continue.

Although the number of apartments and residences increased in California between the years 1977 and 1978 there seems to be no increase in the number of reported building fires. This could be indicating an increase in early detection of potential fires such that they are being suppressed prior to doing any reportable harm. This is definitely a problem when trying to determine the efficiency of smoke detectors in residences, especially when official records are the only information base.

While civilian fire-related deaths appear to be on the decline in California it is interesting to note that there has been little change in the number of fire-related injuries, both to civilians and fire fighters. It appears that although the early warnings given by smoke detectors may be responsible for reduction in deaths, there has been little shift in the percent of injuries reported for residential fires. This presents an interesting problem in that the Applied Physics Lab of Johns Hopkins University (APL) has estimated at least an 80 percent reduction in this form of civilian injury along with a 71 percent reduction in deaths[9]. It would seem that as fire-related deaths decrease, so should fire-related injuries. Apparently, in California at least, smoke detectors are having an effect on the number of expected residence fires but not as great an effect in reducing injuries as might be expected.

Table 3.1. Fire Statistics (CFIRS) for California [6,7] Residences and Apartments.

Fire-Related Incidents	Total Number		Residential and Apartment Fires - Percent of all Building Fires	
	1977	1978	1977	1978
Residential and Apartment Fires	38,690	38,640	67	68
Civilian Injuries	1,414	1,417	55	57
Civilian Deaths	206	160	60	45
Firefighter Injuries	869	882	49	47
Firefighter Deaths	1	0	50	0

On the average the residential and apartment fires in California claim about 56 percent of the total fire-related deaths per year (five-year average). The age bracket for persons involved in residential fire deaths is illustrated in Figure 3.2. A significant point here is that within the age group of 18 to 45 years over 40 percent of male fire-related deaths occur. If smoke detectors continue to reduce the number of deaths in California this could have significant impact on the number of families that potentially could lose their main wage earner. This has far ranging implications and must be considered as an extremely important point towards the benefits of residential smoke detectors.

To date there have been few reports published which describe the benefits gained from the presence of smoke detectors during a residential fire occurrence. The Ontario Housing Corporation of Canada (OHC) has published two documents which describe the consequence of fires that occurred to corporate dwellings (81,000 rental dwellings, each containing a single ionization type smoke detector)[10,11]. During the 1978 reporting year a total of 97 fire incidents were reported with smoke detectors responding to 70 percent of the events. In 20 percent of these fire incidents smoke detectors were reported to be ineffective in responding to the event and in 10 percent of the events the smoke detectors failed to operate because they were defective units (one percent) or inoperative due to being disconnected by the occupants because of false alarms. In many of the events where smoke detectors were ineffective the units sounded but the fire had already been discovered. It might also be noted that of 86,509 ionization chamber smoke detectors serviced by the OHC the overall defective rate was found to be 2.3 percent. A total of four fatal fires occurred during the 1978 reporting period and the OHC estimates that smoke detectors possibly prevented fatalities in 27 percent of all fires that occurred.

In 1976 Rexford Wilson presented a paper to the State of Massachusetts in which he described the results of an analysis of a study by the National Bureau of Standards[12]. In this paper a Life Safety Index was presented which weighed the value of heat and smoke alarms in reference to a three minute escape time. For a smoke detector system in which a detector is installed on each level of the home, Wilson initially established that 86 percent of the time an alarm would be sounded before a three minute escape time was lost. These values would be expected, according to the report, as long as all life saving factors were optimized. A second paper by Wilson, based on a computer analysis of the

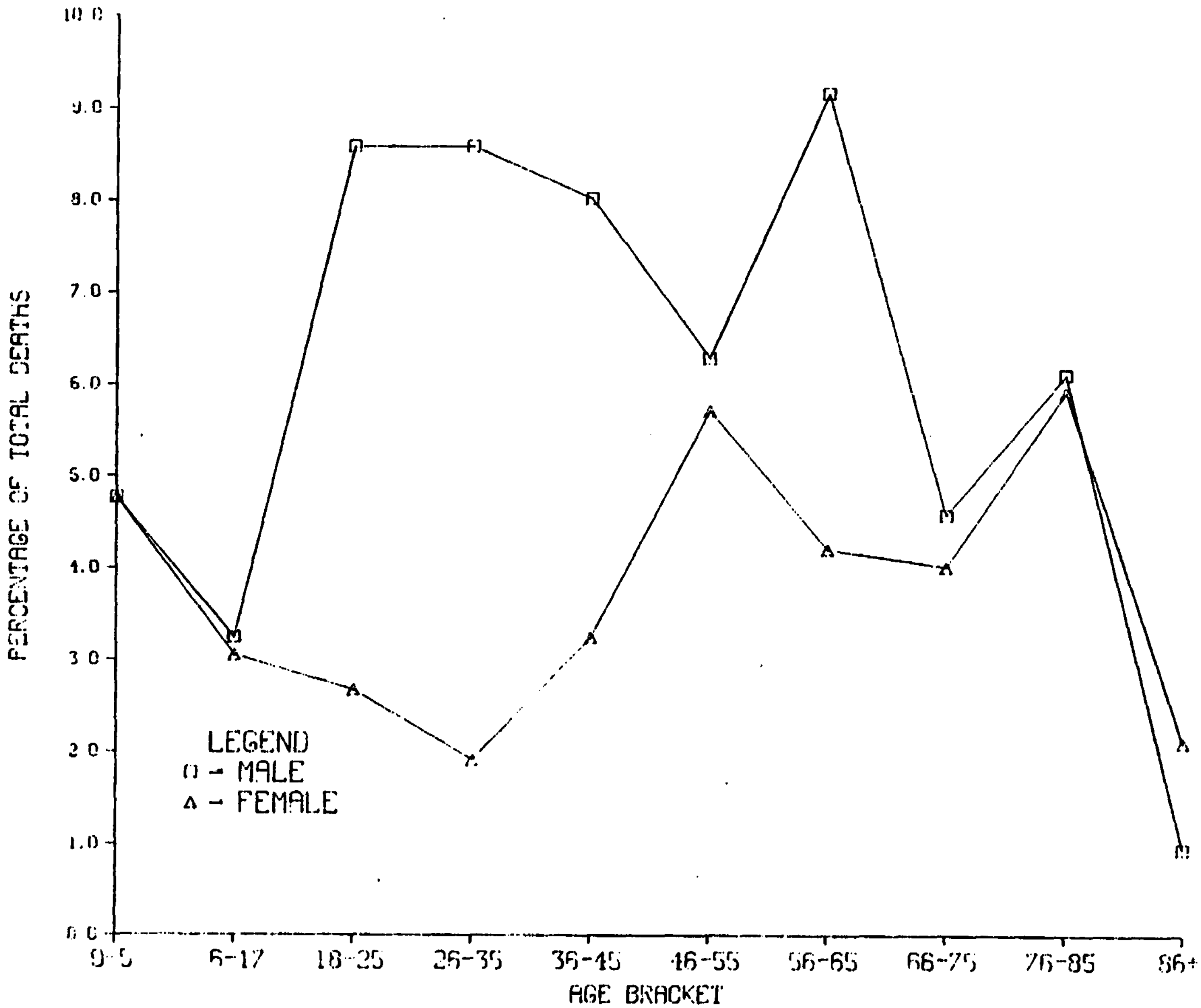


Figure 3.2. Relation of Age and Sex to Death by Fire - California 1977.

previous data, indicated a Life Safety Index of 89 percent for an every level system[13].

Wilson's value of 89 percent is considered as being optimistically high by some members of the smoke detector industry but it is a value that is used in some advertising copy. If the OHC values are reconsidered some support is found for the Wilson value. Of the 97 fires in the 1978 Canadian study only 67 (70 percent) are considered as detected by the smoke detectors. But, as stated by Wilson, the Life Safety Index value is dependent upon optimized conditions and any factors that reduce the maximized parameters will reduce the number (percent) of lives saved. In the OHC report seven detectors were inoperable, two fires started in basements where no detectors were located, and five other fires were detected but were not counted due to circumstances such as smoke detectors alarming after the fire was detected by the occupant, infirm occupant, or being ignored even when sounding. Under optimum conditions this would give a total of 81 fires detected which gives an 84 percent alarm rate - a value much closer to that predicted by Wilson. If the three minute escape value can be related to possible lives saved an even closer approximation of the Wilson value is found in the OHC data. In the OHC report, possible lives saved, based on events as they occurred, is estimated as 26 persons. Four persons lost their lives which gives a total of 30 individuals involved in life threatening circumstances. This would give a value of 87 percent (26/30) as the percent of lives saved due to the presence of smoke detectors. There is no way to prove that the lives of the 26 persons were actually saved by the smoke detector warnings but they all were in such circumstances that if they did not become aware of the situation in time they could have lost their lives.

The estimation of the life saving factor for smoke detectors is a subjective analysis at best. An early (1962) Canadian study, commonly referred to an the McGuire report, gave an estimation of 41 percent as the expected reduction in fire fatalities that could be expected due to the presence of smoke detectors[5]. In 1968 the Applied Physics Laboratory of John Hopkins University published its study of fire fatalities that occurred in a series of fires in the State of Maryland and Washington, D.C. The APL study indicated a 71 percent reduction in lives lost if a minimum number of detectors are installed in accordance with the guidelines set down in Code NFPA-74-1. As with the Wilson study, the APL values require that all systems are designed, installed, and maintained properly and that all occupants respond correctly to an alarm. The 71 percent reduction in lives lost is considered as that for definite saves. An even more optimistic value of 86 percent is offered in the APL report when the "possible lives saved" are added to the "definite saves."

The above data and estimates can now be summarized as follows:

- 70% The percent of residential fire-related deaths among all fire-related deaths in the United States.
- 41-89% The various estimates that have been published regarding the life saving factor for installation of smoke detectors.
- 70% The percent of fires detected by smoke detectors in structures of the Ontario Housing Corporation.
- 87% The percent of lives saved in potential life threatening situations of the Ontario Housing Corporation, 100 percent of residences equipped with smoke detectors.
- 22% The noted reduction in lives lost to residential fires in California, with 20 percent of residences containing smoke detectors.

It is still too early in the accumulation of data to establish a life saving factor for smoke detectors based on actual case histories. The most extensive records to date are those of the Ontario Housing Corporation. Should these OHC values hold true for residential and apartment units in the U. S. there is bound to be a distinct reduction in deaths related to fires in these dwellings. At the present time the National Bureau of Standards is predicting a reduction of 50 percent for fire-related fatalities(14). It would appear from the data presently available that this level of reduction is quite likely to occur and in time there may be even a greater reduction in residential fire-related deaths due to the presence of smoke detectors.

For a bottom line estimate as to the life saving benefit of residential smoke detectors a value of 50 percent reduction in fire related fatalities will be utilized. Also, an assumption of two-thirds will be used for the eventual number of residences with functioning smoke detectors. This would produce a range of values between 1750 and 2800 for annual lives saved due to the presence of smoke detectors. This is based on the estimate that 70 percent of fire related deaths are due to the residential fires and a total annual fire related death toll between 7500 and 12,000 persons.

3.1.2 Property Savings

In the United States many fire insurance companies offer a small (one to two percent) reduction in residential fire premiums when the insured has installed smoke detectors. A two percent reduction in residential property loss would amount to an annual savings of approximately $29,000,000[15]. That the fire insurance companies are willing to offer this premium reduction would seem to indicate that they have some substantial knowledge of the functions of smoke detectors and their ability to reduce property damage via early warning. A number of inquiries into insurance companies, national insurance company associations, and insurance information associations, revealed that the estimated reduction in property losses was simply a number "pulled from the air" for a competitive sales position.

Property loss due to fire can reach staggering proportions in regards to dollar amounts involved. Table 3.2 is a comparison of monetary loss to property fires in three advanced countries and serves to illustrate this point[16]. For Great Britain an estimated 50 percent reduction is predicted for property loss should there be a wide spread installation of smoke detectors. For Switzerland, the average fire loss has been shown to be reduced by one-third for buildings with smoke detectors. For the United States, the amount of property loss is indicated to be $\$4.17 \times 10^9$. This figure is higher than the amounts shown in the Statistical Abstracts for the United States for 1975 [17] but serves to illustrate the staggering losses that occur due to fire. Since 1975 inflation alone has caused the monetary loss to increase dramatically. This can be illustrated in data from CFIRS for 1977 and 1978, see Table 3.3. During these two years the number of residential and apartment fires in California decreased by 1.4 percent yet the dollar amount of structural damage went up 53 percent, almost 41 million dollars. It is evident from this that any method of reducing the potential loss from property fire will lead to large reductions in monetary loss.

The Applied Physics Laboratory has estimated that the proper installation of smoke detectors could result in 68 percent reduction in property loss. This value was based on the analysis of 117 residential fires in the Maryland/Washington D. C. area. In the OHC report for 1978 an estimation of reduction in property loss was made based on a group of residences (81,000) containing ionization type smoke detectors. Their findings indicate that a 67 percent (65/97) reduction in property damage occurred that year due to the

Table 3.2. Property Loss Due to Fire.

Country	Period	Fire Loss
Switzerland	1960-1967	250×10^6 (Swiss Francs)
United Kingdom	1969-1974	860×10^6 (Pounds)
United States	1975	4.17×10^9 (Dollars)

Table 3.3. Residential and Apartment Loss Due to Fire - State of California.

Structure	Total Number of Fires 1977	Total Number of Fires 1978	Dollar Amount of Loss 1977	Dollar Amount of Loss 1978
Dwellings	27,655	27,536	55,807,046	82,673,332
Apartments	11,035	11,104	20,801,784	34,797,236
TOTAL	38,690	38,640	76,608,830	117,470,568

presence of the smoke detectors. For California, there appears to be only a slight drop in number of residential and building fires but this, in fact, may not be so. It must be remembered that for California, there is a very large annual increase in dwelling structures, all of which, by law, must be equipped with smoke detectors. When this is considered it appears that there has been a larger reduction in dwelling fires in California than the 1.4 percent as indicated.

From the scant amount of available data, as presented above, it appears that residential smoke detectors are playing a definite role in reducing property loss due to fire. A summary of the estimated or actual observations follows:

- 50% - Great Britain - Estimation
- 33% - Switzerland - Measured
- 68% - APL - Estimation
- 67% - OHC - Measured

The percent of homes that will eventually have functioning smoke detectors is not known. This factor must be combined with the estimate for reduction in loss upon installation of smoke detectors to reach an estimate of the impact of these fire warning systems. Other factors exist which will influence the estimate of property loss reductions. The major factor here is the number of fires that are signaled by the smoke detectors, subsequently extinguished, and never reported by the residential occupant. If we assume that eventually two-thirds of the residences in the United States have functioning smoke detectors, we could make the following estimates as to the eventual potential dollar amount of residential property savings, based on the range of reductions indicated above:

$$\$1.4 \times 10^9 \times 0.33 \times 0.67 = \$310 \times 10^6$$
$$\$1.4 \times 10^9 \times 0.68 \times 0.67 = \$638 \times 10^6$$

This savings, from $310,000,000 to $638,000,000 is based on the amount of residential fire losses for the United States for 1976[15]. As numbers of houses and inflation continue to increase, so will the dollar amount of the potential savings with the installation of smoke detectors. Again as with lives saved, there are hidden savings in such things as reduced calls to the fire department, paramedics, hospital and medical costs, work and wages, and a host of others that can quickly add substantial amounts to this dollar figure. It would appear, as a conclusion, that with a functioning system and correct response of residential occupants, there will be substantial property savings with the installation of smoke detectors.

3.2 RADIOLOGICAL IMPACTS OF ICSD'S DURING THEIR LIFE SPAN

3.2.1 General Approach

The radiological impacts of ICSD's must be summed over their total life span. For normal usage the radiological impacts will be from external doses to exposed individuals and from inhalation or ingestion of the radioactive material where possible. In order to evaluate the radiological impacts, the dose to the maximally exposed individual and the collective dose to the exposed population are reported for each specific life span activity. The maximally exposed individual is defined as the individual who receives the largest dose or dose commitment of any person in the exposed population associated with the specific life span activity. All assumptions regarding the maximum individual are outlined in each section to follow.

For dose commitments resulting from inhalation or ingestion of radionuclides, 50-year dose commitment factors are utilized. Fifty-year dose commitment factors relate the dose an individual will receive as a result of retention of radioactive material in the body during the fifty years following the intake. Estimates of dose commitments to the major organs as determined by the radionuclide inhaled or ingested are made where appropriate. The calculational methods used to estimate doses are described in Appendix B.

The following sections describe the processes involved, people involved, and assumptions made in order to estimate dose and dose commitments during each life span activity. A summation of all data is given following the life span sections. Only the reference ICSD, namely the Am-241 unit, is considered in this section. Alternative ICSD's with Ra-226 and Ni-63 are discussed in Sections 4 and 5. Where collective or average individual doses are assessed, the average activity per ICSD is taken to be 3 uCi. In some instances, however, 5 uCi per detector is used in order to assess doses to maximumly exposed individuals.

In the broad, sweeping series of assessments presented below, it is evident that lack of specific information exists concerning many important factors. Thus, assumed values are employed in a number of calculations. Every effort has been made to use values which are best estimates, and which, if in error, are erroneous on the conservative side. Also, the reference cases which are analyzed are considered reasonable scenarios. However, should better information become available for incorporation into these assessments, the results can easily be adjusted in either direction to reflect these calculational refinements.

3.2.2 Manufacture

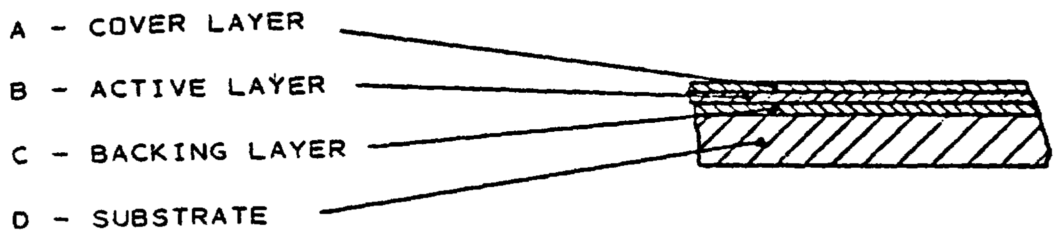
The manufacture of Am-241 ionization chamber smoke detectors essentially involves two processes by which occupational doses are possible. The first process involves the manufacture of the Am-241 source used in the ICSD. The second process involves the actual manufacture of the ICSD itself.

The Am-241 alpha sources are essentially a rolled foil with the Am-241 contained in a gold matrix sealed between a silver backing and a thin gold alloy cover. The radioactive americium is in an oxide form, AmO_2. The following discussion pertains to one manufacturer, but is considered appropriate to all manufacturers.

The manufacture of the alpha sources starts with AmO_2 being uniformly mixed with gold and formed into a briquette. The briquette is sintered at above 800^{o}C. The briquette is then mounted between a backing of silver and a front cover of gold and sealed by hot forging.

The composite briquette is then cold rolled in several steps until the required active area is achieved. The result is the gold cover ends up about 0.002-0.003 mm in thickness and the total piece thickness is 0.2 mm. The strips normally are 20 mm wide and cut into 1 m long pieces. Figure 3.3 illustrates one manufacturer's alpha source foil[18].

Sources are then made by either cutting strips from the foils or by punching them out. When strips are cut, they are usually between 1 and 3 mm



A - GOLD - PALLADIUM ALLOY 0.002MM

B - AMERICIUM OXIDE PLUS GOLD 0.002MM

C - GOLD 0.001MM

D - SILVER 0.20MM - 0.25MM

Figure 3.3. Am-241 Alpha Source Foil.[18]

wide. They are fixed to metallic or plastic holders by mechanical means such as crimping, soldering, welding, or by using epoxy glues.

Most sources, however, use a circular disc 5 mm or more in diameter. These discs are punched out of the foil sheets. Normally the discs are mounted in metal holders with a thin metal rim which can be rolled over to seal the cut edges completely.

The sources are then either placed in a smoke detector ionization chamber designed by the foil manufacturer and sold as a unit or sent to ICSD manufacturers for incorporation into their own chamber designs.

The general case involves ICSD manufacturers receiving the sources either simply as discs or in holders (at present nearly all are in holders). The workers who manufacture the ICSD's can be classified into two groups: (1) those who handle the sources and (2) those who work on the product which has the source already in an ionization chamber. Both groups may be exposed, but the first group has a higher chance of being exposed.

Exact numbers on actual exposure data are not easily reproduced for the manufacture of foils and smoke detectors. Estimates must be made in order to arrive at adequate values to assess the occupational exposures.

Conversation with one manufacturer of Am-241 foils revealed a cumulative external dose of 0.8 person-rem per curie of Am-241 processed in 1977. Approximately 150 workers were involved and the total amount of Am-241 used was 16.6 curies. The maximum dose for an individual was approximately 800 mrem. Another manufacturer reported 0.2 person-rem per curie of Am-241 processed in 1977. In order to account for the possibility of higher collective doses in other years, the exposure rate was assumed to be one person-rem per curie of Am-241 processed.

For 1978, with 14.1 million detectors distributed, containing a total of 40.7 curies of Am-241, the total dose is found to be 41 person-rem during the manufacture of the Am-241 foils. It is assumed the exposure occurs while the foils are being stamped and cut, washed, weighed, and installed in housings where appropriate.

Internal exposure data on workers is not available. However, the practices utilized as required by the NRC to manufacture Am-241 makes the potential for internal contamination small. Discussion with one manufacturer indicated workers wear shoe covers, lab coats, and gloves. Weekly wipe tests of floors, counters, etc., are performed. All employees were given a general indoctrination presentation including radiation exposure information upon employment.

During the manufacture of the actual ICSD units workers are exposed to the units during various operations or tasks. As mentioned earlier, there are basically two groups: (1) those that handle the sources and (2) those that work on ICSD construction and testing. Observation of the assembly of ICSD's by two manufacturers was made and these two groups were evident. The use of conveyor belts and modern assembly techniques passed the ICSD's in various stages of completion past the assembly workers.

Because of the low exposure level from individual sources (1.2×10^{-2} uR/hr per uCi at one meter for an unassembled or uncovered ICSD) the external exposures expected at a manufacturer's facility are low. Conversation with one manufacturer revealed the yearly (1978) external dose to individual badged workers was as follows:

40%	No measurable dose
40%	Less than 100 mrem
15%	Between 250 and 500 mrem
4%	Between 500 and 750 mrem
One Individual	Between 750 and 1,000 mrem

These numbers correspond to a collective dose of 2.7 to 8.8 person-rem. The range is given to correspond with the manner in which the doses are reported.

Smith et al.(19) estimated the collective external dose for the entire ICSD industry during manufacture by using data reported from three manufacturers. One company used a factor of 2.05 in estimating doses to unbadged workers compared to badged workers. Based on this number, the total corresponding dose to unbadged workers for the above data is 5.5 to 18 person-rem. The amount of Am-241 processed by the manufacturer was 22.5 Ci for 1978. The total activity in all ICSD's with Am-241 was 40.7 Ci for 1978. Therefore, using the above assumptions the total occupational dose accumulated in the ICSD manufacturing industry in 1978 has a range of 15 to 48 person-rem. A value of 48 person-rem will be used in this report. The maximum dose for an individual is taken to be 1,000 mrem. This is based on the badge data given above. It is noted here that the one individual receiving the dose between 750 and 1,000 mrem may have received the dose from other sources, such as a dentist, doctor, etc. The total dose was received in a short time (one reporting period) according to the manufacturer. It is extremely unlikely the dose came from Am-241 foils.

3.2.3 Manufacture Warehousing/Storage

The ideal situation for a manufacturer is not to have to store any final products in their warehouses. This ideal situation, however, is very seldom ever achieved. Storage of goods is normally required for a short time period. The occupational doses resulting from storage operations has already been included in the previous section.

3.2.4 Distribution

The distribution of ICSD's is similar to the distribution of any consumer product. Once the product leaves the manufacturer, it must be transported to various locations for storage and/or local distribution. For retail sale, the product will end up in storage and eventually be sold to the consumer. Some products will end up going to what is identified here as contractor sales. For ICSD's this is the market in which new homes in locales requiring smoke detector installation are being built. The contractor may buy the ICSD's in large quantities. This code market is approaching two million units per year.

It is important to indicate at this point that not all ICSD's distributed in the United States are manufactured here. Some are imported from abroad and then distributed in the United States.

3.2.4.1 Transportation

Because of the complexity of the transportation matrix associated with ICSD distribution, both in terms of exposure times and geometries, it is not possible to model the exposures from this mode in any easy fashion. Study has led to the conclusion that the methodology used by Smith, et al.[19] is as acceptable as can be found. That approach is repeated here. The Final Environmental Statement on the Transportation of Radioactive Material by Air and

Other Modes[20] is intended to serve as background material for regulations dealing with transportation of radioactive materials. The report goes into detail on many forms of radioactive materials that are transported. The report states ". . . assessment of the environmental impact of radioactive material transportation requires a detailed knowledge of the package types, the principal transport modes, the number of packages transported per year, the average quantity of material per package, the average 'transport index' or 'TI' (a measure of the external radiation level), and the average distance traveled per shipment." One TI is defined as being equal to 1 mrem/hr at 3 ft from the surface of a package containing radioactive material. In order to make the assessment more manageable, a list of "standard shipments" was compiled and given in the report.

The estimated total TI for limited shipments, which would include ICSD's, for 1975 was estimated to be 7740. The total collective dose for these limited shipments was found to be 63.3×10^{-3} person-rem.

The dose rate at one meter from an assembled ICSD is assumed to be 8.0×10^{-3} uR/hr or 7.4×10^{-3} urem/hr per uCi of Am-241. In 1978, the total amount of Am-241 distributed in residential ICSD's was found to be 40.7 curies. A total transport index for 1978 ICSD distribution can be formulated by taking the total Am-241 distributed times the dose rate at one meter. The total transport index is equal to

$$\frac{(40.7\ \text{Ci})(10^{6}\ \text{uCi/Ci})(7.4\times10^{-3}\ \text{urem/hr-uCi})(10^{-3}\ \text{mrem/urem})}{(1\ \text{mrem/hr-TI})} = 300\ \text{TI}.$$

In practice, the actual dose rates would be much lower due to the presence of packaging. However, for this analysis 300 TI's will be used. Therefore, the estimated collective dose due to 1978 shipment of Am-241 ICSD's is

$$\frac{(63.3\times10^{-3}\ \text{person-rem})(300\ \text{TI})}{(7740\ \text{TI})} = 2.5\times10^{-3}\ \text{person-rem}.$$

3.2.4.2 Distributor Warehousing

The exposures resulting from distribution warehousing and storage activities are estimated in this section. The reference case involves a warehouse which stores 1,000 units at a time and employs 20 workers. If the average turnover time for this amount of detectors is 50 days, almost 2,000 such warehouse operations would be needed to account for an annual sale of 14 million units.

The exposure rate at three meters from an array containing up to 1,000 ICSD's (3 uCi per unit) is estimated to be about 0.25 uR/hr. (The basis for this estimate is given in Section 3.2.4.3.) If each worker spends 2,000 hours per year at an average distance of three meters from this array, the dose to the total worker population would be about 20 person-rems. The average individual dose would be about 0.5 mrem. This average dose is undoubtedly on the conservative side since few, if any, of the warehouse workers would spend most of their time in such close proximity to the detector array. However, the values arrived at in this assessment serve to illustrate the fact that, even for worst-case situations, exposures to the distributor warehouse population are minimal.

3.2.4.3 Retail Sales

This section assesses the radiological impact associated with the display and purchase of ICSD's in retail outlets. Two specific cases are analyzed:

1. The dose to store workers and shoppers resulting from an array of displayed ICSD's, and
2. The dose to a consumer who purchases an ICSD and carries it on their person for one hour.

Peterson[21] has measured exposure rates from horizontally and vertically stacked arrays of ICSD's, each containing 5 uCi Am-241. He found that the maximum exposure rate occurred from 17 horizontal and seven vertical detectors, and that the total exposure rate was about a factor of three greater than the maximum value obtained from readings observed for individual detectors.

These results cannot be conservatively applied here, however, since exposure rates from a rectangular array would be expected to be greater.

Smith, et al.[19] has calculated an exposure rate of 0.3 uR at two meters from a stacked display containing up to 100 detectors. General Electric Company[22] conservatively estimated the exposure rate at one meter from a stacked array of 384 units containing a total of 1.15 mCi Am-241 to be 1.5 uR/hr. This assessment assumes that the exposure rate at one meter from a retail store array is 1 uR/hr, decreasing to 0.5 uR/hr at two meters, and 0.15 uR/hr at three meters.

The dose to a maximum individual consumer is assessed by assuming that the person spends 0.5 hr at one meter from a stacked array of ICSD's, and then carries two purchased units (5 uCi Am-241 each is used for maximum individual assessment) at a distance of 10 cm for 0.5 hr. The total body dose in such a scenario would be about 4.2 urem.

The population dose is assessed by assuming that, on the average, the entire population spends 0.25 hr at two meters from an ICSD display, and that 14 million purchased detectors (3 uCi Am-241 each is used for average individual or population assessments) are carried at a distance of 25 cm for 0.5 hr. This results in a total body dose of 28.1 person-rems to the population from the sale of ICSD's during a peak year.

The dose to retail clerks working in the vicinity of an ICSD display can be assessed by assuming an average distance of three meters over a period of 2,000 hours. This results in an individual dose of about 0.5 mrem. If one clerk was exposed in such a manner for every 1,000 detectors sold, the total dose to this group of people in a peak sales year would be about seven person-rems.

3.2.5 Use By Purchaser

This section assesses the radiological impact of ICSD use including transport, installation, testing, maintenance, and operation.

3.2.5.1 Transport

The amount of radiation received by the consumer in the process of transporting the purchased ICSD's home depends on source strength, duration of transport, distance from the source during transport, and amount of intervening shielding. This assessment assumes that the purchaser transports two units, each containing 3 uCi Am-241, at an unshielded distance of one meter for a duration of one-half hour.

Utilizing the exposure rate constant at one meter for Am-241 in ICSD's ($8.0\text{-}x10^{-3}$ uR/hr-uCi), the whole body dose contribution from this activity would be

$$(6 \text{ uCi})(8.0 \times 10^{-3} \text{ uR/hr-uCi})(0.93 \text{ urem/uR})(0.5 \text{ hr})$$

$$= 2.2 \times 10^{-2} \text{ urem.}$$

Assuming that, on the average, one person is exposed under similar conditions for each detector sold, the collective dose resulting from the transport of the number of ICSD's purchased during a peak year (14 million) would be

$$(14 \times 10^{6} \text{ ICSD's})(1.1 \times 10^{-2} \text{ urem/ICSD})(0.5 \text{ person-hr})$$

$$= 0.15 \text{ person-rem.}$$

3.2.5.2 Installation and Operation

Activities related to the normal use of ICSD's which warrant radiological assessment are installation, operation, and testing and maintenance activities, including changing batteries and cleaning.

The installation of ICSD's in residences is assessed by assuming an average installation time of one-half hour and an average source-to-body distance of 50 cm. The resultant dose to an individual per ICSD would be

$$\frac{(3 \text{ uCi})(8.0 \times 10^{-3} \text{ uR-m}^2\text{/hr- uCi})(0.5 \text{ hr})(0.93 \text{ urem/uR})}{(0.5\text{m})^2}$$

$= 4.5 \times 10^{-2}$ urem.

The installation of 14 million ICSD's would result in a total body population dose of about 0.6 person-rem..

The dose to the hands of the installer can be estimated by using the results of contact exposure rate measurements reported by General Electric Company[22]. The maximum surface exposure rate was found to be 1.3 uR/hr for an ICSD containing 3 uCi. Thus, the hand dose would be about 0.6 urem per unit installed. The corresponding hand dose to the population resulting from the installation of 14 million units would be about 8.4 person-rem.

The average annual individual dose and the dose to the population resulting from normal ICSD operation are assessed based on the following assumptions:

1. 100 million detectors with an average activity of 3 uCi are installed in 50 million residences.
2. 90 percent of the detectors are installed in hallways and ten percent in bedrooms.
3. Two people are exposed to each bedroom-mounted detector for eight hours per day at an average distance of 3 m.
4. Three people are exposed to each hallway-mounted detector for one hour per day at an average distance of 2 m.

The annual whole body dose to an individual (D_i in urem/yr) would be

$$D_i = \Gamma A k \left(\frac{O_b}{d_b^2} + \frac{O_h}{d_h^2} \right)$$

where

A	=	Average Am-241 activity per detector (uCi),
O_b	=	Occupancy factor in bedroom (hr/yr),
O_h	=	Occupancy factor in hallway (hr/yr),
d_b	=	Average source-to-subject distance in bedroom (m),
d_h	=	Average source-to-subject distance in hallway (m),

Γ = Exposure rate at one meter from an Am-241 source within an ICSD (8.0×10^{-3} uR-m^2/hr-uCi), and

k = Constant relating dose rate in tissue to exposure rate in air(0.93 urem/uR).

Thus, assuming the individual has one detector in both the hallway and bedroom, the annual dose would be

$$(8.0\times10^{-3}\ \text{uR-m}^2/\text{hr-uCi})(3\ \text{uCi})(0.93\ \text{urem/uR})\left(\frac{2920\ \text{hr/yr}}{9\ \text{m}^2} + \frac{365\ \text{hr/yr}}{4\ \text{m}^2}\right)$$

$$= 9.3\ \text{urem/yr.}$$

The collective dose to the population (D_p in person-rem/yr) is given by

$$D_p = \Gamma Ak\left(\frac{n_b n_{bp} O_b}{d_b^2} + \frac{n_h n_{hp} O_h}{d_h^2}\right)$$

where

n_b = Number of detectors in bedroom,

n_h = Number of detectors in hallway,

n_{bp} = Number of people exposed per bedroom, and

n_{hp} = Number of people exposed per hallway.

Based on the assumptions listed above, the annual population dose is calculated as follows.

$$\Gamma Ak = (8.0\times10^{-3}\ \text{uR-m}^2/\text{hr-uCi})(3\ \text{uCi})(0.93\ \text{urem/uR})$$

$$= (2.2\times10^{-2}\ \text{urem-m}^2/\text{hr})(10^{-6}\ \text{rem/urem})$$

$$= 2.2\times10^{-8} \text{ rem-m}^2/\text{hr}.$$

Therefore,

$$D_p = (2.2\times10^{-8} \text{ rem-m}^2/\text{hr}) \left(\frac{(10\times10^6)(2 \text{ people})(2920 \text{ hr/yr})}{9 \text{ m}^2} + \frac{(90\times10^6)(3 \text{ people})(365 \text{ hr/yr})}{4 \text{ m}^2}\right)$$

$$= 695 \text{ person-rem/yr}.$$

In order to assure reliability and to prevent spurious alarms, smoke detectors must be periodically checked for proper operation, cleaned, and in some cases have the batteries replaced. It is assumed here that activities such as these will result in user exposures averaging one hour per year at a distance of 0.5 meter. The resultant dose to an individual possessing two units would be:

$$\frac{(8.0\times10^{-3} \text{ uR-m}^2/\text{hr-uCi})(6 \text{ uCi})(0.93 \text{ urem/uR})(1 \text{ hr})}{(0.5\text{m})^2}$$

$$= 0.18 \text{ urem/yr}$$

The dose to the hands in the above case would be about 1.2 urem/yr.

The whole body dose to the population resulting from the testing and maintenance of 14 million ICSD's would be 1.3 person-rem. The associated hand dose to the population would be about 17 person-rem.

3.2.6 End of Life (Disposal)

Since little information exists concerning the rate at which ICSD's may be returned to the manufacturer for proper disposal, the environmental impact resulting from normal disposal of ICSD's (e.g., incineration or burial) must be assessed. Figure 3.4 schematically presents the pathways by which ICSD disposal activities may result in external or internal human exposure. These pathways of exposure are assessed in the following sections.

3.2.6.1 Disposal with Refuse

It is estimated that as many as 100 million smoke detectors may be sold during the peak sales decade of 1977 to 1986[23]. Assuming for the sake of analysis that all of these detectors are ICSD's, and that these detectors have an average useful life of ten years, ICSD's would be disposed of at a rate of up to ten million units per year for several years after the peak sales period. The disposal rate will gradually decline in the ensuing years reflecting the decline in sales after the peak years of 1978-79. It is also assumed that the average activity per unit will be 3 uCi for Am-241 detectors.

3.2.6.1.1 Municipal Solid Waste Practices

Municipal solid waste from residential, commercial, and institutional sources amounted to 130 million metric tons in 1976 (1.8 kg per capita), and the yearly total is expected to increase to 180 million tons by 1985[24]. The composition of municipal refuse varies widely, but a typical composite has been summarized in Table 3.4. Most of these wastes are collected and transported to a processing or disposal site. Approximately nine percent of municipal refuse is incinerated, seven percent is recycled, six percent is disposed of in sanitary landfills, and less than one percent is used for producing compost. The largest fraction of municipal solid waste, approximately 78 percent of the total amount collected, is deposited in open dumps which do not meet the minimum qualifications of a sanitary landfill[24,26,27]. A significant amount of the solid waste generated is not collected but rather is disposed of in apartment house, institutional or backyard incinerators, in sewer systems or in unauthorized dumping areas. This is apparent due to the fact that in certain urban areas the amount of waste collected per capita is significantly less than the estimated amount of per capita generation[27]. Municipal waste only accounts for about seven percent of the total volume of solid waste generated nationally. Agricultural wastes such as animal carcasses, manure and crop harvesting residues account for about 59 percent of the annual generation, while mineral wastes such as mill tailings and slag represent 31 percent of the waste. The remaining 37

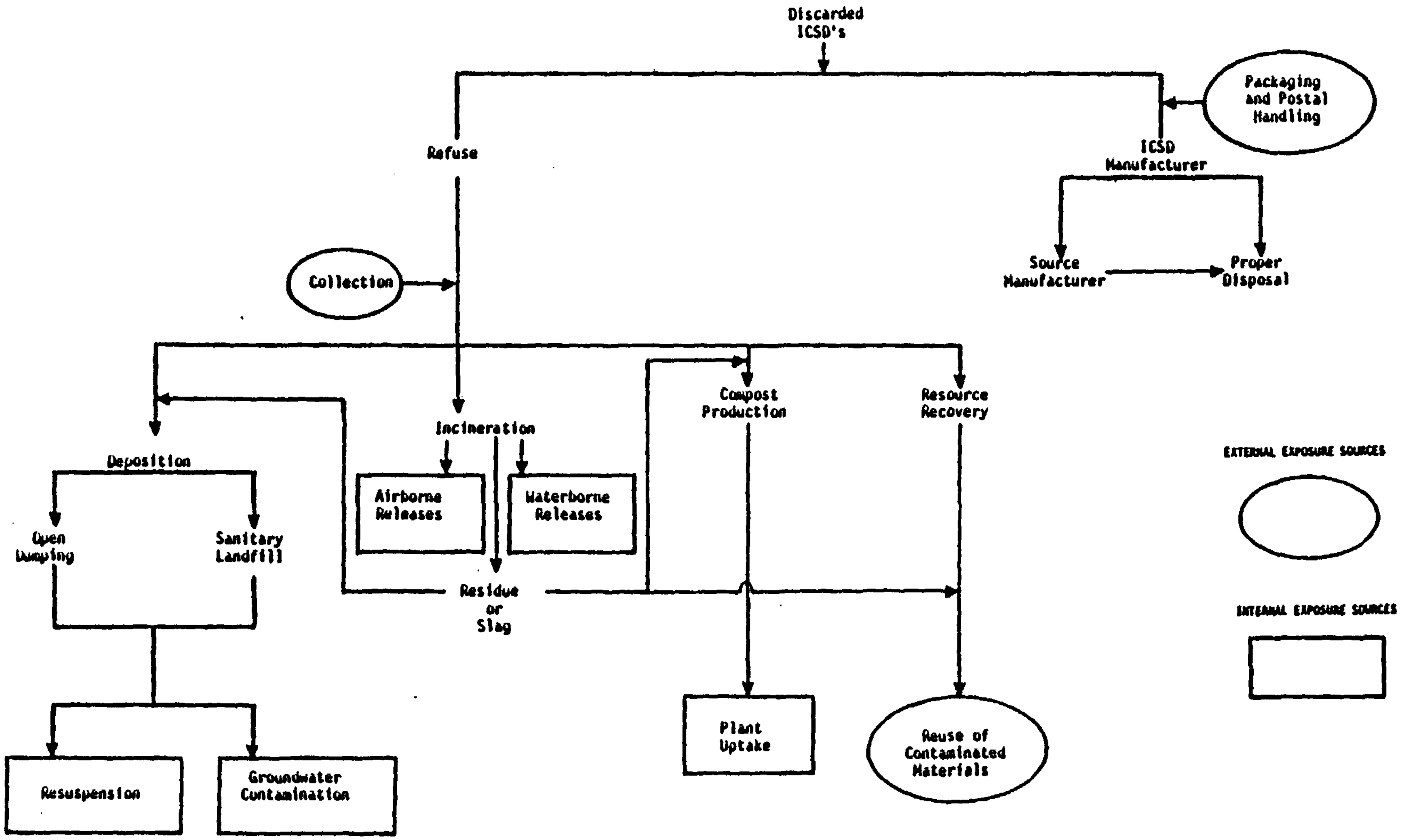


Figure 3.4. Pathways of Exposure Resulting from the Disposal of ICSD's.

Table 3.4. Composition of Municipal Solid Waste Collected From Four Different Cities.[25]

Item	% Composition of Municipal Waste	
	Range	Average
Paper	40-54	45
Wood	1.5-3.5	3
Plastic	2-3	2.5
Glass	3.5-10	6
Metal	7-13	9
Stone, sand	7-8.5	7.5
Organics (food and yard wastes)	20-27	22.5
Rags	1.5-8	4.5

percent is due to waste generation in the manufacturing industry[41]. Although 70 to 80 percent of these industrial wastes are disposed of on the generator's property, a significant fraction will ultimately be desposited in landfills with municipal wastes[24]. The individual steps in the practice of waste collection, processing and disposal are discussed separately below with regards to their importance as pathways of exposure.

3.2.6.1.2 Collection

Approximately 175,000 people and 138,000 vehicles are directly involved in the practice of municipal solid waste collection in this country. Of these vehicles, approximately 78,000 are of the large, compactor variety while the remaining 60,000 are classified simply as vehicles other than compactor trucks. An additional 165,000 operators and 115,000 vehicles are involved in the collection of industrial wastes[24,27].

It is difficult to conceive of any credible scenario which could result in significant exposure of solid waste operators to ionizing radiation as a result of the collection and transport of ICSD's in municipal refuse. Considerable shielding from the gamma radiation, the levels of which are low even without shielding, would be provided by the steel walls of the truck bin as well as the contained refuse. Compaction of the trash could increase the margin of protection by increasing the degree of shielding and the distance between source and operator.

The dose to the municipal waste collection population can be assessed by assuming the following:

1. The number of ICSD's collected annually is ten million with an average activity of 3 uCi per detector.
2. The averaged time that a collected ICSD spends in a truck is two hours at an average detector-to-operator distance of two meters.
3. An average shielding factor of 0.5 is used to account for attenuation by the truck bin, other refuse, etc.
4. The waste collection population consists of 175,000 people and 138,000 vehicles, or an average of 1.3 persons per vehicle.

The total activity collected per year would be 3×10^7 uCi or 220 uCi per vehicle. The annual exposures associated with each vehicle would be:

$$(220\ \text{uCi})(8 \times 10^{-3}\ \text{uR-m}^2/\text{hr-uCi})(0.93\ \text{urem/uR})(2\ \text{hr})(1.3\ \text{persons})(0.5)/(2\ \text{m})^2$$
$$= 0.5\ \text{person-urem/yr}$$
$$= 5.0 \times 10^{-7}\ \text{person-rem.}$$

The average annual individual dose would be about 0.4 urem. This represents a collective dose to the refuse collection population of about 0.07 person-rem.

It is not possible to quantitatively assess the magnitude of the internal exposure hazard, if it does indeed exist, posed by the collection of ICSD's in refuse. It would seem, however, that this hazard would be minimal due mainly to the high degree of Am-241 source integrity which is maintained under normal and stress conditions. Waste packaging, compaction and coverage by other refuse would also tend to minimize the possibility of internal exposure.

3.2.6.1.3 Disposal in Landfills

According to a 1976 EPA report to Congress on the effects of waste disposal practices on ground water, municipal wastes in the U. S. are currently disposed of in about 18,500 land disposal sites, only about 20 percent of which are considered "authorized"[29]. Only about 20 sites are lined and only 60 or so have provisions for leachate control. Most of the 18,500 sites are open dumps which are unacceptable because of burning, water pollution, lack of daily cover, or some combination of these factors. Only about six percent meet the minimum requirements for being considered a sanitary landfill. Table 3.5 summarizes the results of a national survey of land disposal site problems. Of the total sites surveyed, 93 percent had insufficient or no daily cover, 84 percent burned some of their waste, and 45 percent had an existing or potential water pollution problem. Most of these sites also received some industrial wastes.

The disposal of ICSD's in solid waste landfills can result in the exposure of population groups through direct radiation exposure, ingestion of contaminated ground water or food crops, and inhalation of resuspended radioactivity (Figure 3.5). Due to the dilution of ICSD's in large amounts of

Table 3.5. A Summary of Problems Reported for 11,781 Unacceptable Land Disposal Sites.[27]

Problem	Number of Sites	Percent
No cover	1,046	8.9
Burning	304	2.6
Water pollution	320	2.7
Burning and no cover	5,393	45.8
Water pollution and no cover	764	6.5
Burning and water pollution	199	1.6
Burning water pollution and no cover	3,755	31.8
	11,781	

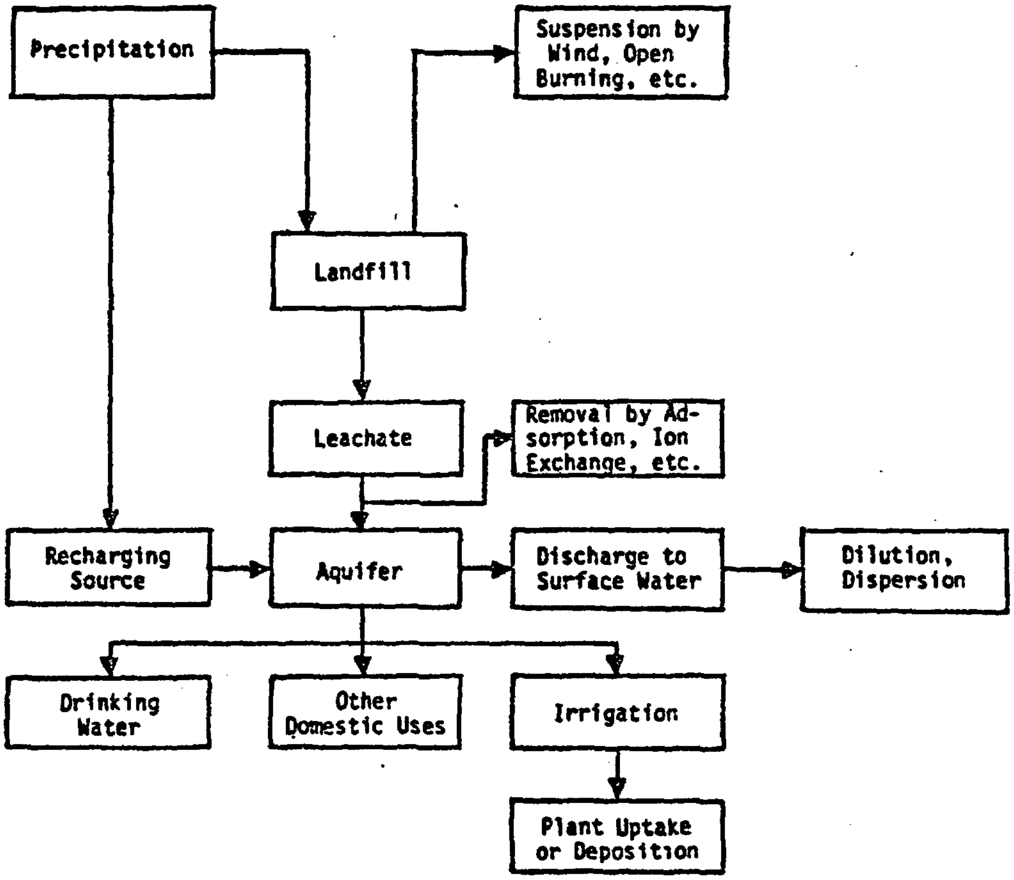


Figure 3.5. Major Factors Influencing the Contamination of Air and Ground Water from Landfill Disposal of ICSD's.

other waste and/or cover materials, the low levels of penetrating radiation emitted by detector sources, and the absence of persons in close proximity to a landfill site for long periods of time, direct radiation should not be considered a significant mode of exposure. The ingestion and inhalation pathways are assessed separately below.

3.2.6.1.3.1 Groundwater Contamination

Municipal waste disposal in landfills can result in groundwater contamination through the generation of leachate formed when water percolates through cover material and refuse. Precipitation which falls on the site can either run off, return to the atmosphere by evaporation or transpiration, or infiltrate the landfill. Surface runoff from surrounding areas, moisture contained in or produced by the decomposition of the refuse, and water entering the landfill from the bottom or sides also contribute to the generation of leachate. The problem of ground water contamination by landfill disposal practices is compounded by the frequent location of landfills or dumps at sites which are particularly susceptible to this type of contamination. Examples of such contamination - prone sites are marshlands, abandoned sand or gravel pits, old strip mines or limestone sinkholes. The EPA estimates that 70 percent of the municipal solid waste landfill sites are in ground water surplus areas, and that the average infiltration of precipitation is ten inches per year. Thus, assuming that the average site comprises an area of 25 acres, the total estimated leachate generation is 90 billion gallons per year, most of which enters the groundwater system[29].

Contaminants that have entered the ground water can move horizontally or vertically, depending on the comparative density and natural flow pattern of the water in the aquifer. The contaminants do not mix readily with native water but tend rather to move as a well-defined slug or plume. The concentration of contaminants in ground water are usually reduced with time and distance by such mechanisms as adsorption, ion exchange, dispersion and decay[29].

Almost half of the U. S. population depends on ground water for drinking water supplies. The U. S. Geological Survey estimates that the total withdrawal of ground water for domestic purposes in 1970 was 9.4 billion gallons per day (35.6 million m^3/day)[29]. Of this amount, it is estimated that five percent (470 million gallons per day) is used for drinking and six percent (564 million gallons per day) for kitchen use. Most domestic water is used for flushing toilets (41 percent) and for washing and bathing (37 percent)[31]. An additional 44.6 billion gallons per day (169 million m^3/day) was withdrawn from ground water sources in 1970 for irrigation purposes. Although the total ground water withdrawal is expected to more than double by the year 2020, the domestic use portion of the ground water supply will grow approximately at the same rate as the population[29].

The environmental health impact resulting from the contamination of ground water by disposal of ICSD's in landfills is assessed below in three different ways. The first assessment is a straightforward calculation, based on conservative assumptions, of the transport of ICSD source contaminants from the landfill to the ground water system to man. The second assessment is the method used by Johnson[32] in which he compares resultant Am-241 levels in soil and water with those of naturally occurring Ra-226. Wrenn[33] has assessed the Am-241 disposal impact by comparing the return to people via diet with the dietary intake of Am-241 fallout from atmospheric weapons tests. The latter two assessments employ methods and assumptions which are somewhat different than those used in this report. Their results are included for the sake of comparison.

An accurate calculation of the transport of Am-241 contamination from landfill to man, and the subsequent radiological impact, is not possible due to lack of specific data concerning many important factors. Although the mechanisms involved are fairly well-understood, a large degree of uncertainty exists in the quantitative aspects of source leaching, transport in soil and water systems, plant uptake, and deposition, translocation and elimination processes in humans. A conservative utilization of the available data, however, can be applied to yield an upper bound or "worst case" estimate.

In the ground water contamination pathway, the first mechanism of importance is the leaching of contamination from ICSD sources. Long term exposure of Am-241 sources to corrosive environments has indicated that deterioration of the foils is linked to corrosion of its silver backing and that the effect increases with the activity loading of the foil[18]. However, even sample foils near the maximum activity loading used in ICSD's showed very slight leakage. The greatest amount released was about 0.01 percent in an immersion test after exposure to a corrosive SO_2 environment for two years. Table 3.6

summarizes the results of the corrosive environment and other source integrity tests.

Since incinerator residue is also disposed of in landfills, incinerated ICSD's must also be assessed for source leakage. Results of 1200°C temperature tests on Am-241 sources indicate that post-test source wipes normally yield loose contamination levels which are less than one percent of initial source activity[34]. Incinerated sources which are subjected to percolation in landfills for long periods of time can be expected to release higher levels of loose contamination. This assessment assumes that ten percent of ICSD's disposed of in landfills have previously been incinerated and that these sources can lose up to ten percent of their initial activity in a year. The remaining 90 percent of ICSD's are assumed to lose up to 0.01 percent of their activity in a year. Here, as in previous analyses, it is assumed that ten million units may be disposed of in a year, and that the average source activity is 3 uCi of Am-241.

Once in the leachate, Am-241 will migrate at a rate dependent on the physical and chemical composition of the soil and the chemical form of the americium. Cline[35] has shown that the downward migration of Am-241$(NO_3)_4$ is largely dependent on soil pH. His results indicated that, after leaching with 100 inches of irrigation water, 98 percent of the americium was retained in the top one centimeter of acid (pH=4.5) soil, whereas only 76 percent remained in the top layer of basic (pH=7.5) soil. Maximum americium penetration was observed to be 20 centimeters in the basic soil and five centimeters in the acid soil. The percolating water can experience one of four types of interactions as it moves through the unsaturated zone above the aquifer. It can either (1) move virtually unchanged, (2) experience a net gain of solute or suspended matter, (3) experience a net loss of solute or suspended matter, or (4) maintain the same total ionic concentration with net exchange of ions with the sorption medium. Adsorption is strongly influenced by particle size of the sorption medium; the more finely divided the solid, the greater the surface area per unit volume. Thus, clays and silts have much greater adsorptive capacities than do sands or gravels. Hajek[36] has reported that the fraction of soil-bound americium which can be readily moved by an invading solution is quite low. The ratio of solution movement to americium movement is reported to be of the magnitude of 10^4 indicating a very slow leach rate.

Table 3.6. Results of Tests in Which Am-241 Foils Were Subjected to Various Corrosive Conditions.[18]

Sample	Activity µCi	Activity Loading µCi/cm^2	Corrosive Atmosphere	Wipe Test nCi	Immersion nCi	Total Activity Lost %
Foil type Am-241 1 cm long strip	160	128	H_2S	N.T.(1)	N.T.	N.T.
			SO_2	1.0	17.0	0.01
			NH_3	6.9	13.6	0.01
			HCl	1.6	7.6	0.01
			Salt Spray	2.0	0.4	0(2)
Foil Type Am-241 1 cm long strip	500	400	H_2S	7.5	13.9	0
			H_2S	26.8	33.7	0.01
			SO_2	10.3	56.9	0.01
			NH_3	N.T.	N.T.	0
			HCl	8.5	38.5	0.01
			Salt Spray	56.3	10.0	0.01
Platinum based foil Am-241 3 mm x 3 mm square	4	44	H_2S	3.5	1.5	0.13
			H_2S	2.1	0.7	0.07
			SO_2	0.7	0.1	0.02
			SO_2	0.6	0.1	0.02
			NH_3	N.T.	N.T.	0
				-	-	
			HCl	1.0	2.4	0.09
			HCl	1.5	2.4	0.10
			Salt Spray	0.4	0.1	0.01
			Sal Spray	0.5	0.1	0.02
Gold based foil Am-241 10 mm x 10 mm square	4	4	H_2S	0.2	0.2	0.01
			H_2S	0.2	0.2	0.01
			SO_2	0.3	0.1	0.01
			SO_2	0.2	0.1	0.01
			NH_3, HCl	N.T.	N.T.	0
			Salt Spray	N.T.	N.T.	0

Notes: (1) N. T. = Not Tested (2) 0 = <0.005%

Another important parameter concerning the movement of contaminants in ground water is the degree to which the contamination is dispersed both longitudinally (in the direction of ground water flow) and transversely. The dispersion coefficient of an aquifer is a measure of the actual dispersion as determined by aquifer permeabilities and hydraulic gradients. The U. S. Geological Survey has determined that, under a gradient of 2 m/km, the rate of ground water flow can vary from 18 m/day in gravel to 0.3 m in 30,000 years for clay[37]. The transverse dispersivity, which may be described as the inherent capability of the aquifer to cause dispersion in a transverse direction is dependent primarily on the complexity (on a microscopic level) of the paths taken by the fluid, and (on a macroscopic level) inhomogeneities within the aquifer[29]. Figure 3.6 depicts two examples of contamination plumes in aquifers with different transverse dispersivities. Since contamination plumes are observed to travel in a rather well-defined manner, it is evident that dilution by the surrounding body of ground water is not a major factor.

From the above discussion, it is apparent that definite statements cannot be made concerning the distance and direction that contamination will travel due to the wide variability of aquifer types and contaminant characteristics. This problem is further compounded by the scarcity of data related to the behavior of americium in soil and plant systems. (See Reference 38 for a review of this subject.) There is reason to believe, however, that the migration of americium in the zone of aeration is a very slow process in which most of the americium will be adsorbed on soil particles[36,38]. Once in the zone of saturation, the contamination plume will travel in a well-defined state, the degree of dispersion depending on aquifer conditions.

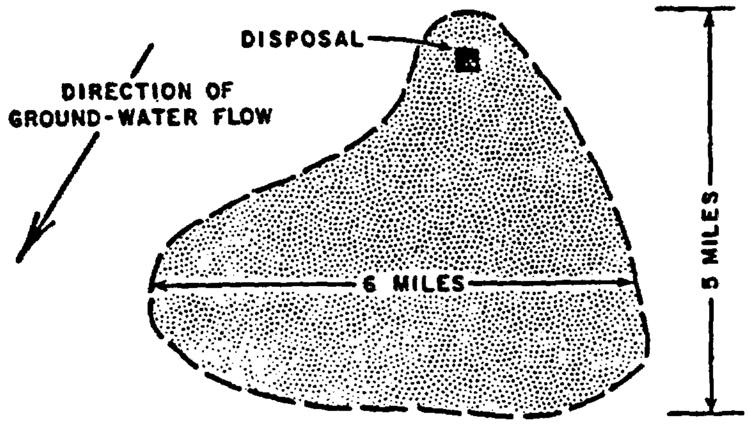
This assessment will assume the following:

1. Ten million ICSD's are disposed of in one year with an average source activity of 3 uCi.

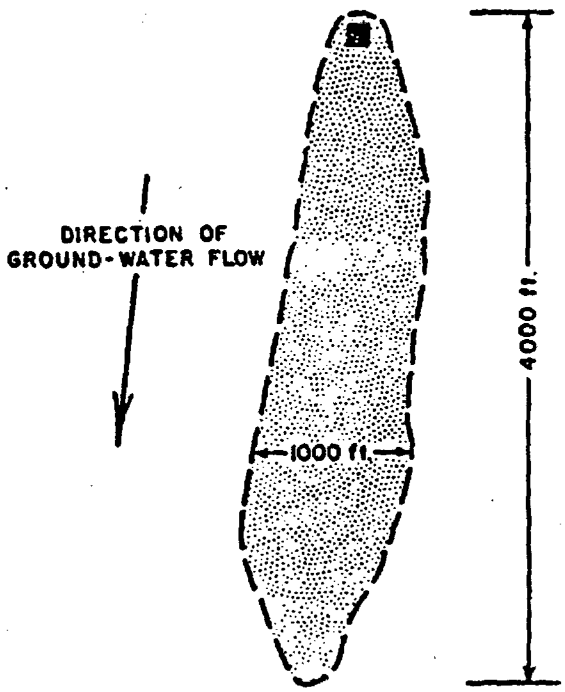
2. Ten percent of ICSD's disposed of in landfills have been previously incinerated and these sources can lose up to ten percent of their initial activity in one year.

3. The remaining 90 percent of ICSD's 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.



a) CHLORIDE PLUME, INEL, IDAHO
Transverse dispersivity: 450 feet
Time: 16 years



b) CHROMIUM PLUME, LONG ISLAND
Transverse dispersivity: 14 feet
Time: 13 years

Figure 3.6. Examples of Transverse Dispersion Patterns of Contamination Plumes.[29]

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.

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*.

The concentration (uCi/ml)of americium in the leachate (A_ℓ) as it enters the zone of saturation would be

$$A_\ell = A_t f_{\ell 1} f_{\ell 2} / V_\ell$$

where

A_t = Total activity in the landfill (uCi),

$f_{\ell 1}$ = Fraction of total activity leached,

$f_{\ell 2}$ = Fraction of activity in the leachate is not removed before entering the zone of saturation, and

V_ℓ = Total volume of leachate produced over the time of interest(ml).

Thus, under the assumed conditions, the average americium concentration in all of the leachate generated in one year would be

$$\frac{(3\times10^{7}\ \text{uCi})(0.5)((0.1)(0.1) + (0.9)(0.0001))}{(90\times10^{9}\ \text{gal})(3.8\times10^{3}\ \text{ml/gal})} = 4.4\times10^{-10}\ \text{uCi/ml}.$$

---

*In light of Environmental Protection Agency recommendation that all ground water withdrawal points should be located a "safe distance from sources of pollution" or "where water resources are severely limited, ground water aquifers subject to contamination may be used for water supply if adequate treatment is provided," this estimate of the fraction of contaminated ground water which reaches drinking water supplies may be grossly exaggerated[39].

Since the concentration guide (10CFR20, App. B) for americium in water is $4x10^{-6}$ uCi/ml for soluble forms and $3x10^{-5}$ uCi/ml for in soluble forms (the latter is probably the more relevant case here), the concentration of this nuclide in the leachate is a very small fraction of the allowable limits: about 0.01 percent of the soluble limit and 0.001 percent of the insoluble limit.

The amount of activity ingested (A_{ing}) as a result of contaminated water in the drinking water supply can be estimated by

$$A_{ing} = V_{\ell} f_{d1} f_{d2} A_{\ell}$$

where

V_{ℓ} = Volume of leachate generated in one year (ml),

f_{d1} = Fraction of contaminated ground water which is withdrawn for domestic water supply (0.01), and

f_{d2} = Fraction of domestic water supply which is consumed as drinking water (0.05).

The dietary intake by the entire U. S. population, A_{ing}, in this scenario would be:

$$A_{ing} = (90x10^{9} gal)(3.8x10^{3} ml/gal)(0.01)(0.05)(4.4x10^{-10} \text{ uCi/ml})$$

$$= 75 \text{ uCi}.$$

The 50-year dose commitment (D_{ing}) to the exposed population from ingestion of contaminated water is estimated by

$$D_{ing} = (A_{ing}) (DCF_i)$$

where

DCF_i = Dose conversion factor for organ i (rem per uCi ingested).

Table 3.7 shows the results of this calculation utilizing the dose conversion factors from the INREM computer code[40]. The dose commitment to the maximally

Table 3.7 . Fifty-year Dose Commitments Resulting from Intake of Contaminated Ground Water and Food Crops.

Reference Case	Intake (μCi)	Dose			
		Total Body	Skeleton	Liver	Kidneys
<u>Ground Water</u>					
Maximally Exposed Individual (rem)	1.6E-4	8.7E-6	1.3E-4	4.6E-5	6.5E-5
Total Population (person-rem)	7.5E+1	4.1E+0	6.2E+1	2.1E+1	3.1E+1
<u>Food Crops</u>					
Average Individual (rem)	1.0E-8	5.7E-10	8.2E-9	2.9E-9	4.1E-9
Total Population (person-rem)	2.3E+0	1.2E-1	1.9E+0	6.6E-1	9.4E-1

exposed individual is assessed in the same manner, except that it is assumed that the annual dietary intake of water (I_w) is 370 liters and consists entirely of ground water contaminated with Am-241 at the same concentration as calculated for leachate (i.e., 4.4×10^{-10} uCi/ml):

$$A_{ing} = I_w A$$

$$= (370\ l)(4.4 \times 10^{-10}\ uCi/ml)(10^3\ ml/l)$$

$$= 1.6 \times 10^{-4}\ uCi.$$

The dose commitments arrived at in this manner are extremely low when compared to total body doses received from natural background radiation over the same period of interest. For the entire ground water-dependent population (48 percent of the total U. S. population), this figure would be approximately ten million person-rem, or about two million times that received in the above assessment (4.1 person-rem). In the case of the maximally exposed individual, the total body dose that person receives from a one-year ingestion of contaminated water represents an amount equal to about 10^{-4} the amount due to natural background. Skeletal doses are also lower by several orders of magnitude.

Johnson[32] has assessed the impact of landfill disposal of ICSD's by comparing the resultant Am-241 concentration in soil and water to that of naturally-occuring Ra-226, a bone-seeking alpha emitter similar to Am-241. He assumed that a steady state U. S. inventory of 156 Ci of Am-241 exists (one ICSD per dwelling, 2.5 uCi per ICSD), and that all detectors are disposed of in landfills after a mean life time of five years, and arrived at a concentration of Am-241 in landfill refuse of 0.11 pCi/g. This estimate does not assume any dilution by soil and is therefore a "worst case" estimate of the concentration. Despite this conservatism, the resultant soil concentration is several times lower than the average concentration of naturally-occurring Ra-226 (about 0.6 pCi/g). Johnson goes on to assume equal solubilities and transfer from soil to diet for radium and americium and arrives at a "worst case" dose rate to the skeleton of 0.002 mrem/yr.

Wrenn[33] has applied the findings of Bennett[41] to show that americium in the environment is very poorly returned to man via diet. The cumulative deposition of Am-241 on the surface of the U. S. as a result of atmospheric weapons testing is now about 5000 Ci, and the current annual average per capita dietary intake is about 0.4 pCi. Thus, assuming no dramatic changes in these figures over the next 70 years, the lifetime intake of an individual would be about 28 pCi. For a population of 200 million people, this represents an integrated lifetime intake of 5.6 mCi, or roughly 10^{-6} of the total americium distributed. Using this value and assuming that ten percent of the Am-241 from ten million detectors (Wrenn assumed 2 uCi each) leaches or otherwise becomes available to move about in the environment, the collective intake would be

$$(10^7 \text{ detectors})(2 \text{ uCi/detector})(0.1)(10^{-6}) = 2 \text{ uCi}.$$

This figure corresponds to 50-year dose commitments to the entire population of 0.11 person-rem for total body, 1.64 person-rem for bone, 0.52 person-rem for liver, and 0.81 person-rem for kidneys.

Contamination of food crops grown on reclaimed landfill sites or on lands adjacent to landfills can result from irrigation with water withdrawn from a contaminated ground water source. Radioactive material can be transferred to the plant by either deposition (as in the case of sprinkler irrigation) or by root uptake. The transfer coefficients describing the movement of americium in the food chain vary widely depending on crop and soil type, climate, method of irrigation, etc.

Although irrigation is used on only about 11 percent of U. S. cropland acreage, irrigated areas contribute about 25 percent of the total crop production value. About 85 percent of the irrigated acreage is in the 17 Western states, and underground aquifers provide for about two-thirds of the irrigated acreage nationwide[42]. The two principal methods of application consist of sprinkler systems such as center pivot, side roll, and hand or mechanical move systems, and surface systems such as ditch or grated pipe networks. Approximately 30 percent of irrigated acreage receives water from sprinkler systems, while surface application systems account for about 70 percent of the irrigation.

Radionuclides which are deposited on the exterior surfaces of crops by sprinkler irrigation will be removed by weathering forces such as wind and rain, and by mechanical forces such as subsequent irrigation. Literature values for the fraction of radioactive fallout (Sr-90, Cs-137, etc.) which is intercepted and deposited on crop surfaces range from 0.3 to 0.6 with a reduction of that fraction by a factor of four after a thirty-day period[43-48]. Assuming an average deposition-to-harvest period of thirty days, this results in a range of

0.075 to 0.15 for the fraction of the deposited activity remaining on the plant surface at the time of harvest. For Am-241 uptake by root systems literature values are on the order of 10^{-4}(49,50).

There are many other factors which tend to reduce the fraction of deposited activity eventually consumed. Among the more important of these factors are the partitioning between plant surfaces and edible portions, losses due to harvesting and food processing, and removal by kitchen activities such as washing or cooking. The partitioning coefficient (i.e., the ratio of deposited activity on the edible portion of the plant to activity on the exterior plant surface) may be as high as unity for leafy green vegetables such as lettuce or spinach, or as low as a small fraction of unity for crops in which the edible portion is protected by a non-edible layer (e.g., nuts, grains or citrus fruits). Other factors such as the different uses to which crops may be put (animal feed, seed production, food products and by-products, etc.) also tend to reduce the fraction of deposited activity which is ultimately consumed by humans.

The assessment of human consumption of contaminated food crops grown on or near landfill sites assumes the following:

1. Ten percent of the 500,000 acres currently used for landfill disposal is reclaimed for the purpose of raising food crops, and an equal amount of land used for raising food crops is located close enough to landfill sites that irrigation with contaminated ground water is likely.

2. 25 percent of the crop acreage is irrigated, and sprinkler - type systems account for 30 percent of this irrigation.

3. The crop acreage receives an average of 36 inches of irrigation water per year. Ground water provides the source for 70 percent of this irrigation, and ten percent of the ground water is contaminated with Am-241 at a concentration of 4.4×10^{-10} uCi/ml.

4. Half of the Am-241 in sprinkler irrigation water is deposited on plant surfaces, and ten percent of this deposition occurrs on edible portions of the plant.

5. 25 percent of the activity deposited remains on plant surfaces at time of harvest, and 25 percent of this residual activity remains on edible portions after harvesting, processing, etc.

6. The plant uptake factor for americium deposited on the soil surface by irrigation is 10^{-4}, and ten percent of this uptake is deposited in edible portions.

7. The amount of deposition on plant surfaces from surface or drip irrigation is negligible, as is plant uptake of americium in the sub-surface soil system.

8. Eighty percent of the edible portions of the harvested crop is consumed.

The total amount of activity ingested from consumption of contaminated food crops (I_c) is estimated by:

$$I_c = A_w V_w (f_d + f_s) f_c$$

where

A_w = Concentration of Am-241 in contaminated ground water (uCi/ml),

V_w = Volume of contaminated ground water used for irrigation (ml),

f_d = Fraction of activity in sprinkler irrigation water which is deposited and retained on edible portions until consumption,

f_s = Fraction of activity deposited on soil which is taken up by edible portions of the plants, and

f_c = Fraction of harvested crops which are consumed.

Using the above assumptions, the activity ingested is

$$I_c = (4.4\times10^{-10}\ \text{uCi/ml})(6.3\times10^{12}\ \text{ml})(1\times10^{-3} + 1\times10^{-5})(0.8)$$

$$= 2.3\ \text{uCi}.$$

This figure represents a 50-year dose commitment to the exposed population of 0.12 person-rem for total body, 1.89 person-rem for bone, 0.66 person-rem for liver, and 0.94 person-rem for the kidneys. If it is assumed that the exposed population in this scenario is the entire U. S. population, the average individual intake would be about 0.01 pCi, which is a factor of forty or so less than the Am-241 dietary intake from weapons testing fallout. Average individual organ dose commitments would be 5.7×10^{-10} rem for total body, 8.2×10^{-9} rem for bone, 2.9×10^{-9} rem for liver and 4.1×10^{-9} rem for kidneys.

3.2.6.1.3.2 Resuspension

Loose Am-241 contamination may become an inhalation hazard if left uncovered at landfill disposal sites. Airborne contamination can result from suspension of particulate matter by open burning, weather, or other factors. Johnson[32] has estimated the degree of resuspension which can be expected by comparing the landfill concentrations of americium (assumed to be uniformly distributed and undiluted by added fill) with soil concentrations of natural uranium. Mean soil concentrations of uranium average 0.93 pCi/g and concentrations in air range from 3.3×10^{-6} pCi/m^3 to 5×10^{-4} pCi/m^3. Using the more conservative figure for air concentration, and applying this ratio to the 0.11 pCi/g value previously determined for Am-241 landfill concentration, the resulting Am-241 concentration in air around landfill sites would be 5.9×10^{-5} pCi/m^3. A person residing in the vicinity of the landfill and breathing 20 m^3/day air at this concentration would have an annual Am-241 intake of 0.43 pCi.

Wrenn[33] has used this same approach to arrive at an estimate of the resuspension of buried incinerator residue. He calculates an air concentration of 4×10^{-6} pCi/m^3, the inhalation of which would result in an annual individual intake of 0.3 pCi.

Since open burning is a common problem contributing to the dispersal of contaminants at landfill sites (see Table 3.5), an assessment of the hazard posed by suspension of loose contamination by this mode is performed below.

Mishima and Schwendiman[51] have determined that the burning of combustible solid wastes contaminated with uranium (to simulate plutonium) resulted in low fractional releases Measured airborne concentrations in the test chamber indicated the presence of from 0.003 to 0.05 percent of the uranium used in the source. Since the uranium forms used were conducive to easy removal (e.g., powders or residues from drying solutions), these values probably represent worst case estimates when related to americium sources, even those in incinerator residue. Using the 0.05 percent value, and assuming that one-half of the ten million detectors disposed of in the reference case are subjected to open burning in landfills, the total amount of americium released would be

$$(10^7 \text{ detectors})(3 \text{ uCi/detector})(0.5)(0.0005) = 7500 \text{ uCi}.$$

Assuming that the number of disposal sites with open burning is ten thousand, the amount of released activity per site would be about 0.75 uCi. Most of this activity will probably be associated with particles less than ten microns mass median aerodynamic diameter.

The amount which is returned to people via diet can be estimated using the previously stated fraction of 10^{-6} of the total environmental americium. The lifetime intake for a population of 220 million people which would result from the release of 7500 uCi would therefore be 7.5×10^{-3} uCi, or about 3.4×10^{-5} pCi per person.

The amount of resuspended americium that is inhaled can be estimated from the data reported by Bennett regarding plutonium fallout[52]. About 16,000 Ci of Pu-239 have been deposited on the U. S. as a result of atmospheric weapons testing. The cumulative inhalation intake from 1954 to 1972 was about 42 pCi per person. Thus, assuming that americium availability is similar to plutonium, the total per capita inhalation by the U. S. population would be 1.5×10^{-4} pCi/yr per Ci available. The average individual inhalation rate resulting from the resuspension of 7500 uCi would be 1.1×10^{-6} pCi/yr. This represents a population inhalation rate of 250 pCi/yr. The doses resulting from these exposures are presented in Table 3.8.

3.2.6.1.4 Incineration

Approximately 13 million metric tons of municipal solid waste are incinerated annually in this country. Most of this incineration occurs in the 300 or so large municipal incinerators currently operating. A significant amount also occurs in thousands of intermediate or apartment complex incinerators which are prevalent in many large urban areas such as New York and Philadelphia. The relative importance of conventional incineration as a means of waste processing in the near future is questionable at this time. Stricter air quality standards

Table 3.8. Fifty-year Total Body and Organ Dose Commitments Resulting From Resuspension of Am-241 in Landfills.

Reference Case	Intake (μCi)	Dose				
		Total Body	Kidneys	Liver	Bone	Lungs
Inhalation[a]						
Individual (rem)	1.1E-12	1.0E-8	2.0E-10	3.3E-10	3.6E-10	5.6E-10
Population (person-rem)	2.5E-4	6.2E-3	4.4E-2	7.8E-2	8.2E-2	1.3E-1
Ingestion						
Individual (rem)	3.4E-11	1.8E-12	1.4E-11	8.9E-12	2.9E-11	-
Population (person-rem)	7.5E-3	4.1E-4	3.2E-3	2.0E-3	6.2E-3	-

a. Inhalation dose assumes particle size of 1 micron and solubility class Y.

and increased capital and operating costs are combining to drive up the overall cost to prohibitive levels. One review recently reported that, despite the increased sophistication of present-day incinerators in the U. S., none is apparently operating in a wholly satisfactory manner[53].

The primary function of an incinerator is to reduce the municipal waste volume to a compact, sterile residue. Some incinerators also have secondary functions such as the generation of steam or some other utilization of waste heat. Non-conventional incineration methods such as pyrolysis result in the production of a storable, transportable fuel from municipal solid waste. These methods, however, are still in early developmental stages in this country.

In conventional incinerators, refuse is either pretreated for size reduction (e.g., shredding or grinding) or fed directly into the combustion chamber via some continuous-feed or batch-feed process. The refuse is oxidized in the combustion chamber in which the temperature is usually regulated by using excess air (i.e., air that is in excess of the amount theoretically required to completely burn the combustible portion of the refuse). Typical furnace gas temperatures are controlled to around 1000-1100^{o}C, although the actual temperature of the flame is approximately 1300^{o}C. These conditions will usually result in reducing the bulk by oxidation to 20-25 percent of the original weight and 10-12 percent of the original volume[27]. The residue which remains consists mostly of metals, glass, ceramics, stones, ash and unburned combustibles. If temperatures in the furnace are maintained at about 1650^{o}C or more, the residue will be reduced to a molten state called slag. Incinerator residue is essentially sterile and compacts well. Thus, if used for landfill, the land can be immediately reclaimed. Alternatively, the metallics in the residue can be separated out for salvage and the residual ash can be used as a valuable substitute for sand and aggregate in building or road construction[27].

Most large incinerators require water in various parts of the incineration process (e.g., gas scrubbing and residue quenching). The water usually becomes contaminated with dissolved or suspended matter and in most cases requires treatment before discharge to prevent or control pollution of surface or ground water systems. The most serious environmental problem associated with incinerators, however, is pollution of the air.

When refuse is burned, large quantities of fine ash particles, water vapor, carbon dioxide and other gases are released. Recently constructed incinerators control the amount of particulate emission by such measures as high efficiency combustion and particulate collection systems such as electrostatic precipitators and gas scrubbers. Table 3.9 shows the particle size distribution obtained from measurements of stack gases in a large municipal incinerator. Particle size and other physical properties of the particulate emissions such as density depend on many factors such as refuse composition, incinerator design and operation and air pollution control systems. The particle size distribution in Table 3.9, for example, is typical of stack gases that have passed through a cleanup system consisting of a combustion settling chamber and a wet baffle system. The density of these particles is about 1.85 g/cm^3.

The concentration of particulates in stack gases and the total amount of particulate releases for several different types of large incinerators are given in Table 3.10. The particle concentration or "dust loading" is expressed in limits of grains (7,000 grains equals one pound) per standard cubic foot of gas normalized to 12 percent CO_2.

Various processing systems have been used to remove particulates and other pollutants from incinerator effluents. Older incinerators used such methods as settling chambers, wet baffle systems or cyclone collectors. Collection efficiencies for these systems vary from around 35 to 75 percent, an insufficient amount of removal for compliance with current emission standards. Efficiencies of 90 to 99 percent are available in currently used systems such as gas scrubbers and electrostatic precipitators. Some average removal efficiencies for various types of air pollution control systems are given in Table 3.11. It is noteworthy that about 70 to 75 percent of the incinerators in the United States were built before 1960 with many dating back to the 1940's and beyond[26,56]. These incinerators require air pollution control retrofitting in order to comply with current regulations.

Prediction of the amount of airborne radioactivity released as a result of incineration of ICSD's with municipal refuse depends on knowledge of ICSD source behavior under conditions of thermal stress. Results of high temperature (1200^{o}C) tests performed on Am-241 ICSD sources indicate that between 0.01 and 0.2 percent of the source activity (with an average value of 0.05 percent) may be released as airborne contamination. Tests involving whole smoke detectors at the same temperature resulted in the release of less than 0.06 percent of source activity[34]. It can be expected, therefore, that incineration of ICSD's should not result in the release of more than about 0.1 percent of source activity.

Table 3.9. Size Distribution of Particles in Incinerator Stack Gas.[27]

Size(μm)	% by Weight
>30	31.3
>20	52.8
>10	79.5
>5	94.0
<5	6.0

Table 3.10. Particulate Emission for Incinerators of Various Designs.[54]

Incinerator	gr/SCF at 12% CO_2	lb/ton of Waste Charged	Gas-Flow Rate (ft^3/min)
A	0.55	10.4	69,800
B	1.12	14.5	131,000
C-1	0.56	4.1	3,890
C-2	0.41	3.4	3,990
C-3	0.30	2.9	4,460
D	0.46	8.8	120,000
E	0.73	8.6	186,000
F	0.72	12.5	165,000
G	1.35	20.4	130,000

Table 3.11. Average Air Pollution Control System Removal Efficiencies (Weight Percent).[55]

Air Pollution Control System	Mineral Particulates	Combustible Particulate	Polynuclear Hydrocarbons	Volatile Metals
None (flue settling only)	20	2	10	2
Dry Expansion Chamber	20	2	10	0
Wet Bottom Expansion Chamber	33	4	22	4
Spray Chamber	40	5	40	5
Wetted Wall Chamber	35	7	40	7
Wetted, Closed-Spaced Baffles	50	10	85	10
Mechanical Cyclone (dry)	70	30	35	0
Medium-Energy Wet Scrubber	90	80	95	80
Electrostatic Precipitator	99.9	99	67	99
Fabric Filter	99.9	99.9	97	99

Three reference cases are assessed here concerning the environmental health impact of incineration of discarded ICSD's:

1. The calculated dose to an individual at the point of maximum exposure to the emission plume from a large municipal incinerator.

2. The calculated dose to the population feeding one incinerator disposal route.

3. The calculated dose to the total U. S. population residing in the environs of large municipal incinerators.

The assumptions used to estimate the amount of Am-241 in incinerator emissions and resultant exposures are as follows:

1. There are a total of 300 municipal incinerators, each processing 300 tons of refuse per day at 50 percent excess air.

2. The number of ICSD's incinerated per year is one million (i.e., ten percent of the ten million which may be disposed of in peak years).

3. The average Am-241 activity per detector is 3 uCi.

4. The fraction of Am-241 released during incineration is 0.1 percent.

5. The efficiency of installed air pollution contol systems for particulates is 90 percent.

6. The aerodynamic mean activity diameter (AMAD) of the released particles is one micron.

7. The number of persons feeding one incinerator disposal route (assumed to be the exposed population) is $(220 \times 10^6)(0.1)/(300)$ = 73,000 persons.

The total activity released in a year (Q) would be

$$Q = Q_i f_s f_r$$

where

Q_i = Initial Am-241 source activity (uCi),
f_s = Fraction of Am-241 released during incineration, and
f_r = Fraction of released activity which escapes with stack gases.

Based on the assumptions listed above,

$$Q = (3 \times 10^6 \text{ uCi})(0.001)(0.1)$$

$$= 300 \text{ uCi}$$

or about 1 uCi per incinerator.

The concentration of americium in the stack gas (X_s) would be

$$X_s = \frac{Q}{V_a W_r}$$

where

V_a = 50 percent excess of the theoretical volume of air required for complete combustion of one pound of refuse (cm^3/lb),

W_r = Weight of refuse incinerated (lb).

The average annual stack gas concentration that would result from the scenario above would be

$$X_s = (1 \text{ uCi})/((2.0 \times 10^6 \text{ cm}^3/\text{lb})(2.2 \times 10^8 \text{ lb}))$$

$$= 2.3 \times 10^{-15} \text{ uCi/cm}^3.$$

The concentration of americium in the stack gas would be about two orders of magnitude below the most restrictive standard for Am-241 concentrations in air. Using the atmospheric dispersion data of Martin[57] and assuming a constant wind speed of 1 m/s under moderately stable meteorological conditions, the maximum downwind concentration (X) can be estimated by

$$X = Q'(X/Q)$$

where

Q' = Release rate in (uCi/sec), with release constant over one year,
X/Q = Atmospheric dispersion coefficient (sec/m^3).

Thus, for this case, the maximum downwind Am-241 concentration would be

$$(3.2 \times 10^{-8} \text{ uCi/s})(2 \times 10^{-5} \text{ s/m}^3) = 6.4 \times 10^{-13} \text{ uCi/m}^3.$$

Assuming an average daily breathing rate of 20 m^3 per day, the maximum exposed individual would inhale about 4.7×10^{-9} uCi per year. If it is conservatively assumed that the average person in the exposed population takes in an amount of Am-241 equal to one-third of that at the point of maximum concentration, the average incinerator population intake would be 1.2×10^{-4} uCi. Summing this over the entire exposed population (i.e., about 20 million persons), the total intake would be about 3.5×10^{-2} uCi. The doses resulting from the above exposures were calculated using the DACRIN[58] computer code, and are presented in Table 3.12.

The intake of dispersed Am-241 via the ingestion pathway is assessed on the basis of the dietary intake factors discussed previously. Since it has been estimated that 10^{-6} of the total environmental americium will eventually be returned to man via dietary intake, the total amount of Am-241 ingested by the exposed population would be about 3.0×10^{-4} uCi, or about 1.3×10^{-11} uCi per individual. Dose commitments associated with these intakes are listed in Table 3.12.

3.2.6.2 Abandonment in Buildings

As long as ICSD sources remain intact, the external radiation represents the most significant mode of exposure. The abandonment of ICSD's in buildings, therefore, is unlikely to constitute a unique hazard situation since the conditions of exposure are not unlike normal residential exposures. The main

Table 3.12. Summary of 50-year Total Body and Organ Dose Commitments Associated with Incineration of One Million ICSD's Containing 3 uCi of Am-241.

Reference Case	Intake (μCi)	Dose				
		Total Body	Kidneys	Liver	Bone	Lungs
Inhalation[a]						
Maximally Exposed Individual (rem)	4.7E-9	1.1E-7	8.7E-7	1.5E-6	1.6E-6	2.6E-6
Population Around Incinerator (person-rem)	1.2E-4	2.9E-3	2.2E-2	3.7E-2	3.9E-2	6.1E-2
Total Exposed Population (person-rem)	3.5E-2	8.2E-1	6.1E+0	1.1E+1	1.1E+1	1.7E+1
Ingestion						
Avg. Individual (rem)	1.3E-11	7.2E-13	5.4E-12	3.8E-12	1.1E-11	-
Population Around Incinerator (person-rem)	1.0E-6	5.4E-8	4.1E-7	2.9E-7	8.2E-7	-
Total Exposed Population (person-rem)	3.0E-4	1.6E-5	1.2E-4	8.6E-5	2.5E-4	-

a. Assumes particle size of 1 micron and solubility class Y.

difference, of course, is the fact that there will be fewer person-hours of exposure in the case of the abandoned buildings.

Demolition of buildings containing ICSD's is another situation which should be considered. Tests have shown that a high degree of source integrity is maintained under conditions of chemical or physical stress[18,34]. For example, impact tests (sources dropped from a height of nine meters onto a flat, rigid surface) and percussion tests (a 1.4 kg steel billet is dropped from a height of one meter onto the sample placed on a sheet of lead supported by a smooth solid surface) have shown that less than 5×10^{-7} and 5×10^{-6} uCi, respectively, were removed in post-test wipe and immersion tests. Abrasion tests in which sources were subjected to impact from a stream of sand particles (SiC grade 120) falling from a height of one meter through a one cm bore glass tube also showed that a high degree of integrity is maintained under severe conditions. After about 8.3 hours of abrasion, 5×10^{-3} uCi (0.001 percent of source activity) was removed by wipe tests. The test foil did not start leaking badly until after about 14 hours of abrasion at which point the active layer was exposed. It is evident, then, that the severe physical forces to which ICSD's may be exposed in the course of building demolition will probably not result in a significant release of radioactivity. Internal doses to personnel involved in the demolition or rubble removal operations will in all likelihood be minimal.

The situation becomes more complex if the building being demolished has been subjected to a substantial amount of fire damage. It is not clear to what extent the integrity of ICSD sources would be maintained after a combination of thermal and mechanical stresses such as would be expected in these instances. It follows, then, that severely burned ICSD's should be considered as potential inhalation hazards and should be handled with caution. It is evident that in demolition operations such as those involving fire-damaged ICSD's, an awareness of the crew regarding potential inhalation hazards would minimize the risk of internal contamination. This aspect is discussed further in Section 3.2.7.2.

3.2.7 Accidents or Misusage

During the use of any consumer product, it is anticipated that accidents or misuse of the product will occur. This is true of ionization chamber smoke detectors. Past experience has shown that accidents do occur. For ICSD's with Am-241 the following accidents are postulated to occur:

1. Ingestion of foil source.
2. Storage fire.
3. Residential fire.

The list is not all inclusive but does represent a variety of accidents or abnormal occurrences. For all cases the doses and dose commitments are calculated in a conservative fashion.

3.2.7.1 Ingestion of Sources

During the manufacturing process of ICSD's, workers can come into direct contact with the small Am-241 foils used in the detectors. It is anticipated that during operations dealing with the foil sources, a foil or two may be misplaced. A case of two foils being accidentally swallowed by a woman working with the sources has been documented[59]. For this study, the swallowing of sources is considered to be the accident of most concern on the assembly of ICSD's.

The documented case involved a woman swallowing two sources of Am-241 each containing a nominal 2.5 uCi of activity. The two sources were passed by the woman after 16 and 24 days respectively. Analysis showed a little less than one percent of the total activity of the two sources was found in the fecal material after removal of the sources. Am-241 was detected in the urine until the second source had been passed. The systemic burden was estimated to have been "very much less" that 1.5 percent of the activity released from the sources. The authors of the journal article concluded "this was not significant from the point of view of radiological protection." They also stated "if the sources of Am-241 involved in this incident are representative of those incorporated in domestic smoke detectors, then the most important conclusion that can be drawn is that they are remarkably secure. Furthermore, what activity is released under these circumstances in so inert that there is negligible (much less than 1.5 percent) absorption into the blood. This is an important and comforting finding in view of the growing numbers of smoke detectors available to the general public."

To calculate the dose commitment the woman will receive from the incident, it is assumed, conservatively, that one percent of the activity was released from the sources and ingested by the woman. Using the dose commitment conversion factors for ingestion given in Appendix B, the 50-year dose commitments to organs of importance are given in Table 3.13.

3.2.7.2 Fires

3.2.7.2.1 Warehouse Fires

The primary radiological concern regarding fires in warehouses where large numbers of ICSD's are stored is the inhalation of released Am-241. The 50-year dose commitment to firefighters involved in the extinguishment, cleanup, and salvage operations is assessed according to the following assumptions:

1. The maximum number of ICSD's to be stored in any distribution warehouse is 1,000 units, each containing 3 uCi Am-241.
2. The volume of air in the warehouse is $3 \times 10^3 m^3$.
3. The breathing rate of persons involved is $1.2 m^3/hr$.
4. 0.1 percent of Am-241 activity is released as airborne particulates having a mean diameter of one micron.

Since it is unreasonable to assume that firefighters would enter a burning building without first ventilating it, there will be a number of air changes resulting in a significant reduction in Am-241 concentration in building air. Also, fires of the magnitude required to release this fraction of americium will also release large amounts of other noxious materials. It is unlikely, therefore, that firefighters would enter the involved building without respiratory protection. It is also unreasonable to assume that the building will not be well ventilated during the salvage and cleanup operations. This assessment assumes that the net effect of the above and other factors is a hundred-fold reduction in Am-241 inhalation.

The average concentration of Am-241 in building air would be

$$(3x10^3 \text{ uCi})(0.001)/(3x10^3 \text{ m}^3)=1x10^{-3} \text{ uCi/m}^3.$$

Table 3.13. Calculated Fifty-year Dose Commitments (Rem) Resulting from Am-241 ICSD Source Ingestion.[a]

Total Body	Bone	Liver	Kidneys
2.7E-3	4.1E-2	1.5E-2	2.1E-2

a. Based on the assumption that 1.0% (0.05 μCi) of the swallowed source activity (5μCi) was ingested.

The total intake over an eight hour period would be

$$(1\times10^{-3}\ uCi/m^3)(9.6\ m^3)(0.01) = 9.6\times10^{-5}\ uCi.$$

This intake, which should be considered an upper level estimate, would result in the organ doses in Table 3.14.

Inventories of detectors at a manufacturer's warehouse can be substantially larger than those at distribution warehouses. At such warehouses, however, firefighters are probably much more likely to be aware of potential hazards involved. It is common practice among most fire departments to familiarize themselves with any industrial or warehouse materials within their area of response which constitute significant exposure hazards. It is also likely that posted warnings or verbal communications from plant personnel will increase the probability of the firefighters being made aware of the presence of radioactive materials. These factors, together with the conservatism included in the distribution warehouse scenario, make it highly unlikely that substantially greater exposures would result. Nevertheless, an assessment is made here for a fire involving 10^5 detectors (3×10^5 uCi) in a warehouse of 3.5×10^4 m^3. Results of this assessment are presented in Table 3.14.

The salvage and cleanup operations following a large warehouse fire can be a source of significant internal deposition if performed in a careless or unsuspecting manner. Wipe tests performed in the interior and exterior of ICSD source mounting areas after high temperature (1200^oC) testing of the detectors resulted in the removal of up to 0.2 percent of the source activity, although only about 0.015 percent of the activity was on the accessible areas outside of the source housing[18]. Suspension of up to 0.001 uCi per detector could conceivably result from mechanical disturbance of the charred debris. The amount of resuspended material that is inhaled and deposited internally depends on many factors such as the volume of air in which the americium is suspended and the size of the suspended particles. Assuming that one percent of the resuspended material is inhaled, and that this activity consists mostly of particles of respirable size (about one micron), the dose commitments listed in Table 3.14 would result. It should once again be emphasized, however, that it is likely that salvage or cleanup operations after fires involving large numbers of ICSD's

Table 3.14. Fifty-year Dose Commitments for Individuals Involved in Firefighting or Cleanup Operations.

Activity[a]	Intake (μCi)	Dose (rem)			
		Total Body	Liver	Bone	Lung
Firefighting					
Distribution Warehouse	9.6E-5	2.3E-3	3.2E-2	3.2E-2	5.0E-2
Manufacturers Warehouse	8.2E-4	2.0E-2	2.6E-1	2.7E-1	4.3E-1
Residence	1.4E-7	3.5E-6	4.8E-5	4.8E-5	7.8E-5
Salvage and Cleanup	1.0E-5[b]	2.4E-4	3.2E-3	3.3E-3	5.2E-3

a. See text for assumed conditions

b. Intake per detector involved.

would be conducted with some awareness of the potential hazards and with some measure of protection.

3.2.7.2.2 Residential Fires

This assessment deals with possible internal exposures to residents or firefighters as a result of firefighting, salvage and cleanup operations. The 50-year dose commitment to persons involved is estimated based on the following assumptions:

1. Two residential ICSD's are involved, each with 3 uCi Am-241.
2. The volume of house air is $500 m^3$.
3. The breathing rate of persons involved is $1.2 m^3/hr$ and the operation lasts for one hour.
4. 0.1 percent of Am-241 activity is released as airborne particulates having a mean diameter of one micron.

As in the case with warehouse fires, credit must be taken for the degree of protection afforded the involved persons by ventilation or the use of respiratory protection. This assessment assumes that the net effect of these and other protective features will be hundred-fold reduction in the amount of Am-241 inhaled. The total Am-241 intake over one hour would be

$$(6\ \text{uCi})(0.001)(1.2\ m^3)(0.01)/(500\ m^3) = 1.4 \times 10^{-7}\ \text{uCi}.$$

Dose commitments associated with the amount of inhaled activity are given in Table 3.14.

As mentioned previously, salvage and cleanup operations can constitute a potential inhalation hazard if conducted in a careless or unsuspecting manner. Disturbance of charred debris can result in the suspension of up to 0.001 uCi of Am-241 per detector involved.

3.2.8 Summary of Radiological Health Impact

A summary of the doses determined for the reference cases analyzed above, and an estimation of the total number of resultant somatic and genetic health effects are presented in this section. Tables 3.15 through 3.18 summarize the dose assessments, and Table 3.19 lists the number of health effects which are estimated to result from these doses.

It is worth repeating here that one should not place a great deal of confidence in the estimated doses due to the number of assumptions and generalities which had to be made in the dose estimation process. These estimates, however, should be considered of value in delineating the upper bound of the total dose delivered to the population as a result of the manufacture, use and disposal of the number of Am-241 ICSD's distributed in peak sales years. The largest total body dose contribution (about 100 person-rem) results from external exposure of the population to the gamma radiation emitted by the ICSD source, while the greatest amount of internal exposure probably results from the inhalation of airborne contamination released during incineration of discarded ICSD's and from the ingestion of drinking water from contaminated aquifers. Internal doses received from ingestion of contaminated food crops are estimated to be less than those resulting from the incineration inhalation and drinking water pathways.

The total number of fatal cancers which would be expected to result from the population dose arrived at in this study is 0.03, and the total number of genetic effects is 0.02. Thus, even though the calculated doses represent upper level estimates, a single cancer death or serious genetic effect is not expected to result from a yearly exposure of the occupational work force and the general population to ionizing radiation from activities associated with Am-241 ICSD use.

The total number of health effects which could result from accidental exposures (such as may be incurred from fires or demolition of buildings) is not estimated here since the degree of uncertainty involved is large. However, since the number of individuals involved in such instances represent a small fraction of the population, and since the individual doses resulting from these exposures are small, the radiological health impact from accidental exposure situations is expected to be less than that from normal production and use.

Table 3.15. External Doses Associated with Manufacture and Distribution of Am-241 ICSD's.

Activity	Dose	
	Individual (rem)	Population (person-rem)
Manufacture[a]	1.0E+0	4.8E+1
Transportation	-	2.5E-3
Distribution[b]	5.0E-4	2.0E+1
Retail Sales		
Consumers	4.2E-6	2.8E+1
Retail Clerks	5.0E-4	7.0E+0
Total		1.0E+2

a. Includes Warehousing and Storage at Manufacturers

b. Includes Storage at Distribution Warehouses

Table 3.16. Annual External Doses Associated with Normal Use and Disposal of Am-241 ICSD's.

Activity	Dose	
	Individual (rem)	Population (person-rem)
Transport	2.2E-8	1.5E-1
Installation	4.5E-8	6.3E-1
Maintenance[a]	1.8E-7	1.3E+0
Operation	9.3E-6	9.7E+1
Waste Collection	4.0E-7	7.0E-2
Total		9.9E+1

a. Includes testing, cleaning, changing batteries, etc.

Table 3.17. Summary of 50-year Total Body and Organ Dose Commitments Associated with Am-241 ICSD Disposal.

Reference Case	Dose							
	Total Body		Liver		Bone		Lungs	
	I[a]	II[b]	I	II	I	II	I	II
Inhalation								
Incineration	1.1E-7	8.2E-1	1.5E-6	1.1E+1	1.6E-6	1.1E+1	2.6E-6	1.7E+1
Resuspension	1.0E-8	6.2E-3	3.3E-10	7.8E-2	3.6E-10	8.2E-2	5.6E-10	1.3E-1
Ingestion								
Incineration	7.2E-13	1.6E-5	3.8E-12	8.6E-5	1.1E-11	2.5E-4	-	-
Contaminated Groundwater	8.7E-6	4.1E+0	4.6E-5	2.1E+1	1.3E-4	6.2E+1	-	-
Irrigation	5.7E-10	1.2E-1	2.9E-9	6.6E-1	8.2E-9	1.9E+0	-	-
Resuspension	1.8E-12	4.1E-4	8.9E-12	2.0E-3	2.9E-11	6.2E-3	-	-

a. Column I represents either maximum or average individual dose (see text for details)(rem).

b. Column II represents total population dose (person-rem).

Table 3.18. Summary of Total Body and Organ Doses (person-rem) Associated with Annual Manufacture, Distribution, Use and Disposal of Am-241 ICSD's.

Organ	Internal Source	External Source	Total
Liver	3.3E+1	8.8E+1[a]	1.2E+2
Bone	7.5E+1	1.1E+2[b]	1.9E+2
Lung	1.7E+1	1.1E+2[b]	1.3E+2
Gonads	2.5E+1	9.9E+1[c]	1.2E+2[d]
Total Body	5.0E+0	2.0E+2	2.1E+2

a. Derived by multiplying external exposure (2.2E+2 R) by 0.4 (see Appendix B)

b. Derived by multiplying external exposure by 0.5

c. Derived by multiplying external exposure by 0.45

d. Total gonadal dose to the population. The genetically significant dose (GSD) would be somewhat less

Table 3.19. Summary of Total Health Effects Expected from Annual Manufacture, Use and Disposal of Am-241 ICSD's.

Tumors	Dose (person-rem)	Total Cancer Mortality Or Genetic Defects
Liver	1.2E+2	1.8E-3
Bone	1.9E+2	9.5E-4
Lung	1.3E+2	3.3E-3
Total Body	2.1E+2	2.1E-2
Total		2.7E-2
Genetic Defects	1.2E+2	2.4E-2

The cancer mortality risk resulting from all life span activities (including manufacture, ten years of use, and disposal) associated with 14 million ICSD's is presented in Table 3.20. It is conservatively estimated that less than one fatal cancer is expected to result from exposures associated with the number of ICSD's sold in a peak sales year. For comparison, the spontaneous cancer mortality rate in the United States is about 1700 mortalities per year per million people. (See Appendix C). For a total population of 220 million people, the corresponding number of cancer mortalities per year in the United States is about 370 thousand. The benefits derived from the use of Am-241 detectors, in terms of life and property savings, are discussed in Section 5.

The regulations and guidelines concerning smoke detectors containing Am-241 are discussed in Section 2.3. An applicant for a license is required to demonstrate their product is designed and will be manufactured such that certain criteria are met. The criteria deal with dose and dose commitments during normal use, effectiveness of safety features, and dose and dose commitements from low and negligible probability events. Based upon the dose assessments performed in this section, a comparison to the safety criteria follows.

First, wear and abuse of the Am-241 ICSD's during normal handling and use was found not to result in a significant reduction in the effectiveness of safety features. Two reasons are responsible for this conclusion: (1) the external radiation levels are very low and (2) the containment of the Am-241 in foils is very effective.

In regards to normal usage, excluding manufacturing, all calculated doses and dose commitments were found to be less than Column I in Table 2.2. For accident or abnormal situations all calculated doses and dose commitments were found to be less than both Columns II and III. From this standpoint, it is apparent that Am-241 ICSD's, as manufactured, easily are within the criteria set forth in 10CFR32.27.

3.3 NON RADIOLOGICAL IMPACTS

The single major bulk component of both ICSD and photoelectric smoke detectors is the plastic housing that surrounds the unit. This material is a thermoplastic phenylene-oxide based resin which has a functional temperature

Table 3.20. Summary of Doses and Health Effects from Manufacture, 10 Years of Normal Use and Disposal of 14 Million Am-241 ICSD's.

Organ	Dose (person-rem)			Estimated Cancer Mortality
	Internal Source	External Source	Total	
Liver	3.3E+1	4.8E+2	5.1E+2	7.7E-3
Bone	7.5E+1	6.0E+2	6.8E+2	3.4E-3
Lung	1.7E+1	6.0E+2	6.2E+2	1.6E-2
Total Body	5.0E+0	1.1E+3	1.1E+3	1.1E-1
				1.4E-1

range of, 40°F to above 300°F. For planning situations this material has the important characteristic of being self-extinguishing. The material is highly resistant to aqueous chemical environments and has excellent impact strength[60]. Should this plastic material undergo pyrolytic decomposition or flaming combustion, a considerable variety of chemical compounds could be produced. The production and kind of chemicals produced depends upon the amount of heat and oxygen present during the heating or burning process. The plastic itself contains no nitrogens or halogens which in turn greatly reduces any possibility of producing hydrogen cyanide or hydrochloric acid[61]. As to the actual products produced during thermal degradation of the plastic no document has been located that is specific to the major type used in smoke detector housings. No single substance exists that is completely free of toxic effects to humans under specific conditions. In a publication on toxicity of plastic combustion products a hazard ranking was developed for several different polymeric materials and Douglas Fir[62]. The hazard ranking, reading from highest to lowest was polytetrafloroethylene > polyvinyl chloride > Douglas Fir and flexible polyurethane foam > fiber glass reinforced polyester > copper coated wire with mineral insulation. Although the exact chemical compositions of the plastic housing material is unknown the main thermal decomposition products would be carbon dioxide and water[61]. Carbon monoxide can be expected to be evolved from the burning plastic but the quantity would depend upon the available oxygen. These thermal decomposition products place the plastic material slightly above wood in the human toxicity scale. The fact that the plastic is self extinguishing makes it unlikely to be a toxic problem under conditions of potential human survivability. That the plastic would not be undergoing thermal decompostion under these conditions is somewhat confirmed by information from the California Fire Marshall's Office[63]. In what few instances that have been noted by that office, the plastic was damaged by heat, the housing had lost much of its shape, but little if any of the housing seemed to have been lost to vaporization. It therefore seems highly unlikely that the plastic material of the smoke detector will contribute a life or health threat to building occupants.

The other non-radiological components of smoke detectors consist of circuit boards and semiconductor material, photoelectric apparatus, wiring, stainless steel plates and screws, and in some units a 9-volt battery. These electronic components could contain any or all of the following:

Germanium, Silicon, Zinc, Sulfur, Phosphorous,
Cadmium, Mercury, Lead, Arsenic, Copper, Silver,
Gold, Selenium, Tellurium, Thallium, Phenolic Resins

Some of the elements in these electric components are highly toxic (e.g., Cd, Hg, Pb, As) and for industrial exposures, can have slow cumulative action.

In the smoke detector units the average circuit board is no more than three inches by three inches and weighs about three grams (0.1 ounce). The boards are made of epoxy resin and glass with copper on their surface. These boards are made to pass UL tests and therefore, do not support combustion. The basic semiconductor material is silicon which is doped with specific elements in molecular amounts. Silicon is a vital trace material in the human body (0.026 percent per body weight[64]. When silicon is combined with oxygen it becomes silica (silicon dioxide), a material which is responsible for silicosis, a chronic fibrotic pulmonary disease. For this disease to develop, prolonged exposure is required, an exposure situation which is not the type that would develop under the presently considered circumstances.

Slight, if any potential nonradiological impact can be seen for residential smoke detectors. For a typical residential installation (two detectors) the event probabilities involved in exposing the building occupant to toxic nonradiological products from the smoke detector would be an occurrence of extremely small consequences.

4. ALTERNATIVES

The previous section dealt with the environmental impact of ICSD's with Am-241. This section deals with alternatives to present day Am-241 ICSD's. Those alternatives considered are as follows:

1. ICSD with less Am-241
2. ICSD with Ra-226
3. ICSD with Ni-63
4. Photoelectric detector
5. Combination unit
6. "Tube bundle" detector system
7. Taguchi semiconductor gas sensor
8. Thermal sensors

4.1 ICSD WITH Am-241

An obvious way to reduce the radiological hazards of Am-241 ICSD's is to scale down the amount of activity in each detector. Any reduction in activity would reduce the radiological environmental impacts in a linear fashion. Table 2.3 illustrates the reduction that has taken place in average ICSD activity since 1975. It appears that 1 uCi per unit will become standard in general. Reduction below this level is not easily quantified at this time.

It has been pointed out that to develop a smoke detector with minimum amounts of radioactive material, specifically 0.3 uCi, there is a demanding engineering requirement to the electronics of the unit in that the sensitivity must be increased to 3 to 5 times that of todays commercial product[65]. Since the ion current at 0.3 uCi will be very low it is felt that the physical design of the unit will have to be fairly open. This becomes a particle entry problem in terms of false alarms which in turn requires very sophisticated electronics. An approach to developing units that contain less radioactive material requires a more precise understanding of smoke detection and smoke detectors. Mathematical approaches to this level of understanding are becoming more important as the smoke detector field gains maturity. Charles D. Litton of the U. S. Bureau of Mines has published a series of reports that is based on a mathematical approach to the design and function of smoke detectors[66-68]. In one of his latest publications[67], Litton has employed reduced source approximations to a somewhat standardized ICSD chamber and has shown the optimum source for the unit to be 0.3 uCi of Am-241. This is a signficant reduction in Am-241 and points to the importance of developing and refining the theories of fire and fire detection.

4.2 ICSD WITH Ra-226

Ra-226 ICSD's have been distributed in the past. Table 2.5 illustrates the past distribution of Ra-226 ICSD's by company. The range of activity is from 0.05 to 1.5 uCi per unit. The majority of the units contained 0.05 uCi per unit. Am-241 ICSD's today have essentially replaced Ra-226 ICSD's in the market. Ra-226 ICSD's are very similar in design to their Am-241 counterparts. The source foils are constructed in much the same way as the Am-241 foils. The basic difference is the activity compound is radium sulfate instead of americium oxide.

The radiological parameters for Ra-226 are listed in Table 2.1. The dose rate at one meter for an uncovered Ra-226 source is 8.3×10^{-1} uR/hr per uCi of Ra-226. For Am-241 it is 1.2×10^{-2} uR/hr per uCi. The ratio of the two is about 70. The calculated mean weighted gamma-ray energy of Ra-226 in equilibrium with its daughter products is about 0.75 MeV. Thus, the amount of attenuation occuring within the ICSD housing and components would be somewhat less than that of the 0.06 MeV gamma-ray of Am-241. The organ dose conversion factors for external radiation sources would also be higher for Ra-226. The net effect of the above factors is that the external radiation dose from a Ra-226 ICSD is about 90 times higher than the external radiation dose from a similar Am-241 ICSD containing the same amount of activity.

Tests have shown that less than five percent of Ra-226 activity is released from incineration at 925°C[69]. The incineration of one-tenth of the Ra-226 ICSD's disposed of at the rate of 10^6 per year is assessed here assuming the same conditions as in the Am-241 case, except for the average activity per detector (0.05 uCi) and the maximum activity release (five percent).

The total activity released in a year would be

$$(1x10^{6} units)(0.05\ uCi/unit)(0.1)(0.05)(0.1) = 25\ uCi$$

or about 0.08 uCi per incinerator. Using the same assumptions for incineration as used for the Am-241 analysis in Section 3, the concentration of radium in the stack gases would be about $1.9x10^{-16}$ uCi/cm^3, which is about ten thousand times lower than the standard for Ra-226 concentrations in air in unrestricted areas. The maximum downwind ground level concentration would be

$$(2.6x10^{-9}\ uCi/s)(2x10^{-5}\ s/m^{3})$$

$$= 5.2x10^{-14}\ uCi/m^{3}\ .$$

The amount of activity inhaled by a person continuously breathing air of this concentration would be about $3.8x10^{-10}$ uCi per year. The intakes and associated organ doses for the reference population groups are given in Table 4.1.

4.3 ICSD WITH Ni-63

When the residential ICSD industry was in its infancy about seven or eight years ago, a consideration as to the type of source material to be used was addressed by some manufacturers. Those manufacturers who considered Ni-63 as a source at that time were for the most part rather quickly discouraged. A primary problem in considering Ni-63 was that little previous work had been done in the use of this nuclide in a consumer product and therefore the initial cost of such development was considered prohibitive, especially when Ra-226 or Am-241 were available and considerable documentation of their use and hazards had been developed. Ni-63 is found at the present time in a smoke detector employed for commercial applicatons but not in a consumer-oriented product. There is, at present, a company developing a Ni-63 detector for the consumer market.

Table 4.1 Comparison of Inhalation Dose Commitments Resulting from Incineration of ICSD's with Different Radionuclides.

Reference Case	Radionuclide	Intake (uCi)	Dose (per 10^6 ICSD's)[a]				
			Total Body	Kidneys	Liver	Bone	Lungs
Maximally Exposed Individual (rem)	Ni-63	1.2E-12	4.7E-15	-	1.0E-14	1.5E-13	1.4E-14
	Ra-226	3.8E-10	7.4E-8	2.6E-11	9.1E-13	1.0E-7	3.9E-8
	Am-241	3.3E-10	7.9E-9	6.2E-8	1.1E-7	1.1E-7	1.9E-7
Population Around Incinerator (person-rem)	Ni-63	3.1E-8	1.2E-10	-	2.5E-10	3.7E-9	3.4E-10
	Ra-226	9.5E-6	1.9E-3	6.5E-7	2.3E-8	2.5E-3	9.8E-4
	Am-241	8.3E-6	2.1E-4	1.6E-3	2.6E-3	2.8E-3	4.4E-3
Total Exposed Population (person-rem)	Ni-63	9.3E-6	3.5E-8	-	7.6E-8	1.1E-6	1.0E-7
	Ra-226	2.9E-3	5.7E-1	2.0E-4	7.0E-6	7.5E-1	2.9E-1
	Am-241	2.5E-3	5.9E-2	4.4E-1	7.9E-1	7.9E-1	1.2E+0

a. Assumes particle size of 1 micron and solubility class W for Ni-63 and Ra-226, and Class Y for Am-241.

The construction of a Ni-63 source is different than the Ra-226 and Am-241 foils. The construction consists of the Ni-63 electroplated as a film coaxially on a nickel-plated monel wire. The Ni-63 is overplated with a rhodium barrier film. A four-inch segment would include 30 uCi of Ni-63. The product for the consumer is presently designed to contain 30 uCi of Ni-63 per unit. Although the projected amount of source material per smoke detector employing Ni-63 is 30 uCi, when the maximum permissible body burden (bone) is compared with that for Am-241 the Ni-63 has a 4000:1 advantage over Am-241[70]. These factors would appear to give an ICSD utilizing Ni-63 a reasonable chance of commercial success in the consumer market place.

For external considerations the very low level photon emissions from the beta source are taken to be 10 keV at an intensity of 2×10^{-4} per Ni-63 disintegration. The resulting dose rate at one meter (assuming a point source) would be about 1.8×10^{-4} uR/hr per uCi of Ni-63. A source with 30 uCi of Ni-63 results in a dose rate at one meter of 5.4×10^{-3} uR/hr. However, because the energy is taken to be 10 keV, the effective dose rates are much lower compared to 50 keV photons. For comparison sake, the external dose rates are taken to be zero. No consideration of beta dose or skin dose is made at this point.

High temperature (1200°C) testing of Ni-63 sources has revealed that an extremely small fraction (less than 0.01 percent) of the source activity is released in effluent air and by post-test wipes[71]. Assuming incineration of one-tenth of the Ni-63 ICSD's disposed in a year, each containing 30 uCi of Ni-63, would result in a maximum release of

$$(1 \times 10^{6} \text{ units})(30 \text{ uCi/unit})(0.1)(0.0001)(0.1) \approx 30 \text{ uCi}$$

or about 0.1 uCi per incinerator. The concentration of Ni-63 in the stack gases would be about 2.3×10^{-16} uCi/cm^3, which is about seven orders of magnitude below the standard for concentrations of this radionuclide in air. The maximum downwind ground level concentration would be

$$(8.7 \times 10^{-12} \text{ uCi/s})(2 \times 10^{-5} \text{ s/m}^3)$$

$$= 1.7 \times 10^{-16}\ uCi/m^3 .$$

The intake resulting from continuous inhalation of air contaminated with these levels of Ni-63 would be 1.2×10^{-12} uCi per year. Organ dose commitments for exposed persons are listed in Table 4.1.

The engineering problems of source containment and electronics design, as well as the problem of getting new designs approved, are all considerations which limit the industry to materials presently employed. The costs to a company to produce a new smoke detector employing new designs is more than the majority of manufacturers are willing to bear. Even in the case of the Ni-63 units, most manufacturers claimed to be unaware such a device is being developed for the consumer market. A point made by these manufacturers was that once someone did go to such a cost the others would probably follow, but few are willing to be burdened with the initial research and development costs.

4.4 PHOTOELECTRIC DETECTOR

Photoelectric detectors for the most part operate on the light-scattering principle. A sensing chamber contains a light source and a light receiver. The two are arranged such that the source light normally does not enter the receiver. When smoke particles are present in the sensing chamber, light can be scattered into the receiver. The increase in luminous flux at the receiver is proportional to the concentration of smoke particles in the chamber. When the flux reaches a predetermined level an alarm is triggered. Figure 4.1 illustrates an example of light-scattering detector optics.

Early photoelectrics used incandescent bulbs for light sources. Power requirements made line access necessary. Though incandescent bulb models are still being made, the introduction of low-power light emitting diodes (LED) has improved reliability. The introduction of LED light sources was basically to reduce lamp replacement maintenance. Life expectancy of incandescent lamps was one to three years[2]. Life expectancy of LED light sources is greater than thirty years.

Because of careful study of low velocity flow dynamics and the elimination of light-tight labyrinths by means of electronic ambient light

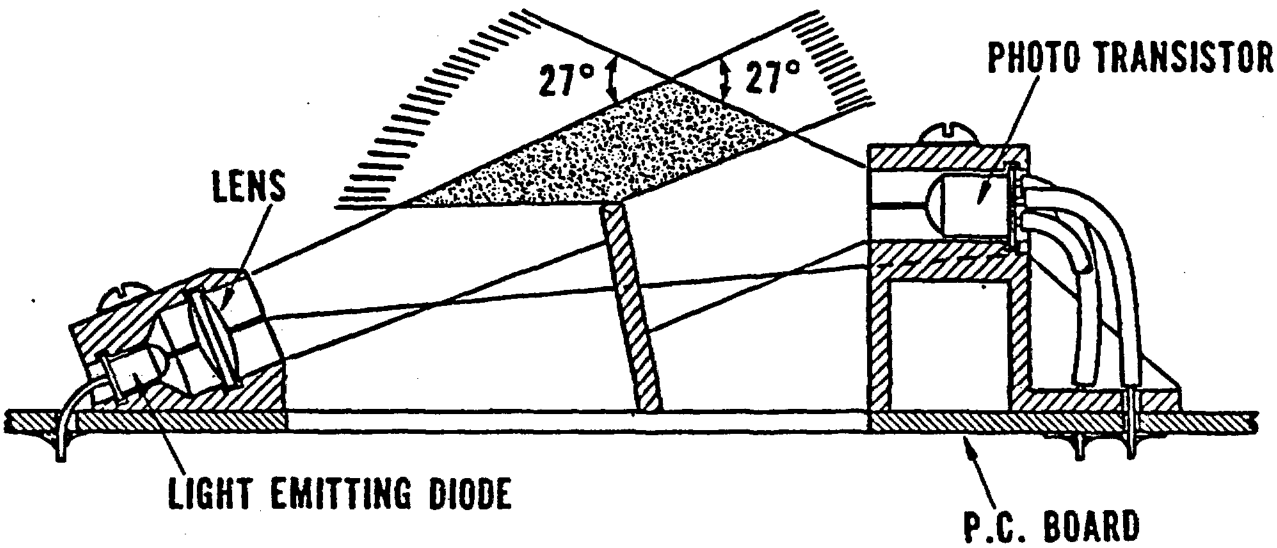


Figure 4.1. Photoelectric Detector Optics.[2]

rejection, ease of smoke entry into photoelectric detectors has improved greatly in recent years.

Since both ICSD's and photoelectric detectors are available in the consumer market, comparisons have been made of their use and reliability. As to which unit is superior is primarily related to who is describing the units. Similar tests, such as a smoldering furniture fire, can lead to opposite results under similar circumstances[72,73]. Inquiries to some state and federal agencies have revealed prejudices toward the ICSD units based on early reports that had been obtained. These biases are, in many cases, admittedly based on results of comparisons and detection requirements that no longer apply to current detector models. But, because of these biases, there still exist some requirements or inferred requirements towards installing ICSD's rather than photoelectric smoke detectors. This situation exists for some major federal and state government buildings as well as residential installations for entire states.

The sensitivity of smoke detectors to particle size has been investigated in a joint study by the National Bureau of Standards and the University of Minnesota[74]. A monodisperse aerosol generation system was developed to test detector sensitivity for light-scattering type detectors (photoelectric) and ICSD's. Figure 4.2 illustrates detector sensitivity versus particle size for a photoelectric unit and an ICSD unit. The detector sensitivity is defined as the detector output minus the background reading divided by the particle concentration. The uncertainty in the sensitivity was estimated to be ± 30 percent[2].

Figure 4.2 implies the ICSD unit is more sensitive to particle sizes smaller than 0.3 um and the photoelectric unit is more sensitive to particle size greater than 0.3 um. Bukowski and Mullholland[2] feel important practical implications can be concluded from this information if the work by Bankston et al.[75] at the Georgia Institute of Technology is considered. This work indicated the smoke particles generated in the flaming mode of combustion for Douglas fir, polyvinylchloride, and rigid urethane foam are generally smaller than 0.3 um. The same materials undergoing combustion or pyrolysis in the non-flaming mode produce particles larger than 0.3 um. Using this information it can be concluded that the ICSD is more sensitive to particles generated from flaming materials while the photoelectric detector is more sensitive to particles generated by non-flaming materials. This has been demonstrated in various small- and large-scale fire tests[73,76].

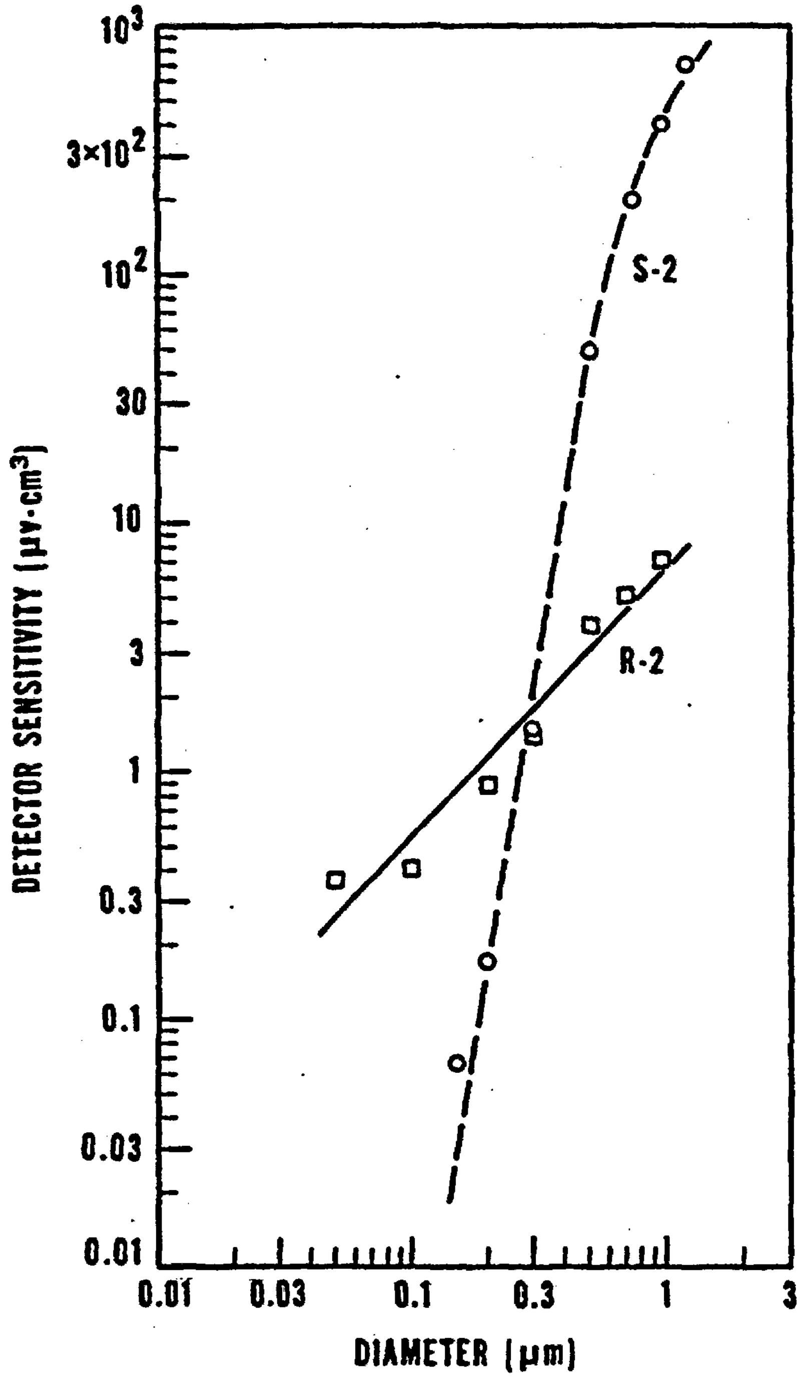


Figure 4.2. Detector Sensitivity Versus Particle Size for a Light-Scattering Type Detector (S-2) and for an Ionization Type Detector (R-2) [2]

4.5 COMBINATION UNIT

A new alternative recently introduced on the market place is the combination unit or "photo-ion" unit which contains both a photoelectric detector and an ionization chamber smoke detector. The advantage of the combination unit is the utilization of the sensitivities of both types of detectors. Quick detection of both large and small particles can be achieved.

4.6 "TUBE BUNDLE" DETECTOR SYSTEM

The Bureau of Mines has always been concerned with the detection of toxic gases and fires in mines and has investigated the problem on a continuous basis. One method of combustion products detection developed by this bureau is referred to as the "tube bundle" method[77,78]. This system consists of a centrally located ionizaton chamber for detecting smoke particles and a series of tubes leading from the chamber to various tunnel locations. Ambient air from each tube's distal location is pumped to the ionization chamber in a continuous manner and thereby tested for gas and smoke particulate. This system has been proposed as a method to be used in multi-family complexes and if it could be shown to be cost effective it could prove to be applicable to these structures. Since this methodology effectively removes the source material of the ionization chamber from the immediate occupant's environment it has the ability of reducing the exposure of the public to radiation. Also, since the actual detector mechanism is removed from the immediate care or misuse by the residential occupants, some situations which have resulted in detector failure and fire-related occupant death will be overcome.

This alternative is presently not judged to be a practical alternative for the residential consumer since it is more applicable to apartments or bigger buildings.

4.7 TAGUCHI SEMICONDUCTOR GAS SENSOR

Since all fires are basically gas fires it is reasonable to investigate the detection of gases when discussing fire detection. One of the more frequently mentioned gas detectors is the Taguchi gas detector. This solid-sate Japanese instrument is used by some American manufacturers in their gas detection products. In the Taguchi gas detector the sensing element is a metal-oxide semiconductor which is internally heated such that the surface oxygen is in a highly excited state. Contact of the surface with an oxidizable or reducible gas results in a change in conductivity of the metal-oxide semiconductor. Detection of this change indicates the presence of a gas.

Because of a standardization of the definition "smoke particle" the Taguchi instrument and other gas detectors can not be marketed as a smoke detector. Although the unit is intended as a gas detector it could conceivably be used as a home fire warning device. Unfortunately, since the device is a good gas detector, it appears to be too sensitive for home use due to the continued release of cosmetic and other volatile consumer products. These products release enough material to the atmosphere to cause a gas detector to register and frequently sound false alarms. No future refinements are expected for the Taguchi gas detector, such that it could be employed in the home, and it is, therefore, not expected to enter the residential fire detection consumer market(79).

4.8 THERMAL SENSORS

Other forms of fire detection, such as rate of rise and fixed temperature heat detectors, are available for the consumer market but these have not been as successful as smoke detectors. Tests have been conducted which give a significant advantage to the smoke detectors in terms of occupant escape time(73). There have been objections to the manner in which the tests were conducted, but no data was found which supports the heat detectors as the instrument of choice for a residential fire warning device(80). Until further tests can be conducted under simulated residential fire conditions that show an equal or superior performance for the rate of rise or fixed temperature devices, it appears that the consumer market for fire warning devices will continue to be dominated by some form of smoke detector.

5. COST AND RISK VERSUS BENEFIT ANALYSIS

5.1 GENERAL

The acceptability of levels of radiation exposure for certain activities has been determined using cost-benefit analysis in the past. Risk-benefit analysis also helps to determine the acceptability of levels of radiation exposure. Two questions are posed by such analysis:

1. What is the incremental cost to incrementally reduce exposure?
2. How much benefit is received as opposed to risk?

In regards to the first question, it is obvious that if no substantial exposure reduction can be made by spending a relatively large amount of money, the cost is not justified. In regards to the second question, if benefits acquired far outweigh the risks (benefits and risks being equated) the level of exposure should be judged acceptable.

Benefits are often hard to quantify since some benefits may be tangible while others may be intangible. The National Environmental Policy Act (NEPA) of 1969 states that "for purposes of complying with the Act, the weighing of the merits and drawbacks of the various alternatives need not be displayed in a monetary cost-benefit analysis and should not be when there are important qualitative considerations. In any event, an environmental impact statement should at least indicate those considerations, including factors not related to environmental quality, which are likely to be relevant and important to a decision."

For this report the following objectives are pursued in regards to cost- and risk-benefit analysis. Each alternative plus the "standard" Am-241 ICSD will be compared. For the sake of comparison, reduction of person-rem versus cost will be made. Where appropriate a risk-benefit analysis will be made. Where radiation exposure is involved the use of health effects will be made. The ratio of the number of lives saved in fires to the excess cancers resulting from exposures will be given.

The smoke or fire detectors considered are:

1. ICSD with Am-241
2. ICSD with Ra-226
3. ICSD with Ni-63
4. Photoelectric detector
5. Combination unit
6. Thermal sensors

The "tube bundle" detector system and Taguchi gas sensor are not considered for reasons given in Section 4.

5.2 COSTS

The market for smoke or fire detectors has become extremely competitive. The cost of ICSD units has declined drastically in the last few years. The average unit price in 1971 was $125.00 per detector while in 1977 it was $25.00[2]. Recently, the price of units was changing even faster. A quick survey of a number of retail outlet stores in a large western city found a large spread in prices of single unit ICSD's.

For a standard ICSD with no extras such as battery backup (AC line models) or light (to see in the dark) the prices ranged from a low of $6.99 to a high of $29.99. Extra features added to the price. In general AC-line cord models were found to be slightly less expensive than battery models. Of the 15 to 20 models observed, only two were of the photoelectric type. Another was a combination unit with both a photoelectric detector and ionization chamber. Both photoelectric detectors were $19.99. The combination unit was $29.99. Other units contained extra features such as test buttons, heat sensors, lights to light the way in case of darkness, and battery backups for AC-line models. One heat detector (set at 135^{o}F) was found to cost $19.99.

For purposes of comparison the following prices are considered to be typical for the units listed. The numbers are based upon the survey discussed above and educated guesses for such units as the Ni-63 ICSD (not available to the consumer):

1.	ICSD with Am-241	$12.00
2.	ICSD with Ra-226	$12.00
3.	ICSD with Ni-63	$15.00
4.	Photodetector	$20.00
5.	Combination unit	$30.00
6.	Thermal sensor (complete unit)	$20.00

5.3 BENEFIT VERSUS RISK FOR Am-241 ICSD'S

A broad summary of risks has recently been developed and assembled by Cohen and Lee[81]. (See Table 5.1.) The data was developed on a "days of life expectancy lost" basis to facilitate the understanding of risk by the general public. Near the very bottom of the table can be found the category "smoke alarm in home." For smoke alarms, Cohen and Lee indicate an increase in life expectancy. This assumption is based on the idea that residential fires reduce the average life expectancy by 27 days and that residential smoke alarms would reduce this value by approximately one-third or ten days. This sort of risk assessment is far from definitive when trying to analyze the full impact of a product but serves to give some perspective of the level of risk being discussed.

For the purposes of comparison, the benefits derived from ICSD's and other smoke detectors are lives saved and property damage loss reduced. For ICSD's the risk associated with their use is the resultant dose commitments and potential health effects.

The potential number of lives that may be saved by smoke detector usage is discussed in Section 3.1. In the United States it is estimated between 5250 and 8400 lives are lost in residential fires each year. This is roughly 70 percent of all fire deaths in the United States. The estimates for a life-saving factor for smoke detectors range from 41 to 89 percent. This corresponds to between 2150 and 7500 potential lives saved each year if the total population (220 million people) utilizes smoke detectors. The best estimate of the life saving factor for smoke detectors is 50 percent[14]. The range of potential lives saved for 50 percent would be from 2600 to 4200.

The potential for saving property was estimated in Section 3.1 to range from 33 to 68 percent for residential fires. For 1976, assuming two-thirds utilization of smoke detectors, the potential for property saved ranged from 310 to 638 million dollars. Fourteen million detectors would account for between 44

Table 5.1. Loss of Life Expectancy Due to Various Causes.

Cause	Days
Being unmarried - male	3500
Cigarette smoking - male	2250
Heart disease	2100
Being unmarried - female	1600
Being 30% overweight	1300
Being a coal miner	1100
Cancer	980
20% Overweight	900
<8th grade education	850
Cigarette smoking - female	800
Low socioeconomic status	700
Stroke	520
Living in unfavorable state	500
Army in Vietnam	400
Cigar smoking	330
Dangerous job - accidents	300
Pipe smoking	220
Increasing food intake 100 cal/day	210
Motor vehicle accidents	207
Pneumonia - influenza	141
Alcohol (U. S. average)	130
Accidents in home	95
Suicide	95
Diabetes	95
Being murdered	90
Legal drug misuse	90
Average jobs - accidents	74
Drowning	41
Job with radiation exposure	40
Falls	39
Accidents to pedestrians	37
Safest jobs - accidents	30
Fires - burns	27
Generation of energy	24
Illicit drugs (U. S. average)	18
Poison (solid, liquid)	17
Suffocation	13
Firearms accidents	11
Natural radiation (BEIR)	8
Medical X-rays	6
Poisonous gases	7
Coffee	6
Oral contraceptives	5
Accidents to pedalcycles	5
All catastrophes combined	3.5
Diet drinks	2
Reactor accidents - UCS	2*
Reactor accidents - Rasmussen	0.02*
Radiation from nuclear industry	0.02*
PAP Test	-4
Smoke alarm in home	-10
Air bags in car	-50
Mobile coronary care units	-125
Safety improvements 1966-76	-110

*These items assume that all U. S. power is nuclear. UCS is Union of Concerned Scientists, the most prominent group of nuclear critics.

and 91 million dollars. At a cost of twelve dollars per Am-241 ICSD, the initial cost of fourteen million detectors is 168 million dollars. Without doing a full economic evaluation (which is not justified), it is seen that the Am-241 ICSD's will easily be cost-effective over their ten-year life in terms of initial cost compared to potential property savings.

Table 3.20 summarized the total health effects from the manufacture, use, and disposal of 14 million Am-241 ICSD's. Fourteen million units represents the peak distribution year (1978). The total fatal cancers were found to be 0.14. The total body dose was found to be 1100 person-rem.

Fourteen million smoke detectors would service about 21 million people if every residence is assumed to have two detectors and three occupants. Therefore, the potential life-saving per year by 14 million smoke detectors would range from

$$21 \times 10^6 / 220 \times 10^6 \times 2150 = 210 \text{ lives/year}$$

to

$$21 \times 10^6 / 220 \times 10^6 \times 7500 = 720 \text{ lives/year.}$$

Assuming a 50 percent life-saving factor, the range would be 250 to 400 lives saved per year. If the useful lifespan of a smoke detector is ten years, the number of lives saved would range from 2100 to 7200 in ten years. The best estimated range would be from 2500 to 4000 lives saved.

Considering benefit-to-risk with lives saved as the benefit and estimated cancer mortalities as the risk, the benefit-to-risk ratio for Am-241 ICSD's is found to range from

$$2100/0.14 = 15{,}000 \text{ lives saved/mortality}$$

to

$$7200/0.14 = 51{,}000 \text{ lives saved/mortality.}$$

The best estimated range would be from 18,000 to 29,000 lives saved per mortality.

5.4 ANALYSIS FOR ALTERNATIVES

5.4.1 General

Section 4 discussed alternatives to present-day AM-241 ICSD's. In order to assess alternatives, a basis or bases must be established on which to judge alternatives compared to Am-241 ICSD's. A major part of the analysis to follow concerns cost-versus-reduction in radiation exposure. Section 3 discussed the radiological consequences of Am-241 ICSD use. Section 4 discussed the radiological aspects of ICSD alternatives. Alternatives without radioactive material, of course, produce no radiological consequences. There is no basis for non-radiological consequences and it is felt the difference between these consequences for different alternatives would be indistinguishable.

The total body dose due to the manufacture, use, and disposal of 14 million Am-241 ICSD's was found to be 1100 person-rem. On a per unit basis the total body dose per detector is 7.9×10^{-5} person-rem. Therefore, if an alternative with a negligible radiological impact compared to an Am-241 ICSD is utilized, 7.9×10^{-5} person-rem is the dose reduction realized by using the alternative. The cost of reducing the 7.9×10^{-5} person-rem is simply the cost difference between the alternative and the Am-241 ICSD. This can be represented in equation form as follows:

$$C_{DR} = \Delta C / \Delta D$$

where

C_{DR} = cost of dose reduction (\$/person-rem),
ΔC = cost of alternative - cost of Am-241 ICSD(\$),
ΔD = dose reduction (person-rem).

If the dose reduction is assumed to be 7.9×10^{-5} person-rem, then

$$C_{DR} = \Delta C / (7.9 \times 10^{-5} \text{ person-rem}).$$

Figure 5.1 illustrates this equation.

Estimates[82] of the monetary value of avoiding the detriment possibly associated with a collective dose of one person-rem have been attempted in the past. Although all estimates are subjective in nature, the range is from 10 to

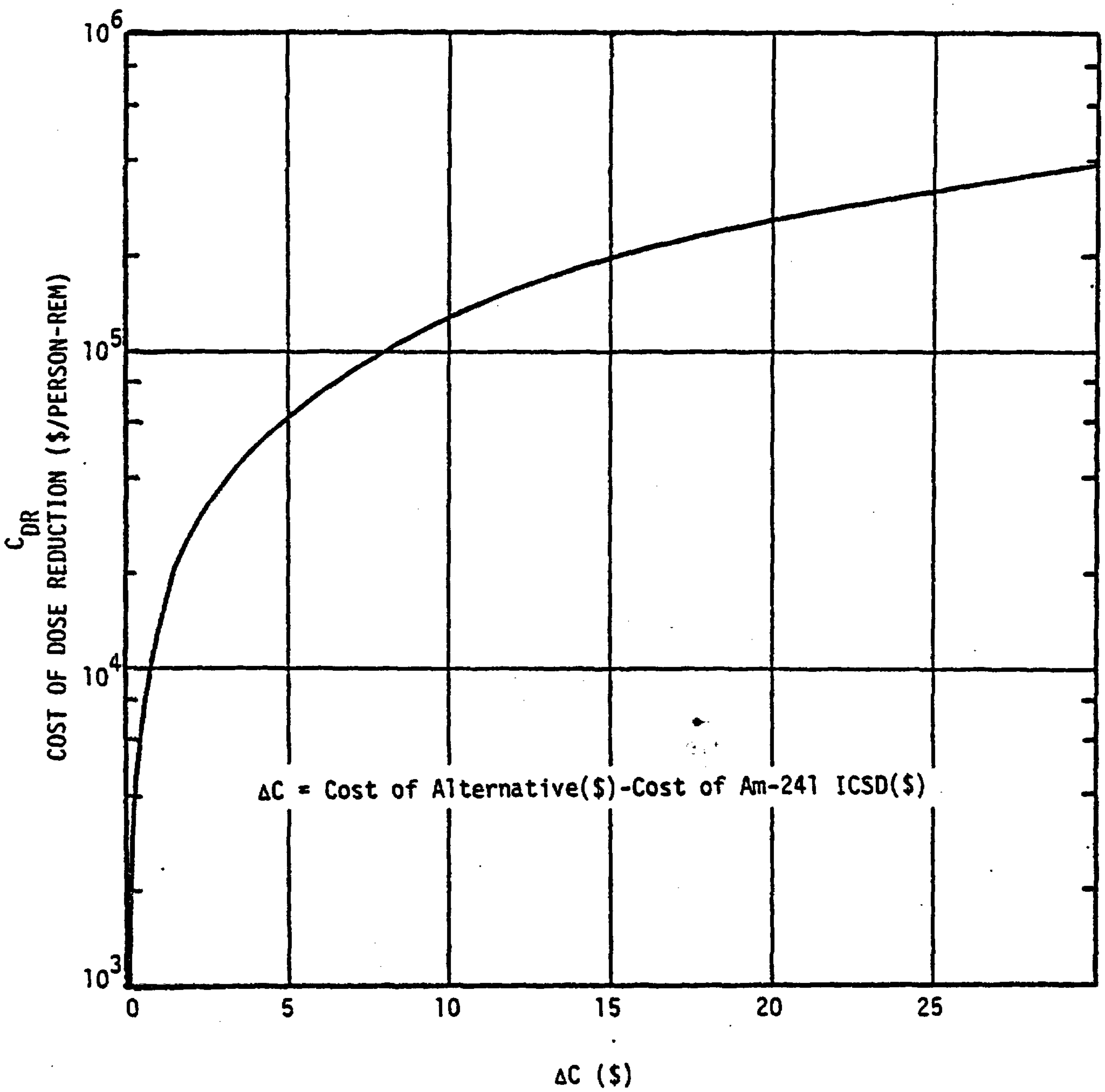


Figure 5.1. Cost of Dose Reduction for Alternatives versus Am-241 ICSD.

250 dollars per person-rem. If 1000 dollars per person-rem is used as the point at which an alternative is viable (10CFR50, Appendix I used this value for total body person-rem accumulated within 50 miles of a nuclear power plant), then the corresponding ΔC is found to be

$$\Delta C = (7.9 \times 10^{-5} \text{ person-rem}) (\$1000/\text{person-rem}) = \$0.08 .$$

Essentially, the alternative must cost within \$0.08 of the Am-241 ICSD if \$1000 per person-rem is used as the criteria.

In the following discussion of alternatives, the cost of dose reduction will be used where appropriate.

5.4.2 Am-241 ICSD's with Less Activity

A reduction of activity in Am-241 ICSD's has occurred over the past years. As technology improves, the amount will continue to decrease. A correlation between cost and reduction is not possible at this time. However, any reduction in activity that has little impact on the cost will lower estimated doses and dose commitments. Therefore, such an Am-241 ICSD would be a better alternative to present Am-241 ICSD's with more activity.

5.4.3 Ra-226 ICSD's

In Section 4.2 it was estimated that the external exposure from Ra-226 sources was about 90 times higher than for equal amounts of Am-241. However, Ra-226 ICSD sources typically contain significantly less activity than Am-241 ICSD sources. Table 2.5 indicates 0.05 uCi of Ra-226 to be the most common amount of activity. Since the average Am-241 is 3 uCi per ICSD, there is about sixty times more activity in the reference Am-241 ICSD as compared to the Ra-226 ICSD. The resulting external doses from use of the Ra-226 ICSD's would only be about 50 percent higher than for similar use of Am-241 ICSD's.

If it is assumed ICSD's can be constructed using smaller amounts of Ra-226 than 0.05 uCi then the resulting external doses would be essentially the same as for the reference Am-241 ICSD's. Thus, the decision as to whether the Ra-226 ICSD is a good alternative to the Am-241 ICSD would have to be made based upon other criteria. One consideration is the relative half-lives. The half-life for Ra-226 is 1620 years while the half-life for Am-241 is 458 years. Am-241 is more favorable in this comparison, since it will not persist in the environment as long as Ra-226.

Another consideration is that Radon-222 (Rn-222), a gas, is a daughter product of Ra-226. Small amounts of Rn-222 are released from the Ra-226 sources. Measurements of radon emanation from Ra-226 foils have been made by Hall and Hunt[18]. They found the emanation at room temperature to be as high as 1.7×10^{-2} nCi per day from a 0.66 uCi source. At higher temperatures the release was found to be in the hundreds of nCi per hour. Though the releases are small, the release of Rn-222 is considered a negative aspect of Ra-226 use in ICSD's. The Rn-222 decays into radioactive non-gaseous daughters which emit penetrating radiation.

Therefore, based upon the above considerations, Ra-226 does not appear to be a good alternative to Am-241 for use in ICSD's.

5.4.4 Ni-63 ICSD's

The external doses from proposed Ni-63 ICSD's are extremely low compared to Am-241 ICSD's. Resultant dose commitments from incineration are found to be orders of magnitude below similar incineration of Am-241 ICSD's. Therefore, radiologically, the Ni-63 ICSD is found to be better in terms of dose compared to Am-241 ICSD's.

Assuming equal abilities to detect fires, the major comparison for Ni-63 ICSD's to Am-241 ICSD's is in the cost of dose reduction. In Section 5.2, the estimated cost of an Am-241 ICSD was stated to be twelve dollars. The cost of a Ni-63 ICSD was estimated to be fifteen dollars. Therefore, the cost difference between the Ni-63 ICSD and Am-241 ICSD is three dollars. The cost of dose reduction is

$$C_{DR} = \$3/(7.9 \times 10^{-5} \text{ person-rem})$$
$$= \$38{,}000/\text{person-rem}.$$

Figure 5.1 can also be used to derive this number. A cost of dose reduction of \$38,000 per person-rem is considerably higher than the \$1000 per person-rem used for comparison in Section 5.4.1.

If $1000 per person-rem is used as the criteria for selecting an alternative, then given the choice of an Am-241 ICSD versus a Ni-63 ICSD at approximately the same cost, the Ni-63 ICSD is the better alternative.

5.4.5 Photoelectric Detector

Section 4 discusses the use of photoelectric detectors. The difference in its ability to detect and warn of fires compared to ICSD's is discussed at length. The conclusion, however, is that no firm statements can be made regarding which detector type has the best response. Each apparently is more sensitive to different types of fires. The ICSD reacts quicker to fast-burning fires while the photoelectric detector reacts quicker to smoldering or slow-burning fires. If the responses do follow the above conclusion, it is felt that the ICSD unit may have a slight edge over the photoelectric detector since response is more critical to fast-burning fires. Also, since the circuitry of photoelectric detectors is slightly more complex than ICSD's, (given both source and receiving components) the reliability may be correspondingly less than for ICSD's. However, supporting data is lacking.

Because supporting data is not available for comparison, it is assumed photoelectric detectors respond to fires equally well when compared to ICSD's. Using Figure 5.1, it can be seen (assuming as given in Section 5.2 that the photoelectric detector costs twenty dollars or eight dollars more than an Am-241 ICSD) that the cost of dose reduction for present photoelectric detectors is $100,000 per person-rem. Again, to be viable, it must cost approximately the same as the Am-241 ICSD.

5.4.6 Combination Unit

The "photo-ion" unit contains both a photoelectric detector and an ICSD. It definitely offers the greatest protection from fires to a consumer because it utilizes the sensitivities of both types of detectors. The radiological consequences should be approximately the same as the basic ICSD, but it is at a cost disadvantage to a basic ICSD. The question that is raised with a combination unit is the added amount of safety. Again, the data to support its obvious position as the best source of protection is lacking.

However, a very crude calculation can be made to try to evaluate how many additional lives combination units must save to be cost effective.

Section 5.3 stated the total fatal cancers due to the manufacture, use and disposal of 14 million Am-241 ICSD's was found to be 0.14. The total body dose was found to be 1100 person-rem. Crudely equating the fatal cancers (0.14) to the collective total body dose (1100 person-rem), one fatal cancer would result from 7900 person-rem total body. Using the cost of dose reduction criteria of $1000 per person-rem, then the cost of a saved life would be

$$(7900 \text{ person-rem/life}) (\$1000/\text{person-rem}) \\ = \$7.9\text{x}10^6/\text{life}.$$

The cost of a combination unit is given as thirty dollars in Section 5.2. It, therefore, costs eighteen dollars more than the Am-241 ICSD. Using the $1000 per person-rem cost of dose reduction criteria, the additional cost of the combination units can be equated to additional lives saved. The additional cost of using 14 million combination units ($18 per unit) divided by the crudely-calculated value of life ($\$7.9\text{x}10^6$) would be the number of additional lives that must be saved, or

$$(14\text{x}10^6 \text{ units})(\$18/\text{unit})/(\$7.9\text{x}10^6/\text{life}) \\ = 32 \text{ lives}.$$

Therefore, for the combination units to be cost effective, they must save at least 32 additional lives. (Fourteen million units used for ten years). The estimated range of lives saved using 14 million Am-241 ICSD's for ten years was found to be 2100 to 7200. An additional 32 lives saved is found to represent 0.4 to 1.5 percent of the estimated lives saved. Thus, if the combination units are found to be greater than 1.5 percent more effective than Am-241 units, they would be cost-effective as an alternative.

5.4.7 Thermal Sensors

Section 4 states thermal sensors alone are at a significant disadvantage to smoke detectors. Since their cost is higher than ICSD's by about the same amount as photoelectric detectors, they are judged not to be a viable alternative to Am-241 ICSD's.

5.5 CONCLUSIONS

The cost-to-benefit ratio for presently manufactured Am-241 ICSD's is of such a magnitude as to make the use of these detectors a justifiable use of radioactive material by the consumer. If the development of Ni-63 ICSD's results in a product of comparable sensitivity and cost, the Ni-63 ICSD should be considered the better option. The use of Ra-226 ICSD's is not judged to be a better alternative to Am-241 ICSD's because of a longer half-life and because of emanation of Rn-222.

Because of an apparent difference in response to fires by photoelectric detectors as compared to ICSD's and because of its greater cost, the photoelectric detector is not judged to be a better option to ICSD's. However, if future data were to show it was comparable to ICSD's in overall response, and if its cost became comparable to ICSD's, it would be considered the better option.

The use of the combination unit cannot be justified or dismissed as a better or worse option to ICSD's because data is lacking on its life-saving advantage over ICSD's. However, the unit is considered to offer the greatest degree of fire protection available to the consumer in a single unit. If the life-saving effectiveness of combination units is found to be greater than the effectiveness of Am-241 ICSD's by a considerable amount, their use is cost effective. Crude calculations showed this amount to be only 1.5 percent.

6. FUTURE PRODUCTS

Predicting trends in fire detection equipment to be used in the future can only be an educated guess. Based upon trends during the past ten years, it is obvious that the use of early fire warning products such as ICSD's has become widespread and the public has accepted the need based upon the derived benefits.

The development of ICSD's has shown tremendous progress both in terms of economics and sophistication. Today's units have been engineered with many features that provide greater sensitivity and reliability. Photoelectric detector development, though lagging behind ICSD's, has begun to reach new levels of sophistication.

Smoke detector manufacturers were quick to take advantage of the advances in microelectronic components. At the present stage of technology some units are in the fourth generation of MOS-FET chip design. This technology offers a number of advantages including a wide range of operating voltages, ability to detect an extremely broad range of slight changes in voltages, extremely small size, and substantial reduction in manufacturing costs. At least two manufacturers are developing advanced chips for use in photoelectric smoke detectors which should lead to a reduction in price of these units and thus a more competitive position in the consumer market.

Units are appearing, or will soon, that communicate with each other by means of a radiofrequency transmission. Some units will inform the occupant, by means of a difference in warning signal, whether they are in the room that is the source of the hazard or if it is in another location. This ability to detect in one area and set off warnings in all areas is being combined with intrusion alarms as a more total home security system. Since the circuits for smoke detectors read a shift in signal level they lend themselves well to intrusion alarming. Some manufacturers have gone so far as to indicate a potential future unit that incorporates a microprocessor to perform numerous functions as a result of various signals.

The new electronics employed in smoke detectors is leading to greater sensitivities along with a reduction in false signals. Chip technology allows for greater freedom in signal detection such that a detector can count occurances over a period of time and only sound an alarm when a significant number of events occur. Such systems could turn on lights for people who can see and cause lights to blink for people who are deaf.

Integrated circuitry for smoke detectors does not improve the smoke detectors without creating some problems. A significant shortcoming of chip design, as pointed out by more than one manufacturer, is that the detector field is always changing. Regulations are not the same from country to country and regulations within the same country are also changing. As the state-of-the-art changes, new requirements are placed on the IC design. Trends of this nature lead to IC's in the form of custom chips and there are considerable cost factors to constantly changing chip design. Not all manufacturers can afford the research and development cost and, therefore, the chips begin to come under the control of only a few manufacturers.

The distribution of ICSD's in the near future (to 1987) is of great interest to manufacturers and distributors. Based upon discussion with a number of manufacturers, it appears the market will start to decrease as saturation begins to take place. The years of 1978 and 1979 should prove to be peak years with a down trend to follow. One estimate of ICSD distribution is given in Table 6.1. This estimate is based upon the assumption that photoelectric detectors will not replace ICSD's to any significant degree in the future. Also Ni-63 ICSD's are assumed not to be on the market. Figure 6.1 illustrates the actual number of Am-241 units distributed from 1972 to 1978 and the estimated distribution from 1979 to 1986. Figure 6.2 illustrates the amount of Am-241 distributed, actual and projected, for the same time period. Figure 6.3 illustrates the average amount of Am-241 per unit, actual and projected, for the same time period.

Table 6.1. Estimated Future Distribution of Residential ICSD's.

Year	Units Distributed (millions)
1979	12
1980	10
1981	8
1982	8
1983	8
1984	7
1985	6
1986	5
Total (1979-1986)	64

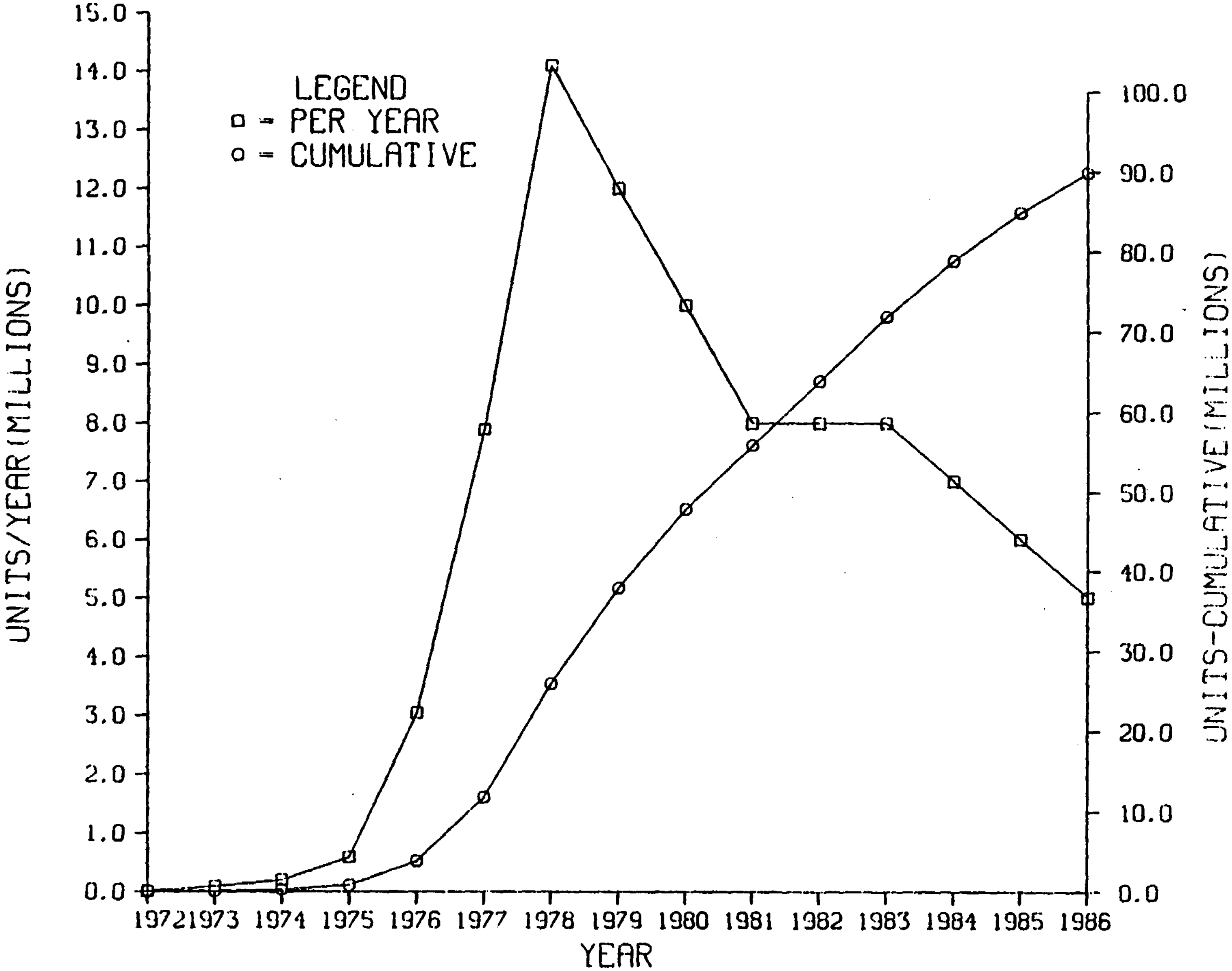


Figure 6.1. Distribution of Am-241 ICSD Units - Actual (1972-78) and Projected (1979-86)

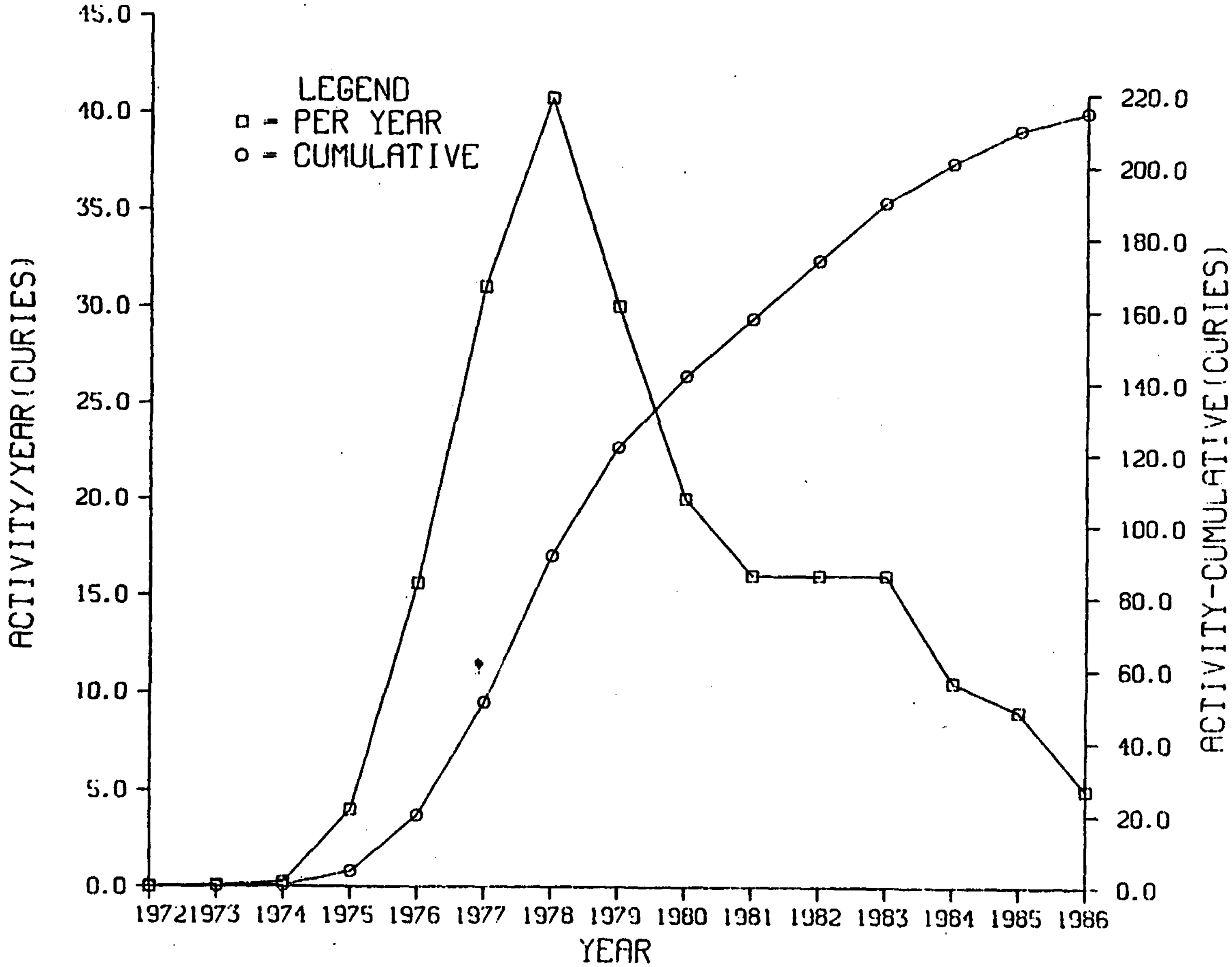


Figure 6.2. Distribution of Am-241 ICSD Activity - Actual (1972-78) and Projected (1979-86).

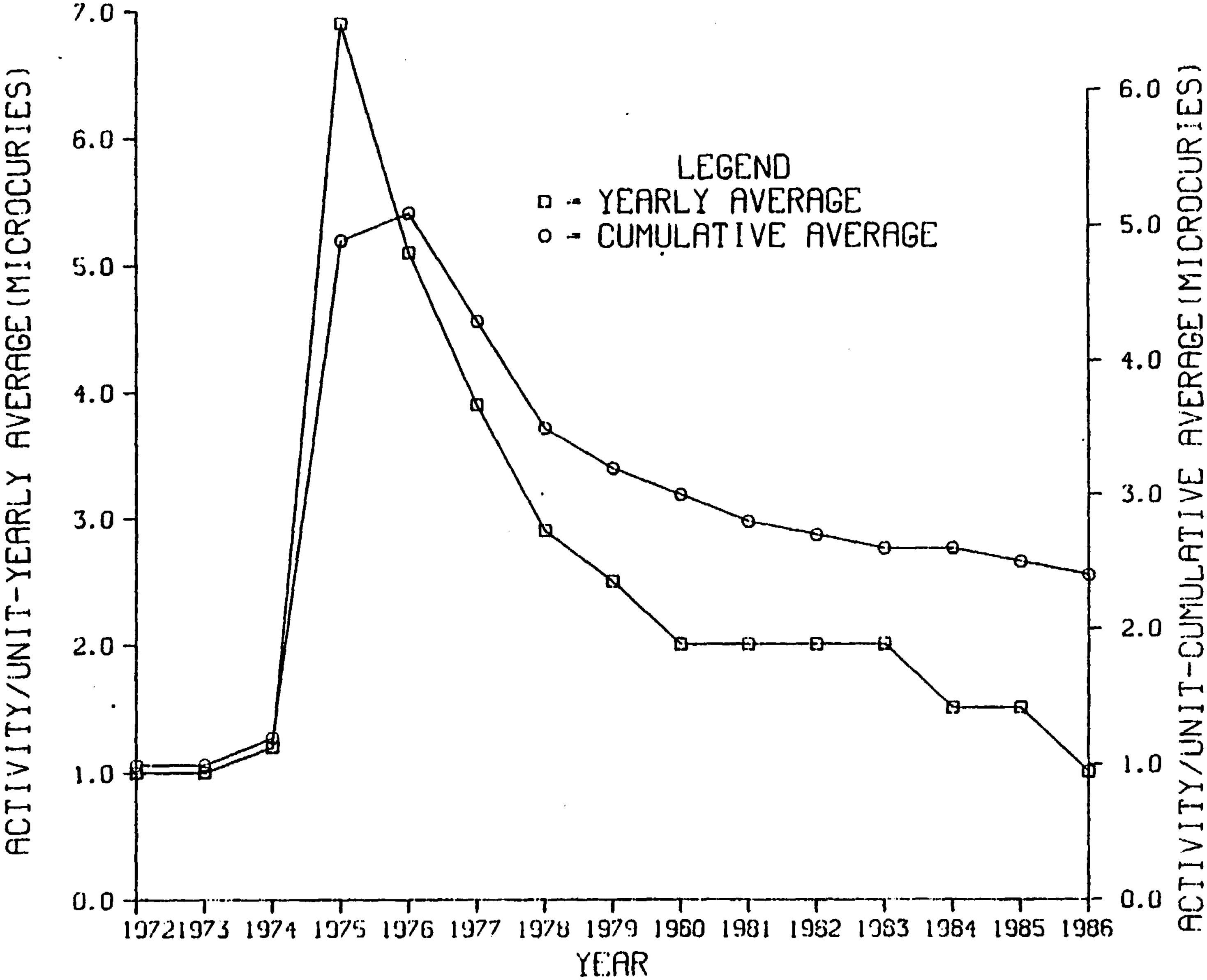


Figure 6.3. Average Activity per Am-241 ICSD - Actual (1972-78) and Projected (1979-86).

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APPENDIX A

TOXICITY OF RESIDENTIAL FIRES

A.1 PHYSIOLOGICAL EFFECTS OF FIRE AND SMOKE

The single most lethal factor in residential fires is exposure to toxic gases. In extensive studies of the cause of death of fire victims, autopsy examinations have identified carbon monoxide poisoning as the major contributor in more than 50 percent of the victims examined[A1,A2]. The degree of toxicity associated with carbon monoxide poisoning is illustrated in Figure A.1[A3]. A study by Phillips[A4] can be used as an example of the rate and amount of carbon monoxide that might be evolved during a smoldering fire. In the study a burning cigarette was used to start a smoldering fire in a sheet and mattress combination in a dormatory room. The purpose of the test was to study the response times of various smoke detectors. As the smoldering fire progressed during the test the room atmosphere was sampled for carbon monoxide and carbon dioxide levels. Figure A.2 illustrates the rise in carbon monoxide level as the test progressed. After a duration of 70 minutes the mattress was still smoldering (no flames), the carbon monoxide level was 750 ppm, the carbon dioxide level was 6000 ppm, and the room contained a considerable amount of smoke. In regards to the carbon monoxide levels found during the tests, it is interesting to note from Figure A.1 that for even a 70-minute exposure at 0.075 percent carbon monoxide, the symptomatic response of fire victims would be in the headache range. Of course these ranges are for a standard person and the age and physical and mental states of the individual would affect the response.

Along with a buildup of carbon monoxide during a fire there is a decrease in oxygen, an increase in carbon dioxide and temperature levels, and development of other gas and smoke particles. All of these can potentially work synergistically to induce physiological impairment sooner than each would do singularly. The length of exposure parameter greatly influences the physiological insults with which the components of a fire challenge the human body. A five minute exposure to 0.5 to 1.0 percent carbon monoxide is sufficient to cause lethality while 15 minutes exposure to 0.3 percent carbon monoxide

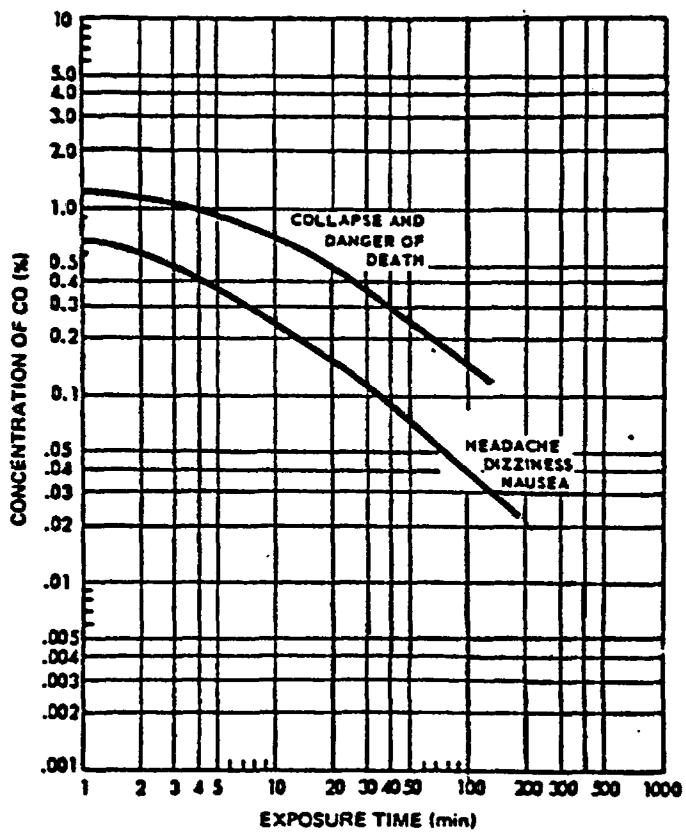

Figure A.1. Effects of CO on Man as a Function of Concentration and Time.

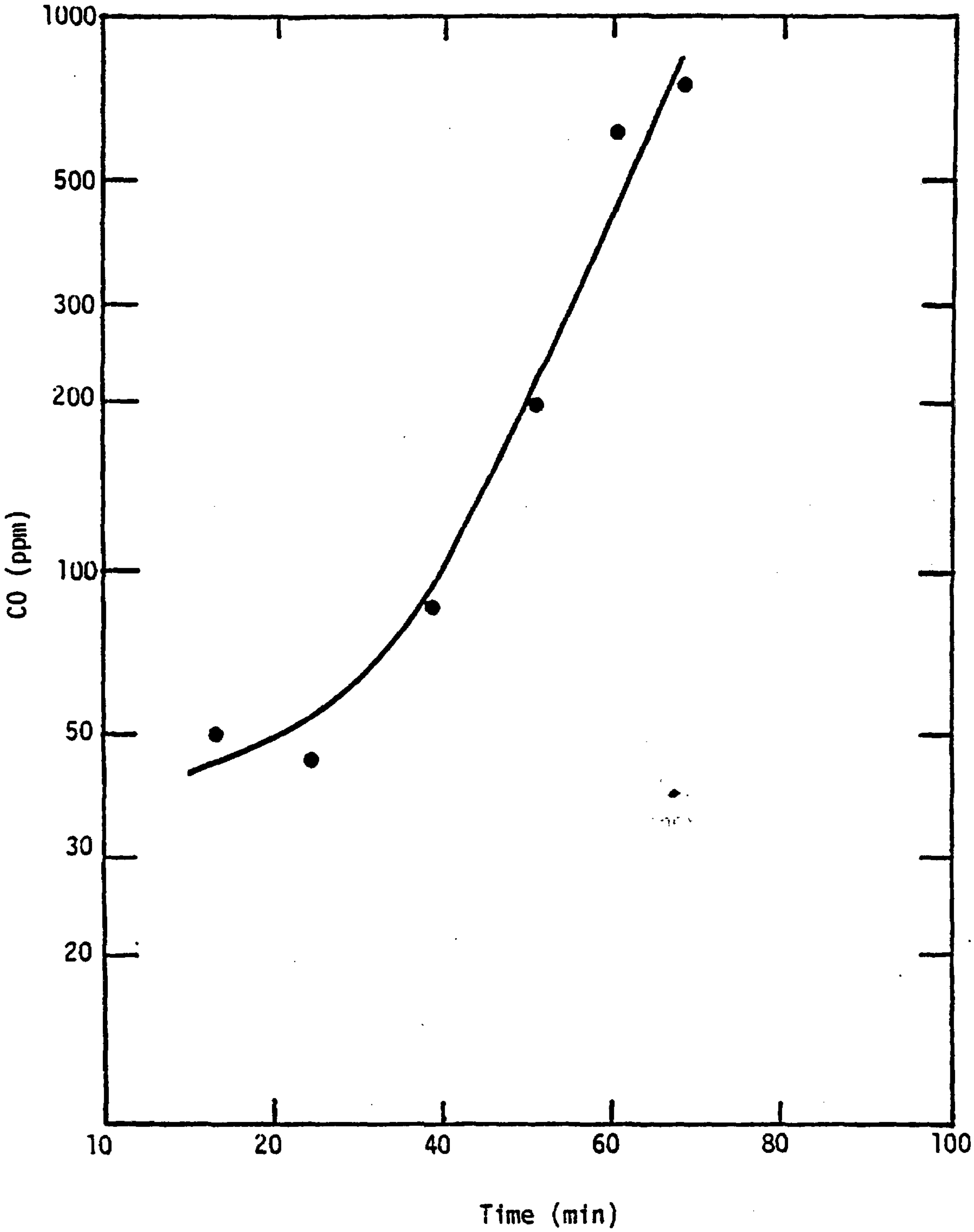

Figure A.2. Carbon Monoxide Production from Smoldering Fire-Started by Cigarette Burning into Sheet and Mattress.

induces physiological impairment. Figure A.3 indicates the minimum escape time for a healthy, clothed person exposed to extreme temperatures[A5]. A time comparison of exposures that can lead to fatality is illustrated as follows:[A1]

<u>5 Minute Lethal Factors</u>

Temperature - 200°C

CO - 0.5-1.0 percent

O_2 - 6.0 percent

<u>15 Minute Impairment Factors</u>

Temperature - 125°C

CO - 0.3 percent

O_2 - 17.0 percent

There is growing evidence that products of combustion other than carbon monoxide may be responsible for fire fatalities. The combustion products from polyurethane can amount to 100 or more different compounds - each of which may be toxic. From many of the items found in a modern residence, toxic products, such as hydrochloric acid and hydrogen cyanide, can be liberated. These products can combine with other aerosols to increase the potential for synergistic effects.

Smoke particles could conceivably contribute to a suffocation problem of fire victims but the probability of the particles being a major cause of death would depend upon a number of variables. One important variable for the sleeping victim is that at a low respiratory rate a higher percentage of the inhaled particles are deposited on lung surfaces[A6]. This variability is illustrated in Figure A.4. Little is actually known of the effect of smoke particles on lung tissue[A7]. Since the size range for smoke particles is quite variable and is affected by time and distance, the significant criterion for effective fire warning is that the detector be as sensitive to aerosols as is possible without undue amounts of false alarms.

The above information is intended to indicate some of the variables that must be considered when trying to determine if some form of fire warning will be capable of saving lives. The major criterion for the reduction of fire fatalities is that the potential victims be warned early enough during the developmental phase of a fire such that they can escape before some form of

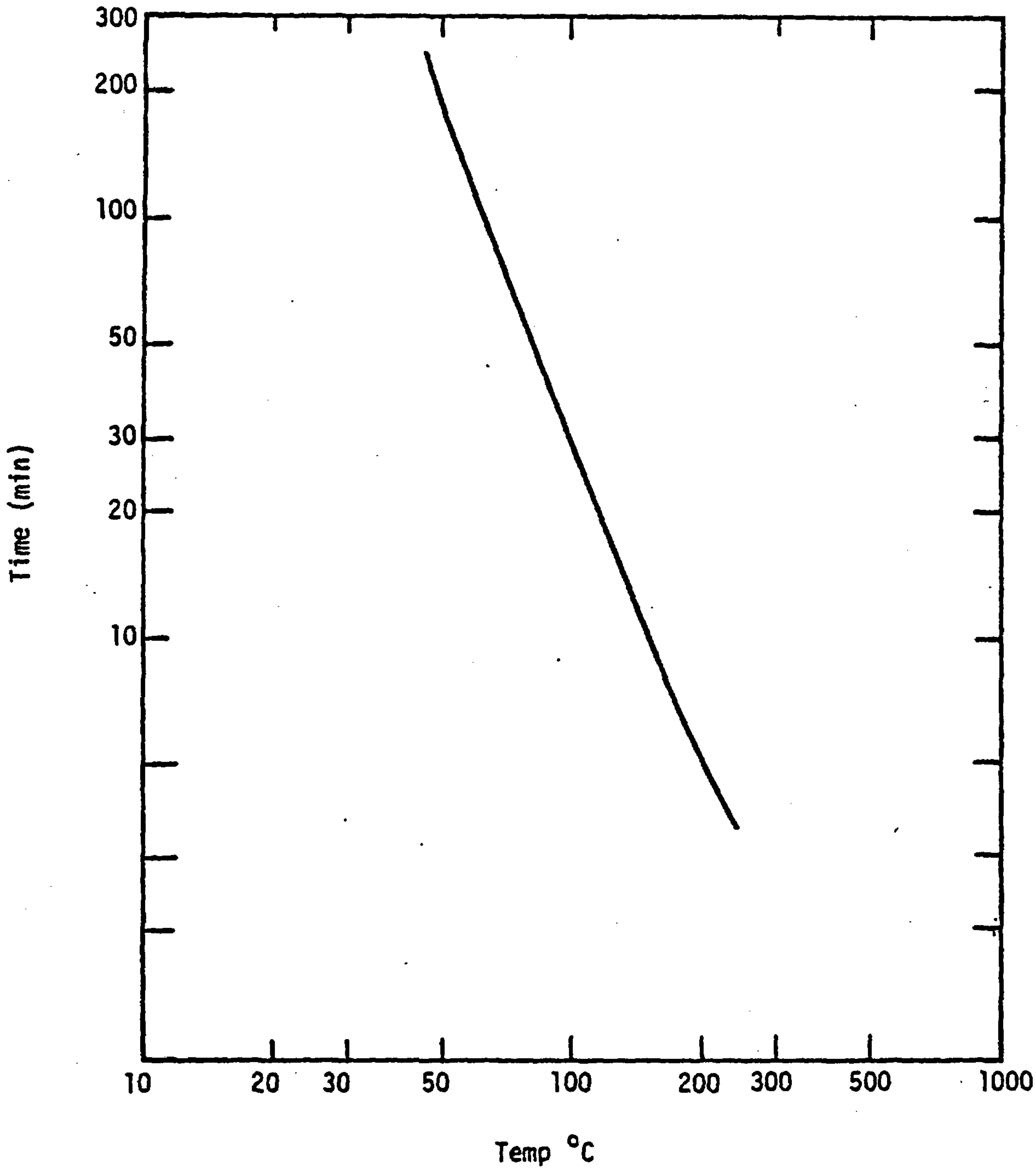

Figure A.3. Minimum Escape Time for a Healthy, Clothed Person at Extreme Temperatures. The Curve is Based on the Minimum Time of Conscious Activity (Observations) and on the Increase of the Body Temperature (Calculations).

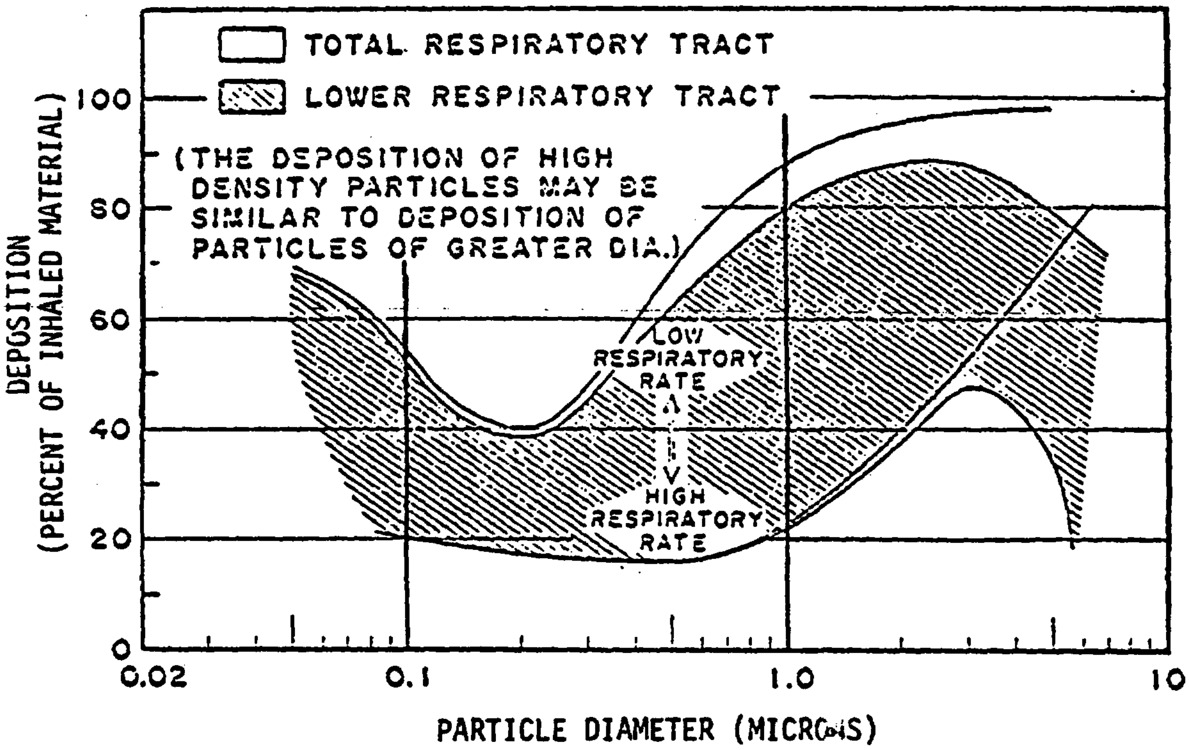

Figure A.4. Deposition of Particles in Respiratory Tract.

physiological insult incapacitates them. Detector methods exist which can sound an alarm based on sensing the various physical parameters of fire. Information based on field tests of these detector instruments definitely indicates smoke alarms are the single most appropriate method for residential installation[A4,A8,A9]. These detectors can warn building occupants of a fire long before toxic gas or temperature effects become critical and, thus, they have the potential of saving lives.

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APPENDIX B

DOSE CALCULATIONAL METHODS

B.1 EXTERNAL DOSE

The external radiation hazard from Am-241 is primarily due to the presence of the 0.0596 MeV gamma rays emitted in 36 percent of all disintegrations. Also present in the gamma-ray spectrum are numerous neptunium x-rays. For Am-241 sources in complete ICSD units, these low energy x-rays are almost completely attenuated by the ionization chamber wall, detector housing, or other components. The gamma-ray spectrum of a shielded and unshielded source are illustrated in Figures B.1 and B.2. The attenuation of the x-rays, coupled with the fact that the escaping x-rays are of low energy and not truly penetrating radiation, justifies not including the x-ray component of the gamma-ray spectrum in the assessment of the total body external radiation dose from Am-241 ICSD's.

The external radiation exposure rate from an unshielded Am-241 source resulting from the 60 keV gamma rays is derived as follows:

$$I_\gamma = (6.58\times10^{-5})(E)(\mu/\rho)(\phi)$$

where

I_γ = the exposure rate (R/hr)

E = the gamma-ray energy (MeV)

μ/ρ = the mass-energy attenuation coefficient (cm^2/g)

ϕ = the photon flux (γ/cm^2-s)

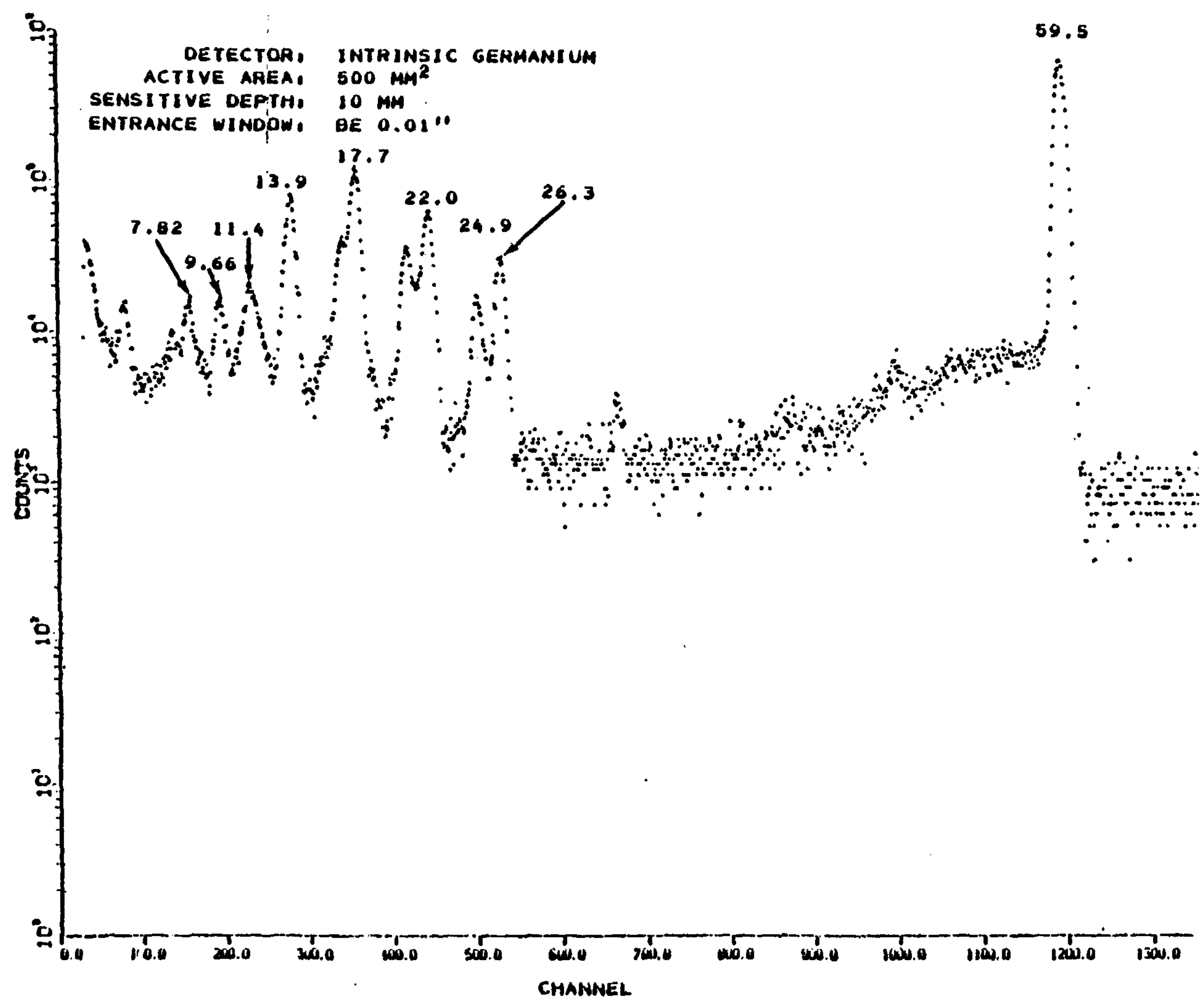

Figure B.1. Gamma-Ray Spectrum of an Unshielded Am-241 Source Showing Multiple X-Ray Peaks (Energy Values in keV).

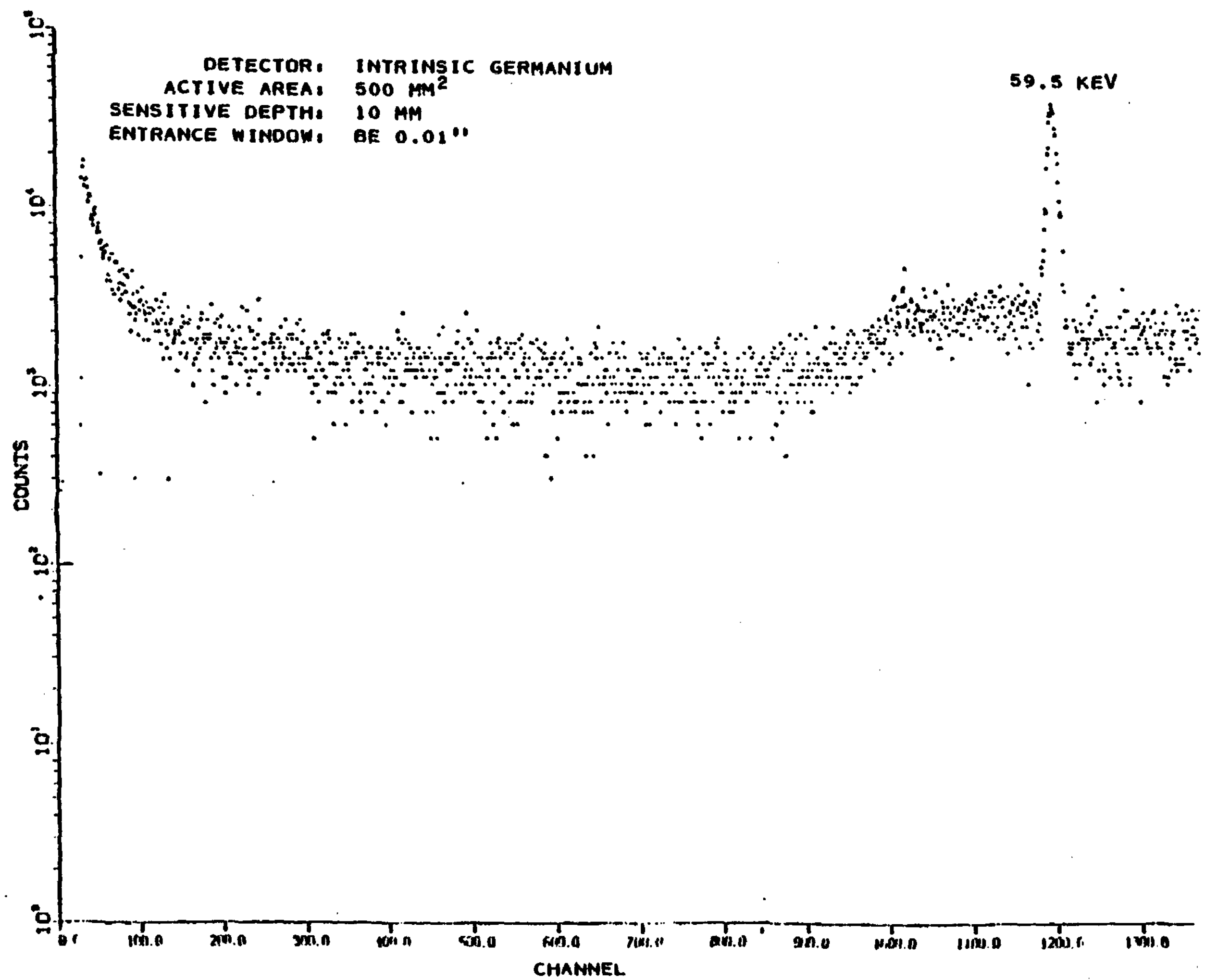

Figure B.2. Gamma-Ray Spectrum of ICSD Containing 3 μCi Am-241 Source.

The constant (6.58×10^{-5}) is the result of unit conversions from ergs to MeV, seconds to hours, and ergs per gram to roentgens, and has units of (R-s-g/MeV-hr). For a 1 uCi source, the exposure rate at a distance of one meter is

$$I_\gamma = (6.58 \times 10^{-5} \text{ R-s-g/MeV-hr})(0.06 \text{ MeV}/\gamma)(0.0292 \text{ cm}^2/\text{gm})(0.1\ \gamma/\text{cm}^2\text{-s})$$

$$= 1.2 \times 10^{-8} \text{ R/hr}$$

Since ICSD's are available in a wide variety of shapes and compositions and are not symmetrical regarding the amount of attenuating construction material surrounding the source, it is not possible to accurately calculate the exposure rates at various distances from ICSD's. There is enough uniformity of design among the most popular models, however, to reasonably estimate these values. Also, measured exposure rates from various models have been reported in license applications and other literature. Peterson(B1) reported measured values as high as 0.29 uR/hr at a distance of 25 cm from an unassembled (without plastic housing) detector containing 5 uCi. Using the inverse square law, the calculated dose rate at one meter would be 1.8×10^{-2} uR/hr for a detector containing 5 uCi. On a per unit basis this corresponds to a value of 3.6×10^{-3} uR/hr-uCi at one meter. Graham(B2) reported measured dose rates as high as 19 urem/hr at 30 cm from an industrial type ICSD containing 80 uCi of Am-241. This higher than expected value is explained by the inclusion of the x-ray component of the exposure rate, a practice which is not appropriate for total body dose calculations as discussed previously. General Electric Company(B3) has reported measured exposure rates of up to 0.123 uR/hr at 25 cm from a detector containing 3 uCi. This corresponds to a value of 2.6×10^{-3} uR/hr-uCi at one meter. Measurements taken in other directions yielded readings from 5 to 75 percent lower.

The measured exposure rates reported by Peterson and by General Electric Company are of special interest since the type of detectors used account for a large fraction of the total distribution to date. Since the maximum values reported in their tests are significantly lower (due to detector attentuation) than the calculated exposure rates for an unshielded source, an added measure of conservatism should be included in the value to be used for external dose assessment. This will offset any effects due to radiation "streaming" through attenuation voids, and will prevent underestimating exposure rates from other model ICSD's for which no measurement data are available. The assessments performed in this report use a value of 8.0×10^{-3} uR/hr-uCi at one meter from an intact ICSD, and 1.2×10^{-2} uR/hr-uCi from an unassembled or uncovered ICSD.

Measurements and calculational estimates have also been reported for various configurations of packaged smoke detectors[B1,B2]. Results of these analyses are presented in sections as they pertain to particular situations under discussion.

The basic equation used for estimating the total body dose rate from penetrating radiation emanating from an Am-241 point source is:

$$D_{ext} = \frac{\Gamma A n N k}{d^2}$$

where

D_{ext} = the dose rate (urem/hr)

Γ = the exposure rate at one meter from an Am-241 source within an ICSD (8.0×10^{-3} uR-m^2/hr-uCi)

A = the average Am-241 activity per detector (uCi)

n = the number of ICSD's

N = the number of exposed individuals

d = the source-to-subject distance (meter)

k = a constant relating the dose rate in tissue to exposure rate in air (urem/uR)

The constant k is derived as follows:

$$k = 0.869\ \beta$$

where 0.869 is the fraction of a urad (or urem) absorbed in air per uR of exposure, and β is the ratio of the mass-energy absorption coefficients of tissue to air. For 60 keV photons, the value of β is

$$\frac{(0.0312\ cm^2/g)}{(0.0292\ cm^2/g)} = 1.07$$

and

$$k = (0.869\ urem/uR)(1.07) = 0.93\ urem/uR.$$

The dose calculated in this manner represents the amount of energy absorbed by one gram of exposed tissue-equivalent material, and is substantially greater than the "effective somatic dose" due to the attenuation which occurs between the skin and the sensitive organs during whole body irradiation. O'Brien(B4) has applied three-dimensional approximations of organ and tissue gamma-ray doses in reference male and female phantoms to the organ weighting factors proposed by Jacobi(B5). For 50 keV photons, O'Brien calculated an effective somatic dose of 0.501 rem/R for males and 0.562 rem/R for females. Although doses arrived at in this manner more accurately reflect the concept of "whole body dose," these refinements are not employed in the radiological assessments performed in this report since general agreement does not exist regarding values for the organ weighting factors.

The dose to a specific organ (D_{ij}) from external (photon) sources of energy j is estimated by

$$D_{ij} = D_{ext}\ k_{ij}$$

where k_{ij} is the effective organ dose conversion factor (rem/R) for organ i and photon energy j. The factors used here (except for total body) are interpolated from the data of O'Brien and Sanna(B6). Values for 60 keV photons are given in Table B.1.

Table B.1. Organ Dose Conversion Factors for External 60 KeV Photon Source.

Organ	k (rem/R)
Liver	0.4
Bone	0.5
Lungs	0.5
Ovaries	0.3
Testes	0.6

B.2 INTERNAL DOSE

Doses to the total body and to specific organs as a result of radionuclide inhalation were calculated using the DACRIN computer code[B7] which is based on the ICRP model for lung dynamics[B8,B9]. Fifty-year dose commitment values were calculated assuming a mass median aerodynamic diameter of one micron for the inhaled particles. Values for dose conversion factors (DCF), which relate dose commitments for specific organs to the amount of inhaled radioactivity, are listed in Table B.2. A schematic diagram of the DACRIN metabolic model is given in Figure B.3. Values of the clearance parameters are listed in Table B.3.

Ingestion doses were calculated using the 50-year dose conversion factors generated by the INREM computer code[B10]. These factors relate dose commitments for specific organs per unit of ingested activity and are given in Table B.4.

Table B.2. Fifty-year Dose Conversion Factors for Inhalation of Ni-63, Ra-226 and Am-241.[B7]

Radionuclide	Dose Conversion Factors (rem/μCi)[a]			
	Total Body	Liver	Skeleton	Lungs
Ni-63	3.8E-3	8.2E-3	1.2E-1	1.1E-2
Ra-226	1.0E+2	2.4E-3[b]	2.7E+2	1.0E+2
Am-241	2.4E+1	3.2E+2	3.3E+2	5.2E+2

a. Assumes particle size of 1 micron and solubility class W for Ni-63 and Ra-226 and Y for Am-241.

b. From Reference B11.

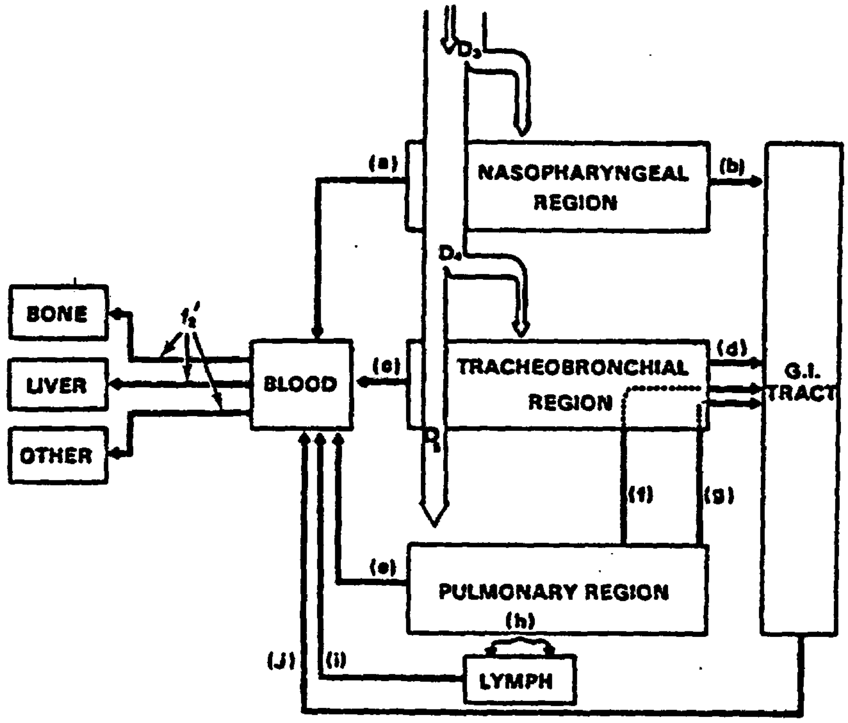

Figure B.3. Schematic Diagram of DACRIN Metabolic Model

Table B.3. Values of the Clearance Parameters for the Task Group Lung Model.

COMPARTMENT	$k^{(a)}$	D $T_k^{(b)}$	D $f_k^{(c)}$	W T_k	W f_k	Y T_k	Y f_k
NP	a	0.01	0.5	0.01	0.1	0.01	0.01
	b	0.01	0.5	0.40	0.9	0.4	0.99
TB	c	0.01	0.95	0.01	0.5	0.01	0.01
	d	0.2	0.05	0.2	0.5	0.2	0.99
P	e	0.5	0.8	50	0.15	500	0.05
	f	n.a.	n.a.	1	0.4	1	0.4
	g	n.a	n.a.	50	0.4	500	0.4
	h	0.5	0.2	50	0.05	500	0.15
L	i	0.5	1	50	1	1000	0.9

(a) Metabolic pathways from lung.
(b) Removal half time in days from compartment via pathway k.
(c) Fraction removed from compartment via pathway k.

Table B.4. Fifty-year Dose Conversion Factors for Ingestion of Ni-63, Ra-226 and Am-241.[B10]

Radionuclide	Dose Conversion Factors (rem/μCi)			
	Total Body	Liver	Skeleton	Kidneys
Ni-63	4.30E-3	8.91E-3	1.35E-1	No data
Ra-226	3.11E+1	2.39E-3[a]	3.02E+02	6.77E-2[a]
Am-241	5.42E-2	2.85E-1	8.21E-1	4.07E-1

a. From Reference B11.

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APPENDIX C
RADIOLOGICAL HEALTH EFFECTS

C.1 INTRODUCTION

The estimation of serious health effect risks resulting from internal exposure to americium is made difficult by the lack of specific human data relating effects with exposures. This fact also applies to the effects resulting from prolonged exposure to low levels of lightly-ionizing external radiation fields such as those produced by Am-241. The purpose of this appendix is to briefly summarize the state of knowledge regarding internal and external radiation effects. This knowledge provides the basis used to estimate the radiological health impact, in terms of cancer mortality and serious genetic diseases, which would result from the reference cases of ICSD use and disposal assessed in the main text of this document.

C.2 CARCINOGENESIS

Much literature in recent years has concerned itself with estimating the extent of cancer incidence and mortality resulting from low levels of ionizing radiation. These studies have drawn primarily from observations of carcinogenic effects following human exposure to comparatively high levels of radiation which were delivered at high dose rates. The externally exposed population groups which are the most widely studied are the atomic bomb survivors of Hiroshima and Nagasaki, a group of British patients who were treated by spinal irradiation for ankylosing spondylitis, and a group of Israeli children who received radiation for treatment of thyroid disorders. Two groups of people that have been subjected to relatively large amounts of internal contamination are uranium miners and a population of women who used radium paint in making luminous timepieces.

Excessive cancer death rates observed in externally exposed populations are primarily due to leukemia and cancers of the breast, lung and gastrointestinal tract, a pattern which follows fairly closely the estimated[C1]

Table C.1. Spontaneous Cancer Mortality Rates For the United States.

Cancer Type	Mortality (Per 10^6 Persons Per Year)
Leukemia	71
Lung, trachea, bronchi	379
Stomach	67
Rest of GI tract	264
Pancreas	91
Breast	152
Bone	9
Thyroid	5
All others	666
Total	1704

normally-occurring cancer mortality rates (Table C.1). It should be emphasized, however, that the increased mortality was observed at doses and dose rates which are many orders of magnitude greater than those encountered in this report. Thus, the estimation of risk at very low total doses and dose rates must be extrapolated on the basis of a linear, non-threshold relationship, a practice which has been seriously questioned by some organizations. For example, the National Council on Radiation Protection and Measurements (NCRP) has commented that:

> "The NCRP continues to hold the view that risk estimates for radiogenic cancers at low doses and low dose rates derived on the basis of linear (proportional) extrapolation from the rising portions of the dose-incidence curves at high doses and dose rates ... cannot be expected to provide realistic estimates of the actual risks from low level, low-LET radiations, and have such a high probability of overestimating the actual risk as to be of only marginal value, if any, for purposes of realistic risk-benefit evaluation."[(C2)]

More recently, a "Dissenting Report" of the National Academy of Sciences Subcommittee on Somatic Effects[(C3)] concluded that for low-LET radiation at doses of between a few and about 100 rad the dose-effect relation for total carcinogenic effect is very unlikely to be linear in this range. The dissenting group went on to say:

> "We conclude furthermore that risk estimates for whole body irradiation that are based on individual organ risk estimation in BEIR-III are overestimates of incidence at low doses. We do not believe that there is adequate information to determine accurately the magnitude of the error. It seems likely, however, that it is as much as an order of magnitude and possibly more."

While the controversy regarding the estimation of effects of exposure to low levels of lightly-ionizing radiation is not likely to be settled in the near future, the currently practiced policy of most responsible organizations is to extrapolate risk estimates derived at high dose and dose rates to lower levels of exposure, adding the proper caveats. This is done in the belief that it is more prudent to overestimate the risk than to underestimate it. Table C.2 summarizes the coefficients of risk for whole body irradiation estimated by various responsible organizations.

There seems to be more general agreement regarding the acceptance of linear dose-effect relationship for high-LET radiation, such as that produced by alpha irradiation of internal organs from inhaled or ingested actinides. Lack of specific human data makes the task of estimating cancer mortality from inhaled or ingested alpha-emitting radionuclides difficult except for the case of radium ingestion. Estimates made in this study for internal deposition of Am-241 are therefore highly uncertain. Table C.3 summarizes the currently available risk factors which can be applied to internal exposure to alpha-emitting radionuclides.

C.3 GENETIC EFFECTS

Genetic effects occur as a result of changes or alterations of the genetic material in germ cells. They may result from exposure to a variety of environmental factors including heat, ionizing and nonionizing radiation, and numerous chemicals. These genetic alterations can arise from changes within one or more of the purine or pyrimidine bases comprising the gene or from changes in the number or structure of chromosomes.

Genetic effects can be induced by exposure of the testes and ovaries to either external radiation fields or to internally deposited radionuclides. Ingestion or inhalation of transuranics, for example, may result in the translocation of transuranics to the gonads. Once deposited in these organs, the radionuclides can cause a significant dose to sensitive stem cells. Tests involving plutonium deposition in various animal species have shown, however, that the total deposition of inhaled plutonium in the gonads is low enough such that even allowing for preferential exposure of stem cells, the dose to these cells would not be expected to exceed the total body average[C11,C12]. It is likely that the same can be said for americium.

One conventional approach to assess the genetic health impact of ionizing radiation is to arrive at a "doubling dose," which is an estimate of the radiation dose that results in a twofold increase in the spontaneous mutation rate. Given the doubling dose, which is arrived at on the basis of experimental evidence, and assuming that the burden of human ill health attributable to

Table C.2. Comparison of Health Risk Estimates (Tumor Deaths or Genetic Defects) Associated with Collective Dose of 10^6 Organ-rem.

	BEIR-I[C4]	UNSCEAR[C5]	ICRP[C6]	NRC[C7]
Leukemia (red marrow)	20	20	20	28.4
Breast	45[a]	50	25	25.6
Lung	16-100[b]	25-50	20	22.2
Bone	2-17[b]	2-5	5	NS[c]
Liver	1-7[b]	10-15	NS	NS
Thyroid[d]	1.6-9.3[d]	10[e]	5[e]	4.3[f]
GI Tract[g]	30	10-15	NS	13.6
All Fatal Cancers	50-78[b,h] 92-165[b,i]	100	100	121.6
Genetic Defects	50-500[j,k] 10-100[j,l]	20-30[m] 185[n]	100[o]	95-165[p]

a. Derived from observed incidence in females by correcting for 50% cure rate and inclusion of males in population.

b. Lower value represents absolute risk model with 30 year plateau following latent period; higher value represents relative risk model with lifetime plateau.

c. NS-Not specified

d. Values represent incidence of thyroid cancers per year per 10^6 person-rem in irradiated children. The risk for adults is somewhat lower.

e. Mortality risk for general population.

f. Incidence of thyroid cancers per year per 10^6 person-rem in irradiated children and adults.

g. Includes stomach.

h. Based on atomic bomb survivor data.

i. Based on ankylosing spondylitis patient data.

j. Lower value assumes doubling dose of 200 rem, higher valve assumes doubling dose of 20 rem.

k. Specific genetic defects including dominant, recessive and chromosomal diseases.

l. Defects with complex etiology including congenital anomalies, anomalies expressed later, constitutional and degenerative diseases.

m. Seriously affected cases per million liveborn.

n. Total detrimental genetic effects over all generations.

o. Serious hereditary ill health within the first two generations.

p. Total genetic disorders (autosomal dominant, multifactoral, chromosomal aberrations and spontaneous abortions) over all generations.

Table C.3. Comparison of Health Risk Estimates (Tumor Deaths or Genetic Effects) Associated with Internally-delivered Organ Dose of 10^6 Rem.

	BEIR-I[C4]	UNSCEAR[C5]	ICRP[C6]	NRC [C7]	MRC [C8]	Mays [C9]	Newcombe [C10]
Lung Tumors	16 - 100[a]	25 - 50	20	22	25	20	NS[b]
Bone Tumors	2 - 17[a]	d - 5	5	7	5	4	NS
Liver Tumors	1 - 7[a]	10 - 15	NS	NS	20	10	NS
Genetic Defects	50 - 500[c] 10 - 1000[d]	20 - 30[e] 155[f]	100[g]	95 - 165[h]	NS	NS	10

Notes:

a) Lower value represents absolute risk model with 30 year plateau; higher value represents relative risk model with lifetime plateau.

b) NS - Not Specified

c) Specific genetic defects including dominant, recessive and chromosomal diseases.

d) Defects with complex etiology including congenital anomalies, anomalies expressed later, constitutional and degenerative diseases.

e) Seriously affected cases per million liveborn.

f) Total detrimental genetic effects over all generations.

g) Serious hereditary ill health within the first 2 generations; additional damage to later generations would be of same magnitude.

h) Total genetic disorders (autosomal dominant, multifactoral, chromosomal observations and spontaneous abortions) over all generations.

normally occurring mutations is known (and is the same for radiation-induced mutations), one can directly estimate the detrimental genetic effects for any specific radiation dose. The 1977 UNSCEAR Report reviews and discusses the state of knowledge on this topic and arrives at a doubling dose of 100 rem, while the BEIR-III report ascribes to a range of 50 to 250 rem.

C.4 HEALTH EFFECT RISK COEFFICIENTS

The coefficients of risk used for the purposes of estimating cancer mortality and genetic detriment are listed in Table C.4. These risk estimates are based on the best currently available literature values (as shown in previous tables) and are generally considered to be upper level estimates. Thus, although a lower level of risk - or even zero risk - cannot be entirely ruled out on the basis of currently available data, the use of upper level estimates based on the linear, non-threshold hypothesis is considered to represent the most prudent approach to the low level risk assessment performed in this report.

Table C.4. Health Effect Risk Estimates Used in this Report.

Cancer	Tumor Deaths or Serious Genetic Defects Per 10^6 Organ-Rem
Liver	15
Bone	5
Lung	25
All Other Fatal Cancers[a]	100
Total	150
Genetic Defects	200

a. Primarily leukemia and cancers of the breast, GI tract and thyroid.

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NRC FORM 335 (7-77)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-1156

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
Environmental Assessment of Ionization Chamber Smoke Detectors Containing Am-241

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
R. Belanger, D.W. Buckley, J.B. Swenson

5. DATE REPORT COMPLETED
MONTH October YEAR 1979

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Science Applications, Inc.,
1200 Prospect Street
La Jolla, California 92038

DATE REPORT ISSUED
MONTH November YEAR 1979

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
U.S. Nuclear Regulatory Commission
Material Certification and Procedures Branch
Division of Fuel Cycle and Material Safety, NMSS
Washington, D.C. 20555

10. PROJECT/TASK/WORK UNIT NO.

11. CONTRACT NO.
NRC-02-78-045

13. TYPE OF REPORT
Technical Report

PERIOD COVERED *(Inclusive dates)*
January, 1979 through October, 1979

15. SUPPLEMENTARY NOTES

14. *(Leave blank)*

16. ABSTRACT *(200 words or less)*

The NRC is reevaluating the adequacy of existing policy dealing with the distribution of consumer products containing radioactive material. One such consumer product is the ionization chamber smoke detector (ICSD), which in recent years has become widely distributed.

This report is the assessment of the impact of ICSD's on people and the environment. Its benefits and risks are evaluated for presently-distributed ICSD's against alternatives. The work is intended to be a source of information for a generic environmental impact statement (GEIS) on consumer products containing radioactive material which will be written in the future.

The report concludes that the sum of doses to the population from the annual production, distribution, use, and disposal of 14 million Am-241 ICSD's is much lower than that which could potentially result in one cancer death. The use of Am-241 ICSD's is justifiable as a means to prevent loss of life and property. The estimated benefit-to-risk ratio is more than 15,000.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
Unlimited

19. SECURITY CLASS *(This report)*
Unclassified

21. NO. OF PAGES
177

20. SECURITY CLASS *(This page)*
Unclassified

22. PRICE
S

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

POSTAGE AND FEES PAID
U.S. NUCLEAR REGULATORY
COMMISSION

U.S. MAIL