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Estimated Radiation Doses from Thorium and Daughters Contained in Thoriated Welding Electrodes

L. M. McDowell-Boyer

Prepared for the
U.S. Nuclear Regulatory Commission
Office of Standards Development
Division of Engineering Standards
Under Interagency Agreement DOE 40-543-75

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HIGHLIGHTS

Thoriated-tungsten welding electrodes, containing 1 to 2% thoria (ThO_2) by weight, are potential sources of radiation exposure to members of the general public involved in gas tunsten-arc welding. Therefore, potential doses associated with the distribution, use and disposal of these commonly available consumer products were estimated.

Exposure scenarios were developed to describe what are believed to be typical conditions under which exposure to radioactive thorium and daughters may occur. Source terms for both internal and external exposures were estimated on the basis of documented release rates of thorium and daughters from electrodes during welding, of known thoria (ThO_2) concentrations in electrodes, and on the basis of estimated production rates of thoron (^{220}Rn) in electrodes. Radiation doses were estimated for maximally-exposed individuals and for the portion of the U.S. population potentially exposed, under the assumed conditions, per million thoriated electrodes distributed, used, and disposed of annually.

The maximum estimated 50-year dose commitment was for welders who work both in a shop and, although rare, at home, for a total welding time of 1200 hr/year. The maximum individual dose commitment for a year of welding was estimated to fall within the range of 20 millirem to 1 rem to the bone (2.4 to 88 millirem to the whole body), with typical doses between 0.9 and 160 millirem to the bone for welders (0.07 to 14 millirem to the whole body). Uncertainties regarding thorium loss to fumes and subsequent suspension in air prevented estimation in a more narrow range. The total collective dose commitment was estimated to range between 7.9×10^2 and 6.4×10^3 man-rem to the bone (56 to 5.4×10^2 man-rem to the whole body).

SUMMARY

Some welding electrodes used in gas tungsten-arc welding contain between 1 and 2% radioactive thoria by weight which, as an alloy, provides several advantages to this welding process. Radiation doses potentially received by members of the general U.S. population as a result of the distribution, use, and disposal of one million thoriated-tungsten welding electrodes were estimated in this assessment, although the actual magnitude of distribution is unknown. Persons considered potentially exposed to thorium and daughters contained in these consumer products included truck drivers, United Parcel Service (UPS) employees,* warehouse and retail personnel, and retail customers, all assumed to be involved in distribution from manufacturers to consumers; welders and other welding shop personnel involved in the use of these products; and members of the general population who may be exposed to airborne radionuclides as a result of incineration or burial of discarded electrodes. Doses resulting under abnormal circumstances, where electrodes stored in a warehouse might be subjected to fire such that all radionuclides contained in the products are volatilized, or where welders may carry extra electrodes in a shirt pocket, were also estimated.

The magnitude of the radiation source to which individuals may be exposed was estimated from literature regarding electrode characteristics and loss of electrode material during welding. Exposure scenarios were developed from information obtained through informal interviews with welders and from documentation on consumer product distribution procedures

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*This group chosen only as a representative group of parcel handlers.

and common disposal methods utilized in the United States. When uncertainties existed regarding the value of specific parameters necessary to quantify exposure, estimates were made from supplementary data.

The maximum individual and collective dose commitments, or dose ranges, estimated in this assessment are summarized in the following table (Table A). The maximally exposed individual indicated from exposure scenarios developed is the welder, who is estimated to receive a bone dose commitment between 20 millirem and 1 rem (2.4 to 88 millirem whole body dose commitment). In this assessment, welders who may receive such doses were assumed to be engaged in welding with thoriated electrodes in a shop for 4 hr/day (1000 hr/year) and in welding at home for 4 hr/week (200 hr/year). For what are assumed more typical conditions, with no home welding, bone dose commitments were estimated to range between 0.9 and 160 millirem (0.07 to 14 millirem whole body dose commitment). Because uncertainties regarding the amount of thorium and daughters that may become airborne during welding were great, only ranges of potential doses could be calculated.

The collective dose commitment estimated for the annual distribution, use, and disposal of one million thoriated welding electrodes was estimated to range between 7.9×10^2 to 6.4×10^3 man-rem to the bone (56 to 5.4×10^2 man-rem to the whole body). These values represent the potential dose received by the general U.S. population over a 50-year period following exposure during one year.

Table A. *Summary of maximum individual, typical individual, and collective doses received from distribution, use, and disposal of thoriated welding electrodes (per 10^6 electrodes annually)*

Stage	Size of population affected	Maximum individual dose/dose range (millirem)		Typical individual dose/dose range (millirem)[a]		Collective dose/ dose range (man-rem)	
		Critical organ	Whole body	Critical organ	Whole body	Critical organ	Whole body
Distribution[b]	2.51E+07[c]	2.2E-01 (bone)	2.0E-01	1.5E-05–1.7E-01 (bone)	1.4E-05–1.5E-01	7.9E-01 (bone)	7.2E-01
Use[d]	1.01E+05	2.0E+01–1.0E+03 (bone)	2.4–8.8E+01	8.8E-01–1.6E+02 (bone)	7.2E-02–1.4E+01	5.7E+02–6.2E+03 (bone)	4.8E+01–5.3E+02
Disposal[d]	2.18E+08	1.9E-01 (bone)	6.9E-03	1.0E-06 (bone)	3.4E-08	2.2E+02 (bone)	8.1
Abnormal circumstances[b,e]	unknown	3.5 (skin)	2.9			unknown	
TOTAL COLLECTIVE DOSE						7.9E+02–6.4E+03	5.7E+01–5.4E+02

[a]Typical values represent average doses received by all individuals in each group within designated stage.

[b]Doses represent external exposure during one year.

[c]*2.51E+07 notation is equivalent to 2.51 x 10^7.*

[d]Doses represent 50-year internal dose commitment received per one year's exposure.

[e]Considers a warehouse fire and carrying electrodes in shirt pocket.

1. INTRODUCTION

Thoriated-tungsten welding electrodes, containing 1-2% thoria (ThO_2) by weight, are commonly used in gas tungsten-arc welding.[1-4] Concern over hazards that may exist due to internal or external radiation exposure to radioactive thorium and thorium daughters contained in, or released from, these products led to this assessment of potential doses associated with the distribution, use, and disposal of thoriated electrodes.

Thoriated-tungsten electrodes were introduced almost 30 years ago[1,2] to replace pure tungsten electrodes for a variety of arc welding situations. Reported advantages associated with thoriated tungsten over pure tungsten include easier starting, greater arc stability, and less weld metal contamination.[1-3]

A few empirical investigations into the potential health hazards associated with volatilization of thorium and daughters during welding have been reported in the literature.[1,5] Results have suggested that the maximum permissible concentration for thorium in air will seldom, if ever, be exceeded in the immediate vicinity of a welder, and will even less likely be exceeded in the welder's breathing zone, based on alpha activity measurements.[1] However, none of these previous studies have attempted to estimate doses actually received by welders and nearby persons, nor to calculate potential exposures and doses received based on the measurements of electrode material lost during welding.

This assessment addresses the matter of doses potentially received during the use of thoriated welding electrodes, as well as doses received by members of the general public potentially exposed to thorium and daughter radionuclides during transport and distribution to retail units and during disposal of these products. A physical description of the electrodes and of the assessment strategy used in this theoretical study follows. Subsequently, detailed descriptions of exposure conditions assumed for dose calculations will be given for each stage of the assessment. Circumstances which may be considered abnormal, but which may lead to radiation exposures to thorium and daughters are also discussed. Estimated doses to maximally exposed individuals, typically exposed individuals, and to the exposed population group are presented, based on an assumed annual distribution of one million welding electrodes. (The actual number of electrodes distributed annually is unknown.)

1.1 Product Description

Thoriated-tungsten welding electrodes are used in the gas tungsten-arc welding process, a process in which an electrical arc is produced between a nonconsumable, gas-cooled electrode (e.g., an electrode that does not supply filler material) and the work metal, thus heating the metal. Tungsten, which has the highest melting temperature of all metals, is the best material for nonconsumable electrodes. Thoriated-tungsten electrodes contain between 1 and 2% thoria (ThO_2) by weight and are superior to pure tungsten electrodes in several respects. They have higher electron emissivity, better current-carrying capacity, longer life, and greater resistance to contamination.[6] With these electrodes, arc starting is easier and the arc is more stable.

Thoriated-tungsten electrodes are produced in nine standard diameters (between 0.254 and 6.35 mm) and six standard lengths (between 7.62 and 60.96 cm).[6] The electrode diameter is generally chosen such that the electrode will operate at near-maximum current-carrying capacity.[7] Because typical currents of 300 amps are used in arc welding,[6] and the maximum current capacity of thoriated-tungsten electrodes with diameters equal to 0.238 cm (3/32 in.) has been found to be between 340 and 375 amps,[8] the typical diameter of thoriated electrodes was chosen to be 0.238 cm for this assessment. The typical length of electrodes was assumed to be 15.24 cm, although a variety of lengths, as well as diameters, may be used for different applications.

The thoria content of electrodes, although ranging from 1 to 2% by weight, was assumed to be 2% for this assessment. It was also assumed that the thorium was uniformly dispersed throughout the tungsten electrode, since it is generally alloyed with thoria.[7] However, striped electrodes have been available, which consist of pure tungsten with only a longitudinal strip of thoriated tungsten (2%).[6]

The radioactive thorium, ^{232}Th and ^{228}Th, used in the manufactured electrodes is assumed to have been separated from daughter products 20 years prior to the marketing date of the product in this assessment. This implies, then, that the radioactive daughters of ^{232}Th or ^{228}Th will have achieved approximately 91% and 87% of equilibrium with the two thorium isotopes, respectively.[9] This assumption is used throughout in calculating doses received from external and inhalation exposure to thorium isotopes and daughters.

The life-time of each thoriated-welding electrode will depend on the amount and conditions of use. Although these electrodes are generally considered nonconsumable,[4] appreciable consumption occurs during normal use[1] and may be increased if improper use results in oxidation or contamination of the electrode.[7] Assumptions regarding the average useful lifetime of these products are discussed in Sect. 3 of this report.

Data concerning the magnitude of the annual production and distribution of thoriated-tungsten electrodes were not available for this assessment. Through informal conversations with a few manufacturers of the rods, however, it appears that approximately four manufacturers are actively producing these products in the United States at this time. This assessment considered that each of four manufacturers produced 250,000 thoriated electrodes annually, resulting in a total of one million electrodes being manufactured and distributed each year. One million was chosen merely as a convenient number with which to scale the results of this assessment, given additional information regarding the magnitude of distribution.

1.2 Assessment Strategy

In order to assess the potential radiation exposures and doses received by the U.S. population from thoriated-tungsten welding electrodes, the number of electrodes distributed, used, and disposed of annually in the United States, and the number of persons potentially exposed to radioactive thorium and daughters during any of these activities must be considered. Numerical data of these types were not available for this assessment. The numbers of potentially exposed individuals were estimated from collateral data regarding the average rate of electrode usage by welders; from documented information on typical distribution procedures applied to consumer products; and from hypothetical exposure scenarios developed in this assessment to account for the distribution, per one million electrodes, to an assumed one thousand retail establishments across the country.

Because time, distance, and shielding are all factors that determine doses received as a result of exposure to radioactive materials, values of these parameters were estimated for all individuals potentially involved in the distribution, use, and disposal of welding electrodes. Values chosen for these factors are believed to represent typical exposure conditions. Details of, and rationale behind, assumed exposure conditions are presented in subsequent sections.

Doses to individuals and the population were estimated using the CONDOS computer code,[10] where radiation doses associated with one year of product use, distribution, or disposal are calculated from input data describing exposure conditions for various activities of concern. Doses are calculated by this code for both external and internal exposure situations, with results being reported for total body and several reference organs. For this assessment, external exposure to radioactive thorium and daughters is assumed to occur as a result of exposure to direct radiations emitted during decay of isotopes present in the thorium decay chain and to bremsstrahlung produced within the tungsten rod. Nuclear decay data for natural thorium and daughter products were taken from Kocher.[11]

Internal exposure via inhalation of radioactive thorium and daughters is assumed to occur as a result of the release of gaseous thoron from electrodes, and from volatilization of radioactive materials during welding and incineration of discarded welding rods. Immediate and uniform dispersion of airborne nuclides was assumed to occur following release into specific volumes surrounding exposed individuals. Air volumes and air exchange rates during welding were specified to conform to minimum standards presently required of the welding industry.

To calculate external doses received by individuals in a year, external dose conversion factors from the EXREM-III computer code[12] are applied to annual external exposure estimates in the CONDOS code. External doses are reported for the critical organ (i.e., the organ receiving the highest dose per unit exposure) and for the whole body, the latter being a more commonly reported value. Fifty-year dose commitment factors used to convert internal radiation exposures over one year to individual dose commitments are taken from the INREM-II computer code,[13] and its implementation using documented retention functions and metabolic parameters for nuclides in the thorium decay chain.[14] Internal dose commitments are reported for the critical organ and whole body. The factors in this latter document, which are based on a quality factor (QF) of 10 for alpha radiation, were used in this assessment, although others were available which incorporate a QF of 20. The maximum error that could occur as a result of using a QF equal to 10, if 20 were more appropriate, is that the internal doses calculated would be low by a factor of not more than 2.

Collective doses were estimated by assuming that all members of any particular exposed group receive similar doses to those received by the "typical" individual for which external and internal doses were calculated. Thus, the multiplication of group size by individual exposures was carried out to give estimated collective doses in man-rem per year for each group. These group doses were then summed to give a total population dose.

2. DISTRIBUTION

The potential radiation exposures and doses received by members of the general public who are actively or passively involved in the annual distribution of one million thoriated-tungsten electrodes were assessed according to the strategy outlined in Sect. 1.2. The assumptions upon which estimated doses are based, as well as the numerical results of the collective dose assessment, are presented in the following discussion and tables, respectively.

Both internal and external exposure to thorium isotopes and/or radioactive decay products were considered in assessing potential radiation dose received during distribution of thoriated electrodes. Internal exposure may occur as a result of the release of the inert gas, ^{220}Rn, commonly known as thoron, from the electrodes, and subsequent inhalation. Thoron is produced directly from the decay of ^{224}Ra, which is present in the electrodes as a radioactive decay product of thorium. The rate of thoron release will depend on its production rate, and characteristics of the rod which influence its emanation from solid particles within the welding rod and its diffusion in interparticle space.[15] Because neither of these latter two parameters are known for tungsten electrodes, it was assumed that the inhalation exposure to thoron and radioactive daughters was a result of the complete release of all thoron produced in the rods, and that the rate of thoron release equals its production. Daughters of thoron were assumed to be in equilibrium with the parent upon release. More refined release calculations were not deemed necessary in light of the negligible doses estimated ($<10^{-8}$ millirem) for this pathway.

Volatilization of thorium and radioactive decay products other than thoron was assumed to be negligible during distribution, and thus, only external exposure to these isotopes was considered. The basis for this assumption was the knowledge of the minimum temperatures at which compounds of each element present will boil or sublime,[16] indicating that neither of these processes will occur at atmospheric temperatures or pressures normally encountered during distribution.

External exposures to particles or rays emitted by isotopes in the thorium decay chain and to bremsstrahlung produced within the welding electrodes from beta emissions were estimated for segments of the population potentially involved in distribution. Estimated annual exposures to external radiation took into account any shielding provided by packing material or cargo transporters that were considered likely to be present.

To develop exposure scenarios for individuals potentially involved in distribution per one million thoriated electrodes, values of several parameters were estimated in lieu of actual data. Maximum annual dose estimates for members of this population group were less 1 millirem, and therefore, the time-consuming collection of these data was not considered cost-effective. Included among these parameters are the number of electrodes leaving and arriving at each destination at any one time, the number of individuals potentially exposed during distribution from manufacturers to users, and the time and conditions of exposure in each location considered. In order to estimate values more realistically, a recently prepared document concerning the procedures used to transport and distribute consumer products was consulted.[17] Values of parameters used regarding the exposure time, distance from source, shielding, and ventilation rates are provided in the appendix of this report.

A flow diagram representing the distribution scheme from which exposure scenarios were developed is presented in Fig. 1. Welding electrodes were assumed to be available to consumers only after receipt by retail outlets. Distribution to these retail outlets was accomplished through direct delivery by local manufacturers or delivery from nearby warehouses or parcel delivery terminals [United Parcel Service (UPS) assumed in hypothetical exposure scenarios]. Each retail outlet was assumed to receive two shipments of 500 electrodes, or a total of 1000 electrodes annually, and each warehouse, to receive five shipments of 2000 electrodes annually, or a total of 10,000 electrodes.

For transportation of shipments to destinations at distances greater than 32 km (20 miles) from each manufacturer, the UPS system was chosen to be representative of the mode of shipment utilized. This choice was made on the basis of the small size and weight of electrodes, such that cartons of 100 rods, the assumed packaged number, would meet specifications applied to parcels the UPS will accept. By assuming that each warehouse and retail destination is reached through independent chains of UPS terminals, it is believed that the number of individuals assumed exposed to the thoriated rods through the UPS system is maximized.

Several groups of individuals were identified as groups potentially exposed during the distribution of welding rods, as outlined in Fig. 1. Because truck transport was the means of shipment assumed, several

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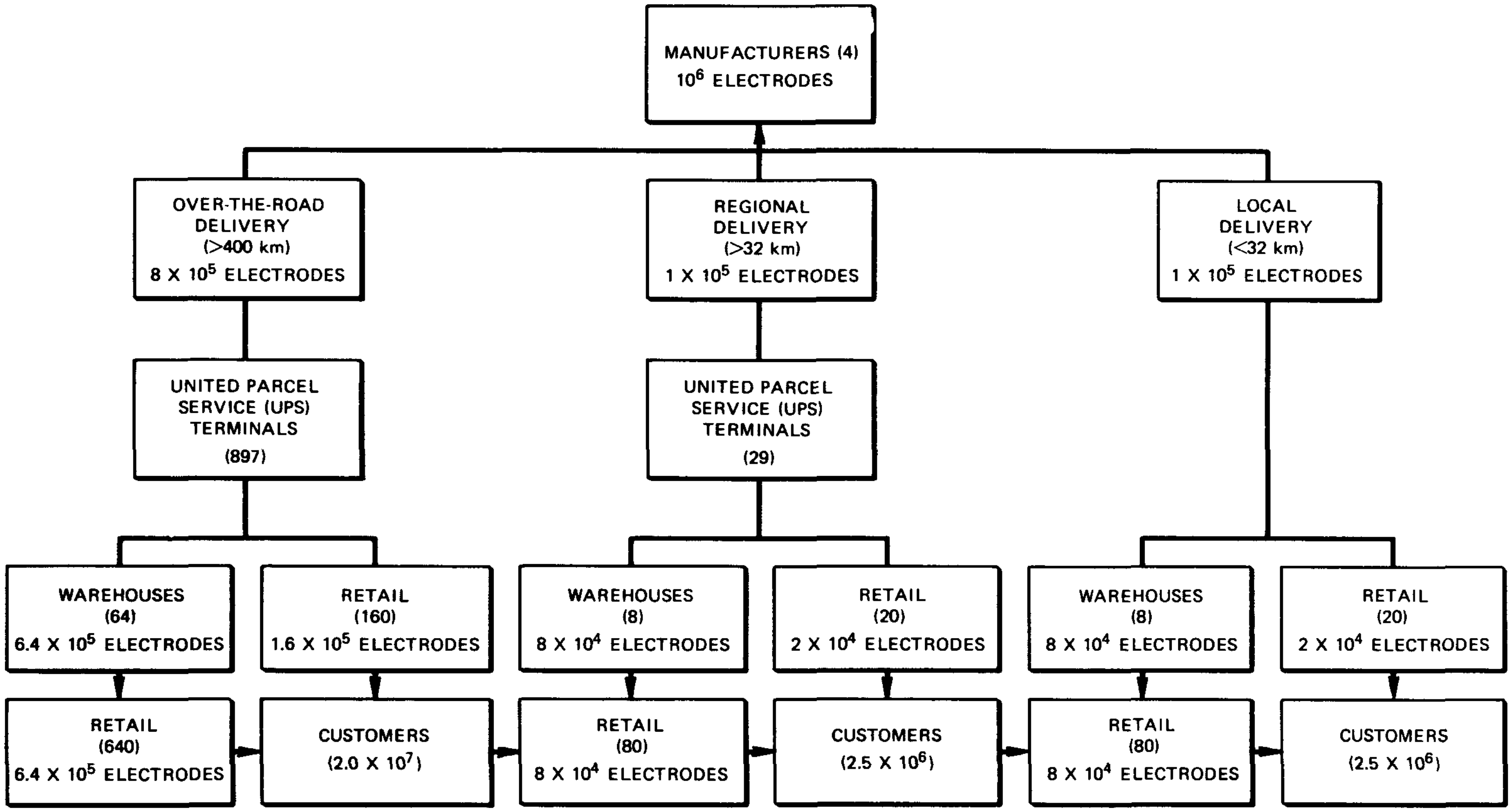

Fig. 1. Flow diagram for distribution of 10^6 thoriated welding electrodes (numbers in parentheses reflect the number of distribution units of given type assumed to be involved at each step).

groups of truck drivers may be exposed during driving, handling, and loading and unloading shipments. These include manufacturer's drivers, who transport cartons to retail outlets, warehouses, and UPS terminals; UPS drivers, who transport cartons between terminals and to final destinations including retail outlets and warehouses; and warehouse employees, who transport cartons to retail outlets. Exposure times and distances, shielding provided by the trucks, and volumes associated with the cargo compartments of the trucks were derived for truck drivers from information provided in the transport and distribution document mentioned earlier.[17] Air concentrations of thoron to which truck drivers may be exposed during driving or loading and unloading cargo were calculated with the CONDOS computer code assuming air changes in the specified cargo compartment volumes of three per hour during driving and one per hour during loading and unloading. Shielding against external radiation was assumed to be provided by the truck only during regional or over-the-road transport between UPS terminals. Additional shielding was assumed to be provided to all truck drivers by cardboard packaging material of thickness equal to 0.32 cm (1/8 in.) for shipments containing 500 rods, and equal to 0.95 cm (3/8 in.) for shipments containing 2000 rods. Two truck drivers from each manufacturer and from each warehouse were assumed to handle all deliveries from their respective origins, while a different UPS driver was involved in each shipment from the manufacturer.

In addition to truckdrivers, other UPS employees were considered as potentially exposed during distribution of one million thoriated electrodes.

These included receiving desk clerks, sorters, processors, loaders, and unloaders, whether actively involved with the processing of a shipment or near enough to the shipment to be exposed potentially through external or internal pathways. Exposure scenarios were designed for these individuals after consulting the transport and distribution document.[17] Shielding consisting of 0.32 cm (1/8 in.) of cardboard and one air change per hour in a terminal of volume equal to 1100 m^3 (40,000 ft^3) was assumed. The same employees were assumed to be exposed to shipments to any one destination during a year, but different warehouse or retail destinations were assumed to involve different UPS employees.

Employees of retail or warehouse outlets comprised two other groups of individuals potentially exposed to external or internal radiation as a result of the distribution of one million thoriated welding rods. To develop exposure scenarios for these groups, it was necessary to estimate the number of welding rods stored or displayed at any one time by each unit involved, given the previously assumed number shipped to each during the year. For each warehouse and retail unit, the number of rods stored or displayed at any one time was assumed to be equal to one-half of the total number of electrodes received during the year. For each warehouse, exposures were assumed to be received by each of five employees from both handling of each carton (100 rods per carton) for 5 min/year and storage of 50 cartons for 2000 hr/year. For each retail outlet, handling of each of 10 cartons for 5 min/year by each of five employees, and display of five cartons at any one time were assumed to result in external and internal radiation exposures.

The last group of individuals assumed exposed to radiation as a result of the distribution of one million thoriated welding rods were customers in retail outlets. Assuming each outlet received 100 customers per day for 250 days/year, there were a total of 2.5×10^7 customers to be considered. Of these 2.5×10^7, 10,000 were assumed to purchase, handle, and transport one carton of 100 rods each year. All customers, however, were assumed to be exposed to air concentrations of thoron and direct radiations from the rods for 0.5 hr/year at a distance of 610 cm (20 ft).

Following these general guidelines, individual and collective exposures and doses were calculated for the distribution stage of this assessment. Table 2.1 lists the estimated critical organ and whole-body doses for individuals and the populations comprising each exposed group. Estimated internal dose commitments ($<10^{-8}$ millirem) resulting from the assumed complete release of all thoron produced within the welding electrodes are not included in this table, since they were negligible with respect to doses received from external exposure to radiation emitted from the electrodes. The typical doses listed in Table 2.1 were calculated by averaging individual doses in each exposed group. Collective doses were calculated by summing these average individual doses within each group. A total collective dose of 0.79 man-rem to the bone, or 0.74 man-rem to the whole body, was estimated. This value represents the collective dose received by approximately 2.51×10^7 individuals in the general U.S. population. It was estimated that the maximally exposed individual may receive an annual bone dose of 0.22 millirem, as a result of external exposure to packaged rods during distribution from manufacturer

Table 2.1. Individual and collective doses to bone and whole body received during distribution of thoriated tungsten welding electrodes (per 10^6 electrodes distributed annually)

Population group	Maximum individual dose (millirem)		Typical individual dose (millirem)[a]		Collective dose (man-rem)	
	Bone[b]	Whole body	Bone[b]	Whole body	Bone[b]	Whole body
Truck drivers	2.2E-01[c]	2.0E-01	1.6E-03	1.5E-03	5.6E-03	5.2E-03
UPS terminal employees	1.6E-01	1.5E-01	2.0E-04	1.9E-04	1.1E-02	9.9E-03
Retail employees	6.4E-02	6.0E-02	6.4E-02	6.0E-02	3.2E-01	3.0E-01
Warehouse employees	1.7E-01	1.5E-01	1.7E-01	1.5E-01	6.6E-02	6.2E-02
Customers	4.9E-04	4.5E-04	1.5E-05	1.4E-05	3.8E-01	3.5E-01
TOTAL					7.9E-01	7.2E-01

[a]Typical values represent average dose received by all individuals in each group.

[b]Bone is critical organ for external exposure to thorium and daughters.

[c]2.2E-01 notation is equivalent to 2.2×10^{-1}.

to local retail outlets or UPS terminals for a total of 122 hr exposure during the year.

3. USE

Exposure to thorium and daughters may occur during use and preparation for use of thoriated welding electrodes through various modes. External exposure may occur during handling and storage of these electrodes in tool boxes. Persons exposed to external radiation include both welders and non-welders in the vicinity. Internal exposure may occur through inhalation of welding fumes containing thorium and daughters, and of thoriated particulates that may become airborne during grinding of the electrodes to form a tip. Persons internally exposed may again include both welders and non-welders.

3.1 Thorium Loss from Electrodes

Welding fumes may contain volatilized thorium and radioactive daughters as a result of the high temperatures acnieved at the tip of the electrode during arc welding.[1,3] Measurements of the amount of thoriated tungsten lost from electrodes during welding, presumably due to volatilization, have been reported in the literature.[1-3] However, only one study, by Breslin and Harris,[1] was undertaken to determine actual losses of thorium and daughters. While the other two studies[2,3] reportedly determined total material loss by gravimetric means, this first study involved measurement of losses through both gravimetric means and by air sampling procedures where the alpha activity contained within the fumes was extrapolated back to thorium and daughter activity lost. The average rate of thorium and daughter loss during welding, determined in this study by Breslin and Harris, was 6.0 mg/hr for a continuous welding period of 10 min. This loss rate includes that loss due to striking, or initiating, the arc to begin welding. This latter process is generally carried out by either touching the electrode to the work or imposing high-frequency arc stabilizers on the system to cause a spark to jump from the electrode to the work.[6,7] Losses of electrode material during this activity may exceed those encountered during the remainder of the welding process.[2,18] Therefore, the frequency of starting may influence the radionuclide loss rate for a specified amount of welding. For the purposes of this assessment, it was assumed that 10 min was a reasonable estimate of the average welding time per arc initiation, based on informal conversations with professional welders, and thus, that this value of 6.0 mg/hr might be an appropriate value to consider in estimating thorium loss during welding.

To estimate thorium loss rates from the other studies,[2,3] one must hypothesize that volatilization of thorium and daughters occurs at the same rate as tungsten volatilization during welding; a hypothesis not empirically substantiated at present, although suggested by data obtained by Breslin and Harris.[1] If this hypothesis is accepted, then the thorium and daughter loss is estimated to average about 0.8 mg/hr from these studies, by assuming 2% of the total loss rate given will be radionuclide loss and by normalizing the data to 10-min welding periods per arc initiation. This average loss rate indicates that the value of 6.0 mg/hr derived from the Breslin and Harris study could overestimate thorium losses from electrodes, and subsequently doses calculated, by an order of magnitude. The observed discrepancy is addressed by calculating a range of potential doses in this assessment.

Contaminated electrodes, or those which have been either oxidized or contaminated with the weld metal, were estimated to release thorium and daughters at 10 times the rates assumed for normal electrodes, based on measurements made by Breslin and Harris. Thus, loss rates between 8.0 and 60 mg/hr were estimated for contaminated electrodes in this assessment. It is believed that contaminated electrodes may unknowingly be used for welding, although infrequently, and it was assumed that this use occurred 10% of the time allocated to actual welding.

Airborne concentrations of thorium and daughters resulting from volatilization during welding will depend on the fraction of the material lost that may condense on metallic surfaces present or be included in the molten metal weld. Although the study by Breslin and Harris indicated that thorium and daughter loss to fumes approximated the total gravimetric loss of these nuclides, suggesting complete volatilization, Urbain[18] suggests that less than 20% of the total electrode material lost from tungsten electrodes is present in the fumes. Because further data regarding volatilization were not available, the doses calculated here reflect a range in assumed volatilization efficiencies between 20 and 100%, along with the range in assumed thorium loss rates.

Inhalation of thoriated particulates that may become airborne during tapering, or tip grinding, of electrodes is an additional means by which welders may be exposed to radionuclides present in these electrodes. The magnitude of exposure will depend on the amount of material lost by grinding and the portion of that material which becomes airborne. The amount of material lost from tapering electrodes of the size considered in this assessment may be estimated from literature concerning welding procedures,[7] which indicates that the taper ranges from three to six diameters in length, or from 0.71 cm to 1.4 cm in length for electrodes of diameters of 0.238 cm.

The portion of electrode material lost due to grinding that becomes airborne will depend on the resultant particle size distribution, with smaller particles being more readily suspended. Information is not available on this size distribution, but it was assumed for this assessment that 10% of the material lost during grinding becomes airborne.

3.2 Exposure Conditions

To assess radiation exposure and dose as a result of the use of one million thoriated welding electrodes annually in the United States, it again becomes necessary to postulate typical exposure conditions which may be encountered by several groups of individuals. Much of this was accomplished through informal discussions with persons actually involved in either the welding industry or an occupation which provides support to this industry through supply of materials. Again, parameter values used regarding exposure time, distance from source, shielding, and ventilation rates are provided in the appendix.

Exposure scenarios developed to account for the use of one million thoriated electrodes were based on the assumption that one-half of the arc-welder population could be considered occasional welders, welding for only one day a week, while one-half of the population consisted of arc-welders who devote the majority of their work time to the occupation, welding for five days a week, 50 weeks/year. The occasional users were assumed to use only one new electrode per week, while heavy users were assumed to use two new electrodes per week. It was also assumed that a few (50) heavy users may do some arc-welding in their homes for additional income, although the occurrence of this is probably rare due to high equipment costs. Because inert gas arc-welders may use a number of different welding materials in their profession, including thoriated-tungsten, pure tungsten, and carbon steel wire, additional assumptions regarding the fraction of time devoted to welding with thoriated-tungsten had to be made. Welders in each group of either heavy or occasional users were assumed to utilize typically thoriated-tungsten 50% of their welding time. Maximally exposed individuals, assumed to comprise only 10% of each group, were assumed to utilize thoriated-tungsten 100% of their welding time. Thus, using the above classifications and descriptions of welders, it was estimated that approximately 25,000 welders might be involved each year in the use of the assumed one million electrodes.

Persons in the vicinity of welders but not actually welding may be exposed to welding fumes or external radiation from the electrodes. The exposure scenarios developed for this assessment accounted for these non-welders by assuming that three individuals in addition to the welder were exposed to fumes and external radiation during welding processes.

Although gas tungsten-arc welding is adaptable to both manual and automatic operation,[7] it was assumed that all welding is done manually in this assessment. This assumption was made because the extent to which automatic procedures would shield welders from external exposure or inhalation of fumes could not be postulated on the basis of the literature reviewed.

To calculate doses received by welders and non-welders during the use of thoriated welding electrodes, several assumptions had to be made regarding the time of exposure, source distance, shielding provided, effective ventilation, and diffusion characteristics of the welding fumes and particulates generated. Values of the first three parameters (time, distance, and shielding) were estimated for heavy and occasional users, as well as non-welders, based on contacts made with occupational welders concerning daily activities. The appendix to this report provides the values assigned to these parameters for the population groups considered. Briefly, exposure times were estimated by assuming that all users were actually welding 4 hr/day for every day of on-the-job welding (5 days/week for heavy users; 1 day/week for occasional users), and that heavy users doing welding at home were engaged for 4 hr/week. The average distances from the electrodes during welding, grinding, and other non-welding activities while on the job or welding at home were assumed to be 30 cm, 30 cm, and 90 cm, respectively, for all welders, and 360 cm for all activities for nearby non-welders. Shielding for external radiation was considered to be provided by either polyethylene electrode holders, air, or the iron sides of tool boxes in which electrodes may be stored. Shielding provided by welder's helmets which are assumed to be worn at all times during welding was estimated to reduce fume concentrations inside the helmet by a factor of 3, based on measurements made for Fe_2O_3 fumes.[19]

Ventilation rates and diffusion characteristics of the fumes generated during welding will affect the airborne concentration of thorium and daughters to which welders and non-welders may be exposed. The replacement of contaminated air with clean air due to ventilation and the diffusion of contaminated air away from the welder are both processes which will serve to reduce a welder's exposure to fumes. Plating-out of airborne thorium which is diffusing away from the welder will tend to decrease the non-welders exposure. Unfortunately, the rates at which these processes are occurring are not known for all types of welding situations. Therefore, for this assessment, air concentrations to which welders may be exposed were estimated by assuming that equilibrium concentrations of thorium and daughters existed in the breathing zone of the welder during welding. For non-welders, at an average distance of 360 cm, it was assumed that only 20% of the equilibrium concentration remained airborne for their exposure. These equilibrium concentrations were calculated by dividing the thorium release rates discussed earlier by an assumed ventilation rate for each workplace (i.e., the welding shop or the home). Ventilation rates in welding shops were assumed to conform to the standard provided by the American National Standards Institute (ANSI), Standards Committee Z49 (ref. 20), specifying a rate of 57 m^3/min (2000 cfm) in a welder's workplace. This ventilation rate was assumed to apply to the entire workshop, such that non-welders were also allowed a rate of 57 m^3/min. Because ventilation requirements for welding would not be enforced in the home, and it is conceivable that welding done at home may take place in an enclosed portion of the dwelling, such as a basement or workshop, ventilation rates typical of an average dwelling were assumed. A rate of 2.3×10^8 cm^3/hr was used, which corresponds to a 1000 ft^2 area (8-ft ceiling) with one air change per hour.[21] Non-welders near a welder at home were not considered in this assessment.

It is not clear whether this type of equilibrium estimate will lead to over- or underestimates of exposure, since it may be argued that the actual dynamics of diffusion may either increase or decrease concentrations of fumes in the welders breathing zone. A study conducted by Breslin and Harris,[1] where radioactive dust was sampled during welding with thoriated electrodes, with filter samples taken both in the breathing zone of welders and within a six-inch radius of the welding arc, showed no detectable alpha activity in the breathing zone, but up to 210 dpm ThO_2 per cubic meter (or approximately 0.2 mg of ThO_2 per cubic meter, assuming 1000 dpm = 1 mg in the vicinity of the arc). The detection limits of the scintillation counting done in this study were never less than 0.9 dpm/m^3 (or approximately 9×10^{-4} mg of ThO_2 per cubic meter), however, and sometimes were as high as 33 dpm/m^3 (or approximately 3.3×10^{-2} mg of ThO_2 per cubic meter), and therefore, air concentrations of the magnitude estimated in this assessment (1.75×10^{-3} mg of ThO_2 per cubic meter) may not have been detectable. Thus, the results of the Breslin and Harris study do not preclude the possibility that the air concentrations estimated for this assessment exist in the breathing zone of the welder, but do indicate that a concentration gradient exists, with higher concentrations being present near the arc than in the welders breathing zone. It might be expected, therefore, that concentrations of thorium and daughters to which welders or non-welders are exposed are overestimated in this assessment, but the magnitude of this error is not known, especially in light of the uncertainty associated with the actual ventilation rate which is provided during welding.

3.3 Estimated Doses

Doses for individuals and exposed populations, including both welders and non-welders, were estimated based on assumptions outlined in Sects. 3.1 and 3.2 for the use of one million thoriated electrodes in one year. Due the uncertainties inherent in these estimations with respect to the thorium loss rate and the percentage of material lost that becomes airborne (see Sect. 3.1), internal dose ranges were calculated and are presented in Tables 3.1 and 3.2. Lower doses are based on an assumption of a thorium loss rate of 0.8 mg/hr and a 20% volatilization of material lost. Upper range values for dose are based on a thorium loss rate of 6.0 mg/hr and 100% volatilization.

Individuals considered maximally exposed in each of the groups identified, including both heavy and occasional users and non-welders, were determined as follows. For heavy users, an individual who welds 4 hr/day, 250 days/year, in a welding shop and additionally welds 4 hr/week, 50 weeks/year, in his home using thoriated tungsten at all times was considered the maximally exposed individual. The maximally exposed occasional user was assumed to weld 4 hr/day, 50 days/year, in a welding shop using thoriated tungsten electrodes. For non-welders, the maximally exposed individual was assumed to be in the vicinity of a heavy user for 4 hr/day, 250 days/year, during welding with thoriated tungsten. Typical dose commitments or doses given in Tables 3.1 and 3.2 represent the

Table 3.1. Individual and collective doses and dose ranges for bone received during use of thoriated-tungsten welding electrodes (per 10^6 electrodes used annually)

Population group	Maximum individual dose (millirem)		Typical individual dose (millirem)[a]		Collective dose (man-rem)	
	Internal[b]	External	Internal[b]	External	Internal[b]	External
Welders-heavy users	8.0–3.0E+02[c]	1.6E-01	4.4–1.6E+02	9.0E-02	5.3E+01–2.0E+03	1.1
-with home welding	2.0E+01–1.0E+03	1.8E-01			*d*	*d*
Welders–occasional users	1.6–6.0E+01	9.1E-03	8.8E-01–3.3E+01	5.0E-03	1.1E+01–4.1E+02	6.3E-02
Non-welders	2.0E+01–1.5E+02	2.6E-03	6.7–5.0E+01	8.7E-04	5.1E+02–3.8E+03	6.6E-02
TOTAL					5.7E+02–6.2E+03	1.2

[a] Typical values represent average dose received by all individuals in each group.

[b] Value given represents 50-year bone dose commitment.

[c] 3.0E+02 notation is equivalent to 3.0×10^{-2}.

[d] Welding at home contributes insignificantly to collective dose.

Table 3.2. Individual and collective doses and dose ranges for whole body received during use of thoriated-tungsten welding electrodes (per 10^6 electrodes used annually)

Population group	Maximum individual dose (millirem)		Typical individual dose (millirem)[a]		Collective dose (man-rem)	
	Internal[b]	External	Internal[b]	External	Internal[b]	External
Welders-heavy users	6.8E-01[c]–2.5E+01	1.5E-01	3.7E-01–1.4E+01	8.4E-02	4.8–1.8E+02	1.1
-with home welding	2.4–8.8E+01	1.7E-01			*d*	*d*
Welders-occasional users	1.3E-01–5.0	8.4E-03	7.2E-02–2.7	4.6E-03	9.1E-01–3.4E+01	5.8E-02
Non-welders	1.3–1.0E+01	2.4E-03	5.6E-01–4.2	8.0E-04	4.2E+01–3.2E+02	6.1E-02
TOTAL					4.8E+01–5.3E+02	1.2

[a]Typical values represent average dose received by all individuals in each group.

[b]Value given represents 50-year whole-body dose commitment.

[c]6.8E-01 notation is equivalent to 6.8 x 10^{-1}.

[d]Welding at home contributes insignificantly to collective dose.

average individual doses estimated for each group. Individual doses were based on the previously discussed assumption that 90% of the welder populations were using thoriated tungsten only 50% of the time and that the remaining 10% used thoriated tungsten 100% of the time. Typical doses for non-welders were adjusted to this latter assumption. Home welding was not accounted for in typical doses as it is believed to be very rare. Group doses and the total collective doses given in Tables 3.1 and 3.2 were calculated by summing individual doses estimated in each group. The maximum individual bone dose commitment for welders was estimated to range between 2.0×10^1 and 1.0×10^3 millirem (1 rem) for a one-year exposure. For welders not engaged in welding at home, and for occasional welders, maximum dose ranges were estimated to be 8.0 to 300 and 1.6 to 60 millirem, respectively. It should be emphasized that these values represents the 50-year dose commitment, and do not imply that the total doses are received during the year of exposure. Likewise, a maximum individual bone dose commitment range between 20 and 150 millirem was estimated for non-welders. The estimated maximum values for non-welders approached those for welders because exposures of non-welders were not reduced by the use of welders' helmets. External doses for all groups were estimated to be less than one millirem. All of these internal dose ranges for welders may be overestimated if diffusion of fumes from the welding arc is slow, so as to reduce the air concentration in the breathing zone, or if mechanical ventilation is applied near the arc.

A potential collective dose commitment ranging between 5.7×10^2 and 6.2×10^3 man-rem to the bone per year of exposure to one million electrodes was estimated. Both internal and external bone doses are included in this range. Collective whole-body dose commitments were calculated to range between 4.8×10^1 to 5.3×10^2 man-rem. These ranges represent the collective dose commitment received by an assumed 1.0×10^5 individuals involved directly or indirectly in the use of one million thoriated welding electrodes each year.

4. DISPOSAL

Radiation exposures and doses may result from various methods commonly employed to dispose of nonregulated consumer products containing radioactive materials, such as thoriated welding electrodes. In order to assess the potential doses received by members of the general U.S. population from such disposal, it is necessary to consider the implications of each disposal method employed on dispersal of discarded radioactive material, as well as the number of individuals potentially exposed to the radioactive material.

For this assessment of thoriated electrodes, two methods of disposal were considered probable means by which one million electrodes may be disposed of each year. These methods were selected on the basis of a documented review of industrial solid waste disposal practices in the United States.[22] This review indicated that ultimate disposal of over 80% of industrial solid waste occurred via incineration or transport to dumping grounds, and that these two methods were utilized with an approximately equal probability. Thus, for this assessment, it was assumed that 50% of the discarded electrodes (5×10^5) are disposed of by incineration, while the remaining 50% are transported to dumps.

Salvage or recycle of used electrodes was considered negligible in light of the difficulty in remelting tungsten (melting point = 3400°C), and thus, the economic disadvantage to salvaging the scrap.

Radiological exposure to thorium and daughters as a result of disposal of thoriated electrodes may occur as a result of volatilization of the radionuclides during incineration, or release of thoron from dumping areas receiving used electrodes. Direct external exposure to radiations from discarded electrodes will probably be insignificant since the maximum energy of gamma or bremsstrahlung radiation produced in the decay chain is 2.26 MeV, with an average energy much lower. Even at this higher energy, one could expect the radiation intensity to be decreased to less than 10% of the original intensity at a distance of 500 m (approximately 1/3 mile), assuming that air is the sole attenuating medium, an unlikely occurrence in an actively used solid waste disposal area. In addition, it is not expected that an individual would remain at a distance less than 500 m from a designated dumping area for a sufficient length of time to receive significant exposure or dose.

Volatilization of thorium and daughters may occur during incineration to an extent dependent on the temperatures to which the thoriated electrodes are exposed, the length of the exposure period, the evaporation rate of the compounds present, and the chemical conversion processes catalyzed by the heat. Furthermore, because the radionuclides contained in the tungsten electrodes are present in concentrations much smaller than that of tungsten atoms, the degree of volatilization of tungsten compounds may greatly influence the release of these nuclides from the electrodes. For this assessment, it is assumed that complete volatilization of tungsten, and all radionuclides present, occurs during incineration. This assumption was based on documented information concerning the rate of oxidation of tungsten and subsequent evaporation of the tungsten oxide which is produced,[23] indicating that, at maximum temperatures achieved during incineration (1316–1649°C),[24] complete volatilization may occur. This assumption of complete volatilization represents the upper limit of what may occur during incineration, and it is realized that the thoriated tungsten may not reach these maximum temperatures for a sufficient length of time, and that the various compounds formed which contain the radionuclides may not be as readily volatile at these temperatures.

The release of thoron from dumping areas was estimated in a manner identical to that described in Sect. 2 of this report. That is, it was assumed that all thoron produced in the rods being disposed of by dumping during a year is released to the atmosphere from each dumping area. Again, it is believed that this will represent an upper limit of the aerosol source strength, since gas diffusion rates in compact materials such as electrodes will likely decrease the ultimate emanation of thoron. Instead, the thorium daughters would probably buildup in the soil, to be buried at the time of disposal area decommissioning.

The source strength, or total radioactivity released from each disposal site, was finally estimated by making assumptions regarding the amount of thoriated tungsten annually disposed of at each site. It was assumed that disposal sites, or 100 incinerators plus 100 dumping areas, across the country each received 5000 discarded electrodes per year for this assessment, such that one million electrodes are accounted for. The amount of thorium and daughters contained in 5000 rods was estimated by subtracting the total amount assumed lost during welding (see Sect. 3) from the amount originally present following manufacture.

Diffusion of airborne radionuclides and their deposition on soil and vegetation were estimated through implementation of a recently developed computer code, AIRDOS-EPA,[25] using annual average meteorological data obtained from 18 stations across the United States. Both ingestion and inhalation pathways are considered in this code, such that doses from thorium and daughters released from disposal sites may be estimated from exposures to contaminated air and food.

The population distribution assumed to exist around each disposal site in this assessment was identical to that developed for an assessment of population dose received from the Liquid Metal Fast Breeder Reactor Program.[26] The total collective dose calculated was also based on the assumption that for each of the 200 disposal areas, 0.5% of the total U.S. population (or approximately one million individuals) was residing within the 72-km (45-mile) radius encompassed by the AIRDOS-EPA model considerations. This implies, then, that each individual in the United States is assumed to be exposed to airborne and deposited radionuclides from one type of disposal site considered in this assessment. It is believed that this latter assumption will lead to further overestimation of the collective dose due to disposal, since it is unlikely that the entire population will reside within 72 km of a site at which 5000 thoriated electrodes are disposed of each year. However, it was not deemed necessary to pursue the development of more realistic scenarios in light of the negligible doses (<1 millirem) calculated for this pathway.

The collective doses calculated for an estimated U.S. population of 218 million were as follows. Due to disposal in dumping areas and subsequent thoron releases, the dose from inhalation of thoron and daughters was estimated to be 2.6 man-rem to the lung (5.2×10^{-2} man-rem to whole body), and from ingestion of contaminated foodstuffs, was estimated to be 1.9×10^{-4} man-rem per year to the bone (1.4×10^{-5} man-rem to whole body). Due to incineration, the dose from inhalation of all volatilized thorium and daughters was estimated to be 3.3×10^{1} man-rem to the bone (1.0 man-rem to whole body), and from ingestion of contaminated foodstuff, was estimated to be 1.9×10^{2} man-rem to the bone (7.1 man-rem to whole body). Doses to bone or lung are critical organ doses.

Maximally exposed individuals were assumed, in this assessment, to remain at a distance of 1000 m from each disposal site for an entire year. Ingestion doses were estimated assuming that the individual's diet consisted of only locally produced foodstuffs. The inhalation dose for the maximally exposed individual at 1000 m from a dumping area was thus calculated to be 1.7×10^{-2} millirem to the lung (3.4×10^{-4} millirem to whole body), and the ingestion dose was estimated to be 9.4×10^{-7} millirem to the bone (6.4×10^{-8} millirem to whole body) due to thoron and daughters. For the maximally exposed individual at 1000 m from an incinerator, the dose commitments were calculated to be 2.8×10^{-2} millirem to the bone (8.8×10^{-4} millirem to whole body) for inhalation, and 1.6×10^{-1} millirem to the bone (6.0×10^{-3} millirem to whole body) for ingestion.

Conservative values were generally chosen to estimate doses potentially received as a result of disposal of one million thoriated electrodes annually, and thus, the values given here probably overestimate the actual doses. Nevertheless, it has been estimated that an individual could conceivably receive a 50-year dose commitment as high as 1.9×10^{-1} millirem to the bone as a result of disposal of one million electrodes during one year, and that the total collective dose may be approximately 3.3×10^{1} man-rem (to the bone) due to inhalation and 1.9×10^{2} man-rem (to the bone) due to ingestion of contaminated foodstuffs. Corresponding collective whole-body dose commitments of 1.0 man-rem due to inhalation and 7.1 man-rem due to ingestion were also calculated.

5. DOSES UNDER ABNORMAL CIRCUMSTANCES

It is conceivable that inhalation exposure to thorium and daughters may occur as a result of volatilization of the radionuclides during a warehouse, workshop, or home fire. Individuals might include those remaining in an unaffected area of the structure prior to evacuation, or those in the vicinity of the structure as smoke and fumes are released. The extent of volatilization will depend on the temperatures achieved in such fires, as well as the time through which the various temperatures are maintained.

Because the number of electrodes present in any one warehouse, welding shop, or home is not expected to exceed 5000, which is equal to the number assumed to be incinerated at a disposal site, it can be postulated that maximum exposed individual and collective doses for those outside, but in the vicinity, of a burning structure would be approximately equal to those calculated in Sect. 4 of this report. That is, one would not expect individual bone dose commitments to exceed 1.6×10^{-1} millirem, nor collective dose commitments to exceed 1.9 man-rem for any one warehouse, assuming complete volatilization of thorium and daughters. This latter assumption of complete volatilization, however, is probably overestimating what would actually occur since it would not be expected that the temperatures of fires in a warehouse would approach those attained in incinerators (1650°C).

If a small fire occurred near the electrodes, such that individuals might remain in an unaffected portion of the warehouse for a period of time before evacuation, potential doses received from volatilized radionuclides would be highly variable depending on the temperatures reached near electrodes, and the turbulence caused by the fire within the warehouse. Because the melting points of many of the nuclides in the thorium chain are high enough to preclude complete volatilization at temperatures initially obtained in a small fire, and because evacuation of a warehouse would probably occur before significant volatilization of these nuclides could occur, it is believed that doses to individuals present in a warehouse during the beginning of a fire would not be significant.

An additional circumstance of exposure that would not be expected to be a normal occurrence is the practice of carrying extra electrodes in a pocket of a workshirt. In doing so, the direct exposure of welders to the radioactive materials contained in the electrodes may be enhanced over exposures resulting from storage of extra electrodes in the welder's toolbox. It is doubtful that this practice would be engaged in normally since sharpened electrodes would readily tear holes in the cloth of the pocket, and unsharpened electrodes, from 7.62 to 60.96 cm in length (3 to 24 inches) would likely be a nuisance when carried in the pocket. Nevertheless, the external dose to an individual carrying three 15.24 cm long electrodes in a chest pocket for 8 hr/day, 250 days/year, was estimated to be 3.5 millirem to the maximally exposed point on the skin. This estimate neglects shielding provided by cloth under the pocket, but accounts for self-absorption provided by the tungsten in the electrode.

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APPENDIX

Table A.1 Tabular listing of exposure parameters used in the dose calculations

***** DEFINITIONS AND DIMENSIONS OF VARIABLE NAMES *****

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DESCRIPTORS ARE GIVEN FOR:
   THE RECYCLING PROCEDURE (IN THE TABLE TITLES)
   THE EXPOSED GROUP OF PERSONS - BY JOB TITLE (AS CENTERED HEADINGS)
   THE STEPS PERFORMED BY THE GROUP MEMBERS IN CARRYING OUT THE PROCEDURE (LEFT-HAND ENTRIES WITH NO ASSOCIATED PARAMETERS), AND
   THE EXPOSURE ACTIONS INVOLVED IN CARRYING OUT EACH STEP BY THE INDICATED GROUP OF PERSONS.
NM     = NUMBER OF PERSONS IN A GROUP
EVPROB = PROBABILITY THAT ALL GROUP MEMBERS WILL BE INVOLVED IN THE EXPOSURE EVENT
R      = EFFECTIVE RADIUS (CM) OF THE CONTAMINATED AIR VOLUME
CONC   = CONCENTRATION (G/CU CM) OF SOURCE MATERIAL IN THE CONTAMINATED AIR SPACE
TINH   = DURATION (HR/YEAR) OF BREATHING CONTAMINATED AIR
TIMM   = DURATION (HR/YEAR) IN CONTAMINATED AIR
AMT    = QUANTITY (G/YEAR) OF SOURCE MATERIAL INGESTED
TDIR   = DURATION (HR/YEAR) OF EXPOSURE TO EXTERNAL SOURCE
SI     = SOURCE GEOMETRY INDEX NUMBER, AS FOLLOWS:
          SI   SOURCE GEOMETRY
          --   ----------------------
           1   POINT SOURCE W/ OR W/O EXTERNAL SHIELDING
           2   LINE SOURCE (ON PERPENDICULAR BISECTOR) W/ OR W/O EXTERNAL SHIELDING
           3   DISK SOURCE (ON AXIS) W/ OR W/O EXTERNAL SHIELDING
           4   CYLINDRICAL SURFACE SOURCE (ON PERPENDICULAR BISECTOR OF AXIS) W/O EXTERNAL SHIELDING
           5   SEMI-INFINITE, HOMOGENIOUS VOLUME SOURCE W/ OR W/O EXTERNAL SHIELDING
           6   INFINITE, HOMOGENIOUS SLAB SOURCE W/ OR W/O EXTERNAL SHIELDING
           7   CYLINDRICAL, HOMOGENIOUS VOLUME SOURCE (NON-ABSORBING, ON AXIS) W/O EXTERNAL SHIELDING
           8   CYLINDRICAL, HOMOGENIOUS VOLUME SOURCE (SELF-ABSORBING, ON PERPENDICULAR BISECTOR OF AXIS) W/ OR W/O EXTERNAL SHIELD
           9   SPHERICAL, HOMOGENIOUS VOLUME SOURCE (NON-ABSORBING) W/O EXTERNAL SHIELDING
          10   SPHERICAL, HOMOGENIOUS VOLUME SOURCE (SELF-ABSORBING) W/ OR W/O EXTERNAL SHIELDING
          11   CYLINDRICAL, HOMOGENIOUS VOLUME SOURCE (SELF-ABSORBING, ON AXIS) W/ OR W/O EXTERNAL SHIELDING
SM     = SOURCE MATERIAL INDEX NUMBER, AS FOLLOWS:
           0 = YOU HAVE NAMED YOUR OWN      7 = WATER
           1 = ALUMINUM                     8 = CONCRETE
           2 = IRON                         9 = LUCITE
           3 = COPPER                      10 = POLYETHELENE
           4 = TUNGSTEN                    11 = GLASS (PYREX)
           5 = LEAD                        12 = WOOD (CELLULOSE)
           6 = URANIUM                     13 = AIR
SDEN   = DENSITY (G/CU CM) OF THE SOURCE MATERIAL
Z      = ATOMIC NUMBER OF SOURCE MATERIAL
QUAN   = TOTAL WEIGHT (G) OF SOURCE MATERIAL IN A POINT SOURCE
       = WEIGHT/LENGTH (G/CM) IN A LINE SOURCE
       = WEIGHT/AREA (G/SQ CM) IN A SURFACE SOURCE
       = WEIGHT/VOLUME (G/CU CM) IN A VOLUME SOURCE
HGHT   = LENGTH OR HEIGHT (CM) OF THE SOURCE
RAD    = RADIUS (CM) OF THE SOURCE
DIST   = DISTANCE (CM) BETWEEN CENTROID OF SOURCE AND EXPOSED PERSON
AM     = ABSORBER MATERIAL INDEX (SEE SM)
ADEN   = DENSITY (G/CU CM) OF ABSORBING MATERIAL
TA     = THICKNESS (CM) OF ABSORBING MATERIAL
```

Table A.2 Exposure parameters for distribution

STEP * EXPOSURE ACTION	(NN) *EVPROB	R	CONC	TINH	TIMM	AMT	TDIR	SI	SM	SDEN	Z	QUAN	HGHT	RAD	DIST	AM	ADEN	TA
							TRUCK TRANSPORT											
LOCAL DRIVERS	(8.00E 00)																	
*DRIVE-5	*1.0E 00	120	2.5E-20	2.5E 01	0.0	0.0	2.5E 01	11	4	19.3	74	3.4E-01	15.2	2.7	181	12	0.7	0.3
*HANDLE-5	*1.0E 00	120	0.0	0.0	0.0	0.0	4.5E 00	11	4	19.3	74	3.4E-01	15.2	1.2	31	12	0.7	0.3
*L/UL-5	*1.0E 00	120	7.5E-20	2.6E 01	0.0	0.0	2.6E 01	11	4	19.3	74	3.4E-01	15.2	2.7	91	12	0.7	0.3
*DRIVE-20	*1.0E 00	120	9.8E-20	2.5E 01	0.0	0.0	2.5E 01	11	4	19.3	74	3.4E-01	76.2	2.4	181	12	0.7	0.9
*HANDLE-20	*1.0E 00	120	0.0	0.0	0.0	0.0	1.7E 01	11	4	19.3	74	3.4E-01	15.2	1.2	31	12	0.7	0.3
*L/UL-20	*1.0E 00	120	3.0E-19	2.6E 01	0.0	0.0	2.6E 01	11	4	19.3	74	3.4E-01	76.2	2.4	91	12	0.7	0.9
WAREHOUSE DRIVERS	(1.60E 02)																	
*TO RETAIL	*1.0E 00	120	2.5E-20	5.0E 00	0.0	0.0	5.0E 00	11	4	19.3	74	3.4E-01	15.2	2.7	181	12	0.7	0.3
*HANDLE	*1.0E 00	120	0.0	0.0	0.0	0.0	8.5E-01	11	4	19.3	74	3.4E-01	15.2	1.2	31	12	0.7	0.3
*L/UL	*1.0E 00	120	7.5E-20	5.1E 00	0.0	0.0	5.1E 00	11	4	19.3	74	3.4E-01	15.2	2.7	91	12	0.7	0.3
UPS REGIONAL-5	(4.00E 01)																	
*DRIVE-5	*1.0E 00	250	0.0	0.0	0.0	0.0	5.0E 00	11	4	19.3	74	3.4E-01	15.2	2.7	826	1	2.7	0.4
*	*															12	0.7	0.3
UPS REGIONAL-20	(4.00E 01)																	
*DRIVE-20	*1.0E 00	250	0.0	0.0	0.0	0.0	5.0E 00	11	4	19.3	74	3.4E-01	76.2	2.4	826	1	2.7	0.4
*	*															12	0.7	0.9
UPS-LOCAL RETAIL	(3.60E 02)																	
*DRIVE-5	*1.0E 00	180	8.2E-23	7.5E-01	0.0	0.0	7.5E-01	11	4	19.3	74	3.4E-01	15.2	2.7	336	12	0.7	0.3
*HANDLE-5	*1.0E 00	180	0.0	0.0	0.0	0.0	1.7E-01	11	4	19.3	74	3.4E-01	15.2	1.2	31	12	0.7	0.3
*L/UL-5	*1.0E 00	180	2.5E-20	2.5E-01	0.0	0.0	2.5E-01	11	4	19.3	74	3.4E-01	15.2	2.7	91	12	0.7	0.3
UPS-LOCAL WHSE	(3.60E 02)																	
*DRIVE-20	*1.0E 00	180	3.3E-22	7.5E-01	0.0	0.0	7.5E-01	11	4	19.3	74	3.4E-01	76.2	2.4	336	12	0.7	0.9
*HANDLE-20	*1.0E 00	180	0.0	0.0	0.0	0.0	6.6E-01	11	4	19.3	74	3.4E-01	15.2	1.2	31	12	0.7	0.3
*L/UL-20	*1.0E 00	180	0.0	2.5E-01	0.0	0.0	2.5E-01	11	4	19.3	74	3.4E-01	76.2	2.4	91	12	0.7	0.9
UPS OTR-5	(1.28E 03)																	
*DRIVE-5	*1.0E 00	250	0.0	0.0	0.0	0.0	5.0E 00	11	4	19.3	74	3.4E-01	15.2	2.7	826	1	2.7	0.4
*	*															12	0.7	0.5
UPS OTR-20	(1.28E 03)																	
*DRIVE-20	*1.0E 00	250	0.0	0.0	0.0	0.0	5.0E 00	11	4	19.3	74	3.4E-01	76.2	2.4	826	1	2.7	0.4
*	*															12	0.7	0.9
							UPS EMPLOYEES											
DESK CLERKS-REG	(4.00E 00)																	
*HANDLE	*1.0E 00	600	0.0	0.0	0.0	0.0	2.0E 00	11	4	19.3	74	3.4E-01	15.2	1.2	31	12	0.7	0.3
*DIRECT-5	*1.0E 00	600	5.6E-22	1.0E 01	0.0	0.0	1.0E 01	11	4	19.3	74	3.4E-01	15.2	2.7	151	12	0.7	0.3
*DIRECT-20	*1.0E 00	600	2.2E-21	1.0E 01	0.0	0.0	1.0E 01	11	4	19.3	74	3.4E-01	76.2	2.4	151	12	0.7	0.9
DESK CLERKS-OTR	(4.00E 00)																	
*HANDLE	*1.0E 00	600	0.0	0.0	0.0	0.0	1.6E 01	11	4	19.3	74	3.4E-01	15.2	1.2	31	12	0.7	0.3
*DIRECT-5	*1.0E 00	600	5.6E-22	8.0E 01	0.0	0.0	8.0E 01	11	4	19.3	74	3.4E-01	15.2	2.7	151	12	0.7	0.3
*DIRECT-20	*1.0E 00	600	2.2E-21	8.0E 01	0.0	0.0	8.0E 01	11	4	19.3	74	3.4E-01	76.2	2.4	151	12	0.7	0.9
SORT/PROCESS	(6.56E 03)																	
*HANDLE	*1.0E 00	600	0.0	0.0	0.0	0.0	2.5E-02	11	4	19.3	74	3.4E-01	15.2	1.2	91	12	0.7	0.3
LOADERS	(5.88E 03)																	
*HANDLE	*1.0E 00	600	0.0	0.0	0.0	0.0	3.3E-02	11	4	19.3	74	3.4E-01	15.2	1.2	31	12	0.7	0.3
OTHER EMP-LOCAL	(1.76E 02)																	
*NEAR-5	*1.0E 00	600	5.6E-22	1.1E 02	0.0	0.0	1.1E 02	11	4	19.3	74	3.4E-01	15.2	2.7	611	12	0.7	0.3
*NEAR-20	*1.0E 00	600	2.2E-21	1.1E 02	0.0	0.0	1.1E 02	11	4	19.3	74	3.4E-01	15.2	2.4	611	12	0.7	0.3
OTHER EMP-REG RETAIL	(8.80E 02)																	
*NEAR-5	*1.0E 00	600	5.6E-22	2.5E 00	0.0	0.0	2.5E 00	11	4	19.3	74	3.4E-01	15.2	2.7	611	12	0.7	0.3
OTHER EMP-REG WHSE	(3.52E 02)																	
*NEAR-20	*1.0E 00	600	2.2E-21	6.3E 00	0.0	0.0	6.3E 00	11	4	19.3	74	3.4E-01	76.2	2.4	611	12	0.7	0.3
OTHER EMP-OTR RETAIL	(2.82E 04)																	
*NEAR-5	*1.0E 00	600	5.6E-22	2.5E 00	0.0	0.0	2.5E 00	11	4	19.3	74	3.4E-01	15.2	2.7	611	12	0.7	0.3
OTHER EMP-OTR WHSE	(1.13E 04)																	
*NEAR-20	*1.0E 00	600	2.2E-21	6.3E 00	0.0	0.0	6.3E 00	11	4	19.3	74	3.4E-01	76.2	2.4	611	12	0.7	0.3
							STORAGE/DISPLAY											
RETAIL EMPLOYEE	(5.00E 03)																	
*HANDLE	*1.0E 00	380	0.0	0.0	0.0	0.0	8.3E-01	11	4	19.3	74	3.4E-01	15.2	1.2	31	12	0.7	0.3
*DISPLAY	*1.0E 00	380	2.2E-21	2.0E 03	0.0	0.0	2.0E 03	11	4	19.3	74	3.4E-01	15.2	2.7	611	12	0.7	0.3
WHSE EMPLOYEE	(4.00E 02)																	
*HANDLE	*1.0E 00	600	0.0	0.0	0.0	0.0	8.3E 00	11	4	19.3	74	3.4E-01	15.2	1.2	31	12	0.7	0.3
*STORAGE	*1.0E 00	600	5.6E-21	2.0E 03	0.0	0.0	2.0E 03	11	4	19.3	74	3.4E-01	76.2	3.8	611	12	0.7	0.9
CUSTOMERS	(2.50E 07)																	
*HANDLE	*4.0E-04	380	0.0	0.0	0.0	0.0	8.3E-02	11	4	19.3	74	3.4E-01	15.2	1.2	31	12	0.7	0.3
*DISPLAY	*1.0E 00	380	2.2E-21	5.0E-01	0.0	0.0	5.0E-01	11	4	19.3	74	3.4E-01	15.2	2.7	611	12	0.7	0.3
*DRIVING	*4.0E-04	80	1.1E-22	5.0E-01	0.0	0.0	5.0E-01	11	4	19.3	74	3.4E-01	15.2	1.2	91	12	0.7	0.3

Table A.3 Exposure parameters for use

STEP * EXPOSURE ACTION	(NM) *EVPROB	R	CONC	TINH	TIMM	AMT	TDIP	SI	SM	SDEN	Z	QUAN	HGHT	RAD	DIST	AM	ADEN	TA
					SHOP WELDING													
HEAVY USERS	(1.26E 04)																	
*WELDING	*9.0E-01	900	1.8E-12	1.0E 03	1.0E 03	0.0	1.0E 03	11	4	19.3	7	3.4E-01	15.2	0.1	31	10	0.9	0.3
*GRINDING	*1.0E 00	900	4.6E-10	4.2E 00	4.2E 00	0.0	2.5E 01	11	4	19.3	7	3.4E-01	15.2	0.1	31	13	0.0	30.0
*TOOL BOX-DIRECT	*1.0E 00	900	0.0	0.0	0.0	0.0	2.0E 03	11	4	19.3	7	1.4E 00	15.2	0.3	91	2	7.9	0.2
*ROD OXIDIZED	*1.0E-01	900	1.8E-11	1.0E 03	1.0E 03	0.0	1.0E 03	11	4	19.3	7	3.4E-01	15.2	0.1	31	10	0.9	0.3
*HOME WELDING	*3.6E-03	900	2.6E-11	2.0E 02	2.0E 02	0.0	2.0E 02	11	4	19.3	7	3.4E-01	15.2	0.1	31	10	0.9	0.3
*HOME-ROD OXID	*4.0E-04	900	2.6E-10	2.0E 02	2.0E 02	0.0	2.0E 02	11	4	19.3	7	3.4E-01	15.2	0.1	31	10	0.9	0.3
*HOME-DIRECT	*4.0E-03	900	0.0	0.0	4.0E 02	0.0	4.0E 02	11	4	19.3	7	3.4E-01	15.2	0.3	91	2	7.9	0.2
OCCASIONAL USERS	(1.26E 04)																	
*WELDING	*9.0E-01	900	1.8E-12	2.0E 02	2.0E 02	0.0	2.0E 02	11	4	19.3	7	3.4E-01	15.2	0.1	31	10	0.9	0.3
*GRINDING	*1.0E 00	900	4.6E-10	8.3E-01	8.3E-01	0.0	5.0E 00	11	4	19.3	7	3.4E-01	15.2	0.1	31	13	0.0	30.0
*TOOL BOX-DIRECT	*1.0E 00	900	0.0	0.0	0.0	0.0	4.0E 02	11	4	19.3	7	3.4E-01	15.2	0.1	91	2	7.9	0.2
*ROD OXIDIZED	*1.0E-01	900	1.8E-11	2.0E 02	2.0E 02	0.0	2.0E 02	11	4	19.3	7	3.4E-01	15.2	0.1	31	10	0.9	0.3
NON-WELDERS	(7.58E 04)																	
*WELDING	*9.0E-01	900	1.8E-12	6.0E 02	6.0E 02	0.0	6.0E 02	11	4	19.3	7	3.4E-01	15.2	0.1	361	10	0.9	0.3
*GRINDING	*1.0E 00	900	0.0	0.0	0.0	0.0	1.5E 01	11	4	19.3	7	3.4E-01	15.2	0.1	361	13	0.0	360.0
*TOOL BOX-DIRECT	*1.0E 00	900	0.0	0.0	0.0	0.0	1.2E 03	11	4	19.3	7	8.5E-01	15.2	0.2	361	2	7.9	0.2
*OXIDIZED ROD	*1.0E-01	900	1.8E-11	6.0E 02	6.0E 02	0.0	6.0E 02	11	4	19.3	7	3.4E-01	15.2	0.1	361	10	0.9	0.3

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