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Evaluation of remediation worker risk at radioactively contaminated waste sites

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Abstract

This paper presents a methodology for estimating worker risk occurring during remediation of radioactively contaminated sites. The methodology was applied to estimate remediation worker risks associated with remediation of 17 DOE sites. Fatal construction and off-site transportation risks associated with remediation of the sites were also evaluated. Cancer risks associated with exposure to radiation were found to be about nine times lower on average than construction- and transportation-related accident fatalities.

1. Introduction

The U.S. Department of Energy (DOE) has generated and disposed of large quantities of wastes as a result of 50 years of nuclear weapons production. This waste has been disposed of in environmental locations such as buried reactors, waste pits, holding ponds, and landfills. Many of these waste sites have begun to release contamination off-site and potentially pose risks to humans living or working in the vicinity of these sites. The cleanup of these sites will cost more than $100 billion and require more than 30 years to complete. A major concern during the cleanup will be the protection of thousands of workers engaged in the cleanup. In addition to the well-known safety hazards associated with conventional construction operations, cleanup workers at DOE facilities will encounter radiation exposures from both radioactive waste and mixed waste. Risks to workers engaged in remediation activities should be well-characterized, and occupational health and safety protection programs should be developed to mitigate such hazards.

In a preliminary effort to understand the nature and extent of worker risk encountered during environmental restoration activities, we characterized

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remedial worker risk resulting from remediation activities at 17 radiologically contaminated DOE sites. These 17 sites were found at a variety of DOE installations throughout the United States, such as the Savannah River Site, Hanford Site, Oak Ridge Reservation, and others. Site types consisted of a waste pit, silo, settling basin, seepage basins (2), trench, creeks, drums, a landfill, a holding pond, liquid waste process areas, a contaminated building, a buried reactor, canals, contaminated ground water, and uranium mill tailings sites (2).

2. Remedial worker risk assessment methodology

The methodology for assessing risks to remedial workers at hazardous waste sites consists of two main elements: (1) estimating radiological doses and risks, and (2) estimating construction- and transportation-related risks. Exposure to chemicals is not considered in this study. The primary steps in the worker risk methodology are as follows:

- identify remedial alternatives,
- identify specific activities and worker types for each alternative,
- identify number of workers and person-hours for each activity,
- estimate radiological doses for each activity,
- estimate risks.

2.1 Remedial alternative identification

For each of the 17 sites, three distinct remedial alternatives were chosen for evaluation. For example, at the nuclear reactor, remediation alternatives considered included: (1) decontamination and on-site disposal of materials, (2) decontamination and off-site disposal of materials, and (3) entombment in concrete. For the waste pit, remediation alternatives considered included: (1) application of a cap, (2) removal of major portion of waste and application of a cap, and (3) leaving waste in place, stabilization and application of a cap.

2.2 Identification of activities and worker types

The next step in evaluating worker risk is to identify specific activities and worker types for each alternative. For example, alternative (2) for the waste pit consisted of removal of the major portion of the waste followed by application of a cap. The type of workers involved in excavation may include operators of backhoes, front-end loaders, cranes, dump trucks, and others who serve as support personnel such as spotters/observers, supervisors, and health and safety personnel. Capping may include grading above the waste material that remains, applying the cap, and covering the site with topsoil. Further examples of worker types associated with possible alternatives are shown in Table 1.

TABLE 1

Examples of remediation alternatives and worker types

Site types and associated alternatives	Worker types[a]
Site Type: *Reactor Building* Decontamination, off-site disposal Decontamination, on-site disposal Entombment	Decommissioning and decontamination crew: Iron workers Pipefitters Electricians Loaders, haulers
Site Type: *Holding Pond* Drilling monitoring wells, capping Drilling, soil mixing, cap Drilling, removal, off-site disposal	Drilling crew Heavy equipment operators Dump truck drivers Loaders, haulers
Site Type: *Seepage Basin* Nonremoval, cap Removal, off-site disposal, cap Stabilization, cap	Heavy equipment operators Laborers Dump truck drivers Loaders, haulers
Site Type: *Silos* Removal (remote equipment maintenance), treatment, off-site disposal Removal, treatment, on-site disposal Removal, contaminant separation, off-site disposal	Remote equipment operators Equipment maintenance personnel Mixer Loaders, haulers
Site Type: *Tailings Pile* Nonremoval, stabilization, cap Removal, on-site disposal, cap Removal, off-site disposal, cap	Heavy equipment operators Laborers Dump truck drivers Loaders and haulers, maintenance personnel
Site Type: *Ground water* Pump and treat, slurry wall, cap Partial removal, pump and treat, slurry wall, cap Total removal, incineration, in situ treatment of VOCs	Drilling crew Construction crew Heavy equipment operators Laborers Dump truck drivers Loaders, haulers Operation and maintenance crew (pump operators)
Site Type: *Solid Waste Management Units* Number of small caps In situ stabilization, large cap Partial removal, consolidation, stabilization	Heavy equipment operators Dump trucks drivers Loaders/laborers
Site Type: *Pond Waste Management* Decant, storage, dewater, on-site storage Decant and dewater, on-site storage Decant, fix, off-site disposal	Fork lift operators Laborers Loaders, haulers

[a] Health and safety personnel and supervisors are also assumed to be present on-site.

2.3 Exposure to radionuclides

Exposure to radionuclides can be either internal or external. External exposure refers to the irradiation of human tissues by radiations emitted by radionuclides that are outside the receptor's body. Exposure to external radiation can have an effect on internal tissues as well as external tissues. Internal exposure refers to the irradiation of human tissues by radiations emitted by radionuclides that are inhaled, ingested, or absorbed through the skin. The most important modes of external exposure are: (1) immersion in air containing gamma-emitting radionuclides and (2) exposure to contaminated ground surface, surface soil, or equipment surfaces. The exposure routes evaluated in this study include direct radiation and inhalation. Ingestion and dermal contact were thought to be not as significant as direct radiation and inhalation and were therefore not considered in the worker risk evaluation. Effective dose equivalents (EDEs) attributed to direct irradiation and inhalation of radionuclides were estimated for each worker type.

2.4 Radiological dose estimates

Once the remedial alternatives for each site have been selected and site data have been gathered, potential radiological doses must be estimated. Dose estimation data need to include: (1) worker type involved in the remediation activity, (2) radionuclides to which workers may be exposed, (3) source-to-receptor distances, (4) exposure durations, and (5) shielding configurations. Table 2 lists generic worker types, source-to-receptor distances, shielding, and exposure durations used to estimate direct radiation exposure rates.

Direct radiation exposure rate estimates can be calculated using MicroShield (version 3.0), a microcomputer adaptation of ISOCHILD [1]. The source-to-receptor distances and shielding configurations varied among the workers and remediation alternatives.

Operators of front-end loaders, backhoes, and cranes can be consolidated into the heavy equipment operator category and assigned similar source-to-receptor distances and shielding thickness unless otherwise indicated in site reports. Loaders, laborers, health and safety personnel, and supervisors can be assigned similar source-to-receptor distances, and an assumption made that there is no shielding unless it is otherwise indicated in site reports.

The radionuclide inventories can be corrected for radioactive decay if the dates of analyses are known; otherwise, no decay correction is applied. In addition, if adequate measured exposure rate data are available, they should be used in the analysis in place of modeled exposure rates. Since many radionuclides may be present at a waste site, a dose conversion coefficient of 0.7 rem/R, where R is Röntgen, was selected to ensure that the EDEs would not be underestimated for the radionuclides found at remedial waste sites [2]. This conversion coefficient overestimates EDEs from nuclides emitting photons of energies less than 1.5 MeV. Later versions of MicroShield can estimate EDEs based on the ICRP methodology [2].

TABLE 2

Examples of source-to-receptor distances and exposure durations

Worker type	Source-to-receptor distance	Exposure duration
Heavy equipment operator	2 m above waste with 0.64 cm shielding (iron)	Full time[a]
Crane operators	2 m above waste with 0.64 cm shielding (iron)	Full time
Observer	1 m above waste without shielding	Full time
Dump truck driver	1.5–2 m with 0.64 cm shielding (iron)	Dependent on amount of material to be handled
Drillers	1 m with no shielding	Full time
Fork life operators	1.5 m without shielding	Dependent on amount of material to be handled
Hauler	1.5–2 m from waste with 0.64 cm shielding (iron)	Dependent on amount of material to be handled
Loaders	0.5–1 m from material with no shielding (depending on activity)	Dependent on amount of material to be handled
Decommissioning and decontamination crew	0.51 m from materials, with/without shielding depending on activity	Full time
Laborers	0.5–1 m from waste without shielding (depending on activity)	Full time
Health and safety personnel	0.5–1 m from waste without shielding (depending on activity)	Full time
Other support personnel	1 m above the waste	1/4 to 1/2 time depending on activity

[a] Full time is defined as 8 hrs/d, 5 d/wk.

Doses from inhalation of particulate radioactive material should be calculated for workers involved in activities that may involve dust generation, such as excavation or other earth-moving activities. Data needs for estimating radiation doses from inhalation of radionuclides include: (1) worker type involved in the activity, (2) radionuclides to which workers may be exposed, (3) exposure durations, (4) soil resuspension factors, and (5) radionuclide air concentrations.

For earth-moving activities, a resuspension factor of 0.0005 g/cm^3 was used [3]. This factor assumes that 10% of the resuspended dust particles are of the respirable size (<20 μm) and that dust is suppressed by surface wetting [3]. For other activities that may result in airborne releases, EDE calculations were based on measured air concentrations or calculated using conservative methods where a certain amount of material is released into a specified air volume. The estimated intake was multiplied by the dose conversion factor to yield EDEs [4]. Measured radon concentrations should be used to estimate doses (Working-Level-Month, WLM) when radium contamination is present.

2.5 Radiological risk estimates

Fatal cancer risks were estimated for exposure from direct radiation and inhalation of radionuclides. For direct radiation, the EDE was multiplied by a risk factor of 4×10^{-4}/rad to yield fatal cancers associated with low linear energy transfer (LET) radiation [5]. For low-LET radiation, the estimated EDE was assumed to be equivalent to the absorbed dose. For inhalation, the risk factor used was based on the type of radiation emitted. If the energy was low-LET, the risk factor was 4×10^{-4}/rad. If alpha emitters were present, the EDE was divided by 20 and multiplied by the fatal cancer risk factor 3.1×10^{-3}/rad for high-LET radiation [5]. These risk factors were considered to be conservative since they can be used to estimate general public cancer fatalities instead of occupational cancer fatalities. If radon was present, the risk factor for fatal lung cancer (3.6×10^{-4}/WLM) was used [5]. In future analyses, nominal probability coefficient values as described in ICRP [6] should be used.

2.6 Example calculation

An example calculation for direct radiation cancer fatality risks posed by hypothetical site remediation activities is shown below. The "site" being remediated is a region of contaminated soil 10 m long, 10 m wide, and 3 m deep, with an inventory of 10^4 pCi/g of ^{137}Cs. The remediation alternative illustrated is capping the contaminated region with a concrete and clay cap. This remediation activity can be further divided into the following subactivities: construct cutoff wall, construct concrete slab, rough grade fill, cover site with clay, cover site with sand, cover site with geomembrane, cover site with geotextile, cover site with topsoil, seed and plant area. The risks attributed to each of these activities are then evaluated for two worker types, laborers and heavy equipment operators, for direct radiation exposure to ^{137}Cs.

For each subactivity involving direct radiation exposure, shielding assumptions must be made. Laborers and any workers not operating heavy equipment are assumed to have a 1 m air shield. This represents the distance from the last shield associated with the source to the torso (and vital organs) of the worker. Heavy equipment operators are assumed to have a 1 m air shield, a 0.01 m steel shield (the thickness of the frame and cab of the dozer), and a 0.5 m air shield (the distance from the floor of the equipment to the operator's torso). These thicknesses and dimensions represent the average dimensions and thicknesses of several pieces of heavy equipment used in earth moving activities. Shielding associated with the source consists of uncontaminated soil overburdens, concrete vaults housing tanks, or anything associated with the source that separates it from a receptor. The thickness of a source shield is typically the thickness of the material separating the source and the receptor. The exception to this is during the removal of the shield. Since risk increases as shield thickness decreases, the thickness of a shield being removed is assumed to be half of its thickness before removal. Conversely, the shielding increases as material covers the contaminated area, decreasing the risks. Shielding and personnel assumptions for each subactivity are shown in Table 3.

Based on these shielding assumptions and site dimensions, MicroShield calculates an EDE using rotational geometry. Rotational geometry EDEs represent a uniform dose to the receptor's entire body. It is the dose the receptor would receive if he or she were rotating at a fixed distance from a stationary source. The EDE rates for each of the subactivities are shown below in Table 4. By multiplying the EDE rates by the number of person-hours spent on each activity, the EDE (rem) is obtained.

Cancer fatality risks from direct radiation exposure are derived by multiplying the EDE (rem) by a fatality risk factor (risk/rem) of 1.4×10^{-4} risk/rem, derived from ICRP 60 [6]. The resulting population risks for each subactivity are shown in Table 5. These population risks are obtained by calculating the risk to an individual laborer (or heavy equipment operator) in each worker category and multiplying by the number of laborers (or heavy equipment operators) involved in the activity.

2.7 Construction and transportation risk estimates

In addition to radiological hazards, remedial workers may face safety risks from participation in construction and transportation activities. Two primary safety risks that workers encounter are fatalities from construction accidents and transportation accidents. The Department of Labor's (DOL) Bureau of Labor Statistics publishes fatality rates for major industrial classifications. Those remediation workers who are involved in demolition activities, the use of earth-moving equipment, electrical work, and building activities, can be classified as construction workers. Construction industry fatality rates can be used to estimate fatality risks for remedial workers that were classified as construction workers [7]. The 1988 fatality rate for the construction industry is 24.5 fatalities/100,000 full-time workers [7], which is equivalent to $\sim 1.2 \times 10^{-7}$ fatalities/person-hour. These fatality data are representative of establishments in the private sector with 11 employees or more and may not be representative of remediation workers. The Bureau of Labor Statistics believes that the fatality rates are significantly understated since fatalities are difficult to measure in an establishment sample survey [7]. In this study, the fatality rate is multiplied by the total number of construction-related person-hours to yield the risk attributed to a given construction activity.

Transportation of waste material to disposal sites and other hauling activities are also occupational hazards associated with site remediation. Only off-site transportation fatality rates, based on risk per mile driven, are used. The round trip mileage associated with off-site disposal is estimated by multiplying the number of round trip miles by the number of trips to yield the total number of transportation miles associated with remediation. The mileage is

TABLE 3

Shielding and personnel assumptions for example site

Subactivity	Number of laborers	Shielding for laborers	Number of heavy equipment operators	Shielding for heavy equipment operators
Construction of cutoff wall	2	1 m air	2	1 m air, 1 cm steel, 0.5 m air
Construction of concrete slab	6	1 m air	2	7.6 cm concrete, 1 m air, 1 cm steel, 0.5 m air
Rough grade fill	3	15 cm concrete, 1 m air	1	15 cm concrete, 1 m air, 1 cm steel, 0.5 m air
Cover region with clay	3	15 cm concrete, 1 m air	1	15 cm concrete, 1 m air, 1 cm steel, 0.5 m air
Cover region with sand	4	15 cm concrete, 1 m air	2	15 cm concrete, 0.5 m soil, 1 m air, 1 cm steel, 0.5 m air
Cover with geomembrane	4	15 cm concrete, 0.5 m soil, 1 m air	2	15 cm concrete, 0.5 m soil, 1 m air, 1 cm steel, 0.5 m air
Cover with geotextile	3	15 cm concrete, 1 m soil, 1 m air	1	15 cm concrete, 1 m soil, 1 m air, 1 cm steel, 0.5 m air
Cover region with topsoil	4	15 cm concrete, 1 m soil, 1 m air	2	15 cm concrete, 1 m soil, 1 m air, 1 cm steel, 0.5 m air
Seeding and planting	4	15 cm concrete, 1 m soil, 1 m air	0	N/A

TABLE 4

EDEs for each subactivity

	Cutoff wall	Concrete slab	Rough grade fill	Clay cover	Sand cover	Geomem-brane	Geo-textile	Topsoil cover	Seed and plant
Laborer EDE rate (mrem/h)	2.04	2.04	1.13E−1	1.13E−1	5.91E−4	5.91E−4	2.83E−6	2.83E−6	2.83E−6
HEO[a] EDE rate (mrem/h)	7.62E−1	7.62E−1	6.48E−2	6.48E−2	3.36E−4	3.36E−4	1.6E−6	1.6E−6	N/A
Laborer person-hours	13	205.5	6	8.25	2.67	26.67	15	6	3
HEO person-hours	13	68.5	2	2.75	1.33	13.33	5	3	N/A
Laborer EDE (rem)	2.65E−2	4.18E−1	6.8E−4	9.35E−4	1.58E−6	1.58E−5	4.25E−8	1.7E−8	8.5E−9
HEO EDE (rem)	9.9E−3	5.22E−2	1.3E−4	1.78E−4	4.47E−7	4.48E−6	7.98E−9	4.79E−9	N/A

[a] Heavy equipment operator.

TABLE 5

Cancer fatality risks for each example subactivity

Subactivity	Laborer cancer fatality risk	Heavy equipment operator cancer fatality risk
Construction of cutoff wall	1.1E−5	4.0E−6
Construction of concrete slab	1.7E−4	2.1E−5
Rough grade fill	2.7E−7	5.2E−8
Cover region with clay	3.7E−7	7.1E−8
Cover region with sand	6.3E−10	1.8E−10
Cover with geomembrane	6.3E−9	1.8E−9
Cover with geotextile	1.7E−11	3.2E−12
Cover region with topsoil	6.8E−12	1.9E−12
Seeding and planting	3.4E−12	N/A

then multiplied by 2×10^{-9} fatalities/mile to yield the driver fatality risk, derived from the National Highway Traffic Safety Administration Report for Combination Trucks Involved in Fatal Crashes 1977–1990.

3. Results and discussion

We have presented a methodology for estimating radiation exposure and risk to remediation workers during remediation of radioactively-contaminated sites. A specific example was given to show details of the calculation methods. Using this methodology, worker risk estimates were generated for three distinct remedial alternatives at 17 radiologically contaminated waste sites (Table 6). As shown in Table 6, a wide range of fatal cancer risks exists among the alternatives where direct radiation is involved. The direct radiation risk values vary by as much as a factor of 60 among alternatives at the same site. This variation is due in part to different exposure durations and shielding assumptions that are specific to the activity being performed.

Site-specific factors such as contaminant inventory and exposure durations during remediation activities contribute significantly to the overall remediation risks posed to workers. However, a comparison across sites and remediation activities shows that despite the site-specific factors involved, direct radiation and radionuclide inhalation risks are on average significantly lower than either construction- or transportation-related risks. The distribution of risks (ratio of radiation-induced fatalities to construction and transportation fatalities) among all the alternatives is shown in Fig. 1. In approximately 60% of the alternatives, fatalities from radiation exposures were less than fatalities from construction and transportation. Although radiation fatalities are, in general, 9 times less than construction and transportation fatalities, the

TABLE 6

Number of worker fatalities during remediation activities

Site/alternative	Direct radiation	Inhalation	General construction	Transportation
Site #1				
Physical stabilization, slurry wall, cap	9E−3	–	8E−3	–
Removal, treatment, on-site disposal	4E−4	8E−2	9E−3	–
Removal, treatment, off-site disposal	1E−3	8E−2	9E−3	6E−3
Site #2				
Removal, treatment, on-site disposal	6E−2	2E−3	2E−3	–
Removal, treatment, off-site disposal	6E−2	2E−3	2E−3	1E−2
Removal, contaminant separation, on site disposal	8E−2	2E−3	3E−3	–
Site #3				
Stabilize and cap	2E−2	4E−2	2E−3	–
Excavate all contaminated material	2E−2	4E−2	2E−3	5E−5
Chemically stabilize and cap	1E−2	4E−2	2E−3	–
Site #4				
Cap site	8E−9	1E−4	2E−4	–
Excavate hot spots and cap	9E−8	1E−4	2E−4	–
Excavate all contaminated material	3E−7	5E−4	2E−4	–
Site #5				
Monitoring wells, fill with dirt, cap	3E−4	1E−5	7E−4	–
Monitoring drill wells, deep soil mixing, and cap	2E−2	6E−4	3E−2	–
Monitoring drill wells, excavate, and off-site disposal	6E−4	2E−4	1E−2	2E−4
Site #6				
Dismantle, decontaminate, and on-site disposal	3E−5	–	2E−4	–
Dismantle, decontaminate, and off-site disposal	3E−5	–	2E−4	2E−6
Dismantle and entomb in concrete	2E−4	–	2E−4	–
Site #7				
Decontamination of components, on-site burial	8E−3	–	Data were unavailable to estimate construction risks for this site	–
Decontamination of components, off-site burial	8E−4	–		3E−6
Entombment of reactor building underground components	1E−3	–		–
Site #8				
Removal, treatment, on-site disposal	3E−3	2E−12	4E−4	3E−5
Removal, treatment, off-site disposal	3E−3	2E−12	4E−4	–
Encapsulation by concrete, soil excavation	4E−4	2E−12	3E−4	–

(continued)

TABLE 6. Continued

Site/alternative	Direct radiation	Inhalation	General construction	Transportation
Site #9				
Excavate contaminated sludge and soil	2E−5	6E−5	3E−3	4E−5
Partial excavation and cap	2E−6	6E−6	3E−4	–
Stabilize and cap	4E−6	9E−6	6E−4	–
Site #10				
Cap source areas	5E−4	–	2E−2	–
Excavation, consolidation/disposal, stabilization, and capping	1E−2	3E−6	2E−2	–
Excavation, consolidation/disposal, stabilization, verification, capping	1E−2	3E−6	2E−2	–
Site #11				
Channel diversion, excavation, stabilization	5E−4	7E−5	2E−2	–
Stabilization	2E−5	4E−6	6E−3	–
Diversion, filling, and capping	6E−5	8E−5	2E−2	–
Site #12				
Decant, dewater, on-site storage	7E−4	–	4E−2	–
Decant, dewater, off-site storage	1E−3	–	4E−2	2E−2
Decant, grout, off-site storage	2E−3	–	6E−2	3E−2
Site #13				
Maintenance and inspection, cleanup of mercury droplets	6E−5	–	–	–
Gutting of equipment, decontamination of building structure	4E−4	–	4E−1	–
Demolition of building, excavation, backfilling	4E−4	–	4E−2	–
Site #14				
Containment (capping), local land use restrictions	3E−11	4E−5	1E−2	–
Containment, in situ treatment, local land use restrictions	5E−11	7E−5	2E−2	–
Excavation, off-site disposal	5E−11	4E−5	1E−2	2E−2
Site #15				
Pumping, treating, off-site discharge	1E−13	3E−3	1E−2	–
Pumping, treating, on-site use	1E−13	3E−3	1E−2	–
In situ bioremediation	8E−13	2E−3	9E−4	–
Site #16				
On-site stabilization	3E−4	8E−3	4E−2	–
Off-site disposal at location #1	9E−4	2E−2	1E−2	9E−4
Off-site disposal at location #2	1E−3	4E−2	2E−1	2E−1
Site #17				
Stabilization	4E−3	3E−2	2E−2	2E−4
Off-site disposal at location #1	1E−2	3E−1	3E−2	4E−3
Off-site disposal at location #2	3E−2	6E−1	6E−1	2E−2

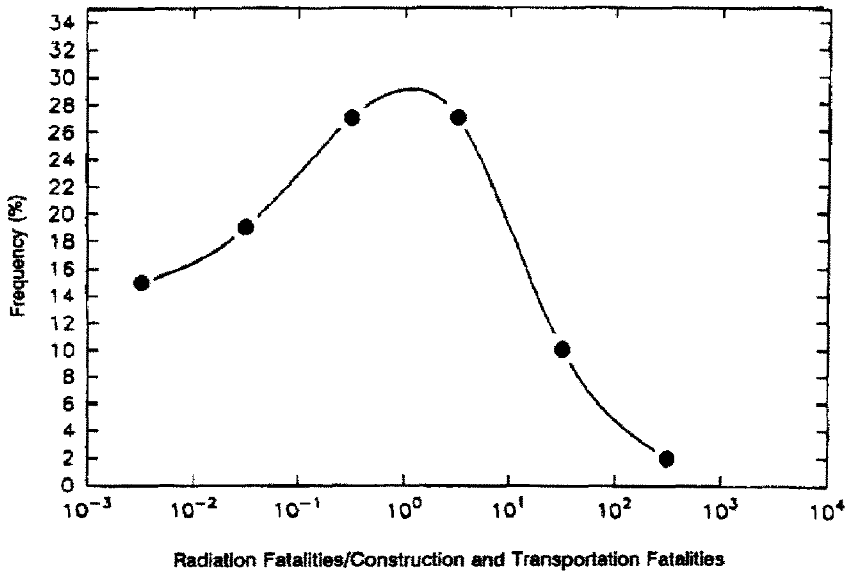

Fig. 1. Probability distribution of risks.

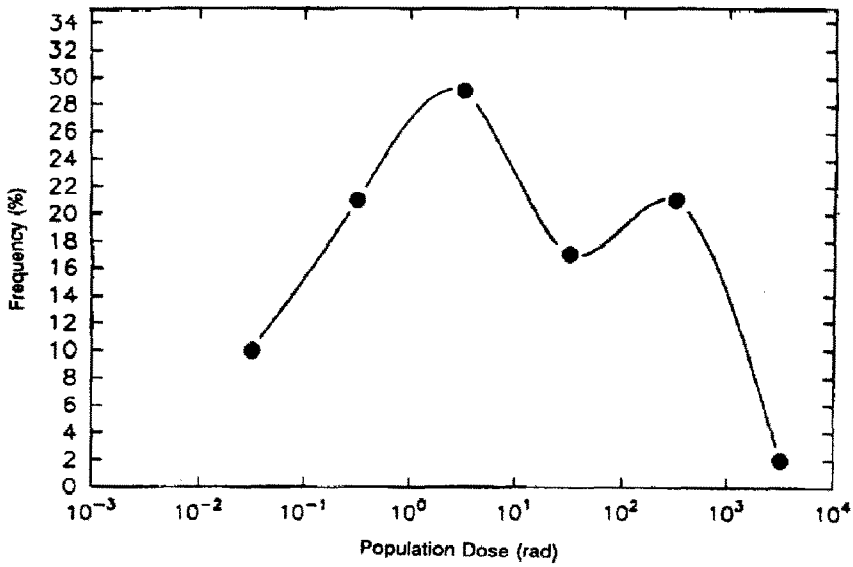

Fig. 2. Probability distribution of radiation dose.

radiation doses received by worker populations are still relatively high, as shown in Fig. 2.

There are three major classes of waste at DOE sites: hazardous chemical, mixed (chemical and radiological), radioactive wastes. This pilot study evaluated only the radioactive waste component. In future evaluations it will be important to include potential chemical exposures and their associated contribution to worker risks. The protocol described in the EPA Risk Assessment

Guidance for Superfund would be applicable for carcinogenic and noncarcinogenic chemicals [4].

This pilot study evaluated only fatality risks; however, cancer incidence and work-related illness/injuries are other categories that would broaden the range of worker-related effects evaluated for site remediation. Illness/injury risks would be pertinent for chemical exposures as well as construction, transportation, and heat stress accidents. In addition, a data base that maintains these types of statistics for remediation workers would be useful information for worker health follow-up studies.

4. Conclusion

For 17 radiologically contaminated sites, cancer fatality risks associated with exposure to radioactive materials and accident fatality risks associated with construction and off-site transportation were estimated. In general, risks from exposure to direct radiation and inhalation of radionuclides are low. Radiation-induced cancer fatalities from direct radiation and inhalation of radionuclides are on average 9 times lower than fatality risks from construction and transportation accidents. For the 17 sites, there were 48 remediation alternatives that posed both radiation (direct radiation and inhalation) and safety (construction and transportation) risks. In approximately 60% of these alternatives, risks from radiation exposure were less than risks from construction and transportation. Radiation doses still appear to be high, however, warranting more stringent worker protection measures. For future studies it is important to have as much site-specific information as possible. In addition to waste inventory data, this information should include planning documents that give information such as estimates of worker types, number of workers per activity, and job duration. It is also important to maintain a data base of remediation worker exposure data and work site accident data. This information would result in more realistic worker dose estimates and ultimately to more representative risk estimates and better protection of worker health.

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