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Radiation Dose Assessment for Military Personnel of the Enewetak Atoll Cleanup Project (1977–1980)

Revision 1

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14. ABSTRACT

During 1977–1980, the U.S. Department of Defense (DoD) conducted a radiological cleanup of Enewetak Atoll. The Enewetak Atoll Cleanup Project (ECUP) was carried out by a Joint Task Group established by the Defense Nuclear Agency, and involved the cumulative participation of approximately 6,000 military service members. This report provides a revision to the technical basis for performing individualized radiation dose assessments for these ECUP veterans. The technical approach, survey and monitoring data, and radiation dose estimation methods are described. Example dose assessments for hypothetical, high-sided example exposure scenarios result in doses that are well below applicable regulatory limits. Guidelines are provided for performing individual ECUP radiation dose assessments, including a questionnaire to gather pertinent information from participants. As discussed in this report, ECUP veteran exposures resulted in doses that are less than doses associated with adverse health effects.

15. SUBJECT TERMS

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UNIT CONVERSION TABLE

U.S. customary units to and from international units of measurement*

U.S. Customary Units	Multiply by / Divide by†		International Units
Length/Area/Volume			
inch (in)	2.54	$\times 10^{-2}$	meter (m)
foot (ft)	3.048	$\times 10^{-1}$	meter (m)
yard (yd)	9.144	$\times 10^{-1}$	meter (m)
mile (mi, international)	1.609 344	$\times 10^{3}$	meter (m)
mile (nmi, nautical, U.S.)	1.852	$\times 10^{3}$	meter (m)
barn (b)	1	$\times 10^{-28}$	square meter (m^2)
gallon (gal, U.S. liquid)	3.785 412	$\times 10^{-3}$	cubic meter (m^3)
cubic foot (ft^3)	2.831 685	$\times 10^{-2}$	cubic meter (m^3)
Mass/Density			
pound (lb)	4.535 924	$\times 10^{-1}$	kilogram (kg)
unified atomic mass unit (amu)	1.660 539	$\times 10^{-27}$	kilogram (kg)
pound-mass per cubic foot (lb ft^{-3})	1.601 846	$\times 10^{1}$	kilogram per cubic meter (kg m^{-3})
pound-force (lbf avoirdupois)	4.448 222		newton (N)
Energy/Work/Power			
electron volt (eV)	1.602 177	$\times 10^{-19}$	joule (J)
erg	1	$\times 10^{-7}$	joule (J)
kiloton (kt) (TNT equivalent)	4.184	$\times 10^{12}$	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350	$\times 10^{3}$	joule (J)
foot-pound-force (ft lbf)	1.355 818		joule (J)
calorie (cal) (thermochemical)	4.184		joule (J)
Pressure			
atmosphere (atm)	1.013 250	$\times 10^{5}$	pascal (Pa)
pound force per square inch (psi)	6.984 757	$\times 10^{3}$	pascal (Pa)
Temperature			
degree Fahrenheit (ºF)	[T(ºF) − 32]/1.8		degree Celsius (ºC)
degree Fahrenheit (ºF)	[T(ºF) + 459.67]/1.8		kelvin (K)
Radiation			
curie (Ci) [activity of radionuclides]	3.7	$\times 10^{10}$	per second (s^{-1}) [becquerel (Bq)]
roentgen (R) [air exposure]	2.579 760	$\times 10^{-4}$	coulomb per kilogram (C kg^{-1})
rad [absorbed dose]	1	$\times 10^{-2}$	joule per kilogram (J kg^{-1}) [gray (Gy)]
rem [equivalent and effective dose]	1	$\times 10^{-2}$	joule per kilogram (J kg^{-1}) [sievert (Sv)]

*Specific details regarding the implementation of SI units may be viewed at http://www.bipm.org/en/si/.

†Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.

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Revision Notes

This revision updates and expands technical information and guidance in the original version of DTRA Technical Report DTRA-TR-17-003, dated April 13, 2018. Many of the revisions are driven by responses to questionnaires from veterans of the Enewetak Cleanup Project (ECUP), and information and data recently compiled from project documentation.

The revision extends the original report to include three new appendices that address three technical issues: (1) validating the method for estimating doses from handling contaminated debris; (2) assessing internal doses from the possible consumption of local foods by ECUP participants; and (3) calculating height-specific beta skin doses for non-contact exposure to contaminated soil using newly estimated beta-to-gamma dose ratios for ECUP dose assessments. The information in these new appendices is summarized in the body of the report in Sections 6 and 7. Additions and minor revisions of dose assessment parameter values are made in the text and tables in Sections 6, 7, and 8, and other appendices of the original technical report. The example radiation dose assessments included in Section 8 are revised by applying updated default parameter values and assumptions discussed in Section 6 and 7. Other relevant changes are made in Sections 2, 3, and 4.

The dose assessment equations and text of Appendix C are revised to incorporate updated information and revised equations. Specific improvements in dose reconstruction methods in this revision include: revised analysis of activity concentrations in lagoon and ocean water to assess exposure from swimming (Sections 6.2.3 and 7.3, and new Appendix J); estimation of consumption of local foods (Section 7.4 and new Appendix M); inclusion of additional radionuclides in soil for dose assessments for individuals exposed in the 1960s timeframe (Sections 3.1 and 8.4); guidance on the use of Controlled Island Access forms for determining respiratory protection levels; and guidance for consideration of dermal soil loading when estimating skin doses from dermal contamination (Section 6.3.1). Uncertainties in doses that are based on TLD readings are revised and further discussed in Section 6.4.3 with details provided in revised Appendix D. The entries in Table A-1 are rearranged to follow a chronological order by the start date of each project activity.

In addition, numerous editorial changes are made, and tables, figures, and references are updated as appropriate. Text is clarified where needed and sub-sections are added to improve the report organization.

The conclusions reached in this revision are unchanged from those in the original version of the report. This Technical Report, DTRA-TR-17-003(R1), supersedes the original version dated April 13, 2018.

Executive Summary

This report documents the technical basis for performing individualized radiation dose assessments (RDA) for veterans who participated in the cleanup of Enewetak[1] Atoll from 1977 to 1980. The report is a revision of the technical report published in April 2018 by the Defense Threat Reduction Agency (DTRA). A summary of revisions and updates is given in the "Revision Notes" included in this report.

Approximately 6,000 military service members of the United States Department of Defense (DoD) participated in the Enewetak Atoll Cleanup Project (ECUP) as part of the radiological cleanup, rehabilitation, and resettlement of Enewetak Atoll in the Marshall Islands. To implement this effort, DoD established a Joint Task Group (JTG) within the Defense Nuclear Agency (DNA) and initiated the cleanup project, as authorized by Congress (Congress, 1977).

Enewetak Atoll was one of two primary locations in the Pacific Ocean where the United States conducted atmospheric tests of nuclear devices from 1946 to 1958 (DNA, 1981). Radioactive contamination from the nuclear detonations remained at Enewetak Atoll after testing ended. During the early 1970s, previous residents of the atoll, who had been relocated prior to the start of testing, expressed interest in returning to their homeland as they were promised.

From 1948 to 1958, the United States conducted 43 nuclear tests on the Enewetak Proving Ground at Enewetak Atoll (DNA, 1981). The tests were conducted primarily on the northern islands to minimize contamination of the base camp islands located in the southeast islands of the atoll. The tests resulted in measurable residual radiation from fallout that deposited primarily on the northern islands of the atoll. The major radioactive contaminants remaining in the 1970s included the transuranic (TRU) radionuclides plutonium-239 (Pu-239), plutonium-240, (Pu-240), and americium-241 (Am-241), as well as the fission and activation products cesium-137 (Cs-137), strontium-90 (Sr-90), and cobalt-60 (Co-60). These radionuclides formed the primary potential sources of exposure to radiation through external exposure as well as through inhalation of airborne contaminants in suspended soil, and ingestion of soil, water, and dust. Small amounts of other fission products and TRU nuclides were present but were determined not to be important in ECUP dose assessments. Media that could be the source of radiation exposure included principally soil and dust, but also potentially contaminated debris, equipment, lagoon water and sediments, locally harvested food, and drinking water.

Planning for the cleanup of Enewetak Atoll began in the early 1970s following the U.S. government's decision to return the atoll to the Trust Territory of the Pacific Islands. This required collecting information about the nature and extent of the radioactive contamination through the approximately 40 islands of the atoll. The Atomic Energy Commission (AEC) and DoD conducted radiological surveys and completed several studies during the early to mid-1970s. These efforts led to the conclusion that the islands of Enjebi, Lujor, Aomon, Boken, and Runit had radioactive soil contamination above satisfactory levels that would require cleanup (DNA, 1981). The principal investigations conducted by AEC, DoD, and their contractors include:

[1] In 1974, the U.S. government changed its spelling of the name of the atoll from Eniwetok to Enewetak to more closely represent the way it was pronounced by the Marshallese people.

- A preliminary radiological survey and initial reconnaissance conducted in May 1972 by representatives from AEC, DNA, the U.S. Environmental Protection Agency (USEPA) and the University of Washington (AEC, 1972; DNA, 1972; Stevens, 1972; TTPI, 1972)
- An engineering study under DNA contract to Holmes & Narver, Inc. (H&N) of the atoll to include recommendations and cost estimates for cleanup of the atoll (H&N, 1973)
- A radiological field survey conducted in late 1972 to develop sufficient data to characterize the radiological environment of Enewetak Atoll (AEC, 1973a)
- An environmental impact statement evaluating the cleanup, rehabilitation and resettlement of the Enewetak Atoll (DNA, 1975).

The cleanup was conducted under a comprehensive radiation safety and monitoring program, appropriate for occupationally exposed individuals, to provide extensive oversight of all project activities and preserve robust monitoring and personnel exposure records. Decades after the cleanup was completed, ECUP veterans developed adverse medical conditions and expressed concerns that their exposures during ECUP were the cause of their ills. Discussions of the ECUP veterans in the news and through contact with congressional representatives led to proposed legislation in several Congresses to include ECUP participants in veterans' compensation programs for radiation exposed individuals. In the fall of 2016, DTRA directed its radiation dose assessment support team to develop a technical basis document to assist the agency in responding to VA requests for dose information for ECUP veterans' claims.

The overall approach to develop the technical basis for assessing radiation doses for ECUP veterans was organized into five parts:

1) Identification of major cleanup project components
2) Development of the dose estimation methodology
3) Preparation of guidelines for veteran claim implementation
4) Development of dose calculation tools
5) Preparation of the original technical basis document and this revision.

Beginning in late 2016, a team of historians, health physicists, other scientists and engineers, and support personnel reviewed a large collection of documents and records pertaining to ECUP, covering periods from the early 1970s to the early 1980s. The goal was to evaluate and compile information relevant to the potential exposure to radiation of DoD personnel who participated in the cleanup project during 1977–1980. Extensive repositories of records at the Defense Threat Reduction Information Analysis Center (DTRIAC) at Kirtland Air Force Base (AFB), NM, and the Nuclear Testing Archive at Las Vegas, NV, were searched for pertinent documents. Transfer of the DTRIAC collection to DTRA and scanning to digital form improved the efficiency of searches and formed the basis for a searchable repository for future veteran radiation dose assessments.

Records of radiation dosimetry obtained from film badges and thermoluminescent dosimeters (TLDs), which were assigned throughout the duration of the ECUP, provide an overall impression of the external exposures of ECUP participants. However, as observed during atomic testing, the hot, humid, and sometimes wet atoll environments affected the performance of film dosimeters with the result that many of these devices could not be properly evaluated for dose, especially during the initial months of the ECUP. Supplementing film dosimeters with TLDs improved dose monitoring significantly. Nevertheless, administrative procedures were required to estimate the doses for individuals whose film badge dosimeters could not be evaluated. (DNA, 1981)

Review of ECUP bioassay records in the form of nasal smears and urinalysis testing results indicate that internal deposition of plutonium nuclides was not observed except in samples from a few individuals. Results from a second sample from each of these individuals showed no detectable radioactivity from plutonium in all such samples. (DNA, 1981)

To characterize the scenarios of exposure of ECUP personnel, specific coherent project tasks were identified and categorized into nine major project components including soil cleanup, debris cleanup, radiological support, and six others. Methods to estimate radiation doses for various exposure pathways are based mainly on the standard methods developed by DTRA for the Nuclear Test Personnel Review Program (DTRA, 2017). All necessary equations to estimate external, internal and skin doses for ECUP personnel, as well as upper-bound doses at least at the 95^{th} percentile confidence level, are provided.

For external exposures, it is concluded that measurements of radiation exposure rates based on the 1972 aerial radiological surveys conducted by the AEC would tend to overestimate the conditions that prevailed during the cleanup project during 1977–1980. These exposure rates are recommended as default values to be used to estimate high-sided external whole-body gamma doses.

For internal exposures, it is estimated that over 99 percent of the calculated internal dose from inhalation of suspended soil and dust for most internal organs would result from the three TRU radionuclides Pu-239, Pu-240, and Am-241. With respect to the airborne activity concentrations of suspended soil and dust from undisturbed ground, it is recommended to use island-average soil activity concentrations from the 1972 AEC soil-sampling program (AEC, 1973a). For estimating internal doses from exposures to contaminated soil that was excised from the islands of Boken, Enjebi, Lujor, Aomon, and Runit, then transported, mixed and contained in the Cactus Crater and dome on Runit, it is recommended that the air activity concentrations should be based on the TRU concentrations of the soil removed from each island. These concentrations are derived from the total estimated activity removed from each island as reported in DNA (1981). Using the total TRU activity and the total volume of soil removed from each of the five islands, an average soil concentration for each island and overall weighted averages are estimated. In addition, air sampling results are available in the form of weekly statistical summaries, including the weekly maximum concentrations.

Based on the information described in this report and summarized above, the study team was able to build a collection of pertinent radiation data and combine them with conservative assumptions and sound calculations to produce credible, high-sided dose estimates in favor of ECUP veterans. Using these data and assumptions, several examples of dose estimation for ECUP exposure scenarios are described. They include sample assessments for personnel who were involved in soil cleanup, debris cleanup, and boat transport of contaminated soil. In addition, an example dose assessment for Air Force personnel who were assigned temporary duty at Enewetak in 1965 is included. This latter example was developed to serve as a basis to estimate doses in support of specific VA claims from veterans who performed duties on Enewetak in the 1960s before the start of the ECUP.

Finally, guidelines are presented that supported the development of a standard operating procedure (SOP) to be used to perform individual radiation dose assessments for ECUP veterans in response to VA requests. For such individualized dose assessments, it is important to collect veteran-specific information and data that can be used to adjust or complement the scenarios of exposures and assumptions identified in this report. For this purpose, an ECUP-specific questionnaire was developed and has been used to collect veteran-specific information from claimants. If additional sources of exposures and pathways are identified in the questionnaire, supplemental doses are estimated using standard dose reconstruction techniques. Since the publication of the original version of this technical report, a standard operating procedure, "Radiation Dose Assessment for Participants in the Enewetak Cleanup Project", was developed and published by DTRA (DTRA, 2019). Section 9 of this report describing the guidelines for SOP development is maintained in this revision for completeness.

Based on discussions in this report, it is confirmed that ECUP participants conducted all cleanup work within a structured and effective radiation protection program as reported in DNA (1981) and elsewhere, which served to minimize radiation doses. The highest of the estimated upper-bound total effective radiation doses for any of the included sample assessments is 0.22 rem (2.2 mSv) above natural background. This dose is similar to the average individual effective dose of 0.31 rem (3.1 mSv) to the U.S. population from ubiquitous background radiation including radon (NCRP, 2009a). It is also substantially lower than the whole body occupational dose limit of 5 rem (50 mSv) per year that was in place for personnel during ECUP. As a result of the ECUP radiation protection program, the generally low levels of contamination encountered, and as confirmed by example dose assessments, it is concluded that ECUP participants' exposures resulted in whole-body and organ doses much lower than doses associated with adverse health effects. This conclusion is supported by the following statement from the Health Physics Society's position statement regarding radiation health risks:

> "Substantial and convincing scientific data show evidence of health effects following high-dose exposures (many multiples of natural background). However, below levels of about 100 mSv [10 rem] above background from all sources combined, the observed radiation effects in people are not statistically different from zero." (HPS, 2019)

Section 1.

Introduction

This report serves as the technical basis document for performing individualized radiation dose assessments (RDA) for veterans who participated in the cleanup of Enewetak[2] Atoll from 1977 to 1980. Approximately 6,000 military service members of the United States Department of Defense (DoD) participated in the cleanup project. The DoD established a Joint Task Group (JTG) within the Defense Nuclear Agency (DNA) to conduct the cleanup, as authorized by Congress in Public Law 95-134 (Congress, 1977), in an operation named the Enewetak Atoll Cleanup Project (ECUP). Enewetak Atoll was one of two primary locations in the Pacific Ocean where the United States conducted atmospheric tests of nuclear devices during the mid-1940s through 1962 (DNA, 1981). Radioactive contamination from nuclear detonations remained after testing ended. During the early 1970s, previous residents of the atoll, who had been relocated prior to the start of testing, expressed interest in returning to their homeland as they were promised.

The JTG performed the cleanup using personnel from the U.S. military services assisted by DoD civilian employees and contractors, the U.S. Atomic Energy Commission (AEC)[3] and other agencies (DNA, 1981). The cleanup was conducted under a comprehensive radiation safety and monitoring program, appropriate for occupationally exposed individuals, to provide extensive oversight of all project activities and preserve robust monitoring and personnel exposure records. Major cleanup activities included:

- Clearance of vegetation and removal of contaminated soil and debris
- Demolition and removal of uncontaminated buildings and debris
- Transportation of contaminated soil and debris to disposal sites at the lagoon or Cactus Crater on Runit Island
- Preparation of the atoll for resettlement.

During the past few years, veterans have filed claims with the Department of Veterans Affairs (VA) asserting that adverse medical conditions they have developed were associated with their radiation exposures during ECUP. The VA's decisions have not satisfied the affected veterans who have pursued other forms of redress. In reaction, legislators have introduced bills in the U.S. House of Representatives and the U.S. Senate that would include participation in ECUP as a radiation-risk activity (Congress, 2008, 2009) or to establish presumptive service connection for ECUP participants in a manner similar to that established for atomic test veterans (Congress, 2017a, b). In addition, bills in the House of Representatives (Congress, 2017c) and Senate

[2] In 1974, the U.S. government changed its spelling of the name of the atoll from Eniwetok to Enewetak to more closely represent the way it was pronounced by the Marshallese people.
[3] A portion of AEC was reorganized into the Energy Research and Development Administration (ERDA) in January 1975, which was subsumed into the Department of Energy (DOE) at its creation in August 1977.

(Congress, 2017d) proposed amendments to the Radiation Exposure Compensation Act (RECA) to include radiation exposure during cleanup of Enewetak Atoll.

In 2016, the Defense Threat Reduction Agency (DTRA)—successor to DNA and DoD's lead agent for providing dose assessments for atomic veterans—initiated the effort to identify, compile, and review available ECUP records and to prepare this technical report to serve as a comprehensive technical basis document to support ECUP veterans RDAs. Extensive repositories of records at the Defense Threat Reduction Information Analysis Center (DTRIAC) at Kirtland Air Force Base (AFB), NM and the Nuclear Testing Archive at Las Vegas, NV were identified and searched for pertinent documents. More than 150 boxes of relevant documentation were moved from the DTRIAC collection to DTRA and were digitally scanned to form a searchable repository of information about ECUP operations, reports, memos, letters, monitoring data, etc. A team of historians, health physicists, other scientists and engineers, and support personnel evaluated this information, including radiation monitoring results such as personnel dosimetry, air sampling results, exposure rates from external radiation, and bioassay results. The review of the documentation indicated that the ECUP radiation safety program was effective, and that the highest recorded whole body dose was 0.07 rem, which is about 70 times lower than the annual occupational dose limit of 5 rem in effect at the time (DNA, 1981; USNRC, 1975).

DTRA then tasked its Nuclear Test Personnel Review (NTPR) Program support contractor to prepare this report with support from DoD's Dose Assessment and Recording Working Group (DARWG) and professional health physics experts of the military services who are ECUP veterans. This team accomplished the aforementioned document review, the data analyses, the development of dose assessment methods, and performed the calculations of example dose estimates discussed in this report. This document presents the relevant historical information, exposure analyses and dose estimates for example ECUP participation scenarios.

1.1 Background

Enewetak Atoll is a small ring of islands approximately 2,500 miles west of Hawaii and is the only surface feature of one of the three island chains known as the Marshall Islands Group (DNA, 1981, Figure 1-3). The atoll contains some 40 named islands, two coral heads large enough to have been named by the Enewetak people, a number of small, unnamed islets, and long stretches of submerged reefs. Section 2.1 provides additional discussions of the atoll's characteristics.

From 1948 to 1958 the United States conducted 43 nuclear tests on the Enewetak Proving Ground at Enewetak Atoll (DNA, 1981). Prior to the start of testing, the Enewetak people were relocated to Ujelang Atoll, about 124 miles southwest of Enewetak. The tests were conducted primarily on the northern islands to minimize contamination of the base camp islands located in the atoll's southeast. The tests resulted in small, but observable, residual radiation environments, primarily on the northern islands of the atoll. The major radioactive contaminants remaining in the 1970s included transuranic (TRU) radionuclides Pu-239, Pu-240, and Am-241, as well as the fission and activation products Cs-137, Sr-90, and Co-60. Small amounts of other fission products and TRU nuclides were present but would not be important in dose assessments. Section 2.2 provides additional discussions of the atoll's use for nuclear testing.

During the 1971 review required by the agreement between the United States and the Trust Territory of the Pacific Islands (TTPI), it was determined that Enewetak Atoll was no longer needed for nuclear testing and should be returned to the TTPI (Johnston and Williams, 1972). Efforts to return the Enewetak people identified the need for detailed assessments of the conditions on the various islands of the atoll and development and implementation of plans and programs to restore the atoll to acceptable conditions for habitation. The AEC and DoD conducted radiological surveys and completed several studies during the early to mid-1970s, which identified that the islands of Lujor, Aomon, Boken and Runit had radioactive contamination above acceptable levels that would require cleanup (DNA, 1981). At the same time, restoration actions on non-contaminated islands and test facilities were recommended. The principal studies conducted by AEC, DoD, and their contractors include:

- A preliminary radiological survey and initial reconnaissance conducted in May 1972 by representatives from AEC, DNA, the U.S. Environmental Protection Agency (USEPA) and the University of Washington (Stevens, 1972; DNA, 1972; TTPI, 1972; AEC, 1972)
- An engineering survey under DNA contract to Holmes & Narver, Inc. (H&N) of the atoll to include recommendations and cost estimates for cleanup of the atoll (H&N, 1973)
- A radiological field survey to develop sufficient data on the total radiological environment of Enewetak Atoll (AEC, 1973a)
- An environmental impact statement on the cleanup, rehabilitation and resettlement of the Enewetak Atoll (DNA, 1975).

The assembled studies provided the input needed for planning cleanup efforts and assessments of the expected conditions after cleanup was complete. These plans led to the implementation of ECUP within the period of 1977 to 1980. Significant milestones during the first year included mobilization efforts starting March 15, 1977 and ECUP's D-Day on June 15 (DNA, 1981). Appendix A includes a list of ECUP milestones. Summary discussions of the history of ECUP are presented in Section 2. The radiological conditions prior to the cleanup, the radiological safety program, and other related aspects are detailed in Section 3.

1.2 Veterans' Concerns

Many veterans who participated in ECUP continue to express concerns about whether their radiation exposures have contributed to various medical conditions they are experiencing. Many of them have joined organized groups to share information and concerns about their health and perceived problems with the radiation controls used during the project. Some groups have been very active and have raised interest in the media, for example in a recent New York Times article (Philipps, 2017) and in Congress. Bills in both the 114th and 115th Congresses were introduced to "provide for treatment of veterans who participated in the cleanup of Enewetak Atoll as radiation exposed veterans for the purposes of the presumption of service-connection of certain disabilities by the Secretary of Veterans Affairs" (Congress, 2015, 2016, 2017a, b) and for consideration under the Radiation Exposure Compensation Act (RECA) by the Department of Justice (Congress 2017c, Congress 2017d).

Specific veterans' concerns about inadequate radiological controls included reduced levels of personal protective equipment such as anticontamination suits and lack of respirators, allegations of falsified radiation monitoring and dosimetry records, and defective air sampling and radiation dosimetry equipment. Concerns about radiological controls, challenges and significance are discussed in Section 3.2.2.

1.3 Purpose and Scope

The purpose of this report is to serve as the technical basis document for performing RDAs for ECUP participants and to discuss the approach, methods, and examples of dose results of a study to estimate upper-bound radiation doses that may be assigned to individuals in the Population of Interest (POI). The POI consists of about 6,000 military service members who participated in ECUP within the period 1977 to 1980.[4] The POI is described in Section 2 and includes members of the three military service components of the JTG (Army Element, Navy Element and Air Force Element) as well as those in the DNA/JTG itself.

1.4 Radiological Quantities

This report discusses methods for the calculation of two radiation dose quantities, i.e., the effective dose and equivalent dose. These quantities apply to both exposures from sources outside the body and sources inside the body. The absorbed dose is a measure of the energy deposited in an organ or tissue. The equivalent dose to a tissue or organ from radiation is the absorbed dose multiplied by a radiation weighting factor. The radiation weighting factor is unitless and relates absorbed dose to the probability of a stochastic radiation effect, such as cancer or changes in hereditary characteristics. For example, alpha particles are known to be 10 to 20 times more effective than beta particles or gamma rays. The effective dose is the sum of the organ weighted equivalent doses to all tissues and organs in the human body. Effective dose is commonly used to determine compliance with regulatory limits. Doses and other radiological quantities in this report are stated in conventional units (rad, rem, Ci, R, etc.) because those units were used prior to and during the cleanup period. When useful for comparison, more recent doses reported in SI units[5] (Gy, Sv, Bq, etc.,) are stated in conventional units with SI units in parentheses. All doses reported in this report are assumed to be in addition to background.

Internal doses in organs and tissues result from radiation emitted from radioactive materials in the body. Doses are accrued over the entire time that the radioactive materials remain in the body. In some cases, the radioactive materials remain for very short periods such as a few weeks, or months while in other cases, such as for Pu, the radioactive material is retained for many years. A convenient way to compare the potential radiation effects from these varied conditions, committed doses are calculated. A committed dose is the total dose to an organ or tissue over a specified time period, such as 50 years for an occupationally exposed individual or over 70 years, 80 years or some other number of years for members of the public. Committed equivalent doses or committed effective doses can be calculated. In this report, internal doses are estimated using the 50-year committed effective dose to the whole body and the 50-year committed equivalent dose to specified organs or tissues.

1.5 Technical Approach

The characterization of exposure to radiation described in this report is designed to provide the technical basis for radiation dose assessments in response to future VA requests for

[4] The inclusive dates January 1, 1977 through December 31, 1980 are the period of participation for the ECUP proposed in recent legislation. (Congress, 2017a, b)
[5] SI means Système International d'Unités (International System of Units).

dose information that are needed in the processing of veteran claims. The report discusses pertinent historical and technical information combined with relevant technical methods used in radiation dose assessments. It includes a compilation of information and data that can be used by a radiation dose assessment (RDA) analyst to assign or estimate conservative external and internal radiation doses and corresponding upper-bound doses that could have been accrued by a veteran who participated in the ECUP between 1977 and 1980.

Potential radiation exposures are categorized at the project activity level to estimate conservative upper-bound doses based on a veteran's account of his or her participation information. High-sided conservative parameter values are selected to reflect the higher end of the range of plausible values. The upper-bound dose is estimated to be at least as high as the 95th percentile dose based on comparisons of similar assessments using a probabilistic analysis that accounts for uncertainties in the determination of dose distributions. To carefully compile all project activities performed by ECUP participants that are relevant to this technical basis study, a three-level structure, described in detail in Section 5, is devised where ECUP-relevant operations are subdivided into nine project components, which are subdivided into a number of major tasks and specific project activities.

Project activities and related sources of radiation and exposure pathways are discussed in Section 5. Section 6 discusses external dose estimation methods, use of dosimetry records, and the method to estimate external dose uncertainties. Section 7 includes methods and assumptions for selecting dose parameters values for estimating internal doses, as well as uncertainties in internal doses. The methods presented in Section 6 and Section 7 and the radiation monitoring data compiled in Section 4 constitute the basis for performing future individual radiation dose assessments for ECUP participants. In Section 8, examples of scenarios of participation and radiation exposure are presented showing how doses can be estimated by an RDA analyst in the case of future veteran claims and VA requests for dose information.

Standard dose reconstruction techniques used in RDAs are based on standard procedures and methods developed for other veterans' RDA programs such as the DTRA NTPR Program (DTRA, 2017). As shown in Figure 1, the overall approach to develop the technical basis for assessing radiation doses for ECUP veterans organized the effort into five parts: identification of major project components, development of the dose estimation methodology, preparation of guidelines for veteran claim implementation, development of dose calculation tools, and preparation of this technical basis document. The following steps were adopted as part of the approach to develop the technical basis for estimating upper-bound doses for veterans who participated in ECUP:

1) Review historical information and data related to ECUP to include planning, data collection, project implementation components, tasks and activities, and related personnel records of exposure to radiation
2) Collect additional information from veterans and military services with emphasis on radiation measurements, radiation exposure potential, and implemented radiation safety procedures
3) Compile and evaluate available dosimetry records of ECUP military personnel

4) Use all collected historical information to develop activity-based exposure scenarios and pathways of exposure for individuals who participated in specific project activities and tasks (project activities and tasks are discussed in detail in Section 5)

5) Estimate conservative, also referred to in this report as high-sided, external and internal doses and corresponding upper-bound doses for example exposure scenarios using standard dose reconstruction methods and techniques

6) Propose guidelines and procedures for individualized RDAs that DTRA or military services can use for VA claims

7) Develop an ECUP veteran questionnaire with questions that would help collect individual information that can be used as veteran-specific dose input data.

An RDA implementation process is shown in Figure 1. This process shows the dose development phase covered by this report combined with the implementation aspects for individualized veteran dose assessments.

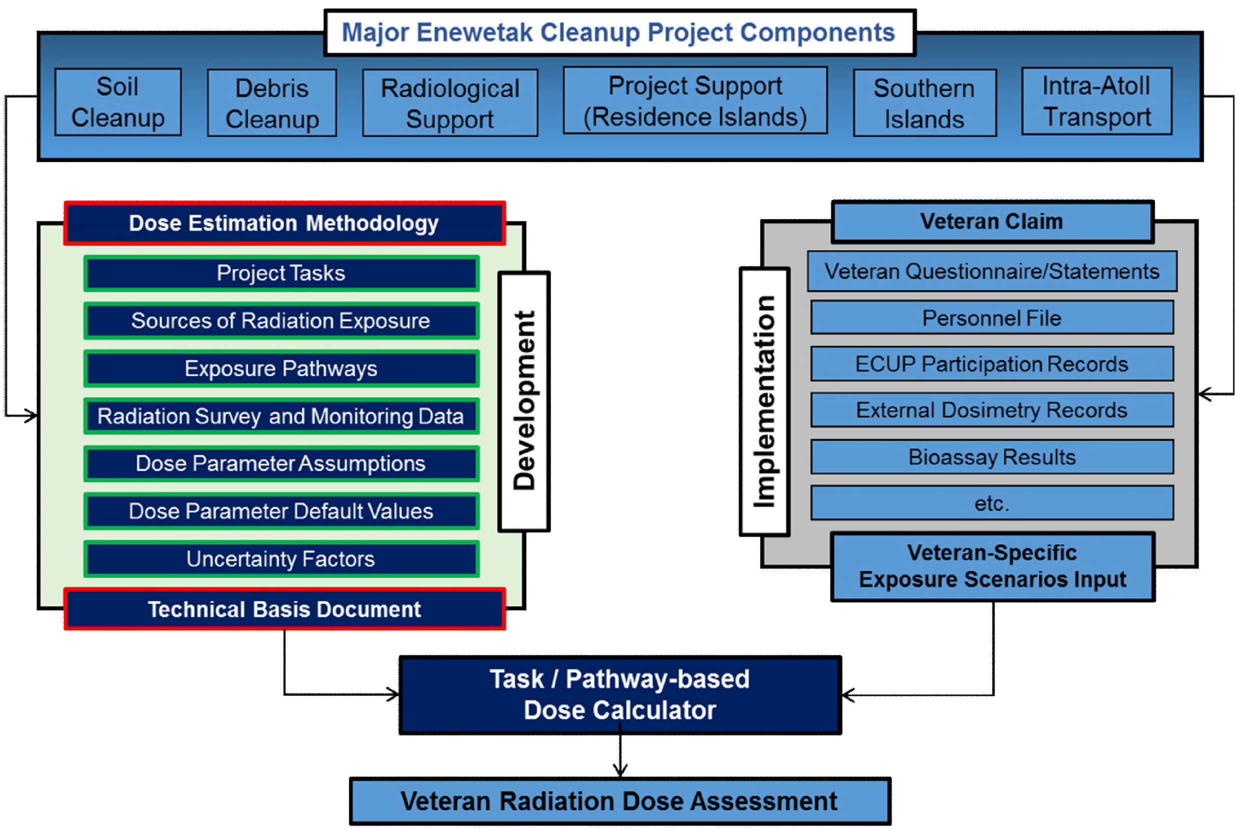


Figure 1. Radiation dose assessment development and implementation process

Section 2.

Enewetak Atoll and Cleanup Project

This section describes the geographic layout of Enewetak Atoll and the naming convention of the islands, including the designations of the Enewetak people. It also lists the atmospheric nuclear tests conducted in the atoll from 1948 to 1958 and their locations. A broad overview of the actions to cleanup Enewetak Atoll starting in 1972, along with the basis and strategy for conducting the cleanup, and considerations for returning the islands to the Marshallese population are detailed.

2.1 Enewetak Atoll Setting

Enewetak Atoll, shown in Figure 2 is approximately 23 by 17 statute miles with the long axis running northwest to southeast. The land surface area totals 1,761 acres or 2.75 square miles. The lagoon has an area of approximately 388 square miles. Its depth averages 160 feet with a maximum of approximately 200 feet. There are three entrances to the lagoon: the east channel or Deep Entrance, 180 feet deep, lying between Medren and Japtan; the Wide Passage in the south, 6 miles in width; and a 24-foot deep channel called the Southwest Passage. The atoll contains some 40 named islands, two coral heads large enough to have been named by the Enewetak people, and a number of small, unnamed islets and long stretches of submerged reefs. Table 1 provides the names used by the people of Enewetak and U.S. government-assigned names and codes for the islands.[6] (DNA, 1981)

As can be seen from Figure 2, the atoll is divided into 22 northern islands Bokoluo to Runit and 18 southern islands Inderal to Biken. The northern islands, listed in Table 1, were assigned female code names in alphabetical order (Alice to Yvonne) in a clockwise direction. The southern islands, also listed in Table 1, were assigned male code names continuing clockwise (Alvin to Leroy). Smaller islands and other features were named later, disrupting the original alphabetical order of assignment. Data indicate that elevated levels of external radiation and contamination were found in the northern islands, while low levels less than 4 $\mu R\ h^{-1}$ were characteristic of the southern islands (AEC, 1973a).

2.2 Use of Enewetak Atoll for Nuclear Testing

The U.S. government decided in 1947 to develop the atoll for use as an atmospheric nuclear testing site in the Pacific. The decision involved much negotiation by organizational elements of the U.S. government, primarily AEC, DoD, and DOI, representatives of the TTPI (of which the Marshallese people of Enewetak Atoll were part), and the President as the final decision maker. Use of the atoll as a nuclear testing site required moving and relocating the Enewetak Atoll inhabitants to Ujelang Atoll, another neighboring atoll a few hundred miles away. Enewetak Atoll was developed into a logistics support base and proving ground for nuclear testing. Enewetak Atoll was part of the Pacific Proving Ground in the Marshall Islands, which included another nuclear test site, Bikini Atoll. (DNA, 1981)

[6] In this report, "Island Name" means the name used by the people of Enewetak, and "Site Name" means the name assigned by the U.S. government, mainly for use during the atomic testing program.

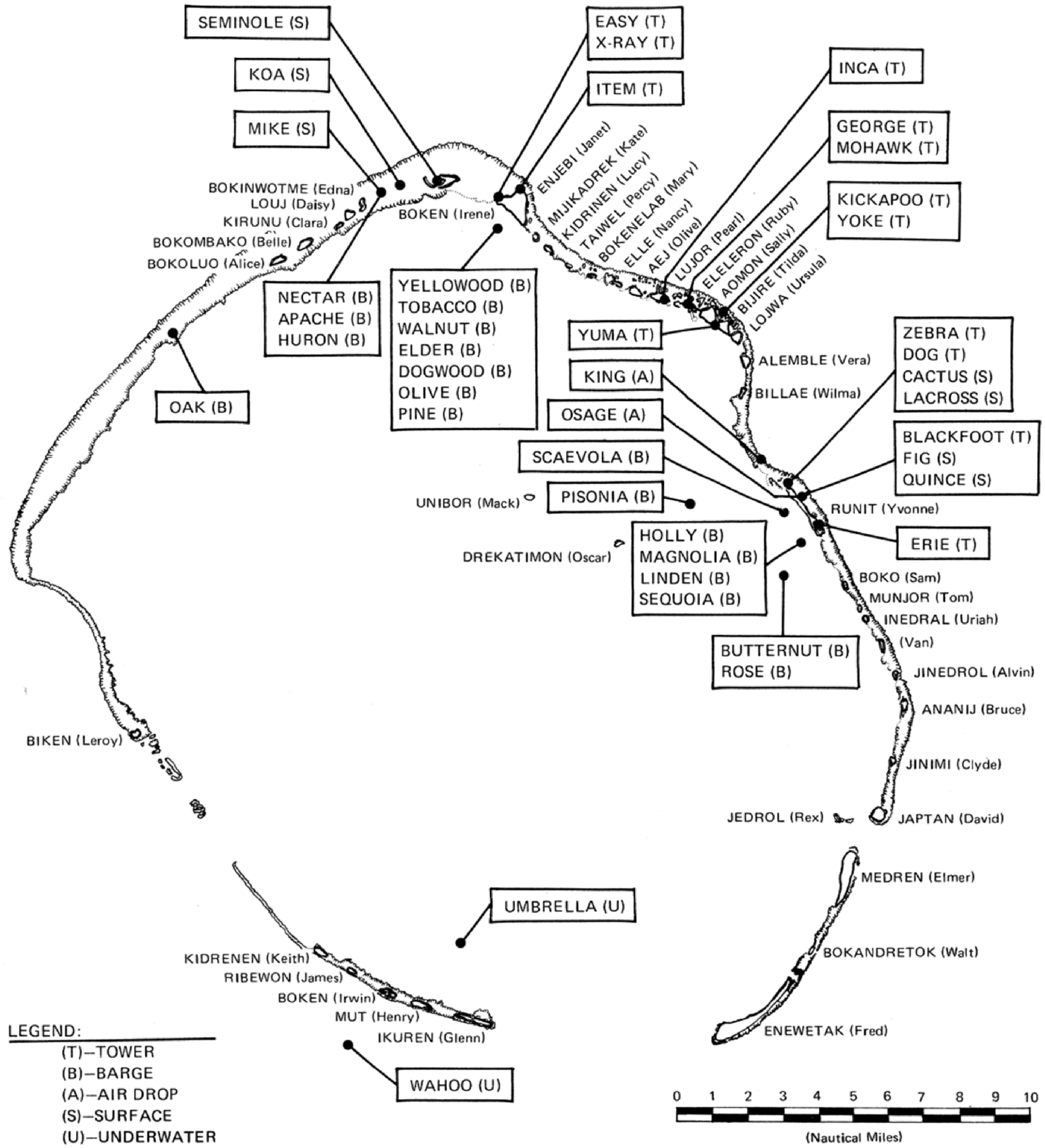


Figure 2. Enewetak Atoll islands and nuclear detonation sites (DNA, 1981)

Table 1. Compendium of island names and corresponding site names

Island Code[*]	Site Name	Island Name[†]		Island Name	Site Name
Northern Islands				Aej	Olive
FA	Alice	Bokoluo		Alembel	Vera
FB	Belle	Bokombako		Ananij	Bruce
FC	Clara	Kirunu		Aomon	Sally
FD	Daisy	Louj		Bijile	Tilda
FE	Edna	Bocinwotme		Biken	Leroy
FH	Helen	Bokaidrik		Billae	Wilma
FI	Irene	Boken		Bocinwotme	Edna
FJ	Janet	Enjebi		Bokaidrik	Helen
FK	Kate	Mijikadrek		Bokandretok	Walt
FL	Lucy	Kidrinen		Boken	Irene
MP	Percy	Taiwel		Boken	Irwin
FM	Mary	Bokenelab		Bokenelab	Mary
FN	Nancy	Elle		Boko	Sam
FO	Olive	Aej		Bokoluo	Alice
FP	Pearl	Lujor		Bokombako	Belle
FR	Ruby	Eleleron		Drekatimon	Oscar (coral head)
FS	Sally	Aomon		Eleleron	Ruby
FT	Tilda	Bijile[‡]		Elle	Nancy
FU	Ursula	Lojwa		Enewetak	Fred
FV	Vera	Alembel		Enjebi	Janet
FW	Wilma	Billae		Ikuren	Glenn
FY	Yvonne	Runit		Inedral	Uriah
Southern Islands				Japtan	David
MS	Sam	Boko		Jedrol	Rex
MT	Tom	Munjor		Jinedrol	Alvin
MU	Uriah	Inedral		Jinimi	Clyde
MV	Van	—[§]		Kidrenen	Keith
MA	Alvin	Jinedrol		Kidrinen	Lucy
MB	Bruce	Ananij		Kirunu	Clara
MC	Clyde	Jinimi		Lojwa	Ursula
MC	David	Japtan		Louj	Daisy
MR	Rex	Jedrol		Lujor	Pearl
ME	Elmer	Medren (aka Parry)		Medren (aka Parry)	Elmer
MW	Walt	Bokandretok		Mijikadrek	Kate
MF	Fred	Enewetak		Munjor	Tom
MG	Glenn	Ikuren		Mut	Henry
MH	Henry	Mut		Ribewon	James
MI	Irwin	Boken		Runit	Yvonne
MJ	James	Ribewon		Taiwel	Percy
MK	Keith	Kidrenen		Unibor	Mack (coral head)
ML	Leroy	Biken		—[§]	Van
MO	Oscar (coral head)	Drekatimon			
MM	Mack (coral head)	Unibor			

[*] Island code was assigned by JTG.

[†] As confirmed by the Enewetak people during the Ujelang field trip of July 1973 (or from Dr. Jack A. Tobin).

[‡] Shown as Bijire in DNA (1981).

[§] The Enewetak people had no name for this island.

The United States conducted 43 nuclear tests on Enewetak Atoll from 1948 to 1958. The tests ranged in yield from a few kilotons (kt) to megatons (Mt). Figure 2 also provides the locations within the atoll where the individual nuclear tests were conducted. The tests were primarily conducted in the atoll's northwestern and northeastern quadrants to minimize radioactive contamination to base camps on the southern islands. Each test caused measurable effects to some portions of the atoll's islands. Some produced major changes to the topography of some islands. Other changes noted were construction of buildings to house equipment and labs for measuring and recording nuclear effects (DNA, 1981). The visible effects of these changes include:

- Elugelab and Lidilbut islands and most of Bokaidrikdrik and Eleleron were obliterated.
- Large craters were formed on the reefs on the north end of Runit.
- Surface profiles of ground zero points were changed.
- Coconut palms and other vegetation were destroyed in many areas.
- Causeways, landfills, and the areas excavated for test preparations changed the topography of some islands, for example a constructed causeway stopped the water flow between Aomon and Eleleron.
- Large structures and bunkers for test measurements and observations remained after the testing.
- Semi-permanent buildings were left standing mostly in the southeastern islands.
- Tons of concrete rubble and metal debris were left in place after the tests.

Conditions not readily visible included contaminated soil and debris on many islands and contaminated waters in the surrounding lagoon and ocean, including contaminated sediments. Many miles of cable were laid in the lagoon and between some islands for instrumentation, communications, and the activation of nuclear devices. Radionuclides were also distributed in the form of radioactive debris, soil and water. Debris and soil were mostly on the surfaces of many islands and in the surrounding waters, and to a lesser extent in burial sites (crypts) and bunkers on certain islands. All of these effects had a significant influence on formulating plans and actual execution of cleanup operations.

Atmospheric nuclear testing ceased in 1962 in advance of the signing of the Limited Test Ban Treaty by the United States, UK, and USSR in 1963. In the early 1970s, the U.S. government decided that control of Enewetak Atoll should be returned to the TTPI (Johnston and Williams, 1972) and felt a moral and potentially legal obligation to remediate the atoll due to debris, unexploded ordnance, abandoned buildings, and atoll-wide radiological contamination and to resettle the Enewetak people with a supporting agricultural, housing, and community infrastructure. (DNA, 1981)

2.3 Enewetak Cleanup Project Summary

In 1972, representatives of the Office of Micronesian Status Negotiations (MSN), DoD, DOI and AEC discussed plans for the radiological cleanup, rehabilitation, and resettlement of Enewetak Atoll in the Marshall Islands resulting in a decision to conduct the ECUP project

(DNA, 1981). From 1972 to 1976, AEC, DNA, EPA, University of Washington, U.S. Air Force (USAF), TTPI, and the Enewetak people were involved in determining the on-going scope of work necessary to conduct the cleanup (DNA, 1981). From mid-1977 through March 1980, the cleanup was executed by DoD and involved Army, Navy, and Air Force units and personnel. During that time, the Department of Energy (DOE) performed radiological characterizations and certifications, and the DOI conducted the rehabilitation and resettlement project.

The primary purpose of the radiological debris and soil cleanup was to reduce the TRU elements (plutonium and americium) to levels that would not pose long-term hazards to the returning people of Enewetak. While removing TRU-contaminated debris and soil, other radionuclides present were also removed. The cleanup consisted of three separate efforts:

- Transfer and disposal of uncontaminated ("green"), contaminated ("yellow") debris, and structures into the lagoon, see Section 3.2.2 for definition of green and yellow debris
- Crater-entombment of radiologically contaminated debris and structures transported from the islands
- Crater-entombment of radiologically contaminated soil excised on the islands and then transported from the islands.

The crater formed by the Cactus event on Runit Island was established as a permanent disposal location for ECUP in 1977. The crater was used for entombment of contaminated soil and "red" debris; see Section 3 for debris classification. Contaminated soil was mixed with cement, attapulgite clay, and salt water to form a slurry that was placed in the crater using tremie equipment mounted on a floating barge. Contaminated debris requiring crater disposal, i.e., classified as "red", was placed in the crater with cranes, bulldozers, or dump trucks and encapsulated within soil-cement slurry. A concrete dome cap was used to seal the crater after it was filled with the radiologically contaminated soil-cement mix and debris. (DNA, 1981)

The atoll islands were classified based on intended use by the resettled Enewetak people as determined by an acceptable soil contamination level to which a given island would be remediated. Radiological soil survey results identified which islands required remediation. They formed the basis for the development of the remediation and radiological safety plans. Soil plutonium concentration levels determined the necessity and extent of soil remediation. Three levels of residual plutonium were used to guide decontamination activities:

- Level 1: Plutonium concentration greater than 400 pCi g^{-1}—soil removal by scraping
- Level 2: Plutonium concentration from 40 to 400 pCi g^{-1}—individual case consideration
- Level 3: Plutonium concentration less than 40 pCi g^{-1}—no cleanup required.

The soil survey results originally identified 12 islands with concentrations above the 40 pCi g^{-1} limit. However, not all of the 12 islands required remediation because they were not intended for residential use. The final island survey (DOE, 1982a) identified 30 islands below Level 3 criteria and they were classified for residential use. Seven islands with concentrations between 40 and 160 pCi g^{-1} were designated for agricultural use. Two islands with concentrations over 160 pCi g^{-1} were designated for food gathering. One island, Runit, the site of the Cactus Crater, was quarantined permanently (DNA, 1981).

The concentration range of 160 to 400 pCi g^{-1} was set as the criterion for islands from which food could be harvested, but planting for agricultural use was restricted. Islands with concentration ranges from 40 to 160 pCi g^{-1} were acceptable for harvesting and planting. Islands with concentrations below 40 pCi g^{-1} were suitable for habitation. The decision to quarantine Runit (concentration above 400 pCi g^{-1}) was based on reestablishing priorities against available resources. During the course of the cleanup operation, the decision was made not to cleanup Runit (DNA, 1981).

In 1986, the U.S. government returned Enewetak Atoll to the Republic of the Marshall Islands, formerly TTPI. Today, all of the islands, except Runit, and the lagoon are accessible. Runit remains quarantined due to residual sub-surface soil contamination and the presence of the Cactus Crater dome.

2.4 Cleanup Basis and Strategy

Initial plans and approaches started well before the U.S. government decision to conduct the actual cleanup. In the early 1970s, the AEC embarked on an island-by-island aerial radiological survey of Enewetak Atoll (AEC, 1973a) to derive ground-level radiation exposure rates associated with the beta and gamma-emitting radionuclides described later in Section 3. DNA commissioned an engineering survey and study of the various terrains and environments that would be encountered on the atoll (H&N, 1973) and prepared an Environmental Impact Statement (EIS) (DNA, 1975), taking into account the sensitivities of restoring the islands for safe re-habitation by the Enewetak people and for their self-sustainment. The EIS provided an exhaustive development of alternative cleanup plans and presented a best alternative choice for decision makers (DNA, 1975).

Management of the entire cleanup operation was assigned to a JTG reporting directly to the Commander, Field Command DNA (FCDNA). The JTG (Figure 3) was responsible for all aspects of the operation on Enewetak, including a comprehensive radiation safety program. After substantial planning, the personnel mobilization effort began in March 1977. Work on preparing for construction of the Lojwa base camp began in April 1977 and the first transportation units, including Navy landing craft and an Air Force Airfield Team arrived in May 1977. Also, an advanced party of the JTG arrived during the spring of 1977 to begin organizing the group. D-day occurred June 15, 1977 and efforts to organize the JTG and establish policies continued. Mobilization continued until November 1977. In practice, mobilization and cleanup efforts overlapped by several months. Some cleanup operations began long before November 17, 1977 and some mobilization efforts were not completed until much later (DNA, 1981).

Two islands, Enewetak and Lojwa were selected for development as base camps or residence islands, because levels of radiation were found to be at background levels comparable to those of the United States and their strategic locations enhanced cleanup operations. They required no radiological cleanup. Enewetak Island was the main base for operational administration, supply management, air transportation, and central communications. It was large enough to accommodate various buildings and support structures and support an air field long enough for handling large cargo aircraft, such as the USAF C-5A. Lojwa was the base camp to support the bulk of daily cleanup operations on the mostly contaminated northern islands. It

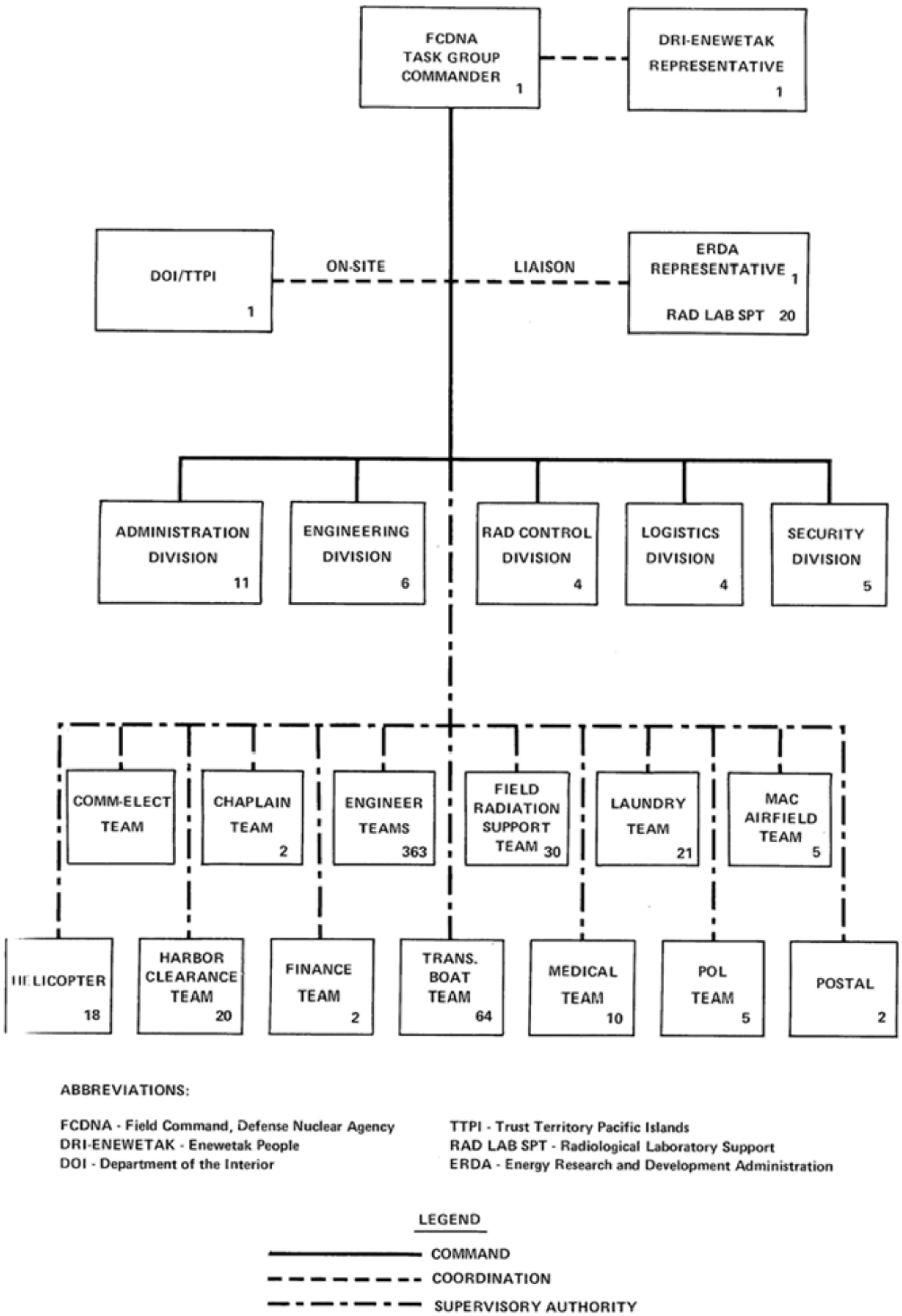


Figure 3. Joint Task Group organization (DNA, 1981)

facilitated daily travel to and from work sites to housing facilities by eliminating large distance time-consuming travel from housing facilities on Enewetak Island (DNA, 1981). Preparation for actual cleanup involved detailed radiological surveys to describe accurately any redistribution of the residual radioactive contaminants on the islands since the initial 1972 survey (AEC, 1973a). These began in July 1977 with surveys on Enjebi Island. Enjebi was chosen because of its ease of access and conduciveness regarding efforts to test out new procedures, including methods for brush clearing. Also, a tracked vehicle, configured for the in situ measurement of plutonium (IMP) was deployed to assess ground-level concentrations of TRU by the measurement of Am-241 activity. These initial surveys aided in working out the details of IMP operations, brush clearing, and soil sampling as well as implementing procedures for determining plutonium surface soil concentrations from IMP measurements.

By late August 1977, the techniques for the three separate efforts had been worked out, but concerns about the allocation of resources to complete the cleanup of items required by the EIS (DNA, 1975) caused priorities for the effort to change. Items requiring attention included removal of plutonium from the Aomon burial sites (crypts), removal of plutonium-contaminated soil from Boken, Lujor, and Runit, and removal of residual large building debris from Enjebi. There was a decision to establish three designated debris disposal sites in the Enewetak lagoon for the cleanup operations as shown in Figure 4 (DNA, 1981). Only contaminated debris meeting the radiological conditions to be considered as “yellow” debris were disposed of at these lagoon sites, see Section 3.2.

Other preparations including clearing of channels to the primary islands, and location and disposition of unexploded ordnance by Service explosive ordnance disposal (EOD) personnel were completed by the end of October 1977. Cleanup on Lujor officially began on November 1, 1977. Operations continued but experienced two tropical storms—Typhoon Mary in December 1977 and Typhoon Nadine in January 1978 that interrupted operations. Upon resumption of cleanup activities, the established DNA cleanup priorities were to:

- Continue cleanup of Aomon for agricultural use, with an option to cleanup to residential levels
- Begin soil cleanup on Enjebi beginning with the areas of highest contamination; and after considering available resources for Boken and Lujor
- Cease work on Enjebi
- Concentrate on soil removal on Boken and Lujor.

In addition, cleanup on Runit was again considered and decisions made to cleanup small and large areas, with plutonium concentrations over 160 pCi g^{-1}, as resources were available, but not use any special resources (DNA, 1981).

Soil cleanup presented several management and technical problems that required reassessments of some of the original plans, introduced delays in completion of certain tasks, and required confirmation of cleanup levels and disposal plans. Nevertheless, cleanup was carried out using an orderly process of assessment, planning, and testing of procedures before full-scale implementation. The testing involved balancing considerations for radiation safety, and other safety issues, with the efficiency, practicality, and effectiveness of the proposed procedures.

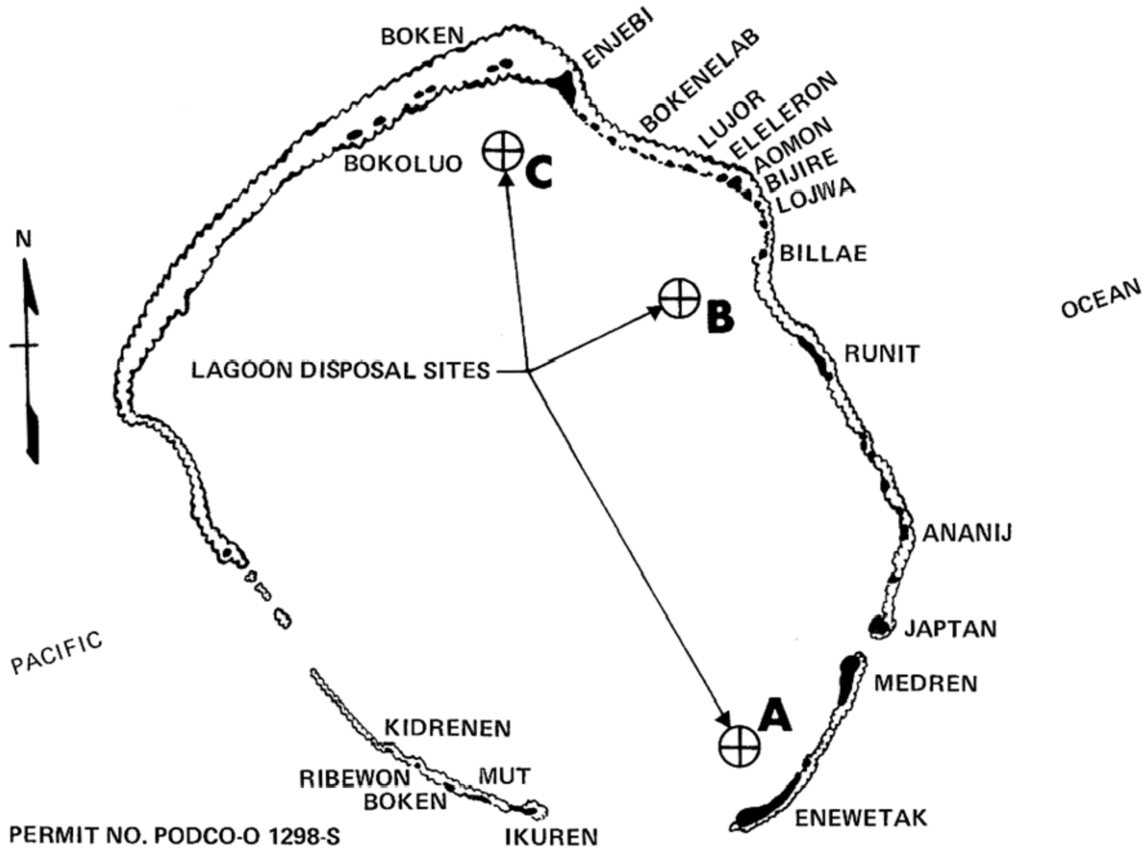


Figure 4. Lagoon disposal sites

Pilot testing of alternative soil removal processes began in March 1978 and considered the following basic steps:

- Identify the site and scope of work
- Implement radiation safety and control procedures
- Survey and stake the boundaries of soil excision areas
- Remove excess brush
- Excise (scrape surface with bulldozer blade) the area and windrow (bulldoze into long line piles) excised soil to prepare for movement to landing craft
- Resurvey the excised area using the IMP and/or soil samples
- Repeat previous steps until residual soil concentrations were reduced to desired levels
- Transport soil from windrows to beach stockpiles
- Transport soil from beach stockpiles to stockpiles on Runit.

Each of the basic steps was fully tested and evaluated to satisfy safety and efficiency criteria. All of the operations were conducted with the oversight of the Field Radiation Support Team (FRST) radiological control personnel under the direction of J-2 health physicists. Ultimately, surface soil removal was accomplished using bulldozers for scraping 6-inch deep cuts and windrowing. (DNA, 1981)

Transport from cleanup sites to contaminated island beaches used a variety of trucks depending on the ability to negotiate the sand surface, beach, etc. Soil transport from the beach to Runit was conducted with bulk haul of the soil in modified landing craft, using fully tested procedures. Sampling for airborne activity concentrations during transport confirmed the operations could be conducted without respiratory protection while in transit.

A second cleanup of Lujor was completed during June and July 1979 after a resurvey identified areas with levels above the 160 pCi g^{-1} limit. Also, cleanup of the Aomon burial sites (crypts) required unique efforts because of their unknown construction and contents. Following several additional studies and excavations beginning in July 1978, initial excavations began in January 1979 and the entire operation including restoration was completed by the end of May 1979. Cleanup of Runit remained the only outstanding effort (DNA, 1981).

The Runit cleanup involved contaminated small areas (hotspots) and plutonium-coated, metallic fragments, as well as contaminated debris. The cleanup proceeded in parallel with completion of the tremie operations to fill the crater and to place the concrete cap. While conducting a survey of Runit, cleanup teams were faced with discovery of additional high (red level) survey readings greater than 100 μR h^{-1} at one foot on debris requiring crater disposal. Discoveries of additional red-level debris on Runit in November 1979 and a few other islands in October 1978 continued until completion in February 1980. Afterwards, the final concrete capping of the Runit crater was accomplished by March 31, 1980. Following additional restoration activities on Enewetak Island and demobilization activities, the project proceeded to completion. On May 13, 1980, the demobilization forces departed Enewetak Atoll, 3 years after the initial elements arrived on Enewetak Atoll to initiate ECUP (DNA, 1981).

2.5 Functional Organization of the Population of Interest

As described in Section 2.4, management of the cleanup operation was assigned to a JTG that was responsible for all aspects of the operation on Enewetak. The JTG was staffed by individuals from the Army, Navy and Air Force in five divisions that reported to the Commander, JTG (CJTG). The CJTG was also given supervisory authority for direction and control over the Military Service Components of the JTG. The total number of participants and units composing the military service elements and the FCDNA JTG that make up the ECUP Population of Interest (POI) are shown in Table 2.

Table 2. Military Service component and DNA/JTG staffing of the Enewetak cleanup population of interest

U.S. Army Element	U.S. Navy Element	U.S. Air Force Element	FCDNA/JTG
2,670	2,207	740	246
• Engineer Units • Helicopter Team • LARCs and amphibious vehicle operations • Chaplain Team • Finance Team • General Laundry Team • Decontamination Laundry	• Harbor Clearance Units and Water-Beach Cleanup Teams • Intra-atoll Transportation • Radiological and laboratory technicians	• Field Radiation Support Team • Medical team • Radiological and lab technicians • Communications-electronics team • Petroleum-oil-lubricants team • Airfield team • Postal team	• Commander, JTG • Administration • Engineering • Radiological Control • Logistics • Security

Section 3.

Radiological Aspects of the Enewetak Atoll Cleanup Project

3.1 Radiological Condition of Enewetak Atoll Prior to Cleanup Activities

The radiological surveys performed in the years leading to the cleanup project served as the basis for identifying the radionuclides of concern, from a dose perspective, as Cs-137, Sr-90, Co-60, Pu-239, Pu-240 and Am-241. These radionuclides were produced from the nuclear test detonations and were deposited throughout the islands on vegetation, ground surfaces, lagoon sediment and water, as well as the remaining buildings, building rubble, and equipment used during the atmospheric test era. Cesium-137 (half-life 30.0 years) and Sr-90 (half-life 29.12 years) were direct by-products originating from the fission of the nuclear fuel. Cobalt-60 (half-life 5.27 years) originated from the neutron activation of elemental cobalt contained in iron and steel or scrap metal and building materials during the nuclear detonation. Plutonium-239 (half-life 24,065 years), and Pu-240 (half-life 6,537 years) that were not consumed by the nuclear detonations remained at the atoll, and Am-241 (half-life 432.2 years) was produced as a decay product of Pu-241 (half-life 14 years), which would have been present as a small fraction of the total plutonium, typically less than 1 percent by mass (DOE, 1982a).

Small quantities of the TRU radionuclides Pu-238 and Pu-241, and fission products, such as antimony isotope Sb-125 and europium isotope Eu-155, also remained at Enewetak Atoll, but they were not significant in ECUP dose assessments. Although analysis results for Pu-241 from the 1972 Enewetak radiological survey were not located, analyses for Pu-238 in soil were conducted but it was often not detected. When positive Pu-238 concentrations were measured, they were typically much less than Pu-239 (AEC, 1973a). In addition, soil activities of other fission products, primarily Sb-125 and Eu-155, were measured in trace amounts, but calculations indicated that these radionuclides contributed at most an additional 3 to 5 percent of the total 1972 exposure rates (AEC, 1973a). Because the primary additional fission products have smaller radioactive half-lives than those of the radionuclides of concern listed above, they would contribute even less to the total exposure rates during ECUP than the 3 to 5 percent estimated for 1972. Therefore, because of their low concentrations and/or radiological decay characteristics, these additional radionuclides are not included in ECUP radiological dose assessments. However, these shorter-lived fission products are included in the dose estimates of personnel who visited Enewetak Atoll prior to the ECUP in the mid-1960s as discussed in Section 8.4.

DNA and AEC jointly conducted an extensive island-by-island radiological survey of the atoll in 1972. Prepared plans and results for the effort are available in AEC (1973a, b) and DOE (1982b). Section 4 presents an extracted summary of the survey results showing island-by-island measurements of external exposure rates and soil concentrations in 1972. These measurements provided the baseline for the planning and conduct of the cleanup operations.

3.2 Radiation Safety Program and Radiological Controls

The foremost goal of the cleanup operation was to maintain radiation exposures to personnel according to the "ALARA" principle, i.e., "as low as reasonably achievable" (DNA, 1981). High-level governmental interest kept intense focus on this goal. In fact, according to

DNA, “No other aspect of the Enewetak radiological cleanup operation received the attention, priority, and detail that the radiation safety (RADSAFE) program received” (DNA, 1981). The program discussed below describes the cleanup policies and guidance and the radiological control practices implemented to minimize radiation exposure.

Potential internal exposure from all of the residual radionuclides (see Section 2.2) presented the most significant risk especially from the alpha particles emitted by Pu-239/240 and Am-241 and, to a lesser extent, from the beta particles emitted by Co-60 and Sr-90. Almost all Co-60 was entrained in steel and Sr-90 was highly mobile in the environment. In addition, x-rays and gamma rays emitted by Co-60 and Am-241 contribute to the internal exposure. The radiations emitted by these radionuclides present minimal exposure risk when outside the body, but upon entry to the body via inhalation, ingestion, or wounds, bodily tissues and organs could be irradiated. Inhalation of radioactive contaminants suspended in the air was the primary route of entry. Intake of the isotopes of plutonium and americium was of most concern because they emit alpha particles, were present in substantial quantities at Enewetak, and tend to be retained in the body for periods significantly longer than the other radionuclides.

3.2.1. Radiation Safety Program

Three levels of on-site administration consisting of the Radiation Protection Officer (RPO), the Radiation Control Committee (RCC), and the FRST managed the radiation protection program. The duties of the RPO, defined in AR 40-14 (USA, 1975) as “the individual designated by the commander to provide consultation and advice on the degree of hazards associated with ionizing radiation and the effectiveness of measures to control these hazards,” were fulfilled by the J-2 officer on the JTG staff (Figure 3), designated as the RPO for Enewetak Atoll. A staff of radiation specialists within the J-2 organization engaged in day-to-day operational activities for the RPO, with alternate RPOs providing field oversight of the FRST activities.

Radiation safety strategy considered that personnel engaged in cleanup operations involved digging, construction, and soil hauling, which could result in significant resuspension of radioactive contamination. To this end, a continuous assessment and careful management of all potential exposure pathways were maintained. To assure that radiation doses were minimized, radiation protection program guidance adhered to federal guidelines and regulations which required radiation exposures be kept ALARA—a philosophy still in use today.

The regulations contained in Title 10, Code of Federal Regulations (CFR), Part 20 (USNRC, 1975) were adopted for personnel radiation dose limits during ECUP. Army Regulation (AR) 40-14, “Control and Recording Procedures for Occupational Exposures to Ionizing Radiation” (USA, 1975) implemented the Federal radiation dose limits contained in these regulations which were in effect at the time in the United States for radiation workers. The dose limits are summarized below:

1) The accumulated dose equivalent of radiation to the whole-body, head and trunk, active blood-forming organs, gonads, or lens of the eye will not exceed:
   - 1.25 rem in any calendar quarter, nor
   - 5 rem in any calendar year.
2) The accumulated dose equivalent of radiation to the skin of the whole-body (other than hands and forearms), cornea of the eye, and bone will not exceed:

- 7.50 rem in any calendar quarter, nor
- 30 rem in any calendar year.

3) The accumulated dose equivalent of radiation to the hands and wrists or the feet and ankles will not exceed:
   - 18.75 rem in any calendar quarter, nor
   - 75 rem in any calendar year.
4) The accumulated dose equivalent of radiation to the forearms will not exceed:
   - 10 rem any calendar quarter, nor
   - 30 rem in any calendar year.
5) The accumulated dose equivalent of radiation to the thyroid, other organs, tissues, and organ system will not exceed:
   - 5 rem in any calendar quarter, nor
   - 15 rem in any calendar year.
6) Individuals under 18 years of age, females known to be pregnant, and occasionally exposed individuals will not be exposed to a whole-body dose equivalent of more than:
   - 2 millirem in any one hour, nor
   - 100 millirem in any 7 consecutive days, nor
   - 500 millirem in any calendar year, nor
   - 10 percent of the values in 2., 3., 4., and 5. above for other parts of the body.
7) Individuals over 18 years of age, but who have not yet reached their 19th birthday, will not be occupationally exposed to ionizing radiation exceeding:
   - 1.25 rem dose equivalent to the whole body in any calendar quarter, nor
   - 3 rem in the 12 consecutive months prior to their 19th birthday.

The RCC reviewed procedures involved in the handling of radioactive materials. It made recommendations concerning protective measures required in radiologically controlled areas, and monitored the implementation of the Enewetak Atoll radiological protection program. The committee, chaired by the JTG Deputy Commander/Chief of Staff, met at least once a calendar quarter. Other committee members included the J-2, the Engineering Management Officer (J-3), the Assistant J-3 (Atoll Safety Officer), Service Element Commanders, the Staff Surgeon, the Enewetak Radiation Support Project (ERSP) manager, and the FRST Non-commissioned Officer in Charge (NCOIC). The FRST implemented the atoll radiation protection program at each worksite.

The J-2 tailored the general guidance to the situations existing at Enewetak by developing 18 Standing Operating Procedures (SOPs) and 12 Enewetak Atoll Instructions (EAIs) (DNA, 1981) (see Appendix H. for a topical listing of SOPs and EAIs). After RCC and CJTG approval, these documents informed workers of what to do and how to carry out radiation safety procedures designed to keep personnel exposures ALARA. Personnel protection equipment (PPE) was a means to isolate personnel from potential internal sources of exposure and surface contamination on the body. Enewetak Atoll Instruction No. 5707.1, Personnel Protection Levels, established the basic policies and procedures and established four basic levels of personnel protection (I through IV) including two sublevels within levels II and III (Table 3). The levels allowed for a full range of protective outerwear from normal work clothing to complete encapsulation of the individual within protective clothing and mask. The level required was that most appropriate for the potential hazard, and was evaluated continuously at each work site on each island by the FRST personnel.

The action levels were indicators of the radiological status of a given island's situation and provided points at which specific activities should occur, thus the term action level. The first action level was set at one-tenth of the levels noted in Table 3, and the second at one-half of the levels. If an action level was reached, the FRST members performed the actions specified and alerted the RPO to the potential hazard development. As a matter of basic policy, eating, drinking, and smoking were strictly regulated to minimize contamination that could enter the body by these routes (EAI 5605 referenced in Appendix H). Likewise, careful attention was paid to immediately identify any cut, wound, or break in the skin to minimize the probability for intake into the body (EAI 5710 referenced in Appendix H).

3.2.2 Radiological Controls

3.2.2.1 Radiation Controlled Areas – Equipment and Personnel

The FRST strictly managed access to controlled islands by the implementation of procedures that restricted and controlled personnel movements. Controlled Island Access forms provided a daily log of an individuals' presence on these islands and the use and type of protective clothing and equipment employed. A sample of the form is shown in Figure 5 and these logs became part of the official ECUP record. The degree of radiological protection provided by clothing and respiratory protection equipment was specified by the criteria shown in Table 3. The program included the radiological monitoring of personnel, vehicles, and equipment. Personnel exiting a radiation-controlled area were monitored for contamination. Measurements determined the level of contamination and the extent of personnel decontamination required, if any, before release from the controlled area. In addition, monitoring was used to document whether the equipment was cleared for release for unrestricted use.

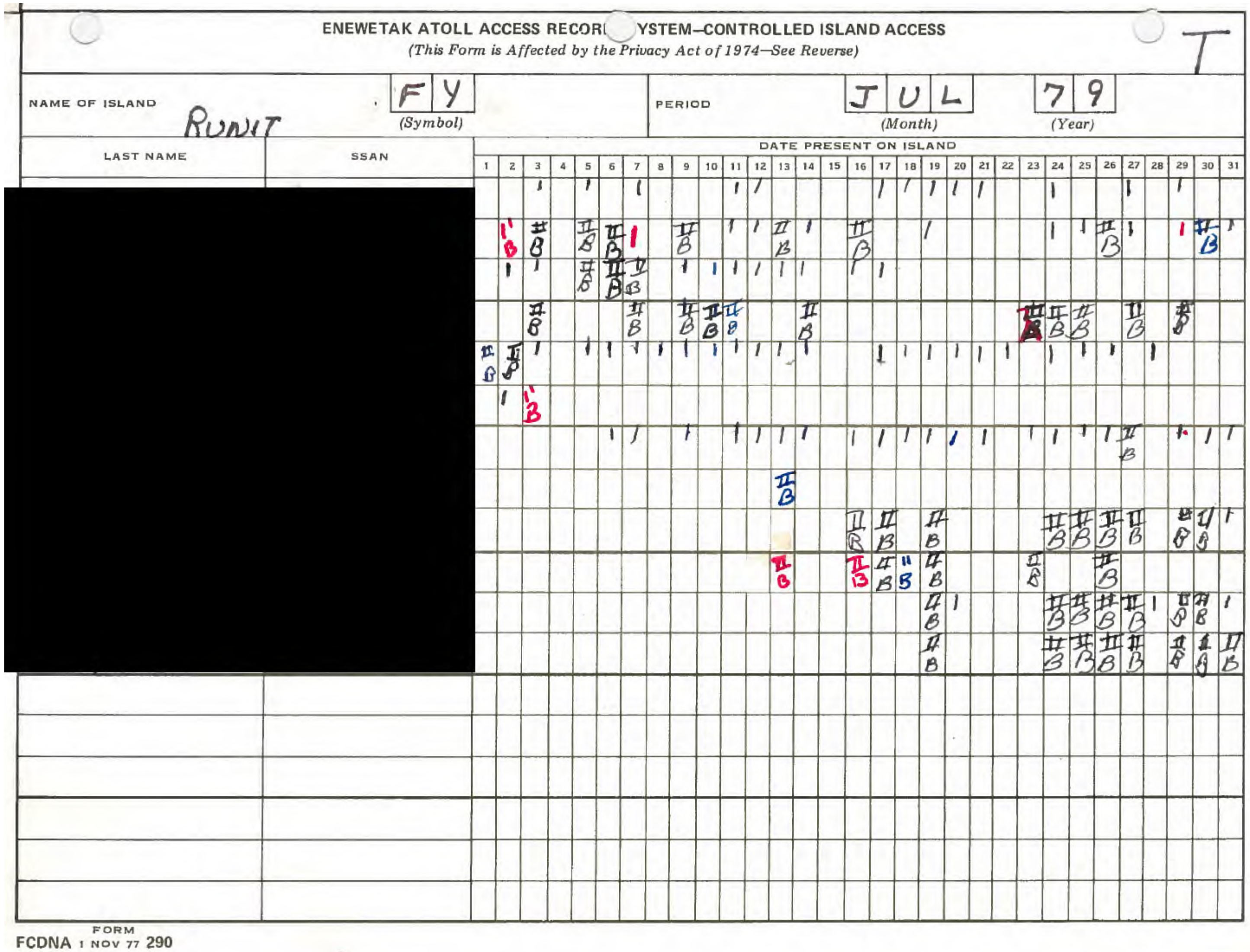
Two sets of criteria were applied for contamination control: one for personnel leaving a radiation area through a hot line, and the other for vehicles and equipment being moved to a radiologically clean area (DNA, 1981).

For personnel, the following criteria were used:

- Alpha skin contamination limit - Must not exceed 200 dpm per 100 cm^2 at contact
- Beta skin contamination limit - Must not exceed 400 dpm per 15 cm^2 at 1 inch

For vehicles and equipment, the following criteria were used:

- Alpha radiation surface contamination limit - Must not exceed 1,000 dpm per 100 cm^2 fixed on, or 20 dpm per 100 cm^2 removable from the surface
- Beta radiation surface contamination limit - Must not exceed 5,000 dpm per 100 cm^2 fixed on, or 200 dpm per 100 cm^2 removable from the surface
- Gamma radiation limit - Must not exceed 15 $\mu R\ h^{-1}$ at 1 foot from the surface



ENEWETAK ATOLL ACCESS RECORD SYSTEM—CONTROLLED ISLAND ACCESS

(This Form is Affected by the Privacy Act of 1974—See Reverse)

T

NAME OF ISLAND Runit | F Y (Symbol) | PERIOD J U L (Month) | 7 9 (Year)

LAST NAME	SSAN	DATE PRESENT ON ISLAND
[redacted]		

FCDNA FORM 1 NOV 77 290

Figure 5. Controlled Island Access Form – Sample for Runit, July 1979, with personally identifiable information redacted

Table 3. Personnel radiation protection levels

<table>
<tr><th rowspan="2">Level*</th><th rowspan="2">Protective Clothing</th><th rowspan="2">Personnel Monitoring Areas</th><th colspan="3">Action Levels</th></tr>
<tr><th>Personnel</th><th>Air</th><th>Ground</th></tr>
<tr><td>I</td><td>None</td><td>Boots
Hands
Hair</td><td rowspan="3">Alpha < 60 cpm
Beta < 200 cpm
Gamma < 15 μR h^{-1}</td><td rowspan="2">Alpha < 55 cpm h^{-1}
Beta < 3,250 cpm h^{-1}</td><td>Alpha < 300 cpm
Beta < 540 cpm
Gamma < 2,000 μR h^{-1}</td></tr>
<tr><td>II</td><td>A. Rubber boots

B. Rubber boots and surgical masks</td><td>As above plus arms and legs</td><td rowspan="2">Alpha < 3,000 cpm
Beta < 7,200 cpm
Gamma < 2,000 μR h^{-1}</td></tr>
<tr><td>III</td><td>A. Rubber boots, gloves (as appropriate), full-face or half face positive pressure respirator

B. Same as IIIA plus anticontamination clothing</td><td>Whole Body</td><td rowspan="2">Alpha< 5,500 cpm h^{-1}
Beta < 3,250 cpm h^{-1}</td></tr>
<tr><td>IV</td><td>Same as IIIB except gloves are now required, a full-face mask is required, and all openings in clothing are taped shut</td><td>Whole body</td><td>Alpha < 300,000 cpm
Beta < 7,200 cpm
Gamma < 2,000 μR h^{-1}</td><td>Alpha < 300,000 cpm
Beta < 7,200 cpm
Gamma < 2,000 μR h^{-1}</td></tr>
</table>

* Table from DNA (1981)

3.2.2.2 Contaminated Soil and Debris

Radiological criteria were established for the disposal of contaminated soil and debris. All contaminated soil was transported to Runit for disposal in the Cactus Crater. Contaminated debris was disposed of either in the Cactus Crater or at designated locations within the Enewetak Atoll lagoon shown in Figure 4, in accordance with the following criteria:

- Red (C – Crater) - Gamma radiation level taken within 1 foot of object ≥100μR h^{-1}
- Yellow (L – Lagoon) - Gamma radiation level taken within 1 foot of surface >15 μR h^{-1}, but <100 μR h^{-1}
  - Beta radiation level >5,000 dpm per 100 cm^2 at contact
  - Alpha radiation level >1,000 dpm per 100 cm^2 at contact
- Green (R – Release) - Below all "Yellow" limits.

3.2.2.3 Personnel Dosimetry

All personnel entering any controlled island were required to wear a dosimetric device; e.g., a film badge, a self-reading pocket dosimeter, and/or a thermoluminescent dosimeter (TLD). Personnel dosimetry provided the means by which an individual's external beta/gamma dose could be measured and documented. The primary dosimetric device was the film badge—as prescribed by AR 40-14 (USA, 1975). The U.S. Army Lexington-Blue Grass Depot Activity (LBDA) provided film badge dosimeters to the ECUP. They were issued on-site and returned to LBDA for evaluation per AR 40-14 (USA, 1975). The dosimetry results were returned to Enewetak and recorded on DD Forms 1141. Dosimetry results were sent to the medical facility at the individual's base of permanent assignment at first. Retroactively, they were sent directly to the applicable Service Dosimetry Center. In response to a Radiation Safety Audit and Inspection Team (RSAIT) audit recommendation, the JTG were able to effect changes to policies and procedures that were identified as redundant and unnecessary. Whenever film badges were damaged or lost, and when supplemental dosimetry was not used, JTG assigned administrative doses, computed according to methods approved by the Surgeon General of the Army (LBDA, 1978). Later, the methods were amended by FCDNA to supersede the initial administrative doses with recalculated administrative doses (FCDNA, 1978).

3.2.2.4 Air Sampling, Nasal Smears, and Urine Bioassays

An air sampling program was an important part of the radiological controls for internal exposures. It provided a basis for the FRST to establish respiratory protection levels and to document airborne radionuclide levels in work and living environments. Extensive air sampling was conducted in these areas to monitor air concentrations for comparison with Maximum Permissible Concentrations (MPCs) based on the exposure guidelines shown in Table 3. The MPCs in air established by the U.S. Nuclear Regulatory Commission (USNRC) (USNRC, 1975) were used to set limits for these environments. The MPC for insoluble plutonium in air, which is 40 pCi m^{-3}, was based on 40 hours per week occupancy for a workweek. Since the ECUP workweek was typically 60 hours, the MPC was adjusted to 27 pCi m^{-3}. In living environments, such as Lojwa base camp, the general population MPC was adjusted based on a 168-hour week (24 hours a day for 1 week).

Airborne action levels were set at 10 and 50 percent of the MPCs (DNA, 1981). The 10-percent MPC action level required nasal smears to be taken from all personnel in the area not wearing respiratory protection, according to the procedures in FCRR SOP 609-04.01 (FCRR, 1978a). The 50-percent MPC action level also required that respiratory protection be worn if work was to continue per SOP 608-05 (FCRR, 1977a). When these action levels were detected, all contaminated smear(s) and air filter(s) were expeditiously transferred to the Radiological Laboratory for analysis (DNA, 1981).

In addition to the 10-percent action level, nasal smears were obtained whenever deemed appropriate based on conditions such as air sampling results or concern for radioactivity levels in a given work area, to assess the potential for uptake into the body (FCRR, 1978a). While the nasal smears gave an immediate but only rough indication of a potential intake by measuring radioactive particles trapped in the nose, they did not indicate whether an intake actually occurred or how much radioactive material may have been inhaled (DNA, 1981).

Nasal smears were supplemented by urine bioassays whenever applicable action levels were exceeded. In the event of an intake, urinalysis would provide the best way to determine internal dose based on the circumstances. In addition, all individuals who spent more than 30 days on radiologically controlled islands were required to submit a urine sample at the end of their assignment before departure from the atoll. All samples consisted of an individual's urine output for a 24-hour period. Samples were shipped for analysis to the USAF Occupational and Environmental Health Laboratory (USAF OEHL) at Brooks AFB, Texas (DNA, 1981). Details of the urine bioassay procedures can be found in (FCRR, 1978a).

3.2.2.5 Independent Radiation Safety Audits and Inspections

DNA Director commissioned 10 RSAITs to provide independent inspections of the radiological protection program and evaluate its efficacy. The team was given the widest authority to review all aspects of the RADSAFE program. The Director, Armed Forces Radiobiology Research Institute (AFRRI) headed the team, which included members, generally health physicists, from each of the Services and ERDA/DOE. The RSAIT performed broad-range inspections of radiation safety as well as environmental and occupational safety on the atoll. They reviewed all established procedures to ensure that radiation safety was achieved. They then visited selected islands and inspected the actual practices to ensure that the procedures were adequately implemented.

The RSAIT made ten inspection visits to the atoll. Visits were scheduled as frequently as would be useful, initially quarterly and eventually about three per year. The duration of each inspection visit was scheduled to allow thorough observation of working conditions at the site of RADSAFE operation on RSAIT-selected islands of the cleanup project. Formal written reports were provided to Director, DNA; Commander, Field Command; and each of the Services upon conclusion of each trip. During the visits, the team identified and documented issues and recommended actions to improve cleanup operations.

The RSAIT provided an independent assessment mechanism to demonstrate compliance and identify operational difficulties with established policies and procedures. In particular, RSAIT reports confirmed that day-to-day practices, together with recommended improvements, were effective in controlling radiation exposures to ECUP personnel to the limits of federally established radiation standards.

3.3 Identification and Resolution of Radiological Control Issues

3.3.1. Film Badge Issues

The high heat and humidity conditions at Enewetak damaged 90 to 100 percent of the film badges during the initial months of the cleanup. Typically, this damage was such that, if the wearers had received low doses, they would have been obscured by damage, which compromised the film badge image used to quantify exposure. Administrative doses were calculated (LBDA, 1978; FCDNA, 1978) for the period of exposures of damaged film badges.

The first remedial action was to segregate badges visually found to be compromised by moisture from those that were dry when making shipments to LBDA. Previously, badges were aggregated together during shipment and wet badges comingled with dry badges in shipping boxes. This action reduced the number of damaged film badge to a level as low as 50 percent, still an undesirable result. An assistance visit to Enewetak by LBDA representatives led to the suggestion of sealing the film badges inside two plastic bags, with a small packet of desiccant in the inner bag. This method reduced film badge damage to as low as 11 percent in one issue period and as high as 20 percent in one other period, but did not eliminate the problem.

Another solution was the addition of U.S. Navy-provided CaF_2:Mn TLDs (DT-526/PD) to be worn as supplemental dosimeters. The TLDs were hermetically sealed devices, intended for underwater use by Navy divers, and were unaffected by heat and humidity such as at Enewetak. Additionally, they were read on site at the atoll and their readings recorded. Beginning in May 1978, workers on radiologically controlled islands were issued and wore TLDs and film badges together based on the availability of TLDs. This practice was not fully implemented until March 1979. (RSAIT, 1979a) TLDs also replaced self-reading pocket dosimeters as the dosimetry device for visitors.

3.3.2. Inoperable Air Samplers

Anecdotal ECUP veteran information indicated that the number of air samplers failing in use was high, especially the ones positioned on controlled access islands, and compromised the ability of the FRST team to adequately measure the airborne activity. Continuous air sampling was found to tax the performance of the equipment and frequent outages were experienced at the outset of the cleanup operation. The Precision Measurements Equipment Laboratory (PMEL) at Lojwa, a radiation instrument repair and calibration lab, maintained a staff and large number of replacement parts. The PMEL technicians were able to keep pace with outages by repairing samplers in the field or bringing them back to the lab for more complex maintenance while leaving behind an operable sampler (DNA, 1981). The repaired sampler was then made available to an exchange pool of equipment for other emerging repair/maintenance requirements. New samplers were ordered and kept in supply to replace those that were beyond restoration. The RSAIT did not report any findings that air sampler down time contributed to reduced capability to produce periodic assessments of airborne activity concentrations (RSAIT, 1977a, b; 1978a, b, c, d; 1979a, b).

3.3.3. Availability of Personal Protective Equipment

Initially in the cleanup operations, workers on controlled access islands wore full-face mask respirators. Later in the operation, forced air supply, high filtration masks replaced them. These masks were worn as a precaution to protect against airborne activity concentrations. The personal protective equipment (PPE) was bulky, physically confining and taxing, and a significant hindrance to the task of handling and removing contaminated debris and soil. During this initial period, air sample measurements were taken to assess radioactive air concentrations, but not enough samples were taken to establish when, where, and how often, the PPE should be worn. During this stage, based on limited data, practices to protect workers from airborne radioactivity were necessarily conservative.

As air concentration data were amassed on a larger number of controlled islands, the practice of wearing the bulky PPE was reevaluated and found to be unnecessary for adequate airborne source protection in most cases. Respiratory PPE was necessary whenever contaminated soil moving operations were performed (RSAIT, 1978c). Paper masks were found to be protective only for keeping hands, cigarettes, and other substances from entering workers' mouths (Cherry, 2018a) and for occupational health protection, such as in high dust conditions. The RSAIT became concerned that full-face respirators being worn for extended periods presented an occupational health hazard to workers and reduced efficiency for accomplishing work tasks (RSAIT, 1978a). The RSAIT strongly recommended that PPE requirements be based on air sample activity concentration measurements taken on specific controlled islands while work was being conducted, or by specific local, island-based decisions. The actions implemented from the RSAIT recommendation reduced the need for confining respirators in many cases to only using protective clothing and paper masks. This was the case for all controlled-access islands, except for Runit where it was common to find increased activity concentration levels requiring PPE that was more protective than paper masks.

ECUP veterans' perception was that the lack of availability of certain types of PPE, such as respirators, was the reason for using masks. The need to decrease worker PPE protection was actually based on review and sound technical analysis of air sampling data (RSAIT, 1978a and 1978c).

3.3.4. High Air Sampler Readings from Natural Radon

There were several situations of field air sample concentrations measuring higher than 10 percent of the MPC limit for alpha activity established by federal regulations (USNRC, 1975). However, in each of these cases, subsequent laboratory sample analysis showed the second readings were within the limit of 10 percent of the MPC. Dr. John Auxier, a senior health physicist who was on-site with the RSAIT, suggested during a discussion with an alternate RPO that the samples with high readings were counted right after their removal from the filter holders without sufficient time for decay of naturally occurring short-lived, alpha-emitting radionuclides such as radon progeny (Cherry, 1978). The senior health physicist indicated that scientifically accepted radiological practices called for letting samples remain unmeasured for at least two hours to allow for decay of radon progeny collected on the filters.

The Enewetak Rad Lab conducted a test by taking a controlled air sample to verify the presence, nature, and short half-lives of the radionuclides measured. An investigation determined that sample results that exceeded the action level of 10 percent of MPC were as a result of making alpha activity measurements before the two-hour waiting period had elapsed (Cherry, 1978). Following the test, the FRST field procedures were changed for any filter showing values at or above the 0.1 MPC action level on the initial measurement in the field to take a second reading at one-half hour after the initial reading (RSAIT, 1979a). No subsequent measurements above 10 percent of MPC limit were observed after the procedural change was implemented, confirming the new wait-time procedure was appropriate and effective.

3.3.5. High Individual Film Badge Readings

During a period of several days of surveying contaminated debris on a controlled island, four FRST technicians were given permission to bivouac on the island overnight for one night. The film badges of two of the technicians recorded doses of 0.400 rem and 0.430 rem, whereas the dosimeters of the other two technicians had zero readings. The high doses were about two orders of magnitude greater than expected based on average exposure rates on that island. An investigation was conducted that involved an assessment of the validity of the high film badge doses based on worker activities and known radiation exposure rates on the island. Although there appeared to be no known circumstances that could account for the recorded doses, it was possible to inadvertently expose the film badges if they had not been stored in a low background area when not in use. To test this possibility, a TLD dosimeter was placed in close contact with a radiological instrument check source. This TLD reading indicated an exposure rate of 5 mR h^{-1}, which was not consistent with the readings of the two technicians' film badges.

As a further test, TLD dosimeters were placed on a pile of contaminated steel debris on the island that was known to contain the activation product Co-60. The TLDs were exposed for 24 hours after being placed on the debris pile, with resulting readings of 0.519 and 0.465 rem. Reasonable agreement was observed between the technicians' film badge readings and the TLD readings resulting from exposure on the debris pile. The investigation concluded that it was likely that the two technicians did not receive the radiation doses measured by their film badges. (Bauchspies, 1978)

Section 4.

Radiological Survey and Monitoring

4.1 External Radiation

The Enewetak Radiological Survey performed by AEC in 1972 provided a database and general concepts for radiological cleanup. The predominant radioactive contaminants were identified as Sr-90, Cs-137, Co-60, Pu-239/240, and Am-241. An aerial survey for gamma radiation levels for all land areas was also conducted as part of the survey. Table 4 presents the average exposure rates at 1 meter above the surface derived from the aerial survey data for each island. The ranges shown are from measurements made with a Baird-Atomic, Inc. NaI scintillation instrument. Exposure rates determined in aerial surveys represent radiations emitted by soil, debris, and other contaminated material. (AEC, 1973a)

It is evident that the northern half of the atoll had higher exposure rates than the southern islands in 1972. However, one of the southern islands, Biken, had slightly elevated activities as compared to other southern islands. Biken is situated within the fallout patterns from several shots that took place on the eastern and northern sides of the atoll. In addition, the island's dense vegetation slowed down the migration of fallout particles through the soil by environmental processes (AEC, 1973a).

Starting in June 1978 and ending in October 1979, Navy TLDs were posted to monitor environmental radiation levels on a number of northern islands for extended periods of about 30 to 60 days. Actual monitoring sites on the islands were not noted in the hand-written logs found in the ECUP records, except for Enjebi (Janet), Boken (Irene), Aomon (Sally), Runit (Yvonne), Bijire (Tilda), and Lojwa (Ursula) where multiple sites of posted TLDs were specified. No records of the policy, procedures, and specific placement for the environmental TLDs have been found in the ECUP record collection at the time of this report's publication. Table 5 presents the net exposure rates derived from the environmental TLD data by island and locations, where given, during various monitoring periods. Appendix B-1 contains the complete environmental TLD data transcribed from the logs.

Lojwa Island was established as the location of a temporary base camp in the northeast sector of the atoll to support cleanup efforts in the northern islands, after it was removed from the list of controlled access islands in May 1977 (DNA, 1981; CJTG, 1977a). The environmental radiation levels on Lojwa were closely monitored and reported weekly on Enewetak Cleanup SITREP reports (hereinafter SITREP), numbered 5–124 in CJTG (1977b), during the period from June 26, 1977 to September 30, 1979.[1] This was to ensure that the external radiation levels continued to be within radiological limits allowed for ECUP residents on the island. The reported average exposure rates taken with a micro-R meter on Lojwa ranged from approximately 2 to 5 $\mu R\ h^{-1}$ (CJTG, 1977b).

[1] CJTG prepared and submitted weekly Enewetak Cleanup Situation Reports (SITREPs) from May 24, 1977 (SITREP No. 1) through May 14, 1980 (SITREP No. 155). This collection of SITREPs is cited as CJTG (1977b).

Table 4. Summary of exposure rates at 1 meter above the surface

Island Name	Site Name	Average Exposure Rate ($\mu R\ h^{-1}$ at 1 meter)*	Range of Exposure Rates ($\mu R\ h^{-1}$ at 1 meter)†
Bokombako	Belle	115	5–200
Bokoluo	Alice	81	4–170
Boken	Irene	80	3–560
Lujor	Pearl	70	1–400
Kirunu	Clara	42	5–100
Enjebi	Janet	40	2–150
Runit	Yvonne	33	1–750
Louj	Daisy	21.3	5–140
Mijikadrek	Kate	19	3–22
Kidrinen	Lucy	14	1–20
Eleleron	Ruby	14	1–42
Elle	Nancy	12	1–50
Aej	Olive	11	1–15
Bokenelab	Mary	10	2–12
Biken	Leroy	7.6	3–8
Aomon	Sally	7	3–110
Bocinwotme	Edna	6	5–8
Bijire	Tilda	6	2–11
Taiwel	Percy	5	2–11
Lojwa	Ursula	5	1–7
Alembel	Vera	5	1–6
Ribewon	James	3	0–5
Billae	Wilma	2	1–3
Ananij	Bruce	1.2	0–1
Boko	Sam‡	0.31	0–1
Munjor	Tom‡	0.31	0–1
Inedral	Uriah‡	0.49	0–1
-	Van‡	0.33	0–1
Jinedrol	Alvin‡	0.31	0–1
Jinimi	Clyde‡	0.15	0–1
Japtan	David‡	0.31	0–5
Jedrol	Rex‡	0.53	0–1
Medren aka Parry	Elmer‡	0.31	0–2
Bokandretok	Walt‡	0.18	0–1
Enewetak	Fred‡	0.26	0–1
Ikuren	Glenn‡	0.53	0–1
Mut	Henry‡	0.34	0–1
Boken	Irwin‡	0.54	0–2
Kidrenen	Keith‡	0.64	0–2

* Converted from 1972 aerial survey results for each island AEC (1973a).

† Ranges are from measurements made at each soil sampling location on each island using a Baird-Atomic survey instrument (AEC, 1973a).

‡ Activity levels on these islands are lower than the limit of sensitivity of the aerial survey equipment; for these, exposure rates are derived from soil sample activity concentration data (AEC, 1973a).

Table 5. Net average exposure rates by location and monitoring period derived from environmental TLDs posted on selected islands

Island	Exposure Rate (μR h^{-1})													
	Jun - Jul 78	Jul - Aug 78	Sep - Oct 78	Oct - Nov 78	Nov - Dec 78	Dec 78 - Jan 79	Jan - Feb 79	Feb - Mar 79	Mar - Apr 79	Apr - May 79	May - Jun 79	Jun - Jul 79	Jul - Aug 79	Aug - Oct 79
Bokoluo (Alice)	-	-	23	24	18	4	31	21	25	23	-	15	13	15
Bokombako (Belle)	8*	8	55	36	40	7	68	49	50	50	-	33	23	18
Bokenelab (Mary)	-	-	-	6	3	2	4	5	8	5	5	-	7	5
Edna's Daughter	-	-	-	-	6	5	11	6	8	7	11	5	11	8
Olive	-	-	1	5	1	1	4	3	2	2	2	2	2	3
Pearl (Park Bench)	-	-	-	-	-	-	-	-	23	12	12	-	-	-
Lujor (Pearl)	7*	3	11	0	1	2	0	-	-	-	-	-	-	-
Pearl (Beach)	-	-	-	-	-	-	-	3	2	3	1	0	5	-
Mary's Daughter	-	-	-	16	11	15	18	21	21	12	15	-	10	12
Janet (FRST Shack)	7*	-	-	-	-	-	-	-	4	-	-	-	-	-
Janet (Farm)	43*	36	3	9	5	4	8	8	6	9	6	6	9	4
Janet (Farm Shack)	13*	8	-	7	4	-	4	8	7	9	6	-	-	-
Janet (North Point)	33*	-	18	14	16	7	14	9	10	11	10	-	8	7
Janet (Trailer)	10*	8	-	5	0	2	8	5	3	4	3	9	3	2
Percy	-	-	-	-	4	3	7	8	13	7	7	7	3	2
Ruby	-	-	8	11	2	-	9	10	0	10	9	0	b	8
Nancy	-	-	-	16	9	10	13	12	13	12	10	-	-	7
Pearl's Daughter	-	-	-	-	9	27	11	13	14	8	13	8	26	5
Kate	-	-	3	6	4	5	7	7	8	7	6	7	4	0
Edna	-	-	-	9	2	10	7	6	7	5	7	-	1	10
Daisy	-	-	5	6	5	3	9	6	8	6	8	5	11	4
Clare	-	-	5	3	4	5	9	6	7	9	4	9	9	2

Table 5. Net average exposure rates by location and monitoring period derived from environmental TLDs posted on selected islands (cont.)

Island	Exposure Rate (μR h^{-1})													
	Jun - Jul 78	Jul - Aug 78	Sep - Oct 78	Oct - Nov 78	Nov - Dec 78	Dec 78 - Jan 79	Jan - Feb 79	Feb - Mar 79	Mar - Apr 79	Apr - May 79	May - Jun 79	Jun - Jul 79	Jul - Aug 79	Aug - Oct 79
Irene (Set 1)	17[*]	19	-	35	68	81	90	76	99	98[†]	9[†]	74[†]	97[†]	63[†]
Irene (Set 2)	-	-	0	13	9	7	11	9	10	6[‡]	12[‡]	10[‡]	11[‡]	7[‡]
Vera	8[*]	-	2	2	9	1	2	3	4	4	5	5	6	2
Sally (Hotline)	8[*]	4	-	3	1	[§]	8	3	3	3	0	-	-	-
Sally (Crypt)	-	-	3	7	5	6	10	7	9	11	-	-	-	-
Wilma	7	20	-	2	2	2	0	3	3	1	1	2	3	1
Lucy	-	-	0	6	3	6	7	5	8	6	5	7	3	2
Runit (N. Boat Ramp)	10[*]	-	13	2	4	-	-	0	7	6	-	5	-	1
Runit (S. Quarry)	6	0	2	13	4	-	-	3	7	-	1	3	1	-
Runit (Cactus Crater)	31[*]	-	24	25	16	-	23	20	-	29	24	22	25	13
Runit (Hotline)	21	-	0	2	0	1	4	3	4	0	1	5	0	1
Runit (Debris Pile)	-	-	2500	-	-	-	-	-	-	-	-	-	-	-
Runit (FRST Shack)	-	-	-	-	-	2	4	4	4	3	2	2	1	2
Lojwa (FRST)	-	3	2	2	0	0	4	1	2	3	2	1	1	0
Lojwa (PMEL)	-	-	-	2	0	0	2	1	2	0	2	1	0	1
Lojwa (Mess Hall)	-	-	-	2	0	1	2	1	1	0	1	-	-	2
Tilda (FRST Bunker)	7[*]	3	2	-	0	1	0	3	3	2	-	1	0	0
Tilda (EOD Small Bunker)	-	-	-	5	1	2	4	3	2	2	3	3	2	-

[*] This cell contains the gross reading from the TLD instrument and the corresponding exposure rate is based on the uncorrected reading.
[†] Located at pit on Irene
[‡] Located at bunker on Irene
"-" indicates blank cell, which means that TLD data are not available to calculate an exposure rate.

In Table 5, Irene (Set 1) and Irene (Set 2) represent two entries in each environmental TLD log with no further identification as to what areas of the island the two distinct measurements were made. However, from a comparison of exposure rates to those reported in AEC (1973b) from the 1972 survey of Irene, it appears that TLD Set 1 is from the main island of Irene where the crater from Shot Seminole at Operation Redwing was formed, and TLD Set 2 is from the western islet or what remained of Helen.

4.2 Soil Survey

The AEC conducted soil sampling on each island as part of the Enewetak Radiological Survey in 1972. The principal radionuclides present in the samples were the same as reported in Section 4.1. The samples were collected manually and analyzed in the laboratory. The mean values for soil activity concentrations in the top 15 cm of soil, shown in Table 6, were compiled and reported in DOE (1982a) for Pu-239/240, Cs-137 and Sr-90, and in AEC (1973a) and DOE (1982b) for Co-60. The mean concentrations of Am-241 are estimated from the mean concentrations of Pu-239/240 as discussed in Appendix G.

4.3 Debris Survey

Measurements of exposure rates from contaminated debris made during the cleanup period were not located for inclusion in this report. All debris was surveyed in accordance with FCRR SOP 608-02.02. The surveys were conducted primarily to classify debris into three disposal categories. The radiological criteria used to classify debris are described in Section 3. A large majority of debris collected was not contaminated. Only about 2.5 percent of the total volume of debris that was collected during ECUP was contaminated with radioactive material (DNA, 1981).

During the 1972 radiological survey of Enewetak Atoll's islands, measured contact exposure rates greater than the local ambient levels were reported for undisturbed scrap debris on Enjebi, Runit, Lujor, Eleleron, Aomon, and Bokoluo (AEC, 1973a). The exposure rate measurements are reproduced in Appendix K, except for Bokoluo. Bokoluo island was not included because it had no contaminated debris, except for the wreckage of a beached LCM, which had a recorded exposure rate of 8 mR h^{-1} (AEC, 1973a; DNA, 1981).

The contact exposure rate data for contaminated debris on the five islands were analyzed in detail using the maps and location data from Engineering Study reports prepared by Holmes and Narver (H&N) (H&N, 1973). The number of exposure rate measurements and the minimum, maximum and geometric mean are shown in Table 7. The geometric mean of each of the five datasets is not significantly different from the median and therefore is considered representative of the average debris exposure rate on each of the five islands.

Debris contact exposure rates were measured at 276 debris locations on these islands, with measurements at 250 locations or 90 percent of measurements ranging from 0.001 to 0.40 mR h^{-1}. At 25 debris locations, exposure rate measurements ranged from 0.50 to 8.5 mR h^{-1} in several isolated areas. In one isolated area on Runit, a maximum exposure rate of 60 mR h^{-1} was measured. In that area, a pile of concrete rubble and metal debris, estimated to be a volume of 222 yd^3, was located on the reef north of the runway and near the Shot Erie ground zero. Aside from the one isolated area on Runit, measurements at six debris locations ranged from 1 to 3 mR h^{-1} in areas confined to the central and northern areas of Runit.

Table 6. Soil concentration data, surface to 15 cm depth soil samples, from the 1972 radiological survey

Island		Island-average Soil Concentrations in Top 15 cm (pCi g^{-1})												
		Sr-90*			Cs-137*			Pu-239/240*			Co-60†			Am-241‡
Island Name	Site Name	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Mean
Bokoluo	Alice	14	107.9	430	0.7	44.1	141	3.9	15.6	68	1.4	5.9	33	10.4
Bokombako	Belle	9.8	148.9	670	0.4	47.5	170	4.2	27.1	100	3.1	10	30	18.1
Kirunu	Clara	13	99.2	310	0.8	35.4	110	3.5	31.6	88	0.91	6.4	20	21.1
Louj	Daisy	3.4	107.7	380	0.9	10.5	33	3.8	31.6	98	6.4	11	26	21.1
Bocinwotme	Edna	30	68.6	220	2.7	4.7	6.4	13	19.4	24	0.33	0.43	0.63	12.9
Boken	Irene	8.4	52.8	570	0.2	7.3	41	2.4	26.2	280	0.12	5.4	520	5.2
Enjebi	Janet	1.6	72.9	630	0.6	27.0	180	0.1	16.2	175	0.02	1.9	33	3.2
Mijikadrek	Kate	1.6	43.5	200	0.1	13.1	37	0.2	11.3	50	1.6	2.7	5.8	7.5
Kidrinen	Lucy	4.4	30.1	83	0.1	10.3	25	1.5	7.7	23	0.26	1.5	3.8	5.1
Taiwel	Percy	3.6	34.6	73	0.1	7.3	17	1.5	9.0	23	0.08	0.47	2.9	6.0
Bokenelab	Mary	1.2	34.8	140	0.03	8.4	26	0.9	10.1	35	0.74	1.5	4.8	6.7
Elle	Nancy	3.6	39.3	110	0.01	11.6	28	1.3	10.1	28	0.56	1.6	5.3	6.7
Aej	Olive	2.0	21.5	70	0.1	7.7	28	1.9	8.4	30	0.65	1.5	4.1	5.6
Lujor	Pearl	2.3	28.3	140	0.2	12.4	55	0.3	38.3	530	3.6	12	70	7.7
Eleleron	Ruby	7.1	24.3	63	0.7	3.2	7.2	3.0	14.5	24	0.29	0.93	16	9.7
Aomon	Sally	0.9	16	140	0.1	5.7	30	0.2	11.0	130	0.05	0.54	69	2.2
Bijire	Tilda	2.2	19.1	54	0.04	4.2	20	1.1	6.5	34	0.61	1.2	1.9	4.3
Lojwa	Ursula	0.9	8.2	19	0.1	2.6	7.8	0.2	1.8	4.2	0.05	0.31	1.7	1.2
Alembel	Vera	1.1	12.5	68	0.03	4.4	12	0.6	4.3	25	0.02	0.3	2.2	2.9
Billae	Wilma	0.3	6.0	19	0.3	2.0	7.2	0.1	1.8	5.3	0.01	0.12	0.7	1.2
Runit	Yvonne	1.2	3.3	30	0.02	1.00	3.6	0.02	8.7	50	0.01	0.64	20	1.7
Boko	Sam	0.5	0.72	0.8	0.02	0.38	0.5	0.03	0.09	0.2	-	0.04	-	0.06
Munjor	Tom	0.18	0.72	1.2	0.07	0.32	0.56	0.01	0.08	0.13	-	0.04	-	0.05
Inedral	Uriah	0.05	0.45	1.0	0.02	0.11	0.23	0.02	0.08	0.12	-	0.15	-	0.05
n/a	Van	0.1	0.41	0.81	0.05	0.14	0.20	0.04	0.08	0.11	-	0.09	-	0.05
Jinedrol	Alvin	0.21	0.44	0.74	0.03	0.11	0.29	0.02	0.06	0.11	-	0.68	-	0.04
Ananij	Bruce	0.03	0.59	1.8	0.02	0.40	1.1	0.02	0.09	0.22	-	0.12	0.74	0.06

Table 6. Soil concentration data, surface to 15 cm depth soil samples, from the 1972 radiological survey (cont.)

Island		Island-average Soil Concentrations in Top 15 cm (pCi g^{-1})												
		Sr-90*			Cs-137*			Pu-239/240*			Co-60†			Am-241‡
Island Name	Site Name	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Mean
Jinimi	Clyde	0.12	0.23	0.36	0.02	0.06	0.13	0.04	0.06	0.11	-	0.04	-	0.04
Japtan	David	0.08	0.55	2.6	0.03	0.40	1.0	0.004	0.05	0.23	0.009	0.03	0.14	0.03
Jedrol	Rex	0.03	0.51	1.6	0.02	0.51	1.2	0.02	0.04	0.06	-	0.09	0.36	0.03
Medren (Parry)	Elmer	0.02	0.76	5.1	0.02	0.32	1.2	0.01	0.21	5.5	0.01	0.06	0.88	0.14
Bokandretok	Walt	0.25	0.41	0.6	0.04	0.15	0.3	0.02	0.04	0.06	-	0.04	0.05	0.03
Enewetak	Fred	0.16	0.61	1.5	0.02	0.25	0.48	0.02	0.08	0.4	0.02	0.04	0.15	0.05
Ikuren	Glenn	0.09	1.37	3.9	0.01	0.60	1.8	0.005	0.11	0.3	-	0.21	0.25	0.07
Mut	Henry	0.13	0.75	2.2	0.004	0.25	0.7	0.07	0.14	0.23	-	4.3	63	0.09
Boken	Irwin	0.14	0.69	1.6	0.008	0.13	0.47	0.01	0.13	0.22	-	0.62	6.5	0.09
Ribewon	James	0.13	0.69	2.2	0.02	0.08	0.22	0.02	0.08	0.16	-	6.5	46	0.05
Kidrenen	Keith	0.03	0.88	1.8	0.01	0.28	0.81	0.01	0.11	0.17	-	0.17	0.83	0.07
Biken	Leroy	0.42	16.8	34	0.5	5.06	10	0.02	1.15	2.3	0.04	0.58	5.0	0.77

* Data from DOE (1982a, Tables 7-1 to 7-3).

† For the northern islands and Leroy, the mean is the geometric mean reported in AEC (1973a); an arithmetic mean was not reported. For the southern islands except Leroy, the mean values are reported in DOE (1982b).

‡ Only mean values are reported for Am-241. These values are calculated based on the mean Pu-239/240 concentrations in this table and estimated TRU to Am-241 ratios. A detailed discussion is included in Appendix G.

"-" Indicates "no data"

Table 7. Exposure rates measured at contact on islands with contaminated debris

Island		Number of Measurements	Debris Contact Measurement (μR h^{-1})			
Island Name	Site Name		Mean	Median	Min	Max
Enjebi	Janet	160	27	19	3	8,500
Runit	Yvonne	85	29	30	1	60,000
Lujor	Pearl	15	147	250	3	5,000
Eleleron	Ruby	6	19	18	6	120
Aomon	Sally	10	35	19	8	3,000

In addition, on Enjebi, there were 12 debris locations island-wide with exposure rates that ranged from 0.5 to 8.5 mR h^{-1}. On Lujor, six debris locations with exposure rates from 0.8 to 5 mR h^{-1} were found confined to the surface of the ground zero area of Shot Inca. On Aomon, the highest exposure rate of 3 mR h^{-1} was found at one debris location outside of a bunker.

It is important to note that the measured contact exposure rates described above do not represent the general exposure conditions for ECUP participants in debris-handling scenarios. Debris exposure rates to cleanup operators are expected to have been lower than the measured contact exposure rates by at least an order of magnitude. About 80 percent of the contact exposure rates measured at debris locations in 1972 were less than 0.1 mR h^{-1}, which was the threshold to mark debris in the red category that would be removed for disposal in the Cactus Crater; see Section 3. Applicable exposure rates for participants in debris-handling scenarios are discussed in Section 6 and Appendix K.

4.4 Air Monitoring

Airborne activity concentrations were monitored during the cleanup of Enewetak Atoll. One to five air samplers were positioned downwind of all earthmoving operations. Filters were monitored every two hours and changed every day (DNA, 1981).

Throughout the cleanup project, approximately 900,000 m^3 of air were sampled, of which 760,000 m^3 of air were sampled on the controlled islands. The radiation laboratory on Enewetak Island analyzed about 5,200 air filter samples. No significant airborne radioactive material of any type was detected. (DNA, 1981)

The Radiological Safety Plans officer periodically reported summaries of air sampling data collected on controlled islands throughout the cleanup project. Examples of summaries for Enjebi are shown in Table 8. In addition, weekly summaries of air sampling results for various locations were reported in weekly SITREPs. The sampling locations included areas on the controlled access islands, on residence islands, as well as watercrafts that transported excavated contaminated soil. Similar statistics as those shown in Table 8 were used to summarize the data collected for the weekly SITREP at these locations. Data summary Types A to F defined in Table 9 correspond to Columns AAA to FFF in the weekly SITREPs. A sample SITREP containing air-sampling results is provided in Appendix B-3

In addition, environmental air samples were routinely collected on Lojwa to verify that this resident island for ECUP participants remained within the established radiological limits. The total volume of air sampled and the findings were reported on weekly SITREP reports, numbered 5-124 of CJTG (1977b), during the period from June 9, 1977 to September 30 1979. The results consistently showed that there was no detectable or no significant activity found on the air filters.

Table 8. Summary of air sampling data for Enjebi (Norton, 1980)

Type	Data Summaries	Apr–Sept† 1977	Jan–Dec 1978	Jan–mid May† 1979
A	Volume of air sampled (m^3)	35,398	51,516	17,289
B	Number of filters analyzed	115	359	108
C	Zero readings	58	211	27
D	< 0.27 pCi m^{-3} (≤ 1% MPC*)	55	148	81
E	0.27 to < 2.7 pCi m^{-3}	2	0	0
F	≥ 2.7 pCi m^{-3} (≥ 10% MPC)	0	0	0
G	Highest reading (pCi m^{-3})	0.39	0.18	0.15
H	Average reading (pCi m^{-3})	0.08	0.03	0.03

* The MPC was established at 27 pCi m^{-3} for insoluble airborne Pu-239, which is based on a 60-hour workweek for personnel entering controlled access islands; details are included in Section 3.2.2 (USNRC, 1975).

† The reference does not report results for Oct–Dec 1977, nor results after mid May 1979.

The overall statistics of the air sampling data collected during the cleanup can be found in Appendix B of DNA (1981).

Table 9. Summary of air sampling data collected throughout the Enewetak Cleanup Project

Type	Data Summaries	Enewetak Cleanup Project
A	Volume of air sampled (m^3)	866,227
B	Number of filters analyzed	5,204
C	Zero readings	2,667 (51.2%)
D	< 0.27 pCi m^{-3} (≤ 1% MPC*)	2,336 (44.9%)
E	0.27 to < 2.7 pCi m^{-3}	201 (3.9%)
F	≥ 2.7 pCi m^{-3} (≥ 10% MPC)	0

* The MPC was established at 27 pCi m^{-3} for insoluble airborne Pu-239, which is based on a 60-hour workweek for personnel entering controlled access islands; details are included in Section 3.2. (USNRC, 1975)

4.5 Lagoon and Ocean Water

Activity concentrations of fission and activation products, and TRU radionuclides were measured in samples of lagoon and ocean water during the 1972 AEC radiological survey (AEC, 1973a). Fifty-four lagoon, crater, and ocean water samples were collected at 38 locations shown in Figure J-1. Forty samples were collected from the lagoon, twelve from craters, and two samples were collected from the ocean near the Deep Entrance of the atoll, east of Medren and Japtan Islands. Cesium and plutonium were detected in all samples. Fifteen lagoon samples, primarily from the northern half of the lagoon, contained detectable amounts of Co-60, Eu-155, Bi-207, or Am-241; these radionuclides were not found in any other water samples. Results for several other radionuclides (Rh-102m, Ru-106, Sb-125, Eu-152, and U-235) were below detection limits in all samples. Table 10 provides a summary of the means and ranges of activity concentrations for Cs-137, Pu-239/240, and Pu-238 in 32 shallow and 8 deep lagoon water samples. Results for these three radionuclides in the two ocean water samples are provided in Table 11. Sampling locations and analysis results for all fifty-four water samples are shown in Table J-1.

Table 10. Radionuclide activity concentrations in lagoon water samples

Sample Depth (ft)	Water activity concentrations (fCi kg^{-1})*					
	Cs-137		Pu-239/240		Pu-238	
	Mean	Range	Mean	Range	Mean	Range
3	325	59–766	29	0.38–96.1	4	0.03–14.9
90–195	341	190–497	506	2.8–3780	164	0.14–1280

* See Table J-1 for sample results and locations.

Table 11. Radionuclide activity concentrations in ocean water samples near Enewetak Atoll

	Water activity concentrations (fCi kg^{-1})		
Sample Location and Depth*	Cs-137	Pu-239/240	Pu-238
East of Medren (3 ft)	32	0.43	0.01
East of Japtan (3 ft)	146	0.21	0

* Ocean samples were taken from two locations near the Deep Entrance to the lagoon. See Figure J-1 for sample locations.

Table 12 provides the mean activity concentrations of Cs-137 and Pu-239 in surface water in four quadrants of the lagoon (AEC, 1973a). As expected, the data show that the northwestern and northeastern quadrants exhibit the highest concentrations because most of the Enewetak tests were conducted on and near the islands in these quadrants, and the islands in these quadrants had the highest measured soil contamination levels in the atoll (see Section 4.2). The southwestern quadrant concentration levels were somewhat elevated, likely because the islands in this quadrant received fallout from atmospheric nuclear tests that took place on the islands in the northeastern quadrant of the atoll (AEC, 1973a).

Table 12. Mean activity concentrations of Cs-137 and Pu-239 in surface water samples collected from the four quadrants of the lagoon

Sample Location in Enewetak Lagoon	Activity Concentration (fCi L^{-1})*, †	
	Cs-137	Pu-239
Southeastern quadrant	226	9.1
Northeastern quadrant	334	42.6
Northwestern quadrant	579	33.4
Southwestern quadrant	332	21.6
Ocean, east of Enewetak Atoll	89	0.3

* From Table 56 of AEC (1973a).

† The units fCi L^{-1} and fCi kg^{-1} are considered equivalent in AEC (1973a).

4.6 Lagoon Sediments

Radionuclides were distributed non-uniformly in lagoon sediments of Enewetak Atoll. The sediment layer was generally thin, and most sampling conducted in 1972 was limited to no more than a few centimeters due to the nature of the sedimentary deposits. The highest activity concentrations were generally in the northwestern portion of the lagoon, and the southern portion of the lagoon was generally uncontaminated (AEC, 1973a). Table 13 provides the mean activity concentrations of radionuclides found in lagoon sediments averaged over the entire lagoon. Radionuclide activity concentrations in lagoon sediments for all areas of the lagoon are presented in Figures 52–64 and Tables 45–47 of AEC (1973a).

Table 13. Mean radionuclide activity concentrations in Enewetak Lagoon sediments

Radionuclide	Activity per Unit Area (mCi km^{-2})*
Sr-90	586
Pu-239/240	463
Eu-155	369
Am-241	172
Bi-207	163
Cs-137	78
Co-60	73
Sb-125	22
Rh-102m	8.4
Eu-152	2.5
Rh-101	1.2

* From Table 47 of AEC (1973a)

4.7 Food and Drinking Water

4.7.1. Local Foods

Local terrestrial and marine foods were collected during the Enewetak Radiological Survey from October 1972 to February 1973 (AEC, 1973a). The survey goals were to provide the data needed for rating the relative importance of radionuclides and pathways leading to doses to future residents of Enewetak Atoll. The data also helped guide cleanup decision-making affecting the future use of the islands and provided a basis for radiological levels encountered by ECUP workers that may have consumed local foods.

Because of their relatively long half-lives, activity concentrations in foods, and potential contribution to internal doses, Co-60, Sr-90, Cs-137, and Pu-239/240 are considered key radionuclides for all local foods included in this analysis. In addition, Am-241 is included for one local food (fish).

There were limited terrestrial foods available for sampling during the 1972–1973 survey (DNA, 1981). Coconuts and coconut crabs were sampled and are included in this analysis. Coconuts were a staple food of the Enewetak people, but very few coconut trees were growing on the atoll after the nuclear testing ended in 1958. Multiple samples of coconut meat and milk from various islands were analyzed and the results are shown in Table 14 and Table 15. Coconut crabs were part of the diet for the native Enewetak population and ECUP participants might have eaten them according to some anecdotal accounts (Cherry, 2018b; Fitzgerald, 2017). Table 16 presents the activity concentrations of the key radionuclides found in coconut crabs from various islands at Enewetak Atoll (AEC, 1973a). Analysis results for less consumed foods such as pandanus, breadfruit, and arrowroot are not included here because no accounts suggesting that ECUP participants consumed these foods were found.

Table 14. Activity concentration of radionuclides in coconut meat at Enewetak Atoll

Island		Concentration (pCi g^{-1} dry weight)*			
		Co-60	Sr-90	Cs-137	Pu-239/240
Louj	Daisy	< 0.059	0.200	7.17	No data
Boken	Irene	< 0.067	0.067	1.77	0.0362
		< 1.7	1.61	5.11	< 0.034
Enjebi	Janet	< 0.069	0.207	84.7	No data
Bokenelab	Mary	< 0.055	0.136	14.3	0.0005
		< 0.017	14.1	5.58	< 0.43
Elle	Nancy	< 0.054	0.167	18.8	< 0.0006
Alembel	Vera	< 0.053	0.134	9.30	0.00013
Runit	Yvonne	0.077	0.011	3.96	No data
		< 0.066	< 0.054	1.99	< 0.0020
Ananij	Bruce	< 0.014	No data	0.582	No data
Japtan	David	< 0.060	0.014	2.59	0.0027
		< 0.012	0.026	0.399	0.0034
Medren	Elmer	< 0.028	< 0.075	3.45	< 0.0052
		< 0.068	0.032	2.14	0.00044
Enewetak	Fred	< 0.020	0.030	2.39	No data
		< 0.021	0.367	0.530	< 0.0058
Ikuren	Glenn	< 0.053	< 0.049	1.30	< 0.0013
		< 0.029	0.02	1.01	< 0.0025
Mut	Henry	< 0.007	<0.028	0.565	< 0.001
Boken	Irwin	0.074	<0.086	0.29†	< 0.0027
Kidrenen	Keith	< 0.064	<0.056	0.952	< 0.0009
Biken	Leroy	< 0.015	0.189	3.9	0.00073

* Data were extracted from Table 164 in AEC (1973a).

† The number "0.29" is presumed to be the value athough"0.2~9" is shown in Table 164 in AEC (1973a).

Table 15. Activity concentrations of radionuclides in coconut milk at Enewetak Atoll

Island		Concentration (pCi (g, wet)$^{-1}$)*			
		Co-60	Sr-90	Cs-137	Pu-239/240
Louj	Daisy	< 0.051	0.068	0.084	< 0.0016
Boken	Irene	< 0.15	< 0.077	No data	< 0.0086
Enjebi	Janet	< 0.03	0.084	11.2	< 0.0005
Bokenelab	Mary	< 0.016	0.042	4.52	< 0.0046
Elle	Nancy	< 0.06	0.051	6.65	< 0.0010
Japtan	David	< 0.012	< 0.023	1.09	< 0.0015

* Data were extracted from Table 165 in AEC (1973a).

Table 16. Activity concentrations of radionuclides in coconut crab at Enewetak Atoll

Island		Concentration in Muscle (pCi (g, dry)$^{-1}$)*			
		Co-60	Sr-90	Cs-137	Pu-239/240
Ananij	Bruce	0.198	0.185	1.98	0.0012
Ikuren	Glenn	0.247	Not Reported	1.88	0.0013
Ribewon	James	1.05	0.079	1.25	0.00076
Kidrenen	Keith	0.42	1.19	1.92	0.0014
Biken	Leroy	1.23	1.58	12.6	0.0031

* Data were extracted from Table 169 in AEC (1973a).

The marine sampling program was focused on fish since they are commonly eaten by the Marshallese and might have been consumed by ECUP workers during recreational activities (Cherry, 2018b; Fitzgerald, 2017). The sampling included reef and bottom (lagoon) feeders as well as pelagic species. The concentrations of key radionuclides averaged over all fish from the entire atoll are summarized in AEC (1973a). In addition to fish, marine invertebrates that were reportedly consumed were also sampled, including lobsters and clams. Enewetak cleanup veterans have indicated that local lobsters were eaten (Fitzgerald, 2017). One ECUP veteran suggested that ECUP participants might have also eaten the large "killer" clams, *Tridacna gigas*, during the deployment. The giant clam and the smaller clam, *Tridacna crocea*, were the two species collected during the 1972–1973 survey. The differences in the activity concentrations between the larger and smaller clams were not significant (AEC, 1973a). Because of the claim suggesting consumption of the giant clam, only the consumption of mantle and muscle of giant clams is considered here, assuming that the viscera and kidney were not consumed. Activity concentrations of radionuclides in clams from various islands at Enewetak Atoll are shown in Table 17. Average concentrations of key radionuclides in the edible parts of all local foods considered here as potentially consumed by ECUP participants are shown in Table 18.

Table 17. Activity concentrations of radionuclides in clams at Enewetak Atoll

Island		Concentration in Mantle and Muscle (pCi (g, dry)$^{-1}$)[*,†,‡]		
		Co-60	Sr-90	Pu-239/240
Bokoluo	Alice	3.9	0.10	0.05
Bokombako	Belle[§]	18	0.5	0.24
Enjebi	Janet	20	0.02	0.094
Mijikadrek	Kate	0.5	0.01	0.50
Bijile	Tilda	1.3	0.009	0.49
Jedrol	Rex	22	0.013	0.015
Bokandretok	Walt[§]	2.5	0.018	0.06
Ikuren	Glenn[§]	7.6	0.21	0.016
Mut	Henry	13	0.02	0.90
Biken	Leroy[§]	4.5	0.01	0.014

* Data were extracted from Table 39 in AEC (1973a).

† Only the activity concentrations for "mantle and muscle" of the clams were used for consumption of giant clams.

‡ Cs-137 and Am-241 were not detected in the vast majority of the analyzed clam samples so they were not included.

§ Sr-90 was not detected in the samples collected from these islands. To high side the average activity concentrations, their respective detection limits for Sr-90 were used.

Table 18. Average activity concentrations of radionuclides in the edible part of local foods at Enewetak Atoll that were potentially consumed by cleanup participants

Food	Activity Concentration (pCi g^{-1}, dry weight)[*,†,‡]				
	Co-60	**Sr-90**	**Cs-137**	**Pu-239/240**	**Am-241**
Fish	2.00	0.075	0.39	0.248	0.114
Spiny Lobster	0.29	0.020	0.018[§]	0.0060	–
Coconut Meat	0.12	0.80	7.5	0.030	–
Coconut Milk	0.053	0.058	4.71	0.0030	–
Coconut Crab	0.629	0.759	3.93	0.0016	–
Clam (giant)[**]	9.33	0.091	–	0.24	–

[*] Averages based on data reported in AEC (1973a) except as noted otherwise: for coconut meat, see Table 164; for coconut milk, see Table 165; for coconut crab, see Table 169; for fish, average concentrations are reported in Table 158 except for Sr-90 the average concentration is for muscle only and is taken from Table 159; and for lobster, average concentrations are reported in Table 41 except for Cs-137 (see note below). (AEC, 1973a)

[†] The concentrations are in pCi g^{-1} dry weight except pCi g^{-1} wet weight in coconut milk.

[‡] The averages are calculated with non-detect sample concentrations set equal to the detection limits.

[§] Concentrations of Cs-137 in spiny lobster muscle were not reported in AEC (1973a). The value shown is the highest value in samples collected in 1978–1979 reported in Table 6 of Ebert and Ford (1986).

[**] Concentrations are from Table 39 (AEC, 1973a). In addition to Am-241, Cs-137 was not detected in the vast majority of the analyzed clam samples. So they were not considered as key radionuclides for clams.

"–" indicates not detected in any sample or not considered as a key radionuclide (AEC, 1973a).

4.7.2. Drinking Water

One drinking water sample was taken for radiological analysis from the distillation plant on Enewetak Island during the 1972 AEC radiological survey (AEC, 1973a). No radiological contamination was found in the water. However, Sr-90 and Pu-239 were detected in two sludge samples from the plant. The highest Pu-239 concentration in the sludge was 56 pCi g^{-1} (DNA, 1981).

Three tap water samples from Enewetak Island and one from a water truck on Enjebi were collected in March 1978. The tap water was distilled from seawater. The activity concentrations of Cs-137, Pu-239/240, and Pu-238 were measured in these samples. The results of the analysis are shown in Table 19 as reported in Noshkin et al. (1981).

Additional drinking water samples were taken in December 1979 from campsite facilities, the community center, dining hall, Dorm Building 462, recreational center, and clinic. However, the samples were analyzed for bacteriological and chemical contents only (USAF Clinic/SGV, 1980).

Table 19. Activity concentrations in drinking water from Enewetak and Enjebi Islands

Sample type	Island sampled	Date collected	Concentration (fCi L^{-1})*		
			Cs-137	Pu-239/240	Pu-238
Distilled seawater	Enewetak	3/18/78	18 (8)†	0.6 (40)	< 0.1
Distilled seawater	Enewetak	3/18/78	20 (8)	0.4 (50)	< 0.1
Distilled seawater	Enewetak	3/18/78	22 (8)	0.3 (70)	< 0.1
Water truck	Enjebi	3/21/78	10 (14)	5.4 (22)	0.2 (40)

* Data taken from Noshkin et al. (1981).

† Values in parentheses are the percent standard deviation of the counting error.

4.8 Personnel Dosimetry (Film Badge, TLD)

This section provides a summary of personnel dosimetry records compiled during the ECUP operations. As mentioned in Section 3.2, the U.S. Army LBDA administered the film badge personnel monitoring program for ECUP-monitored workers per AR 40-14 (USA, 1975). Beginning in May 1977, film badges were issued to all ECUP workers assigned to controlled access islands. In May 1978, the program was supplemented by Navy-supplied TLDs to reduce the need to administratively assign doses because many film badges were damaged by high ambient temperatures and humidity on the atoll. The JTG policy (DNA, 1981) was to issue TLDs together with film badges to the extent that these were available (RSAIT, 1979a). In March 1979, TLDs and film badges were issued together to all controlled island access workers. Generally, workers wore dosimeters for four to five weeks and were reissued new dosimeters as long as they continued duty on controlled access islands.

The LBDA evaluated the film badges received from Enewetak and entered the dosimetry readings in a database now maintained by U.S. Army Dosimetry Center (ADC) at Redstone Arsenal in Huntsville, AL. The Navy-supplied TLDs were read on-site and readings were sent to the LBDA to be stored in the ADC database. Cumulative dosimetry readings for controlled island access workers were sent from the JTG via DD Form 1141 to the dosimetry center of the individual's respective military service. The military personnel film badge dose records are summarized in Table 20.

The highest, valid dosimeter reading for an individual participant was 0.070 rem, which is less than 1.4 percent of the 5.0 rem yearly limit established for the project. Two single film badge readings of 0.400 and 0.430 rem were recorded. In-depth investigations revealed that these did not represent valid doses to individuals but that they may have resulted from film badges having been left on or near contaminated debris or a calibration check source overnight (Bauchspies, 1978).

Administrative dose assignments were required per AR 40-14 (USA, 1975) and were designed to use conservative assumptions so the dose estimates were biased high. Administratively assigned doses ranged from 0 to 0.020 rem for any one-month issue period according to the ADC database for ECUP dosimetry. Finally, over 7,500 TLD readings were recorded starting in May 1978. Dose records for TLDs are summarized in Table 20.

Table 20. Summary of personnel dosimetry (DNA, 1981)

Film Badge Dosimetry		
Doses Reported	12,248	
Zero Readings*	8,361	(68.3%)
1–10 mrem	3,712	(30.3%)
11–20 mrem	157	(1.3%)
> 20 mrem	18	(0.1%)
TLD		
Doses Reported	7,519	
Zero Readings*	2,763	(36.7%)
1–10 mrem	4,735	(63.0%)
11–20 mrem	12	(0.2%)
> 20 mrem	9	(0.1%)

* Readings with reported values of zero were obtained from dosimeters with doses of less than 1 mrem.

4.9 Bioassay

A bioassay program was used to assess and document internal deposition of radioactive material, which might have occurred through inhalation, ingestion, or skin penetration (i.e., wounds). The two principal bioassay techniques used were the nasal smear (nose swipe) and urinalysis.

4.9.1. Nasal Smears

Nasal smears were used at the hotlines for plutonium-contaminated areas as the primary method of checking the adequacy of respiratory protection (DNA, 1981). During the project, over 1,100 nasal smears were obtained and analyzed. Results listed in Table 21 indicate that about 65 percent of the samples showed no detectable activity, i.e., zero or less than the minimum detectable activity (MDA). Of those smears that did show activity, the highest was 3.64 dpm (1.64 pCi of plutonium), which is much lower than the maximum allowable level for plutonium of 500 dpm (DNA, 1981).

Table 21. Results of nasal smears

Parameter	Value*
Total Nasal Smears Taken	1,145
Range of activity	0–1.64 pCi of Pu
Activity = 0	317 (27.7%)
Activity < MDA	439 (38.3%)
Activity > MDA	389 (34.0%)

* Data from DNA (1981)

4.9.2. Urine Bioassay

As part of the ECUP Bioassay Program (FCRR, 1978a), over 2,000 24-hour urine samples were analyzed for activity concentrations, primarily for total or gross beta radiation (GB), Pu-239, and K-40. On a random basis, some samples were also analyzed specifically for Cs-137, Co-60, or Co-57. Summary results are listed in Table 22.

Table 22. Summary of urine bioassay results

Parameter	Value*
Total Urine Samples Taken	2,338
Potassium-40 (K-40)	– Range: < 50 to 4,100 pCi L^{-1} – 2,313 readings (98.9%) ≤ 2500 pCi L^{-1}
Gross Beta (GB)	– Range: < 300 to 4,200 pCi L^{-1} – 2,315 readings (99.0%) ≤ 2500 pCi L^{-1}
Ratio of GB to K-40	– Range: 0.27 to 3.05 – 2,305 readings (98.6%) ≤ 2.00
Plutonium-239 (Pu-239)	– Range: < MDA to 0.12 pCi d^{-1} – 2,332 readings (99.7%) < MDA

* Data from DNA (1981)

The naturally occurring radionuclide K-40 accounts for a very small fraction of about 0.012 percent of natural potassium (NNDC, 2019), and enters the body through a normal diet. An adult person normally excretes 25 to 125 millimoles of potassium per day (Anderson, 2003), which would include about 820 to 4,100 pCi of K-40. Assuming that the average daily excretion volume of urine is 1.5 L, the normal range of K-40 concentration in urine is about 550 to 2,700 pCi L^{-1}. Figure 6 shows an example report of a urine sample analysis, which shows almost equal values of GB and K-40 activity concentrations. Because K-40 is a beta-emitter, it accounts for essentially the entire GB measured in this sample, with insignificant amounts of other beta-emitting radionuclides present.

In addition to K-40, the GB count was indicative of any beta-emitting radionuclides such as Cs-137, Sr-90, and Co-60, which might have been taken up at Enewetak. If any bioassay results had indicated possible uptake of these beta-emitters, specific measurements for Sr-90 or Cs-137 would have been made. "Significant uptake" was defined using a threshold GB value on the order of 5,000 pCi L^{-1} and a GB to K-40 ratio threshold value of 3. No bioassay results exceeded the GB threshold. The highest GB to K-40 ratio was 3.05, and in that sample the GB value was well below the GB threshold value. These results indicate there was no significant uptake of beta-emitting radionuclides by ECUP participants. (DNA, 1981)

```
: 15 JUN 78                          S773D :
:----------------------------------------        SAMPLE ANALYSIS RESULTS          :
: COMMANDER JTG ATTN: FCRR                 :     ------ -------- -------          :
: ENEWETAK ATOLL APO SF 96333              : USAF RADIOLOGICAL HEALTH LAB(AFLC)   :
:                                          :   WRIGHT-PATTERSON AFB, OHIO 45433   :
:                                          :                                      :
:                                          :                                      :
:=================================================================================:
:     IDENTIFICATION     :  TYPE OF SAMPLE  :DATE RECEIVED : RHL NUMBER           :
:------------------------:------------------:--------------:----------------------:
:                        :      URINE       :  17 APR 78   :  17800483            :
:                        :  180038084MK     :              :                      :
:=================================================================================:
:ANALYSIS: POTASSIUM 40                                                           :
:  RESULT:   628. PICOCURIES PER LITER                                            :
:---------------------------------------------------------------------------------:
:ANALYSIS: GROSS BETA                                                             :
:  RESULT:   630. PICOCURIES PER LITER                                            :
:---------------------------------------------------------------------------------:
:ANALYSIS: PLUTONIUM 239 ALPHA SPECT                                              :
:  RESULT: LESS THAN .1 PICOCURIES PER 24 HOURS          DATE COUNTED 7816:
:---------------------------------------------------------------------------------:
:ANALYSIS: SAMPLE VOLUME                                                          :
:  RESULT: 3500. MILLILITERS                                                      :
:---------------------------------------------------------------------------------:
:ANALYSIS: PLUTONIUM 236 SPIKE RECOVERY                                           :
:  RESULT:   68.3 PERCENT                                                         :
-----------------------------------------------------------------------------------
```

Figure 6. Example of urine bioassay report (some information redacted)[8]

Plutonium activity concentration results were based on an individual's total daily (24-hour) urine output, and were reported as pCi of Pu-239 in the sample[9] (see Figure 6). At the time ECUP was underway, a trigger level was established based on the proposal of the American Health Physics Society Plutonium Bioassay Committee that, if the plutonium concentration exceeded 0.20 pCi per 24-hour sample, a second sample should be taken for verification. No ECUP samples exceeded this trigger level. Results for all but 6 of over 2,000 samples were below the MDA. The six samples that exceeded the MDA included one measurement at 0.05, two at 0.06, two at 0.08, and one at 0.12 pCi. In each case where the MDA was exceeded, dose estimates were made. The estimates indicated that no significant doses were received. Moreover, a second sample was obtained from each individual where the initial measurement exceeded the MDA and, in each case, the second sample result was less than the MDA. (DNA, 1981)

[8] This report was generated by the USAF Radiological Health Laboratory, which at the time was in the process of being relocated to Brooks AFB, TX and reorganized under the USAF OEHL.
[9] Pu-239 activity value includes contributions from Pu-240.

Section 5.

Sources, Pathways and Scenarios of Radiation Exposure

Participants in the ECUP were potentially exposed to external gamma and beta radiation and internal radiation from the intake of radioactive materials by inhalation and ingestion, or through wounds. As discussed in Section 3, the radionuclides of concern are Sr-90, Cs-137, Co-60, Pu-239/240, and Am-241. In this section, contaminated media encountered by ECUP participants during the cleanup are discussed in Section 5.1, and relevant external, internal, and skin exposure pathways are identified in Section 5.2. Participants' potential exposures to contaminated materials are categorized based on a set of project components, tasks, and specific project activities that are presented in Section 5.3.

5.1 Potential Sources of Radiation Exposure

Potential sources of radiation exposure for ECUP participants include contaminated soil, (by itself and mixed into slurry), debris, concrete structures, lagoon water and sediment, food and drinking water. These sources are discussed in the following sub-sections.

5.1.1. Contaminated Soil

Contaminated soil was a source of potential radiation exposures to several categories of ECUP personnel who performed activities associated with soil cleanup operations or other project tasks. Contaminated soil consisted of undisturbed and disturbed ground surface soil; soil excised and placed into windrows, piles, dump trucks, and landing craft; and soil mixed with cement in the Cactus dome.

Ground surface soil on Enewetak Atoll islands was potentially contaminated with radioactive material. External exposure rates from soil, and activity concentrations in soil are shown in Table 4 and Table 6, respectively. This source might have been encountered during brush removal, soil and debris cleanup operations, as well as during other activities such as radiological sampling and monitoring, and construction activities. Personnel who worked on the southern islands and residence islands may have been exposed to isolated spots of contaminated surface soil (DNA, 1981). However, in general, the soil on the southern islands was not contaminated and the average external exposure rates were less than the cosmic radiation background range of 3.9 to 4.7 $\mu R\ h^{-1}$. This background range is based on TLD readings of 10 to 12 mR accumulated over a three-and-one-half month exposure period (AEC, 1973a).

Windrows and piles of excised contaminated soil represented another potential source of radiation exposure. These sources were located on the islands of Boken, Enjebi, Lujor, Aomon, and Runit, where contaminated soil was removed and eventually contained in the Cactus Crater and dome (DNA, 1981). Soil windrows and piles are treated as a different source category from undisturbed surface soil because they have different source geometries than contaminated ground such as size and shape, they had a greater likelihood for soil suspension, and they may have had higher contaminant concentrations than the surrounding ground. Soil activity concentrations of excised soil that was placed into windrows or piles are discussed in Section 7. This soil was a potential source of exposure for individuals who were involved in soil removal and transport, as well as those who performed radiological control and survey activities.

Contaminated soil transported to Runit was off-loaded and moved to stockpiles for use during the tremie disposal operations. Stockpiled soil was loaded onto trucks and transported to the batch plant for incorporation with cement, water and other aggregates to produce the slurry that was disposed of in the Cactus Crater to form hardened concrete. Soil activity concentrations of transported and stockpiled soil are discussed in Section 7. A discussion of the soil slurry as a source of potential exposure to radiation is given in Subsection 5.1.2.

Exposure to contaminated soil excised from the five islands mentioned above was possible during transport by dump trucks, landing craft, and floating platforms. Other individuals who may have been exposed to contaminated soil were those who worked at the batch plant including the screening plant. In addition, personnel who provided close support to tremie operations in and around contaminated soil had the potential to be exposed to this source of radiation.

Exposure to contaminated soil during transport by dump trucks, landing craft, and floating platforms was also possible for the limited quantity of soil removed from Medren. Medren is not included as one of the soil-removal islands above because the soil removed from Medren did not contain any TRU contamination (DNA, 1981). It is mentioned here because about 110 yd^3 of soil contaminated with Co-60 that was identified in a limited area on the island was removed and transported to Runit over a four-day period in February 1978. The contaminated soil on Medren was excavated by backhoe, loaded directly into dump trucks that were driven to the boat ramp and transported by LCUs to Runit (DNA, 1981). Personnel potentially exposed to this source include operators of heavy equipment, e.g., dump trucks, loaders, and water transport personnel.

Another potential source of radiation exposure was the contaminated soil that was mixed with cement and water to form the dome over the Cactus Crater on Runit. The soil-cement dome was constructed over the hardened concrete slurry and debris that filled the crater during the tremie operations. The operators of heavy equipment and other personnel involved in this activity, such as surveyors, ground spotters/guides, radiological monitors, etc., could have been exposed to this source of radiation.

5.1.2. Soil Slurry

Contaminated soil slurry was produced for containment in the Cactus Crater on Runit during the tremie operations. The contaminated soil that was removed from islands other than Runit was stockpiled on Runit. The soil was mixed with cement, attapulgite clay, and water at the batch plant on Runit, and then loaded onto transit-mix trucks. The components were mixed to form slurry in the transit-mix trucks as they were enroute to the tremie pump positioned at the rim of the crater. The slurry was then pumped through a small feeder pipe to a floating barge where it flowed down through a tremie pipe to the bottom of the crater. In some areas of the crater, the transit-mix trucks dumped the slurry directly into the crater at its rim. In addition, contaminated debris stockpiled on Runit from other islands was placed in the crater. Slurry was used to choke this debris and encase it into the concrete mass. The tremie operations started on June 15, 1978 and were completed on February 10, 1979 (DNA, 1981).

Because of the inclusion of contaminated soil, slurry was a potential source of exposure to individuals involved in the mixing, transporting, and pumping operations. Soil activity concentrations of excised soil before mixing into slurry are discussed in Section 7. Slurry that was rejected from pumping due to unsatisfactory consistency and homogeneity was dumped from the transit-mix trucks into trenches and was allowed to harden. Once hardened, blocks of the dried material were loaded into dump trucks, transported to and dumped directly into the crater. This "processed tremie" method was used only when necessary and disposal was limited to eight loads per day unless approved by CJTG (DNA, 1981).

5.1.3. Contaminated Debris

Contaminated debris was collected from the islands of Enjebi, Lujor, Eleleron, Aomon, and Runit, and transported for disposal at lagoon disposal sites and the Cactus Crater. Most of the contaminated debris was removed from Runit and Aomon, with Runit debris accounting for over 50 percent of the total volume (DNA, 1981; DOE, 1982a). The debris cleanup activities consisted of offshore collection by divers, winch operators, and EOD personnel; onshore collection from beach and inland areas; consolidation and handling by heavy equipment, e.g., bulldozers, cranes, etc.; loading, off-loading, and transport using dump trucks, landing craft, barges and floating platforms; and disposal in the lagoon or in the Cactus Crater on Runit. The divers, operators of heavy equipment on-land and offshore, personnel involved in water transport and disposal of debris, as well as those who performed radiological control and survey activities, could have been exposed to this source of radiation.

Another type of contaminated debris consisted of small plutonium-contaminated fragments that were located and removed from the Fig-Quince ground zero (GZ) area on Runit and the Kickapoo GZ area on Aomon. These fragments were located and removed primarily by members of the FRST during November and December 1977 for the Fig-Quince area (DNA, 1981), and October 1978 for the Kickapoo area (DNA, 1981).

In addition to being a potential source of external exposure, there was a potential for dermal contamination and internal exposure from soil suspended during handling contaminated debris.

5.1.4. Contaminated Concrete Structures

Concrete debris consisting primarily of non-contaminated slabs, blocks, pads, walls, and rubble was found on several islands (DNA, 1981; H&N, 1973). Concrete structures including bunkers and buildings were also located on several islands. In many cases, bunkers were not radiologically contaminated and were made safe by covering or sealing with concrete or by removing doors and protruding hazards and leaving them otherwise intact for subsequent use (e.g., as typhoon shelters) (DNA, 1981; H&N, 1973). Contaminated concrete structures were present on several islands, primarily the islands of Enjebi, Boken, Aomon, and Bijire. Much of the contamination that caused these structures to be classified as yellow debris was surface beta radiation (DNA, 1981). Several techniques such as sandblasting and chipping were used to clear away the surface contamination and leave the structures intact and in place (DNA, 1981). Covering a concrete vault on Enjebi with 6 inches of concrete was also used to render a contaminated concrete vault safe (DNA, 1981). However, the two concrete crypts located near the Yuma and Kickapoo GZs had some plutonium surface contamination and were broken up by explosive demolition and then disposed in the lagoon (DNA, 1981). The "Enjebi Hilton," a multi-level building 52 ft wide, 196 ft long, and 36 ft high, had extensive beta contamination on the roof. This building was demolished by a wrecking ball and explosives after the contaminated portions had been chipped loose and transported to Runit for containment (DNA, 1981). Personnel who conducted sandblasting and chipping work may have been exposed to the dust generated by the abrasive engineering tools. Internal exposure from the inhalation of suspended contaminated dust generated by the engineering equipment was also possible.

5.1.5. Lagoon Water and Sediment

Water and sediments in the lagoon and to a lesser extent nearby ocean water were contaminated with fission products and TRU radionuclides as shown in Table 10 to Table 13. Lagoon water and sediments were potential sources of exposure to members of the Water Beach Cleanup Team (WBCT), the Underwater Demolition Team (UDT), and EOD personnel. In addition, ECUP personnel engaging in water-based recreational activities, such as swimming and sailing, were potentially exposed to these sources. The WBCT personnel could have been exposed to contaminated lagoon water and sediments as they worked at depths up to approximately 15 feet to retrieve debris by hand and winches attached to bulldozers or LCMs. They also participated in offshore cleanup of debris collected by boats and floating platforms (DNA, 1981). Members of the UDT were potentially exposed to these sources of exposure when they set charges to open or clear channels for boat navigation.

Personnel water-based activities, such as boating conducted on the surface of lagoon water presented a potential for external exposure to radiation from gamma emitters from contaminants distributed in the water. Potential for significant internal exposure to alpha, beta, and gamma emitters by ingestion was possible only if personnel left the boat and came into contact with lagoon water. Divers and recreational swimmers also had the potential for skin exposure and whole body external exposures from immersion in the water. If individuals disturbed the sediment of the lagoon or ocean floor, the water activity concentration levels in the immediate vicinity could temporarily increase if the sediments contained radioactive contaminants.

5.1.6. Other Sources

Other potential sources of radiation exposure include contaminated equipment and PPE laundry, as described below.

5.1.6.1 Contaminated Equipment

Equipment considered worthy of retention was monitored for both fixed and removable contamination before being released for reuse in uncontrolled areas. Decontamination was performed if contamination was detected and levels exceeded the release limits set forth in Enclosure 1 of FCRR SOP 608-03.1, “Decontamination of Facilities and Equipment.” Personnel who surveyed equipment to evaluate whether or not it was contaminated, and those who actually performed decontamination, could have been exposed to external and internal radiation as a result of inhalation of resuspended contaminated soil and dust from the surface of the equipment.

When contaminated equipment was found, dry removal procedures were in general attempted before wet procedures. In addition, wet techniques were selected only when the spread of contamination could be controlled (FCRR SOP 608-03.1). Procedures available at Enewetak to manage contaminated items included:

- Brushing or scraping
- Vacuuming
- Filing and grinding
- Damp wiping down
- Ultrasonic cleaning, if applicable
- Hosing down with available water and detergents
- Steam cleaning
- Sealing for fixation, e.g., painting
- Disposing as contaminated debris.

5.1.6.2 Decontamination Laundry Facility on Lojwa

Personnel clothing decontamination was performed at the Decontamination Laundry Facility (DLF) on Lojwa. FRST contamination control areas or hot line operations personnel separated all items being sent to the DLF into three categories: (1) clothing, (2) plastic ware, e.g., gloves, boots, booties, etc., and (3) respiratory protection masks (respirators) (FCRR SOP 608-10) (FCRR, 1978b). Clothing found to have hot spots in excess of 2,000 dpm was disposed of as radioactive waste, rather than sent to the DLF (FCRR SOP 608-03.1)(FCRR, 1977b). All contaminated items returned to Lojwa were double-bagged with each bag individually sealed by a knot or tape. FRST personnel made two copies of a list of all contaminated items describing: (1) the spot where activity was found on each item, (2) the typical readings and the type of probe used, (3) the date packaged, (4) the island location, and (5) the name of the FRST member filling out the list. A copy of this list was placed inside the outer bag (FCRR SOP 608-10) (FCRR, 1978b).

The DLF was considered a radiologically controlled area. FRST had supervisory control for radiation safety and maintained, at a minimum, Access Rosters, Team Chief Reports, and Air Sampler Data Logs for the DLF.

The DLF personnel who operated the facility could receive external radiation exposure and internal exposure as a result of inhalation of resuspended contaminated soil and dust from the personnel protective clothing and respirators.

5.1.7. Drinking Water and Food

When the Enewetak base camp was being prepared for the cleanup forces starting in June 1974 and until the March 1980 demobilization, water distillation units installed on Enewetak and Lojwa Islands were used to provide potable drinking water to cleanup participants. Records show that ocean water was the source and distilled water was supplied throughout the cleanup project (1977–1980) for all drinking, cooking, bathing, and cleaning needs. (DNA, 1981)

As discussed in Section 4.7.1, samples of produced water were collected in 1978 from Enewetak and Enjebi Islands and analyzed for Cs-137, Pu-239/240, and Pu-238. Trace levels of Cs-137 and plutonium isotopes in the samples were about 3–5 orders of magnitude below the current maximum contaminant levels for drinking water in the United States (USEPA, 2017b).

The food consumed by cleanup participants was supplied by the food service using ingredients supplied through the military logistics system. As a result, prepared food and drinking water were not potential direct sources of exposure to radiation. Although the consumption of local terrestrial and marine food by cleanup personnel was plausible, the availability and access to such foods was limited. Very few coconut trees were growing at Enewetak Atoll. Other edible food such as pandanus, breadfruit, and arrowroot were even less available (DNA 1981). Some veterans may have caught and consumed lobsters or fish (Cherry, 2018b). Other local foods may have included coconut crab and coconut milk and meat, as well as giant clams. However, given the scope of the cleanup project and potential contamination of local food, it is expected that in general, personnel refrained from eating such foods. In cases where local foods were consumed, the specifics of such consumption can be used to assess exposure on a case-by-case basis. Therefore, the potential consumption of local foods is included in the ECUP Questionnaire to participants and is assessed in Section 7.4 and Appendix M.

Incidental ingestion of contaminated soil and dust through food and beverage consumption is considered a potential source of exposure to radiation for participants while on contaminated islands and is discussed in Section 7.2. In addition, an evaluation of potential exposure from the consumption of drinking water is discussed in Section 7.4.2.

5.2 Exposure Pathways for Dose Assessment

In general, an exposure pathway is the route followed by radiation or contaminants from a source via air, soil, water, or food to a human receptor. In the context of the ECUP and potential exposure to radiation, pathways involve exposure of the whole body to gamma radiation from external sources, exposure of internal organs and tissues to radiation emissions from internally deposited radioactive materials, and exposure of the skin to external sources of gamma and beta radiation.

5.2.1. Exposure of the Whole Body to Radiation from External Sources

Direct exposure to the radiation emitted by radioactive contamination is the primary pathway relevant to ECUP personnel. Sources of radiation that may have resulted in direct exposure to radiation of ECUP participants include:

- Fallout mixed in the top layer of soil of contaminated islands
- Stockpiles of contaminated soil and debris
- Contaminated soils and debris, during transport by trucks and boats
- Contaminated concrete slabs and building debris
- Slurry of mixed contaminated soil and cement, during preparation, transport and disposal in the Cactus Crater
- Soil-cement mix produced and contained in the Cactus dome
- Lagoon and ocean waters, while retrieving debris and during recreational diving or swimming
- Contaminated equipment and decontamination laundry.

Direct exposure from contaminated ground surfaces was the most likely potential external radiation exposure pathway for ECUP participants. This exposure pathway applies to participants who were working or residing on islands with radiation levels above background, whether involved in cleanup activities or not. Direct exposure to soil that was excised, windrowed, stockpiled, and transported for ultimate containment in Cactus Crater on Runit represents a similar pathway for those individuals who were involved in soil cleanup activities.

5.2.2. Exposure of the Skin to Radiation from External Sources

Exposure of the skin to external sources of gamma and beta radiation could have occurred from the same sources listed for whole body exposure in the preceding subsection. In addition, exposure could have occurred if contaminated material was deposited directly on the skin or clothing.

5.2.3. Exposure of Organs and Tissues to Radiation from Internal Sources

Exposure of internal organs and tissues could have occurred from the intake and deposition of radioactive materials inside the body. Potentially contaminated media and routes of entry relevant to ECUP participants include:

- Inhalation of soil suspended in air during brush removal and soil excision
- Inhalation of airborne soil during loading, off-loading and uncovered transport on trucks, boats and barges
- Inhalation of suspended soil during soil-cement mix operation in the Cactus dome
- Inhalation of dust, e.g., from breaking down solidified slurry or from sandblasting during decontamination of concrete surfaces
- Ingestion of food, including locally obtained food and water
- Inadvertent ingestion of lagoon or ocean water while extracting offshore debris or swimming
- Incidental ingestion of soil and dust
- Absorption of material into the blood stream through open wounds.

Suspension of contaminated soil during soil removal, handling, and transport was the most likely internal radiation exposure pathway for ECUP participants. This exposure pathway applies to participants who were working or residing on islands with radiation levels above the background level.

5.3 Participant Activities and Potential Exposure to Radiation

The ECUP POI can be considered to consist of groups of individuals with similar exposure scenarios. These groups are based on conducting similar project activities that involved the same or similar sources of radiation and potential exposure pathways. Each of the functional service organization and JTG units was assigned various responsibilities and tasks. Some of these tasks involved potential exposures to the radiation sources described above in Section 5.2. To evaluate the scenarios of exposure for ECUP personnel, specific activities within coherent project tasks were identified and categorized into the following top-level project components:

- Soil cleanup
- Debris cleanup
- Radiological support
- Southern islands (except Enewetak)
- Project support on the residence island of Enewetak
- Project support on the residence island of Lojwa
- Intra-atoll transport
- Pre-cleanup and demobilization
- Recovery and disposal of unexploded ordnance by EOD teams.

Within each of the top-level ECUP project component listed above, second-level tasks and third-level specific project activities were identified to best characterize personnel involvement in the cleanup effort and associated potential sources of radiation exposures. The tasks and activities related to each project component are discussed in subsequent subsections.

Participants in some of the project teams conducted consistent and similar activities. However, members of other teams performed varying activities at different times and at different locations. For example, personnel in some of the general support units, such as the Finance Team and Airfield Team, conducted activities that were relatively consistent within the unit and were limited in both scope and location. The radiation dose assessment for participants in these types of units can be characterized by evaluating the scenarios of exposure for one of the two Project Support components for the residence islands of Enewetak or Lojwa; see list of project components above.

Personnel in other units, such as the U.S. Army Engineer units and the FRST, were responsible for conducting a wide range of activities. These participants performed tasks at locations on multiple islands, and at different phases of the cleanup project. For these participants, a single unit-level radiation dose assessment cannot be performed. Rather, exposure scenarios associated with participation in project tasks on various islands or water transport vessels would be identified. These activity-based exposures to sources of radiation would constitute the basis for performing individualized dose assessment in response to future VA requests for dose information.

Project personnel may have participated in multiple project components and tasks, and consequently, were the subject of distinct scenarios of exposure to radiation. In these cases, the scenarios of exposure should be assessed for an individual based on all activities performed under all project components. External and internal doses are estimated for all project component activities according to the methods discussed in Section 6 and Section 7.

Project tasks within each project component and associated potential sources and pathways of radiation exposure are described in the following sub-sections. Participant groups that performed similar activities or operated in similar radiation environments are also identified.

5.3.1. Soil Cleanup

5.3.1.1 Tasks, Activities and Exposure Pathways

The soil cleanup project component comprises five distinct tasks, each with several inherent activities. These activities were conducted primarily by personnel in the U.S. Army Element (Engineer units, LARC unit), U.S. Navy Element (Intra-atoll transportation teams, Harbor Clearance units, WBC teams), and DNA/JTG Element (Engineering team). Radiological support personnel were also involved in soil cleanup activities as discussed for the Radiological Support Project Component. Under the soil cleanup project component (Table 23), the following are the main tasks that personnel performed:

- Brush removal
- Soil removal (except Runit) and transport to Runit
- Tremie disposal of contaminated soil slurry in the Cactus Crater
- Runit soil cleanup
- Direct disposal by soil-cement mixing into Cactus dome.

Each of the above tasks involved specific activities that were potentially associated with exposure to radiation. Soil cleanup activities involved excision of soil contaminated with radioactive materials from five islands, transport of the soil to Runit Island, and disposal in the Cactus Crater and dome. The five islands are Boken, Enjebi, Lujor, Aomon, and Runit (DNA, 1981). In addition, a small quantity, about 110 yd^3, of soil contaminated with Co-60 was removed from a limited area on Medren and was disposed in the Cactus Crater.

Activities under each task are listed with specific sources of exposure in Table 23. These activities generally took place over the period from mid-1978 to mid-1979. Brush removal activities, which generally preceded soil removal, are included in the soil cleanup project component. As shown in Table 23, external sources of exposure for this project component consist of direct exposure to soil surfaces, soil piles, and soil-cement mixtures. Sources of internal exposure pathways consist of inhalation of suspended soil or soil mixtures. In addition, exposure from incidental ingestion of contaminated soil and dust applies to all participants; this pathway is generic in nature and is applicable to all project components. Therefore, it is not specifically shown in Table 23.

Table 23. Tasks, activities and sources of exposure – Soil Cleanup Project Component

Tasks and Activities	Sources of External Exposure						Sources of Internal Exposure			
	Soil Surfaces	Soil Piles	Piles during Bulk Transport	Soil-cement Mixture	Slurry during Pumping	Rejected Slurry	Soil Suspended from Surface during Soil Disturbance	Soil Suspended while Handling (e.g., loading, unloading)	Soil Suspended during Transport	Soil-cement Suspended during Mixing or Spreading
Brush removal task										
Uproot bushes and vegetation	×	×					×			
Burn uprooted vegetation										
Transport ashes to Runit										
Soil removal (except Runit) and transport to Runit task										
Remove and windrow	×	×					×			
Load soil on dump trucks		×						×		
Transport soil to stockpiles			×						×	
Load soil on LCMs or LCUs		×	×					×		
Transport to Runit		×							×	
Transport to stockpile	×								×	
Tremie disposal in Cactus Crater task										
Load soil onto dump trucks		×						×		
Transport soil to batch plant			×						×	
Mix soil into slurry					×					×
Transport slurry to pump					×					
Pump slurry through pipes					×					
Discharge slurry into trenches						×				
Place hardened, rejected slurry into crater						×				

Tasks and Activities	Sources of External Exposure						Sources of Internal Exposure			
	Soil Surfaces	Soil Piles	Piles during Bulk Transport	Soil-cement Mixture	Slurry during Pumping	Rejected Slurry	Soil Suspended from Surface during Soil Disturbance	Soil Suspended while Handling (e.g., loading, unloading)	Soil Suspended during Transport	Soil-cement Suspended during Mixing or Spreading
Runit soil removal and transport to Cactus dome task										
Remove and windrow soil	×	×					×			
Load soil on dump trucks		×						×		
Transport soil to Cactus dome			×						×	
Place soil over Fig-Quince soil	×		×					×		
Direct disposal by soil-cement mixing into Cactus dome task										
Load soil onto dump trucks	×							×		
Transport soil on trucks to crater			×						×	
Spread and mix soil with cement				×						×
Construct key wall				×						×
Construct containment cap	×	×		×						×

5.3.1.2 Soil Cleanup – Potential Exposure Scenarios

To characterize the type of activities performed by project personnel, several consolidated cleanup operations under the soil cleanup project component were identified. The following subsections describe these project operations and the type of personnel that were involved in conducting them.

5.3.1.2.1 Soil Removal and Transport

The scenario of exposure for individuals in this participant group includes activities involving disrupting and handling contaminated soil on four soil removal islands and Runit. Specifically, activities in this exposure scenario are those that may have resulted in suspension of contaminated soil during removal, transport, and disposal such as:

- Uprooting, pushing/moving and windrowing vegetation
- Excision, windrowing and piling contaminated soil
- Loading and unloading bulk contaminated soil as follows:

  - At soil removal sites
  - At beach stockpiles
  - On and off boats
  - At boat ramp on Runit
  - At soil stockpiles on Runit
  - At batch plant on Runit
- Transporting soil by trucks
- Transporting soil by boats
- Burning windrowed brush
- Loading and unloading contaminated ash-soil mix from burned vegetation
- Transporting contaminated ash-soil mix for disposal on Runit
- Placing a 12-inch layer of relatively clean soil over the Fig-Quince area.

Personnel involved in the above activities can be generally categorized in the following subgroups:

- Operators of earthmoving machinery, e.g., bulldozers, backhoes, front loaders, bucket loaders, etc.
- Truck drivers
- Boat crew members
- Batch plant personnel
- Support personnel, such as surveyors, ground spotters and guides.

Other groups of personnel, such as FRST members, were associated with soil removal and transport activities. However, their activities are described under the "Radiological Support" project component.

5.3.1.2.2 Tremie Operations

Personnel who were involved in tremie operations in the Cactus Crater on Runit performed activities that can be described as follows (DNA 1981):

- Loading contaminated soil from stockpiles onto dump trucks
- Driving dump trucks from contaminated soil stockpiles to concrete batch plant
- Mixing contaminated soil with cement and water at the batch plant
- Depositing tremie mix into transit-mix trucks at the batch plant
- Driving transit-mix trucks from batch plant to concrete pump next to the crater

- Pumping contaminated soil-cement slurry in tremie piping
- Operating the tremie crane and barge on the crater water surface.

In addition, as presented in Section 5.1.2, rejected slurry was handled by the "processed tremie" method. The activities involved in this method are described as follows:

- Discharging rejected slurry from the transit-mix trucks into excavated trenches to let it harden
- Breaking large hardened slurry blocks into smaller pieces
- Loading hardened slurry chunks into dump trucks
- Driving dump trucks and offloading the hardened slurry chunks into the crater.

The groups of individuals listed below participated in the activities for tremie operations, which include the "processed tremie" method for rejected slurry:

- Transit-mix truck drivers transporting slurry to crater rim
- Operators of slurry disposal equipment, e.g., tremie pumps, barge, crane, etc.
- Excavators of trenches for rejected slurry
- Operators of equipment for preparation, transport and disposal of rejected, hardened slurry.

Other groups of personnel may have been associated with tremie operations. However, their activities are described under separate project components.

5.3.1.2.3 Soil-Cement Operations

The remaining group of personnel that conducted activities under the Soil Cleanup component, that are not discussed under other project components, are those individuals who were involved in the soil-cement operations on Runit. The purpose of this operation was to construct the dome over the hardened slurry that filled the Cactus Crater. The following activities were conducted (DNA, 1981):

- Loading, transporting and dumping contaminated soil at the crater containment site by truck
- Spreading the soil in approximately 6-inch layers using a grader
- Dumping bags of cement onto soil at the ratio of two bags per cubic yard of soil
- Mixing dry cement with the soil using a disc harrow towed by a bulldozer
- Watering down the dry mixture and compacting the wetted mixture with a vibratory roller compactor.

Construction of the key wall and containment cap are also included in the soil-cement grouping of activities. Key wall construction did not involve handling contaminated soil but it was constructed at the perimeter of the dome at least partially during the period of soil-cement activities. Construction of the containment cap took place directly on top of the compacted soil-cement mixture. Also, partial cap construction was started before all of the soil-cement activities were complete (DNA, 1981).

Personnel conducting soil-cement, key wall and containment cap construction activities included the following:

- Dump truck and water truck drivers
- Operators of graders, bulldozers, and roller compactors
- General construction engineers and personnel
- Support personnel, such as surveyors, ground spotters and guides.

5.3.2. Debris Cleanup

5.3.2.1 Tasks, Activities and Sources of Exposure

The Debris Cleanup Project Component comprised eight tasks shown in Table 24, each with a number of specific activities. These activities were conducted primarily by personnel in Army Engineer Units, Army LARCs and Amphibious Vehicle operations, Navy Harbor Clearance Units, EOD teams, WBC teams, and DNA/JTG Engineering (DNA, 1981). Personnel associated with the Radiological Support Project Component (see Section 5.3.3 below) were also involved in these debris cleanup activities. The following are the main tasks that personnel performed (see detailed activities and relevant sources of radiation exposure in Table 24):

- Onshore debris removal and transport to beach stockpile area at islands other than Runit
- Offshore debris removal and transport for islands other than Runit
- Transport and disposal at lagoon dump sites of “yellow” debris from beach stockpiles loaded on trucks from islands other than Runit
- Transport and lagoon disposal of bulk “yellow” debris from islands other than Runit
- Transport and offloading of “red” debris to Runit stockpiles for islands other than Runit
- Disposal of “red” debris from islands other than Runit in the Cactus Crater
- Collection and disposal of Runit debris in donut hole in Cactus dome
- Disposal of “red” debris collected during Cactus dome and antechamber dome extension constructions.

Personnel removed, transported, and disposed of approximately 1,800 yd^3 of contaminated debris from the islands of Enjebi, Lujor, Eleleron, and Aomon. Contaminated debris from these islands was disposed of at three designated sites in deep areas of the lagoon shown in Figure 4 or into the Cactus Crater and dome on Runit. In addition, about 4,000 yd^3 of contaminated debris was collected onshore and offshore of Runit and disposed of in the Cactus dome and two antechamber extensions. Non-contaminated debris was removed from 34 islands with the largest quantities removed from Enewetak and Medren Islands (DNA, 1981). The soil of several of these islands had some level of contamination with radioactive materials. Table 6 (Section 4.2) provides island-by island mean soil activity concentrations.

The lagoon was chosen for the disposal of debris that was radiologically classified as "yellow" or "green." The Cactus Crater and dome were chosen for disposal of debris classified as "red." Definitions for the radiological classifications are given in Section 3.2.2. All debris stockpiled on Runit, regardless of source, was moved locally for disposal in Cactus Crater and dome with heavy equipment, such as cranes with clamshells, front loaders, dump trucks and bulldozers.

Each of the tasks listed above involved several activities that could have been associated with exposure to radiation while handling both contaminated and non-contaminated debris, such as inoperable equipment, abandoned vehicles, orphaned laboratory sources, and building materials containing source contamination. Activities under each task are listed along with potential sources of exposure in Table 24. The debris cleanup and disposal took place during three periods. From mid-1977 to May 1979, contaminated debris from the four islands listed above was collected and disposed of. All cleanups were completed by late 1978, except for Enjebi, which was completed in May 1979. Following the first phase and up to late 1979, debris on Runit was collected and disposed of in the Cactus dome. During this same timeframe, resurveys of the four islands indicated additional "red" debris removal was necessary. That debris was collected and transported to Runit for disposal during February to May 1979 (DNA, 1981).

As shown in Table 24, sources of external exposure to radiation for the debris cleanup project component consisted of direct exposure to contaminated debris during retrieval, stockpiling, transport, movements over contaminated ground, and disposal. Additionally, contaminated soil in the ground was a source of exposure applicable to personnel involved in the removal of non-contaminated debris from all the remaining soil-contaminated northern islands. Internal exposure pathways consisted of inhalation of suspended soil created by movement of debris and disposal activities in contaminated environments. In addition, exposure from incidental ingestion of contaminated soil and dust applies to all participants involved in debris cleanup who worked on contaminated islands. This pathway is common in nature and is applicable to all project components. Therefore, it is not specifically shown in Table 24, but it is discussed in Section 7.2.

5.3.2.2 Debris Cleanup: Potential Exposure Scenarios

The activities by personnel associated with the debris cleanup tasks listed in Table 24 are generally similar but differ with respect to the sources of the debris, timeframe of disposal actions, and the location of disposal sites. There were three phases of disposal activities on Runit. "Red" debris from the four islands other than Runit with contaminated debris was continuously being transported to Runit for disposal in the crater. Runit debris cleanup and disposal activities were postponed until cleanup of the other four islands was complete. The following subsections describe potential scenarios of exposure that are relevant to specific debris cleanup tasks and participant groups that performed them.

Table 24. Tasks, activities and sources of exposure – Debris Cleanup Project Component

Tasks and Activities	Sources of External Exposure							Sources of Internal Exposure	
	Ground Surface	Debris on Beach and Underwater (Small/Large)	Debris Piles during Collection and Transport to Beach Areas (Y/R)*	Piles on Beach (Y/R)	Piles during Transport by Boat or Barge (Y/R)	Debris Piles on Runit (R)	Debris Disposed in Crater and Donut (R)	Soil Suspended from Ground while Handling Debris (e.g., Collecting, Loading, Unloading)	Soil Suspended during Transport to and from Stockpiles
Onshore debris removal and transport to beach stockpile area at islands other than Runit									
Disassemble/break up oversized debris	×	×	×		×			×	×
Remove debris by hand; move to piles	×	×		×				×	
Remove debris by engineering equip (bulldozers)	×		×	×				×	×
Load debris on trucks with loaders and cranes	×		×	×				×	
Transport debris by truck to beach stockpiles	×		×	×				×	×
Offshore debris removal and transport for islands other than Runit									
Manually remove small debris	×	×	×	×					
Retrieve large u/w debris by divers using winches	×	×	×	×				×	
Transport offshore debris to stockpile or lagoon dump sites	×	×	×	×	×			×	×
Transport and disposal at lagoon dump sites of "yellow" debris from beach stockpiles loaded on trucks from islands other than Runit									
Load trucks w/ beach stockpile debris w/ loaders and cranes	×		×	×	×			×	
Drive loaded trucks onto landing craft	×		×		×				
Transport "yellow" debris for lagoon disposal			×		×				
Offload yellow debris from trucks on boats by cranes on a barge			×		×				

Tasks and Activities	Sources of External Exposure							Sources of Internal Exposure	
	Ground Surface	Debris on Beach and Underwater (Small/Large)	Debris Piles during Collection and Transport to Beach Areas (Y/R)*	Piles on Beach (Y/R)	Piles during Transport by Boat or Barge (Y/R)	Debris Piles on Runit (R)	Debris Disposed in Crater and Donut (R)	Soil Suspended from Ground while Handling Debris (e.g., Collecting, Loading, Unloading)	Soil Suspended during Transport to and from Stockpiles
Transport and disposal of bulk "yellow" debris from islands other than Runit									
Load bulk "yellow" debris onto landing craft	×		×	×					
Transport "yellow" debris for lagoon disposal			×		×				
Offload yellow debris with loaders/cranes at lagoon dump sites			×		×				
Transport and offloading of "red" debris for other than Runit									
Transport red debris to Runit collection point	×		×		×			×	×
Offload red debris to Runit stockpile w loaders/cranes			×		×			×	×
Cactus Crater disposal of "red" debris from islands other than Runit									
Dispose of debris in crater	×		×			×	×	×	×
Dispose of bags of soil with Pu fragments	×					×	×	×	×
Bulldoze oversized debris to edge of crater	×					×	×	×	×
Runit debris collection and disposal in a donut hole in the Cactus dome									
Collect debris from South Runit (1977)	×	×	×	×		×		×	
Collect metal debris from reef near runway and Blackfoot areas	×	×	×	×		×		×	
Manually remove small debris from beach/underwater areas	×	×	×	×		×		×	

Tasks and Activities	Sources of External Exposure							Sources of Internal Exposure	
	Ground Surface	Debris on Beach and Underwater (Small/Large)	Debris Piles during Collection and Transport to Beach Areas (Y/R)*	Piles on Beach (Y/R)	Piles during Transport by Boat or Barge (Y/R)	Debris Piles on Runit (R)	Debris Disposed in Crater and Donut (R)	Soil Suspended from Ground while Handling Debris (e.g., Collecting, Loading, Unloading)	Soil Suspended during Transport to and from Stockpiles
Retrieve large underwater by divers using winches	×	×	×	×		×		×	
Transport offshore debris to beach stockpile area	×		×	×		×		×	
Truck RUNIT debris beach stockpile to Donut Hole in dome	×		×	×		×		×	×
Dispose debris in Donut Hole using a bulldozer	×					×	×	×	
Dispose of soil bags with Pu-contaminated fragments (Fig-Quince)	×					×	×	×	×
Disposal of "red" Runit debris collected during Cactus dome and antechamber constructions									
Dispose debris from Lacrosse crater in depressions in Cactus mound surface	×					×	×	×	×
Dispose metallic debris inside dome cap sections	×					×	×	×	×
Construct two dome extensions after dome capping for "red" debris	×							×	
Choke "red" debris with clean concrete slurry	×						×	×	

* Debris classified as "yellow (Y) and red (R)"

5.3.2.2.1 Debris Removal, Transport, and Disposal for Islands other than Runit

The scenario of exposure for individuals who participated in debris removal, transport, and disposal involved handling of both contaminated and non-contaminated debris on over 30 islands. Preparations for and actual transport and unloading at the disposal sites in this scenario resulted in external exposures. They resulted from directly handling debris, piles at a distance, ground shine from contaminated soil on the ground surface, and offshore debris collection. Specific activities associated with debris removal, transport, and disposal are:

- Disassembling, breaking up, and removing debris
- Retrieving large underwater debris by divers using winches
- Transporting debris by truck to beach stockpile, lagoon dump sites or Runit
- Loading trucks with loaders and cranes with clamshells and driving them onto landing craft
- Transporting and offloading "yellow" debris for lagoon disposal by bulldozers, crane and clamshell
- Transporting and offloading "red" debris to Runit collection areas by bulldozers, crane and clamshell
- Transporting "red" debris from Runit collection areas and disposing in Cactus Crater and dome.

Personnel involved in the above activities can be generally categorized into the following subgroups:

- Heavy machinery operators, e.g., bulldozers, backhoes, front end loaders, bucket loaders, cranes with clamshells, and winches
- Truck drivers
- Boat crew members
- EOD personnel
- Divers.

Other groups of personnel, such as brush removal teams, are not included under debris cleanup, but are discussed under the Soil Cleanup Project Component.

5.3.2.2.2 Debris Collection and Disposal on Runit

The scenario of exposure for individuals who participated in debris cleanup on Runit involved the collection and disposal of "red" debris brought in from four debris-removal islands other than Runit, or removed from South Runit, Blackfoot ground zero (GZ), Lacrosse crater, and within the Cactus Crater areas. The scenario also includes in-water debris collection as well as activities involving soil and debris being prepared for disposal and the actual disposal. Another scenario, unique to Runit, was the disposal of "red" debris consisting of plutonium embedded in rock-like materials, collected from Aomon and Runit. External exposures resulted from directly handling the debris, piles at a distance, and ground shine from contaminated soil on the ground surface. Specific activities associated with debris collection and disposal on Runit include:

- Collecting and transporting offshore debris to beach stockpile area
- Collecting and moving debris from South Runit, nearby reefs, old runway, and Blackfoot GZ areas
- Manually removing and retrieving small and large underwater debris from beach and underwater areas and trucking and disposing debris in Donut Hole in Cactus dome
- Disposing of debris in Cactus Crater
- Disposing of bags of soil with plutonium fragments
- Bulldozing oversized debris to edge of Cactus Crater
- Disposing of metallic debris inside dome cap sections
- Disposing of debris from Lacrosse crater in depressions in Cactus mound surface
- Constructing two dome extension antechambers after dome became full
- Choking “red” debris with clean concrete slurry in crater antechambers.

Personnel involved in the above activities can be generally subdivided into the following groups:

- Heavy machinery operators, e.g., bulldozers, backhoes, front-end loaders, bucket loaders, cranes with clamshells, and winches
- Truck drivers
- Boat crew members
- EOD personnel
- Divers
- Surveyors and construction workers involved in the dome extension and capping.

Other groups of personnel, such as brush removal teams, are not considered under debris cleanup, but are described under the Soil Cleanup Project Component in Section 5.3.1.

5.3.3. Radiological Support

5.3.3.1 Tasks, Activities and Sources of Exposure

The Radiation Control Division (J-2) staff developed detailed procedures for specific operations that provided the workers what to do and how to do it in the field of radiation safety so that personnel exposures were kept as low as reasonably achievable (DNA 1981). The FRST, under J-2 staff (alternate RPO) supervision, oversaw on-site radiological safety and conducted field sampling of soil and debris. The Navy and Air Force also furnished technicians to work with the radiological support contractors, thus reducing the cost of radiological survey and laboratory operations (DNA 1981). In addition, the "Radiation Safety Audit and Inspection Team" (RSAIT) was chartered by the DNA Director to independently assess the radiological protection program. The team comprised members from each of the Services and ERDA/Department of Energy (DOE) (DNA 1981). The radiological support component includes the following five major tasks:

- Provide operational radiological control
- Perform radiological surveys and sample collection
- Provide radiological laboratory support
- Oversee radiation control at Army-operated decontamination laundry
- Conduct radiation safety audit and inspections.

The activities associated with each of the tasks above entailed possible exposures to radiation. The potential exposure pathways are identified in Table 25 for each of the activities.

Table 25. Tasks, activities and sources of exposure – Radiological Support Project Component

Task and Activities	Sources of External Exposure							Sources of Internal Exposure		
	Ground Surface or Subsurface	Soil Pile	Debris Pile	Contaminated PPE	Contaminated Equipment	Contaminated Samples	Check sources for Calibration	Soil suspension while Supervising On site	Soil Resuspension from PPE	Soil Resuspension from Equipment
Radiological control										
Operate hot line monitoring stations	×	×	×					×	×	
Collect and deliver contaminated PPE to laundry at Lojwa				×						
Decontaminate personnel and equipment	×				×					×
Radiological surveys and sample collection										
Survey radiation levels and collect samples	×	×	×			×		×		
Take nasal swabs	×	×				×		×		

Task and Activities	Sources of External Exposure							Sources of Internal Exposure		
	Ground Surface or Subsurface	Soil Pile	Debris Pile	Contaminated PPE	Contaminated Equipment	Contaminated Samples	Check sources for Calibration	Soil suspension while Supervising On site	Soil Resuspension from PPE	Soil Resuspension from Equipment
Radiological laboratory support										
Decontaminate radiological instrumentation					×					
Calibrate radiological instrumentation							×			
Perform radiological sample analyses						×				
Army-operated decontamination laundry										
Launder contaminated PPE				×					×	
Monitor washers and dryers for residual contamination					×					×
Sample laundry effluents						×				
Radiation Safety Audit and Inspection										
Evaluate radiological protection practices on-site	×	×	×					×		

5.3.3.2 Radiological Support: Potential Exposure Scenarios

The following subsections describe potential scenarios of exposure that are relevant to radiological support tasks and participant groups who performed them.

5.3.3.2.1 Radiological Control and Surveys

The individuals in this potentially exposed group are FRST members who operated the atoll radiation protection program. Specific assignments included the following (DNA, 1981):

- Controlling hot lines
- Operating air samplers
- Issuing, collecting, and reading supplementary personnel dosimetry devices

- Performing radsafe procedures at each work site, e.g., soil and debris cleanup sites
- Monitoring personnel, facilities, and equipment
- Overseeing decontamination of personnel, facilities, and equipment as required.
- Collecting and delivering contaminated PPE to laundry at Lojwa
- Taking nasal swabs.

Personnel involved in the above activities can be generally categorized into the following subgroups:

- Health physicists
- Health physics, radiological control, bioenvironmental engineering and safety technicians
- Other military specialties as assigned.

5.3.3.2.2 Radiological Laboratory Support

The technicians provided by Navy and Air Force worked with contractors, such as Holmes & Narver Pacific Test Division to furnish radiological support. They conducted the following activities necessary to establish cleanup requirements, to evaluate the effectiveness of cleanup work, to maintain functional and accurate radiation probes, and to certify the results of radiological cleanup (DNA 1981):

- Performing radiological sample analyses
- Performing soil and debris surveys
- Decontaminating radiological instrumentation
- Calibrating radiological instrumentation.

Personnel involved in the above activities can be generally categorized into the following subgroups:

- Health physicists
- Radio-analytical chemists
- Radiation specialists
- Health physics, radiation control or bioenvironmental engineering technicians
- Precision measurement equipment laboratory (PMEL) technicians.

5.3.3.2.3 Decontamination Laundry

The Army Laundry Team from 613th Field Service Company began providing laundry service on June 17, 1977. They operated a general laundry at Enewetak Camp and a decontamination laundry at Lojwa Camp for cleaning washable personal protective equipment. The Lojwa laundry was operated under supervision of the FRST. The FCRR SOP 608-10, “Decontamination Laundry Procedures” (FCRR, 1978b), provided detailed guidance on the operation and monitoring of the facility (DNA, 1981). The Laundry team performed the following activities:

- Laundering contaminated PPE
- Monitoring washers and dryers for residual contamination
- Sampling laundry effluents.

Personnel involved in the above activities can be generally categorized into the following subgroups:

- Laundry technicians
- Health physics, radiological control, bioenvironmental engineering and safety technicians.

5.3.3.2.4 Radiation Safety Audit and Inspection

The RSAIT was given the broadest range of authority to scrutinize all aspects of the radsafe program. The RSAIT comprised a multi-disciplinary group of radiation safety, occupational safety and health, and medical specialties, many of whom were health physicists (or equivalent military specialty). The group was headed by the Director of AFRRI (Armed Forces Radiobiology Research Institute) (DNA 1981).

The RSAIT visits were scheduled as frequently as would be useful; they started at quarterly intervals, but eventually were reduced to about three times per year. Their work involved the following (DNA, 1981):

- Reviewing all procedures established for radiation, environmental, and occupational safety
- Visiting the various islands and observing the practices actually in use to ensure that the procedures were appropriately performed.

The RSAIT visited the atoll ten times during the cleanup. The duration of each visit depended on the time required for thorough inspection of actual working conditions at the site of each radsafe operation on the atoll.

Personnel involved in the above activities can be generally categorized into the following subgroups:

- Health physicists
- Health physics, radiological control, bioenvironmental engineering and safety technicians
- Medical specialists
- Other military specialists as assigned.

5.3.4. Southern Islands (except Enewetak)

This project component contains three distinct tasks. Only one of the tasks involved exposure to radiation sources. The cleanup tasks performed in the southern islands other than Enewetak include the following:

- Remove contaminated soil from Medren
- Remove non-contaminated debris from southern islands
- Retrieve unexploded ordnance by EOD teams.

The first task above involved a small quantity of Co-60 contaminated soil from limited areas on Medren that was removed and contained in the Cactus Crater. Activities under the task are listed with specific potential exposure pathways in Table 26. These activities took place during February 7–10, 1978 (DNA 1981). As shown in Table 26, external exposure pathways for this project component consist of direct exposure to soil surfaces and soil piles. Internal exposure pathways consist of inhalation of suspended soil. In addition, exposure from incidental ingestion of contaminated soil and dust applies to all participants; this pathway is not shown in Table 26.

Table 26. Tasks, activities and exposure pathways – Southern Islands Project Component

Tasks and Activities	Sources of External Exposure			Sources of Internal Exposure		
	Soil Surfaces	Soil Piles	Piles during Bulk Transport	Soil Suspended from Surface during Soil Disturbance	Soil Suspended while Handling (e.g., Loading, Unloading)	Soil Suspended during Transport
Soil removal from Medren and transport to Runit task						
Remove soil with backhoes	×			×		
Load soil on dump trucks	×				×	
Transport trucks by LCU to Runit			×			×
Offload soil from trucks to stockpile	×	×			×	

Personnel involved in the above activities on Medren can be generally categorized into the following subgroups:

- Operators of earth moving machinery, e.g., backhoes, front loaders
- Truck drivers
- Boat crew members
- Support personnel, such as surveyors, ground spotters and guides.

The participants conducting the second and the third tasks of this project component did not handle radioactive materials and were not near contaminated soil (DNA, 1981). These participants had no sources of exposure to radiation. Therefore, these tasks are not listed in Table 26.

5.3.5. Project Support on Residence Islands – Enewetak

Enewetak Island was the primary residence and support base for ECUP. The results of the Enewetak Radiological Survey indicated that Enewetak Island had levels of contamination comparable to or lower than those due to worldwide fallout in the United States (AEC, 1973a). The tasks listed below were conducted on Enewetak, to support the cleanup project:

- Construct and maintain facilities and structures
- Provide medical and dental care
- Install and maintain telecommunication equipment and stations
- Maintain petroleum, oil, and lubrication stores and resupply forward areas
- Operate and maintain postal service
- Operate food services
- Provide welfare and recreation services
- Operate airfield and offload/load cargo
- Participate as crewmembers on supply ships or aircraft.

Personnel involved in the above activities can be generally categorized into the following subgroups:

- Civil engineers, construction workers
- Medical doctors and dentists, nurses, medical assistants
- Electrical engineers, communication electronics technicians, radiomen
- Post servicemen
- Chefs and cooks
- Pilots, airmen, aircraft fuel technicians
- Crewmen
- Other military specialists as assigned.

The participants conducting the tasks above on Enewetak Island did not handle radioactive materials and were not near contaminated soil and debris. Therefore, these personnel had no potential sources of exposure.

5.3.6. Project Support on Residence Island – Lojwa

Based on the data collected and analyzed, Lojwa Island was cleared from the controlled access island list on May 27, 1977 because it was found to be radiologically safe (CJTG, 1977a). Lojwa was then established as the location of a temporary base camp in the northern islands to support cleanup in that area and to reduce transportation time and requirements (DNA, 1981). The tasks performed on Lojwa to support the cleanup project are listed below:

- Construct and maintain facilities and structures
- Provide medical and dental care
- Install and maintain telecommunication equipment and stations
- Maintain petroleum, oil, and lubrication stores and resupply forward areas
- Operate and maintain postal service
- Operate food services
- Provide welfare and recreation services.

Personnel involved in the above activities can be generally categorized into the following subgroups:

- Civil engineers, construction workers
- Medical doctors and dentists, nurses, medical assistants
- Electrical engineers, communication electronics technicians, radiomen
- Post servicemen
- Chefs and cooks
- Other military specialists as assigned.

The participants conducting the tasks above on Lojwa did not handle radioactive materials and were not near contaminated soil or debris that required cleanup. The island-average external exposure rate on Lojwa is shown in Table 4.

5.3.7. Intra-Atoll Transport

Transportation of people, equipment, supplies, and materials from island to island during the ECUP project depended heavily on boat transportation. In addition, air transportation by helicopter supported the primary missions of MEDEVAC and Search and Rescue (SAR), as well as other support on an as-needed basis.

Intra-atoll boat transportation was assigned to the Navy, primarily its Boat Transportation Team, with one exception. The Army provided amphibious lighters (Lighter Amphibious Resupply, Cargo LARCs), which were able to cross several hundred yards of the shallow reefs that surrounded many of the islands and prevented access by Navy landing craft.

The following activities were performed by intra-atoll air transportation personnel:

- Transport personnel and materials during MEDEVAC and SAR missions
- Transport personnel and equipment during command, control, and logistical missions
- Transport ERDA personnel and equipment during gross radiological surveys of islands.

Personnel who performed intra-atoll transportation can be categorized into the following subgroups:

- Boat crewmembers including Boatswain's Mates, Enginemen, Hull Technicians, Electrician Mates, and other Navy specialties
- Army heavy equipment operators
- Army aviation personnel including pilots, flight engineers, and other aircrew.

Intra-atoll transportation personnel were expected to perform their functions 6 days per week, 10 hours per day, but may have exceeded those levels to accomplish their missions.

The service members who performed the first three tasks listed for boat transportation and all tasks for air transportation above did not handle radioactive materials directly and were not near contaminated soil or debris. Therefore, there are no sources of potential exposure for these individuals. During transportation of contaminated soil or debris, service members in this project component did not handle radioactive materials directly, but were present near the contaminated soil or debris, usually at a distance and not in direct contact. Nevertheless, service members performing the latter two activities are included in the Soil Cleanup or Debris Cleanup project components.

5.3.8. Pre-cleanup Mobilization and Demobilization

The ECUP effort was characterized by major cleanup functions represented by soil cleanup, debris cleanup, and radiological safety that involved possible radiation exposures. In addition, other major efforts removed and disposed of uncontaminated materials in order to prepare the atoll for resettlement of the Enewetak people. These activities starting in the summer of 1977 and extending into the fall of 1979 account for most of the total project timeframe.

The success of ECUP operations depended on effective planning and preliminary preparation efforts during a mobilization period and on similarly effective ramp-down efforts to finalize the departure of project military service members and units, DOE, and contractor personnel during a demobilization period from March 26, 1979 until May 13, 1980. Mobilization and demobilization activities overlapped with cleanup activities in some cases. Activities during both phases could have involved radiation sources on islands before and after cleanup.

5.3.8.1 Mobilization

The activities during mobilization that may need evaluation to assess radiation exposure include:

- A visit by a Navy survey team, assisted by FCDNA, to thoroughly investigate Enewetak Atoll water and beaches from November 30 through December 15, 1976 for harbor clearance, beach access, and traffic ability
- A December, 1976 visit to the atoll by Pacific Air Forces Surgeon's Office in preparation for establishing a Medical Clinic at Enewetak Camp and a Medical Aid Station at Lojwa Camp
- An OPLAN development conference at Enewetak Atoll during February 21 through March 9, 1977
- The installation of radio communications equipment by an Air Force installation team starting on March 16, 1977
- The arrival of an initial party of the CJTG's staff including the Logistics Officer, an Engineer Construction NCO and radiation safety officer on April 5, 1977, presumably on Enewetak Island
- A joint Army-Navy effort of the project from April 8 to May 9, 1977 to remove aggregate from a stockpile on Enjebi (Janet) Island to Lojwa (Ursula) Island to make concrete for use in constructing the forward base camp
- The arrival on May 3, 1977 of six enlisted Navy personnel to receive and put into service the first increment of landing craft
- Arrival of an advance party of the Commander, JTG, base construction forces and support teams on May 17, 1977
- Site preparation, surveying, and construction of concrete slabs for buildings on Lojwa starting May 17, 1977 by Army engineering troops billeting temporarily in tents there
- Arrival of the first contingent of the FRST on June 28, 1977
- Construction of facilities on South Runit under personnel protection requirements until July 15, 1977
- Arrival of a detachment of the Underwater Demolition Team Eleven on September 13, 1977 to begin channel clearance and underwater demolition work at islands throughout the atoll requiring access by boats
- Arrival and setup of the Navy Water-Beach Cleanup Team on October 15, 1977.

These listed activities were performed primarily on uncontrolled islands such as Enewetak and Lojwa. It seems reasonable to conclude that any doses received during these activities would be less than similar activities on the same islands for full, six-month durations.

A few exceptions to the above include aggregate handling on Enjebi to establish a stockpile on Runit, and construction activities on south Runit, which both involved somewhat elevated concentrations of radioactive contaminants. In these cases, dose assessments that consider the specific circumstances of the exposures would be a reasonable approach.

5.3.8.2 Demobilization

Demobilization primarily involved logistics oriented activities, i.e., razing base camp facilities; disposing of excess materiel; and shipping personnel, equipment, and supplies to other locations. Most of the effort involved uncontaminated equipment, debris, and other items. These activities started well before cleanup was completed. The first demobilization event involved the retrograde of equipment by ship in March 1979. Stringent procedures were followed to assure that only items that met established radiation clearance limits left the atoll. During the entire process, only one piece of equipment was found to be contaminated. Although below release limits, it was sent from Enewetak Island to Runit for decontamination. (DNA, 1981)

Contaminated equipment was handled through a separate process whereby all equipment that had ever been on a controlled island was moved through Runit for assessment. A primary concern of radiological control was to assure that contaminated equipment was not removed from a radiologically controlled island to an uncontrolled island within the atoll. Before equipment was removed from a controlled island, it was monitored by the FRST and, if necessary, decontaminated before being released. (DNA, 1981)

These monitoring and decontamination efforts were accomplished on Runit by members of the FRST assisted by members of the equipment user organizations. FRST members performed the monitoring tasks, advised, and assisted in decontamination, and performed reassessment and certification that equipment met release limits.

With respect to radiation exposure assessment, the radiological control activities during demobilization were essentially the same as the FRST duties during soil and debris cleanup. Assessment of doses was included in the Radiological Support Project Component. Personnel monitoring with film and TLD badges continued throughout the demobilization phase.

Exposures to support group members during demobilization were similar to their activities during soil and debris cleanup, including truck and equipment driving, maintenance, etc. Therefore, exposures for these individuals are included in the Soil Cleanup and Debris Cleanup Project Components.

5.3.9. Unexploded Munitions Recovery and Disposal

Unexploded munitions existed on land, and in water areas adjacent to islands, reefs and other landmasses of Enewetak Atoll. When the presence of these objects caused safety concerns for cleanup personnel, EOD personnel were employed to locate, identify, recover and dispose of the items.

Early in the mobilization phase, EOD specialists assigned to the FRST were primarily responsible for recovery and disposal of all unexploded munitions found on land. By early October 1977, FRST EOD personnel had collected over 300 rounds of munitions on the southwest beach of Enjebi (Janet). These were destroyed by multiple detonations in mid-October. Later in the cleanup, the FRST EOD specialists were released and the U.S. Navy EOD Detachment assumed the entire EOD function (DNA, 1981).

The Navy EOD Detachment worked to deal with unexploded munitions in offshore areas, primarily around the island of Medren. As for the munitions found on land, the munitions were either collected for disposal later, or detonated in place if considered dangerous.

It can be reasonably concluded that since the munitions were remnants of earlier combat actions, they were not contaminated with radioactivity and presented no exposure potential. In some cases, particularly when EOD specialists may have accompanied FRST personnel into controlled areas, an exposure potential may have existed. For these situations, dose assessments for EOD personnel would be similar to those of the FRST personnel they accompanied.

Section 6.

External Radiation Dose Assessment Methods

The ECUP personnel were exposed to radiation from external sources while evaluating radiological conditions on the islands, cleaning up and disposing of contaminated soil and debris and performing other ancillary and support activities. Estimates of radiation doses resulting from external sources follow the principles of DTRA's dose reconstruction methods for the NTPR Program (DTRA, 2017).

This section discusses the use of personnel dosimetry records consisting of film badge and TLD readings for estimating external doses to ECUP personnel. Discussions are included on the application of dose reconstruction methods using results from radiation survey data presented in Section 4 when dosimetry records are not usable or available. The dose reconstruction methods that would be used for ECUP veterans' assessments are discussed in Section 6.2.

The methods discussed provide estimates of dose to the whole body and internal organs primarily from gamma-ray radiation. The possible exposure of the skin to beta-particle radiation is not normally measured with whole-body dosimeters. Consequently, methods developed for skin dose assessments are discussed in Section 6.3 and can be used to estimate skin doses.

Finally, all doses either from recorded dosimetry or from dose reconstruction estimates have associated uncertainties that must be taken into account for a complete report of the doses for ECUP personnel. Section 6.4 discusses methods for estimating and reporting dose uncertainties and upper-bound doses.

6.1 Dosimetry Records

6.1.1. Sources of Dose Records

The availability, completeness, and considerations for using the dosimetry records are discussed in terms of the sources and difficulties with some of the results, such as those from damaged film badges. The following five sources of dosimetry records have been identified during research for this project:

- DD Form 1141 "Record of Occupational Exposure to Ionizing Radiation"
- ADC (formerly called LBDA) database
- Department of Army (DA) Form 3484 "Photodosimetry Report"
- Thermoluminescent Dosimetry Report
- TLD Control Card.

6.1.2. DD Form 1141

DD Form 1141 is the official document used by the Military Services to record radiation doses to personnel engaged in radiation work. These forms were prepared by FCDNA Enewetak and sent to the dosimetry center of the individual's Military Service. Although this policy was in effect during ECUP operations (DNA, 1981), not all Centers received these records, recorded the results, or preserved the ECUP-specific DD Forms 1141.

A sample DD Form 1141 is shown in Figure 7, with the following information:

- Blocks 1 through 5 at the top of the form contain the individual's personal identification information.
- Columns 6 through 12 contain dose data.

The "from" and "to" entries, columns 7 and 8, capture the period of exposure for the corresponding dose entry in column 12. In column 6, entries without an asterisk are considered as resulting from valid film badge doses, i.e., from undamaged film badge. Entries in column 6 with one asterisk denote the corresponding entry in column 12 is an administratively assigned dose. Entries with two asterisks in column 6 denote the corresponding entry in column 12 is a TLD dose.

6.1.3. ECUP Dosimetry Data

The ECUP personnel dose records have been maintained in the ADC database. External doses for cleanup personnel are accounted for by three sources of information in the database: film badge dosimetry, TLD dosimetry, and administratively assigned doses.

FCDNA implemented the use of TLDs in tandem with film badges starting in May 1978 (DNA, 1981) with full implementation in Mar 1979 (RSAIT, 1979a). The TLDs were a means of overcoming environmental problems that caused damage to film badges because TLDs were sealed and protected from the environment. Thus, TLD dose data are considered a valid source for dose records.

DA Form 3484, provided by LBDA to FCDNA, contained a record of the film badge processing data by batch for all film badges turned in to LBDA from ECUP operations. That form was provided as a record to FCDNA indicating the disposition of the dosimeters, i.e., valid or damaged. Doses were assigned based on the readings of valid dosimeters. Administrative doses were assigned when film badges were damaged. The form served as a worksheet for populating dose data in the LBDA (now ADC) database.

Other forms such as the TLD Reports and TLD Control Cards, both filled out on a recurring basis, provided a local record of TLD dose data. The TLDs were read out on site at the Enewetak Operation by radiological control technicians. These forms provided a means for transmitting TLD data to LBDA to include in its database.

6.1.4. Administrative Doses

Administrative doses were assigned using procedures developed by FCDNA to replace damaged film badge results (FCDNA, 1978). Amended DD Forms 1141 were prepared for these individuals to record these administratively estimated doses. The administrative doses are high-sided estimates of ECUP worker doses. For this reason, the recommendation is to use reconstructed doses in place of administrative doses. Further discussion about external dose estimation methods is included in Section 6.2.

RECORD OF OCCUPATIONAL EXPOSURE TO IONIZING RADIATION

FOR INSTRUCTIONS, SEE REVERSE OF SHEET.

1. IDENTIFICATION NUMBER	2. NAME *(Last, first, middle initial)*	3. SOCIAL SECURITY NUMBER	4. RANK/RATE TITLE OF POSITION	5. DATE OF BIRTH *(Day, month, year)*
	[redacted]	[redacted]	[redacted]	[redacted]

PLACE WHERE EXPOSURE OCCURRED	PERIOD OF EXPOSURE		DOSE THIS PERIOD (rem) 1. Method of monitoring is presumed to be film badge reading unless otherwise specified under Item 16, "REMARKS."				ACCUMULATED DOSE (rem)		INITIAL
ACTIVITY 6	FROM (Day-Mo-Yr) 7	TO (Day-Mo-Yr) 8	SKIN DOSE (Soft) 9	GAMMA AND X-RAY 10	NEUTRON 11	TOTAL THIS PERIOD 12	TOTAL LIFETIME 13	PERMISSIBLE LIFETIME 5(N-18) 14	PERSON MAKING ENTRY 15
ENEWETAK ATOLL	No Prior Occupational Exposure							05,000	GBW
ENEWETAK ATOLL *	22Apr78	21 May78	NR	00.000	NU	00.000	00.000	05,000	GBW
ENEWETAK ATOLL	22May78	18Jun78	NR	00.009	NU	00.009	00.009	10,000	GBW
ENEWETAK ATOLL *	18Jun78	15Jul78	NR	00.000	NU	00.000	00.009	10.000	GBW
ENEWETAK ATOLL	16Jul78	19Aug78	NR	00.000	NU	00.000	00.009	10.000	GBW
ENEWETAK ATOLL **	20Aug78	16Sep78	NR	00.001	NU	00.001	00.010	10.000	GBW
ENEWETAK ATOLL *	17Sep78	11Oct78	NR	00.000	NU	00.000	00.010	10.000	GBW
ENEWETAK ATOLL	Film Badge Discontinued				11 OCT 1978				GBW
ENEWETAK ATOLL	REVIEWED BY RPO		23 JUL 1979			[redacted]		[redacted]	

16. REMARKS *(Continue on additional sheet if necessary)*

NR - NONE REPORTED
NU - NOT USED
* Administrative Dose Assigned IAW Para. 12c(1), AR40-14, 20 May 75
** Thermoluminescent Dosimetry

TO BE RETAINED PERMANENTLY IN INDIVIDUAL'S MEDICAL RECORD

DD FORM 1 MAY 67 1141 — PREVIOUS EDITIONS ARE OBSOLETE.

Figure 7. Example of partial DD Form 1141, with personally identifiable information redacted

6.2 External Dose Estimation Methods

To augment personal dosimetry measurements, radiation doses for exposures from external sources can be estimated using dose reconstruction methods developed by DoD dose assessment programs, such as DTRA's NTPR Program (DTRA, 2017). This is necessary sometimes to supplement incomplete, lost, or unreliable dosimetry records. The methods employed in dose assessments include the use of high-sided estimates of parameter values in the calculation of doses to personnel for all applicable exposure pathways. Sources and pathways of exposure to radiation for ECUP participants are described in Section 5. When necessary, external doses from exposure to contaminated soil, contaminated debris, or other contaminated material, e.g., equipment or laundry, are estimated based on the measured or estimated exposure rates and the type and duration of each activity. Estimated external doses are combined with an uncertainty factor to estimate upper-bound doses that are expected to exceed the 95th percentile dose if determined from a distribution of doses of individuals exposed to the same or similar sources and levels of radiation and monitored with personal dosimeters.

This section describes the assumptions and parameter values that are used to estimate doses from exposure to radiation external to the body. The equations used for the external dose estimation are presented in Appendix C. Exposure scenarios and results of example radiation dose calculations for ECUP personnel are presented and discussed in Section 8. For veteran claims, dose estimates prepared in response to VA requests should consider all sources of radiation and pathways that are applicable to the individual. Finally, a veteran radiation dose assessment should be performed following the recommended guidelines discussed in Section 9.

6.2.1. Soil Cleanup

The most common potential external radiation exposure source for ECUP participants was undisturbed contaminated soil, for which island-specific exposure rates have been determined and were used to estimate the island-average exposure rates shown in Table 4. These island-specific exposure rates are based on measurements made during the 1972 radiological survey (AEC, 1973a), and the island-average values are used as conservative estimates for the ECUP radiation dose assessments for exposures during the cleanup project period of 1977–1980. The 1972 exposure rates are considered overestimates of the actual average exposure rates that prevailed during ECUP because they were not adjusted to reflect radioactive decay or weathering of the radioactive soil contaminants from 1972 to 1977. Furthermore, they are considered overestimates for dose calculations because they are assumed constant values that did not decrease as cleanup of contaminated soil and debris progressed throughout the duration of the project.

Direct measurements have not been located for exposures to excised soil in other configurations, such as in piles, during transport, and when mixed in slurry or cement. For these situations, the island-average exposure rates can be used to estimate external exposure rates for individuals. For example, the exposure rate from a pile of soil, e.g., as stockpiled on a beach or as bulk-hauled in a truck or boat, can be estimated using the undisturbed soil/ground exposure rate together with a distance modifier such as the ratio of measurement distance to receptor distance from the source. Exposure rates for contaminated soil in mixtures, e.g., mixed with cement, can be bounded by using the undisturbed soil/ground exposure rates. These should be conservative estimates because of 1) the finite and small sizes of slurry pipes, transit-mix trucks, and dome sections as compared to the infinite plane geometry of the surveyed islands, and 2) the dilution of the soil with cement, attapulgite, and water.

External doses and upper-bound doses for ECUP participants who were involved in soil cleanup or other on-shore activities are estimated using the equations presented in Appendix C-1. Parameter values and assumptions for estimating external doses for these exposure scenarios are shown in Table 27 to Table 29, and brief discussions of these parameters and assumptions follow.

- **Island-average exposure rate:** The island-average exposure rates shown in Table 4, which are based on the 1972 radiological survey, are used as default values for scenarios involving exposures to contaminated soil for a veteran who performed activities on specified islands as reported on Controlled Island Access Logs or other references.

  In some exposure scenarios, the veteran may have conducted work on multiple islands. In these scenarios, averages of the individual island-average exposure rates may be appropriate to use to estimate external doses. For example, a simple average of exposure rates for all northern islands for cases where a veteran spent time on several of the northern islands, but the islands are not known. In other scenarios, such as soil removal work on several known islands, a weighted average of the relevant island exposure rates can be used, weighted by the time spent on each island, if known, or by the fraction of the total volume of soil removed from each island. The rationale for weighting the individual exposure rates by volume of soil removed is based on the assumption that the amount of soil removed is proportional to the amount of time a worker involved in soil removal activities would have spent on each island. This is the approach used in the example scenario described in Section 8.2.1. Guidance on averaging methods for estimating external exposure rates for scenarios involving work on multiple islands is shown in Table 28 for four categories of worker participation.

Table 27. Parameter values and assumptions for estimating external doses from contaminated soil

Parameter	Value	Rationale/Reference/Comment
External exposure rate	Island-specific or multi-island average	The 1972 island-average exposure rates shown in Table 4 are conservatively used for 1977-1980. See Table 28 for guidance on averaging when multiple islands are involved.
Duration of duty tour	Variable (default = 6 months [26 wk])	Based on individual's arrival and departure records, if available
Work schedule	10 h d^{-1} for 6 d wk^{-1}	This is the default assumption for all participants (DNA, 1981).
Time spent outdoors and indoors on residence island	See Table 29	
Protection factor	Tent: 1.5 Building: 2.0	(DTRA, 2017, SM ED02)
Film badge conversion factor (for 3 orientations relative to a source)	Facing source: 1.0 rem R^{-1} Standing upright: 0.7 rem R^{-1} Facing away: 0.5 rem R^{-1}	(DTRA, 2017, SM ED02)
Fraction of time exposed to source	0.1 to 1 (default = 1)	Fraction of a workday or of work duration that a worker is exposed to a source

Table 28. Averaging methods to determine exposure rates or soil activity concentrations for scenarios where ECUP veterans worked on multiple islands

Type of Work	If work islands are known		If work islands are not known
	Durations on specific islands are known	Durations on specific islands are not known	
Work involving or supporting soil-removal activities*	TWA† using values for known soil-removal islands	VWA‡ using values for known soil-removal islands	VWA using values for all soil-removal islands
General work only on northern islands§,**	TWA using values for known northern islands	SA†† using values for known northern islands	SA using values for all northern islands
General work only on southern islands§,**	TWA using values for known southern islands	SA using values for known southern islands	SA using values for all southern islands
General work on northern and southern islands	TWA using values for known northern and southern islands	SA using values for known northern and southern islands	SA using values for all northern islands‡‡

* Soil-removal islands and the volume of soil removed from each of the five soil-removal islands are shown in Table 37.

† TWA = Time-weighted average of values, e.g., exposure rates or soil activity concentrations. Time-weighted averages are based on the amount of time spent on each island.

‡ VWA = Volume-weighted average of values, e.g., exposure rates or soil activity concentrations. Volume-weighted averages are based on the volume of soil or debris removed from each island.

§ Northern and southern islands are identified in Table 1.

** "General work" can be any work other than participation in direct soil-removal or debris-removal work, such as sampling, monitoring, and surveying.

†† SA = Simple average (arithmetic mean) of values.

‡‡ Using SA for all northern islands for this scenario will likely result in a high-sided average exposure rate or soil activity concentration.

Table 29. Time spent outdoors and indoors on residence islands

Work Location, Day of Week, and Worker Category	Daily Duration ($h\ d^{-1}$)		Rationale/Reference/Comment
	Outdoor	Indoor*	
Enewetak and Lojwa Support Workers†			
Workdays (6 d wk^{-1}):			
Outdoor Workers	15	9	Outdoor time is working and recreation; indoor time is sleeping and eating
Indoor Workers	5	19	Outdoor time is recreation; indoor time is sleeping, eating, and working
Non-Workdays (1 d wk^{-1}):			
Outdoor and Indoor Workers	15	9	Outdoor time is recreation; indoor time is sleeping and eating
Northern Island Workers (Lojwa Island)‡ and Southern Island Workers (Enewetak Island)§			
Workdays (6 d wk^{-1})	5	9	Outdoor time is recreation; indoor time is sleeping and eating
Non-Workdays (1 d wk^{-1})	15	9	Outdoor time is recreation; indoor time is sleeping and eating

* On all days, sleeping and eating are assumed to take 8 h and 1 h, respectively.

† Participants normally assigned to work locations on Enewetak Island or Lojwa Island with billeting on the same island.

‡ Northern-Island Workers are those participants who were billeted on Lojwa Island but were normally assigned to work locations on other northern islands. These workers may have also occasionally conducted work on Lojwa Island.

§ Southern Island Workers are those participants who were billeted on Enewetak Island but were normally assigned to work locations on other southern islands. These workers may have also occasionally conducted work on Enewetak Island.

- **Duration of duty tour:** Enewetak Atoll arrival and departure cards, FCDNA Forms 288 and 289, respectively, are available for individuals who visited or worked at Enewetak Atoll during the cleanup project. The dates on these cards determine the value for this parameter. If these cards are not located, and reliable dates are not available elsewhere, the default duration of duty can be assumed to be 6 months based on the typical ECUP assignment of 4–6 months (DNA, 1981).
- **Work schedule:** The default work schedule for all participants is 10 h d^{-1}, 6 d wk^{-1}, and ECUP workers typically did not work on Sundays (DNA, 1981). For northern island workers, it is assumed that the 10 h d^{-1} work schedule includes an average travel time of 1 hour each way between Lojwa and the work site. This is a reasonable average value based on transit

times derived from LCU boat logs and FRST Operational Reports[10], which included transit times between Lojwa and Enjebi, and Lojwa and Runit.

- **Time spent indoors on a residence island:** For all participants, the default daily schedule is 8 h d^{-1} of sleeping and 1 h d^{-1} eating meals, which are assumed spent indoors on one of the residence islands. In addition to the daily 9 h d^{-1} for sleeping and eating, an additional 10 h d^{-1} is assumed spent indoors on workdays if a participant's normal work location was indoors on a residence island.
- **Time spent outdoors on a residence island:** All non-work time other than sleeping and eating is assumed recreational time spent outdoors on the residence island. For all participants, this amounts to 5 h d^{-1} on workdays and 15 h d^{-1} on non-workdays. This is a high-siding assumption because less time would be spent outdoors if, for example, some recreation was spent indoors, or if additional time was spent sleeping or resting indoors on non-workdays. If a participant's normal work location was indoors on the residence island or on a northern island, the only outdoor time on the residence island is assumed daily recreational time of 5 h d^{-1}. In addition to 5 h d^{-1} spent outdoors for daily recreation by all participants, an additional 10 h d^{-1} is assumed spent outdoors on the residence island on workdays for participants whose normal work location was outdoors on the residence island.
- **Protection factor:** This parameter accounts for the degree of protection from radiation afforded by the walls and floor of a tent or building where an individual was located while indoors. The value used is dependent upon the type of structure where most of a participant's indoor time was spent.
- **Film badge conversion factor:** The film badge conversion factor is the ratio of dose recorded on a properly worn film badge to free-in-air integrated exposure, and is used to convert an exposure to a dose. The factor accounts for body shielding of the film badge to gamma radiation, and is assigned the values of 0.7 for the standing position on a planar surface, 1.0 for facing the source of radiation, and 0.5 for facing away from a source (DTRA, 2017, SM ED02).
- **Fraction of time exposed to source:** This factor is intended to account for the fraction of time that an ECUP worker is actually exposed to a specific external source of radiation. Examples of scenario characteristics that could be accounted for include fraction of a workday that an individual is on a specific island, or is near a specific distinct source (e.g., debris piles). Because of the difficulty in determining an appropriate value, and to simplify veteran dose assessments, the recommended default value for this parameter is 1.0.

6.2.2. Debris Cleanup

Contaminated debris measurements made just before and during the cleanup project were not located in project documents or other sources. However, exposure rate measurements of contaminated debris were made during the 1972 radiological survey conducted by AEC (AEC, 1973a). These measurements were conducted in support of the engineering study of the cleanup

[10] FRST Operational Reports are the daily reports prepared by a FRST Team Chief on JTG Form 16 for a specific Controlled Access Area. The forms contain serial numbers of survey meters used, and a Narrative section that may contain times, activities conducted, use of PPE, and other items relevant to radiological control.

project developed for DNA (H&N, 1973). These debris exposure rate data were compiled from AEC (1973a) and are reported in Appendix K.

The available debris exposure rate measurements are not directly applicable to veteran dose assessments. This is primarily because they are contact measurements that are not representative of exposure rates at distances from the debris items or piles at which personnel were typically located. In addition, the measurements were made on individual pieces of debris, whereas personnel who were involved in debris-handling activities would likely have been tasked with removing, transporting, and disposing of debris items and piles with a large range of radioactivity and sizes. Therefore, actual debris exposure environments are difficult to characterize for estimating doses.

As described in Section 4.3, contaminated debris was removed from five northern islands: Enjebi, Runit, Lujor, Eleleron, and Aomon. The island-average exposure rates on these islands, which would have included contributions from the contaminated debris on each island, are recommended for use in dose assessments for contaminated debris cleanup activities. This recommendation is supported by an analysis of the 1972 debris survey data that showed that for each of the five islands of interest, island-average exposure rates are much larger than the respective mean exposure rates at average handling distances from the debris. A summary of the results of this analysis is shown in Table 30, which contains a comparison of the estimated mean exposure rates from debris in debris-cleanup scenarios with the respective island-average exposure rates. Additional details of the analysis are included in Appendix K.

Table 30. Comparison of mean contaminated debris exposure rates and island-average exposure rates

Island with Contaminated Debris		Mean Contaminated Debris Exposure Rate at 10 ft* (μR h^{-1})	Island-Average Exposure Rate (μR h^{-1})†
Island Name	Site Name		
Enjebi	Janet	1.3	40
Runit	Yvonne	1.4	33
Lujor	Pearl	7.1	70
Eleleron	Ruby	0.93	14
Aomon	Sally	1.7	7

* Exposure rates are estimated for a 10-ft diameter disk source assuming contact measurements are taken at an average distance of 0.5 ft. In addition, operators of contaminated debris-handling equipment were typically positioned an average of 10 ft away from debris piles, see Appendix K.

† See Table 4.

The comparison in Table 30 shows that the island-average exposure rates are considerably higher than the mean contaminated debris exposure rates for all five islands at a representative exposure distance of 10 ft. Thus, island-average exposure rates are adequate to be used as the basis for estimating veterans' external doses in general debris-cleanup scenarios. However, there were several debris sites on the five islands with debris exhibiting relatively high contact exposure rates that could possibly expose individuals to radiation levels higher than the corresponding island-average exposure rates. For these sites, an external dose can be calculated using the debris contact exposure rate adjusted for the individual's distance from the specified debris and duration of exposure stated by the veteran. This external dose would be based on a single or combination of debris exposure rate measurements that are selected based on the veteran's statements and responses in their ECUP Questionnaire. Contact exposure rate measurements for all debris surveyed in 1972 were reported in AEC (1973a) and are compiled in Appendix K.

Parameter values and assumptions for estimating external doses for ECUP participants, who were involved in soil-removal activities, also apply to debris cleanup activities, which are shown in Table 27 to Table 29. For these exposure scenarios, external doses and upper-bound doses are estimated using the equations presented in Appendix C-1. In cases where a veteran performed debris cleanup activities on multiple islands, parameter values are estimated using simple or weighted averages across relevant islands as indicated for soil-removal activities in Table 28. Weighted averages for debris-cleanup activities can be calculated using the debris volumes shown in Table 31 and extracted from Figure 5-34 of DNA (1981).

Table 31. ECUP participant debris cleanup volumes at Enewetak Atoll

Island Name *	Site Name	Total volume of debris†,‡,§ (yd^3)
Northern Islands		
Bokoluo	Alice	1,575
Bokombako	Belle	28
Kirunu	Clara	505
Louj	Daisy	5
Bokaidrikdrik	Helen	15
Boken	Irene	1,890
Enjebi	Janet	16,477**
Mijikadrek	Kate	1,073
Kidrinen	Lucy	257
Taiwel	Percy	2
Bokenelab	Mary	158
Elle	Nancy	<1
Aej	Olive	1
Lujor	Pearl	271**
Eleleron	Ruby	251**
Aomon	Sally	2,914**
Bijire	Tilda	720
Lojwa	Ursula	2,115
Alembel	Vera	<1
Billae	Wilma	64
Runit	Yvonne	15,602**

Table 31. ECUP participant debris cleanup volumes at Enewetak Atoll (cont.)

Island Name *	Site Name	Total volume of debris†,‡,§ (yd^3)
Southern Islands		
Ananij	Bruce	95
Japtan	David	790††
Jedrol	Rex	28
Medren (aka Parry)	Elmer	41,028††
Enewetak	Fred	110,780††
Ikuren	Glenn	908
Mut	Henry	215
Boken	Irwin	270
Ribewon	James	254
Kidrenen	Keith	140
Biken	Leroy	197
n/a	Van	10
Bokandretok	Walt	10
	Total	**198,650**

* Nine islands that had no debris removed are not included in this table

† Debris volumes are from DNA, 1981, Figure 5-34.

‡ The debris volumes in this table include debris used as shore protection.

§ Volumes in this table are volumes of uncontaminated debris unless indicated otherwise.

** The total volumes for these five islands include the following volumes of contaminated debris: Enjebi (530 yd^3), Lujor (255 yd^3), Eleleron (250 yd^3), Aomon (728 yd^3), Runit (4,120 yd^3).

†† A total of 55,000 yd^3 of debris were removed from these three islands by a scrap contractor (DNA, 1981, Figure 5-34). The volumes removed by the scrap contractor are excluded from the values in this table.

6.2.3. External Dose from Lagoon Water and Sediments

ECUP participants may have accrued an external dose while swimming in potentially contaminated lagoon or ocean water. A simplified seawater immersion dose methodology is documented for use in DoD's NTPR program (Weitz, 2012). Applying this methodology and using the highest mean Cs-137 surface water activity concentration of 579 fCi L^{-1} (Table 12) results in a dose rate from immersion in water lower than 0.001 μrem h^{-1} to the whole body. A similar dose rate can also be estimated using EPA dose coefficients for water immersion (USEPA, 1993). Furthermore, using the highest mean near-surface water activity concentrations in Table 10–Table 12, and assuming swimming in the lagoon for 1 hour every day of a 6-month assignment, the resulting external effective whole body or organ dose (including skin) would be less than 0.001 mrem. Based on these results, swimming in the lagoon or ocean water was not a significant source of external exposure for ECUP participants and any related dose would be subsumed within applied upper-bound dose uncertainties.

The sediments of the Enewetak lagoon also presented a potential source of external exposure to ECUP participants while swimming, walking, or working in the shallow waters of the lagoon. Using the mean activity concentrations of all significant radionuclides in Enewetak lagoon sediments shown in Table 13, together with the dose coefficients from USEPA (1993), the dose rate 1 m above Enewetak sediments was calculated to be approximately 0.01 mrem h^{-1} to any internal organ, and approximately 0.1 mrem h^{-1} to skin. Note that the mean lagoon sediment activity concentrations reported in Table 13 greatly overestimate the concentrations near the southern islands of the atoll, and it is not suitable to use these concentrations for dose estimates near any southern island, including residence islands. Furthermore, these estimates do not account for the shielding that would be provided by intervening lagoon water, which would reduce the dose rate by about a factor of 2 for every foot of water between the sediment and an exposed individual (Voss, 2001). Because of these considerations, residual radioactivity in the Enewetak lagoon sediments was not a significant source of exposure for ECUP participants and any related external dose would be subsumed within applied upper-bound dose uncertainties.

6.3 Skin Dose

Assessing the dose to the skin requires investigating the two major pathways of exposure: skin contamination and external non-contact sources of radiation. The methods discussed in Sections 6.1 and 6.2 can be used to estimate the gamma radiation dose to the skin from external sources. The skin doses from these two routes of exposure were not measured, i.e., there are neither dosimeter results for the skin nor measurements of contamination on the skin of the workers. Therefore, the doses are estimated by adapting methods developed for the DoD dose assessment and other U.S. government radiation assessment programs (Apostoaei and Kocher, 2010; DTRA, 2010a; DTRA, 2010b; USEPA, 2002) discussed in Section 6.2. Potential doses from hot particles on the skin are not considered here; however, if hot particles are of concern the user should consult the scientific literature for guidance (e.g., USNRC, 2013 or NCRP, 1999).

Chapter 4 of NCRP Report No. 130 (NCRP, 1999) presents a detailed review of the biology of the skin and its response to radiation. For radiation protection, it is assumed that the basal layer (at a nominal depth of 70 micrometers (μm)) of the epidermis contains the cells of concern for skin cancer (DTRA, 2010a). The assumption that the basal layer contains the cells of concern is based on the continuous division of cells occurring there. The location of the cells of interest should be taken in to account when estimating the radiation dose to the skin regardless of the source.

6.3.1. Skin Dose from Dermal Contamination

Apostoaei and Kocher (2010) present a detailed process for calculating skin doses from fallout radionuclides deposited on the skin. In their report, they discuss models for skin contamination from descending fallout, suspension, and other sources and pathways. They also discuss the effects of showering and the radiation dose from alpha emitters. The methods of Apostoaei and Kocher (2010) and DTRA (2010b) are adapted for this report; the user should refer to these documents for a detailed analysis of skin dose from dermal contamination. The focus here is on radionuclides that were resuspended from the ground. Other sources, such as potentially contaminated lagoon water adhering to the skin after swimming, are not significant sources of skin dose. Moreover, to simplify the assessment, some factors that decrease the skin doses, such as clothing, self-attenuation of alpha particles, and shielding of alpha radiation by water, perspiration, or soil, are not included here. These factors can be difficult to accurately estimate, and omitting them helps to ensure that the assessment is high-sided. In addition, no accounting is made for incomplete removal of soil from the skin following a workday, e.g., inefficient or no showering. The methods of Apostoaei and Kocher (2010) can be used to account for these conditions, if necessary. However, the dose consequences of deviations from complete removal of contaminants from the skin following every workday are countered by the use of high-sided parameter values and application of upper-bound uncertainties.

A high-sided skin dose from dermal contamination is estimated over a total time of 12 hours. This is based on the assumption that the total amount of contaminated soil that could have gradually accumulated on bare skin over an 8 to 10-hour workday was deposited at the beginning of the workday and remained on the skin until completely removed by showering 2 to 4 hours after the workday ended. The recommended parameter values shown or referenced in Table 32 are used in conjunction with the equations shown in Appendix C for deterministic estimates of the skin dose from dermal contamination. Brief discussions of several of these parameters that are not discussed elsewhere in this report follow Table 32.

Table 32. Parameter values and assumptions for skin dose from dermal contamination

Parameter	Value	Rationale/Reference/Comment
Work schedule	8–10 h d^{-1} for 6 d wk^{-1}	DNA (1981)
Daily exposure to dermal contamination	12 h d^{-1}	Value is the daily work hours plus an additional 2–4 hours at which time complete removal of contaminated soil is assumed
Dose coefficient	See Table 33 and Table 35	(Cross et al., 1992; NCRP, 2009b)
Skin dose modification factor	See Table 34	Used with beta dose coefficients (Apostoaei and Kocher, 2010, Table 4-2)
Resuspension factor	10^{-9}–10^{-7} m^{-1}	(Bramlitt, 1977); see Appendix E
Deposition velocity	3600 m h^{-1}	(Apostoaei and Kocher, 2010, Table 4-2)
Interception and retention fraction	See Table 36	(Apostoaei and Kocher, 2010, Table 4-1)
Duration of duty tour	Variable (default = 6 months)	Based on individual's arrival and departure records
Fraction of workday exposed	0.1 to 1 (default = 1 for full time)	Fraction of a workday (not the total duration of exposure) that an ECUP worker is exposed to suspended soil, based on combination of task durations and analyst judgment
Resuspension depth	1 cm	Assumed reasonable value, see Section 7.1
Soil density	1.5 g cm^{-3}	(AEC, 1973a; DOE, 1982a); see Section 7.1
Activity concentrations of undisturbed soil	Island-specific mean values	See Table 6
Activity concentrations of excised soil	Island-specific weighted-average values shown in Table 43	Weighted average calculated from estimated total TRU activities and total volumes of soil removed from soil-removal islands (DNA, 1981)

The total dermal contamination skin dose is the sum of the doses from exposure to all the radionuclides present. If it is important for the risk assessment, then the dose from each type of radiation must be calculated and reported separately. Recommended dose coefficients for beta radiation emitted from Co-60, Sr/Y-90, and Cs-137 were selected from Table 5 of Cross et al. (1992) for a depth of 70 µm and are shown in Table 33. Because the recommended dose coefficients for beta radiation are applicable to a depth of 70 µm (7 mg cm^{-2}), Apostoaei and Kocher (2010) developed the Skin Dose Modification Factor (SDMF) to account for different depths of the skin cells of interest at different skin sites. The SDMF is used in conjunction with the beta dermal contamination dose coefficients. The recommended values for the beta SDMF from Apostoaei and Kocher (2010) are shown in Table 34.

Table 33. Recommended dermal contamination dose coefficients for Co-60, Sr/Y-90, and Cs-137 (for beta dose)

Radionuclide	Dose Coefficient ($rem\ cm^2\ pCi^{-1}\ h^{-1}$)
Co-60	3.830×10^{-6}
Sr-90 / Y-90	1.204×10^{-5}
Cs-137	5.687×10^{-6}

Table 34. Recommended values for beta SDMF

Skin Site	SDMF
Face, behind ears*, forehead, neck, shoulders, chest*, torso, under belt*, and upper legs	1.3
Back of neck*, forearms, lower legs, and under boot edge*	0.9
Scalp*, palms of hands, backs of hands*, and soles of feet	0.3

* SDMF values for these skin sites are not available in Apostoaei and Kocher (2010). The indicated values are recommended based on similar skin thickness or proximity to other sites on the body.

The recommended dose coefficients for alpha emitters of concern (NCRP, 2009b) are shown in Table 35. The dose coefficients for alpha radiation vary with skin sites because the depth of the skin cells of interest was taken into account when the dose coefficients were developed. Dermal contamination alpha dose coefficients are also available in Apostoaei and Kocher (2010). The dose coefficients from NCRP (2009b), and Apostoaei and Kocher (2010), agree to within 2.5 percent.

Table 35. Recommended dermal contamination dose coefficients for Pu-239/240 and Am-241(for alpha dose)

Skin Site	Dose Coefficient (rem cm^2 pCi^{-1} h^{-1})	
	Pu-239/240	Am-241
- Forearms - Upper and lower legs - Under boot edges	7.4×10^{-4}	1.3×10^{-3}
- Chest - Under the belt	6.7×10^{-3}	8.2×10^{-3}
- Face - Shoulders - Back and sides of torso - Scalp - Neck and behind ears - Back of neck* - Forehead	6.4×10^{-3}	7.4×10^{-3}
- Palms of hands - Backs of hands - Soles of feet	0	0

* Alpha dose coefficients for this skin site are not available in NCRP (2009b) or Apostoaei and Kocher (2010). The indicated values for this site are recommended based on its proximity to "neck and behind ears".

The deposition velocity describes the rate of deposition of suspended airborne soil particles onto the skin. This parameter is dependent on several conditions, especially particle sizes, the amount of movement of an individual within the suspended dust cloud, and the strength of the wind. The default deposition velocity of 3600 m h^{-1} (1 m s^{-1}) was selected based on the range of deposition velocities recommended in Apostoaei and Kocher (2010) for individuals in motion in a dust cloud. That range has minimum, mode, and maximum values of 0.3, 1.0, and 3.0 m s^{-1}, respectively. Higher deposition velocities are possible in conditions of strong winds such as are typical at Enewetak Atoll. However, situations of high wind-driven skin deposition of contaminated soil were minimized during ECUP because of the requirement to wear protective clothing when it was necessary to conduct work downwind of soil-moving operations (EAI No. 5707.1).

The interception and retention fraction quantifies the fraction of airborne soil moving by an individual that is deposited and retained on the skin. The value of this parameter varies with different areas of the body due to factors such as the presence or absence of hair or clothing. The value is normally less than 1.0 for most skin sites, but values greater than 1.0 are possible for areas of the body such as under a collar that can accumulate deposited soil. Recommended interception and retention fractions are taken from Apostoaei and Kocher (2010) and are shown in Table 36.

Table 36. Recommended values for the interception and retention fraction

Skin Site	Interception and Retention Fraction
Face, neck*, shoulders, back and sides of torso, forehead, palms of hands, and soles of feet*	0.015
Chest (unspecified amount of hair)	0.03
Forearms, backs of hands*, upper legs, and lower legs (above boot edge)	0.06
Scalp	0.23
Back of neck under collar, under belt, under boot edge, and behind ears	1.5

* Interception and retention fractions for these skin sites are not available in Apostoaei and Kocher (2010). The indicated values are recommended based on similarity to or proximity to other sites.

The dose analyst should be aware of a reasonable upper bound of soil loading on the skin when using Equation C-14. When concentrations of soil on the skin exceed about 2 mg cm^{-2}, the soil becomes visible and *ad hoc* cleaning is likely (Apostoaei and Kocher, 2010). Using the ranges of relevant parameter values shown in Table 32 and Table 36 in Equation C-14, the calculated soil loading on various skin sites ranges from approximately 0.0008 to 8 mg cm^{-2}. These calculated soil-loading values will exceed 2 mg cm^{-2} only in high-retention areas of the body where the interception and retention fraction is 1.5, and for these sites, only in situations of sustained soil suspension greater than 1×10^{-8} m^{-1}. For these situations, the dermal soil loading parameter in Equation C-14 should be limited to a value no higher than 2 mg cm^{-2}.

6.3.2. Skin Dose from External Non-Contact Sources of Radiation

The equation for estimating the dose to skin from non-contact sources of radiation at a specific height or distance from external sources of radiation can be found in Appendix C. This equation is used with the parameter values and scenario assumptions listed in Table 37 and Table 38.

The beta-to-gamma dose ratios for exposure to radionuclides in soil estimated from the 1976 studies of Crase et al. (1982) at Enewetak Atoll have been determined to be reasonable for use in ECUP skin dose assessments. Using the median beta-to-gamma dose ratio of 0.29 calculated for a height of 100 cm, which is based on the information reported in Crase et al. (1982), additional ratios for a range of heights from 1 to 200 cm were estimated and are shown in Table 38. The method used to estimate the beta-to-gamma dose ratios for various heights above the ground is described in Appendix L.

Table 37. Parameter values and assumptions for skin dose from external non-contact radiation

Parameter	Value	Rationale/Reference/Comment
Exposure duration	Variable	Calculated using values for "Work schedule" and "Duration of duty tour" below
Work schedule	6 d wk^{-1} 8–10 h d^{-1}	(DNA, 1981)
Duration of duty tour	Variable (default = 6 mo = 26 wk)	Based on individual's arrival and departure records
Fraction of workday exposed	0.1 to 1 (default = 1)	Fraction of a workday that an ECUP worker is exposed to contaminated soil or other source of external non-contact radiation
Exposure rate from soil	Island-specific	Island-specific exposure rates are shown in Table 4. See Section 6.2 for additional guidance on this parameter.
Ratio of the beta dose to the gamma dose	See Table 38	Rationale and additional guidance is provided in Appendix L
Modification Factor	0 to 1 (default = 1)	Default value assumes bare skin and no other modifications.

Table 38. Beta-to-gamma dose ratio for external non-contact radiation sources for all islands at Enewetak Atoll

	Skin Height above Contaminated Ground Surface* (cm)							
	1	**20**	**40**	**80**	**100**	**120**	**160**	**200**
Beta-to-gamma Dose Ratio	1.2	0.72	0.45	0.34	0.29	0.25	0.18	0.14

* See Appendix L for guidance on determining beta-to-gamma ratios for heights not shown in this table and for estimating heights of various body locations.

As an aid in estimating the height of a veteran's skin site, reference heights from the ground for 11 anatomical locations and 3 postures, including standing, sitting in a chair and sitting on the ground, are provided in Appendix L. If the height above ground of a required skin site is not one of the heights given in Table 38, an equation is provided in Appendix L that can be used to estimate the beta-to-gamma ratio for the specific height, i.e., for any skin site for an ECUP veteran. Alternatively, interpolation techniques can be used to estimate ratios between the values listed in Table 38.

6.3.3. Uncertainties and Upper-bound Skin Doses

The dose estimation methods described above that use high-sided default values result in conservative estimates of skin doses for ECUP participants. However, parameter values applicable to an individual veteran could be much different from the default assumptions, resulting in large uncertainties in the calculated skin doses. For example, scenario or veteran circumstances that could result in a veteran's skin dose that is higher than the dose estimated using default parameter values include the following:

- A higher soil suspension than the recommended value for a given scenario
- A skin thickness less than what is incorporated into the dermal dose coefficients and SDMF values
- An amount of water or sweat on a veteran's body that may result in retention at a specific skin site greater than what is assigned
- Incomplete removal of all accumulated dermal contamination at the end of each day.

On the other hand, factors that could result in a veteran's skin dose that is lower than the dose estimated using default parameter values include the following:

- Self-absorption of alpha emissions by contaminated soil particles deposited on the skin
- Attenuation of alpha and beta emissions from dermal contamination by accumulated soil on the skin
- The presence of clothing versus the default assumption of bare skin
- Lower soil concentrations or soil suspension than the recommended default values
- Less time spent near contaminated soil than the default assumption.

If taken into consideration, some of the above factors would reduce or possibly eliminate a dominant skin dose exposure pathway, i.e., dermal contamination with alpha-emitters. The uncertainty in skin dose introduced by one of these factors, i.e., self-absorption of alpha particles, is due to characteristics such as unknown and variable shapes of soil particles and locations of alpha-emitting radionuclides in or on soil particles. Characteristics of soil particles contaminated with alpha-emitting radionuclides are hard to accurately quantify, and if quantified would carry large uncertainties. Therefore, self-absorption of alpha particles is not included in the ECUP skin dose estimation to simplify and high side the analysis. This approach is reasonable because estimated doses that do not include consideration of self-absorption of alpha particles are always higher than doses that include self-absorption. Similar over-estimation bias results from the assumption that contaminated soil was deposited on bare skin rather than on clothing. Deposition of contaminated soil on clothing would not result in a skin dose from deposited alpha-emitters because of full attenuation by the clothing.

In addition to the pathway and scenario-related uncertainties discussed above, skin dose estimates involve other potential sources of uncertainty including measurement, data recording and processing errors, and spatial variability in environmental concentrations of contaminants. These aspects are discussed in Section 6.4.

To help ensure that ECUP skin doses are not underestimated, upper-bound uncertainty factors, as defined in Section 6.4, are described here for use with the skin dose estimates calculated using the methods detailed above. The use of an uncertainty factor with high-sided skin dose estimates to arrive at estimates of upper-bound skin doses is consistent with the use of uncertainty factors with the high-sided external and internal dose estimates for ECUP veterans described in this report.

Based on the standard methods developed for DTRA's NTPR program an uncertainty factor of 3 is recommended for doses due to external non-contact skin exposures for ECUP veterans. This is based on the use of this factor for non-contact skin doses in the NTPR standard methods (DTRA, 2017). For the more complex exposure pathway of dermal contamination, uncertainty factors ranged from approximately 3 to 14 based on historical skin dose assessments performed for the NTPR program (DTRA, 2017). Because of the use of high-sided assumptions and parameter values described above, an uncertainty factor of 10 is considered adequate for use with the calculated ECUP skin doses due to dermal contamination.

Finally, for both skin dose exposure pathways, i.e., dermal contamination and exposure to non-contact sources, the uncertainties are assumed correlated. Therefore, the upper bounds of each component of the skin dose for a specific skin location are summed to estimate the total upper-bound skin dose. Treating all pathway dose components as correlated is a highly conservative approach that results in overestimates of upper-bound doses.

6.4 Uncertainties and Upper-bound External Doses

Sources of uncertainty in estimating external doses for ECUP veterans are similar to those identified in other radiation dose assessments developed by DTRA (DTRA, 2017; Dunavant et al., 2017). These are generally attributed to, among others, imperfection in measuring instruments, spatial and temporal distributions, procedural errors, and data recording and processing errors. The following is a non-exhaustive list of potential sources of uncertainties in external dose estimation:

- Instrument precision
- Operator measurement and recording errors
- Uncertainties due to data acquisition and data processing tools, such as data mapping
- Spatial variability when only average values are reported or a few measurements are taken
- Variability in the exposure times
- Uncertainties in the isotopic mix of radioactive materials and method of estimating exposure rates
- Imperfect knowledge of individual's scenario of participation and radiation exposure, such as location and time, as well as shielding.

The following subsections discuss the uncertainties in reconstructed, film badge, and TLD doses. Upper bound uncertainty factors are discussed. The method for applying uncertainty factors to individual dosimeter readings and for summing doses and deriving upper bound doses to an individual who wore multiple dosimeters, with or without reconstructed dose, are given in Appendix C.

6.4.1. Uncertainty in Reconstructed External Doses

Following the procedures an standard methods (SM) used for NTPR dose calculations, an uncertainty factor of 3 can be assigned to each external dose component calculated for the ECUP personnel (Schaeffer, 2015; Kocher, 2009; DTRA, 2017, SM UA01). In addition, it is generally appropriate to assume that the components of the external dose are uncorrelated, i.e., they vary independent of each other. Therefore, to determine an upper-bound external dose, the uncertainties of the external dose components are combined in quadrature (DTRA, 2017, SM UA01) as described in Appendix C. Using this uncertainty approach, the upper-bound dose is considered to exceed the 95th percentile dose determined from a hypothetical distribution of film badge doses for individuals exposed to the same sources of radiation. In addition, the uncertainty factor accounts for relatively small doses not explicitly estimated that are less than a few percent of the overall external dose, e.g., dose from swimming.

6.4.2. Total Bias and Uncertainty in Film Badge Doses

This section discusses the three principal sources of uncertainty in film badge dosimetry, namely laboratory, radiological (calibration), and environmental (NAS-NRC, 1989). It includes estimates for the bias and uncertainty factors for each source. A summary of the overall bias and laboratory, radiological and environmental uncertainty is provided. A method for applying the factors to film badge readings is described in Section 6.4.4.

6.4.2.1 Laboratory Bias and Uncertainty

Variations in laboratory techniques for processing film badges are important contributors to film badge dose uncertainty (Daniels and Schubauer-Berigan, 2005). Factors that come into play are consistency in dark room technique and control of the temperature while developing the film. Assuring that chemicals used in the film development do not become contaminated or depleted over time and tightly controlling the variation of laboratory room and chemical bath temperatures, result in technique consistency. The selection of the reference temperatures is important, as well as is tightly controlling the durations that films are kept in each of the multiple chemical process baths. These factors all can affect the relationship between film optical density and the known exposure intensity, a relationship that establishes the dose reported for a film badge of a given optical density (NCRP, 2007). Bias is 1.0 and the uncertainty for the laboratory source of error at the upper bound of a 95 percent confidence interval (CI) (97.5 percentile) is 1.3 (NAS-NRC, 1989; NCRP, 2007; Daniels and Schubauer-Berigan, 2005). A summary of laboratory uncertainty factors derived from a study of film badge dosimetry (comparable to that used at ECUP), used at four National Laboratories and one Naval Shipyard (Daniels and Schubauer-Berigan, 2005, Figure 3) were used to estimate the values in Table 39. This table shows the uncertainty factors corresponding to various dose levels for laboratory uncertainty. The uncertainty factor increases as the dose decreases to the film badge's limit of detection of 20 mR (NAS-NRC, 1986). From the limit of detection to 70 mR, the uncertainty factor reaches an asymptotic value of 1.3.

Table 39. Average film badge laboratory uncertainty factors for various dose ranges

Dose Range (mrem)*	Average Uncertainty Factor†
21–30	1.8
31–40	1.65
41–50	1.45
51–60	1.4
61–70	1.3
> 70	1.3

* For a film badge dose at or below the MDL of 20 mrem including 0 mrem, the dose should be estimated by reconstruction; see Section 6.4.2.5 for further information.

†Derived from Daniels and Schubauer-Berigan (2005, Figure 3)

6.4.2.2 Radiological Bias and Uncertainty

The overall accuracy and precision of film badge are optimum for high energy (>100 keV) gamma radiations (NCRP, 2007 pg. 155). The high-energy gamma radiation sources detected at ECUP were Cs-137 and Co-60. Matching the energy of the calibration source's gamma radiation to the energies of the radiation in the field is a method for minimizing bias and uncertainty (NCRP, 2007). The degree of traceability of the calibration source to national standards can also contribute to bias and uncertainty and likewise for the design and wearing configuration of the film badge (NAS-NRC, 1989). The overall bias is 1.1 and the associated uncertainty for radiological sources of error at the upper bound of a 95 percent CI (97.5 percentile) is 1.1 (NAS-NRC, 1989; NCRP, 2007; Daniels and Schubauer-Berigan, 2005).

6.4.2.3 Environmental Bias and Uncertainty

Film badge calibrations and processing are done under tightly controlled environmental conditions in the laboratory while the environment for ECUP personnel wearing the badge can dramatically vary. The same can be said for control films that are kept on site nearby the ECUP person's actual work location. These control film badges are maintained to measure background environmental radiation levels and are stored indoors under somewhat more controlled conditions than the work sites. In addition, wearing intervals and the amount of transit time to and from the processing laboratory can affect latent image fading on the badge creating a loss of signal when the film is processed. Additionally, the background fog level (natural darkening) can raise the signal. The effects of these factors have been found to be self-cancelling as regards bias and uncertainty (Daniels and Schubauer-Berigan, 2005). The overall bias is 1.0 and the associated uncertainty for environmental sources of error at the upper bound of a 95 percent CI (97.5 percentile) is 1.1 (NAS-NRC, 1989; NCRP, 2007; Daniels and Schubauer-Berigan, 2005).

6.4.2.4 Summary of Bias and Uncertainty Factors and Application to Film Badge Readings

Table 40 contains a summary of the bias and uncertainty factors discussed in the previous three subsections. Using the NAS analysis methods (NAS-NRC, 1989), the bias factors are combined multiplicatively and the uncertainties are combined in quadrature. The results of these computations are shown in Table 40 as the total bias and uncertainty factors.

Table 40. Bias and uncertainty factors for various sources of error for film badge dosimetry

Sources of Bias and Uncertainty	Bias Factor	Uncertainty Factor
Laboratory	1.0	1.3 – 1.8
Radiological	1.1	1.1
Environmental	1.0	1.1
Total	1.1	1.3 – 1.8

6.4.2.5 Lowest Reliable Film Badge Doses

The minimum detectable level (MDL) is the minimum exposure that can be statistically distinguished from zero in the laboratory. The MDL is usually established at the point where the laboratory uncertainty is ± 100 percent at the 95 percent confidence interval (NAS-NRC, 1989). In an information bulletin furnished in LBDA (1973), the lowest reliable film badge dose is discussed. The methods and procedures described there are applicable for ECUP film badge doses because they were used for the cleanup project (Peters and Bramlitt, 1979). It was stated that films that show 0.00 optical density units are reported as a 0.0 dose. However, films may receive small amounts of radiation that are not reflected on the film due to the limitations of the film sensitivity. In addition, small doses may be shown on films known not to have been exposed to radiation. This is caused by inherent inaccuracies in films and densitometer uncertainty for low exposures. Because of these uncertainties, doses below the limits shown in Table 41 are considered highly uncertain. In addition, at these lower limits, the inaccuracies may be very large (LBDA, 1973). For the most important radiations potentially encountered by ECUP participants, i.e., energy greater than 200 keV, the lowest reliable film badge dose is 20 mrem.

Table 41. Lowest reliable film badge doses

Gamma or X-Ray Energy (keV)	Lowest Reliable Dose* (mrem)
< 100	2
100–200	10
> 200	20
Beta Radiation	40

* LBDA (1973)

A preliminary evaluation of the ADC dose data for ECUP participants showed that over 5,700 doses from undamaged film badges out of more than 11,000 film badge doses are less than or equal to the MDL of 20 mrem. In addition, in a 1986 report by NAS-NRC that reviewed the U.S. Army radiation dosimetry system, it was stated that one of the characteristics of the Army film badge, which was used at the ECUP, is that readings below about 20 mrem are so inaccurate that the results cannot be reported with any confidence (NAS-NRC, 1986).

For the reasons stated above, for a film badge dose at or below the MDL of 20 mrem, including 0 mrem, the dose and upper-bound should be estimated by reconstruction. The methods used to estimate external gamma doses using environmental data are discussed in Sections 6.2 and 6.4.1.

6.4.3. Uncertainty in TLD Doses

An assigned ECUP participant TLD dose consists of the net TLD reading of the TLD worn by a participant. The net TLD reading is determined by subtracting the background exposure (see below) from the TLD reading of the participant's TLD. The uncertainty in the assigned TLD dose is composed of the uncertainty in these two components, i.e., the participant's TLD reading and the uncertainty in the background exposure. These uncertainties and their use in determining the overall uncertainty in a participant's TLD dose are described in detail in Appendix D and are summarized in the following subsections.

6.4.3.1 Uncertainties in TLD Readings

The uncertainty in an ECUP participant's TLD reading results from the following three sources (USN, 1975; USN, 1988):

- Zero offset for the TLD reader zero reference level
- Truncation of the digit on the display corresponding to tenths of a milliroentgen (mR)
- The maximum allowable limit for system accuracy during performance testing.

The uncertainties contributed by these three sources are estimated and combined in quadrature as described in detail in Appendix D, to result in uncertainties at least at the 95th percentile confidence level. The resulting uncertainties and uncertainty factors for ECUP participants' TLD readings are shown in Table 42.

Table 42. Upper-bound uncertainty factor as a function of participant TLD reading

TLD Reading (mR)	Upper-bound Uncertainty	Upper-bound Uncertainty Factor
1	0.60	1.60
2	0.80	1.40
3	1.04	1.35
4	1.31	1.33
5	1.59	1.32
6	1.87	1.31
7	2.16	1.31
8	2.46	1.31
9	2.75	1.31
10	3.05	1.30
> 10*	Use Equation D-1	1.30

* Upper-bound uncertainty at 95% confidence level is approximately 30% of the reading for TLD readings greater than 10 mR.

6.4.3.2 Background and Net TLD Dose Uncertainties

To determine the participant's net TLD reading, an averaged total background exposure may be available on a TLD Report listing the details of the participant's TLD badge reading. If a TLD Report is not available, a background exposure is estimated using ECUP control TLD readings or corrected readings. These consist of 15 sets of 10 background exposure results from control TLDs that were exposed during 10 separate periods from July 1978 to February 1980. The control TLD readings were obtained from the ECUP radiation safety program records. A mean background exposure rate of 0.116 mR d^{-1} is calculated from the 150 control TLD readings, including corrected readings. If a TLD Report is not available, the background exposure is determined by multiplying the mean background exposure rate by the number of days in the TLD wearing period. As described in Appendix D, statistical analysis was used to determine a 95th percentile background exposure rate of 0.125 mR d^{-1} for the 150 control TLD readings. The resulting uncertainty factor for the background exposure rate is therefore 1.08 (0.125/0.116), that can be rounded up to 1.1. Therefore, the uncertainty associated with the total background exposure is 0.10 × total background exposure, or 10 percent. The uncertainty in the background exposure thus calculated is combined in quadrature with the uncertainty in the participant's TLD reading, from Table 42, to estimate the total uncertainty in a participant's assigned TLD dose.

6.4.4. Method for Calculating Total Doses and Total Upper Bound External Doses

The total bias and uncertainties associated with each category of external dose identified in the previous sub-sections (reconstructed doses, valid film badge doses, and TLD doses) should be calculated for all dose periods for an ECUP participant. Total uncertainties for each dose category should be combined as described in Appendix C. The total external dose and the total upper-bound external dose should then be calculated as described in Appendix C.

Section 7.

Internal Radiation Dose Assessment Methods

Bioassays can provide a basis for estimating radionuclide intakes and internal doses. As described in Section 4.8.2, bioassay results for the majority of individuals consisted of a single urine sample submitted at the end of their assignment. Results for all individuals who submitted a sample indicated that Pu-239 activity concentrations were less than the MDA. Because internal doses determined from a single bioassay result, especially for a result less than MDA, may not provide a credible estimate of total radiation exposure of internal organs and tissues (Boecker et al., 1991), these bioassay results are not recommended for use in ECUP internal dose assessments.

Radiation doses to organs and tissues due to exposures from internally deposited radioactive material can be estimated using well-established dose reconstruction methods developed by DoD dose assessment programs, such as DTRA's NTPR Program (DTRA, 2017). The methods employed in dose assessments for compensation programs rely on high-sided estimates of parameter values used in the calculation of doses to personnel for all applicable exposure pathways. Sources and pathways of exposure to radiation for ECUP participants are described in Section 5. Estimated internal doses are combined with uncertainty factors to calculate upper-bound doses that are expected to exceed the 95th percentile of dose distributions if determined using probabilistic analysis.

This section describes the assumptions and parameter values that are used to estimate doses for ECUP participants from internal radiation exposures of organs and tissues. The equations used for dose estimation are presented in Appendix C. Examples of exposure scenarios and results of radiation dose calculations for ECUP personnel are presented and discussed in Section 8. For veteran dose estimates that would be prepared in response to VA requests, all sources of radiation and intake pathways that are applicable to the individual should be considered; a veteran's RDA would be performed following the recommended guidelines discussed in Section 9.

7.1 Inhalation of Suspended Soil

Internal doses from inhalation of suspended contaminated soil are estimated based on the types of jobs performed by ECUP participants, durations of exposures, and soil activity concentrations, which in turn depend on the location where the job was conducted or from where the soil was removed. The parameter values and exposure scenario assumptions shown in Table 43 are used to estimate internal doses from the inhalation of airborne radioactive materials using the methods presented in Appendix C. Activity concentrations of undisturbed soil are extracted from radiological survey data compiled in Section 4. Estimated activity concentrations in excised soil are based on total estimated TRU activity and total volume of soil removed from each contaminated island as reported in DNA (1981). The estimated concentrations and the volume of soil removed from each island are shown in Table 44 with a more detailed analysis given in Appendix B-2. The respiratory protection factors are shown in Table 45 and are discussed in Appendix F.

Table 43. Parameter values and assumptions for estimating internal doses from inhalation of suspended soil

Parameter	Value	Rationale/Reference/Comment
Activity concentrations of undisturbed soil	Island-specific or multi-island average	Mean island-specific values are shown in Table 6. See Table 28 in Section 6.2.1 for guidance on averaging when multiple islands are involved.
Activity concentrations of excised soil	Island-specific (See Table 44)	Calculated from estimated total TRU activity and total volume of soil removed from each contaminated islands (DNA, 1981)
Work schedule	10 h d^{-1} for 6 d wk^{-1}	(DNA, 1981)
Average daily time spent outdoors • Outdoor workers: • Indoor workers − Workdays: − Non-workdays:	 15 h d^{-1} for 7 d wk^{-1} 5 h d^{-1} for 6 d wk^{-1} 15 h d^{-1} for 1 d wk^{-1}	The times listed here are total time outdoors (residence + work islands). All non-work time other than sleeping and eating is assumed recreational time spent outdoors on the residence island (see Table 29 in Section 6.2.1).
Duration of duty tour	Variable (default = 6 months)	Based on individual's arrival and departure records
Resuspension factor	10^{-9} to 10^{-7} m^{-1}	(AEC, 1973a; Bramlitt, 1977); see data analysis in Appendix E
Depth of soil available for suspension	1 cm	(DTRA, 2017, SM ID01; AEC, 1973a)
Soil density	1.5 g cm^{-3}	(AEC, 1973a; DOE, 1982a)
Mass loading	40–600 μg m^{-3}	(Oztunali et al., 1981; AEC, 1973a; Yu et al., 2015); see Appendix E
Enhancement factor	< 1 to 6.5 (Default = 3)	See Appendix E
Breathing rate	1.2 m^3 h^{-1}	Applicable to an adult male during light activity/exercise (DTRA, 2017, SM ID01)
Respiratory protection factor	See Table 45	See Appendix F
Inhalation dose coefficients	Organ- and radionuclide-specific; AMAD = 1 μm, (rem pCi^{-1})	Worker dose coefficients, extracted from ICRP Publication 68 (ICRP, 2011)
Fraction of time exposed to source	0.1 to 1 (default = 1)	Fraction of a workday that an ECUP worker is exposed to suspended soil, based on questionnaire responses and task durations

Table 44. Estimated average activity concentration of contaminated soil excised and moved to Cactus Crater and dome

Island with Contaminated Soil Removed	Total TRU Activity (Ci)*	Soil Volume Removed (yd^3)*			Average TRU Activity Concentration ($pCi\ g^{-1}$)†
		Disposed in Crater	Disposed in Dome	Total	
Medren	0	110	0	110	0‡
Aomon	1.29	10,603	0	10,603	106
Aomon Crypt	0.93	448	9,328	9,776	83
Boken	1.01	421	4,516	4,937	178
Enjebi	2.57	43,023	9,984	53,007	42
Lujor	1.70	0	14,929	14,929	99
Runit	7.22	0	10,735	10,735	587
Overall totals (Runit not included)	7.50	54,605	38,757	93,362	70§
Overall Totals (Runit included)	14.72	54,605	49,492	104,097	123§

* Total TRU activity values and soil volumes are from Figure 8-34 of DNA (1981).

† Soil activity concentrations are based on an average bulk soil density of 1.5 g cm^{-3} (AEC, 1973a; DOE, 1982a).

‡ The 110 cubic yards of soil removed from Medren was contaminated only with Co-60, with hotspots ranging between 20–2000 pCi g^{-1}. Based on soil volumes removed and their maximum concentrations, the average Co-60 activity concentration in this soil is estimated to be less than 170 pCi g^{-1}. (DNA, 1981)

§ These average TRU soil activity concentrations are weighted averages calculated using total soil volume removed from each island.

Table 45. ECUP personnel protection levels and respiratory protection factors

ECUP Personnel Protection Level	ECUP Respiratory Protection*	Respiratory Protection Factor†
I or IIA	None	1
IIB	Surgical mask (dust mask)	1
IIIA or IIIB	Full-face negative pressure respirator	50
	Half-face positive pressure respirator	50
	Full-face positive pressure respirator	1,000
IV	Full-face positive pressure respirator	1,000

* Half-face, negative pressure respirators (protection factor of 10 [USNRC, 1976]) are mentioned in some ECUP documentation (e.g., FCRR SOP 608-10 “Decontamination Laundry Procedures”). However, this respirator type is not listed in the ECUP Personnel Protection Level documentation (EAI No. 5707.1; DNA, 1981).

† For use in ECUP dose assessments, the respiratory protection factor for work in Controlled Access areas can normally be determined from the Personnel Protection Level specified in relevant Controlled Island Access forms. When Level IIIA or IIIB is indicated in the Controlled Island Access form, a respiratory protection factor of 50 should be used unless it is known that a full-face, positive pressure respirator was worn.

Discussions of the parameter values and assumptions for exposure scenarios involving inhalation of suspended soil are included below.

- **Soil activity concentrations:** Activity concentrations for both undisturbed and excised soil are required, but their use depends on a specific individual's participation and exposure scenario. Both of these sets of values are island-specific as shown in Table 6 and Table 44.

  Scenarios involving general work on an island would likely involve only undisturbed soil. Island-average activity concentrations for undisturbed soil on each island are shown in Table 6 and are recommended for use in these scenarios. These mean values are primarily arithmetic means and generally high side the central estimates of the soil activity concentration distributions.

  The average TRU activity concentration calculated for soil removed from each of the five soil-removal islands is shown in Table 44. These soil activity concentrations calculated for excised soil would be appropriate for use in scenarios involving exposure to suspended soil during soil removal disturbances such as bulldozing, loading, and unloading activities. In addition, these soil activity concentrations are significantly higher than the island-average TRU activity concentrations in the top 15 cm of undisturbed soil for all soil-removal islands. To simplify internal dose calculations, all radioactivity in excised soil can be assumed Pu-239 as long as total TRU activity concentrations from Table 44 are used to estimate airborne activity concentrations of suspended soil or soil that is incidentally ingested. The basis for this assumption is discussed in Appendix G. If measured airborne activity concentrations in suspended excised soil are used for dose estimates, all radionuclides of concern should be included. However, such measurements are generally not available for use in inhalation dose estimates over extended periods.

  In cases where a veteran worked on multiple islands, the estimated soil activity concentration to which he was exposed depends on the nature of work and the amount of time he worked on each island. For example, if the veteran participated in soil-excavation work and the number of days on each island is known based on the Controlled Island Access forms (see Figure 5), a time-weighted average of the soil activity concentrations for excised soil from each relevant island may be used. However, if the amounts of time spent on the islands are not certain, a volume-weighted average of the individual island excised soil activity concentrations can be used. This method is based on the assumption that the amount of time spent on an island by a worker involved in soil-removal activities is proportional to the amount of soil removed from the island. This is the approach used in the example scenario described in Section 8.2 for debris-cleanup work, and it can be applied to excised soil as shown by the weighted average concentrations presented in Table 44. Guidance on averaging methods for estimating soil activity concentrations for scenarios involving work on multiple islands is shown in Table 28 for four categories of worker participation. The overall volume-weighted average TRU soil activity concentrations in Table 44 can be used for excised soil that was stockpiled on Runit.

- **Work schedule:** The work schedule for individuals involved in handling excised soil or near suspended soil depended on several factors. The default values shown in Table 43 are based on a 10-hour workday for 6 days each week. For northern island workers, it is assumed that there was a total of two hours spent traveling between Lojwa and the work island each workday. This is a reasonable average value based on travel times derived from LCU boat logs and FRST Operational Reports[11] of about one hour each way between Lojwa and Enjebi, and between Lojwa and Runit. The assumed workweek is 6 days because ECUP workers typically did not work on Sundays.

- **Duration of duty tour:** Arrival and departure cards are available for each individual who visited or worked at Enewetak Atoll during the cleanup project. If such records are found to be missing, the default duration of duty is assumed 6 months based on the typical ECUP assignment of 4–6 months (DNA, 1981).
- **Resuspension factor and mass loading factor:** Resuspension factors and mass loading factors used for estimating airborne activity from the suspension of soil are discussed in Appendix E. The lower value of 10^{-9} m^{-1} of the recommended range is an appropriate value for individuals upwind of soil disturbances, and the upper value of 10^{-7} m^{-1} is a more appropriate value for locations downwind of on-going soil disturbances. As indicated in contemporaneous reports and as required by ECUP SOPs, personnel were located upwind of soil disturbances and were rarely downwind during cleanup activities involving airborne contaminated soil and dust. Based on the discussion in Appendix E, the proposed generic value of 100 µg m^{-3} for mass loading is considered a conservative value that can be used as a representative average applicable to the entire duration for personnel not performing activities involving removal or handling of contaminated soil. Further guidance for the use of these values is given in Appendix E.
- **Depth of soil available for suspension:** This value is variable and is not well characterized. However, a value of 1 cm is a typical assumption used in dose assessment studies (AEC, 1973a; DTRA, 2017, SM ID01).
- **Soil density:** Based on 364 soil density measurements for the top 5 cm obtained in December 1979, a mean wet soil density of 1.53 g cm^{-3} with a standard deviation of 0.14 g cm^{-3} was estimated (DOE, 1982a). The value of 1.5 g cm^{-3} was used in DOE radiation dose assessments for future Enewetak inhabitants (AEC, 1973a) and several other relevant publications. Therefore, the value of 1.5 g cm^{-3} is recommended for ECUP dose assessments.
- **Enhancement factor:** This factor is used with the mass loading values to account for the potentially higher airborne activity concentration of suspended soil compared to the source soil. Values for plutonium enhancement factors typically range from less than 1.0 to 6.5, and a reasonably conservative value of 3.0 is used in this report for all radionuclides. This factor is also discussed in Appendix E.
- **Breathing rate**: The default breathing rate of 1.2 m^3 hr^{-1} is based on an adult male performing light activities, comparable to walking at a rate of 3 mph on a flat firm surface (DTRA, 2017, SM ID01). This rate is used as an average, constant breathing rate for all periods and activities where inhalation exposure is applied.
- **Respiratory protection factor**: This factor represents the degree of protection afforded by a respirator, and it is equal to the ratio of the concentration of contaminants outside the respirator to the concentration inhaled. Therefore, the inhaled concentration equals the

[11] FRST Operational Reports are the daily reports prepared by a FRST Team Chief on JTG Form 16 for a specific Controlled Access Area. The forms contain serial numbers of survey meters used, and a Narrative section that may contain times, activities conducted, use of PPE, and other items relevant to radiological control.

ambient concentration divided by the respiratory protection factor. The respiratory protection factors shown in Table 45 are taken from contemporaneous and current USNRC guidance (USNRC, 1976; USNRC, 2017) and are discussed in Appendix F. The numerical protection factor used in dose assessments for ECUP participants can be based on the respiratory protection worn or the Personnel Protection Level specified for a given activity. For work in controlled-access areas, the protection factor is determined from the Personnel Protection Level specified in the relevant Controlled Island Access form (see Figure 5). When Level IIIA or IIIB is indicated in the Controlled Island Access form, a respiratory protection factor of 50 should be assumed, unless it is known that a full-face, positive pressure respirator was worn, in which case a respiratory protection factor of 1,000 is applicable.

- **Inhalation dose coefficients**: To high side the dose estimates, it was assumed that all suspended soil particles were respirable with an average activity median aerodynamic diameter (AMAD) of 1 μm. This conservative assumption results in dose coefficients that are higher than those of AMADs in the 3–10 μm range by factors of up to about 4 for most organs. In addition to particle size, the chemical form of a radionuclide also affects the dose delivered to internal organs. Chemical forms of the radionuclides of concern at Enewetak are not well known. Therefore, when a choice was available in determining the dose coefficients for Sr-90, Sb-125, Pu-239, and Co-60, "unspecified compounds" was assumed. This results in higher dose coefficients by factors of up to 20 for Sr-90 and Pu-239 for most organs. For Co-60, Type M dose coefficients for "unspecified compounds" are generally lower than Type S dose coefficients by a factor of up to 4. For the most important radionuclides of concern with regard to internal dose, e.g., Pu-239, these assumptions high side the organ doses by at least a factor of 8. (ICRP, 2011)
- **Fraction of time exposed to source**: This factor is intended to account for the fraction of a workday that an ECUP worker is actually exposed to suspended soil. Examples of scenario characteristics that could be accounted for include fraction of a workday that soil handling is occurring, and the locations of personnel with respect to the prevailing wind. Because of the difficulty in determining an appropriate value, and to simplify future assessments, the recommended default value for this parameter is 1.0.

7.2 Incidental Ingestion of Soil and Dust

Internal doses from incidental ingestion of contaminated soil and dust may have resulted from inadvertent intake by the mouth of small quantities of soil and dust particles that adhered to food, beverages, cigarettes, or hands. Any ECUP veteran who visited an island with contaminated soil had the potential for incidental ingestion of contaminated soil and dust in the course of their assigned activities. However, use of a dust mask or respiratory protection would preclude this exposure pathway. The dose from this pathway is calculated as a chronic type of exposure that involved non-specific intakes of relatively small quantities of soil and dust. The parameter values and exposure scenario assumptions shown in Table 46 are used to estimate internal doses from this pathway using the methods presented in Appendix C. Activity concentrations in undisturbed soil are extracted from radiological soil survey data compiled in Table 6. Estimated activity concentrations in excised soil are based on total estimated TRU curies and total volume of removed soil from each contaminated island reported in DNA (1981).

These estimated concentrations and the volumes of soil removed from each island are shown in Table 44.

Table 46. Parameter values and assumptions for estimating internal doses from the incidental ingestion of contaminated soil and dust

Parameter	Value	Rationale/Reference/Comment
Incidental soil and dust ingestion rate	0.05 g d^{-1}	Central tendency value for adults in rural setting (USEPA, 2017a)
Activity concentrations of undisturbed soil	Island-specific; values shown in Table 6	Mean values are used for most radionuclides as high-sided central estimates. This pathway should typically be assessed for one of the residence islands.
Work schedule	6 d wk^{-1}	DNA, 1981
Time on residence island	7 d wk^{-1}	Full-time occupancy on residence island is assumed.
Duration of duty tour	Variable (default = 6 months)	Based on individual's arrival and departure records
Fraction of workday exposed	0–1.0	Accounts for time in controlled areas when respiratory protection prevents ingestion
Ingestion dose coefficients	Organ- and radionuclide-specific (rem pCi^{-1})	Worker dose coefficients taken from ICRP Publication 68 (ICRP, 2011)

Brief discussions of the parameter values and assumptions for exposure scenarios involving incidental ingestion of soil and dust are included below.

- **Incidental soil and dust ingestion rate:** The default rate of 0.05 g d^{-1} is recommended in the USEPA Exposure Factors Handbook as the mean value for daily adult incidental ingestion of soil and dust in rural settings (USEPA, 2017a). This mean value is judged a reasonable value to assess this ingestion pathway for ECUP participants.
- **Soil activity concentrations:** Activity concentrations for undisturbed or excised soil may be required, and their use depends on the specific individual's participation and exposure scenario. Both of these sets of values are island-specific. The default ECUP assumption is the use of island-average mean soil concentrations for undisturbed soil, as this is more appropriate for this chronic, long-term exposure pathway.
- **Work duration:** See discussion for this parameter in Section 7.1.
- **Duration of duty tour:** See discussion for this parameter in Section 7.1.
- **Fraction of workday exposed**: This factor accounts for the fraction of a day that incidental ingestion of soil and dust is a potential exposure pathway for an ECUP worker. The factors affecting the specific value used within the range shown in Table 46 are the amount of time spent on a controlled island or near contaminated soil, and the fraction of that time that the

individual is not wearing any respiratory protection that covers the mouth. The latter assumption is valid because this exposure pathway involves contamination on items such as food and cigarettes, or on the hands, to be placed in or near an individual's mouth.

- **Ingestion dose coefficients:** Similar to the inhalation dose coefficients discussed above, when a choice was available in determining the dose coefficients (for Sr-90, Pu-239, and Co-60), "Unspecified compounds" was assumed. For all organs, this assumption results in the use of very similar or higher dose coefficients than those for alternative choices by factors of up to 30 for Sr-90 and up to 50 for Pu-239. Ingestion dose coefficients for Co-60 do not vary much for different chemical forms (ICRP, 2011).

7.3 Incidental Ingestion of Lagoon and Ocean Water

Internal doses from incidental ingestion of potentially contaminated lagoon or ocean water may have resulted from the inadvertent ingestion of small quantities of water during diving duties or recreational water-based activities. Among many waterfront activities, ECUP participants spent time swimming, snorkeling, spearfishing, scuba diving, and sailing in lagoon or ocean waters. It is most likely that these recreational activities took place near the residence islands of Enewetak or Lojwa during off-duty time, i.e., at the end of a workday and on weekends. On the other hand, U.S. Navy divers were involved in underwater inspection, survey, and debris recovery and retrieval among other duties. They used SCUBA gear with or without helmets, or with an ordinary diving mask.

For recreational activities, the estimate of internal doses from the incidental ingestion of potentially contaminated lagoon or ocean water considers the type of the water-based activity, length of exposures, and radionuclide concentrations in the water where the activity took place. Table 10 to Table 12 of Section 4.5 present the sampling results of activity concentrations of Cs-137 and Pu-239/240 for lagoon and ocean water. Other radionuclides were detected in a very small number of samples at concentrations significantly lower than these two radionuclides, at levels that would not affect the dose results. Using the highest mean 3-foot deep sample activity concentrations from Table 10 to Table 12, a water ingestion rate of 36 mL h^{-1} for adult men swimming in seawater[12] (USEPA, 2019), and assuming recreational swimming in the lagoon for 1 h d^{-1} every day of a 6-month assignment, maximum doses were estimated. This scenario is considered bounding for all water-based recreational activities for this pathway. The estimated upper-bound committed effective dose equivalent is 0.007 mrem. The highest organ upper-bound committed dose equivalent is approximately 0.2 mrem for bone surface.

Because of the divers' more frequent and extended contact with lagoon and ocean water, they were more likely to receive a higher radiation dose from this exposure pathway than personnel who were only involved in recreational swimming and sailing. Divers usually wear SCUBA gear with a full-face mask, a diving helmet, or an ordinary diving mask. In a survey among professional divers, it was strongly indicated that they ingested much less water when wearing a full-face mask instead of an ordinary diving mask and even less when wearing a diving helmet. These occupational divers are estimated to swallow about 10 mL of marine water per dive, which is an average over wearing all types of diving masks or helmets (Schijven and de Roda Husman, 2006).

[12] This value is based on an average value of ingesting 27 mL in a 45 min swim (USEPA, 2019).

The duration of a dive for an occupational diver is reported to be typically 60 to 95 minutes (Schijven and de Roda Husman, 2006). Assuming 60-minute dives, a maximum of 8 dives per workday and 6 workdays per week, an ECUP diver could have conducted as many as 1,248 dives over a 6-month period of deployment. Maximized doses were estimated using this number of dives together with the highest concentrations of Cs-137 and Pu-239/240 in Enewetak near-surface water from Table 10 to Table 12, and an ingestion rate of 10 mL per dive. The resulting upper-bound committed effective dose equivalent is approximately 0.01 mrem and the highest organ upper-bound committed dose equivalent is approximately 0.3 mrem for bone surface.

Near-surface water activity concentrations were used in the assessment above. This is because divers were responsible for collecting and surveying debris located offshore from the high tide line out to a depth of 15 feet in the water at low tide (DNA, 1981). Therefore, the activity concentrations measured in the deep-water range of 46–195 feet in craters, shown in Table 10, do not represent the radionuclide concentrations to which the divers may have been exposed to in lagoon water.

Based on the above assessment results, the potential doses to ECUP personnel from incidental ingestion of lagoon or ocean water during recreational swimming or occupational diving are less than 0.001 rem for any organ or effective dose. Therefore, this pathway is not considered a significant exposure pathway for ECUP personnel. Any internal dose related to this type of exposure would be largely subsumed within the upper-bound internal dose uncertainties; hence, there is no need to estimate these doses separately.

7.4 Ingestion of Food and Drinking Water

7.4.1. Consumption of Local Food

As discussed in Section 5, the food consumed by ECUP personnel was prepared using ingredients supplied through the military logistics system and as such, it was not a source of radiation exposure. However, regarding foods obtained from Enewetak Atoll, anecdotes of ECUP veterans indicate that some participants consumed locally gathered marine and terrestrial foods while off-duty (Cherry, 2018b; Fitzgerald, 2017; Tupin, 2018). To evaluate the significance of this potential exposure pathway, an assessment of organ doses from consuming local foods was conducted and is described in detail in Appendix M. Key parameter values are based on the data reported in Section 4 and a summary of the highest organ doses are described below.

Consumption of six local foods are assessed in this report. The most likely local foods that might have been consumed by ECUP participants are fish and spiny lobster from the ocean and lagoon, and coconut meat and coconut milk from the land. Coconut crabs are also included because veterans might have eaten them according to some anecdotal accounts (Fitzgerald, 2017). In addition, giant clams were consumed according to one veteran’s statement in a questionnaire submitted in connection to his radiation dose assessment. Other foods can be assessed on a case-by-case basis if consumption of such foods is claimed by a veteran in their ECUP questionnaire.

Average activity concentrations of key radionuclides that were measured in each of the edible parts of the selected local foods from all samples collected on the atoll are given in Table 18. The wet-to-dry weight ratios and the food consumption rates are listed in Table 47.

The rationale for each assumed consumption rate for ECUP personnel is given in Appendix M. Using these assumptions, committed equivalent doses per serving were calculated using Equation M-1 presented in Appendix M. The highest estimated organ ingestion doses per serving based on these concentrations and parameter values are shown in Table 48. Doses for all organs and foods are given in Appendix M.

Table 47. Parameter values for estimating ingestion doses from eating local foods

Edible Part of Local Food	Wet-to-Dry Ratio*	Consumption Rate (g per serving)
Fish muscle	3.5	300
Spiny Lobster muscle	4.32	500
Coconut Meat	2	400
Coconut Milk	20	300
Coconut Crab muscle	4.1	500
Clams (Giant)	6.4	500

* Values are taken from AEC (1973a), except that the ratio for muscle of the common shore crab is used for coconut crab muscle (Bjerregaard and Depledge, 2002).

Table 48. Estimated dose per serving from the consumption of local foods

Local Food	Estimated Dose (rem per serving)	
	Highest Organ Dose (Organ)	Committed Effective Dose
Fish	9.8×10^{-4} (Bone surface)	3.1×10^{-5}
Spiny Lobster	2.5×10^{-5} (Bone surface)	1.4×10^{-6}
Coconut Meat	5.0×10^{-4} (Bone surface)	9.5×10^{-5}
Coconut Milk	1.3×10^{-4} (Bone surface)	7.1×10^{-5}
Coconut Crab	1.7×10^{-4} (Bone surface)	3.4×10^{-5}
Clams (Giant)	5.8×10^{-4} (Bone surface)	2.7×10^{-5}

The default assumption for ECUP dose assessments is that local food was not consumed. The pathway should be included only if a veteran mentions that local food was consumed. If applicable, the exposure should be assessed using the estimated per-serving doses together with consumption information supplied by the veteran. If a veteran recalls that he ate local foods but doesn't specify the type and amount, then the default assumption is one serving of fish once a month. Fish is the default food because its consumption produces the highest per-serving dose to the bone surface. The default frequency of one serving per month is based on the recollection of an ECUP veteran that the eating of locally gathered fish only took place sporadically (Tupin, 2018).

Based on the upper-bound doses summarized in Table 49, the total internal dose accrued by an ECUP participant who may have potentially consumed local foods can be estimated. Using the default assumption as an example, a veteran who was deployed for 6 months is assumed to have consumed one serving of locally caught fish per month for a total of 6 servings. Using these assumptions, the estimated total upper-bound doses to various internal organs range from less than 0.001 to 0.06 rem, the lowest dose being to the breast and the highest to bone surface. The estimated upper-bound committed effective dose is 0.002 rem. Additional details and results of estimating doses from consuming local foods are given in Appendix M.

Table 49. Upper-bound doses per serving from the consumption of local foods

Local Food	Upper-Bound Dose (rem per serving)	
	Organ Dose Range	Committed Effective Dose
Fish	$3.8 \times 10^{-5} – 9.8 \times 10^{-3}$	3.1×10^{-4}
Lobster	$2.9 \times 10^{-6} – 2.5 \times 10^{-4}$	1.4×10^{-5}
Coconut Meat	$6.2 \times 10^{-4} – 5.0 \times 10^{-3}$	9.5×10^{-4}
Coconut Milk	$5.8 \times 10^{-4} – 1.3 \times 10^{-3}$	7.1×10^{-4}
Coconut Crab	$2.0 \times 10^{-4} – 1.7 \times 10^{-3}$	3.4×10^{-4}
Clams (Giant)	$4.5 \times 10^{-5} – 5.8 \times 10^{-3}$	2.7×10^{-4}

7.4.2. Ingestion of Drinking Water

All water used by ECUP participants for drinking, cooking, and bathing was produced by distilling ocean water (DOE, 1982a). Production volumes of the distillation plants at Enewetak and Lojwa Islands were monitored and reported regularly. An adequate supply of distilled water was achieved throughout the project as reported in the weekly SITREPs. The ocean water mean activity concentrations shown in Table 11 are 0.43 fCi kg^{-1} and 0.21 fCi L^{-1} for Pu-239/240, and 32 fCi kg^{-1} and 146 fCi L^{-1} for Cs-137. These concentrations are comparable to concentrations measured in the western Pacific and north Atlantic Oceans (Aoyama and Hirose, 1995; Morgan and Arkell, 1963; AEC, 1973a). In addition, in the distillation process, water is boiled and steam is condensed to remove salts, metals, minerals, and particulates (USEPA, 2005). This is borne out by available distilled water concentration measurements shown in Table 19. The maximum measured concentration of Cs-137 in distilled water reported in Table 19 is 22 fCi L^{-1}, which is lower than ocean water activity concentrations, and would result in a maximum dose of 1×10^{-8} rem to any organ, based on a full year of ingestion of 2 L d^{-1}. This dose is much lower than the dose criterion in the National Primary Drinking Water Standards for beta and photon emitters of 4 mrem y^{-1} (USEPA, 2017b). Likewise, the Pu-239/240 activity concentrations in both ocean water and distilled water are well below the Maximum Contaminant Level of

15 pCi L^{-1} (15,000 fCi L^{-1}) for alpha particle radiation (USEPA, 2017b). Therefore, ingestion of drinking water is not considered to be a significant pathway for ECUP participants and any related internal dose would be subsumed within applied upper-bound dose uncertainties.

7.5 Puncture Wounds and Cuts

No reports of this potential internal exposure pathway have been located for any ECUP participants. Therefore, assessment of this potential pathway in the future should be handled on a case-by-case basis, using relevant guidance and recommendations (e.g., NCRP, 2006).

7.6 Uncertainties and Upper-bound Internal Doses

Sources of uncertainty in estimating internal doses to veterans who participated in ECUP are similar to those identified in other radiation dose assessments developed by DTRA (DTRA, 2017; Dunavant et al., 2017). Similar to uncertainties in external doses discussed in Section 6.4, sources of uncertainties in internal doses are generally attributed to, among others, imperfection in measuring instruments, spatial and temporal distributions, procedural errors, and data recording and processing errors. Additional sources of uncertainties in internal doses include human physiological characteristics reflected in internal dose estimation parameters such as breathing rates, composition of radioactive material, and radionuclide dose coefficients.

Following the procedures used for the NTPR Program dose assessments, an uncertainty factor of 10 can be assigned to each internal dose calculated for ECUP participants. The uncertainties of the internal dose are assumed to be correlated, i.e., the upper bounds of each component of the internal dose are summed to estimate the total upper-bound internal dose for either the committed effective dose or the organ dose as described in Appendix C. Given an uncertainty factor of 10 and a systematically high-sided calculated dose, the upper-bound internal dose is considered to exceed the 95th percentile dose if determined from a distribution of doses for individuals estimated from internal monitoring measurements (Weitz et al., 2009; NAS-NRC, 2003). In addition, the uncertainty factor applied to high side internal dose estimates should account for relatively small doses that are less than a few percent of the overall internal dose, e.g., doses from potential occasional consumption of locally caught fish or local food, and incidental ingestion of water while swimming or diving. (DTRA, 2017, SM UA01)

Section 8.

Example Radiation Dose Assessment Results and Discussion

This section describes example ECUP radiation exposure scenarios and presents estimated dose results. Dose parameter values and assumptions are provided in the example exposure scenarios to assist veterans in understanding how an individualized dose assessment might be conducted, in the event that personal radiation dosimetry monitoring data are not available or useable. As described in previous sections, the results are high-sided estimates of radiation doses for representative members of participant groups that performed similar tasks and activities during the cleanup project. The exposure scenarios are based on historical ECUP information, monitoring data described in other sections of this report, and other ECUP documentation. Default parameter values were selected to result in high-sided dose estimates.

Estimated organ committed equivalent doses and whole-body committed effective doses are discussed for three example ECUP scenarios in this section (Sections 8.1, 8.2, and 8.3). The dose estimates for these example ECUP scenarios result in upper-bound estimates of the total organ dose for the highest exposed organ (bone surface) from 0.12 to 1.4 rem. These total organ doses are the sums of the external and internal committed organ equivalent doses (Section 1.4). The upper-bound estimates of the total effective doses range from 0.03 to 0.22 rem. These total effective doses are the sums of the external and internal committed effective doses. These doses should be considered bounding doses for ECUP participants who performed similar generic activities for each scenario. The highest of the example upper-bound total effective doses is less than the average (mean) dose to the U.S. population of 0.31 rem from ubiquitous background radiation, including radon (NCRP, 2009a), and is a factor of 10 lower than the occupational dose limits that were in place for ECUP workers, as discussed in Section 3 (USA, 1975).

Dose estimates for an example scenario involving Air Force personnel assigned temporary duty on Enewetak Island in 1965 are described in Section 8.4. This non-ECUP scenario is included to demonstrate the use of the data in this report for scenarios occurring prior to the start of ECUP. A final example scenario (Section 0) describes calculated skin doses for a hypothetical ECUP participant working on two contaminated islands.

8.1 Example Scenario #1: Soil Cleanup Personnel

Soil cleanup tasks were judged the most significant ECUP activities with regard to potential doses because of the constant exposure to contaminated soil and the disruption, suspension, and possible inhalation of contaminated soil and dust. This example of a soil cleanup scenario involves an operator of heavy earthmoving equipment, e.g., bulldozers or front-end loaders, who participated in brush removal and soil removal activities. The heavy-equipment operator is assumed to have excised and loaded soil from Boken and Runit, per the schedule shown in Table 50, and is assumed to have worked on Runit during the entire two-month period of soil removal from that island during June–July, 1979 (DOE, 1982a). In addition, the operator is assumed to have cleared vegetation, and excised and loaded soil, from Boken, which is the island with the highest average soil concentration of TRU other than Runit, for a total of

4 months. This means that the scenario involves heavy equipment operation all day for every working day of an entire 6-month ECUP assignment. This hypothetical work schedule maximizes the estimated doses because reviews of controlled island access logs show that ECUP workers did not go to contaminated islands every workday and most worked on both contaminated and uncontaminated islands.

Specific activities were selected from the listing of Tasks and Activities shown in Table 23. The activities included in this example scenario, including the islands where they were conducted and their durations, are shown in Table 50.

Table 50. Task durations assumed for a maximized exposure scenario for a soil cleanup worker

Scenario Tasks and Activities	Island	Duration of Task		
		Hours per Day	Days per Week	Months
Brush Removal				
Uproot bushes and vegetation	Boken	8	1	4
Soil removal and transport to Runit				
Remove and windrow soil	Boken	4	5	4
Load soil on dump trucks	Boken	4	5	4
Runit soil removal and transport to Cactus dome				
Remove and windrow soil	Runit	4	6	2
Load soil on dump trucks	Runit	4	6	2

External and internal doses were estimated using the exposure pathways indicated in Table 23 and the equations in Appendix C. The island-average exposure rates of 80 μR h^{-1} and 33 μR h^{-1} were used for Boken and Runit, respectively. A value of 1.0 was assumed for the fraction of time exposed to the source for external and internal dose estimates for this example scenario. This factor accounts for the fraction of time during a workday that an ECUP worker was actually near the exposure sources. Data were not available to estimate the fraction of time exposed, and there is no feedback from a veteran for this hypothetical scenario. So in such a case, the conservative default value of 1.0 was used.

Based on the above parameter values used for this example scenario, the external dose calculated for personnel who performed the duty activities described above is 0.056 rem. The high-sidedness of this estimated dose can be confirmed by comparing it to the dosimetry results shown in Table 20. An external dose estimate for assumed residence on Lojwa is also included for this example scenario. Based on an average exposure rate of 5 μR h^{-1}, and 9 h d^{-1} spent inside a tent that is assumed to provide a protection factor of 1.5, the external dose from exposure to Lojwa ground soil for 6 months is estimated to be 0.008 rem. Therefore, the total external dose for this example scenario is 0.064 rem. Applying an uncertainty factor of 3 as described in Section 6.4 results in an upper-bound external dose of 0.2 rem.

For the inhalation exposure pathway, the calculated airborne contaminated soil concentrations are based on mass loading values of 560 μg m^{-3} for soil removal, windrowing, and loading/unloading activities, and 300 μg m^{-3} for brush removal (Oztunali, 1981). These mass loading values correspond to measured or calculated values found in the literature for close proximity to bulldozing and agricultural tillage, respectively. An enhancement factor of 3, as described in Section 7.1 and Appendix E, was also assumed (Shinn et al., 1994). The use of these mass loading values and the enhancement factor resulted in calculated average air concentrations of approximately 1 percent of the ECUP MPC value of 27 pCi m^{-3} for Pu-239/240 for the example work on Boken, and approximately 4 percent of the MPC value for the example work on Runit. This suggests that the calculated hypothetical air concentrations are high-sided because in reality only 4 percent of the more than 5,000 air filters analyzed during ECUP showed air concentrations greater than 1 percent of the MPC (DNA, 1981).

Assumptions for respiratory protection factors are based on documented ECUP procedures such as EAI 5707 "Personnel Protection Levels." A value of 50 for a half facepiece, positive pressure respirator was assumed in this example scenario for all activities on Boken and Runit assuming personnel protection levels of Level IIIA or IIIB. Based on the controlled island access logs, workers were actually often required to wear Level III protective clothing when conducting cleanup work on Boken and Runit. Respiratory protection factors for the respirators used during ECUP are as high as 1,000 for full-face positive pressure respirators prescribed for protection Level III and Level IV (Appendix F). Therefore, the value of 50 is conservative because it results in high-sided doses (DNA, 1981).

Using the parameter values in Table 43, the highest estimated internal organ dose from inhalation of airborne contaminated soil on these islands is 0.083 rem for bone surface. Other calculated inhalation organ doses resulting from soil handling are less than 0.02 rem. The estimated effective dose from inhalation on the two contaminated islands is approximately 0.003 rem. Doses due to inhalation of suspended soil and incidental ingestion of soil and dust were calculated for the residence time on Lojwa. A mass loading value of 100 μg m^{-3} was assumed for Lojwa. The internal dose to bone surface from residing on Lojwa is 0.008 rem. The total internal dose for this scenario for the highest organ dose (bone surface) is therefore 0.091 rem. The effective dose due to intakes via inhalation and incidental ingestion during soil-handling work and while on Lojwa is 0.003 rem. Applying an uncertainty factor of 10 to the internal doses, as described in Section 7.6, results in an upper-bound internal bone surface dose of 0.91 rem and an upper-bound internal effective dose of 0.029 rem.

8.2 Example Scenario #2: Debris Cleanup

Debris cleanup tasks during ECUP presented the potential for external and internal exposures. This example scenario involves a generic debris cleanup worker, for example an operator of heavy equipment such as a crane with clamshell and winches, who participated in debris collection and loading on trucks and other transport vehicles.

8.2.1. External Dose Assessment—Debris Cleanup Scenario

The primary source of external radiation exposure during debris cleanup was exposure to undisturbed contaminated soil during onshore collection, removal, and transport of non-contaminated and contaminated debris. Most debris cleanup activities involved non-contaminated debris, because approximately 98 percent of the volume of debris cleaned up was not contaminated (DNA, 1981). Exposure to "red" and "yellow" debris also was a source of potential external exposure. The primary source of internal radiation exposure during debris cleanup was due to suspended contaminated soil.

Doses for individuals conducting debris cleanup activities were generically estimated using high-sided assumptions as shown in Table 51. For external doses, exposure rates are based on the island-average exposure rates as described in Section 6.2.2. An average exposure rate from contaminated soil and debris was estimated by averaging the exposure rates for the 21 northern islands from which any debris was removed (DNA, 1981). This was derived by weighting the exposure rates by the fractional volume of total debris removed from each of the northern debris-removal islands, with the assumption that the amount of debris removed is proportional to time spent on the island. Assuming that the maximum time of 8 h d^{-1} and 6 d wk^{-1} was spent on these islands for a 6-month period resulted in an external dose of 0.031 rem. Adding the external dose of 0.008 rem for 6-months residence on Lojwa, discussed in the first example scenario (Section 8.1), resulted in a total external dose of 0.039 rem and an upper-bound external dose of 0.12 rem.

Table 51. Exposure parameter values and assumptions for estimating external dose in the debris-handling example scenario

Parameter	Value	Rationale/Reference/Comment
Exposure rate from undisturbed soil on debris-removal islands	35 μR h^{-1}	Weighted average for 21 northern islands that had debris removed
Work schedule	26 wk 6 d wk^{-1} 8 h d^{-1}	(DNA, 1981)
Fraction of time exposed to source	– 1.0 (external dose) – 0.25 (internal dose)	– Default – Analyst judgment
Time spent outdoors on Lojwa	5 h d^{-1} for 6 d wk^{-1} 15 h d^{-1} for 1 d wk^{-1}	See Section 6
Time spent in a tent on Lojwa	9 h d^{-1} for 7 d wk^{-1}	Default schedule is 8 h sleeping and 1 h eating meals indoors every day
Protection factor for a tent	1.5	High-sided assumption that resulted in a higher dose than assuming a metal building (DTRA, 2017, SM ED02)
Film badge conversion factor	0.7 (standing upright on ground)	(DTRA, 2017, SM ED02)

8.2.2. Internal Dose Assessment—Debris Cleanup Scenario

A high-sided internal dose was estimated using weighted average soil concentrations of all radionuclides of concern, derived by weighting the individual island-average soil activity concentrations by the fractional volume of total debris removed from each of the northern debris-removal islands as was done for the external exposure rate estimate above. Suspension of contaminated soil due to debris removal and handling, e.g., removing buried debris and dragging across ground surfaces, was high sided by using a soil mass loading of 300 μg m^{-3} corresponding to agricultural tilling (Oztunali et al., 1981), with an enhancement factor of 3 (Shinn et al., 1994). No respirator other than a dust mask was assumed (protection factor = 1). A fraction of time of exposure of 0.25 was assumed for the fraction of time the veteran was exposed to the airborne source, based on the assumption that soil was suspended by dragging or digging up debris for 25 percent of each workday. The remainder of each workday is assumed to have been spent loading debris onto trucks or other activities that did not generate airborne soil. The parameters discussed above are listed in Table 52. These assumptions resulted in a maximum internal organ dose of 0.122 rem to bone surface due to inhalation of suspended soil during debris collection and handling. The internal dose to bone surface from inhalation of suspended soil and incidental ingestion of soil and dust while residing on Lojwa is 0.008 rem, and thus the total internal dose for bone surface for this example scenario is 0.130 rem. The upper bound internal dose to bone surface is 1.3 rem. The upper bound internal dose to all other organs is less than 0.3 rem. The internal effective dose due to intakes from inhalation during debris-handling work and inhalation and incidental ingestion on Lojwa is 0.004 rem, and the upper-bound total internal effective dose is 0.039 rem for this example scenario.

8.3 Example Scenario #3: Navy Boat Transportation Team

As compared to the other example scenarios that use default assumptions, this scenario is a much closer representation of the actual scenario for an ECUP participant. It involves a hypothetical Navy veteran serving at Enewetak during the period May–November, 1978, as a crewmember of one of the boats of the Boat Transportation Team. It is assumed that the veteran was assigned to one of the landing craft utility (LCU) boats that was modified to transport bulk soil to Runit. The LCU was this individual’s assigned duty station. The residence location in this scenario is assumed the forward camp on Lojwa.

Based on available records, it is assumed that during May and June, 1978, the LCU and its assigned crew were used for general inter-island transport of passengers, Army vehicles and troops, supplies, and equipment between Enewetak, other southern islands, Runit and Lojwa. Starting on July 10, the LCU was used for transporting bulk-contaminated soil to Runit. During the period from July 10 until the end of this example scenario on November 19, 1978, the boat hauled bulk soil primarily from Enjebi to Runit.

There are personal monitoring data used for this example, therefore the dose assessment is more detailed than that for other example scenarios. Descriptions of the external and internal dose estimates are provided in the following subsections.

Table 52. Exposure parameter values and assumptions for estimating internal dose in the debris-handling example scenario

Parameter	Value		Rationale/Reference/Comment
Mass loading factor for debris handling	300 μg m^{-3}		This value corresponds to agricultural tilling (Oztunali et al., 1981); see Appendix E
Enhancement factor	3		See Appendix E
Resuspension factor on Lojwa	2×10^{-8} m^{-1}		Default value
Lojwa soil density	1.5 g cm^{-3}		Default value
Depth of soil available for suspension	1 cm		Default value
Breathing rate	1.2 m^{3} h^{-1}		(DTRA, 2017, SM ID01)
Respiratory protection factor	1.0		No respiratory protection is assumed
Fraction of time exposed to source	0.25		Analyst judgment
Soil concentrations in undisturbed soil on northern islands	Radionuclide	Activity Concentration	Debris was removed from 21 northern islands (DNA, 1981); these soil concentrations are weighted averages for the 21 islands.
	Sr-90	39.4 pCi g^{-1}	
	Cs-137	13.9 pCi g^{-1}	
	Pu-239	12.8 pCi g^{-1}	
	Am-241	3.28 pCi g^{-1}	
	Co-60	1.70 pCi g^{-1}	
Soil concentrations in undisturbed soil on Lojwa	Radionuclide	Activity Concentration	Table 6
	Sr-90	8.20 pCi g^{-1}	
	Cs-137	2.60 pCi g^{-1}	
	Pu-239	1.80 pCi g^{-1}	
	Am-241	1.20 pCi g^{-1}	
	Co-60	0.31 pCi g^{-1}	

8.3.1. External Dose Assessment—Boat Transportation Team

It is assumed that individual dosimetry is available for this dose assessment from a DD Form 1141, DA Form 3484, and records in the ADC database. It is assumed that for the 6-month period from May 22 to November 19, 1978, the dosimetry record consisted of three administrative doses of 0 rem each, and three film badge doses of 0.0, 0.001, and 0.005 rem as shown in Table 53.

Using the external dose methodology guidance outlined in Section 6.1 and DTRA (2019), the administrative doses and the three sub-MDL film badge readings are replaced with reconstructed doses as described below. Major assumptions are listed in Table 54, and additional details are provided below.

Table 53. Dosimetry record for the Navy Boat Transportation example scenario

Period of Exposure (1978)		Type of Record	Dose (rem)	Comment
From	To			
May 22	June 18	Film Badge	0.005	Dose is less than MDL. No work with contaminated soil during the period.
June 18	July 15	Administrative Dose	0.000	Bulk soil haul starting July 10
July16	August 20	Film Badge	0.000	Dose is less than MDL. Bulk soil haul during period
August 21	September 18	Film Badge	0.001	Dose is less than MDL. Bulk soil haul during period
September 18	October 15	Administrative Dose	0.000	Bulk soil haul during period
October 15	November 19	Administrative Dose	0.000	Bulk soil haul during period

Based on available records, the LCU crewmembers did not enter any controlled access areas prior to July 10, 1978. Starting on July 10, the LCU was used for transporting bulk-contaminated soil from Enjebi and Aomon to Runit. Bulk soil on the LCU during transport was the only source of external exposure to crewmembers during the workday.

An LCU transporting contaminated soil was a Controlled Access area. FRST Operational Reports and Controlled Access log sheets that detailed the activities of the LCU were available for review. Based on these records, it is determined that the example LCU transported bulk soil to Runit on 79 days over the period July 10–November 19, 1978, with an average transit time of 1.74 h. The log sheets showed that on some of these days, two trips were accomplished. Given this operational scenario, an estimated external dose of approximately 0.003 rem is obtained, based on a total of approximately 213 hours of over-water transport during the period.

To estimate the hypothetical external dose from residing on Lojwa, the island-average external exposure rate of 5 $\mu R\ h^{-1}$ was used, in addition to the outdoor and indoor times, and other applicable parameter values in Table 54. As a result, an external dose of 0.008 rem is estimated for exposure to Lojwa soil. The total reconstructed external dose for this scenario for time on the LCU and on Lojwa is 0.011 rem. Using an upper-bound uncertainty factor of 3 and the method described in Appendix C results in an upper-bound external dose of 0.028 rem.

Table 54. Key external exposure parameter values and assumptions for the Boat Transportation Team example scenario

Parameter	Value	Rationale/Reference/Comment
Exposure rate from undisturbed soil on Lojwa	5 μR h^{-1}	Table 4
Exposure rate on LCU from bulk soil excised from Enjebi	13 μR h^{-1}	Estimated using exposure rate of 40 μR h^{-1} for undisturbed Enjebi soil, and average distance of 3 m from bulk soil
Work schedule	10 h d^{-1} 6 d wk^{-1} (for 26 wk)	(DNA, 1981)
Average transit time from Enjebi to Runit	1.74 h $trip^{-1}$	Based on review of applicable FRST Operational Reports
Weekly average frequency of trips transporting bulk soil	6.5 trips wk^{-1} (for 19 wk)	Based on review of applicable FRST Operational Reports
Fraction of time exposed to source	1.0	Veteran is exposed to bulk soil on LCU during all transit time between Enjebi and Runit
Time spent outdoors on Lojwa	5 h d^{-1} for 6 d wk^{-1} 15 h d^{-1} for 1 d wk^{-1}	Default schedule
Time spent in a tent on Lojwa	9 h d^{-1} for 7 d wk^{-1}	Default schedule is 8 h d^{-1} of sleeping and 1 h d^{-1} for meals indoors every day
Protection factor for a tent	1.5	High-sided assumption that resulted in a higher dose than assuming a metal building (DTRA, 2017, SM ED02)
Film badge conversion factor	1.0 (facing bulk soil on LCU) 0.7 (standing upright on the ground on Lojwa)	(DTRA, 2017, SM ED02)

8.3.2. Internal Dose Assessment—Boat Transportation Team

The veteran may have been exposed to airborne TRU and other radionuclides during soil loading and unloading operations on his LCU. Because the soil was wetted down and/or covered with a tarp during actual transit operations (FRST Operational Reports; EAI No. 5708.1), inhalation of suspended soil was possible only during the periods of soil loading and unloading. Based on a review of applicable Controlled Access log sheets and FRST Operational Reports for the LCU, the time for loading and unloading soil totaled approximately 210 h over the 79 days of bulk soil haul by the LCU. The FRST Operational Reports confirm that Level IIIA respiratory protection was used by the LCU crewmembers during loading and unloading operations. Based on measured air concentrations from air samplers on the LCU as documented in SITREPs, and the other parameter values and assumptions shown in Table 55, the maximum internal organ dose from inhalation of suspended soil during soil loading and unloading operations is 0.001 rem for bone surface.

A dose from inhalation of suspended soil on Lojwa was also estimated for 182 days of residence on the island for this scenario. Based on conservative assumptions shown in Table 55, the calculated effective dose from inhalation is less than 0.001 rem, and the highest estimated organ dose from inhalation is 0.007 rem for bone surface. The next highest estimated organ dose is 0.001 rem for liver.

An internal dose from incidental ingestion of soil and dust on Lojwa was also estimated for the entire duration of the example scenario. Based on the parameter values and assumptions in Table 55, the effective dose and all organ doses from this exposure pathway are less than 0.01 rem.

The total internal organ doses for this scenario range from less than 0.001 rem for most organs, up to 0.010 rem for bone surface. The next highest estimated total organ dose is 0.02 rem for liver. The total effective dose for this scenario is less than 0.001 rem. Applying an uncertainty factor of 10 to the total internal doses results in upper-bound internal organ doses ranging from less than 0.001 rem for many organs, up to 0.10 rem for bone surface, and an upper-bound effective dose of 0.003 rem.

8.4 Example Scenario #4: Air Force Duty on Enewetak in 1965

This example scenario addresses Air Force personnel that were assigned Temporary Duty at Enewetak in 1965. Although these individuals are not ECUP participants, this example demonstrates that some of the data collected in the 1972 survey and used for assessment of ECUP dose estimates can also be used to assess potential doses to the personnel working at the atoll in the period after nuclear testing had ended and before the start of ECUP (1963–1977).

During this period, the majority of U.S. military activities at the atoll were limited to the main atoll airfield and a Long-Range Navigation (LORAN) station, both located on Enewetak Island. In addition, personnel on transient ships and transport aircraft spent short periods of time at the atoll during ECUP to deliver supplies and equipment, perform maintenance and repairs, pick up retrograde cargo, etc. This example scenario involves aircraft maintenance personnel assigned short-term assignments at Enewetak Island in 1965 to support Air Force aircraft operations. These individuals included, for example, aircraft maintenance technicians and aircraft mechanics. These job assignments were limited to work conducted on Enewetak Island, and did not require access or travel to any other islands in the atoll.

Table 55. Key internal exposure parameter values and assumptions for the Boat Transportation Team example scenario

Parameter	Value	Rationale/Reference/Comment
Breathing rate	1.2 m^3 h^{-1}	(DTRA 2017, SM ID01)
Average air concentration of Pu-239/240 on LCU during loading and unloading	0.001–0.065 pCi m^{-3} Wtd ave. = 0.032 pCi m^{-3}	Based on the detection of alpha radiation on 53 out of a total of 252 filters during the bulk-hauling period. The averages are based on the maximum measured air concentration measured each week, averaged over each weekly period (SITREPs).
Average time of LCU loading and unloading operations	1.7 h $trip^{-1}$	Based on review of FRST Operational Reports for LCU during bulk soil hauling
Weekly average frequency of trips transporting bulk soil	6.5 trips wk^{-1} (for 19 wk)	Based on review of applicable FRST Operational Reports
Respiratory Protection factor on LCU during loading and unloading	50	Use of Level IIIA PPE (full-face or half-face positive pressure respirator) during soil loading/unloading operations (EAI 5708.1; FCRR SOP 608.05; FRST Operational Reports; and Controlled Access logs). A value of 50 is conservatively assumed.
Fraction of time exposed to source	1.0	Veteran is exposed to suspended soil on LCU during all loading and unloading time
Airborne mass loading of Lojwa soil	100 μg m^{-3}	See Section 7 and Appendix E
Enhancement factor	3	See Appendix E
Incidental soil and dust ingestion rate	0.05 g d^{-1}	Central tendency value for adults in rural setting (USEPA, 2017a)
Number of days of participation	182 d (26 wk)	Based on assumed arrival and departure dates
Dose coefficients	Radionuclide-, organ-, and pathway-specific	Worker dose coefficients for inhalation and ingestion from ICRP (2011); see Appendix C
Soil concentrations in undisturbed soil on Lojwa	Radionuclide — Activity Concentration Sr-90 — 8.2 pCi g^{-1} Cs-137 — 2.6 pCi g^{-1} Pu-239 — 1.8 pCi g^{-1} Am-241 — 1.2 pCi g^{-1} Co-60 — 0.31pCi g^{-1}	Table 6

Very low levels of contaminants were detected in the soil at Enewetak Island in 1972. There was no radiologically contaminated debris, and there was no detectable airborne radioactive material (DNA, 1981; DOE, 1982b). In order to estimate potential exposures in 1965, this assessment uses the 1972 soil survey results, adjusted for radioactive decay during the time between the survey and the exposure scenario, which provide the basis for external and internal doses for personnel temporarily at the island in 1965. The potential exposure pathways are direct external exposure to contaminants in the soil, inhalation of airborne radionuclides in suspended soil, and incidental ingestion of soil and dust. External and internal exposures to lagoon and ocean water and sediments have been shown to be insignificant in Sections 6 and 7, and any small doses would be subsumed within applied upper-bound dose uncertainty factors.

8.4.1. External Dose Assessment for Air Force Personnel in 1965

The main potential external exposure pathway for this scenario is direct external exposure to gamma-emitting radionuclides in the soil. The 1972 island-average external exposure rate on Enewetak Island was primarily due to two radionuclides: 0.14 $\mu R\ h^{-1}$ from Cs-137 and 0.12 $\mu R\ h^{-1}$ from Co-60 (AEC, 1973a). The 1965 external exposure rate would have been higher than in 1972 because 1965 is closer to the times of testing and deposition of atmospheric testing fallout. This means there was less time for infiltration of fallout into soil and runoff into the lagoon or ocean (i.e., environmental weathering), and less time for radioactive decay of shorter-lived fission products, and consequently higher soil activity concentrations.

The effects of incorporating environmental weathering into the calculated 1965 exposure rates are estimated to result in soil exposure rates that are approximately 5 percent higher than exposure rates that do not include weathering effects (Till and Meyer, 1983). Although this minimal impact environmental weathering is not included for this 1965 example, the small increase in estimated dose is accounted for by the use of the upper-bound uncertainty factor (see below).

As discussed in Section 3.1, fission products such as Sb-125 and Eu-155 are not included in ECUP radiological dose assessments for the southern islands of Enewetak Atoll because of their minimal contributions to total doses. However, the fractional contributions of Sb-125 and Eu-155 to the total soil exposure rate would have been higher in 1965 than in 1972 due to their relatively short half-lives, and thus they are included in this example. Measurements of 1972 survey soil exposure rates for Sb-125 and Eu-155 were not located. The contributions of these radionuclides to the 1972 exposure rate on Enewetak Island were estimated by first determining approximate soil concentrations using ratios to the Cs-137 soil concentration (AEC, 1973a). Exposure rates from these soil concentrations were then estimated using dose coefficients for soil contaminated to a depth of 15 cm (USEPA, 1993). Using these calculated values and the exposure rates for Cs-137 and Co-60 above, the calculated 1972 exposure rate on Enewetak Island is 0.27 $\mu R\ h^{-1}$. Using the individual radionuclide exposure rates and radioactive decay constants shown in Table 56, an estimated total 1965 exposure rate on Enewetak Island was calculated using radioactive decay principles as shown in Equation 8-1.

$$E_{65Tot} = \sum_{i=1}^{4} E_{72,i} \times e^{\lambda_i t} \qquad (8\text{-}1)$$

where

E_{65Tot}	=	Total 1965 island-average exposure rate on Enewetak Island (μR h^{-1})
$E_{72,i}$	=	1972 island-average exposure rate on Enewetak Island of radionuclide *i* (μR h^{-1})
λ_i	=	Radioactive decay constant for radionuclide *i* (y^{-1})
t	=	Time from the 1965 veteran arrival date to 1972 survey date (y)

Table 56. External dose parameter values and assumptions for the 1965 example scenario

<table>
<tr><th>Parameter</th><th colspan="2">Value</th><th>Rationale/Reference/Comment</th></tr>
<tr><td rowspan="8">Radioactive decay constants</td><td>Radionuclide</td><td>Decay Constant (y^{-1})</td><td rowspan="8">Decay constants were calculated as ln(2) / half life

Half-lives obtained from NNDC (2019)</td></tr>
<tr><td>Sr-90</td><td>0.0240</td></tr>
<tr><td>Cs-137</td><td>0.0230</td></tr>
<tr><td>Pu-239</td><td>0.000029</td></tr>
<tr><td>Am-241</td><td>0.00160</td></tr>
<tr><td>Co-60</td><td>0.132</td></tr>
<tr><td>Sb-125</td><td>0.251</td></tr>
<tr><td>Eu-155</td><td>0.146</td></tr>
<tr><td>Average exposure rates on Enewetak Island</td><td colspan="2">Nov 8, 1972: 0.27 μR h^{-1}
Jul 1, 1965: 0.53 μR h^{-1}</td><td>The 1965 exposure rate was calculated from the 1972 rate as described in the text.</td></tr>
<tr><td>Duration of temporary duty on Enewetak Island</td><td colspan="2">6 months</td><td>This is a high-sided assumption because duty assignments were likely 3–6 months.</td></tr>
<tr><td>Length of workday</td><td colspan="2">10 h d^{-1}</td><td>There are 6 workdays each week.</td></tr>
<tr><td>Average daily time spent outdoors on Enewetak Island
Outdoor worker
Indoor worker</td><td colspan="2">

15 h d^{-1}
6.4 h d^{-1}</td><td>All non-work time other than sleeping and eating is assumed outdoors.</td></tr>
<tr><td>Daily time spent in a tent on Enewetak Island (sleeping and eating)</td><td colspan="2">9 h d^{-1}</td><td>Default schedule is 8 h d^{-1} of sleeping and 1 h d^{-1} eating indoors every day.</td></tr>
<tr><td>Protection factor for a tent</td><td colspan="2">1.5</td><td>(DTRA, 2017, SM ED02)</td></tr>
<tr><td>Film badge conversion factor</td><td colspan="2">0.7 (standing upright on ground)</td><td>(DTRA, 2017, SM ED02)</td></tr>
</table>

Using Equation 8-1 and the four radionuclides discussed above, the total 1965 island-average exposure rate on Enewetak Island is calculated to be 0.53 μR h^{-1}, based on a radiological survey date of November 8, 1972 (AEC, 1973a) and a veteran arrival date of July 1, 1965 (t =

7.4 y). This arrival date was chosen because it is the mid-point of 1965. The calculated 1965 exposure rate is approximately 10 percent higher than what would be calculated without Sb-125 and Eu-155. Using the methods described in Appendix C with this exposure rate and the other parameter values in Table 56 results in an external dose of approximately 0.0015 rem for this scenario. Applying an uncertainty factor of 3 (Section 6.4) results in an upper-bound external dose of 0.005 rem.

8.4.2. Internal Dose Assessment for Air Force Personnel in 1965

The only potential internal exposure pathways for this scenario are inhalation of airborne radionuclides in suspended soil, and incidental ingestion of soil and dust. Mean soil concentrations of Sr-90, Cs-137, Pu-239/240, Am-241, and Co-60 in 1972 are shown in Table 6. The 1972 soil activity concentrations of Sb-125 and Eu-155 have been estimated, based on median activity ratios to the Cs-137 soil concentration on the northern islands (AEC, 1973a). The resulting soil activity concentrations on Enewetak Island are 0.018 pCi g^{-1} and 0.050 pCi g^{-1} for Sb-125 and Eu-155, respectively. Similar to the adjustment to external exposure rate above, the soil activity concentrations for 1965 were estimated from the 1972 soil concentrations using radioactive decay principles as shown in Equation 8-2.

$$C_{6S_i} = C_{72_i} \times e^{l_i t} \qquad (8\text{-}2)$$

where

C_{6S_i}	=	1965 island-average soil activity concentration of radionuclide *i* on Enewetak Island (pCi g^{-1})
C_{72_i}	=	1972 island-average soil activity concentration of radionuclide *i* on Enewetak Island (pCi g^{-1})
$_i$	=	Radioactive decay constant for radionuclide *i* (y^{-1})
t	=	Time from the 1965 veteran arrival date to 1972 survey date (y)

Using the above equation for each radionuclide, the calculated 1965 island-average soil activity concentrations on Enewetak Island were estimated and are shown in Table 57. Other parameter values and assumptions for the 1965 example scenario are also shown in Table 57. The resuspension factor used is the geometric mean of the calculated downwind values shown in Appendix E, and is equivalent to a mass loading value of 100 µg m^{-3}.

Using the methods described in Appendix C and the values in Table 57, inhalation and incidental ingestion doses were calculated resulting in a total committed effective dose of less than 0.001 rem for this scenario. A maximum internal organ dose of approximately 0.0008 rem was calculated for bone surface. Applying an uncertainty factor of 10 to the total internal doses (Section 7.6) results in a maximum internal upper-bound organ dose of 0.008 rem for bone surface and an upper-bound committed effective dose of less than 0.001 rem. Upper-bound internal doses for other organs ranged from much less than 0.001 rem calculated for several organs to 0.002 rem for liver.

Table 57. Internal dose parameter values and assumptions for the 1965 example scenario

<table>
<tr><th>Parameter</th><th colspan="2">Value</th><th>Rationale/Reference/Comment</th></tr>
<tr><td>Duration of temporary duty on Enewetak Island</td><td colspan="2">6 months</td><td>This is a high-sided default assumption because duty assignments were likely 3–6 months.</td></tr>
<tr><td>Breathing rate</td><td colspan="2">$1.2\ m^3\ h^{-1}$</td><td>Default value (DTRA, 2017, SM ID01)</td></tr>
<tr><td>Resuspension factor</td><td colspan="2">$2 \times 10^{-8}\ m^{-1}$</td><td>All suspended particles are assumed to be respirable. See text and Appendix E for discussion.</td></tr>
<tr><td>Depth of soil available for suspension</td><td colspan="2">1 cm</td><td>(DTRA, 2017, SM ID01; AEC, 1973a)</td></tr>
<tr><td>Soil density</td><td colspan="2">$1.5\ g\ cm^{-3}$</td><td>(AEC, 1973a; DOE, 1982a)</td></tr>
<tr><td>Respiratory protection factor</td><td colspan="2">1.0</td><td>No respiratory protection was used.</td></tr>
<tr><td>Incidental soil and dust ingestion rate</td><td colspan="2">$0.050\ g\ d^{-1}$</td><td>Central tendency value for adults in rural setting (USEPA, 2017a)</td></tr>
<tr><td>Average daily time spent outdoors on Enewetak Island
Outdoor worker
Indoor worker</td><td colspan="2">

$15\ h\ d^{-1}$
$6.4\ h\ d^{-1}$</td><td>All non-work time other than sleeping ($8\ h\ d^{-1}$) and eating ($1\ h\ d^{-1}$) is spent outdoors.</td></tr>
<tr><td>Fraction of outdoor time exposed to source</td><td colspan="2">1.0</td><td>Fraction of a workday that an individual is exposed to the source</td></tr>
<tr><td>Dose coefficients</td><td colspan="2">Radionuclide-, organ-, and pathway-specific</td><td>Inhalation and ingestion worker dose coefficients from ICRP (2011); see Appendix C</td></tr>
<tr><td rowspan="2">1965 soil activity concentrations on Enewetak Island</td><td>Radionuclide</td><td>Activity Concentration ($pCi\ g^{-1}$)</td><td rowspan="2">Calculated values for Enewetak Island are based on 1972 mean values in Table 6, except for Sb-125 and Eu-155, which are calculated as described in the text (Section 8.4.2).</td></tr>
<tr><td>Sr-90
Cs-137
Pu-239/240
Am-241
Co-60
Sb-125
Eu-155</td><td>0.73
0.30
0.08
0.05
0.11
0.11
0.15</td></tr>
</table>

8.5 Example Calculation for Skin Dose from Dermal Contamination and External Exposure

This example involves a worker who is assumed to have spent seven weeks working eight hours per day on Kirunu (Clara). The dose assessment is for a skin cancer behind the left ear of the veteran. The example calculation presented below is based on the method described in Section 6.3.1.

To estimate a high-sided skin dose from dermal contamination for this scenario, it is assumed that the total amount of radioactive material accumulated over 8 hours was deposited and distributed uniformly in its entirety at the beginning of the workday and remained constant until completely removed by showering four hours after the workday ended. This results in a fixed skin dose rate for 12 hours over which the radiation dose is calculated. Parameter values used for the dose assessment are shown in Table 58.

Table 58. Parameter values used for the example skin dose calculation

Parameter	Value	Rationale/Reference/Comment
Duration of assignment	49 d	Assumed for this example
Duration of workday	8 h	Default value for time on work island (Table 32)
Work schedule	6 d wk^{-1}	(DNA, 1981)
Duration of exposure to dermal contamination	12 h	Default value (Table 32)
Activity concentrations of undisturbed soil	Radionuclide-specific	Table 6
Soil density	1.5 g cm^{-3}	Default value (Table 32)
Depth of soil available for suspension	1 cm	Default value (Table 32)
Resuspension factor	2×10^{-8} m^{-1}	Default value (Appendix E)
Deposition velocity	3600 m h^{-1}	Default value (Table 32)
Interception and retention fraction	1.5	Table 36
Fraction of workday exposed to suspended soil	1	Default value
Skin depth modification factor (SDMF) for beta-emitters	1.3	Table 34 (SDMF for face and neck)
Dose coefficients for dermal contamination	Radionuclide-specific	Table 33 and Table 35
Beta-gamma dose ratio	0.18	Appendix L
Other modifying factors	1.0	No modifying factors

To calculate the dermal contamination dose to the skin behind the ear, the soil loading of the skin and dermal activity concentrations are first determined using Equations C-14a and C-14b in Appendix C. Using the values specified above, the calculated soil loading is

1.3 mg cm^{-2} at the end of an 8-hr workday. The calculated dermal activity concentrations are shown in Table 59. The values in Table 59 are the areal concentrations of dermal contamination that would be accumulated over an eight-hour workday with no accounting for removal.

The high-sided daily dose for a 12-hour exposure from the dermal contamination from each radionuclide listed in Table 59 is shown in Table 60 (See Equation C-15 in Appendix C). Note that a SDMF of 1.3 was applied to the beta dose coefficients (see Table 58), and the alpha dose coefficients for the face were assumed to apply to the ear. Other modifying factors were assumed equal to 1.0.

Table 59. Example dermal activity concentrations at Kirunu (Clara) for skin dose calculations

Radionuclide	Dermal Concentration (pCi cm^{-2})
Co-60	8.29×10^{-3}
Sr-90	1.29×10^{-1}
Cs-137	4.59×10^{-2}
Pu-239/240	4.10×10^{-2}
Am-241	2.73×10^{-2}

Table 60. Example skin doses for one 12-hour exposure

Radionuclide	Skin Dose (rem)
Co-60	4.96×10^{-7}
Sr-90	2.41×10^{-5}
Cs-137	4.07×10^{-6}
Pu-239/240	3.15×10^{-3}
Am-241	2.43×10^{-3}

The total, high-sided skin dose from dermal contamination for one day of work, 12-hour exposure is 0.006 rem to the skin site behind the ear. Alpha emitters contribute the majority of this dose, and the doses from the beta emitters are insignificant. This worker spent seven weeks, six days per week, working under these conditions, and the total skin dose from dermal contamination accumulated on Kirunu for a skin site behind the ear is 0.235 rem.

For estimating the skin dose from non-contact sources, the mean external gamma exposure rate on Kirunu was 42 μR h^{-1} at 1 meter above the ground. Note that the exposure time is eight hours because it is assumed that the external exposure stopped at the end of the workday.

The total skin dose from external non-contact sources of radiation on Kirunu is estimated from Equation C-16 in Appendix C as 0.012 rem.

The radiation doses to the skin calculated above for working for seven weeks on Kirunu are high-sided estimates, which means that they are biased high but are not upper-bound radiation doses. To ensure that these calculated doses are likely to exceed the 95th percentile, uncertainty factors (UF) are applied as discussed in Section 6.3.3. For the skin dose from dermal contamination, a UF of 10 is recommended, and the resulting upper-bound dermal contamination dose is 2.35 rem. For the non-contact skin dose, a UF of three is recommended, and the calculated upper-bound dose is 0.035 rem. The total estimated skin dose is 0.247 rem, and the total upper-bound skin dose for this example is the sum of the upper-bound doses from each exposure pathway, rounded to 2.4 rem.

For an actual veteran dose assessment, an additional skin dose would be calculated and included for the veteran's time spent on his residence island, presumably Lojwa. Because of the much lower soil activity concentrations and the external exposure rate on Lojwa as compared to Kirunu, the dose for his time on Lojwa would not add significantly to the total skin dose estimated above for Kirunu.

Section 9.

Guidelines for Individualized Radiation Dose Assessments

This section includes guidelines that should be used to create detailed procedures for performing individualized radiation dose assessment for ECUP veterans. Such procedures should be consistent with standard operating procedures and methods employed in other DoD radiation dose assessment programs such as DTRA's NTPR Program for non-presumptive cancers.[13]

Veterans of the military services who participated in ECUP during the period 1977–1980 constitute the target population for this technical basis document report. The various groups of the POI are described in Section 2.5. During project planning and implementation, individuals may have performed a multitude of activities while assigned duty at Enewetak Atoll. The potential sources of radiation and exposure pathways, described in Section 5, should constitute the basis for estimating doses to individuals who participated in identified project activities. In addition, for individualized dose assessments, it is important to collect veteran-specific information and data that can be used to adjust or complement the scenarios of exposures and assumptions identified in this report. Additional doses should be calculated for pathways that were not identified in this report, where needed.

9.1 Collection of Veteran-Specific Information

To perform an individualized dose assessment, it is necessary to determine the veteran's participation in various project activities at various locations on the Enewetak Atoll. An ECUP-specific questionnaire should be used to collect veteran-provided input about his or her activities and scenarios of radiation exposure. A draft of the recommended questionnaire is included as Appendix I.

Furthermore, all information related to the veteran that is available in the DTRA ECUP document collections and historical records should be obtained and added to the dose assessment case file as it is done in other DoD veteran radiation dose assessment programs. The veteran's personnel and medical records from the National Personnel Records Center, St Louis, MO, should be obtained, reviewed, and added to the assessment file if not already included. In addition, the questionnaire should provide many opportunities for the veteran to add comments within the questionnaire or in enclosures and attachments. The veteran should also be invited to submit any documentation in his or her possession that contains information about their time at Enewetak Atoll during the ECUP period.

9.2 Individualized Dose Assessment for ECUP Veterans

Based on the veteran's recollections and statements, and an analysis of relevant data and historical records, the veteran's activities during ECUP and all possible sources of exposure to radiation and pathways should be identified. In as much as possible, the evaluation of exposure to radiation should be related to the pathways identified in this report. For each pathway

[13] Since the publication of the original version of this technical report, a standard operating procedure for ECUP participant dose assessments was developed and published by DTRA (DTRA, 2019). This section of this report describing the guidelines for SOP development is maintained in this revision for completeness.

associated with documented or claimed activities, the supporting data presented in Section 4, Section 6 and Section 7 of this report should be used to estimate all relevant external, internal, and skin doses. In addition, information given by a claimant, whether in the questionnaire or in separate communications, should be taken into account to assume benefit of the doubt to the veteran and to assure consistency with VA (2017) requirements.

Members of ECUP teams who were assigned to radiologically controlled areas were monitored for radiation exposure using film badges, pocket dosimeters, TLDs, bioassays, and possibly other radiation measuring devices. Therefore, as specified in Section 6, doses for some of the exposure pathways would be based on an individual's dosimetry records. Doses for periods not reflected in the individual's dosimetry records would be estimated using the dose assessment methods described in this report.

Exposure pathways other than those identified in this report might need to be added for some ECUP participants. If such additional sources of exposure and relevant pathways are identified, the corresponding doses should be calculated using standard dose reconstruction techniques such as those used in the NTPR Program (DTRA, 2017) or equivalent approved standard procedures and methods. The doses from the additional exposure pathways should then be incorporated in the calculation of the upper-bound total external and total internal doses using the methods described in Appendix C.

Section 10.

Summary and Conclusions

This technical report has been prepared to assemble and characterize information on prevailing radiological conditions of the Enewetak Atoll in the late 1970s that is most relevant and useful in conducting radiation dose assessments for veterans who participated in the ECUP. It also lays out most pertinent dose estimation techniques that are based on accepted methods and procedures, which can be used to perform such assessments.

Beginning in late 2016, DTRA directed a team of historians, health physicists, scientists, and other support personnel to develop a technical basis document to support radiation dose assessments and VA claim processing for ECUP veterans. The team reviewed a large collection of documents and records pertaining to ECUP covering periods from the early 1970s to early 1980s. The goal was to evaluate and compile information relevant to the potential exposure to radiation of DoD personnel who participated in the cleanup project during 1977–1980. The majority of the historical records were maintained in a storage facility at DTRIAC in Albuquerque, New Mexico. Over 150 boxes of documentation were moved from storage at DTRIAC to Northern Virginia where the contents were digitized by DTRA. This ECUP document collection can be accessed and electronically searched to retrieve information about ECUP operations, reports, memos, letters, monitoring data, etc., to respond to requests for information from a variety of public and private sources. In addition, this digital repository can be used to retrieve veteran-specific information to support DTRA radiation dose assessments for VA claim processing.

Planning for the cleanup of Enewetak Atoll began in the early 1970s when the U.S. government decided to return the atoll to the Trust Territory of the Pacific Islands. In order for the Enewetak people to safely return to and live at Enewetak Atoll, it was necessary to characterize and clean up residual radiation from the atmospheric nuclear testing that was conducted during the 1940s and 1950s in the Pacific Proving Grounds. The majority of the islands contaminated with radioactive material remaining from the testing era were in the northern part of the atoll as can be seen in the radiological survey results reported in Section 4**.** The southern islands contained non-contaminated debris and abandoned facilities, and radiation levels on these islands were generally below detection limits. To ensure worker safety, extensive radiation protection and control measures were instituted and access to contaminated islands was restricted. Access of each individual entering a contaminated area was logged on a daily basis. This was the case for small boats and other watercrafts used to transport contaminated soil and debris. Prior to entering a controlled area, individuals were provided with personal protection equipment at the level necessary for the safe conduct of all required work at each location where they worked. Individuals who worked on the contaminated islands were issued radiation dosimeters on a monthly basis.

Participants in the ECUP were potentially exposed to external radiation from the surrounding environment and to internal radiation from the intake of radioactive materials by inhalation and ingestion, or through wounds. Environmental media potentially contaminated with radioactive material that could be the source of radiation exposure included principally soil and dust, but also debris, equipment, lagoon water, sediments, food, and drinking water. To characterize the scenarios of potential exposure of ECUP personnel, specific coherent project tasks have been identified and categorized into nine major project components described in Section 5. Methods to estimate radiation doses for various exposure pathways are discussed in Section 6 and Section 7, and are mainly based on the standard methods developed by DTRA for the NTPR Program. Appendix C contains all necessary equations to estimate external, internal and skin doses, as well as upper-bound doses, for ECUP personnel.

For the external gamma exposure rates, it is concluded that the aerial measurements from the 1972 radiological surveys conducted by the AEC would tend to overestimate the conditions that prevailed during the cleanup project. These exposure rates, shown in Table 4, are recommended as default values to be used to estimate high-sided external whole-body gamma doses. Furthermore, personal dosimetry records were evaluated and are discussed in Section 4. It is reported that of the 12,248 film badge records, about 99.9 percent of doses are lower than the MDL of 20 mrem. Based on an assessment of uncertainties in film badge results, doses lower than the MDL should be replaced with calculated doses based on environmental data when reconstructing external doses of ECUP participants. In addition, over 7,500 TLDs were issued and 99.7 percent of the doses are less than 0.010 rem. It is important to mention that when required, each film badge or TLD was worn for a limited period during a participant's assignment to the atoll. In most cases, an individual who was assigned to restricted access islands was issued several sequential dosimeters. Therefore, a single dosimeter result may not represent an individual's total external dose record.

As for the radionuclides of concern and resultant doses, it is estimated that over 99 percent of the internal dose from inhalation of suspended soil and dust for most internal organs would result from three main TRU radionuclides, namely Pu-239/240 and Am-241. The TRU radionuclides and other radionuclides of concern also contributed to calculated internal doses from incidental ingestion of soil and dust, although these doses were significantly lower than inhalation doses**.** With respect to the activity concentration of airborne suspended soil and dust from undisturbed ground, it is recommended to base them on island-average soil concentrations from the 1972 AEC soil sampling program, which are reported in Table 6. For exposures to contaminated soil that was excised from the islands of Boken, Enjebi, Lujor, Aomon, and Runit, then transported, mixed and contained in the Cactus Crater and dome on Runit, it is recommended that the air activity concentrations should be based on the TRU concentrations of the soil removed from each island. These concentrations are derived from the total estimated activity removed for each island as reported in DNA (1981). Using the total TRU activity in curies and the total volume of soil removed from each of the five islands, an average soil concentration for each island and overall weighted averages are estimated in Section B-2. In addition, air sampling results are available in the form of weekly statistical summaries as shown in Section B-3. Because only the weekly maximum concentrations are reported, these data can be used to estimate extremely conservative internal inhalation doses, as is the case in the example scenario assessment for boat crewmembers discussed in Section 8.

Based on the above information, the study team was able to build a collection of pertinent radiation data and combine them with reasonable assumptions and sound calculations to produce conservative and credible dose estimates. Using the data and information compiled in this report, several examples of dose estimation for ECUP exposure scenarios are presented in Section 8. They include sample assessments of hypothetical participation scenarios for personnel who were involved in soil cleanup such as earthmoving equipment operators, debris cleanup personnel such as crane operators, and crewmembers of boats that were used to transport contaminated soil. In addition, an example dose assessment for Air Force personnel that were assigned temporary duty at Enewetak in 1965 is included. The latter example is developed to serve as a basis to estimate doses in support of specific VA claims from veterans that performed duties on Enewetak in 1965.

Finally, guidelines are presented in Section 9 to support the development of a standard operating procedure to be used to perform individual radiation dose assessments for ECUP veterans in response to VA requests. For such individualized dose assessments, it is important to collect veteran-specific information and data that can be used to adjust or complement the scenarios of exposures and assumptions identified in this report. For this purpose, an ECUP-specific questionnaire, included as Appendix I was developed and is being used to collect veteran-specific information. If additional sources of exposures and pathways are identified in the questionnaire, supplemental doses should be estimated using standard dose reconstruction techniques.

Based on discussions in this report, it is confirmed that ECUP participants conducted all cleanup work within a structured and effective radiation protection program that served to minimize radiation doses as reported in DNA (1981). The highest of the estimated upper-bound total effective radiation doses for any of the included sample assessments is 0.22 rem (2.2 mSv). This dose is similar to the average individual effective dose of 0.31 rem (3.1 mSv) to the U.S. population from ubiquitous background radiation including radon (NCRP, 2009a). It is also substantially lower than the whole body occupational dose limit of 5 rem (50 mSv) per year that was in place for personnel during the ECUP. As a result of the ECUP radiation protection program, the generally low levels of contamination encountered, and as confirmed by example dose assessments, it is concluded that ECUP participants' exposures resulted in whole-body and organ doses much lower than doses that would result in observable health effects. This conclusion is supported by the Health Physics Society official position statement regarding radiation health risks:

> "Substantial and convincing scientific data show evidence of health effects following high dose exposures (many multiples of natural background). However, below levels of about 100 mSv [10 rem] above background from all sources combined, the observed radiation effects in people are not statistically different from zero." (HPS, 2019)

Section 11.

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APPENDICES

Appendix A.

Operational Milestones and Major Activities of the Enewetak Cleanup Project

A-1. Enewetak Cleanup Project Milestones

From 1972 to 1976, planning for the radiological cleanup, rehabilitation, and resettlement of Enewetak Atoll in the Marshall Islands resulted in a decision to conduct a three-year cleanup project. From early 1977 through mid-1980 the Enewetak Cleanup Project proceeded, and was executed by the DoD involving U.S. Army, U.S. Navy, and U.S. Air Force personnel. During that time, the AEC performed radiological characterization and certification, and the DOI conducted the rehabilitation and resettlement project. The following are significant planning and administrative milestones of the cleanup project (DNA, 1981):

- March 15, 1977, mobilization begins
- March 16, 1977, Air Force communications team arrive
- April 5, 1977, first Army-Navy team arrives through May 17, 1977
- April 14, 1977, first Navy sealift
- May 3–16, 1977, Transportation units arrive
- May 17, 1977, advance party arrives
- May–November 1977, Lojwa Camp construction
- June 15, 1977, D-Day
- June 1977, Joint Task Group organized
- June 28, 1977, FRST deployment
- July–November 1977, mobilization continues
- November 1977, Operation Switch I: rotation/replacement of personnel
- November 15, 1977–February 1980, cleanup implementation (See Appendix A-2 for details)
- March 26, 1979, demobilization begins
- September 3–4, 1979, sealift of retrograde cargo
- End of September, 1979, DOE-ERSP demobilization complete
- October 13–14, 1979, all Lojwa Camp personnel move to Enewetak Camp
- October 1979–January 1980, final cleanup and other actions completed
- March 1, 1980, rollup begins
- May 13, 1980, final 45 personnel depart Enewetak Atoll.

A-2. Major Enewetak Cleanup Activities

Table A-1 lists the major activities associated with the debris cleanup, entries D-1 to D-41), soil cleanup, entries S-1 to S-27), and equipment/facility decontamination, entries E-1 and E-2) in the ECUP operation. The entries in Table A-1 are generally arranged to follow a chronological order by the start date of each activity.

Table A-1. Major ECUP cleanup activities for debris, soil, and equipment/facility

Activity Index*	Cleanup Activity	Personnel	Equipment	Activity Location	Start Date†	End Date	References
D-1	FRST completed survey of contaminated debris on Runit, with assistance by WBCT	FRST members, WBCT	Survey instruments for α, β, and γ, check sources, and spray painters	Runit	March 1977	November 1977	(DNA, 1981)
D-2	Debris surveys at Enjebi	USAE or FRST members	Radiation survey instruments, check sources, and spray painters	The contaminated sites include one runway parking area and three concrete structures unusually difficult to decontaminate	First survey, July 1977; second survey, early 1978	First survey, early 1978; second survey, sometime in 1978	(DNA, 1981)
D-3	Manual removal of small debris from offshore areas	WBCT divers	No special equipment	All islands including Runit	Beginning of Cleanup Phase	September 6, 1979, when dome capping ended	(DNA, 1981)
D-4	Large debris retrieval from water -- Diver manually connected winch cable with large debris	WBCT divers	D8 bulldozers and landing crafts with winches	All islands including Runit	Beginning of Cleanup Phase	September 6, 1979, when dome capping ended	(DNA, 1981)
D-5	Large debris under water hoisted to beach stockpiles or aboard the landing crafts	Truck drivers and crane operators	Dump trucks, landing crafts, and floating platforms	All islands including Runit	Beginning of Cleanup Phase	September 6, 1979, when dome capping ended	(DNA, 1981)

Activity Index*	Cleanup Activity	Personnel	Equipment	Activity Location	Start Date†	End Date	References
D-6	Yellow debris on loading for lagoon dumping	Engineering equipment operators, crew members	Bucket loaders, 12.5 ton cranes w/clamshells, landing crafts, and floating platforms	All islands including Runit	Beginning of Cleanup Phase	September 6, 1979, when dome capping ended	(DNA, 1981)
D-7	Yellow debris transport to lagoon dump sites	Crew members	Landing crafts and floating platforms	Routing from an island including Runit to designated lagoon dump sites	Beginning of Cleanup Phase	September 6, 1979, when dome capping ended	(DNA, 1981)
D-8	Yellow debris offloading at lagoon dump sites	Engineering equipment operators, crew members	Bucket loaders, 12.5 ton cranes w/ clamshells, landing crafts, and floating platforms	Designated lagoon dump sites	Beginning of Cleanup Phase	September 6, 1979, when dome capping ended	(DNA, 1981)
D-9	Disassembling and breaking up oversized debris for collection and transport	USAE members	Engineering tools for demolitions	All islands including Runit	Beginning of Cleanup Phase	September 6, 1979, when dome capping ended	(DNA, 1981)
D-10	Survey of contaminated debris	FRST members and truck driver	Exposure rate meters, survey instruments for α, β, and γ, check sources, cameras, and spray painters	All islands including Runit	Beginning of Cleanup Phase	September 6, 1979, when dome capping ended	(DNA, 1981)
D-11	Hand tools used to clear brush from the entire Fig-Quince area	USAE members	Hand tools	Fig-Quince area at Runit	November 1, 1977, at the earliest	November 28, 1977, at the latest	(DNA, 1981)

Activity Index*	Cleanup Activity	Personnel	Equipment	Activity Location	Start Date†	End Date	References
D-12	Debris cleanup at Lujor	USAE members	Equipment not specified	Lujor	November 15, 1977	February 22, 1978	(DNA, 1981)
D-13	FRST surveyed Fig-Quince area for Pu fragments	FRST members	Portable FIDLER probes, shovels, and plastic bags	Fig-Quince area at Runit	November 28, 1977	December 23, 1977	(DNA, 1981)
D-14	General survey of contaminated debris at Aomon	USAE or FRST members, truck drivers	Radiation survey instruments, check sources, cameras, spray painters, shovels, and plastic bags	Aomon	December 8, 1977	January 16, 1978	(DNA, 1981)
D-15	Debris cleanup at Boken	USAE and FRST members	Equipment not specified	Boken	January 4, 1978	July 12, 1978	(DNA, 1981)
D-16	Demolition of "Enjebi Hilton"	USAE members	Air chisels	Enjebi Hilton on Enjebi	January 26, 1978	March 4, 1978	(DNA, 1981)
D-17	Transporting contaminated debris from Enjebi to Runit	Navy Boat Transportation Team, USAE members	Landing crafts or floating platforms	Enjebi Hilton, a large bunker, and a small concrete vault on Enjebi	January 26, 1978	May 15, 1979	(DNA, 1981)
D-18	Removal of bunker surface contamination by sandblasting at Enjebi	USAE members	Sandblasters, hammer drills, and grinders	A large bunker on the east side of Enjebi	March 1978	March 1978	(DNA, 1981)
D-19	Removal by chipping of surface beta contamination of a vault at Enjebi	USAE members	Chipping hammers and drills	A small heavily reinforced, concrete instrument vault at Enjebi	March 1978	May 15, 1979	(DNA, 1981)

Activity Index[*]	Cleanup Activity	Personnel	Equipment	Activity Location	Start Date[†]	End Date	References
D-20	Re-survey of contaminated concrete structures	FRST members and truck driver	Survey instruments for α, β, and γ, check sources, and spray painters	Enjebi, Boken, Aomon, and Bijire	March 1978	March 1978	(DNA, 1981)
D-21	Removal of concrete surface contamination by sandblasting and chipping	USAE members	Sandblasters, hammer drills, grinders, acid, and detergent washers	Enjebi, Boken, Aomon, and Bijire	March–April 1978 time frame	March–April 1978 time frame	(DNA, 1981)
D-22	Debris survey at bunkers on Boken	USAE and FRST members	Radiation survey instruments for betas, check sources, and spray painters	Boken	April 1978	June 1978	(DNA, 1981)
D-23	Debris cleanup at Eleleron	USAE members	Equipment not specified	The peninsula of Eleleron	June 1, 1978	July 10, 1978	(DNA, 1981)
D-24	Cleanup at Bijire	USAE members	Equipment not specified	A concrete photographic bunker (Greenhouse Station 100) on Bijire	June 8, 1978	July 23, 1978	(DNA, 1981)
D-25	Contaminated debris stockpiled from other islands was placed in the crater during the tremie operation.	Equipment operators, USAE members	Trucks and bulldozers	Runit	June 15, 1978	February 10, 1979	(DNA, 1981)

Activity Index*	Cleanup Activity	Personnel	Equipment	Activity Location	Start Date†	End Date	References
D-26	Disposed of contaminated "oversized material" (too large for the tremie pump) by bulldozing it off the edge of the Cactus Crater	Equipment operators, USAE members	Bulldozers and graders	Near Cactus Crater at Runit	After June 15, 1978, the beginning of the tremie operation	February 10, 1979, end of tremie operation	(DNA, 1981)
D-27	Explosive demolition for two Pu-contaminated concrete blocks at Aomon	Army EOD Specialists	Explosives	Aomon -- One block near Yuma GZ and the other near Kickapoo GZ	August 1978	October 1978	(DNA, 1981)
D-28	Cleanup of debris from two demolished Pu concrete blocks at Aomon	Equipment operators, USAE members	Trucks and bulldozers	Aomon -- One block near Yuma GZ and the other near Kickapoo GZ	August 1978	October 1978	(DNA, 1981)
D-29	FRST conducted two surveys to estimate debris volume on Runit	FRST members	Equipment not specified	Runit	September 1978	November 1978	(DNA, 1981)
D-30	Special survey for rusty-colored Pu fragments near Kickapoo GZ at Aomon	J-2, DOE, FRST members	Survey instruments for gammas from Am-241 and check sources	Aomon -- near Kickapoo GZ	October 1978	October 1978	(DNA, 1981)
D-31	Two cleanups of Pu fragments near Kickapoo GZ at Aomon	FRST and JTG J-2 members	Shovels and hand tools	Aomon -- near Kickapoo GZ	October 1978	December 1978	(DNA, 1981; FCDNA, 1979)

Activity Index*	Cleanup Activity	Personnel	Equipment	Activity Location	Start Date†	End Date	References
D-32	Cleanup of a twisted metal debris pile on the reef just north the old runway	USAE members	Equipment not specified	North of the old runway on Runit	October 1978, at the earliest	December 1978	(DNA, 1981; FCDNA, 1979)
D-33	Cleanup metal debris in the area of the Blackfoot GZ	USAE members	Equipment not specified	Blackfoot GZ on Runit	October 1978, at the earliest	December 1978	(DNA, 1981; FCDNA, 1979)
D-34	Bulldozed a large quantity of contaminated debris found unexpectedly in the crater banks into crater (in February, 1979)	Equipment operators, USAE members	Bulldozers	Banks of Cactus Crater at Runit	February 1, 1979	February 2, 1979	(DNA, 1981)
D-35	Delayed contaminated debris from Aomon crypt and Runit placed in the "Donut Hole".	Equipment operators, USAE members	Trucks and bulldozers	Runit	February 1979	Mid-July 1979	(DNA, 1981)
D-36	Survey and re-survey of contaminated debris pulled out from the ocean reef of Runit	FRST members and truck driver	Exposure rate meters, survey instruments for α, β, and γ, check sources, cameras, and spray painters.	The ocean reef of Runit near Lacrosse Crater	Around August 1979	Around August 1979	(DNA, 1981)
D-37	Containment in the cap of reclassified "yellow" to "red" debris found in the ocean reef of Runit	Equipment operators, USAE members	Trucks and bulldozers with winches	Near Lacrosse crater and Cactus Crater at Runit	August 1979	September 6, 1979, when dome capping ended	(DNA, 1981)

Activity Index*	Cleanup Activity	Personnel	Equipment	Activity Location	Start Date†	End Date	References
D-38	Survey of contaminated debris revealed following seasonal recession of beaches in September, 1979	FRST members and truck driver	Exposure-rate meters, survey instruments for α, β, and γ, check sources, cameras, and spray painters	Runit beaches	September 1979	September 1979	(DNA, 1981)
D-39	First extension container for the "red" debris revealed following seasonal recession of beaches in September, 1979	Equipment operators, USAE members	Trucks and bulldozers	The first extension added on the island side of Cactus Crater	September 19, 1979	End of September 1979	(DNA, 1981)
D-40	Survey of additional contaminated beach debris exposed in November, 1979	FRST members and truck driver	Exposure rate meters, survey instruments for α, β, and γ, check sources, cameras, and spray painters	Runit beaches	November 1979	November 1979	(DNA, 1981)
D-41	Second extension container for "red" beach debris discovered in November, 1979	Equipment operators, USAE members	Trucks and bulldozers	The second extension added on the lagoon side of Cactus Crater	Mid-February 1980	The end of February 1980	(DNA, 1981)
S-1	Erie site investigation	AARDC, USAE, and FRST members	SPA-2 micro-R meters, soil probes, drilling equipment, and backhoes	Erie GZ on Runit	June 30, 1977	July 11, 1977	(DNA, 1981)
S-2	Devegetation - extensive	Equipment operators, USAE members	Hand tools, bulldozers, chains, and trucks	Enjebi	July 1, 1977	July 31, 1977	(DOE, 1982a; DNA, 1981)

Activity Index*	Cleanup Activity	Personnel	Equipment	Activity Location	Start Date†	End Date	References
S-3	Devegetation - moderate	Equipment operators, USAE members	Hand tools, bulldozers, and trucks	Boken, Alembel	September 1977	October 1977	(DOE, 1982a; DNA, 1981)
S-4	Devegetation - extensive	Equipment operators, USAE members	Hand tools, bulldozers, and trucks	Bokombako, Lujor, Aej, Aomon, Bijire	October 1, 1977	March 15, 1978	(DOE, 1982a; DNA, 1981)
S-5	Assisting FRST digging trenches to collect subsurface soil samples	USAE members	Digging tools and equipment	Runit	November 28, 1977	December 23, 1977	(DNA, 1981)
S-6	Devegetation - extensive	Equipment operators, USAE members	Hand tools, bulldozers, and trucks	Runit	January 1978	January 1979	(DOE, 1982a; DNA, 1981)
S-7	Devegetation - moderate	Equipment operators, USAE members	Hand tools, bulldozers, and trucks	Bokoluo, Kirunu, Louj, Mijikadrek, Kidrinen, Eleleron, Elle, Bokenelab, Billae	January 1, 1978	March 1, 1978	(DOE, 1982a; DNA, 1981)
S-8	Cleanup of Co-60 contaminated soil at Medren	USAE equipment operators, JTG/J-2, and FRST members	Survey instruments, soil sampling tools, dump trucks, bucket, backhoe loaders, water tank trucks, scrape blades, and LCUs	Two contaminated areas, "Crate", and "Blue Star", which were about 150 feet apart, 300 yards south of the old runway	February 7, 1978	February 10, 1978	(DNA, 1981)

Activity Index*	Cleanup Activity	Personnel	Equipment	Activity Location	Start Date†	End Date	References
S-9	Soil excision/removal at Aomon	Equipment operators, USAE members	Survey instruments, soil sampling tools, IMPs - in situ survey van, dump trucks, bulldozers	Aomon	March 8, 1978	August 1978	(DNA, 1981)
S-10	Plowing experiment on Enjebi	USAE members	D8 bulldozers w/single-plow blades	Enjebi (Area X-1)	June 1978	June 1978	(DNA, 1981)
S-11	Tremie operation Step 1- loading contaminated soil from stockpiles to dump trucks	Equipment operators, USAE members	Loader buckets and trucks	Soil stockpiles on Runit	June 15, 1978	February 10, 1979	(DNA, 1981)
S-12	Tremie operation Step 2 - driving dump trucks from contaminated soil stockpiles to concrete batch plant	Truck drivers	Trucks	Soil stockpiles and concrete batch plant on Runit	June 15, 1978	February 10, 1979	(DNA, 1981)
S-13	Tremie operation Step 3 - contaminated soil mixed with cement at batch plant	Plant operators	Batch plant and screen plant equipment	Batch plant and screen plant on Runit	June 15, 1978	February 10, 1979	(DNA, 1981)
S-14	Tremie operation Step 4 - driving transit-mix trucks from batch plant to concrete pump next to the crater	Truck drivers	Transit-mix trucks	Batch plant and concrete pump on Runit	June 15, 1978	February 10, 1979	(DNA, 1981)

Activity Index[*]	Cleanup Activity	Personnel	Equipment	Activity Location	Start Date[†]	End Date	References
S-15	Tremie operation Step 5 - pumping contaminated slurry into pipes	USAE members	Concrete pump and tremie pipes	Concrete pump next to Cactus Crater on Runit	June 15, 1978	February 10, 1979	(DNA, 1981)
S-16	"Processed Tremie" method: pouring rejected slurry into excavated trenches and placing the hardened slurry into the crater.	Equipment operators, USAE members	Transit-mix trucks and dump trucks	Cactus Crater area at Runit	June 15, 1978	February 10, 1979	(DNA, 1981)
S-17	Soil excision/ removal at Enjebi (Surface)	USAE members	Bulldozers and trucks	Enjebi	July 6, 1978	March 23, 1979	(DNA, 1981)
S-18	Soil excision/ removal at Enjebi (Subsurface)	USAE members	Bulldozers and trucks	Enjebi	December 6, 1978	April 18, 1979	(DNA, 1981)
S-19	Soil excision/ removal at Boken (Subsurface) – 1st operation	Company B, USAE members	Bulldozers, bucket loaders, trucks, LCM-8, LARC-LX	Soil transported from Boken to Enjebi, then to Runit	Mid-January 1979	April 23, 1979	(DNA, 1981)
S-20	Devegetation – moderate on Lojwa	Equipment operators, USAE members	Hand tools, bulldozers, and trucks	Lojwa	February 1, 1979	March 1, 1979	(DOE, 1982a; DNA, 1981)
S-21	Soil-cement mixture operation	Equipment operators, USAE members	Graders, bulldozers with disc harrows and roller compactors, and sprinkler trucks	Cactus Crater on Runit	February 18, 1979	July 26, 1979	(DNA, 1981)

Activity Index*	Cleanup Activity	Personnel	Equipment	Activity Location	Start Date†	End Date	References
S-22	Soil excision/ removal at Fig-Quince on Runit - 1st phase	Equipment operators, USAE members	Bulldozers with clamshells, graders, and dump trucks	Fig-Quince area on Runit	March 13, 1979	March 24, 1979	(DNA, 1981)
S-23	Soil excision/ removal at Enjebi (Plow-X)	USAE members	Bulldozers and trucks	Enjebi	April 1, 1979	May 9, 1979	(DNA, 1981)
S-24	Soil excision and removal at Lujor	USAE, USNE, and FRST members	Bulldozers and bucket loader	Lujor (eastern half of island)	April 7, 1979	July 8, 1979	(DNA, 1981)
S-25	Soil excision/ removal at Fig-Quince on Runit - 2nd phase	Equipment operators, USAE members	Bulldozers with clamshells and graders, and dump trucks	Fig-Quince area on Runit	June 1, 1979	July 26, 1979	(DNA, 1981)
S-26	Soil excision/ removal at Boken (Subsurface) –2nd operation	Company B, USAE members	Bulldozers, bucket loaders, 5-ton dump trucks, LCM-8, LARC-LX, LCU-causeway-LARC combination	Soil transported from Boken to Runit	June 11, 1979	July 7, 1979	(DNA, 1981)
S-27	Placing 12-inch blanket of relatively clean soil (<160 pCi/g) over the Fig-Quince area	Equipment operators, USAE members	Bulldozers and graders	Runit	July 1979	August 1979	(DNA, 1981)
E-1	Laundry facility for cleaning washable personnel protective equipment	USAE members	Washers and dryers	Lojwa	Beginning of Cleanup Phase	End of ECUP	(DNA, 1981)

Activity Index*	Cleanup Activity	Personnel	Equipment	Activity Location	Start Date†	End Date	References
E-2	Decontamination of batch plant to produce clean concrete to build the keywall	Plant operators, USAE members	Batch plant equipment	Batch plant on Runit	Beginning of Cleanup Phase	End of ECUP	(DNA, 1981)

* Key: D for Debris cleanup and decontamination, S for Soil cleanup and E for Equipment/facility decontamination.

† Activities with a Start Date listed as "Beginning of Cleanup Phase" began on or shortly after the official start date of the ECUP cleanup phase of November 15, 1977 (DNA, 1981).

Appendix B.

Radiation Monitoring Data

Results and information pertinent to ECUP radiological conditions and radiation monitoring are provided in this appendix for environmental TLD results, TRU soil activity concentrations in excised soil, and an example weekly summary of air sampling and TLD data.

B-1. Environmental TLD Results

The results of measurements of environmental radiation exposure and exposure rates made during ECUP are listed in Table B-1. These results are the basis of the summary results in Table 5 of the main report.

Table B-1 was developed by manually entering information pertaining to environmental TLDs contained on hand-written data sheets found in the ECUP records to an Excel workbook collection. The environmental TLDs covered a period roughly from June 1978 to October 1979. One monthly report corresponding to an approximate period of August to September 1978 was not found among the records researched. Subsequent searches of the ECUP records collection did not find this monthly report.

The value in column Net Reading for each record was derived from the gross TLD reading, which was not reported in Table B-1. The gross reading was corrected by the application of the dosimeter calibration factor. Background was subtracted from the corrected result, which is then shown as the net reading. The gross reading is greater in value than the corresponding net reading listed in this table. One net exposure rate for Runit debris pile in the table for the period 9/25 to 10/18/78 is the highest reading observed and is about two orders of magnitude higher than most readings.

There are two sets of IRENE readings labeled IRENE (TLD Set #1) and IRENE (TLD Set #2). It appears that TLD Set #1 is from the main island, where Shot Seminole crater is located, and TLD Set #2 is from the western islet, or what remained of the island of Helen.

Table B-1. Environmental radiation exposure and exposure rates measured with TLDs on islands of Enewetak Atoll

Island	DOI*	DOR†	Days	Net Reading (mR)	Net Exposure Rate ($\mu R\ h^{-1}$)
ALICE	9/25/1978	10/30/1978	35	19	23
ALICE	10/30/1978	11/13/1978	14	8	24
ALICE	11/13/1978	12/16/1978	33	14	18
ALICE	12/16/1978	1/24/1979	39	4	4
ALICE	1/24/1979	2/12/1979	19	14	31
ALICE	2/12/1979	3/12/1979	28	14	21
ALICE	3/12/1979	4/11/1979	30	18	25
ALICE	4/11/1979	5/15/1979	34	19	23
ALICE	TLD apparently lost; a blank is shown in the TLD Report				
ALICE	6/14/1979	7/30/1979	46	17	15
ALICE	7/19/1979	8/21/1979	33	10	13
ALICE	8/21/1979	10/10/1979	50	18	15
BELLE	6/21/1978	7/22/1978	31	6‡	8‡
BELLE	7/22/1978	8/22/1978	31	6	8
BELLE	9/25/1978	10/30/1978	35	46	55
BELLE	10/30/1978	11/21/1978	14	18	54
BELLE	11/21/1978	12/16/1978	25	24	40
BELLE	12/16/1978	1/24/1979	39	7	7
BELLE	1/24/1979	2/12/1979	19	31	68
BELLE	2/12/1979	3/12/1979	28	33	49
BELLE	3/12/1979	4/11/1979	30	36	50
BELLE	4/11/1979	5/15/1979	34	41	50
BELLE	TLD apparently lost; a blank is shown in the TLD Report				
BELLE	6/14/1979	7/30/1979	46	36	33
BELLE	7/30/1979	8/21/1979	22	12	23
BELLE	8/21/1979	10/10/1979	50	22	18
MARY	10/23/1978	11/20/1978	28	4	6
MARY	11/20/1978	12/19/1978	29	2	3
MARY	12/19/1978	1/24/1979	36	2	2
MARY	1/24/1979	2/12/1979	19	2	4
MARY	2/12/1979	3/16/1979	32	4	5
MARY	3/16/1979	4/11/1979	26	5	8
MARY	4/11/1979	5/19/1979	38	5	5
MARY	5/19/1979	6/19/1979	31	4	5
MARY	No TLD data for June/July 1979				
MARY	7/17/1979	8/30/1979	44	7	7
MARY	8/30/1979	10/10/1979	42	5	5
EDNA'S Daughter	11/24/1978	12/16/1978	22	3	6

Island	DOI*	DOR†	Days	Net Reading (mR)	Net Exposure Rate (μR h^{-1})
EDNA'S Daughter	12/16/1978	1/24/1979	39	5	5
EDNA'S Daughter	1/24/1979	2/12/1979	19	5	11
EDNA'S Daughter	2/12/1979	3/12/1979	28	4	6
EDNA'S Daughter	3/12/1979	4/11/1979	30	6	8
EDNA'S Daughter	4/11/1979	5/15/1979	34	6	7
EDNA'S Daughter	5/15/1979	6/15/1979	31	8	11
EDNA'S Daughter	6/15/1979	7/30/1979	45	5	5
EDNA'S Daughter	7/30/1979	8/21/1979	22	6	11
EDNA'S Daughter	8/21/1979	10/10/1979	50	9	8
OLIVE	9/25/1978	10/28/1978	33	1	1
OLIVE	10/28/1978	11/20/1978	23	3	5
OLIVE	11/20/1978	12/21/1978	31	1	1
OLIVE	12/21/1978	1/24/1979	34	1	1
OLIVE	1/24/1979	2/12/1979	10	1	4
OLIVE	2/12/1979	3/16/1979	32	2	3
OLIVE	3/16/1979	4/11/1979	26	1	2
OLIVE	4/11/1979	5/16/1979	35	2	2
OLIVE	5/16/1979	6/19/1979	34	2	2
OLIVE	TLD missing				
OLIVE	6/19/1979	8/31/1979	73	3	2
OLIVE	8/31/1979	10/10/1979	41	3	3
PEARL	6/22/1978	7/22/1978	30	5‡	7‡
PEARL	7/22/1978	8/22/1978	31	2	3
PEARL	9/25/1978	10/28/1978	33	9	11
PEARL	10/28/1978	11/20/1978	23	0	0
PEARL	11/20/1978	12/21/1978	31	1	1
PEARL	12/21/1978	1/24/1979	39	2	2
PEARL	1/24/1979	2/12/1979	19	0	0
PEARL (Beach)	2/13/1979	3/10/1979	25	2	3
PEARL (Beach)	3/10/1979	4/17/1979	38	2	2
PEARL (Beach)	4/17/1979	5/19/1979	32	2	3
PEARL (Beach)	5/19/1979	6/18/1979	30	1	1
PEARL (Beach)	6/20/1979	7/23/1979	33	0	0
PEARL (Beach)	8/4/1979	8/31/1979	27	3	5
PEARL (Beach)	TLD lost				
MARY's Daughter	10/23/1978	11/20/1978	28	11	16
MARY's Daughter	11/20/1978	12/19/1978	29	8	11
MARY's Daughter	12/19/1978	1/24/1979	36	13	15
MARY's Daughter	1/24/1979	2/12/1979	19	8	18
MARY's Daughter	2/12/1979	3/16/1979	32	16	21

Island	DOI[*]	DOR[†]	Days	Net Reading (mR)	Net Exposure Rate ($\mu R\ h^{-1}$)
MARY's Daughter	3/16/1979	4/11/1979	26	13	21
MARY's Daughter	4/11/1979	5/16/1979	35	10	12
MARY's Daughter	5/16/1979	6/19/1979	34	12	15
MARY's Daughter	TLD missing				
MARY's Daughter	7/17/1979	8/30/1979	44	11	10
MARY's Daughter	8/30/1979	10/10/1979	42	12	12
JANET (FRST Shack)	6/21/1978	7/21/1978	30	5[‡]	7[‡]
JANET (FRST Shack)	3/16/1979	4/17/1979	32	3	4
JANET (Farm)	6/21/1978	7/21/1978	30	31[‡]	43[‡]
JANET (Farm)	7/22/1978	8/22/1978	31	26.6	36
JANET (Farm)	9/25/1978	10/23/1978	28	2	3
JANET (Farm)	10/23/1978	11/16/1978	24	5	9
JANET (Farm)	11/16/1978	12/20/1978	34	4	5
JANET (Farm)	12/20/1978	1/23/1979	34	3	4
JANET (Farm)	1/23/1979	2/13/1979	21	4	8
JANET (Farm)	2/13/1979	3/12/1979	27	5	8
JANET (Farm)	3/12/1979	4/17/1979	36	5	6
JANET (Farm)	4/17/1979	5/16/1979	29	6	9
JANET (Farm)	5/16/1979	6/18/1979	33	5	6
JANET (Farm)	6/18/1979	7/21/1979	33	5	6
JANET (Farm)	7/21/1979	8/21/1979	31	7	9
JANET (Farm)	8/31/1979	10/10/1979	41	4	4
JANET (Farm Shack)	6/21/1978	7/21/1978	30	9[‡]	13[‡]
JANET (Farm Shack)	7/22/1978	8/22/1978	31	5.6	8
JANET (Farm Shack)	No TLD data for Sept/Oct 1978				
JANET (Farm Shack)	10/23/1978	11/16/1978	24	4	7
JANET (Farm Shack)	11/16/1978	12/20/1978	34	3	4
JANET (Farm Shack)	TLD lost in storm				
JANET (Farm Shack)	1/23/1979	2/12/1979	20	2	4
JANET (Farm Shack)	2/13/1979	3/12/1979	27	5	8
JANET (Farm Shack)	3/12/1979	4/17/1979	36	6	7
JANET (Farm Shack)	4/17/1979	5/16/1979	29	6	9
JANET (Farm Shack)	5/16/1979	6/18/1979	33	5	6
JANET (North Point)	6/21/1978	7/21/1978	30	24[‡]	33[‡]
JANET (North Point)	TLD lost				
JANET (North Point)	9/25/1978	10/23/1978	28	12	18
JANET (North Point)	10/23/1978	11/16/1978	24	8	14
JANET (North Point)	11/16/1978	12/20/1978	34	13	16
JANET (North Point)	12/20/1978	1/23/1979	34	6	7
JANET (North Point)	1/23/1979	2/13/1979	21	7	14

Island	DOI*	DOR†	Days	Net Reading (mR)	Net Exposure Rate (μR h^{-1})
JANET (North Point)	2/13/1979	3/12/1979	27	6	9
JANET (North Point)	3/12/1979	4/17/1979	36	9	10
JANET (North Point)	4/17/1979	5/16/1979	29	8	11
JANET (North Point)	5/16/1979	6/18/1979	33	8	10
JANET (North Point)	TLD missing				
JANET (North Point)	7/21/1979	8/21/1979	31	6	8
JANET (North Point)	8/21/1979	10/10/1979	50	8	7
JANET (Trailer)	6/21/1978	7/21/1978	30	7‡	10‡
JANET (Trailer)	7/22/1978	8/22/1978	31	5.6	8
JANET (Trailer)	No TLD data for Sept/Oct 1978				
JANET (Trailer)	10/23/1978	11/16/1978	24	3	5
JANET (Trailer)	11/16/1978	12/20/1978	34	0	0
JANET (Trailer)	12/20/1978	1/23/1979	34	2	2
JANET (Trailer)	1/23/1979	2/13/1979	21	4	8
JANET (Trailer)	2/13/1979	3/12/1979	27	3	5
JANET (Trailer)	3/12/1979	4/17/1979	36	3	3
JANET (Trailer)	4/17/1979	5/16/1979	29	3	4
JANET (Trailer)	5/16/1979	6/18/1979	33	2	3
JANET (Trailer)	6/18/1979	7/21/1979	33	7	9
JANET (Trailer)	7/21/1979	8/21/1979	31	2	3
JANET (Trailer)	8/21/1979	10/10/1979	50	2	2
PERCY	11/20/1978	12/19/1978	29	3	4
PERCY	12/19/1978	1/24/1979	36	3	3
PERCY	1/24/1979	2/12/1979	19	3	7
PERCY	2/12/1979	3/16/1979	32	6	8
PERCY	3/16/1979	4/11/1979	26	8	13
PERCY	4/11/1979	5/16/1979	35	6	7
PERCY	5/16/1979	6/19/1979	34	6	7
PERCY	6/19/1979	7/17/1979	36	6	7
PERCY	7/17/1979	8/30/1979	44	3	3
PERCY	8/30/1979	10/10/1979	42	2	2
RUBY	9/25/1978	10/28/1978	33	6	8
RUBY	10/28/1978	11/20/1978	23	6	11
RUBY	11/20/1978	12/15/1978	25	1	2
RUBY	12/15/1978	1/24/1979	40		
RUBY	1/24/1979	2/12/1979	19	4	9
RUBY	2/12/1979	3/16/1979	32	8	10
RUBY	3/16/1979	4/20/1979	35	0	0
RUBY	4/20/1979	5/15/1979	25	6	10
RUBY	5/15/1979	6/18/1979	34	7	9

Island	DOI*	DOR†	Days	Net Reading (mR)	Net Exposure Rate (µR h⁻¹)
RUBY	6/18/1979	8/6/1979	49	0	0
RUBY	TLD Lost				
RUBY	8/31/1979	10/10/1979	41	8	8
NANCY	10/28/1978	11/20/1978	23	9	16
NANCY	11/20/1978	12/21/1978	31	7	9
NANCY	12/21/1978	1/24/1979	39	9	10
NANCY	1/24/1979	2/12/1979	19	6	13
NANCY	2/12/1979	3/16/1979	32	9	12
NANCY	3/16/1979	4/11/1979	26	8	13
NANCY	4/11/1979	5/16/1979	35	10	12
NANCY	5/16/1979	6/19/1979	34	8	10
NANCY	TLD missing				
NANCY	TLD lost				
NANCY	8/31/1979	10/10/1979	41	7	7
PEARL'S Daughter	11/20/1978	12/21/1978	31	7	9
PEARL'S Daughter	12/19/1978	1/24/1979	36	23	27
PEARL'S Daughter	1/24/1979	2/12/1979	19	5	11
PEARL'S Daughter	2/12/1979	3/16/1979	32	10	13
PEARL'S Daughter	3/16/1979	4/20/1979	35	12	14
PEARL'S Daughter	4/20/1979	5/15/1979	25	5	8
PEARL'S Daughter	5/15/1979	6/18/1979	34	11	13
PEARL'S Daughter	6/18/1979	7/23/1979	35	7	8
PEARL'S Daughter	7/17/1979	8/31/1979	45	28	26
PEARL'S Daughter	8/31/1979	10/10/1979	41	5	5
KATE	9/25/1978	10/23/1978	28	2	3
KATE	10/23/1978	11/20/1978	28	4	6
KATE	11/20/1978	12/19/1978	29	3	4
KATE	12/19/1978	1/24/1979	36	4	5
KATE	1/24/1979	2/12/1979	19	3	7
KATE	2/12/1979	3/16/1979	32	5	7
KATE	3/16/1979	4/11/1979	26	5	8
KATE	4/11/1979	5/16/1979	35	6	7
KATE	5/16/1979	6/19/1979	34	5	6
KATE	6/19/1979	7/21/1979	32	5	7
KATE	7/21/1979	8/30/1979	40	4	4
KATE	8/30/1979	10/10/1979	41	0	0
EDNA	10/23/1978	11/24/1978	32	7	9
EDNA	11/24/1978	12/16/1978	22	1	2
EDNA	12/16/1978	1/24/1979	39	9	10
EDNA	1/24/1979	2/12/1979	19	3	7

Island	DOI*	DOR†	Days	Net Reading (mR)	Net Exposure Rate (μR h^{-1})
EDNA	2/12/1979	3/12/1979	28	4	6
EDNA	3/12/1979	4/11/1979	30	5	7
EDNA	4/11/1979	5/15/1979	34	4	5
EDNA	5/15/1979	6/15/1979	31	5	7
EDNA	TLD missing				
EDNA	7/17/1979	8/21/1979	35	1	1
EDNA	8/21/1979	10/10/1979	50	12	10
DAISY	9/25/1978	10/30/1978	35	4	5
DAISY	10/30/1978	11/20/1978	21	3	6
DAISY	11/20/1978	12/16/1978	36	4	5
DAISY	12/16/1978	1/24/1979	39	3	3
DAISY	1/24/1979	2/12/1979	19	4	9
DAISY	2/12/1979	3/12/1979	28	4	6
DAISY	3/12/1979	4/11/1979	30	6	8
DAISY	4/11/1979	5/15/1979	34	5	6
DAISY	5/15/1979	6/15/1979	31	6	8
DAISY	6/15/1979	7/30/1979	45	5	5
DAISY	7/30/1979	8/21/1979	22	6	11
DAISY	8/21/1979	10/10/1979	50	5	4
CLARA	9/25/1978	10/30/1978	35	4	5
CLARA	10/30/1978	11/13/1978	14	1	3
CLARA	11/13/1978	12/16/1978	33	3	4
CLARA	12/16/1978	1/24/1979	39	5	5
CLARA	1/24/1979	2/12/1979	19	4	9
CLARA	2/12/1979	3/12/1979	28	4	6
CLARA	3/12/1979	4/11/1979	30	5	7
CLARA	4/11/1979	5/15/1979	34	7	9
CLARA	5/15/1979	6/15/1979	31	3	4
CLARA	6/15/1979	7/30/1979	45	10	9
CLARA	7/30/1979	8/22/1979	23	5	9
CLARA	8/21/1979	10/10/1979	50	2	2
IRENE (TLD SET #1)§	6/21/1978	7/21/1978	30	12‡	17‡
IRENE (TLD SET #1)§	7/22/1978	8/22/1978	31	14	19
IRENE (TLD SET #1)§	No TLD data for Sept/Oct 1978				
IRENE (TLD SET #1)§	10/23/1978	11/24/1978	32	27	35
IRENE (TLD SET #1)§	11/24/1978	12/21/1978	27	44	68
IRENE (TLD SET #1)§	12/21/1978	1/25/1979	35	68	81
IRENE (TLD SET #1)§	1/25/1979	2/13/1979	19	41	90
IRENE (TLD SET #1)§	2/12/1979	3/16/1979	32	58	76
IRENE (TLD SET #1)§	3/16/1979	4/17/1979	32	76	99

Island	DOI*	DOR†	Days	Net Reading (mR)	Net Exposure Rate ($\mu R\ h^{-1}$)
IRENE (Pit) (TLD SET #1)§	4/17/1979	5/15/1979	28	66	98
IRENE (Pit) (TLD SET #1)§	5/15/1979	6/15/1979	31	7	9
IRENE (Pit) (TLD SET #1)§	6/15/1979	7/21/1979	37	66	74
IRENE (Pit) (TLD SET #1)§	7/21/1979	8/21/1979	31	72	97
IRENE (Pit) (TLD SET #1)§	8/21/1979	10/10/1979	50	75	63
IRENE (TLD SET #2)§	9/25/1978	10/23/1978	28	0	0
IRENE (TLD SET #2)§	10/23/1978	11/24/1978	32	10	13
IRENE (TLD SET #2)§	11/24/1978	12/21/1978	27	6	9
IRENE (TLD SET #2)§	12/21/1978	1/25/1979	35	6	7
IRENE (TLD SET #2)§	1/25/1979	2/13/1979	19	5	11
IRENE (TLD SET #2)§	2/12/1979	3/16/1979	32	7	9
IRENE (TLD SET #2)§	3/16/1979	4/17/1979	32	8	10
IRENE (Bunker) (TLD SET #2)§	4/17/1979	5/15/1979	28	4	6
IRENE (Bunker) (TLD SET #2)§	5/15/1979	6/20/1979	36	10	12
IRENE (Bunker) (TLD SET #2)§	6/15/1979	7/21/1979	37	9	10
IRENE (Bunker) (TLD SET #2)§	7/21/1979	8/21/1979	31	8	11
IRENE (Bunker) (TLD SET #2)§	8/21/1979	10/10/1979	50	8	7
VERA	6/22/1978	7/22/1978	30	6‡	8‡
VERA	TLD lost				
VERA	9/25/1978	10/30/1978	35	2	2
VERA	10/30/1978	11/21/1978	22	1	2
VERA	11/21/1978	12/15/1978	24	5	9
VERA	12/15/1978	1/25/1979	41	1	1
VERA	1/25/1979	2/12/1979	18	1	2
VERA	2/12/1979	3/16/1979	32	2	3
VERA	3/16/1979	4/17/1979	32	3	4
VERA	4/11/1979	5/15/1979	34	3	4
VERA	5/15/1979	6/21/1979	37	4	5
VERA	6/21/1979	8/6/1979	46	5	5
VERA	8/4/1979	8/31/1979	26	4	6
VERA	8/31/1979	10/10/1979	40	2	2
SALLY (Hotline)	6/21/1978	7/21/1978	30	6‡	8‡
SALLY (Hotline)	7/22/1978	8/22/1978	31	3	4
SALLY (Hotline)	No TLD data for Sept/Oct 1978				
SALLY (Hotline)	10/23/1978	11/16/1978	24	2	3
SALLY (Hotline)	11/16/1978	12/19/1978	33	1	1
SALLY (Hotline)	TLD lost in storm				
SALLY (Hotline)	1/23/1979	2/12/1979	20	4	8
SALLY (Hotline)	2/12/1979	3/13/1979	29	2	3
SALLY (Hotline)	3/13/1979	4/18/1979	36	3	3

Island	DOI*	DOR†	Days	Net Reading (mR)	Net Exposure Rate ($\mu R\ h^{-1}$)
SALLY (Hotline)	4/18/1979	5/15/1979	27	2	3
SALLY (Hotline)	5/15/1979	6/20/1979	36	0	0
SALLY (Hotline)	TLD missing				
SALLY (Crypt)	9/26/1978	10/23/1978	27	2	3
SALLY (Crypt)	10/23/1978	11/16/1978	24	4	7
SALLY (Crypt)	11/16/1978	12/19/1978	33	4	5
SALLY (Crypt)	12/19/1978	1/23/1979	35	5	6
SALLY (Crypt)	1/23/1979	2/12/1979	20	5	10
SALLY (Crypt)	2/12/1979	3/13/1979	29	5	7
SALLY (Crypt)	3/13/1979	4/18/1979	36	8	9
SALLY (Crypt)	4/18/1979	5/15/1979	27	7	11
SALLY (Crypt)	TLD lost				
WILMA	6/21/1978	7/21/1978	30	5	7
WILMA	7/22/1978	8/22/1978	31	15	20
WILMA	No TLD data for Sept/Oct 1978				
WILMA	10/30/1978	11/20/1978	21	1	2
WILMA	11/22/1978	12/15/1978	23	1	2
WILMA	12/19/1978	1/25/1979	37	2	2
WILMA	1/25/1979	2/12/1979	18	0	0
WILMA	2/12/1979	3/16/1979	32	2	3
WILMA	3/16/1979	4/11/1979	26	2	3
WILMA	4/11/1979	5/15/1979	34	1	1
WILMA	5/15/1979	6/21/1979	37	1	1
WILMA	6/21/1979	8/6/1979	46	2	2
WILMA	8/6/1979	8/30/1979	24	2	3
WILMA	8/30/1979	10/10/1979	41	1	1
LUCY	9/25/1978	10/23/1978	28	0	0
LUCY	10/23/1978	11/20/1978	28	4	6
LUCY	11/20/1978	12/19/1978	29	2	3
LUCY	12/19/1978	1/24/1979	36	5	6
LUCY	1/24/1979	2/12/1979	19	3	7
LUCY	2/12/1979	3/16/1979	32	4	5
LUCY	3/16/1979	4/11/1979	26	5	8
LUCY	4/11/1979	5/16/1979	35	5	6
LUCY	5/16/1979	6/19/1979	34	4	5
LUCY	6/19/1978	7/21/1978	32	5	7
LUCY	7/21/1978	8/30/1979	40	3	3
LUCY	8/30/1979	10/10/1979	41	2	2
RUNIT (N. Boat Ramp)	6/21/1978	7/21/1978	30	7‡	10‡
RUNIT (N. Boat Ramp)	TLD lost				

Island	DOI*	DOR†	Days	Net Reading (mR)	Net Exposure Rate ($\mu R\ h^{-1}$)
RUNIT (N. Boat Ramp)	9/25/1978	10/17/1978	22	7	13
RUNIT (N. Boat Ramp)	10/23/1978	11/17/1978	25	1	2
RUNIT (N. Boat Ramp)	11/17/1978	12/19/1978	32	3	4
RUNIT (N. Boat Ramp)	TLD lost in storm				
RUNIT (N. Boat Ramp)	2/13/1979	3/16/1979	31	0	0
RUNIT (N. Boat Ramp)	3/16/1979	4/17/1979	32	5	7
RUNIT (N. Boat Ramp)	4/17/1979	5/16/1979	29	4	6
RUNIT (N. Boat Ramp)	TLD lost				
RUNIT (N. Boat Ramp)	6/22/1979	7/17/1979	25	3	5
RUNIT (N. Boat Ramp)	TLD lost				
RUNIT (N. Boat Ramp)	8/22/1979	10/10/1979	49	1	1
RUNIT (S. Quarry)	6/21/1978	7/21/1978	30	4	6
RUNIT (S. Quarry)	7/22/1978	8/22/1978	31	0	0
RUNIT (S. Quarry)	9/25/1978	10/18/1978	23	1	2
RUNIT (S. Quarry)	10/23/1978	11/17/1978	25	8	13
RUNIT (S. Quarry)	11/17/1978	12/19/1978	32	3	4
RUNIT (S. Quarry)	TLD lost in storm				
RUNIT (S. Quarry)	2/13/1979	3/16/1979	31	2	3
RUNIT (S. Quarry)	3/16/1979	4/17/1979	32	5	7
RUNIT (S. Quarry)	TLD lost				
RUNIT (S. Quarry)	5/16/1979	6/22/1979	37	1	1
RUNIT (S. Quarry)	6/22/1979	7/17/1979	25	2	3
RUNIT (S. Quarry)	7/27/1979	8/24/1979	28	1	1
RUNIT (Cactus Crater)	6/21/1978	7/21/1978	30	22‡	31‡
RUNIT (Cactus Crater)	TLD lost				
RUNIT (Cactus Crater)	9/25/1978	10/18/1978	23	13	24
RUNIT (Cactus Crater)	10/23/1978	11/17/1978	25	15	25
RUNIT (Cactus Crater)	11/17/1978	12/19/1978	32	12	16
RUNIT (Cactus Crater)	TLD lost in storm				
RUNIT (Cactus Crater)	1/24/1979	2/13/1979	20	11	23
RUNIT (Cactus Crater)	2/13/1979	3/16/1979	31	15	20
RUNIT (Cactus Crater)	TLD lost				
RUNIT (Cactus Crater)	4/17/1979	5/16/1979	29	20	29
RUNIT (Cactus Crater)	5/16/1979	6/22/1979	37	21	24
RUNIT (Cactus Crater)	6/22/1979	7/17/1979	25	13	22
RUNIT (Cactus Crater)	7/27/1979	8/24/1979	28	17	25
RUNIT (Cactus Crater)	8/22/1979	10/10/1979	49	15	13
RUNIT (Hotline)	6/21/1978	7/21/1978	30	15	21
RUNIT (Hotline)	TLD lost				
RUNIT (Hotline)	9/25/1978	10/18/1978	23	0	0

Island	DOI*	DOR†	Days	Net Reading (mR)	Net Exposure Rate (μR h^{-1})
RUNIT (Hotline)	10/23/1978	11/17/1978	25	1	2
RUNIT (Hotline)	11/17/1978	12/19/1978	32	0	0
RUNIT (Hotline)	12/19/1978	1/20/1979	32	1	1
RUNIT (Hotline)	1/24/1979	2/13/1979	20	2	4
RUNIT (Hotline)	2/13/1979	3/16/1979	31	2	3
RUNIT (Hotline)	3/16/1979	4/17/1979	32	3	4
RUNIT (Hotline)	4/17/1979	5/16/1979	29	0	0
RUNIT (Hotline)	5/16/1979	6/22/1979	37	1	1
RUNIT (Hotline)	6/22/1979	7/17/1979	25	3	5
RUNIT (Hotline)	7/27/1979	8/24/1979	28	0	0
RUNIT (Hotline)	8/22/1979	10/10/1979	49	1	1
RUNIT (Debris Pile)	6/21/1978	7/21/1978	30	Reading malfunction	
RUNIT (Debris Pile)	TLD lost				
RUNIT (Debris Pile)	9/25/1978	10/18/1978	23	1380	2500
RUNIT (FRST Shack)	12/19/1978	1/24/1979	36	2	2
RUNIT (FRST Shack)	1/24/1979	2/13/1979	20	2	4
RUNIT (FRST Shack)	2/13/1979	3/16/1979	31	3	4
RUNIT (FRST Shack)	3/16/1979	4/17/1979	32	3	4
RUNIT (FRST Shack)	4/17/1979	5/16/1979	29	2	3
RUNIT (FRST Shack)	5/16/1979	6/22/1979	37	2	2
RUNIT (FRST Shack)	6/22/1979	7/17/1979	25	1	2
RUNIT (FRST Shack)	7/27/1979	8/24/1979	28	1	1
RUNIT (FRST Shack)	8/22/1979	10/10/1979	49	2	2
LOJWA (FRST)	7/22/1978	8/22/1978	31	2	3
LOJWA (FRST)	9/25/1978	10/21/1978	26	1	2
LOJWA (FRST)	10/21/1978	11/16/1978	26	1	2
LOJWA (FRST)	11/16/1978	12/19/1978	33	0	0
LOJWA (FRST)	12/19/1978	1/23/1979	35	0	0
LOJWA (FRST)	1/23/1979	2/13/1979	20	2	4
LOJWA (FRST)	2/13/1979	3/13/1979	28	1	1
LOJWA (FRST)	3/13/1979	4/18/1979	36	2	2
LOJWA (FRST)	4/18/1979	5/15/1979	27	2	3
LOJWA (FRST)	5/15/1979	6/20/1979	36	2	2
LOJWA (FRST)	5/15/1979	6/23/1979	39	1	1
LOJWA (FRST)	7/18/1979	8/24/1979	37	1	1
LOJWA (FRST)	8/22/1979	10/10/1979	45	0	0
LOJWA (PMEL)	10/21/1978	11/16/1978	26	1	2
LOJWA (PMEL)	11/16/1978	12/19/1978	33	0	0
LOJWA (PMEL)	12/19/1978	1/23/1979	35	0	0
LOJWA (PMEL)	1/23/1979	2/13/1979	20	1	2

Island	DOI*	DOR†	Days	Net Reading (mR)	Net Exposure Rate (μR h⁻¹)
LOJWA (PMEL)	2/13/1979	3/13/1979	28	1	1
LOJWA (PMEL)	3/13/1979	4/18/1979	36	2	2
LOJWA (PMEL)	4/18/1979	5/15/1979	27	0	0
LOJWA (PMEL)	5/15/1979	6/20/1979	36	2	2
LOJWA (PMEL)	6/20/1979	7/18/1979	28	1	1
LOJWA (PMEL)	7/18/1979	8/24/1979	37	0	0
LOJWA (PMEL)	8/22/1979	10/10/1979	45	1	1
LOJWA (Mess Hall)	10/21/1978	11/16/1978	26	1	2
LOJWA (Mess Hall)	11/16/1978	12/19/1978	33	0	0
LOJWA (Mess Hall)	12/19/1978	1/23/1979	35	1	1
LOJWA (Mess Hall)	1/23/1979	2/13/1979	20	1	2
LOJWA (Mess Hall)	2/13/1979	3/13/1979	28	1	1
LOJWA (Mess Hall)	3/13/1979	4/18/1979	36	1	1
LOJWA (Mess Hall)	4/18/1979	5/15/1979	27	0	0
LOJWA (Mess Hall)	5/15/1979	6/20/1979	36	1	1
LOJWA (Mess Hall)	TLD missing				
LOJWA (Mess Hall)	TLD missing				
LOJWA (Mess Hall)	8/24/1979	10/10/1979	47	2	2
TILDA (FRST Bunker)	6/21/1978	7/22/1978	31	5‡	7‡
TILDA (FRST Bunker)	7/22/1978	8/22/1978	31	2	3
TILDA (FRST Bunker)	9/25/1978	10/21/1978	26	1	2
TILDA (FRST Bunker)	No TLD data for Oct/Nov 1978				
TILDA (FRST Bunker)	11/16/1978	12/19/1978	33	0	0
TILDA (FRST Bunker)	12/19/1978	1/23/1979	35	1	1
TILDA (FRST Bunker)	1/23/1979	2/13/1979	20	0	0
TILDA (FRST Bunker)	2/12/1979	3/13/1979	29	2	3
TILDA (FRST Bunker)	3/13/1979	4/18/1979	36	3	3
TILDA (FRST Bunker)	4/18/1979	5/15/1979	27	1	2
TILDA (FRST Bunker)	TLD lost				
TILDA (FRST Bunker)	6/20/1979	7/18/1979	28	1	1
TILDA (FRST Bunker)	7/18/1979	8/24/1979	37	0	0
TILDA (FRST Bunker)	8/24/1979	10/10/1979	47	0	0
TILDA (EOD Small Bunker)	10/23/1978	11/16/1978	24	3	5
TILDA (EOD Small Bunker)	11/16/1978	12/19/1978	33	1	1
TILDA (EOD Small Bunker)	12/19/1978	1/23/1979	35	2	2
TILDA (EOD Small Bunker)	1/23/1979	2/13/1979	20	2	4
TILDA (EOD Small Bunker)	2/12/1979	3/13/1979	29	2	3
TILDA (EOD Small Bunker)	3/13/1979	4/18/1979	36	2	2
TILDA (EOD Small Bunker)	4/18/1979	5/15/1979	27	1	2
TILDA (EOD Small Bunker)	5/15/1979	6/20/1979	36	3	3

Island	DOI*	DOR†	Days	Net Reading (mR)	Net Exposure Rate ($\mu R\ h^{-1}$)
TILDA (EOD Small Bunker)	6/20/1979	7/18/1979	28	2	3
TILDA (EOD Small Bunker)	7/18/1979	8/24/1979	37	2	2
TILDA (EOD Small Bunker)	No TLD data for Aug/Oct 1979				

* DOI means date of issue
† DOR means date of return
‡ This cell contains the gross reading from the TLD instrument and the corresponding exposure rate is based on the uncorrected reading.
§ IRENE (TLD SET #2) and IRENE (TLD SET #1) are designated in AEC (1973b) as Irene A and Irene B.

B-2. Average TRU Soil Activity Concentrations – Excised Soil Disposed in Cactus Crater and Dome

Estimated activity concentrations in excised soil are based on total estimated TRU activity and the total volume of soil removed from each contaminated island as reported in DNA (1981). The estimated concentrations and the volume of soil removed from each island are presented in Table B-2. The estimated concentrations of TRU for each island shown in Table B-2 include the total amount of contaminated soil that was disposed of in Cactus Crater and dome.

For Aomon crypt, Boken and Enjebi, removed contaminated soil was disposed of in the Cactus Crater during tremie operations and Cactus dome during soil-cement mix operations. For Aomon and Medren, disposal occurred only in the Cactus Crater and for Lujor and Runit, disposal occurred only in the Cactus dome. Estimates of the TRU activity of the soil removed from Aomon crypt, Boken, and Enjebi, which was contained in the Cactus Crater or in the Cactus dome, are given in Table B-3 and Table B-4, respectively.

Table B-2. Estimated average TRU activity of excised soil disposed in Cactus Crater and dome

Island	Total Island TRU (Ci)*	Soil Volume (yd^3)*			Average TRU Activity (Crater + Dome)	
		Crater	Dome	Total Volume	(pCi cm^{-3})	(pCi g^{-1})†
Medren	0	110	0	110	0	0
Aomon	1.29	10,603	0	10,603	159	106
Aomon Crypt	0.93	448	9,328	9,776	124	83
Boken	1.01	421	4,516	4,937	268	178
Enjebi	2.57	43,023	9,984	53,007	64	42
Lujor	1.7	0	14,929	14,929	149	99
Runit	7.22	0	10,735	10,735	880	587
Weighted Average (without Runit)	7.5‡	54,605‡	38,757‡	93,362‡	105§	**70**§
Weighted Average (with Runit)	14.72‡	54,605‡	49,492‡	104,097‡	185§	**123**§

* Total TRU activity and soil volume data are from table shown in Figure 8-34 "Contaminated Material Cleanup/Containment" (DNA, 1981).

† To estimate values in this table column, the soil bulk density = 1.50 g cm^{-3}.

‡ These values are totals.

§ The weighted average TRU soil activity concentration is estimated as the total activity divided by total soil volume.

Table B-3. Estimated TRU activity of excised soil disposed in Cactus Crater

Island	Total Island TRU (Ci)	Soil Volume (yd^3)	Average TRU Activity ($Ci\ yd^{-3}$)*	TRU in Crater (Ci)*	Average TRU Activity (Crater)	
					($pCi\ cm^{-3}$)	($pCi\ g^{-1}$)
Medren	0	110		0.0	0	0
Aomon	1.29	10,603	0.000122	1.29	159	106
Aomon Crypt	0.93	448	0.000095	0.04	125	83
Boken	1.01	421	0.000205	0.09	268	178
Enjebi	2.57	43,023	0.000048	2.09	64	42
Lujor	1.7	0	0.000114	0.0		
Runit	7.22	0	0.000673	0.0		
Total Soil Volume and Weighted Average Activity Concentration (Crater)		54,605	0.000064	3.50		**56**

* Island-based TRU activity concentration ($Ci\ yd^{-3}$) derived from Table B-2 (crater + dome) is used to estimate TRU activity for each island soil going to Cactus Crater from Aomon crypt, Boken and Enjebi.

Table B-4. Estimated TRU activity of excised soil disposed in Cactus dome

Island	Total Island TRU (Ci)*	Soil Volume (yd^3)	Average TRU Activity ($Ci\ yd^{-3}$)*	TRU in Dome (Ci)*	Average TRU Activity (Dome)	
					($pCi\ cm^{-3}$)	($pCi\ g^{-1}$)
Medren	0	0		0.0		
Aomon	0	0	0.000122	0.0		
Aomon Crypt	0.93	9,328	0.000095	0.89	124.43	83.0
Boken	1.01	4,516	0.000205	0.92	267.59	178.4
Enjebi	2.57	9,984	0.000048	0.48	63.42	42.3
Lujor	1.7	14,929	0.000114	1.70	148.95	99.3
Runit	7.22	10,735	0.000673	7.22	879.72	586.5
Total Soil Volume and Weighted Average Activity Concentration (Dome)		49,492	0.000227	11.22		**197.6**

* Island-based activity per cubic yard of soil derived from Table B-2 (Crater + Dome) is used to estimate TRU activity for each island soil going to Cactus dome from Aomon crypt, Boken and Enjebi.

B-3. Example Weekly Air Sampling and TLD Data Summaries Extracted from a CJTG Situation Report (SITREP)

The JTG prepared and submitted weekly SITREPs on various topics of interest to DNA and DoD. Included in SITREPs are weekly summaries of air sampling and TLD results as shown in Figure B-1. Air sample results are summarized in columns labeled AAA through GGG and have the following meanings:

AAA	=	Volume of air sampled during time period in cubic meters
BBB	=	Number of air filters counted during time period
CCC	=	Number of filters which yield no detectable activity
DDD	=	Number of filters showing values less than 0.01 MPC (0.27 pCi m^{-3})
EEE	=	Number of filters showing average activity equal to or greater than 0.01 MPC, but less than 0.1 MPC (0.27 to 2.7 pCi m^{-3})
FFF	=	Number of filters showing average activity equal to or greater than 0.1 MPC (2.7 pCi m^{-3})
GGG	=	Maximum value read from any one filter during period (in pCi m^{-3}).

JOINT MESSAGEFORM

SECURITY CLASSIFICATION: UNCLASSIFIED

PAGE	DRAFTER OR RELEASER TIME	PRECEDENCE ACT	PRECEDENCE INFO	LMF	CLASS	CIC	FOR MESSAGE CENTER/COMMUNICATIONS CENTER ONLY	DATE – TIME	MONTH	YR
Ø6 OF 19										

BOOK | MESSAGE HANDLING INSTRUCTIONS

FROM:

TO:

WEEK OF 3Ø JUL - 5 AUG 78:

ISLAND	AAA	BBB	CCC	DDD	EEE	FFF	GGG
ENJEBI	1877	11	6	5	Ø	Ø	Ø.Ø3
MAGGIE 9 (LCM 8)	498	7	2	5	Ø	Ø	Ø.Ø8
MESH 2 (LCU)	2Ø54	26	16	1Ø	Ø	Ø	Ø.Ø7
AOMON	13Ø4	8	7	1	Ø	Ø	Ø.Ø1
LOJWA	1Ø11	5	4	1	Ø	Ø	Ø.Ø1
RUNIT	2375	13	2	11	Ø	Ø	Ø.Ø7

(3) TLD DATA SUMMARY OF 1Ø - 16 AUG 78. DATA EXPRESSED IN MILLIROENTGENS (MR):

DATE	NO TURNED IN	NO READ Ø MR	NO READ 1-1Ø MR
1Ø - 16 AUG	6	3	3

(4) AIR SAMPLER STATUS:

OP	IN MAINT	REQ PARTS	REQ ENGINES	SALVAGED	TOTAL
32	Ø	11	24	18	85

C. DOE/ERSP: REF DOE/ERSP MSG 2ØØ5ØØZAUG78, SUBJ: DOE/ERSP SITREP, PROVIDED FCDNA DIRECT.

DISTR:

DRAFTER TYPED NAME, TITLE, OFFICE SYMBOL, PHONE & DATE

SPECIAL INSTRUCTIONS

RELEASER: TYPED NAME, TITLE, OFFICE SYMBOL AND PHONE

SIGNATURE

SECURITY CLASSIFICATION: UNCLASSIFIED

DATE TIME GROUP

DD FORM 173 — REPLACES DD FORM 173, 1 JUL 66, WHICH WILL BE USED.

Figure B-1. Example weekly summaries of air sampling and TLD results extracted from CJTG Enewetak Cleanup SITREP No 66, week ending August 20, 1978

Appendix C.

Dose Calculation Methods

This appendix contains equations for calculating external and internal doses for ECUP participants. Propagation of uncertainties associated with combining external doses from different dose categories, such as reconstructed, film badge, TLD, and doses from different scenarios, for both external and internal doses, are addressed. Upper-bound dose calculations are described as well.

C-1. External Dose Calculations

External doses described in this section for ECUP participants are the external doses that would be recorded on a properly worn dosimeter. In DTRA's NTPR program, these doses are referred to as "film badge doses" (DTRA, 2017, SM ED01).

C-1.1. External Dose from Contaminated Soil

The dose from exposure to a contaminated soil surface is estimated using Equation C-1 (DTRA, 2017, SM ED02):

$$D_{ext} = \dot{E}_{Island} \times T_{act} \times F_B \times F_{Ext} \tag{C-1}$$

where

D_{ext}	=	Dose due to working on or visiting an island (rem)
$\dot{E}_{Island}$	=	Exposure rate for island (R h^{-1})
T_{act}	=	Time duration of work activities or visits to the island (h)
F_B	=	Film badge conversion factor (rem R^{-1})
F_{Ext}	=	Exposure factor for external exposure (unitless)

The dose from exposure to soil piles, windrows, or other bulk soil is estimated using Equation C-2a:

$$D_{pile} = \dot{E}_{pile} \times T_{act} \times F_B \times F_{Ext} \tag{C-2a}$$

where

D_{pile}	=	Dose due to working near bulk soil (rem)
$\dot{E}_{pile}$	=	Exposure rate of bulk soil (R h^{-1})

The dose from exposure to a bulk soil pile like the one transported on an LCU described in the example scenario in Section 8, the exposure rate from the bulk soil in the LCU can be estimated using Equation C-2b:

$$E_{pile} = E_{island} \times \frac{d_{meas}}{d_{LCUsoil}} \quad \text{(C-2b)}$$

where

d_{meas}	=	Distance from the soil surface at which the island exposure rate was measured (m)
$d_{LCUsoil}$	=	Average distance of a veteran from bulk soil during transport in an LCU (m)

Exposure rates from contaminated soil on each island are shown in Section 4 and their use is discussed in Section 6, including for scenarios involving multiple islands. The film badge conversion factor (F_B) in Equations C-1 and C-2 is the ratio of the dose recorded on a properly worn film badge to the free-in-air integrated exposure. This factor accounts for body shielding of a film badge worn on the front of the body from gamma radiation emanating from a contaminated source behind an individual. The film badge conversion factor is assigned a value of 0.7 for the standing position on a planar field, when the contaminated surface is below and partially behind the individual. It is assigned a value of 1.0 for an individual facing the source of radiation, e.g., a pile of contaminated soil, where there is no body shielding between the source and the film badge) (DTRA, 2017, SM ED02). The exposure factor (F_{Ext}) accounts for the fraction of time that an individual is near the source of radiation during a workday.

C-1.2. External Dose from other Sources

For external doses from sources other than soil (e.g., contaminated debris), the term for exposure rate for an island or from bulk soil in the equations above should be replaced by the estimated or measured exposure rate from the specific source. In addition, applicable values for the film badge conversion factor and the exposure factor must be used. Exposure rates applicable to debris-handling scenarios are discussed in Appendix K.

C-1.3. External Dose on Residence Islands

For external dose estimates while on a residence island, one of the two following equations, C-3a or C-3b, should be used:

$$D_{ext} = \dot{E}_{island} \times T_{Dur} \times F_B \times \left[F_O + \frac{(1 - F_O)}{PF}\right] \quad \text{(C-3a)}$$

where

D_{ext}	=	External dose (rem)
F_B	=	Film badge conversion factor (rem R^{-1})
$\dot{E}_{island}$	=	Exposure rate for island (R h^{-1})
T_{Dur}	=	Total duration of exposure (h)
F_O	=	Average fraction of time the participant spent outside
PF	=	Protection factor for land-based structures

$$D_{ext} = \dot{E}_{island} \times T_{days} \times F_B \times [T_{od} + \frac{T_{id}}{PF}] \qquad \text{(C-3b)}$$

where

T_{days}	=	Number of days living on the residence island (d)
T_{od}	=	Average daily time outdoors (h d^{-1})
T_{id}	=	Average daily time indoors (h d^{-1})

C-1.4. External Dose from Seawater Immersion

The following equation shows the calculation of the external dose rate from immersion in seawater. Since Cs-137 is the only key radionuclide of concern for external exposure in seawater (Section 4.5), it is specified in the equation below. The Cs-137+Ba-137m dose coefficient for effective dose for this exposure pathway is 6.26×10^{-17} Sv s^{-1} per Bq m^{-3}. Organ dose coefficients are similar to this value, and are available in USEPA (1993).

$$\dot{D}_{sw} = C_{sw} \times DC_{water.imm} \times \text{Units conversion} \qquad \text{(C-4)}$$

where

$\dot{D}_{sw}$	=	Dose rate from immersion in seawater (rem h^{-1})
C_{sw}	=	Concentration of Cs-137 in seawater (fCi L^{-1})
$DC_{water.imm}$	=	Dose coefficient for immersion in water (organ or effective dose) for Cs-137 (Sv s^{-1} per Bq m^{-3})

and

$$\text{Units Conversion} = (3.7 \times 10^{-5} \text{ Bq fCi}^{-1}) \times (10^3 \text{ L m}^{-3}) \times (3600 \text{ s h}^{-1}) \times (100 \text{ rem Sv}^{-1})$$

C-1.5. External Dose from Sediment

The external dose rate from standing above exposed sediment at Enewetak Atoll is calculated using Equation C-5. Applicable dose coefficients are shown in Table C-1. The shielding provided by the water that is likely to be on top of sediment is ignored to high side the dose rate.

$$\dot{D}_{sed} = \sum_{i=1}^{n}(C_{sed,i} \times DC_{surf,i} \times \text{Units conversion}) \qquad \text{(C-5)}$$

where

$\dot{D}_{sed}$	=	Dose rate from standing above sediment (rem h^{-1})
$C_{sed,i}$	=	Concentration of each radionuclide *i* in sediment (mCi km^{-2})
$DC_{surf,i}$	=	Dose coefficient for exposure to surface of contaminated lagoon sediment for each radionuclide *i* in sediment (organ or effective dose) (Sv s^{-1} per Bq m^{-2})

and

Units conversion
$$= (10^{-6}\ km^2\ m^{-2}) \times (3.70 \times 10^7\ Bq\ mCi^{-1}) \times (3600\ s\ h^{-1}) \times (100\ rem\ Sv^{-1})$$

Table C-1. Dose coefficients for estimating external exposure to contaminated sediment

Radionuclide	Dose Coefficient* ($Sv\ s^{-1}$ per $Bq\ m^{-2}$)
Co-60	2.35×10^{-15}
Sr-90+Y-90	5.60×10^{-18}
Rh-101	2.55×10^{-16}
Rh-102m	4.76×10^{-16}
Sb-125	4.25×10^{-16}
Cs-137+Ba-137m	5.86×10^{-16}
Eu-152	1.10×10^{-15}
Eu-155	5.90×10^{-17}
Bi-207	1.48×10^{-15}
Pu-239	3.67×10^{-19}
Am-241	2.75×10^{-17}

* Dose coefficients are for effective dose, for exposure to contaminated ground surface (USEPA, 1993, Table III.3).

C-1.6. Total External Dose and Upper-bound Doses

The total external dose for an individual is the sum of all reconstructed doses, valid film badge readings, and valid TLD readings. For *n* reconstructed doses, valid film badge readings, or valid TLD readings, the total external dose is calculated using the following equation:

$$D_\gamma = \sum_{i=1}^{n} D_{\gamma,i} + \sum_{i=1}^{n} D_{FB,i} + \sum_{i=1}^{n} D_{TLD,i} \qquad \text{(C-6)}$$

where

D_γ = Total whole body external dose (rem)

$D_{\gamma,i}$ = The i^{th} component of the total reconstructed dose (rem)

$D_{FB,i}$ = The i^{th} component of the total film badge dose (rem)

$D_{TLD,i}$ = The i^{th} component of the total TLD dose (rem)

The total upper-bound external dose is calculated by estimating the upper-bound uncertainties from each category of external dose (reconstructed, film badge, and TLD), and then combining and adding them to the sum of external doses (DTRA, 2017, SM UA01). Note that if film badges are part of the upper-bound calculation, the sum of the bias-corrected film badge readings is used with its associated uncertainty. Recommended uncertainty factors are discussed in Section 6.4. The uncertainty associated with each category of external dose is calculated as follows:

$$u_{\gamma,i} = D_{\gamma,i} \times (UF_{ext} - 1)$$
$$u_{FB,i} = \frac{D_{FB,i}}{BF_i} \times (UF_{FB,i} - 1) \qquad \text{(C-7)}$$
$$u_{TLD,i} = \sqrt{(u_{TLD_{rdg}})^2 + (u_{TLD_{bkg}})^2}$$

The uncertainty components for TLD doses in Equation C-7 ($u_{TLD_{rdg}}$ and $u_{TLD_{bkg}}$) are defined in Appendix D, including the method used to calculate them.

The uncertainties are then combined in quadrature, and the total upper-bound external gamma dose is calculated as follows:

$$UB_{\gamma} = D_{\gamma} + \sum_{i=1}^{n} u_{\gamma,i}^2 + \sum_{i=1}^{n} u_{FB,i}^2 + \sum_{i=1}^{n} u_{TLD,i}^2 \qquad \text{(C-8)}$$

where

$u_{\gamma,i}$	=	Uncertainty associated with the i^{th} component of the total reconstructed dose (rem)
$u_{FB,i}$	=	Uncertainty associated with the i^{th} component of the total mean film badge dose (rem)
$u_{TLD,i}$	=	The uncertainty associated with the i^{th} component of the total TLD dose (rem)
UF_{ext}	=	Uncertainty factor for reconstructed whole body external gamma doses
$UF_{FB,i}$	=	Uncertainty factor for each valid film badge reading *i*
BF_i	=	Bias factor to convert each valid film badge reading *i* to a mean dose
UB_{γ}	=	Total upper-bound whole body external dose (rem)

C-2. Internal Dose Calculations

C-2.1. Inhalation of Suspended Soil

The dose from inhalation of suspended contaminated soil during soil disturbance activities when air sampling data are not available is estimated with Equation C-9a using a resuspension factor, or with Equation C-9b using a mass loading value. The resuspension factor is used with the calculated surface activity density (pCi cm^{-2}), which is estimated assuming a nominal soil thickness that is available for resuspension. The mass loading value estimates the airborne soil loading, and is used with an enhancement factor to account for higher concentrations of contaminants in suspended soil as compared to undisturbed soil. These equations can be used with excised (removed) soil or undisturbed soil. When used with excised soil and the total TRU activity (total curies) is accounted for, the calculation can be limited to Pu-239 activity as described in Appendix G.

$$D_{soil.inh} = \sum_{i=1}^{n} \frac{BR \times C_{soil,i} \times \rho \times Th_{soil} \times K_{susp} \times DC_{inh,i} \times T_{soil} \times F_{inh}}{RPF} \times \text{Units Conversion} \quad \text{(C-9a)}$$

where

$D_{soil.inh}$	=	Inhalation dose from suspended contaminated soil (rem)
BR	=	Breathing rate (m^3 h^{-1})
$C_{soil,i}$	=	Soil activity concentration of radionuclide *i* (pCi g^{-1})
ρ	=	Soil density (g cm^{-3})
Th_{soil}	=	Soil layer thickness available for resuspension (cm)
K_{susp}	=	Resuspension factor (m^{-1})
$DC_{inh,i}$	=	Inhalation dose coefficient for radionuclide *i* (rem pCi^{-1})
T_{soil}	=	Time spent in contaminated area (h)
F_{inh}	=	Exposure factor for inhalation (unitless)
RPF	=	Respiratory protection factor (unitless)

And $\quad$ *Units conversion* = 10^4 cm^2 m^{-2}

$$D_{soil.inh} = \sum_{i=1}^{n} \frac{BR \times C_{soil,i} \times ML \times EF \times DC_{inh,i} \times T_{soil} \times F_{inh}}{RPF} \quad \text{(C-9b)}$$

where

ML	=	Mass loading of airborne soil (g m^{-3})
EF	=	Enhancement factor (unitless)

For the airborne soil inhalation pathway, activity concentrations in soil are either island averages (Section 4) or calculated average values (e.g., for excised soil) (Section 7). These activity concentrations could be for one island or for multiple islands as described in Section 6. ICRP worker inhalation dose coefficients are used, assuming an AMAD of 1.0 µm and absorption type corresponding to unspecified compounds (ICRP, 2011). These assumptions were made in order to produce high-sided estimates of inhalation doses to internal organs. Plutonium and other contaminants at Enewetak may exist in multiple chemical forms (e.g., Robison and Noshkin, 1998). The assumption of “unspecified compounds” is high-siding because it results in the use of inhalation dose coefficients that are generally higher than those associated with other compounds such as insoluble oxides by factors of about 9–20 for Sr-90 and Pu-239 (the lungs are an exception to this generalization) (ICRP, 2011). The higher dose coefficients are due to the higher degree of absorption from the lungs; absorption types associated with unspecified compounds are Type F (Sr-90, Cs-137) and Type M (Co-60, Sb-125, Eu-155, Pu-239, Am-241). The inhalation dose coefficients recommended for use in ECUP dose assessments are shown in Table C-2.

Respiratory protection factors are discussed in Appendix F. The exposure factor for inhalation (F_{inh}) accounts for the fractional time in a workday that an ECUP worker is actually exposed to suspended airborne soil; values of 0.1 to 1.0 can be used.

When representative air sampling data are available, the dose from inhalation of suspended contaminated soil can be estimated with Equation C-10.

$$D_{soil.inh} = \sum_{i=1}^{n} \frac{AC_i \times BR \times T_{soil} \times DC_{inh,i}}{RPF_{resp}} \qquad \text{(C-10)}$$

where

AC_i = Measured air concentration of radionuclide i (pCi m^{-3})

Use of equation C-10 will usually be based on measured air concentrations of Pu-239/240, and estimation of the concentrations of other radionuclides based on their relative concentrations in the soil that is the source of the suspended radionuclides measured. When measured air concentrations of Pu-239/240 are used, estimation of other radionuclide concentrations in air is required for exposures involving either excised or undisturbed soil. The air concentrations used in Equation C-10 (AC_i) should be representative of the average concentrations over the entire period of exposure (T_{soil}). This may require averaging multiple air concentration measurements taken over the period of exposure or taken at other times or locations with similar conditions of exposure.

C-2.2. Incidental Ingestion of Soil and Dust

The dose from incidental ingestion of contaminated soil and dust is estimated as follows:

$$D_{inc.ing} = \sum_{i=1}^{n} q_{soil} \times T_{soil} \times C_{soil,i} \times DC_{ing,i} \tag{C-11}$$

where

$D_{inc.ing}$	=	Dose from incidental ingestion of contaminated soil and dust (rem)
q_{soil}	=	Incidental soil and dust ingestion rate (g d^{-1})
T_{soil}	=	Time spent in contaminated area (d)
$C_{soil,i}$	=	Soil activity concentration of radionuclide *i* (pCi g^{-1})
$DC_{ing,i}$	=	Ingestion dose coefficient for radionuclide *i* (rem pCi^{-1})

This equation can be applied for exposures involving excised or undisturbed soil. For most incidental ingestion scenarios (e.g., incidental ingestion of undisturbed soil on a residence island), average island-specific activity concentrations for all radionuclides and the applicable radionuclide dose coefficients would be used. The ICRP 68 ingestion dose coefficients recommended are based on f1 absorption fractions of 0.3 (Sr-90), 0.1 (Co-60, Sb-125), 1.0 (Cs-137), and 0.0005 (Eu-155, Pu-239, Am-241) (ICRP, 2011). The ingestion dose coefficients recommended for use in ECUP dose assessments are shown in Table C-3.

C-2.3. Consumption of Local Food

Internal doses have been estimated for the potential consumption of locally gathered food by ECUP participants. The unit doses and a description of the assessment of these potential organ doses is described in detail in Appendix M.

C-2.4. Total Internal Dose and Upper-bound Doses

In most cases, internal doses for ECUP participants will be estimated using environmental data, exposure scenario assumptions, and appropriate dose coefficients as described above. The total internal dose for an individual is simply the sum of internal doses from all sources. Using guidance from DTRA's NTPR program, internal dose uncertainties may be combined assuming that all internal component doses are fully correlated (DTRA, 2017, SM UA01). This means that the total upper-bound dose to any organ is calculated by applying the applicable uncertainty factor to each dose component and summing, as shown below.

$$D_{int} = \sum_{i=1}^{n} D_{int,i} \tag{C-12}$$

$$UB_{int} = \sum_{i=1}^{n} (UF_{int} \times D_{int,i}) \tag{C-13}$$

where

D_{int}	=	Total internal dose to a specific organ (or effective dose) from all sources of intake (rem)

$D_{int,i}$	=	The i^{th} component of internal dose to a specific organ (or effective dose) (rem)
UB_{int}	=	Upper-bound total internal dose to a specific organ (or effective dose) (rem)
UF_{int}	=	Uncertainty factor for internal reconstructed doses

An uncertainty factor (UF_{int}) of 10 is used for reconstructed internal doses as discussed in Section 7 (DTRA, 2017, SM UA01).

Table C-2. Inhalation dose coefficients

Organ/Tissue†	ICRP 68 Inhalation Dose Coefficients* (rem pCi^{-1})						
	Co-60	Sr-90	Sb-125	Cs-137	Eu-155	Pu-239	Am-241
Adrenals	2.41×10^{-8}	2.22×10^{-9}	4.07×10^{-9}	1.81×10^{-8}	6.66×10^{-9}	9.25×10^{-6}	9.99×10^{-6}
Bladder Wall	8.88×10^{-9}	4.81×10^{-9}	1.15×10^{-9}	1.85×10^{-8}	7.03×10^{-10}	9.25×10^{-6}	9.99×10^{-6}
Bone Surface	1.37×10^{-8}	1.37×10^{-6}	3.03×10^{-8}	1.78×10^{-8}	4.07×10^{-7}	5.55×10^{-3}	5.92×10^{-3}
Brain	7.03×10^{-9}	2.22×10^{-9}	9.99×10^{-10}	1.52×10^{-8}	9.99×10^{-10}	9.25×10^{-6}	9.99×10^{-6}
Breast	2.15×10^{-8}	2.22×10^{-9}	3.55×10^{-9}	1.44×10^{-8}	1.48×10^{-9}	9.25×10^{-6}	9.99×10^{-6}
Esophagus	2.52×10^{-8}	2.22×10^{-9}	4.07×10^{-9}	1.67×10^{-8}	1.74×10^{-9}	9.25×10^{-6}	9.99×10^{-6}
St Wall	1.59×10^{-8}	2.29×10^{-9}	2.41×10^{-9}	1.70×10^{-8}	2.26×10^{-9}	9.25×10^{-6}	9.99×10^{-6}
SI Wall	1.22×10^{-8}	2.41×10^{-9}	1.92×10^{-9}	1.81×10^{-8}	2.44×10^{-9}	9.25×10^{-6}	9.99×10^{-6}
ULI Wall	1.44×10^{-8}	7.03×10^{-9}	3.66×10^{-9}	1.85×10^{-8}	4.07×10^{-9}	9.25×10^{-6}	9.99×10^{-6}
LLI Wall	1.81×10^{-8}	1.92×10^{-8}	7.40×10^{-9}	2.15×10^{-8}	4.81×10^{-9}	9.25×10^{-6}	9.99×10^{-6}
Colon	1.59×10^{-8}	1.22×10^{-8}	5.18×10^{-9}	1.96×10^{-8}	4.44×10^{-9}	9.25×10^{-6}	9.99×10^{-6}
Kidneys	1.41×10^{-8}	2.22×10^{-9}	1.92×10^{-9}	1.74×10^{-8}	4.81×10^{-9}	2.18×10^{-5}	3.00×10^{-5}
Liver	3.00×10^{-8}	2.22×10^{-9}	4.81×10^{-9}	1.74×10^{-8}	1.30×10^{-7}	1.11×10^{-3}	3.59×10^{-4}
Muscle	1.33×10^{-8}	2.22×10^{-9}	2.07×10^{-9}	1.63×10^{-8}	1.70×10^{-9}	9.25×10^{-6}	9.99×10^{-6}
Ovaries	1.15×10^{-8}	2.22×10^{-9}	1.67×10^{-9}	1.85×10^{-8}	1.70×10^{-9}	7.03×10^{-5}	1.15×10^{-4}
Pancreas	2.00×10^{-8}	2.22×10^{-9}	3.07×10^{-9}	1.85×10^{-8}	5.18×10^{-9}	9.25×10^{-6}	9.99×10^{-6}
Red Marrow	1.52×10^{-8}	5.92×10^{-7}	5.92×10^{-9}	1.67×10^{-8}	3.63×10^{-8}	2.59×10^{-4}	2.04×10^{-4}
ET Airways	6.29×10^{-8}	6.66×10^{-9}	2.33×10^{-8}	2.89×10^{-8}	1.22×10^{-8}	3.52×10^{-5}	3.66×10^{-5}
Lungs	1.81×10^{-7}	2.29×10^{-9}	1.11×10^{-7}	1.63×10^{-8}	6.29×10^{-8}	1.11×10^{-4}	1.26×10^{-4}
Skin	8.51×10^{-9}	2.22×10^{-9}	1.22×10^{-9}	1.37×10^{-8}	8.14×10^{-10}	9.25×10^{-6}	9.99×10^{-6}
Spleen	1.85×10^{-8}	2.22×10^{-9}	2.81×10^{-9}	1.74×10^{-8}	1.59×10^{-9}	9.25×10^{-6}	9.99×10^{-6}

Testes	7.03×10^{-9}	2.22×10^{-9}	7.40×10^{-10}	1.63×10^{-8}	2.96×10^{-10}	7.03×10^{-5}	1.15×10^{-4}
Thymus	2.52×10^{-8}	2.22×10^{-9}	4.07×10^{-9}	1.67×10^{-8}	1.74×10^{-9}	9.25×10^{-6}	9.99×10^{-6}
Thyroid	1.33×10^{-8}	2.22×10^{-9}	1.89×10^{-9}	1.67×10^{-8}	9.25×10^{-10}	9.25×10^{-6}	9.99×10^{-6}
Uterus	9.99×10^{-9}	2.22×10^{-9}	1.26×10^{-9}	1.85×10^{-8}	1.18×10^{-9}	9.25×10^{-6}	9.99×10^{-6}
Effective dose	3.55×10^{-8}	8.88×10^{-8}	1.67×10^{-8}	1.78×10^{-8}	2.41×10^{-8}	1.74×10^{-4}	1.44×10^{-4}

* ICRP 68 dose coefficients for a particle size of 1 μm were obtained from ICRP (2011).

† Abbreviations used in this table: SI Wall = Small Intestine Wall; ULI Wall = Upper Large Intestine Wall; LLI Wall = Lower Large Intestine Wall; ET Airways = Extra-thoracic Airways.

Table C-3. Ingestion dose coefficients

Organ/Tissue†	ICRP 68 Ingestion Dose Coefficients* (rem pCi^{-1})						
	Co-60	Sr-90	Sb-125	Cs-137	Eu-155	Pu-239	Am-241
Adrenals	9.25×10^{-9}	2.44×10^{-9}	1.55×10^{-9}	5.18×10^{-8}	4.81×10^{-11}	5.18×10^{-8}	5.55×10^{-8}
Bladder Wall	9.62×10^{-9}	5.55×10^{-9}	1.59×10^{-9}	5.18×10^{-8}	1.11×10^{-10}	5.18×10^{-8}	5.55×10^{-8}
Bone Surface	7.40×10^{-9}	1.52×10^{-6}	3.33×10^{-8}	5.18×10^{-8}	2.44×10^{-9}	3.03×10^{-5}	3.33×10^{-5}
Brain	5.18×10^{-9}	2.44×10^{-9}	9.62×10^{-10}	4.44×10^{-8}	5.55×10^{-12}	5.18×10^{-8}	5.55×10^{-8}
Breast	4.81×10^{-9}	2.44×10^{-9}	7.77×10^{-10}	4.07×10^{-8}	7.03×10^{-12}	5.18×10^{-8}	5.55×10^{-8}
Esophagus	6.29×10^{-9}	2.44×10^{-9}	9.25×10^{-10}	4.81×10^{-8}	7.40×10^{-12}	5.18×10^{-8}	5.55×10^{-8}
St Wall	9.25×10^{-9}	3.33×10^{-9}	1.81×10^{-9}	4.81×10^{-8}	3.66×10^{-10}	5.55×10^{-8}	5.92×10^{-8}
SI Wall	1.55×10^{-8}	4.07×10^{-9}	3.59×10^{-9}	5.18×10^{-8}	9.99×10^{-10}	6.29×10^{-8}	6.66×10^{-8}
ULI Wall	2.41×10^{-8}	2.15×10^{-8}	9.25×10^{-9}	5.18×10^{-8}	4.44×10^{-9}	1.18×10^{-7}	1.30×10^{-7}
LLI Wall	4.44×10^{-8}	8.14×10^{-8}	2.29×10^{-8}	6.29×10^{-8}	1.30×10^{-8}	2.48×10^{-7}	2.74×10^{-7}
Colon	3.22×10^{-8}	4.81×10^{-8}	1.52×10^{-8}	5.55×10^{-8}	8.14×10^{-9}	1.74×10^{-7}	1.92×10^{-7}
Kidneys	8.88×10^{-9}	2.44×10^{-9}	1.41×10^{-9}	4.81×10^{-8}	6.29×10^{-11}	1.22×10^{-7}	1.70×10^{-7}
Liver	1.63×10^{-8}	2.44×10^{-9}	2.89×10^{-9}	4.81×10^{-8}	7.77×10^{-10}	6.29×10^{-6}	2.00×10^{-6}

Muscle	7.03×10^{-9}	2.44×10^{-9}	1.15×10^{-9}	4.44×10^{-8}	4.44×10^{-11}	5.18×10^{-8}	5.55×10^{-8}
Ovaries	1.59×10^{-8}	2.44×10^{-9}	2.92×10^{-9}	5.18×10^{-8}	3.52×10^{-10}	4.07×10^{-7}	6.29×10^{-7}
Pancreas	9.62×10^{-9}	2.44×10^{-9}	1.41×10^{-9}	5.18×10^{-8}	6.29×10^{-11}	5.18×10^{-8}	5.55×10^{-8}
Red Marrow	7.77×10^{-9}	6.66×10^{-7}	5.55×10^{-9}	4.81×10^{-8}	2.59×10^{-10}	1.44×10^{-6}	1.15×10^{-6}
ET Airways	6.29×10^{-9}	2.44×10^{-9}	9.62×10^{-10}	4.81×10^{-8}	4.44×10^{-12}	5.18×10^{-8}	5.55×10^{-8}
Lungs	6.66×10^{-9}	2.44×10^{-9}	1.07×10^{-9}	4.81×10^{-8}	2.04×10^{-11}	5.18×10^{-8}	5.55×10^{-8}
Skin	4.81×10^{-9}	2.44×10^{-9}	7.77×10^{-10}	4.07×10^{-8}	1.30×10^{-11}	5.18×10^{-8}	5.55×10^{-8}
Spleen	7.77×10^{-9}	2.44×10^{-9}	1.11×10^{-9}	4.81×10^{-8}	3.40×10^{-11}	5.18×10^{-8}	5.55×10^{-8}
Testes	6.66×10^{-9}	2.44×10^{-9}	9.25×10^{-10}	4.44×10^{-8}	2.55×10^{-11}	4.07×10^{-7}	6.29×10^{-7}
Thymus	6.29×10^{-9}	2.44×10^{-9}	9.25×10^{-10}	4.81×10^{-8}	7.40×10^{-12}	5.18×10^{-8}	5.55×10^{-8}
Thyroid	6.29×10^{-9}	2.44×10^{-9}	9.62×10^{-10}	4.81×10^{-8}	4.44×10^{-12}	5.18×10^{-8}	5.55×10^{-8}
Uterus	1.11×10^{-8}	2.44×10^{-9}	1.81×10^{-9}	5.18×10^{-8}	1.59×10^{-10}	5.18×10^{-8}	5.55×10^{-8}
Effective dose	1.26×10^{-8}	1.04×10^{-7}	4.07×10^{-9}	4.81×10^{-8}	1.18×10^{-9}	9.25×10^{-7}	7.40×10^{-7}

* ICRP 68 ingestion dose coefficients were obtained from ICRP (2011).

† Abbreviations used in this table: SI Wall = Small Intestine Wall; ULI Wall = Upper Large Intestine Wall; LLI Wall = Lower Large Intestine Wall; ET Airways = Extra-thoracic Airways.

C-3. Skin Dose Calculations

C-3.1. Skin Dose from Dermal Contamination

To calculate the skin dose from dermal contamination, the level of dermal concentration is first calculated as shown in Equation C-14a and C-14b:

$$C_{skin,i,j} = C_{soil,i} \times SL_{skin,i,j} \qquad \text{(C-14a)}$$

$$SL_{skin,i,j} = \rho \times Th_{soil} \times K_{susp} \times V_d \times r_j \times F_{skin} \times T_{workday} \qquad \text{(C-14b)}$$

where

$C_{skin,i,j}$	=	Dermal (areal) concentration of radionuclide *i* at skin site *j* at the end of a workday (pCi cm^{-2})
$C_{soil,i}$	=	Soil activity concentration of radionuclide *i* (pCi g^{-1})
$SL_{skin,i,j}$	=	Soil loading on skin of radionuclide *i* at skin site *j* at the end of a workday (g cm^{-2})
ρ	=	Soil density (g cm^{-3})
Th_{soil}	=	Soil layer thickness available for resuspension (cm)
K_{susp}	=	Resuspension factor (m^{-1})
V_d	=	Deposition velocity of suspended soil particles (m h^{-1})
r_j	=	Interception and retention fraction for skin site *j* (unitless)
F_{skin}	=	Fraction of workday a worker is exposed to suspended soil (unitless)
$T_{workday}$	=	Duration of the workday (h)

A high-sided daily skin dose from dermal contamination is then estimated using Equation C-15:

$$D_{skin,i,j}^{dermal} = DC_{i,j} \times SDMF_j \times C_{skin,i,j} \times T_{dose} \times [Other\ Factors] \qquad \text{(C-15)}$$

where

$D_{skin,i,j}^{dermal}$	=	Daily skin dose from dermal contamination from radionuclide *i* at skin site *j* (rem)
$DC_{i,j}$	=	Dermal contamination dose coefficient for radionuclide *i* at skin site *j* at a depth of 0.07 mm (e.g., rem cm^2 pCi^{-1} h^{-1})
$SDMF_j$	=	Skin depth modification factor for beta radiation only at skin site *j* (unitless)

T_{dose}	=	Duration of exposure to dermal contamination, equal to the sum of the workday hours and 2–4 h beyond the workday for a total of 12 h at which time complete removal of dermal contamination is assumed (h)
Other Factors	=	Placeholder for other modifying factors such as presence of clothing (unitless)

The recommended skin depth modification factors for beta radiation are shown in Table 34, Section 6.3.1. The parameter SDMF is not used for alpha radiation because the depth of the skin cells of interest is taken into account in the alpha dose coefficients.

C-3.2. Skin Dose from External Sources of Radiation

By appropriately choosing parameter values, a high-sided dose to skin at any height from external non-contact sources of radiation is estimated using Equation C-16:

$$D_{skin}^{ext}(h) = (\dot{E}_{\gamma} \times F_B \times T_{exp\text{-}out} \times \{1 + R_{\beta:\gamma}(h) \times M\}) + (\dot{E}_{\gamma} \times F_B \times T_{exp\text{-}in} \times \frac{1}{PF}) \quad \text{(C-16)}$$

where

$D_{skin}^{ext}(h)$	=	External beta+gamma dose to skin at height *h* (rem)
$\dot{E}_{\gamma}$	=	External gamma exposure rate (R h^{-1})
F_B	=	Film badge conversion factor (rem R^{-1})
$T_{exp\text{-}out}$	=	Duration of exposure to external radiation while outdoors (h)
$T_{exp\text{-}in}$	=	Duration of exposure to external radiation while indoors (h)
$R_{\beta:\gamma}(h)$	=	Beta-gamma dose ratio at height *h* (unitless)
M	=	Any modifying factors, such as accounting for clothing, exposure factor, etc. (unitless, M = 1 for bare, dry skin)
PF	=	Protection factor for land based structures (unitless)

As an alternative to the formulation of Equation C-16, the beta radiation and gamma radiation portions of Equation C-16 can be calculated separately as follows:

$$D_{skin}^{beta}(h) = \dot{E}_{\gamma} \times F_B \times T_{exp\text{-}out} \times R_{\beta:\gamma}(h) \times M \quad \text{(C-17a)}$$

$$D_{skin}^{gamma} = \dot{E}_{\gamma} \times F_B \times T_{exp\text{-}out} + \dot{E}_{\gamma} \times F_B \times T_{exp\text{-}in} \times \frac{1}{PF} \quad \text{(C-17b)}$$

Beta-gamma dose ratios and reference heights of body locations for use in ECUP skin dose assessments are provided in Appendix L. A discussion of the development of the ECUP beta-gamma dose ratios is also included in Appendix L.

C-3.3. Total Skin Dose and Upper-bound Doses

The total skin doses for the dermal and non-contact pathways for each skin site are the sums of the skin doses from each pathway. For upper-bound dose estimates, skin dose uncertainties for each pathway may be combined assuming that all component doses are fully correlated (DTRA, 2017, SM UA01). This means that the total upper-bound skin dose for each pathway for each site is calculated by applying the applicable uncertainty factor to each dose component and summing, as shown below, first for dermal contamination (Equations C-18a and C-18b) and then for external non-contact sources (Equation C-19).

$$D_{site,tot}^{dermal} = \sum_{i=1}^{n} D_{skin,i}^{dermal} \quad \text{(C-18a)}$$

$$D_{site}^{UB,dermal} = UF_{dermal} \times D_{site,tot}^{dermal} \quad \text{(C-18b)}$$

where

$D_{site,tot}^{dermal}$	=	Total dose to a specific skin site from all radionuclides in dermal contamination (rem)
$D_{skin,i}^{dermal}$	=	Skin dose from dermal contamination from radionuclide *i* at a specific skin site (rem)
$D_{site}^{UB,dermal}$	=	Upper-bound dermal contamination dose to a specific skin site (rem)
UF_{dermal}	=	Uncertainty factor for dermal contamination skin doses

$$D_{site}^{UB,ext} = UF_{non\text{-}contact} \times D_{skin}^{ext}(h) \quad \text{(C-19)}$$

where

$D_{site}^{UB,ext}$	=	Upper-bound external beta+gamma dose to a specific skin site at height *h* (rem)
$UF_{non\text{-}contact}$	=	Uncertainty factor for external (non-contact) skin doses
$D_{skin}^{ext}(h)$	=	External beta+gamma dose to skin site at height *h* (rem)

An uncertainty factor of 10 is used for dermal contamination skin doses and an uncertainty factor of 3 for external (non-contact) doses. To calculate the total upper-bound dose for each skin site, the upper-bound doses for dermal contamination and non-contact sources are simply combined as shown below. (McKenzie-Carter, 2014)

$$D_{site}^{UB,total} = D_{site}^{UB,dermal} + D_{site}^{UB,ext} \quad \text{(C-20)}$$

where

$D_{site}^{UB,total}$	=	Total upper-bound dose to a specific skin site from all sources (rem)

Appendix D.

Analysis of TLD Dose Uncertainties

D-1. Introduction

In 1978, the Navy shipped several CP-1112/PD thermoluminescent dosimeter (TLD) readers and a number of DT-526/PD TLD dosimeters to Enewetak Atoll to supplement film badge dosimeters. Film badges were subject to a significant rate of environmental damage. The TLDs provided back-up readings to damaged film badges as the basis for determining the dose of record. The TLD reader and TLD dosimeters used together composed a dosimetry system. Three sources of error contribute to the overall system uncertainty for computation of an upper-bound value for a given TLD reading (USN 1975; USN 1988). The three sources are:

- Zero offset for the TLD reader zero reference level
- Truncation of the digit on the display corresponding to tenths of a milliroentgen (mR)
- The maximum allowable limit for system accuracy during performance testing.

The remainder of this appendix through Section D-5 discusses the above sources of error in TLD readings and contains estimates of TLD reading uncertainties and uncertainty factors. Use of the TLD reading uncertainty factors to estimate uncertainty factors of assigned doses based on TLD readings is discussed in Section D-6.

D-2. Zero Offset

The CP-1112/PD technical manual (TM) (USN, 1975), section 3-3, "Operating Procedures," gives the procedure for checking and resetting the zero reference level. The limit stated in the procedure for this setting is"000 to 003" (no units). This is a source of error corresponding to a range from 0.0 to 0.3 mR.

D-3. Truncation of Display Digit

The CP-1112/PD TM (USN, 1975), Section 3-3, Table 3-2 and paragraphs d(1) and (2) describe the six digital display ranges and reading interpretation. Table 3-2 indicates the lowest decade range of the TLD reader displays in two digits while the other five ranges display in three digits. The TLD reader display shows "XX.M" on the first range corresponding to dosimeter readings from 0 to 99 mR. Because the 10^{th} of the mR digit is not displayed, the actual value could range from XX.0 mR to XX.9 mR if the digit after the decimal point were displayed by the reader. The display will show "XX.M" for nine signal levels in the previously stated range. This truncation introduces a potential error ranging from 0.0 to almost 1 mR.

D-4. Performance Testing Limits

Performance testing data can be used to assess overall dosimetry system uncertainty (NCRP, 2007) versus accounting separately for sources of laboratory, radiological, and environmental error as described for example in NAS-NRC (1989). The U.S. Navy introduced a performance testing program in the early 1980s to test several hundreds of dosimeter processors once a year to specific test limits (USN, 1988). The performance test consisted of testing readers with dosimeters pre-exposed to a National Institute of Standards and Technology radiation standard and evaluating samples of dosimeters drawn from every processing organization's inventory. The maximum allowable uncertainty for the test of each dosimeter processing organization was ±30 percent at least at the 95th percentile confidence level (USN, 1988). This uncertainty corresponds to an uncertainty factor of 0.7 to 1.3 at least at the 95th percentile level.

D-5. Combining Sources of Error

The zero offset error and digit display truncation error are considered independent sources of error since they are caused by completely independent processes. The zero offset error can randomly take values from 0.0 to 0.3 mR with a mid-point value of 0.15 mR, assuming a symmetrical distribution. The truncation error ranges from 0.0 mR to almost 1 mR with a central value of 0.5 mR, also assuming a symmetrical distribution. Because the zero offset and truncation errors are independent, they can be combined using quadrature (NCRP, 2007).

The upper-bound uncertainty for the performance test, a factor of 1.3 at least at the 95th percentile confidence level, is from sources reported in NAS-NRC (1989) that are independent from the zero offset and truncation errors. The performance test uncertainty is equal to 0.3 times the TLD reading.

The average offset error, the average truncation error, and the TLD system performance test uncertainty are combined in quadrature as recommended in NCRP (2007). As a result, for any given TLD reading, denoted by TLD_{rdg}, the upper-bound uncertainty attributable to that reading, $u_{TLD_{rdg}}$, is given by Equation D-1:

$$u_{TLD_{rdg}} = \sqrt{[(0.15)^2 + (0.5)^2 + (0.3 \times TLD_{rdg})^2]} \qquad \text{(D-1)}$$

The upper-bound uncertainty factor for a TLD reading, $UF_{TLD_{rdg}}$, is defined as the ratio of the 95th percentile upper-bound value to the TLD reading, given by Equation D-2:

$$UF_{TLD_{rdg}} = (TLD_{rdg} + u_{TLD_{rdg}})\ (TLD_{rdg}) \qquad \text{(D-2)}$$

Table D-1 provides estimates of $u_{TLD_{rdg}}$ and $UF_{TLD_{rdg}}$. At a reading of about 10 mR, the $UF_{TLD_{rdg}}$ values asymptotically approach a value of 1.3, where the source of error for TLD system performance test predominates over the zero offset and truncation errors.

Table D-1. Upper-bound uncertainty factor as a function of TLD reading

TLD Reading (mR)	Upper Bound Uncertainty	Upper Bound Uncertainty Factor
1	0.60	1.60
2	0.80	1.40
3	1.04	1.35
4	1.31	1.33
5	1.59	1.32
6	1.87	1.31
7	2.16	1.31
8	2.46	1.31
9	2.75	1.31
10	3.05	1.30
>10*	Use Equation D-1	1.30

* Upper bound uncertainty at 95% confidence level is approximately 30% of the reading for TLD readings greater than 10 mR.

D-6. TLD Dose Uncertainty

The external dose assigned to an ECUP participant during a period or periods that a TLD was worn is the net reading of each TLD worn. The assigned dose (net reading) was calculated according to Equation D-3.

$$D_{TLD} = TLD_{rdg} - Bkg \qquad \text{(D-3)}$$

where

D_{TLD}	=	Assigned TLD dose (mR or mrem)
TLD_{rdg}	=	TLD reading (mR)
Bkg	=	Background radiation exposure for TLD wearing period (mR)

The objective is to estimate the uncertainty associated with the assigned TLD dose(s) for use in calculating a total upper-bound external dose. To that end, the TLD reading associated with the assigned TLD dose, the uncertainties in the TLD reading, a background exposure, and the uncertainty in the background exposure must all be estimated.

Rearranging Equation D-3 gives Equation D-4 below.

$$TLD_{rdg} = D_{TLD} + Bkg \qquad \text{(D-4)}$$

Equation D-4 is used together with the assigned TLD dose and an estimate of the background exposure to estimate the TLD reading associated with the assigned TLD dose. The uncertainties in the TLD reading(s) are then estimated using the values in Table D-1, which presents the uncertainties for single TLD readings.

To estimate a background exposure for a given participant TLD reading, 15 sets of readings and corrected readings from control TLDs that were exposed during 10 separate periods from July 1978 to February 1980 were obtained from the ECUP records. Each set contains 10 individual TLD readings, so there are 150 control TLD readings in total. Documentation of the specific placement of the control TLDs was not located, but it is assumed that they reflect primarily cosmic background and other natural radiation (AEC, 1973a). The control TLD readings were converted to daily exposure rates, and a mean of 0.116 mR d^{-1} was calculated. This value is assumed to be representative background exposure rate for all ECUP TLD wearing periods. If a TLD Report that lists an individual's background exposure is not available, the *Bkg* value for a given TLD dose is obtained by multiplying this mean exposure rate by the number of days in a participant's wearing period.

An estimate of the upper-bound uncertainty associated with the background exposure can be obtained statistically from the 15 sets of control TLD readings. Assuming a *t*-distribution in the control TLD readings, a 95^{th} percentile value of 0.125 mR d^{-1} was calculated. Using the mean and 95^{th} percentile values, an uncertainty factor of 1.08 (0.125/0.116) was calculated, which can be rounded up to 1.1. Therefore, the uncertainty associated with the total background exposure is about 10 percent of the background value. The uncertainty factor is used to calculate the upper-bound uncertainty for the background exposure for a specific TLD wearing period ($u_{TLD_{bkg}}$), as shown in Equation D-5.

$$\begin{aligned} u_{TLD_{bkg}} &= Bkg \times (1.1 - 1) \\ &= Bkg \times 0.1 \end{aligned} \qquad \text{(D-5)}$$

Because the uncertainty in a TLD reading from Table D-1 is estimated differently than the uncertainty in the background TLD readings as described above, these uncertainties are assumed independent of each other and hence are uncorrelated. Therefore, they are combined in quadrature, as shown in Equation D-6 below, to estimate the total uncertainty in a TLD dose denoted u_{TLD}.

$$u_{TLD} = \sqrt{(u_{TLD_{rdg}})^2 + (u_{TLD_{bkg}})^2} \qquad \text{(D-6)}$$

The total uncertainty in TLD dose (u_{TLD}) is combined in quadrature with the uncertainties in reconstructed and film badge doses to estimate the total external upper-bound dose as described in Appendix C.

Appendix E.

Resuspension of Soil Contaminants

When measured concentrations of airborne contaminants are not available, two common methods can be used to estimate the air concentration of resuspended soil contaminants: the resuspension factor method and the mass loading method.

E-1. Resuspension Factor Method

The resuspension factor, which is the ratio of airborne activity concentration to surface activity concentration, has been calculated or measured for many types of soil disturbances, and ranges over many orders of magnitude. Typical values range from 10^{-7} to 10^{-5} m^{-1}, and a value of 10^{-6} m^{-1} is often used as a generic value for planning purposes. However, these values apply to periods shortly after depositions of contaminated material when the freshly deposited material is more likely to be suspended than the underlying soil (Anspaugh et al., 2002; AEC, 1973a). Therefore, these values are not applicable to most situations involving the aged deposits of plutonium and other radionuclides at Enewetak during ECUP. For wind-driven resuspension from aged deposits, a more applicable resuspension factor has been estimated to be in the range of 10^{-10} to 10^{-8} m^{-1} (AEC, 1973a; Till and Grogan, 2008). In addition, use of a time-dependent model for the resuspension factor is sometimes recommended for periods long after deposition (Anspaugh et al., 2002; DTRA, 2017; Till and Meyer, 1983). However, methods based on time-dependent models generally do not account for different types of soil disturbances because they incorporate a fixed initial value ($K(0) = 10^{-5}$ m^{-1}).

E-2. Mass Loading Method

The second approach for estimating air concentrations of resuspended contaminants discussed in this report uses the mass loading method. This method estimates an airborne concentration of soil particulates that have been suspended from the ground surface, as mass per unit volume of air. The concentration of a contaminant in the suspended soil is then related to the activity concentration of contaminants in the surface soil to estimate the airborne activity concentration of contaminants. An inherent assumption in this approach is that the contaminants in the soil are reasonably well-mixed within the top layer of soil. Although, the mass loading method is commonly used for non-radioactive particulate matter, e.g., dust, dirt, smoke, it is also appropriate for radioactive soil contaminants as stated in Anspaugh et al. (2002). Environmental standards have been developed for mass loading levels of non-contaminated particulates (USEPA, 2017c). Mass loadings of contaminated soil have been measured for many types of soil disturbances, including in environments similar to Enewetak Atoll. Values of particulate mass loading resulting from various soil disturbances that are relevant to ECUP generally range from 40 to 600 $\mu g\ m^{-3}$ (AEC, 1973a; Oztunali et al., 1981; Shinn et al., 1994, 1996, 1997).

Even though plutonium in aged deposits may be well-mixed in the soil, it can be preferentially associated with the smaller particle sizes that are more likely to become airborne (Anspaugh et al., 2002). To account for a potentially different airborne activity concentration compared to the source soil, an "enhancement" or "enrichment" factor is used with the mass loading values. Values for plutonium enhancement factors range from less than 1.0 to 6.5 (Shinn et al., 1980, 1994, 1997). Although this factor may vary depending upon the type of disturbance, a reasonably conservative value of 3 is used in this report (Shinn et al., 1994). This value is also recommended as the default value to be used for all resuspended radionuclides in ECUP radiation dose assessments.

E-3. Relationship between Mass Loading and Resuspension Factor

To simplify the use of information on contaminant resuspension by future analysts, an equivalency between mass loading and resuspension factor was derived. The derivation starts by setting air concentrations calculated by the two methods equal to each other as shown in Equation E-1, and then solving for the resuspension factor *K*. Assuming an enhancement factor of 3, an average soil density of 1.5 g cm^{-3}, and a soil thickness available for suspension of 1 cm, the relationship between mass loading and resuspension factor is given by Equation E-2. Note that the soil activity concentration, C_{soil}, is unimportant in this derivation because it is the same for both methods and cancels out as can be seen in Equation E-1;

$$K \times C_{soil} \times p \times Th_{soil} = ML \times C_{soil} \times E_f \quad \text{(E-1)}$$

where

K	=	Contaminant resuspension factor (m^{-1})
C_{soil}	=	Soil activity concentration (pCi g^{-1})
ρ	=	Soil bulk density (g m^{-3})
Th_{soil}	=	Depth of soil available for resuspension (m)
ML	=	Mass loading of suspended soil in air (µg m^{-3})
E_f	=	Enhancement factor (unitless)

If

$$p = 1.5 \otimes 10^6 \text{ g m}^{-3},$$

$$Th_{soil} = 0.01 \text{ m},$$

and

$$E_f = 3$$

then, Equation E-1 becomes:

$$K = 2 \times 10^{-10} \times ML \quad \text{(E-2)}$$

Based on the above relationship, the equivalency of various pairs of mass loading and resuspension factors is shown in Table E-1 for selected soil disturbance activities.

Table E-1. Mass loading values and resuspension factors for representative types of ECUP soil disturbances

ECUP Activity or other Relevant Item	Mass Loading ($\mu g\ m^{-3}$)	Resuspension factor (m^{-1})*	Comment
Ambient level on the islands of Enewetak	40	8×10^{-9}	Ambient dust loading under quiet atmospheric conditions (AEC, 1973a)
Generic default value	100†	2×10^{-8}	Default mass loading value is from several sources (e.g., Anspaugh et al., 1975; AEC, 1973a; Yu et al., 2015)
Truck traffic	100	2×10^{-8}	Resuspension factor is the geometric mean (GM) of downwind values calculated from measurements in Bramlitt (1977)
Regulatory limit (maximum PM_{10} 24-h average concentration)	150	3×10^{-8}	Mass loading value is the National Primary and Secondary AAQS (40CFR50.6)
Work involving soil piles	250	5×10^{-8}	Mass loading value is calculated as the GM of values measured near Johnston Island Pu-soil piles: 79 and 178 $\mu g\ m^{-3}$ (Shinn et al., 1994), 256 and 1017 $\mu g\ m^{-3}$ (Shinn et al., 1996)
Clearing vegetation	300	6×10^{-8}	Mass loading value is for agricultural tillage (Oztunali et al., 1981)
Soil excision and windrowing	600	1.2×10^{-7}	Mass loading value is for close proximity to operating bulldozer; basement excavation (Oztunali et al., 1981)

* These resuspension factors were calculated using Equation E-2.

† This value is a conservative value for general activities at Enewetak Atoll and may be used for dose estimation purposes if no other specific value is applicable.

The range of resuspension factors in Table E-1 is approximately 10^{-8} to $10^{-7}\ m^{-1}$, and it includes values that are larger than the range given earlier for aged deposits. The estimates are calculated using assumed values for the soil density, the enhancement factor, and the depth of soil available for resuspension. If, for example, the soil depth is larger than the assumed value of 0.01 m, or if the enhancement factor is smaller than the assumed value of 3, the calculated resuspension factors would be lower than shown. For example, enhancement factors of less than 1.0 have been reported for Pacific island environments such as Enewetak (Shinn et al., 1980). Using an assumed enhancement factor of 1.0 in Equation E-1, with all other parameter values unchanged, would result in calculated resuspension factors of $2.7 \times 10^{-9}\ m^{-1}$ to $4 \times 10^{-8}\ m^{-1}$ in Table E-1.

E-4. Resuspension Factors Estimated for ECUP Aggregate Hauling Activity

During April and May 1977, aggregate was bulk-hauled from a stockpile on Enjebi to Lojwa for use in construction of the forward base camp (DNA, 1981). This was accomplished using scoop loaders, dump trucks, and landing craft mechanized (LCM-8) to move the aggregate. Air samplers were operated upwind and downwind of the aggregate loading and unloading operations, and resuspension factors were estimated using downwind concentrations of Pu-239/240 (Bramlitt, 1977). The resuspension of Pu-239/240 in soil was due to the operation of the heavy mechanized equipment.

The air sampling concentration data and calculated resuspension factors shown in Table E-2 duplicate the calculation of resuspension factors in Bramlitt (1977). In the 1977 memorandum, resuspension factors were estimated only for downwind sampler locations; so upwind estimates are added in Table E-2. Several errors in the original 1977 calculations have been corrected here, although they do not significantly affect the results. Except for those with errors, the resuspension factors for downwind locations in Bramlitt (1977) match the values in Table E-2.

The resuspension factors shown in Table E-2 are calculated using the following equation:

$$K = \frac{AC_{Pu}}{Ca_{Pu}} \tag{E-3}$$

where

K	=	Resuspension factor (m^{-1})
AC_{Pu}	=	Air concentration of Pu-239/240 (pCi m^{-3})
Ca_{Pu}	=	Ground surface activity density of Pu-239/240 (pCi m^{-2}) (= $C_{\mathrm{soil,Pu}} \times \rho \times Th_{soil}$)
$C_{\mathrm{soil,Pu}}$	=	Soil activity concentration of Pu-239/240 (pCi g^{-1})
ρ	=	Soil bulk density (g m^{-3})
Th_{soil}	=	Depth of soil available for resuspension (m)

As pointed out in Bramlitt (1977), the exact location of the samplers with respect to the equipment operations was not available. In addition, several other factors that could affect soil suspension were not documented. However, the calculated resuspension factors are comparable to values reported in the literature and are consistent with estimates from other measurements included in Table E-1.

Mass loading values calculated using Equation E-2 are also shown in Table E-2. The data and results presented in Table E-2 show that at the aggregate pile on Lojwa, the activity concentration was 22 fCi m^{-3} on April 20, 1977 and only 2 fCi m^{-3} the next day on April 21, 1977. Except for that sample and another sample collected on Enjebi where the activity concentration was 11 fCi m^{-3}, all downwind concentrations were lower than 3 fCi m^{-3} with an average of 1.3 fCi m^{-3}. Furthermore, for all measurements, the average mass loading for upwind locations is 18 µg m^{-3}, and in most cases the estimated upwind mass loading values were less than 20 µg m^{-3}. These values are a factor of 5 lower than the proposed generic value of 100 µg m^{-3} (Table E-1). For the downwind locations, excluding the outlier value corresponding to the activity concentration of 22 fCi m^{-3} mentioned above, the average calculated mass loading is less than 120 µg m^{-3}.

Table E-2. Air concentrations, resuspension factors, and mass loading values associated with aggregate hauling

Location	Sample Dates (1977)	Measured Pu-239/240 Air Concentration* (fCi m^{-3})		Calculated Resuspension Factors† (m^{-1})		Calculated Mass Loading Values‡ (µg m^{-3})	
		DW§	UW**	DW	UW	DW	UW
Aggregate Pile at Lojwa	Apr 20	22	0.41	6.7×10^{-7}	1.2×10^{-8}	3333	62
	Apr 21	2.0	< 0.7	6.1×10^{-8}	2.1×10^{-8}	303	106
Enjebi	Apr 22	2.9	0.05	1.3×10^{-8}	2.2×10^{-10}	63	1
	Apr 26	1.6	< 0.08	6.9×10^{-9}	3.5×10^{-10}	35	2
	Apr 28	2.3	0.09	1.0×10^{-8}	3.9×10^{-10}	50	2
	Apr 29	1.9	0.03	8.2×10^{-9}	1.3×10^{-10}	41	1
	Apr 30	1.7	0.02	7.4×10^{-9}	8.7×10^{-11}	37	0.4
Enjebi Beach	Apr 21	11	< 0.4	4.8×10^{-8}	1.7×10^{-9}	238	9
	May 5	1.2	< 0.11	5.2×10^{-9}	4.8×10^{-10}	26	2
	May 6	0.44	ND††	1.9×10^{-9}	-	10	-
	May 7	0.62	ND	2.7×10^{-9}	-	13	-
	May 8	0.31	ND	1.3×10^{-9}	-	7	-
Lojwa	Apr 22	0.67	< 0.06	2.0×10^{-8}	1.8×10^{-9}	102	9
	Apr 26	1.7	0.11	5.2×10^{-8}	3.3×10^{-9}	258	17
	Apr 28	0.77	0.05	2.3×10^{-8}	1.5×10^{-9}	117	8
	Apr 29	0.68	0.11	2.1×10^{-8}	3.3×10^{-9}	103	17
	Apr 30	0.71	< 0.06	2.2×10^{-8}	1.8×10^{-9}	108	9
	May 5	1.2	< 0.3	3.6×10^{-8}	9.1×10^{-9}	182	45
	May 6	2.4	< 0.04	7.3×10^{-8}	1.2×10^{-9}	364	6
	May 7	0.96	0.045	2.9×10^{-8}	1.4×10^{-9}	145	7
	Minimum	0.31	0.04	1.3×10^{-9}	8.7×10^{-11}		
	Maximum	22	0.7	6.7×10^{-7}	2.1×10^{-8}		

* Taken from Enclosure 1 of Bramlitt (1977).

† Calculated using Equation E-3, with $C_{soil,Pu}$ = 2.2 pCi g^{-1} (Lojwa); $C_{soil,Pu}$ = 15.4 pCi g^{-1} (Enjebi); ρ = 1.5 × 10^{6} g m^{-3}; and Th_{soil} = 0.01 m.

‡ Calculated using the Calculated Resuspension Factors in this table and Equation E-2.

§ DW = Downwind location relative to soil disturbance.

** UW = Upwind location relative to soil disturbance. Where air concentration values are listed as "<" (less than), the value shown is used.

†† ND = No Data available for upwind locations on these dates.

Appendix F.

Respiratory Protection Factors

A respiratory protection factor represents the degree of protection afforded by a respirator against airborne contaminants. Numerically it is equal to the ratio of the concentration of contaminants outside the respirator to the concentration inhaled (i.e., inhaled concentration = outside concentration/protection factor). Protection factors for various respirators have been established by the U.S. Nuclear Regulatory Commission. The USNRC guidance on protection factors available in 1976 was published in NUREG-0041, “Manual of Respiratory Protection Against Airborne Radioactive Materials” (USNRC, 1976). Subsequent to ECUP, protection factors were first published in the Code of Federal Regulations in 1983 as Appendix A to Title 10, Part 20 (USNRC, 2017).

Air-purifying respirators were used at ECUP. These included half-face and full-face respirators. Some of the half-face and full-face respirators were equipped with a battery-operated blower unit, i.e., for positive pressure. FRST members were responsible for determining the appropriate respirator to use in a work environment, ensuring that a proper fit was made, and that respirators were used properly at each work site. Guidance and requirements for respiratory protective equipment at ECUP, including selection, usage, testing and fitting, were provided in the ECUP Standing Operating Procedure FCRR SOP 608-05 “Respiratory Protection” and EAI 5707.1 “Personnel Protection Levels.”

The USNRC protection factors available for ECUP in NUREG-0041 and current regulations differ somewhat. The primary difference relevant to respirators in use during ECUP is the protection factor specified for half-face, positive pressure respirator. As shown in Figure F-1, which is a reproduction of Table 6-1 of USNRC (1976), this respirator was assigned a protection factor of 1,000 at the time of ECUP, but is currently assigned a protection factor of 50 as shown in Appendix A of 10 CFR 20, reproduced here as Table F-2, USNRC (2017). Also, the full-face, negative pressure respirator was assigned a protection factor of 50 at the time of ECUP, but is currently assigned a protection factor of 100. These are shown below in Table F-1 for each ECUP Personnel Protection Level as specified in EAI No. 5707.1 “Personnel Protection Levels.” Based on the two sets of protection factors for air-purifying respirators, the more conservative protection factor for each respirator type is recommended for use in ECUP dose assessments as recommended in Section 7 of this report.

Table F-1. Personnel protection levels and respiratory protection for ECUP

ECUP Personnel Protection Level	ECUP Respiratory Protection*	Respiratory Protection Factor†	
		NUREG-0041‡	10CFR20§
I or IIA	None	1	1
IIB	Surgical mask (dust mask)	1	1
IIIA or IIIB	Full-face negative pressure respirator	50	100
	Half-face positive pressure respirator	1000	50
	Full-face positive pressure respirator	1000	1000
IV	Full-face positive pressure respirator	1000	1000

* Half-face, negative pressure respirators (protection factor of 10 [USNRC, 1976]) are mentioned in some ECUP documentation (e.g., FCRR SOP 608-10 "Decontamination Laundry Procedures." However, this respirator type is not listed in the ECUP Personnel Protection Level documentation (EAI No. 5707.1; DNA, 1981).

† The lower protection factor for each respirator type is recommended for use in ECUP dose assessments.

‡ USNRC (1976, Table 6-1).

§ USNRC (2017, Appendix A to Part 20).

TABLE 6-1
PROTECTION FACTORS FOR RESPIRATORS[a]

DESCRIPTION[b]	MODES[c]	PROTECTION FACTORS[d]: PARTICULATES ONLY	PROTECTION FACTORS[d]: PARTICULATES, GASES & VAPORS[e]	SELECTION OF TESTED & CERTIFIED EQUIPMENT: BUREAU OF MINES/NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH APPROVALS
I. AIR-PURIFYING RESPIRATORS				
Facepiece, half-mask[f]	NP	10		30 CFR Part 11 Subpart K
Facepiece, full	NP	50		
Facepiece, half-mask, full, or hood	PP	1000		
II. ATMOSPHERE-SUPPLYING RESPIRATORS				
1. Air-line respirator				
Facepiece, half-mask	CF		1000	30 CFR Part 11 Subpart J
Facepiece, half-mask	D		10	
Facepiece, full	CF		2000	
Facepiece, full	D		50	
Facepiece, full	PD		2000	
Hood	CF		2000[g]	
Suit	CF		h	i
2. Self-contained breathing apparatus (SCBA)				
Facepiece, full	D		50	30 CFR Part 11 Subpart H
Facepiece, full	PD		10,000[j]	
Facepiece, full	R		50	
III. COMBINATION RESPIRATOR				
Any combination of air-purifying and atmosphere-supplying respirators		Protection factor for type and mode of operation as listed above		30 CFR Part 11 § 11.63(b)

[a]For use in the selection of respiratory protective devices to be used where the contaminant has been identified and the concentration (or possible concentration) is known.

[b]Only for shaven faces and where nothing interferes with the seal of tight-fitting facepieces against the skin. (Hoods and suits are excepted.)

[c]The mode symbols are defined as follows:

CF = continuous flow
D = demand
NP = negative pressure (i.e., negative phase during inhalation)
PD = pressure demand (i.e., always positive pressure)
PP = positive pressure
R = demand, recirculating (closed circuit)

[d]1. The protection factor is a measure of the degree of protection afforded by a respirator, defined as the ratio of the concentration of airborne radioactive material outside the respiratory protective equipment to that inside the equipment (usually inside the facepiece) under conditions of use. It is applied to the ambient airborne concentration to estimate the concentration inhaled by the wearer according to the following formula:

$$\text{Concentration Inhaled} = \frac{\text{Ambient Airborne Concentration}}{\text{Protection Factor}}$$

2. The protection factors apply:

(a) Only for trained individuals wearing properly fitted respirators used and maintained under supervision in a well-planned respiratory protective program.

(b) For air-purifying respirators only when high efficiency particulate filters [above 99.97% removal efficiency by thermally generated 0.3 μm dioctyl phthalate (DOP) test] are used in atmospheres not deficient in oxygen and not containing radioactive gas or vapor respiratory hazards.

(c) For atmosphere-supplying respirators only when supplied with adequate respirable air.

[e]Excluding radioactive contaminants that present an absorption or submersion hazard. For tritium oxide, approximately one half of the intake occurs by absorption through the skin so that an overall protection factor of less than 2 is appropriate when atmosphere-supplying respirators are used to protect against tritium oxide; for example:

If the protection factor for a device is:	PF overall for tritium oxide is:
10	1.82
100	1.98
1,000	1.99

(Continued)

Figure F-1. Protection factors for respirators (USNRC, 1976)

(Continued)

Air-purifying respirators are not suitable for protection against tritium oxide. See also footnote g concerning supplied-air suits.

[f]Under-chin type only. This type of respirator is not satisfactory for use where it might be possible (e.g., if an accident or emergency were to occur) for the ambient airborne concentration to reach instantaneous values greater than 10 times the pertinent values in Table I, Column 1 of Appendix B to 10 CFR Part 20, "Standards for Protection Against Radiation." This type of respirator is not suitable for protection against plutonium or other high-toxicity materials. The mask is to be tested for fit with irritant smoke, prior to use, each time it is donned.

[g]The design of the supplied-air hood or helmet (with a minimum flow of 6 cfm of air) may determine its overall efficiency and the protection it provides. For example, some hoods aspirate contaminated air into the breathing zone when the wearer works with hands-over-head. Such aspiration may be overcome if a short cape-like extention to the hood is worn under a coat or coveralls. Other limitations specified by the approval agency must be considered before using a hood in certain types of atmospheres (see footnote h). Manufacturers' recommended pressure settings for the air supply cannot always be relied on to ensure a minimum 6 cfm air flow. Equipment must be operated in a manner that ensures proper flow rates are maintained.

[h]Appropriate protection factors must be determined, taking into account the design of the suit and its permeability to the contaminant under conditions of use.

[i]No approval schedules are currently available for this equipment. Equipment is to be evaluated by testing or on the basis of reliable test information.

[j]This type of respirator may provide greater protection and be used as an emergency device in unknown concentrations for protection against inhalation hazards. External radiation hazards and other limitations to permitted exposure such as skin absorption must be taken into account in such circumstances.

Note 1: Protection factors for respirators, as may be approved by the U.S. Bureau of Mines/National Institute for Occupational Safety and Health (NIOSH) according to applicable approvals for respirators to protect against airborne radionuclides, may be used to the extent that they do not exceed the protection factors listed in this table. The protection factors listed in this table may not be appropriate to circumstances where chemical or other respiratory hazards exist in addition to radioactive hazards. The selection and use of respirators for such circumstances should take into account applicable approvals of the U.S. Bureau of Mines/NIOSH.

Note 2: Radioactive contaminants for which the concentration values in Table I of Appendix B to 10 CFR Part 20 are based on internal dose due to inhalation may, in addition, present external exposure hazards at higher concentrations. Under such circumstances, limitations on occupancy may have to be governed by external dose limits.

Figure F-1. Protection factors for respirators (USNRC, 1976) (cont.)

Table F-2. Assigned protection factors for respirators (USNRC, 2017)

Appendix A to Part 20 – Assigned Protection Factors for Respirators[a]		
	Operating mode	**Assigned Protection Factors**
I. Air Purifying Respirators [Particulate[b] only][c]:		
Filtering facepiece disposable[d]	Negative Pressure	([d])
Facepiece, half[e]	Negative Pressure	10
Facepiece, full	Negative Pressure	100
Facepiece, half	Powered air-purifying respirators	50
Facepiece, full	Powered air-purifying respirators	1000
Helmet/hood	Powered air-purifying respirators	1000
Facepiece, loose-fitting	Powered air-purifying respirators	25
II. Atmosphere supplying respirators [particulate, gases and vapors[f]]:		
1. Air-line respirator:		
Facepiece, half	Demand	10
Facepiece, half	Continuous Flow	50
Facepiece, half	Pressure Demand	50
Facepiece, full	Demand	100
Facepiece, full	Continuous Flow	1000
Facepiece, full	Pressure Demand	1000
Helmet/hood	Continuous Flow	1000
Facepiece, loose-fitting	Continuous Flow	25
Suit	Continuous Flow	([g])
2. Self-contained Breathing Apparatus (SCBA):		
Facepiece, full	Demand	100[h]
Facepiece, full	Pressure Demand	10,000[i]
Facepiece, full	Demand, Recirculating	100[h]
Facepiece, full	Positive Pressure Recirculating	10,000[i]
III. Combination Respirators:		
Any combination of air-purifying and atmosphere-supplying respirators	Assigned protection factor for type and mode of operation as listed above.	

[a] These assigned protection factors apply only in a respiratory protection program that meets the requirements of this Part. They are applicable only to airborne radiological hazards and may not be appropriate to circumstances when chemical or other respiratory hazards exist instead of, or in addition to, radioactive hazards. Selection and use of respirators for such circumstances must also comply with Department of Labor regulations.

Radioactive contaminants for which the concentration values in Table 1, Column 3 of Appendix B to Part 20 are based on internal dose due to inhalation may, in addition, present external exposure hazards at higher concentrations. Under these circumstances, limitations on occupancy may have to be governed by external dose limits.

[b]Air purifying respirators with APF <100 must be equipped with particulate filters that are at least 95 percent efficient. Air purifying respirators with APF = 100 must be equipped with particulate filters that are at least 99 percent efficient. Air purifying respirators with APFs >100 must be equipped with particulate filters that are at least 99.97 percent efficient.

[c]The licensee may apply to the Commission for the use of an APF greater than 1 for sorbent cartridges as protection against airborne radioactive gases and vapors (e.g., radioiodine).

Table F-2. Assigned protection factors for respirators (USNRC, 2017) (cont.)

[d]Licensees may permit individuals to use this type of respirator who have not been medically screened or fit tested on the device provided that no credit be taken for their use in estimating intake or dose. It is also recognized that it is difficult to perform an effective positive or negative pressure pre-use user seal check on this type of device. All other respiratory protection program requirements listed in §20.1703 apply. An assigned protection factor has not been assigned for these devices. However, an APF equal to 10 may be used if the licensee can demonstrate a fit factor of at least 100 by use of a validated or evaluated, qualitative or quantitative fit test.

[e]Under-chin type only. No distinction is made in this Appendix between elastomeric half-masks with replaceable cartridges and those designed with the filter medium as an integral part of the facepiece (e.g., disposable or reusable disposable). Both types are acceptable so long as the seal area of the latter contains some substantial type of seal-enhancing material such as rubber or plastic, the two or more suspension straps are adjustable, the filter medium is at least 95 percent efficient and all other requirements of this Part are met.

[f]The assigned protection factors for gases and vapors are not applicable to radioactive contaminants that present an absorption or submersion hazard. For tritium oxide vapor, approximately one-third of the intake occurs by absorption through the skin so that an overall protection factor of 3 is appropriate when atmosphere-supplying respirators are used to protect against tritium oxide. Exposure to radioactive noble gases is not considered a significant respiratory hazard, and protective actions for these contaminants should be based on external (submersion) dose considerations.

[g]No NIOSH approval schedule is currently available for atmosphere supplying suits. This equipment may be used in an acceptable respiratory protection program as long as all the other minimum program requirements, with the exception of fit testing, are met (i.e., §20.1703).

[h]The licensee should implement institutional controls to assure that these devices are not used in areas immediately dangerous to life or health (IDLH).

[i]This type of respirator may be used as an emergency device in unknown concentrations for protection against inhalation hazards. External radiation hazards and other limitations to permitted exposure such as skin absorption shall be taken into account in these circumstances. This device may not be used by any individual who experiences perceptible outward leakage of breathing gas while wearing the device.

[64 FR 54558, Oct. 7, 1999; 64 FR 55524, Oct. 13, 1999]

Appendix G.

Soil Concentrations of TRU Radionuclides

The major radioactive contaminants at Enewetak during ECUP that may have resulted in external or internal doses to ECUP participants were the TRU radionuclides Pu-239, Pu-240 and Am-241, and the fission and activation products Cs-137, Sr-90, and Co-60 (DNA, 1981; DOE, 1982a). Small quantities of other TRU radionuclides were also present (e.g., Pu-238 and Pu-241) as well as other fission products (e.g., Sb-125 and Eu-155). However, because of their low concentrations and/or radiological decay characteristics, these additional radionuclides are not important from an ECUP radiological dose perspective. (DNA, 1981; DOE, 1982a; AEC, 1973a).

Contaminated soil represents the most likely source of potential exposure to these radionuclides for ECUP participants. Soil radionuclide concentrations used in the dose calculations in this report are based on values measured during the radiological field survey conducted in 1972 and documented in NVO-140 (AEC, 1973a). The 1972 soil concentrations are not modified to account for radiological or environmental processes that would have changed the soil concentrations from the time of the measurements to the start of ECUP in 1977. The most significant of these processes is the radioactive decay of Co-60, which has a radioactive half-life of approximately 5.3 years (NNDC, 2019). Based on the measured exposure rates in NVO-140 (AEC, 1973a), Co-60 accounted for an average of about one-half of the average external exposure rates from undisturbed soil on the islands. Therefore, the island external exposure rates at the beginning of ECUP would have been about 75 percent of the 1972 measured rates due to the radiological decay of Co-60. Additional decay of Co-60 that occurred over the 3-year period of ECUP is also ignored in this report for simplicity.

Several simplifications and other assumptions regarding soil concentrations of certain radionuclides are made in this report for excised soil and undisturbed soil as described below.

G-1. Radionuclide Concentrations in Excised Soil

Radioactive contaminants in excised soil are estimated during ECUP only for the TRU component. To simplify the internal dose estimates for certain scenarios and not understate potential doses, all TRU radioactivity in excised soil is assumed to be Pu-239, and non-TRU radionuclides are not included. This assumption may be used when the total TRU content of the excised soil is included, i.e., for scenarios using the soil activity concentrations of Table 44 in Section 7.1. This is a reasonable assumption for the purposes of the ECUP dose assessments for the following reasons:

- Radioactive content of excised soil was reported simply as total curies (e.g., DNA, 1981, Figure 8-34) or total TRU curies (DOE, 1982a), without identifying individual radionuclides.
- Pu-239 was the predominant TRU radionuclide in Enewetak soil (AEC, 1973a; DOE, 1982a).

- The combined Pu-239+Pu-240 activity was reported in 1972 and during ECUP because the alpha particle energies of these isotopes are almost identical and they cannot be resolved using ordinary pulse-height analysis.
- Pu-238 was present at Enewetak but existed in small quantities and was not routinely measured. When it was measured, it generally accounted for less than 5 percent of the total TRU activity (DNA, 1981; AEC, 1973a).
- The inhalation dose coefficients for TRU radionuclides other than Pu-239 are generally less than or similar to those of Pu-239. The few TRU dose coefficients that are higher than those for Pu-239 are typically only 10–20 percent larger (ICRP, 2011).
- Calculated inhalation doses from Pu-239 are an order of magnitude, or more, larger than internal doses from Sr-90, Cs-137, and Co-60.

The validity of this assumption is demonstrated in Table G-1, where unit-concentration inhalation "doses" for bone surface calculated using two methods are shown. The calculated doses (rem g^{-1}) are not representative of a specific scenario, but are simply relative values that allow comparison of the contribution of each radionuclide to an actual estimated inhalation dose.

Both methods shown in Table G-1 are based on a TRU soil concentration of 1 pCi g^{-1}. In Method #1, the 1 pCi g^{-1} of TRU activity is assumed to be Pu-239, and no other radionuclides are included. In Method #2 the 1 pCi g^{-1} of TRU activity is distributed among the four ECUP TRU radionuclides, and dose contributions from other radionuclides representative of Enewetak soil are included. The total dose calculated using Method #1 (5.55×10^{-3} rem g^{-1}) is within 1 percent of the dose calculated using Method #2 (5.58×10^{-3} rem g^{-1}). This confirms that the simplified approach of Method #1 is acceptable for the ECUP dose assessments where the total TRU content of the soil is accounted for. For other scenarios, e.g., those involving suspension of soil from roadways and general, non-excision, areas on an island, or where measured air concentrations of Pu-239 are used, all radionuclides of concern should be included as described in Appendix C.

G-2. Radionuclide Concentrations in Undisturbed Soil

Undisturbed soil radioactivity concentrations for five of the six radionuclides of concern for all islands are documented in AEC (1973a). Soil concentrations of Am-241 were not typically reported and are therefore estimated for use in the dose estimates of this report. This was done using documented activity ratios of TRU:Am-241 that were developed during ECUP to support the IMP measurement results (DOE, 1982a).

The ratio TRU:Am-241 was found to vary over the range of about 2.5 to 10 at Enewetak islands (DOE, 1982a). There are exceptions to this range, for example the ratio of 14.42 for the Fig-Quince area on Runit. The assumed value for the TRU:Am-241 ratio directly affects the estimated Am-241 soil concentrations. Assuming that Pu-239+240 and Am-241 make up essentially all of the TRU activity, the Am-241 soil concentration varies by a factor of 6 over the range of 2.5–10 assumed for the ratio TRU:Am-241 (Figure G-1).

Table G-1. Comparison of inhalation doses (bone surface) using two different assumptions for TRU and other radionuclide soil content

Radionuclide	Soil Concentration (pCi g^{-1})	Dose Coefficient (rem pCi^{-1})	Dose (rem g^{-1})
Method #1 (used in this report to account for all TRU radioactivity in excised soil):			
TRU*: Pu-239	1.0	5.55×10^{-3}	5.55×10^{-3}
Method #1 Total:			**5.55×10^{-3}**
Method #2:			
TRU*:			
Pu-238†	0.04	4.81×10^{-3}	1.92×10^{-4}
Pu-239‡	0.40	5.55×10^{-3}	2.22×10^{-3}
Pu-240‡	0.40	5.55×10^{-3}	2.22×10^{-3}
Am-241§	0.16	5.92×10^{-3}	9.47×10^{-4}
Sr-90**	2.30	1.37×10^{-6}	3.15×10^{-6}
Cs-137**	0.58	1.78×10^{-8}	1.02×10^{-8}
Co-60**	0.11	1.37×10^{-8}	1.48×10^{-9}
		Method #2 Total:	**5.58×10^{-3}**

* TRU concentrations for each method are highlighted with a bold-line cell border. Both methods are based on a total TRU concentration of 1 pCi g^{-1}.

† The Pu-238 concentration is based on the Pu-238:Pu-239 ratios in Table 14 of NVO-140 (AEC, 1973a).

‡ Pu-239 and Pu-240 concentrations are assumed equal (DOE, 1982a, Table 6-3). Because the Pu-239 and Pu-240 dose coefficients for bone surface are equal, this assumption does not affect the comparison shown in this table.

§ The Am-241 concentration is based on the average Am-241:Pu-239 ratio of approximately 0.4 in Table 14 of NVO-140 (AEC, 1973a).

** Concentrations of Sr-90, Cs-137, and Co-60 are based on 1 pCi g^{-1} of TRU, using the geometric means of soil concentration ratios for all islands that debris-removal activities were conducted (DOE, 1982a; AEC, 1973a).

Because Am-241 contributes different fractions of the total inhalation dose for different organs, the impact of the TRU:Am-241 ratio on organ dose from inhalation of suspended contaminated soil varies depending on the organ of interest. The relative change in inhalation dose for a range of TRU:Am-241 ratios is shown for the representative organs liver, bone surface, lungs, and testes in Figure G-2.

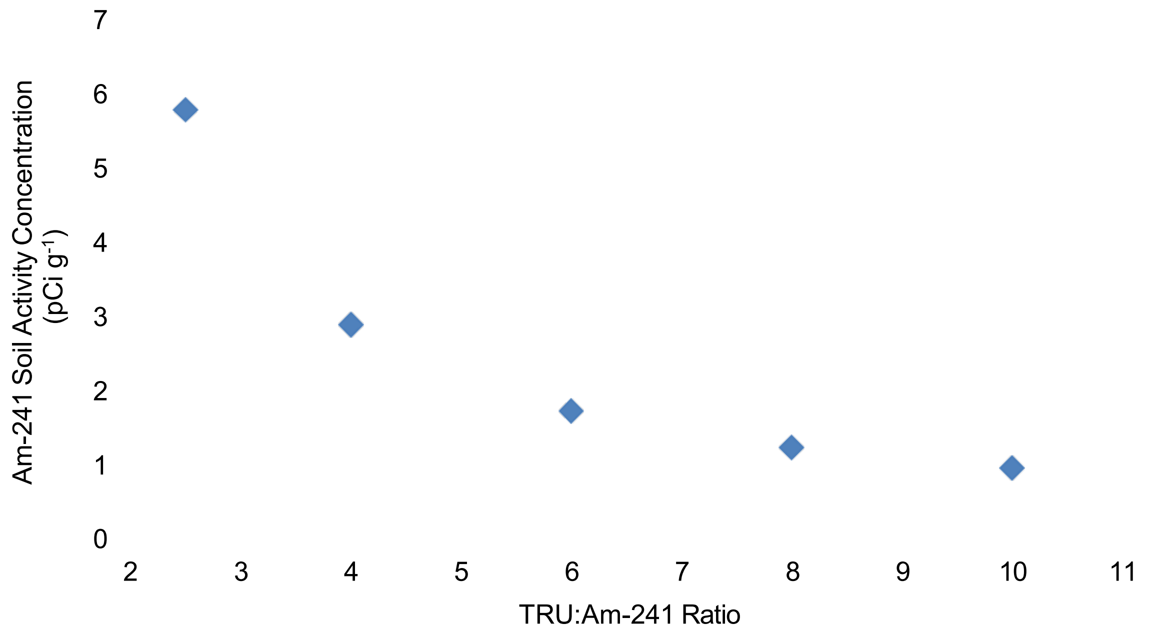

Figure G-1. Estimated soil activity concentration of Am-241 as a function of assumed TRU:Am-241 ratio (Pu-239+240 = 8.7 pCi g^{-1})

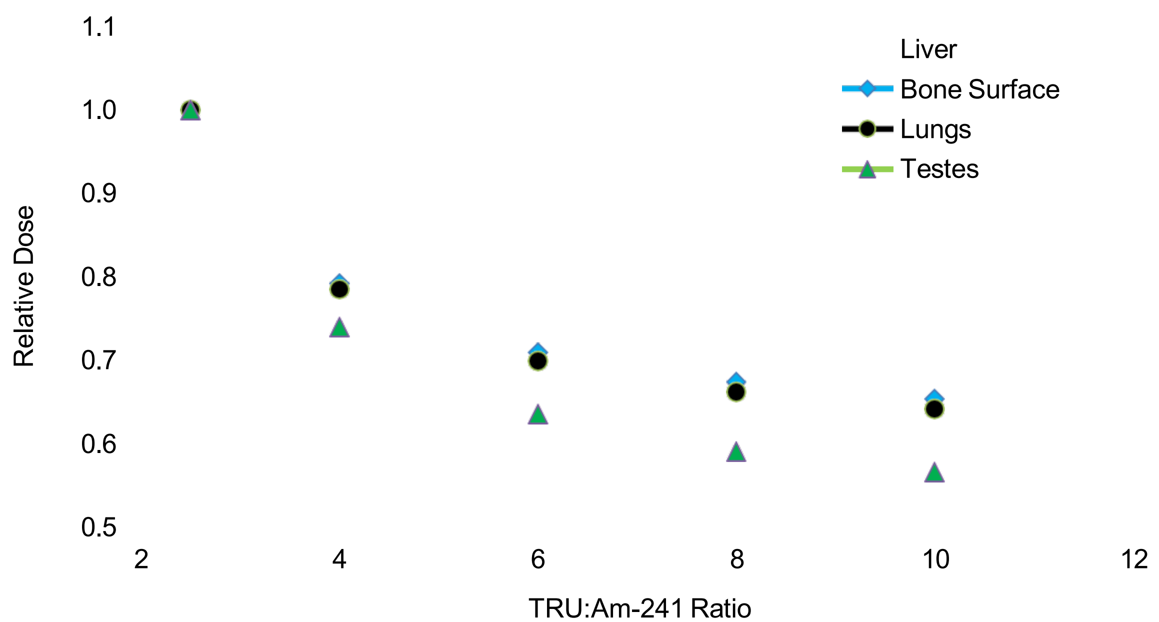

Figure G-2. Effect of TRU:Am-241 ratio on organ inhalation doses

G-3. Recommended TRU:Am-241 Ratios for Undisturbed Soil

The TRU:Am-241 ratios for the five soil removal islands are documented in DOE (1982a), and range from 3.2 to 11.3 (ignoring the high value for the Fig-Quince area). The recommended TRU:Am-241 value for estimating Am-241 soil concentrations for these islands is 6.0, which is the geometric mean of this range (the arithmetic mean is 6.5). The TRU:Am-241 ratios for other islands are not always documented in DOE (1982a). The ratio for other islands, especially the southern islands where no detonations took place, would be expected to be in the range 2.5–4 (DOE, 1982a). Because a lower ratio generally results in higher organ doses (Figure G-2), a ratio of 2.5 is recommended as a conservative value for estimating the Am-241 soil concentrations on all islands other than the five soil-removal islands.

G-4. Use of TRU:Am-241 Ratios

The TRU:Am-241 ratio is used to estimate Am-241 soil activity concentrations in undisturbed soil. As described earlier in this Appendix, TRU radionuclides in Enewetak soil were primarily Pu-238, Pu-239, Pu-240, and Am-241, with Pu-239 being the predominant TRU radionuclide. Because Pu-238 is generally a small fraction of the total TRU activity, the sum of the Pu-239/240 and Am-241 soil concentrations is assumed to be the total TRU soil concentration. That is, TRU activity = (Pu-239/240 + Am-241) activity. Based on this assumption, Am-241 soil concentrations using the TRU:Am-241 Ratio and the Pu-239/240 soil concentrations are estimated using the following equation:

$$C_{Am241} = \frac{C_{Pu239240}}{(\text{Ratio} - 1)} \tag{G-1}$$

where:

C_{Am241}	=	Soil activity concentration of Am-241 in undisturbed soil (pCi g^{-1})
$C_{Pu239240}$	=	Soil activity concentration of Pu-239/240 in undisturbed soil (pCi g^{-1})
Ratio	=	Value of ratio of TRU soil activity concentration to Am-241 soil activity concentration in undisturbed soil (2.5 or 6, depending on island)

Application of the two recommended ratios and the resulting estimated island-average Am-241 soil activity concentrations for all islands are shown in Table G-2.

Table G-2. Am-241 soil concentrations in undisturbed soil for all islands calculated using TRU:Am-241 ratios

Island Name	Site Name	Mean Pu-239/240 Soil Concentration* (pCi g^{-1})	TRU:Am-241 Ratio†	Calculated Am-241 Soil Concentration (pCi g^{-1})
Bokoluo	Alice	15.6	2.5	10.4
Bokombako	Belle	27.1	2.5	18.1
Kirunu	Clara	31.6	2.5	21.1
Louj	Daisy	31.6	2.5	21.1
Bocinwotme	Edna	19.4	2.5	12.9
Boken	Irene	26.2	6	5.2
Enjebi	Janet	16.2	6	3.2
Mijikadrek	Kate	11.3	2.5	7.5
Kidrinen	Lucy	7.7	2.5	5.1
Taiwel	Percy	9	2.5	6.0
Bokenelab	Mary	10.1	2.5	6.7
Elle	Nancy	10.1	2.5	6.7
Aej	Olive	8.4	2.5	5.6
Lujor	Pearl	38.3	6	7.7
Eleleron	Ruby	14.5	2.5	9.7
Aomon	Sally	11	6	2.2
Bijire	Tilda	6.5	2.5	4.3
Lojwa	Ursula	1.8	2.5	1.2
Alembel	Vera	4.3	2.5	2.9
Billae	Wilma	1.8	2.5	1.2
Runit	Yvonne	8.7	6	1.7
Boko	Sam	0.09	2.5	0.06
Munjor	Tom	0.08	2.5	0.05
Inedral	Uriah	0.08	2.5	0.05
n/a	Van	0.08	2.5	0.05
Jinedrol	Alvin	0.06	2.5	0.04
Ananij	Bruce	0.09	2.5	0.06
Jinimi	Clyde	0.06	2.5	0.04
Japtan	David	0.05	2.5	0.03
Jedrol	Rex	0.04	2.5	0.03
Medren (Parry)	Elmer	0.21	2.5	0.14
Bokandretok	Walt	0.04	2.5	0.03
Enewetak	Fred	0.08	2.5	0.05
Ikuren	Glenn	0.11	2.5	0.07
Mut	Henry	0.14	2.5	0.09
Boken	Irwin	0.13	2.5	0.09
Ribewon	James	0.08	2.5	0.05
Kidrenen	Keith	0.11	2.5	0.07
Biken	Leroy	1.15	2.5	0.77

* Mean Pu-239/240 soil concentrations from NVO-213 (DOE, 1982a).

† TRU:Am-241 ratio is 6 for the five soil-removal islands and 2.5 for all other islands.

Appendix H.

List of Standing Operating Procedures and Enewetak Atoll Instructions for Radiological Operations at ECUP

Table H-1 presents the identifying document numbers, titles, and dates of the Standing Operating Procedures (SOPs) and Enewetak Atoll Instructions (EAIs) for topics dealing with radiological operations at ECUP available in the ECUP records. There are 18 SOPs and 12 EAIs referenced in the Radiological Cleanup of Enewetak (DNA, 1981), but no consolidated listing by topical subject.

Table H-1. Standing Operating Procedures and Enewetak Atoll Instructions

Document Number	Title	Revisions and Changes	Date
SOP 608-01	Air Particulate Sampling Procedures	Original	July 21, 1977
SOP 608-02	Debris Survey Procedures	Original 608-02.1 608-02.02 608-02.02 CT1[†] 608-02.02 CT2	n/a[*] December 3, 1977 May 3, 1978 July 2, 1978 July 15, 1978
SOP 608-03	Decontamination of Facilities and Equipment	Original 608-03.1 608-03.01 CT1	October 18, 1977 December 12, 1977 August 18, 1978
SOP 608-04	Hotline Procedures	Original 608-04.1	July 5, 1977 March 17, 1979
SOP 608-05	Respiratory Protection	Original	July 5, 1977
SOP 608-06	Radioactive Source Test Procedures	Original	October 12, 1977
SOP 608-07	Source Accountability and Control Procedures	Original	October 12, 1977
SOP 608-08	Radiological Guidelines for Ground Zero Operations	Original	November 9, 1977
SOP 608-09	Runit Contamination Control Area Procedures	Original 608-09.1	June 2, 1978 January 25, 1980
SOP 608-10	Decontamination Laundry Procedures	Original	July 2, 1978
SOP 608-11	Disposal of Laboratory Generated Radioactive Waste	Original	July 17, 1978
SOP 608-12	Air Sampler Maintenance for the M-102 Air Sampler	Original	August 15, 1978
SOP 608-13	Microwave Oven Survey Program	Original	November 27, 1978
SOP 608-14	Radiological Certification of Enewetak Atoll Retrograde Equipment	Original	March 18, 1979

Table H-1. Standing Operating Procedures and Enewetak Atoll Instructions (cont.)

SOP 609-01	Sample Data Records	Original	July 17, 1978
SOP 609-02	Radiation Dosimetry Records	Original 609-02.1	July 21, 1977 November 17, 1978
SOP 609-03	Radiation Control Sample Identification Procedures	Original 609-03.1	July 17, 1978 March 5, 1979
SOP 609-04	Bioassay Procedures	Original 609-04.01 609-04.01 CT1	July 20, 1977 May 4, 1978 December 18,1978
EAI 5101	Radiation Control Committee	Original 5101.1 5101.2	n/a November 17, 1978 January 25, 1980
EAI 5701	Radiological Briefing for Arriving Persons, Enewetak	Original	August 15, 1977
EAI 5702	Access to Radiologically Controlled Islands	Original 5702 CT1	August 15, 1977 March 17, 1979
EAI 5703	Radiation Monitoring of Blasting Operations	Original	October 18, 1977
EAI 5704	Radioactive Source Test Procedures	Original	October 29, 1977
EAI 5705	FRST Training	Original	February 1, 1978
EAI 5706	Administration of Personnel Dosimetry Program	Original 5706.01 5706.02	n/a March 3, 1979 January 24, 1980
EAI 5707	Personnel Protection Levels	Original 5707.1	April 3, 1978 November 17, 1978
EAI 5708	Bulk Soil Haul Monitoring Procedures Renamed as: Overwater Transportation of Contaminated Soil	Original 5708 CT1 5708 CT2 5708.1 5708.1 CT1	June 7, 1978 July 15, 1978 August 22, 1978 November 18, 1978 March 17, 1979
EAI 5709	Island Debris Removal Completion Procedures	Original	June 7, 1978
EAI 5710	Radiological Control of Personnel Injured in Controlled Areas	Original	July 1, 1978
EAI 5711	Tour Extension Eligibility – Radiological Considerations	Original 5711 CT1	August 19, 1978 September 21, 1978

[*] "n/a" indicates that the date was not available.

[†] "CT" indicates "Change Transmittal"

Appendix I.

Questionnaire for Radiation Dose Assessment for Veterans of the Enewetak Cleanup Project (1977–1980)

This appendix contains the questionnaire that is sent to an ECUP veteran upon receipt of a valid claim or inquiry by the DTRA NTPR Program. The questionnaire is used to collect veteran-specific information that can be used to adjust or complement the scenarios of exposures and assumptions identified in this report in order to produce an individualized radiation dose assessment.

OMB No. 0704-0447

DEFENSE THREAT REDUCTION AGENCY

QUESTIONNAIRE FOR RADIATION DOSE ASSESSMENT FOR VETERANS OF THE ENEWETAK CLEANUP PROJECT (1977–1980)

AGENCY DISCLOSURE NOTICE

Indicate Assignment Category (A list and a map of the Enewetak Atoll islands are enclosed for reference)	**Complete these Sections of the Questionnaire**
☐ (a) You were assigned duties on Enewetak Island and/or Lojwa Island with no work duties on other islands, OR (b) you were in transit through Enewetak Atoll and did not participate in cleanup activities	I, II, III, IV and VII
☐ You were assigned duties only on the southern islands of Enewetak Atoll other than residence islands	I, II, III, V and VII
☐ You were assigned duties on the northern islands of Enewetak Atoll, with or without duties on the southern islands	I, II, III, VI and VII

SECTION I: PARTICIPANT CONTACT INFORMATION

Name of Veteran: (Last, First, Middle Initial)	*Service Number:*	*Social Security Number:*
Mailing Address:		
Telephone:	*Cell Phone:*	*Email:*

If this questionnaire is completed by <u>someone other than the participant</u>, please provide the following:		
Name: (Last, First, Middle Initial)		
Mailing Address:		
Telephone:	*Cell Phone:*	*Email:*

Relationship to veteran:

SECTION II: ASSIGNMENT SUMMARY (DURING ENEWETAK CLEANUP PROJECT)

Military Service	*Unit of Assignment during Enewetak Cleanup Project*

Dates of Assignment at Enewetak Atoll		*Rate/Rank*	*Person(s) who Served with You*
Arrival Date	*Departure Date*	*Job Occupation*	

SECTION III: SKIN CANCER CLAIMS ONLY

If you are filing for a VA disability claim due to, or partly due to, skin cancer or melanoma, provide the following information:

Height: _______feet _______inches

Physical location(s) of skin cancer or melanoma on the body: ______________________________________

SECTION IV: SUPPORT PERSONNEL WITH DUTIES ON ENEWETAK ISLAND OR LOJWA ISLAND

The questions in this section are intended to assess your potential for radiation exposure as a military support person who was **assigned duties on Enewetak Island and/or Lojwa Island with no work duties on other islands, or were in transit through Enewetak Atoll** during the Enewetak Cleanup Project for any time period from January 1, 1977 to December 31, 1980. Please provide detailed answers to the best of your recollection. Qualify as "approximate" where necessary. If you are unable to answer a question, state "unknown". If more space is needed for any question, use additional sheets and include reference to section and question numbers.

1. List all specific duties and related job descriptions that you performed while on Enewetak Island (Letter "E") or Lojwa Island (Letter "L"):

Duty Island (Write E or L)	**Duty and Job Description**

2. Did you handle, transport, work in close proximity or come into contact with objects or materials contaminated with radioactive material?

   Yes ____ No ____

   If "No", go to the next numbered question. If "Yes", answer the following questions:

   a. Describe your activities and circumstances for handling, transporting or working near objects or materials with radioactive contamination:

   b. Approximately how many times were you exposed to radioactive contamination? _______________

   c. On average, how much time did each event take?

3. Did you visit islands other than Enewetak or Lojwa Islands?

Yes ____ No ___

If "No", go to the next numbered question. If "Yes", answer the following question:

a. List the name of the islands you visited, how long the visits lasted, and describe the purpose of each visit (see enclosed list and map of islands for reference; list name or two-letter code in the left-hand column below):

Island Visited	**Duration**	**Purpose of Visit**

4. Are there any other duties, actions or locations that you think may have caused you to be exposed to radiation during your participation in the Enewetak Cleanup Project? ____________________________

5. On which island were you billeted and what was the type of your living quarters (for example, tent, building, etc.)?

6. Where did you eat your meals while on Enewetak or Lojwa Islands? _____________________________

7. Were you instructed NOT to consume locally gathered foods? Yes ____ No ____

8. If you consumed locally gathered food, what foods did you consume; include approximate quantity and how often?

9. Were you issued personal dosimeters during your assignment at Enewetak Atoll (film badges, TLDs or pocket dosimeters)?

   Yes ____ No ____

   If "No", go to question 11. If "Yes", answer the following question:

   a. Provide details, such as what kind of dosimeter(s) you were provided, when did you wear them, in what areas, etc.:

10. Were you advised of the results of the dose readings from your personal dosimeters?

    Yes ____ No ____

    If "No", go to next numbered question. If "Yes", answer the following question:

    a. Provide any details about the doses from your dosimeters:

11. Additional Comments: Please add any information related to your potential exposure to radiation that you believe was not covered under the questions in this section:

SECTION V: PERSONNEL WITH DUTIES ON THE SOUTHERN ISLANDS OF ENEWETAK ATOLL (REFER TO THE ENCLOSED LIST AND MAP)

The questions in this section are intended to assess your potential for radiation exposure as a military service member who was **assigned duties on non-residence southern islands of Enewetak Atoll** (refer to the enclosed list of islands and map) during the Enewetak Cleanup Project for any time period from January 1, 1977 to December 31, 1980. Please provide detailed answers to the best of your recollection. Qualify as "approximate" where necessary. If you are unable to answer a question, state "unknown". If more space is needed for any question, use additional sheets and include reference to section and question numbers.

1. To the best of your recollection, list specific duties and related job descriptions that you performed on the southern islands of Enewetak Atoll. (If more space is needed, use additional sheets and include reference to section and question numbers):

Duty Island	**Duty and Job Description**

2. Did you handle, transport, work in close proximity or come into contact with objects or materials contaminated with radioactive material?

   Yes ____ No ____

   If "No", go to the next numbered question. If "Yes", answer the following questions:

   a. Describe your activities and circumstances for handling, transporting or working near objects or materials with radioactive contamination:

   b. Approximately how many times were you exposed to radioactive contamination? ______________

   c. On average, how much time did each event take? ______________________________________

3. Did you visit any of the northern islands of Enewetak Atoll?

Yes ____ No ____

If “No”, go to the next numbered question. If “Yes”, answer the following question:

a. Describe the purpose of your visits, the name of the islands you visited, and how long the visits lasted:

Island Visited	**Duration**	**Purpose of Visit**

4. Are there any other duties, actions or locations that you think may have caused you to be exposed to radiation during your participation in the Enewetak Cleanup Project? ______________________________

5. On which island were you billeted and what was the type of your living quarters (for example, tent, building, etc.)?

6. Where did you eat your meals:

a. While at work on southern islands? ______________________________

b. On your residence island while off-duty? ______________________________

7. Were you instructed NOT to consume locally gathered foods? Yes ____ No ____

8. If you consumed locally gathered food, what foods did you consume; include approximate quantity and how often?

9. Were you issued personal dosimeters during your assignment at Enewetak Atoll (film badges, TLDs, and pocket dosimeters)

Yes ____ No ____

If "No", go to question 11. If "Yes", answer the following question:

a. Provide details, such as what kind of dosimeter(s) you were provided, when did you wear them, in what areas, etc.:

10. Were you advised of the results of the dose readings from your personal dosimeters?

Yes ____ No ____

If "No", go to next numbered question. If "Yes", answer the following question:

a. Provide any details you remember about the doses from your dosimeters:

11. Additional Comments: Please add any information related to your potential exposure to radiation that you believe was not covered under the questions in this section:

SECTION VI: PERSONNEL WITH DUTIES ON THE NORTHERN ISLANDS OF ENEWETAK ATOLL (REFER TO THE ENCLOSED LIST AND MAP)

The questions in this section are intended to assess your potential for radiation exposure as a military service member who was **assigned duties on the northern islands of Enewetak Atoll** (refer to the enclosed list of islands) during the Enewetak Cleanup Project for any time period from January 1, 1977 to December 31, 1980. You may have been assigned duties on the southern islands in addition to the northern islands. Please provide detailed answers to the best of your recollection. Qualify as "approximate" where necessary. If you are unable to answer a question, state "unknown". If more space is needed for any question, use additional sheets and include reference to section and question numbers.

IMPORTANT NOTE: The Defense Threat Reduction Agency, formerly the Defense Nuclear Agency who was the lead agency of the Enewetak Cleanup Project, generally has a complete record of personnel who visited the restricted access northern islands of the Enewetak Atoll by individual's name, island name and date. This information will be combined with your responses to the questions below, which should include details about your specific job activities, the environmental and site conditions where you worked and radiological protection afforded to you when deemed necessary.

1. Check all cleanup project tasks that you were involved in. List your job occupation and include any relevant comments in the right-hand column below. To assist in your dose assessment, include quantitative information, such as average number of hours per work day engaged in listed tasks, number of times per day, work environment (for example dusty, or soil wetted down, etc.):

Tasks Performed (check all that apply)	**What was your job occupation (include island names and any other comments)**
Contaminated soil cleanup	
☐ Brush clearing/removal	
☐ Soil removal	
☐ Soil loading	
☐ Soil trucking	
☐ Transport by boat	
☐ Concrete/Slurry mixing plant	
☐ Tremie operations (specify your role)	
Debris cleanup (contaminated)	
☐ Collection onshore	
☐ Collection offshore	
☐ Loading	
☐ Offloading at disposal sites	
☐ Transport by boat	

- ☐ Transport by barge
- ☐ Transport by floating platform
- ☐ Crater disposal in (specify your role)

Debris cleanup (non-contaminated)

- ☐ Collection
- ☐ Transport
- ☐ Disposal

Radiological support

- ☐ Radiological control
- ☐ Radiological survey and monitoring
- ☐ Sample collection
- ☐ Radiological laboratory support
- ☐ Radiation control at Army-operated decontamination laundry
- ☐ Radiation safety audit and inspections

Inter-island transport / logistics

☐ Water-based ☐ Air-based

- ☐ Transport of personnel and equipment
- ☐ Transport of cargo (construction materials, water, food, etc.)
- ☐ Boat maintenance
- ☐ Aircraft maintenance

Other activities not listed above

- ☐ ________________________________
- ☐ ________________________________
- ☐ ________________________________

2. What was your typical work schedule?
   a. How many work days per week: ___________
   b. Average hours on northern island(s) per work day: ____________

3. If you were involved in contaminated soil removal, transport or disposal, please answer the following questions:
   a. Was the soil wetted down before removal?.. Yes ____ No ____
   b. Was the soil wetted down after it was loaded for transport by trucks? .... Yes ____ No ____
   c. Was the soil covered with a tarp during transport by truck? .... Yes ____ No ____
   d. Was the soil wetted and covered with tarp during transport by boats?........... Yes ____ No ____

4. Please answer the following questions about personnel protection equipment (PPE):
   a. What type of respiratory protection or other personnel protection equipment (PPE) were you provided while working with contaminated soil or other duties at locations where contaminated soil was handled (check all that applies)?

☐ Full-face mask respirator respirator
☐ Half-face mask
☐ Dust mask
☐ Anti-contamination clothing (Anti-C)
☐ Rubber boots
☐ Gloves
☐ None
☐ Other, describe:

   b. If you used a respirator, what type of respirator did you wear?

☐ Supplied/forced air ☐ Filter cartridge ☐ Did not use a respirator

   c. If you wore a full-face or half-face mask respirator, were you given a fit test?

Yes ____ No ____

   d. Provide detailed description of your work in areas where contaminated soil was disturbed and your use of respiratory protection and other personnel protection equipment:

5. Did you handle, transport, work in close proximity or come into contact with objects or materials contaminated with radioactive material?

   Yes ____ No ____

   If "No", go to the next numbered question.   If "Yes", answer the following questions:

   a. Describe your activities and circumstances for handling, transporting or working near objects or materials with radioactive contamination:

   b. Approximately how many times were you exposed to radioactive contamination? _______________

   c. On average, how much time did each event take? ____

6. Are there any other duties, actions or locations that you think may have caused you to be exposed to radiation during your participation in the Enewetak Cleanup Project?

7. On which island were you billeted and what was the type of your living quarters (for example, tent, building, etc.)?

8. Where did you eat your meals:

   a. While at work on northern islands? ____

   b. On your residence island while off-duty? ____

9. Were you instructed <u>NOT</u> to consume locally gathered foods?   Yes ____ No ____

10. If you consumed locally gathered food, what foods did you consume; include approximate quantity and how often?

11. Were you issued personal dosimeters during your assignment at Enewetak Atoll (film badges, TLDs, and pocket dosimeters)

Yes ____ No ____

If "No", go to question 13. If "Yes", answer the following question:

a. Provide details, such as what kind of dosimeter(s) you were provided, when did you wear them, in what areas, etc.:

12. Were you advised of the results of the dose readings from your personal dosimeters?

Yes ____ No ____

If "No", go to next numbered question. If "Yes", answer the following question:

a. Provide any details you remember about the doses from your dosimeters:

13. Additional Comments: Please add any information related to your potential exposure that you believe was not covered under the questions in this section:

SECTION VII: SIGNATURE

I certify under penalty of perjury under the laws of the United States of America that the information provided on this form is true and correct.

Print Name: ______________________________

Signature: ______________________________ Date: ____________________

SECTION VIII: PRIVACY ACT STATEMENT

AUTHORITY: 42 U.S.C. 2013 (AEC), 38 U.S.C. 1154 and 1112 (Veterans Benefits), 42 U.S.C. 2210 (DOJ compensation program), Pub. L. 108-183 section 601 (Veterans Benefits Act of 2003), Pub. L. 94-367, Pub. L. 100-426 (Radiation Exposure Compensation Act) amended by Pub. L. 100-510, and E.O. 9397 (SSN).

PURPOSE(S): For use by agency officials and employees, or authorized contractors, and other DoD components to provide data or documentation relevant to the processing of administrative claims or litigation; to conduct scientific studies or medical follow-up programs; and in the preparation of the histories of nuclear test programs.

ROUTINE USES: Disclosure of records permitted outside DoD under 5 U.S.C. 552a(b) (Privacy Act) to the Department of Veterans Affairs, Department of Justice, and Department of Labor for identifying and processing claims by individuals who allege job-related disabilities as a result of participation in nuclear test programs and for litigation actions, Veterans Advisory Board on Dose Reconstruction for the purpose of reviewing and overseeing the DoD Radiation Dose Reconstruction Program audits of dose reconstructions and to the Department of Health and Human Services, National Council on Radiation Protection & Measurements, and Vanderbilt University for the purpose of conducting epidemiological studies on the effects of ionizing radiation on participants of nuclear test programs. The DoD 'Blanket Routine Uses' also apply.

DISCLOSURE: Voluntary. However, failure to provide the requested information and authorization may delay or preclude DTRA from providing or releasing information.

Appendix J.

Lagoon and Ocean Water Activity Concentrations

Sampling locations and activity concentrations of radionuclides detected in water samples from the Enewetak Lagoon, craters on several islands of the atoll, and the ocean near the atoll are presented in this Appendix. The information is taken from various figures and tables in (AEC, 1973a) as indicated below.

Fifty-four results from water samples obtained during the 1972 radiological survey are available in AEC (1973a). The sampling locations of these 54 lagoon, crater, and ocean water samples are shown in Figure J-1 (AEC 1973a, Figure 79). Sample identification numbers are given in Figure J-1 next to each sampling location, followed by the sampling depth in feet. Water activity concentrations measured in these samples are shown in Table J-1.

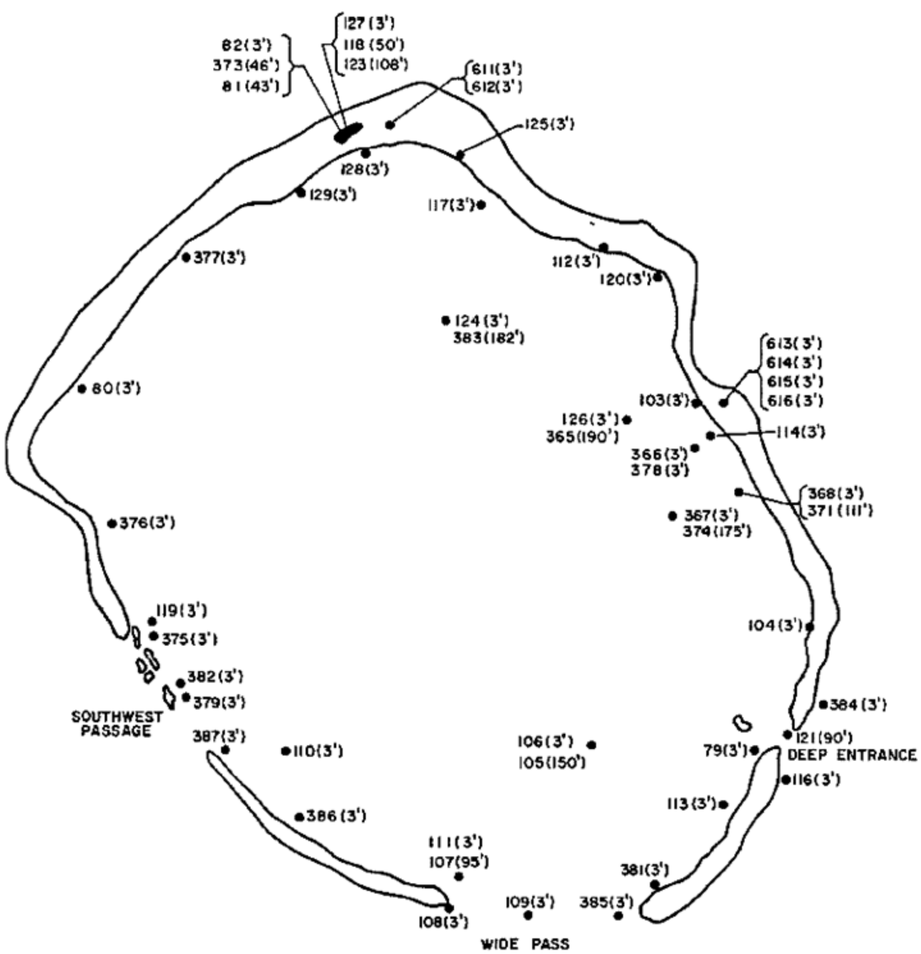

Figure J-1. Location, identification, and sampling depth of 55-liter water samples (AEC 1973a, Figure 79)

Table J-1. Sample characteristics and activity concentrations of Enewetak Atoll lagoon, crater, and ocean water samples

Sample ID #	Sampling Location*	Sampling Depth (ft)	Water sample activity concentration (fCi L^{-1})†, ‡						
			Cs-137	Pu-239/240	Pu-238	Co-60	Eu-155	Bi-207	Am-241
79	Lagoon	3	296	6.0	1.1	-§	-	-	-
80	Lagoon	3	471	32.5	2.7	-	-	-	-
81	Mike crater	93	3200	54.6	1.9	-	-	-	-
82	Mike crater	3	730	23.4	2.0	-	-	-	-
103	Lagoon	3	486	43.6	6.8	116	-	< 224	-
104	Lagoon	3	241	13.1	1.9	-	-	-	-
105	Lagoon	150	300	17.4	2.5	-	-	-	-
106	Lagoon	3	342	22.4	2.2	-	-	-	-
107	Lagoon	95	190	9.6	0.9	-	-	-	-
108	Lagoon entrance	3	229	10.2	1.1	-	-	-	-
109	Lagoon entrance	3	228	9.6	1.0	-	-	-	-
110	Lagoon	3	377	28.9	3.8	-	-	-	-
111	Lagoon	3	258	11.6	1.4	-	-	-	-
112	Lagoon	3	163	15.4	1.9	146	-	< 53	-
113	Lagoon	3	170	4.8	0.6	-	-	-	-
114	Lagoon	3	462	51.9	7.1	518	-	-	-
116	Ocean	3	32	0.43	0.01	-	-	-	-
117	Lagoon	3	107	11.8	1.7	-	-	-	-
118	Koa crater	50	1100	26.4	3.2	-	-	-	-
119	Lagoon	3	290	18.0	2.3	-	-	-	-
120	Lagoon	3	228	7.4	1.1	-	-	-	-
121	Lagoon entrance	90	251	2.8	0.14	-	-	-	-
123	Koa crater	108	8910	1510	236	354	1433	420	346
124	Lagoon	3	579	71.2	10	< 68	-	734	-
125	Lagoon	3	59	6.8	1.6	-	-	-	-
126	Lagoon	3	322	30.4	3.9	< 67	-	261	-
127	Koa crater	3	1170	19	1.7	-	-	-	-
128	Lagoon	3	532	33.1	3	-	-	-	-
129	Lagoon	3	538	44.4	4.4	< 40	-	570	-

Sample ID #	Sampling Location*	Sampling Depth (ft)	Water sample activity concentration (fCi L^{-1})†, ‡						
			Cs-137	Pu-239/240	Pu-238	Co-60	Eu-155	Bi-207	Am-241
365	Lagoon	195	427	3780	1280	842	940	1266	314
366	Lagoon	3	499	77.0	13.3	121	-	258	-
367	Lagoon	3	482	66.2	7.9	-	-	-	-
368	Lagoon	3	410	96.1	14.9	138	-	204	-
371	Lagoon	111	305	75.2	11.2	-	-	-	-
373	Mike crater	46	4220	71.9	7.0	136	-	< 88	-
374	Lagoon	175	462	63.2	9.0	118	-	< 242	-
375	Lagoon	3	305	29.0	3.7	-	-	-	-
376	Lagoon	3	250	18.6	2.6	-	-	-	-
377	Lagoon	3	364	62.9	9.7	< 51	-	413	-
378	Lagoon	167**	497	43.1	7.1	-	-	-	-
379	Lagoon	3	246	14.5	2.1	-	-	-	-
381	Lagoon	3	176	6.8	0.7	-	-	-	-
382	Lagoon	3	766	54.3	4.0	-	-	-	-
383	Lagoon	182	295	53.3	4.6	< 50	67	683	36
384	Ocean	3	146	0.21	0	-	-	-	-
385	Lagoon entrance	3	130	1.6	0.5	-	-	-	-
386	Lagoon	3	291	13.9	2.0	< 61	-	154	-
387	Lagoon	3	109	0.38	0.03	-	-	-	-
611	Seminole Crater	3	970	1330	411	-	-	-	-
612	Seminole Crater	3	212	302	65	-	-	-	-
613	Lacrosse Crater	3	118	57	26	-	-	-	-
614	Cactus Crater	3	935	185	98	-	-	-	-
615	Lacrosse Crater	3	108	46	24	-	-	-	-
616	Cactus Crater	3	302	105	52	-	-	-	-

* See Figure J-1 for sampling locations. Crater locations are identified in Table 58 of AEC (1973a); Sample 612 is incorrectly omitted from Table 58.

† Values for Cs-137, Pu-239/240, and Pu-238 are from Table 55 of AEC (1973a). Values for Co-60, Eu-155, Bi-207, and Am-241 are from Table 54 of AEC (1973a). Values are shown as reported in these tables. Results for several other radionuclides (Rh-102m, Ru-106, Sb-125, Eu-152, and U-235) were below detection limits in all samples (AEC, 1973a).

‡ The unit "fCi L^{-1}" is the same as "fCi kg^{-1}" in AEC (1973a).

§ "-" indicates no result reported.

** The depth shown for Sample 378 in Figure J-1 extracted from AEC (1973a, Figure 79) is assumed incorrect. The correct value is reported here and in Table 55 in AEC (1973a).

Appendix K.

Validation of the Methodology for Estimating External Doses Associated with Handling Contaminated Debris during the Enewetak Cleanup Project

K-1. Introduction

Exposure rate measurements of contaminated debris were made in a 1972 radiological survey performed by teams of the Atomic Energy Commission (AEC) at Enewetak Atoll (AEC, 1973a). The islands from which contaminated debris was removed during ECUP were Janet (Enjebi), Pearl (Lujor), Ruby (Eleleron), Sally (Aomon), and Yvonne (Runit) (DNA, 1981). In this appendix, debris exposure rate data are analyzed and compared with the island-average exposure rates estimated from the 1972 aerial surveys performed by the AEC. Such a comparison allows the validation of the methodology recommended for using island-average exposure rates to assess external doses for ECUP participants who were involved in the cleanup and handling of contaminated debris as discussed in Section 6 of this technical report.

K-1.1. Background

During the preparation of the original version of this technical report in 2018, contaminated debris external exposure rate data collected during ECUP 1977–1980 were not available. Later, debris exposure rate measurements made during the 1972 radiological survey and reported in AEC (1973a) were located, compiled, and analyzed.

K-1.2. Purpose

The analysis in this appendix is provided to validate the hypothesis that island-average exposure rates constitute high-sided values when compared to exposure rates associated with contaminated debris.

K-1.3. Scope and Objectives

The analysis in this appendix applies to individuals who handled contaminated debris during ECUP using heavy equipment such as front loaders, cranes with clamshells, and trucks. These workers moved contaminated debris within a given island and consolidated it into piles on the island shorelines in preparation for transport and disposal offshore. The analysis does not apply to personnel who performed activities related to boat transport of contaminated debris, beach cleanup teams, or those who were involved in handling red debris destined for disposal in the Cactus Crater on Yvonne (Runit) island.

The objectives of the validation analysis are to:

- Develop a methodology for comparing island-average exposure rates from the 1972 aerial surveys with debris exposure rate data collected from direct measurements performed by AEC in the 1972 radiological survey
- Determine exposure rates at distances representative for ECUP workers who performed debris cleanup activities described above

- Compare debris exposure rate data with island-average exposure rates and develop appropriate recommendations.

K-2. Methodology for Estimating and Comparing Debris Exposure Rates

K-2.1. Debris Exposure Rate Data

According to DNA (1981), contaminated debris was removed from five islands: Janet (Enjebi), Pearl (Lujor), Ruby (Eleleron), Sally (Aomon), and Yvonne (Runit). Contemporaneous debris exposure rate data were not available. However, contact exposure rate data and location of contaminated debris from radiological surveys performed in 1972 by AEC were reported in a series of maps for the five islands of interest in AEC (1973a). Descriptions and map locations of such debris are indexed and catalogued in the report of the Engineering Study for a Cleanup Plan of the Enewetak Atoll (H&N, 1973).

Attachment I of this appendix contains the 17 map sheets applicable to the five islands of interest, and exposure rate data are presented in Attachment II of this appendix. Each data point is numbered sequentially on each map sheet to establish a cross-reference between Attachment I and Attachment II by island name, sheet number, and location number.

K-2.2. Representative Exposure Distances and Debris Pile Size

Typical ECUP scenarios depicted in DNA (1981) are for ECUP workers operating a front loader or a crane with a clamshell loading debris into dump trucks or offloading debris in the lagoon. Another relevant scenario is that of truck drivers transporting loads of debris from its original location to stockpiles near the beach for later transport to disposal areas. The estimated distance a person was positioned from debris in loading and transport scenarios is about 10 ft or more, and over 20 ft for crane/clamshell movement of debris. Situations where debris cleanup workers walked close to piles of contaminated debris are possible. However, operators of debris moving machinery and dump trucks rarely would have been located in close proximity of debris piles, as they may only have walked close-by to check on mechanical equipment problems or physical obstacles over short durations, i.e., minutes. For this reason, exposures at distances closer than 10 ft are not considered, and when relevant, these scenarios can be assessed on a case-by-case basis using the methodology described in Section K-2.3.

From a review of pictures in DNA (1981), debris piles were typically 10 to 20 ft in length. A more objective estimate of average pile sizes can be made using the total volume of contaminated debris removed from each island (DNA, 1981). Using these, total volumes, average pile volumes are estimated by assuming that each contact measurement greater than or equal to the criterion of 15 $\mu R\ h^{-1}$ for yellow debris (DNA, 1981) represented a pile of contaminated debris moved by ECUP personnel. To calculate an average size pile for each island, the total volume of contaminated debris removed from the island is divided by the number of measurements greater than or equal to 15 $\mu R\ h^{-1}$. The average pile volumes thus calculated are shown in Attachment III.

K-2.3. Estimation of Mean Debris Exposure Rates

Three commonly used radiation source models were considered to estimate external exposure rate as a function of distance from debris: point source, line source, and disk source. The point source model assumes that the size of the source is small compared to the distance to a point of exposure. The other two models assume that concentrations of radionuclides are distributed uniformly along a line of a finite length or on the surface of a circular disk of a finite radius. Equations K-1, K-2, and K-3 below are adapted from Cember and Johnson (2008) and show the exposure rate as a function of distance *d* for a point, line, and disk source, respectively.

$$I_{pt}(d) = I_{pt}(d_0) \times \frac{d_0^2}{d^2} \quad \text{(K-1)}$$

where

$I_{pt}(d)$	=	Exposure rate at distance *d* from a point source (μR h^{-1})
$I_{pt}(d_0)$	=	Exposure rate at distance d_0 from a point source (μR h^{-1})
d_0	=	Distance from a radiation source with known exposure rate $I_{pt}(d_0)$ (ft)
d	=	Distance from debris that ECUP exposure occurs (ft)

$$I_{line}(d) = I_{line}(d_0) \times \frac{\Theta(d) \times d_0}{\Theta_0 \; d} \quad \text{(K-2)}$$

where

$I_{line}(d)$	=	Exposure rate at distance *d* from a line source, at the mid-point of the line source (μR h^{-1})
$I_{line}(d_0)$	=	Exposure rate at distance d_0 from a line source, at the mid-point of the line source (μR h^{-1})
$\Theta(d)$	=	Angle formed from a point at distance *d* and the ends of the line source (radians)
Θ_0	=	Angle formed from a point at d_0 and the ends of the line source (radians)

$$I_{disk}(d) = I_{disk}(d_0) \times \frac{\ln\left(1 + \frac{R^2}{d^2}\right)}{\ln\left(1 + \frac{R^2}{d_0^2}\right)} \quad \text{(K-3)}$$

where

$I_{disk}(d)$	=	Exposure rate at distance *d* from a disk source, at the center-line of the disk source (μR h^{-1})
$I_{disk}(d_0)$	=	Exposure rate at distance d_0 from a disk source, at the center-line of the disk source (μR h^{-1})
R	=	Radius of disk source (ft)

Figure K-1 shows the graphical representation of the exposure rate as a function of distance for each of the three models described above and assuming uniformly distributed sources for the line and disk source with a known exposure rate of 1 μR h^{-1} at a distance d_0 of 0.5 ft. In this figure, a 5-foot-radius disk source and a 10-foot-long line source are used to estimate exposure rates at various distances from the source.

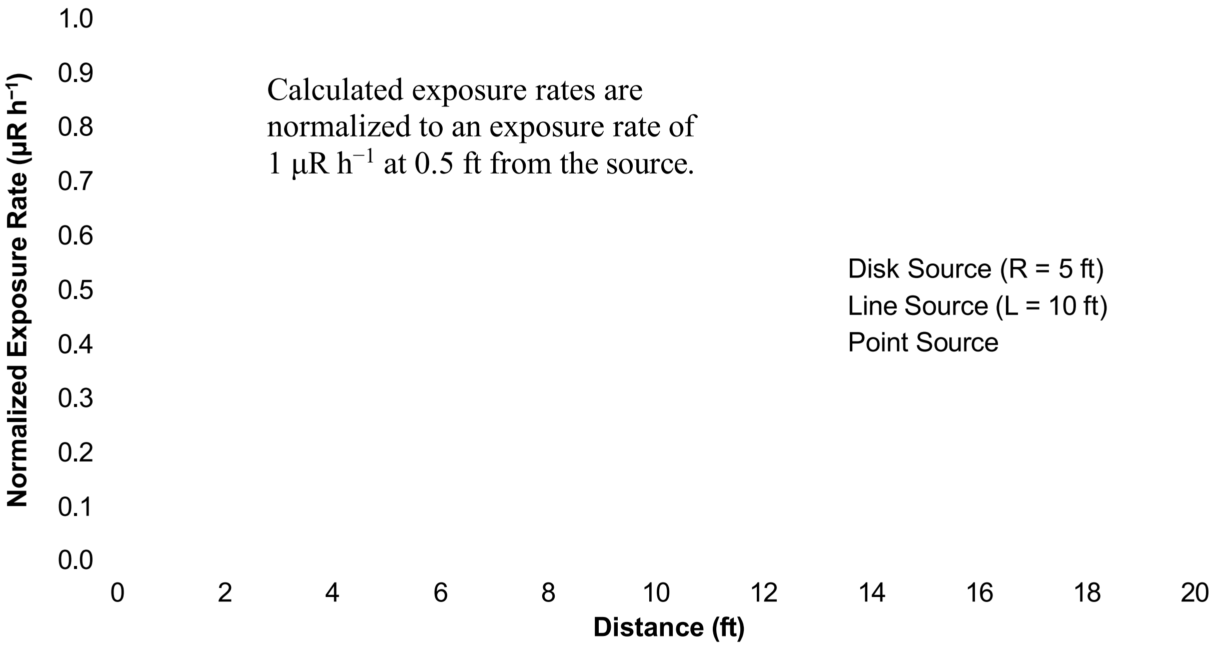

Figure K-1. Exposure rate as a function of distance from radiation sources

The point source model in Figure K-1 shows considerably lower exposure rates at distances to over 20 ft as compared to the line or disk source models. However, the disk source is in general a better representation of the geometry of a debris pile than a point source or a one-dimensional line source at the exposure distances under consideration in this evaluation. The disk source model also provides more conservative estimates of exposure rate as a function of distance than the line or point source models. Therefore, the disk model is selected for the remainder of the analysis to estimate exposure rates for personnel involved in moving, loading and transporting contaminated debris. The results are presented in Section K-3.

To estimate debris exposure rates at the representative exposure distance of 10 ft, a disk with a radius of 5 ft is used for modeling a roughly 10-foot-wide debris pile. Calculations using a disk with a 10-foot radius are also made. These dimensions are consistent with the radii derived from the average-size piles for each island (see Section K-2.2 and Attachment III). These radii for the average debris pile for each island are derived by first representing the average pile volume as an idealized cube, and then calculating the facing area of one side of each cube. Then, the radius of a disk with the same facing area as the cube is calculated. The range of radii thus calculated for the five islands of interest is about 3–9 ft (see Attachment III). Mean exposure rates calculated using these radii and an exposure distance of 10 ft are also shown in Attachment III.

To calculate the mean debris exposure rate for each of the five islands identified above that is applicable to personnel who handled contaminated debris, the 5-foot-radius disk source model is used to obtain the exposure rate at the representative distance of 10 ft using Equation (3). To determine the mean exposure rate for each island, 1) exposure rates are calculated at the 10-foot exposure distance for each reported measurement shown in Attachment II, assuming a representative measurement distance (d_0) of 0.5 ft, and 2) the mean of all 10-foot exposure rates is calculated, which constitutes the mean debris exposure rate for each of the five islands. These island mean exposure rates are then compared to the island-average exposure rates as shown in Section K-3.

K-2.4. Comparison of Mean Debris and Island-Average Exposure Rates

In the original 2018 version of this technical report, an example dose assessment for debris cleanup personnel was included. As a preliminary approach, the island-average exposure rates were used to estimate the external dose. In doing so, it was assumed that the mean exposure rates of contaminated debris were lower than the island-average exposure rates. Therefore, the estimated external dose would be high-sided. The rationale was that the island-average exposure rates, which were derived from the 1972 aerial surveys and some field measurements, included contributions from both soil contamination and radiation emitted by localized sources that included piles of contaminated debris.

To validate the above assumptions and rationale, a comparison is made between the island-average exposure rate and the estimated mean debris exposure rate for each of the five islands identified in Section K-2.1. For each of the five islands that contained contaminated debris, the mean of the debris exposure rates is calculated for a representative exposure distance of 10 ft. Because of the exponential nature of the exposure rate datasets (see Attachment II), they are positively skewed, suggesting lognormal distributions. In addition, most of the medians are not significantly different from the geometric means, again suggesting lognormal distributions. Therefore, the geometric mean is judged the most appropriate estimate of central tendency (NCRP, 2007). The geometric mean is considered most representative of the average debris exposure rate to which a debris cleanup worker would have been exposed on any of the five islands.

K-3. Results and Discussion

K-3.1. Mean Contaminated Debris Exposure Rates

The mean of the debris contact exposure rate measurements as well as corresponding median, minimum, and maximum values for each island are shown in Table K-1. Contact exposure rate measurements were made as close to the debris material as possible, within a few inches. In this analysis, the assumption that the measurement distance was 0.5 ft is conservative, leading to higher estimated rates at the exposure distance of 10 ft. The debris contact exposure rate measurements are provided in Attachment I (maps) and Attachment II (Tables). Table K-1 also includes the number of measurements for each island. It provides the calculated mean exposure rates at the exposure distance of 10 ft estimated using a disk source with a 5-foot radius.

Table K-1. Contaminated debris exposure rates measured at contact and calculated at 10 ft

Islands with Contaminated Debris	Number of Measurements	Contact Measurement (μR h⁻¹)*				Calculated Mean‡ at 10 ft (μR h⁻¹)
		Mean†	Median	Min	Max	
Janet (Enjebi)	160	27	19	3	8,500	1.3
Yvonne (Runit)	85	29	30	1	60,000	1.4
Pearl (Lujor)	15	147	250	3	5,000	7.1
Ruby (Eleleron)	6	19	18	6	120	0.93
Sally (Aomon)	10	35	19	8	3,000	1.7

* It is assumed that contact measurements were made within a few inches of the surface of the debris. To high side the calculated exposure rates in this table, measurements are assumed made at 0.5 ft.

† Geometric mean.

‡ Calculated exposure rates are estimated for each debris contact measurement, from a disk source with a 5-foot radius at an exposure distance of 10 ft. This exposure distance is assumed the closest distance at which personnel would have typically handled contaminated debris using heavy equipment.

K-3.2. Comparison of Mean Debris Exposure Rates with Island-average Exposure Rates

The calculated exposure rates at the representative distance of 10 ft, shown in Table K-1, are compared with the island-average exposure rate as shown in Table K-2. The side-by-side comparison in Table K-2 shows that the island-average exposure rates derived from the 1972 aerial surveys are factors of about 4 to 30 above the means of the debris exposure rates at 10 ft calculated using a 5-foot disk source. Similar exposure rates estimated using a 10-ft radius disk source result in such factors being 2 to 13. A 10-foot radius disk encompasses the calculated disk radii of the average contaminated debris piles on the five islands (see Attachment III, Table III-1).

Table K-2. Comparison of mean calculated exposure rates from contaminated debris data and island-average exposure rates from 1972 aerial survey

Island with Contaminated Debris	Debris Mean Exposure Rate at 10 ft (μR h⁻¹)	Island-Average Exposure Rate (μR h⁻¹)*
Janet (Enjebi)	1.3	40
Yvonne (Runit)	1.4	33
Pearl (Lujor)	7.1	70
Ruby (Eleleron)	0.93	14
Sally (Aomon)	1.7	7

* From 1972 aerial survey, estimated at 1 meter from the ground (AEC, 1973a).

In summary, despite the broadness of the debris exposure rate data, it is found that the island-average exposure rates are considerably higher than the mean of the debris exposure rates for all five islands at the representative distance of 10 ft. However, given the existence of debris at several locations on the five islands with rather high exposure rates as shown in Appendix K and Attachment II, it is possible that an individual was exposed at levels higher than the island-average exposure rates. In such a case, dose estimates can be based on a single or a combination of debris exposure rate measurements that are selected based on a veteran's statements and responses in the ECUP Questionnaire. The selected debris exposure rate measurements would be identifiable to specific geographic island locations. The exposure times should be commensurate with the time it would have taken to clean up the specified volume of debris as documented in H&N (1973).

K-4. Conclusions and Recommendations

The results of the validation confirm that island-average exposure rates derived from the 1972 AEC aerial survey are consistently higher than the means of the debris exposure rates calculated at the representative exposure distance of 10 ft. The island-average exposure rates are a factor 4 to 30 higher than the mean debris exposure rates at the 10-foot reference distance and assuming a disk source with a radius of 5 ft. Similar results are obtained for a disk source with a radius of 10 ft at the representative distance of 10 ft.

The primary recommendation is that for personnel who were involved in direct cleanup activities of contaminated debris on the five islands from which contaminated debris was removed, the island-average exposure rate should be used to estimate external doses. This recommendation does not apply to personnel who performed activities other than debris cleanup on the five islands, e.g., boat transport of contaminated debris. In addition, the recommendation does not apply to personnel who handled red debris destined for disposal in the Cactus Crater on Runit.

Finally, in some cases where specific information is provided by a veteran relating to working on specified contaminated debris documented in H&N (1973), a single or a combination of debris exposure rates can be used to estimate external doses. It would be the dose assessment analyst's decision whether to use this option.

Attachment I.

Maps of the Islands where Contaminated Debris was Removed during ECUP

Figure I-1 through Figure I-17 are maps of the islands of Ruby (Figure I-1), Sally (Figure I-2 and Figure I-3), Pearl (Figure I-4 and Figure I-5), Yvonne (Figure I-6 through Figure I-10), and Janet (Figure I-11 through Figure I-17). All figures were adapted from AEC (1973a). The figures show sequence numbers in red color and exposure rate measurements in black block font that correspond to the respective columns of the tables in Attachment II. The figures are for use in conjunction with the tables in Attachment II.

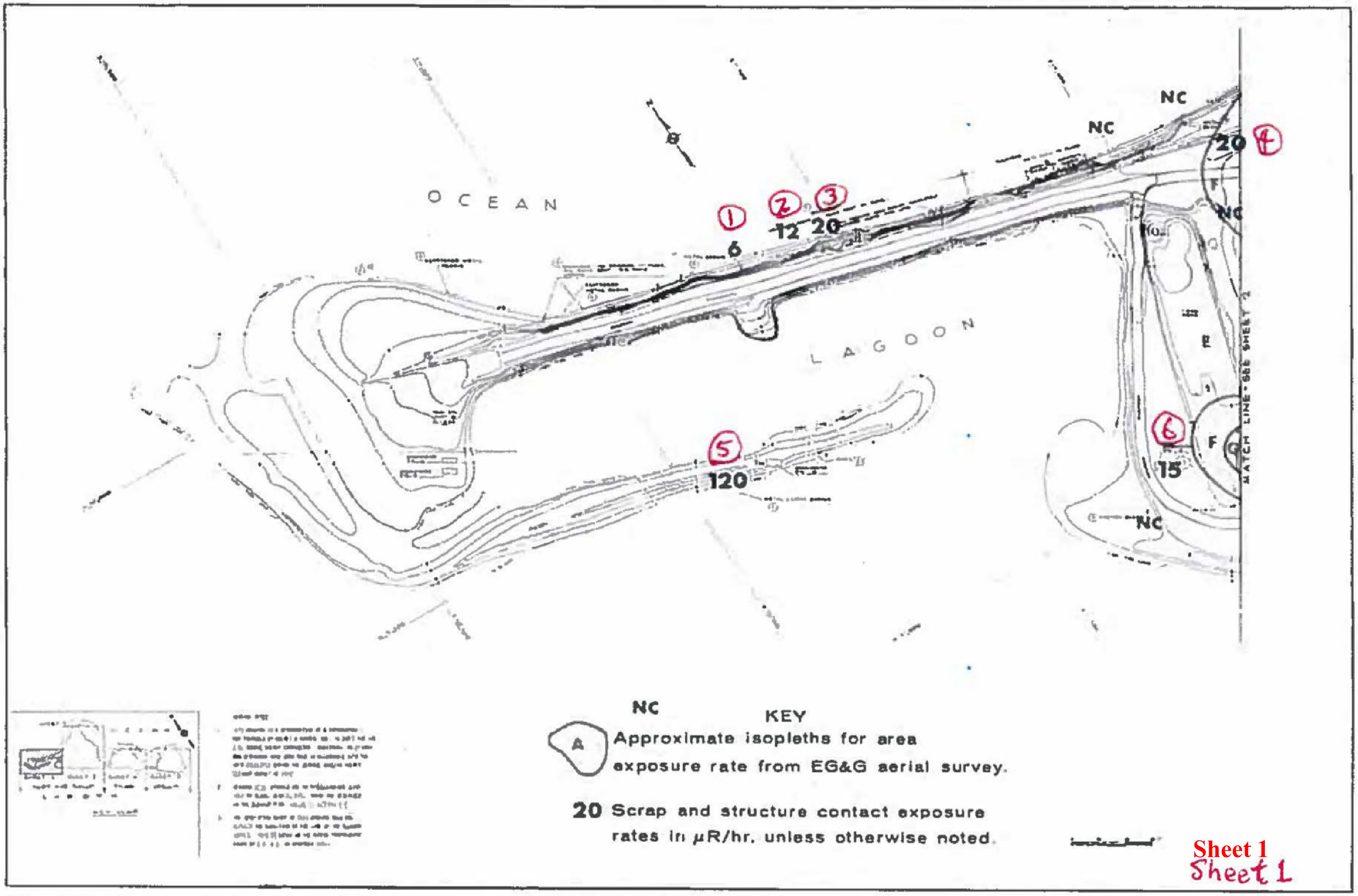

Figure I-1. Measured radiation exposure rates on Ruby

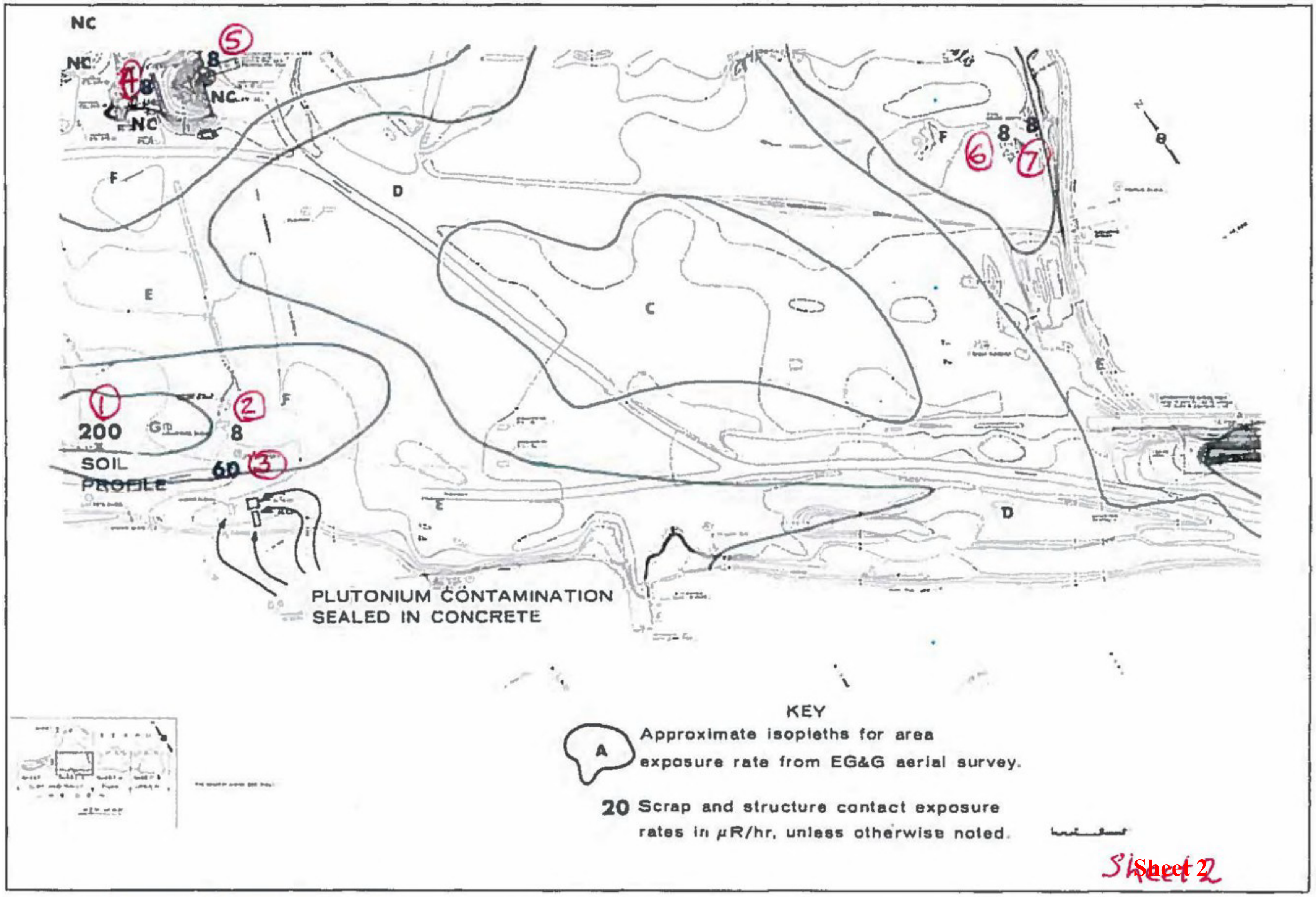

Figure I-2. Measured radiation exposure rates on Sally No. 1

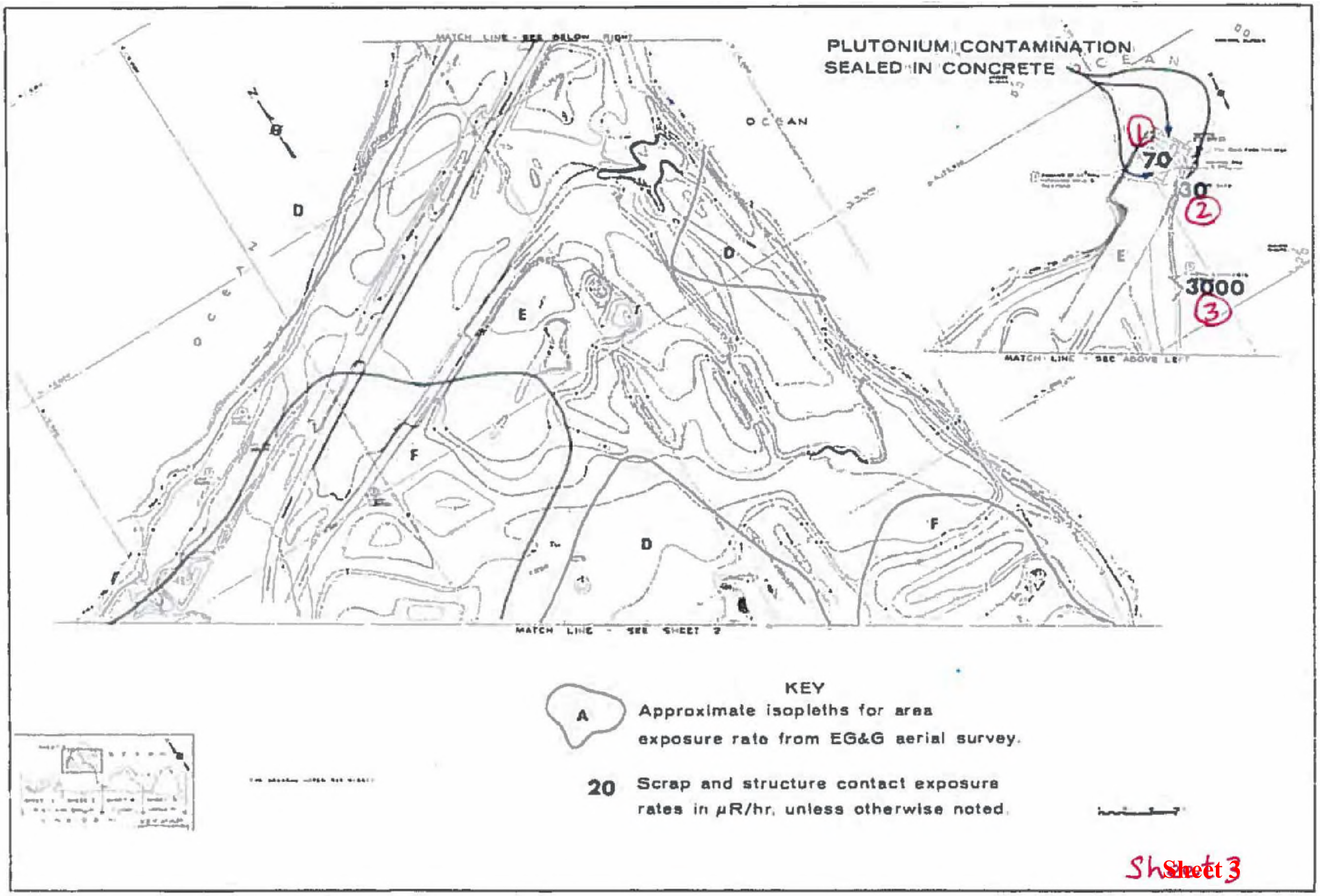

Figure I-3. Measured radiation exposure rates on Sally No 2

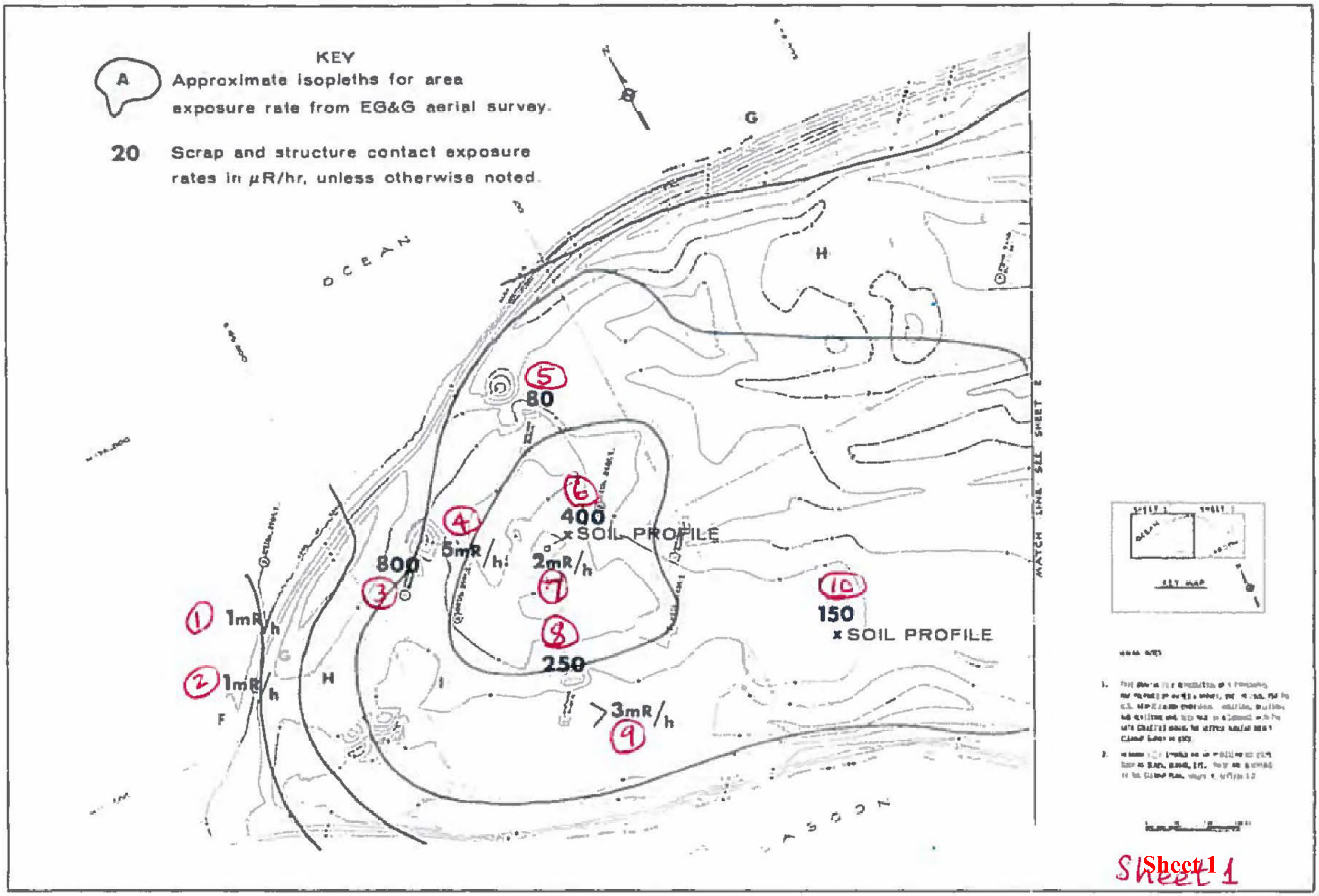

Figure I-4. Measured radiation exposure rates on Pearl No. 1

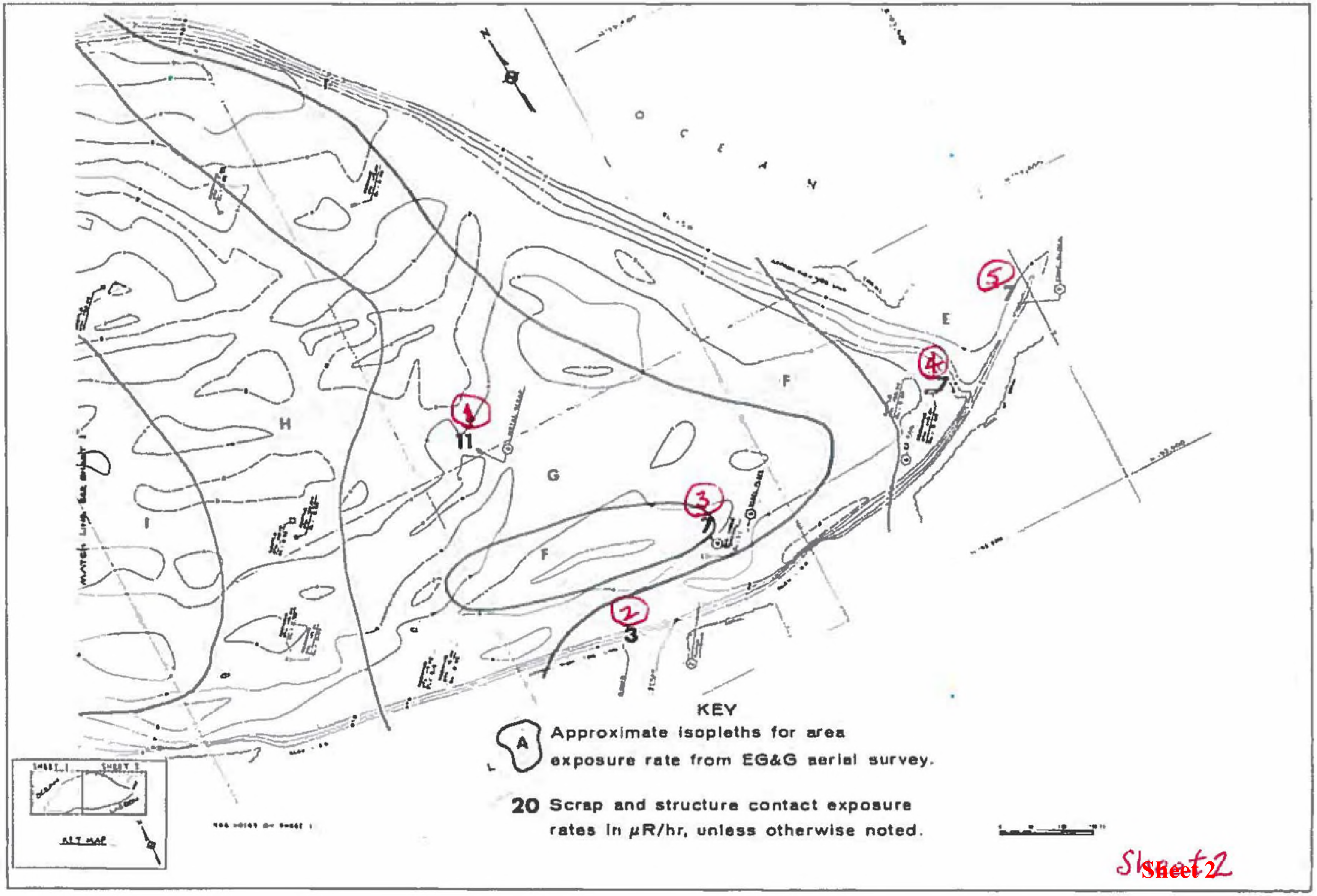

Figure I-5. Measured radiation exposure rates on Pearl No. 2

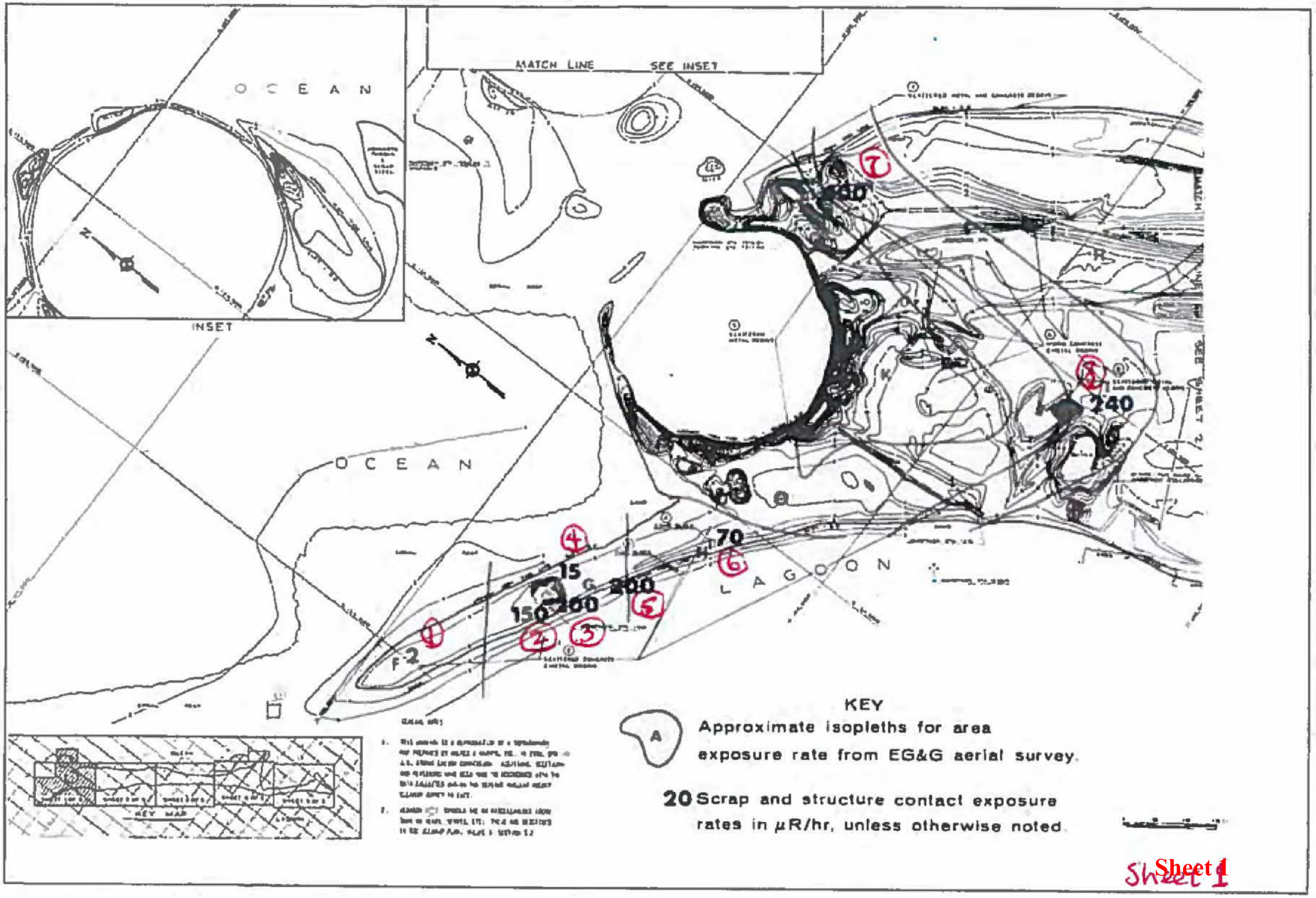

Figure I-6. Measured radiation exposure rates on Yvonne No. 1

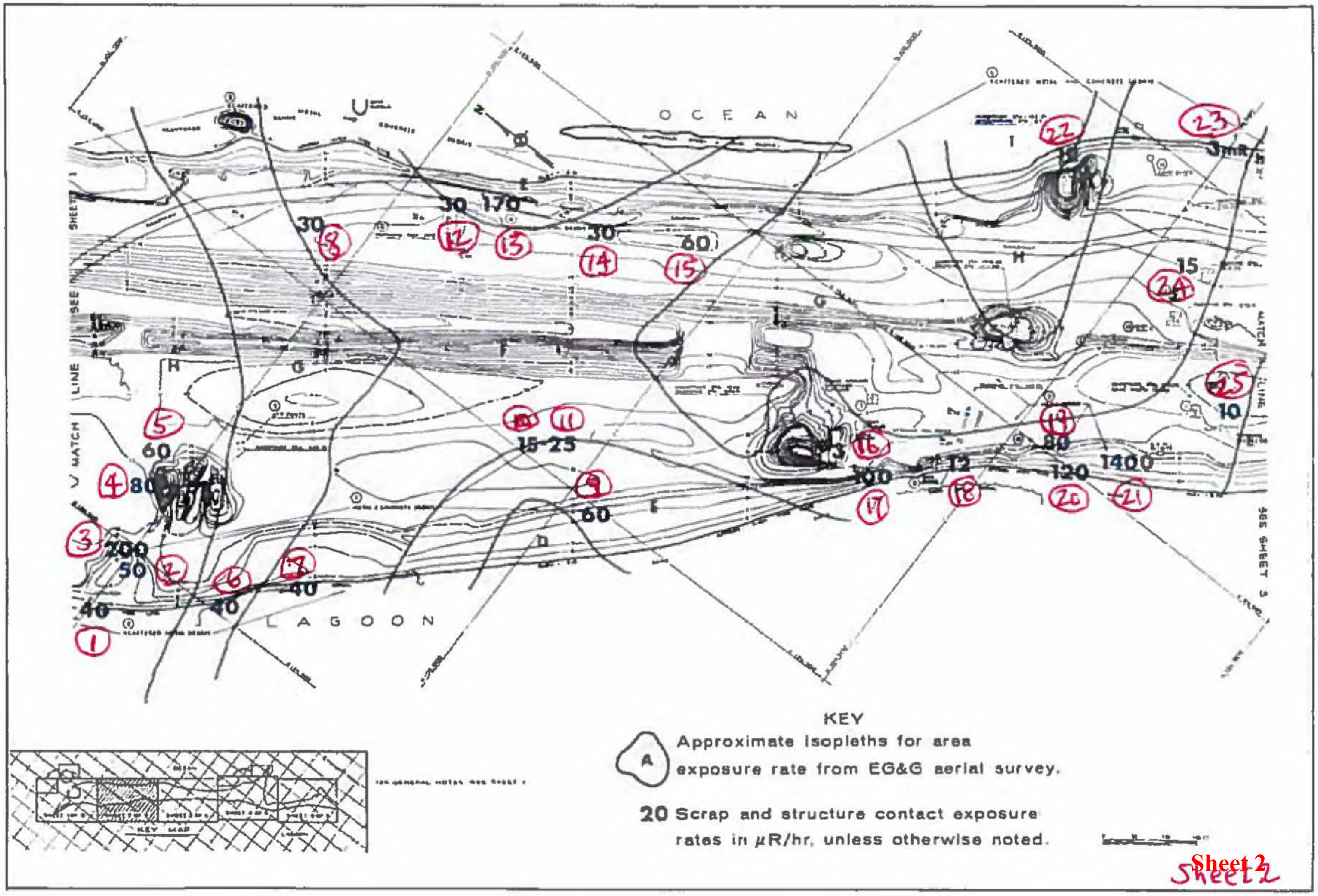

Figure I-7. Measured radiation exposure rates on Yvonne No. 2

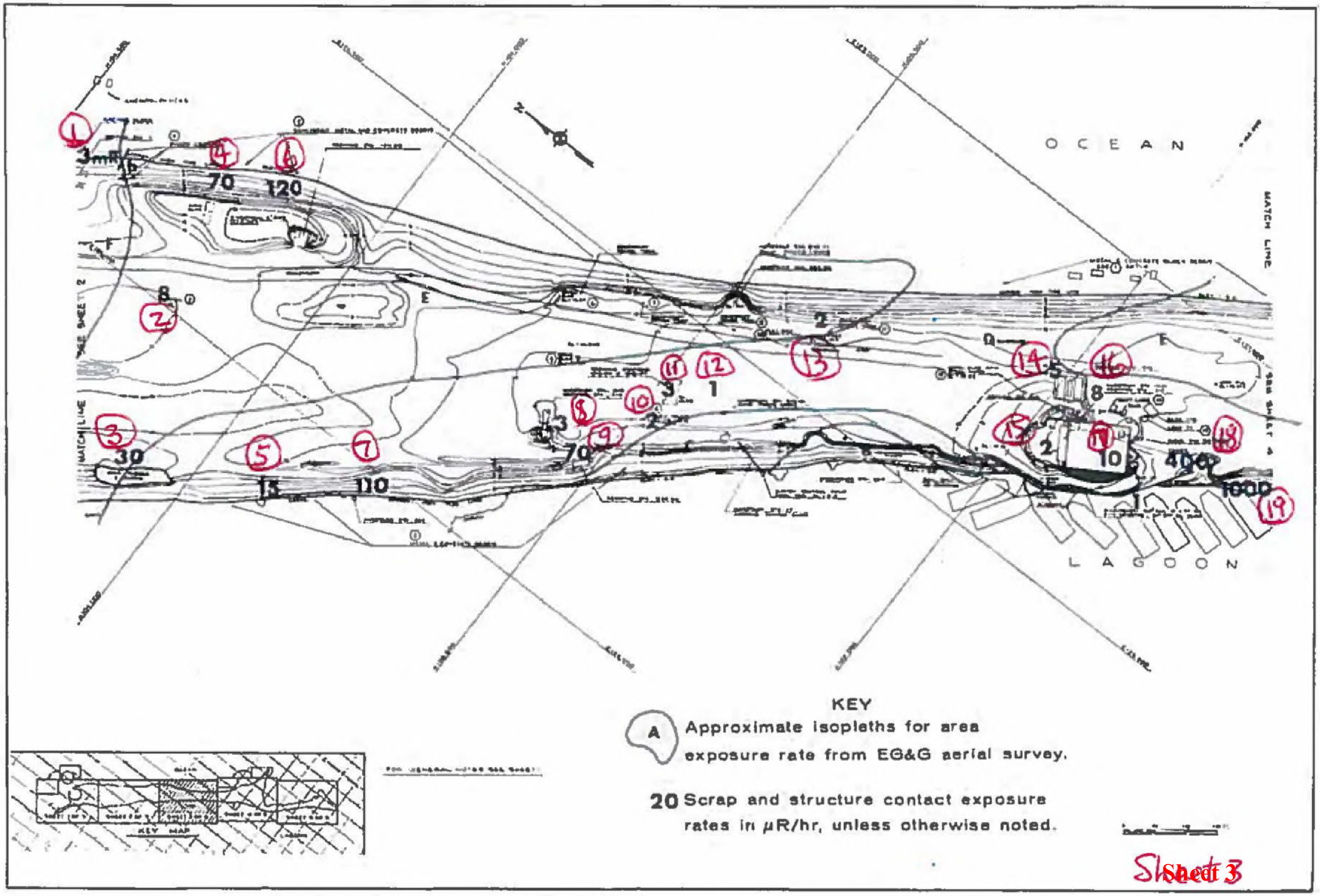

Figure I-8. Measured radiation exposure rates on Yvonne No. 3

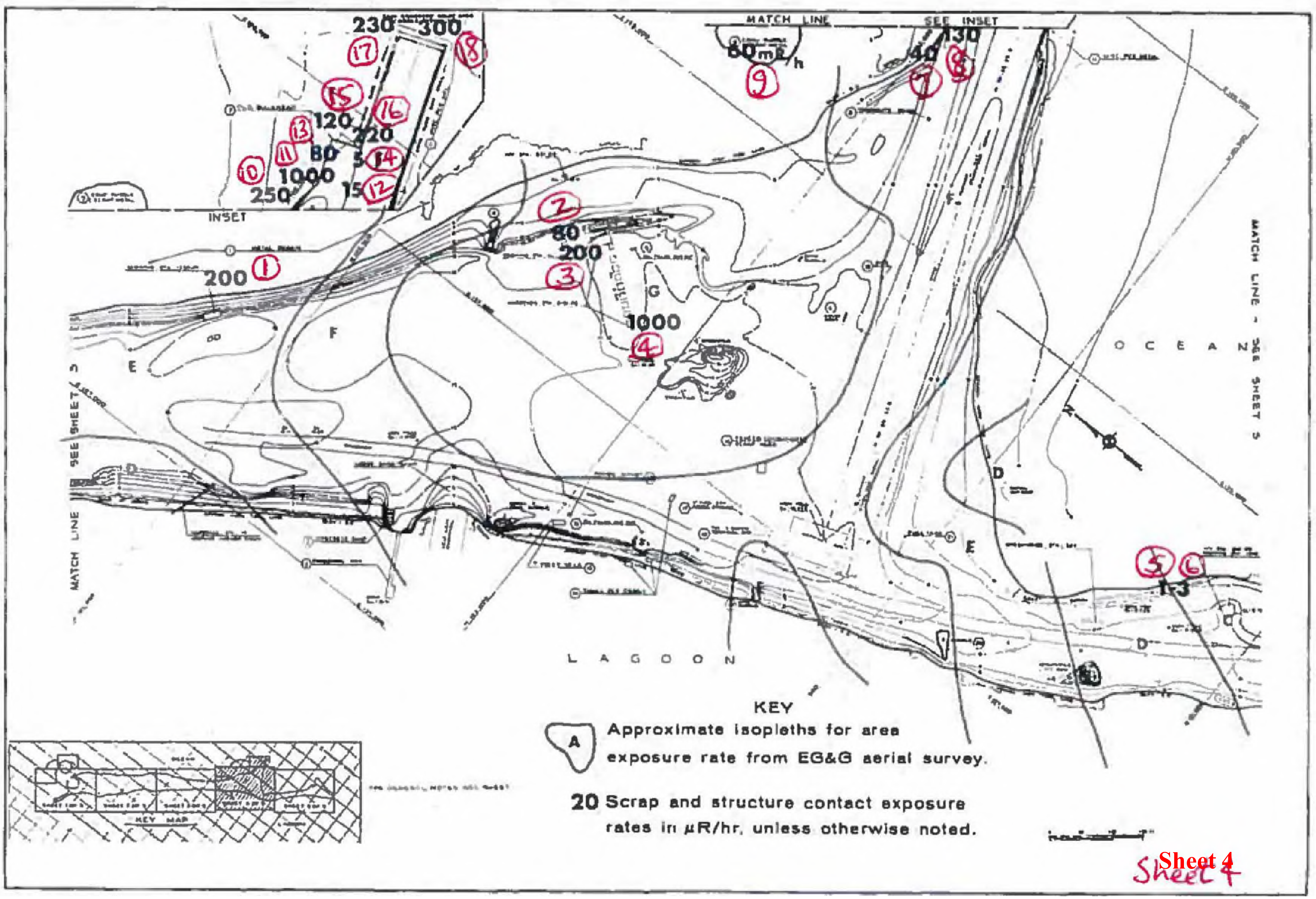

Figure I-9. Measured radiation exposure rates on Yvonne No. 4

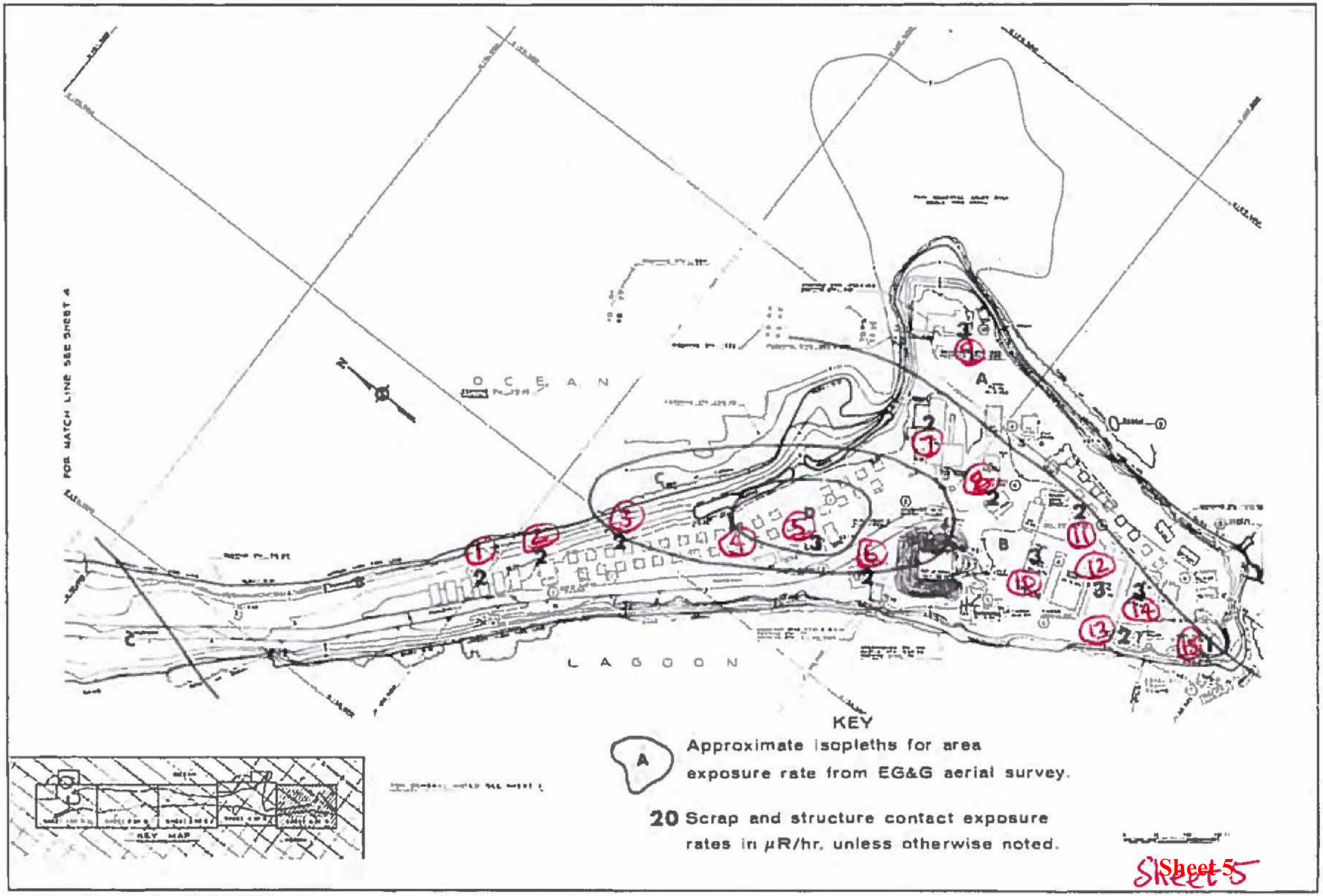

Figure I-10. Measured radiation exposure rates on Yvonne No. 5

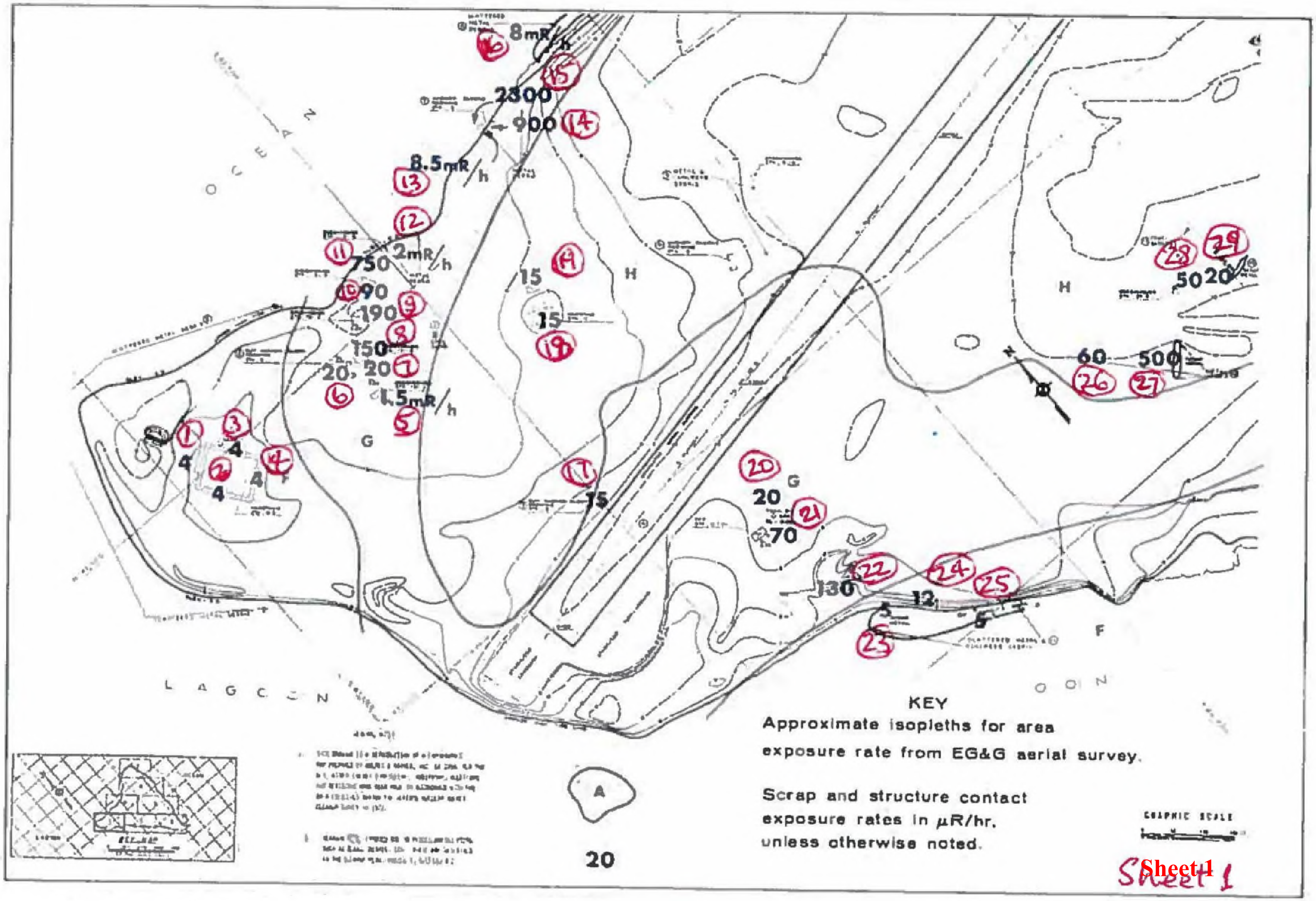

Figure I-11. Measured radiation exposure rates on Janet No. 1

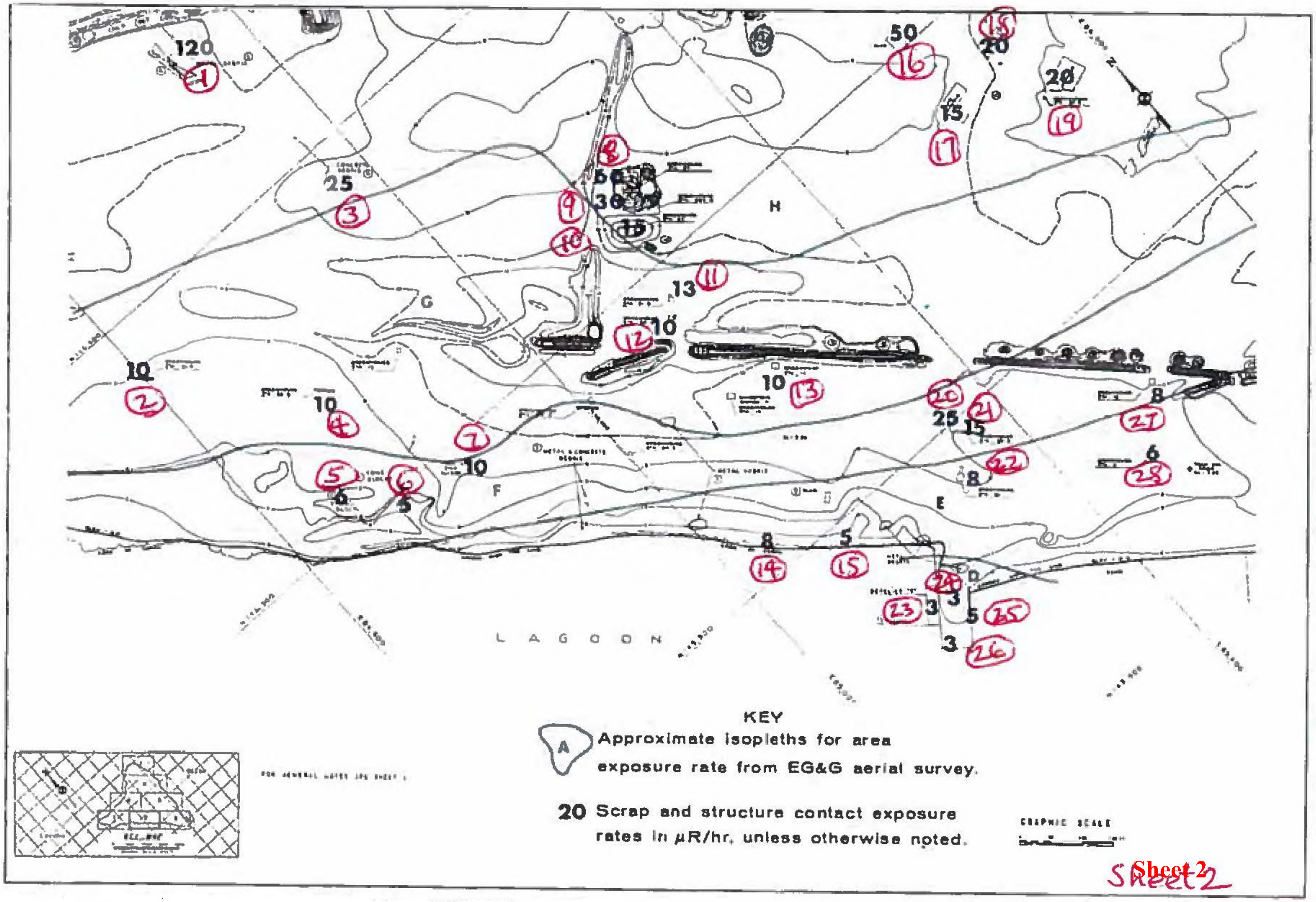

Figure I-12. Measured radiation exposure rates on Janet No. 2

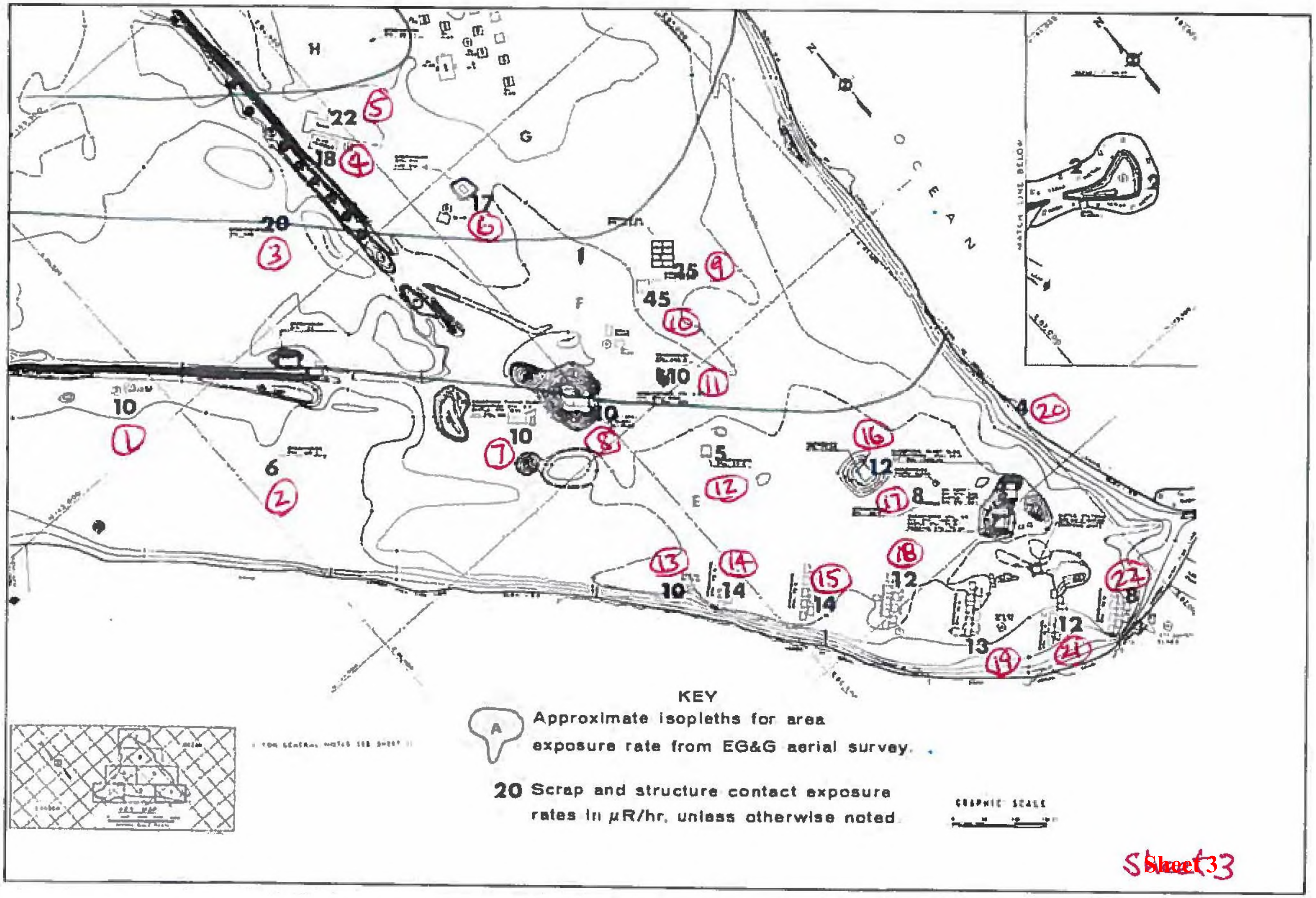

Figure I-13. Measured radiation exposure rates on Janet No. 3

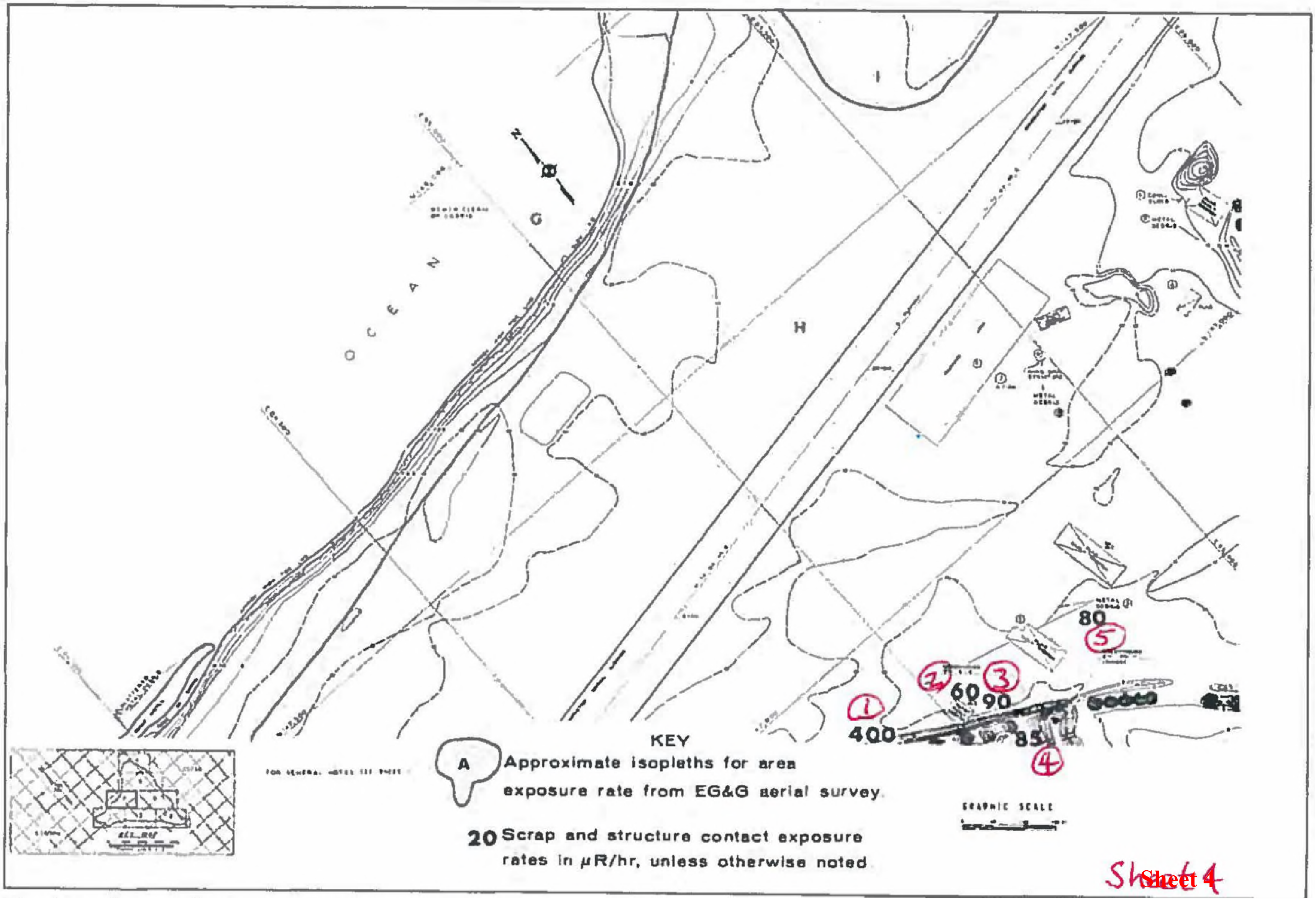

Figure I-14. Measured radiation exposure rates on Janet No. 4

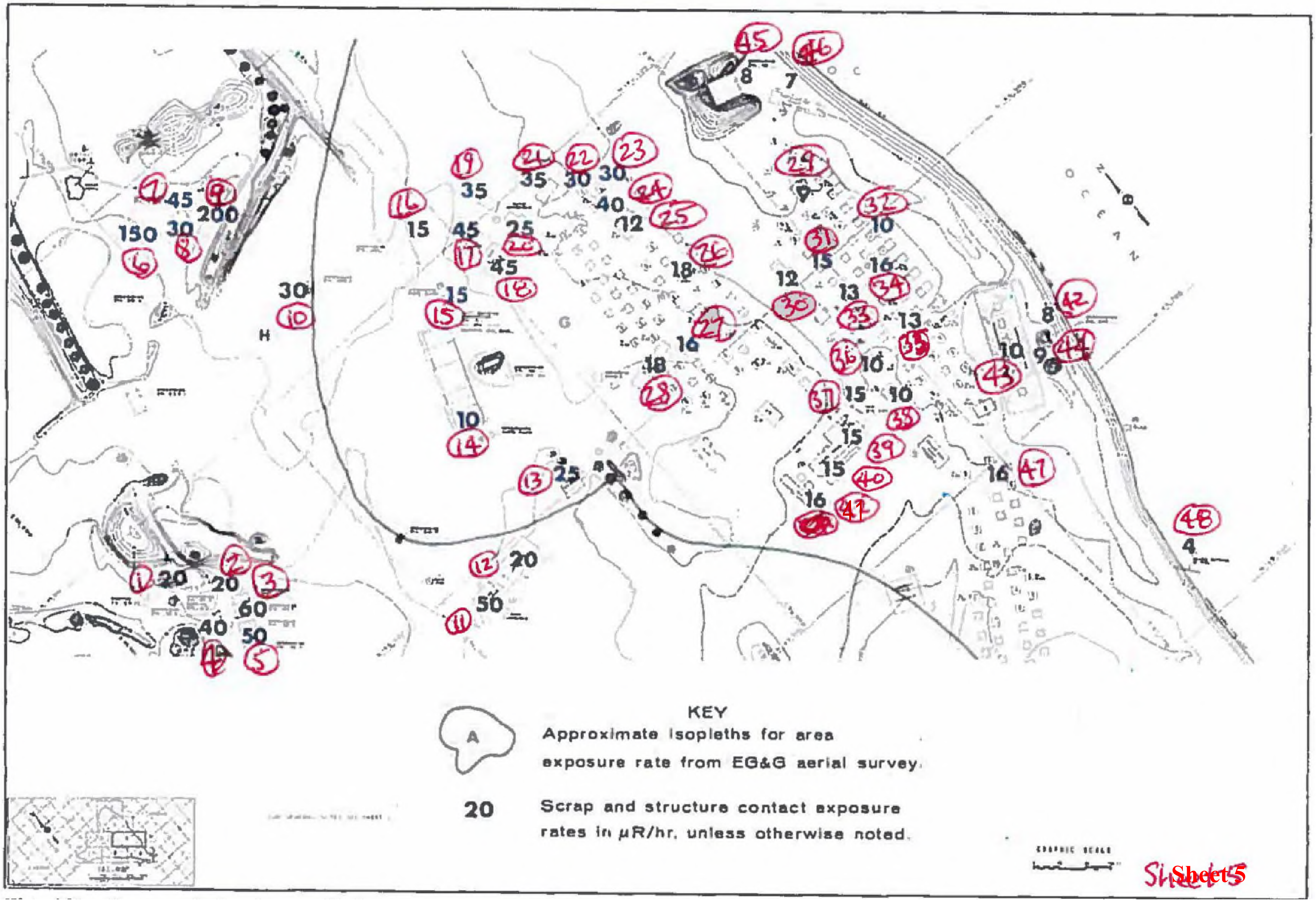

Figure I-15. Measured radiation exposure rates on Janet No. 5

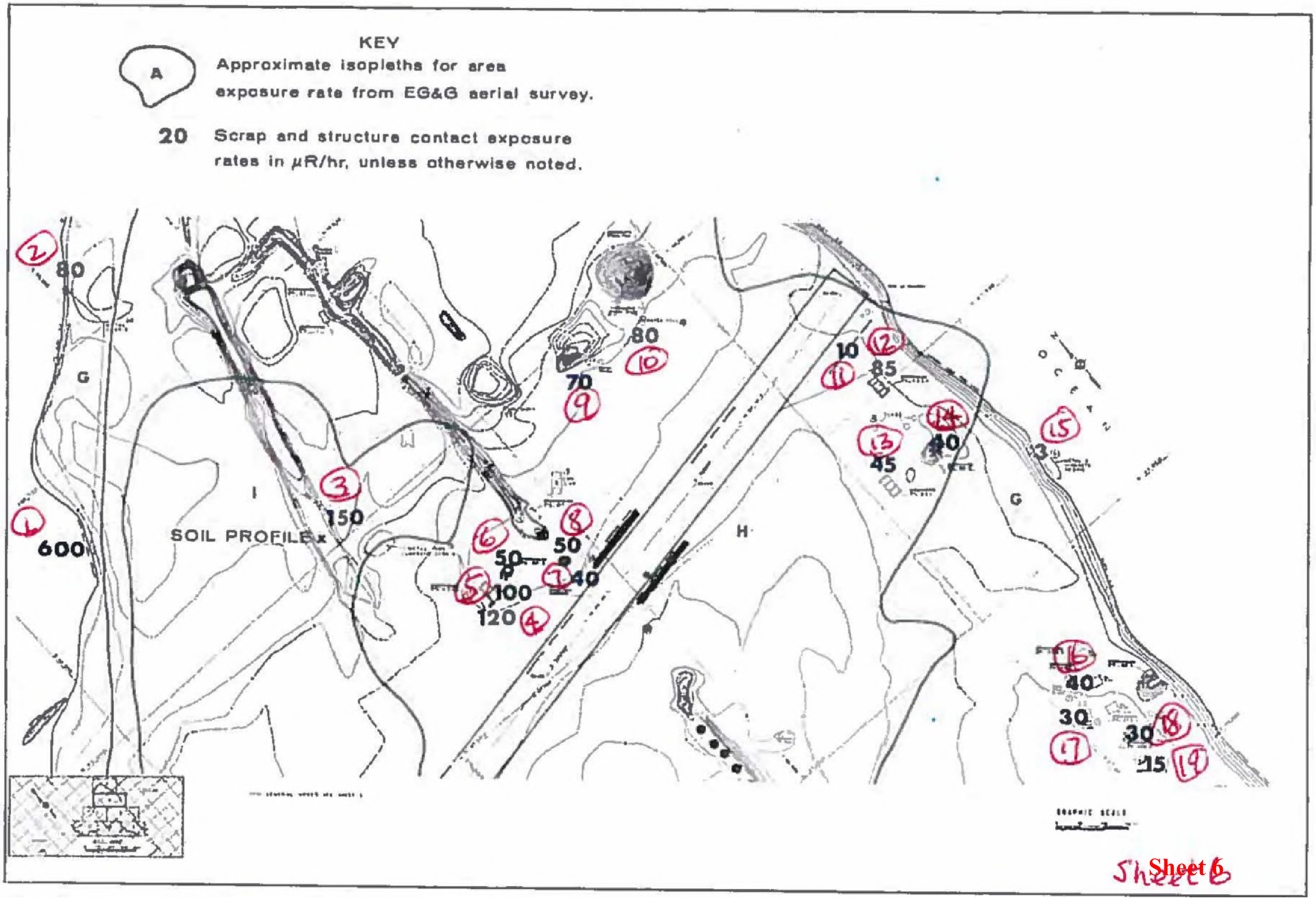

Figure I-16. Measured radiation exposure rates on Janet No. 6

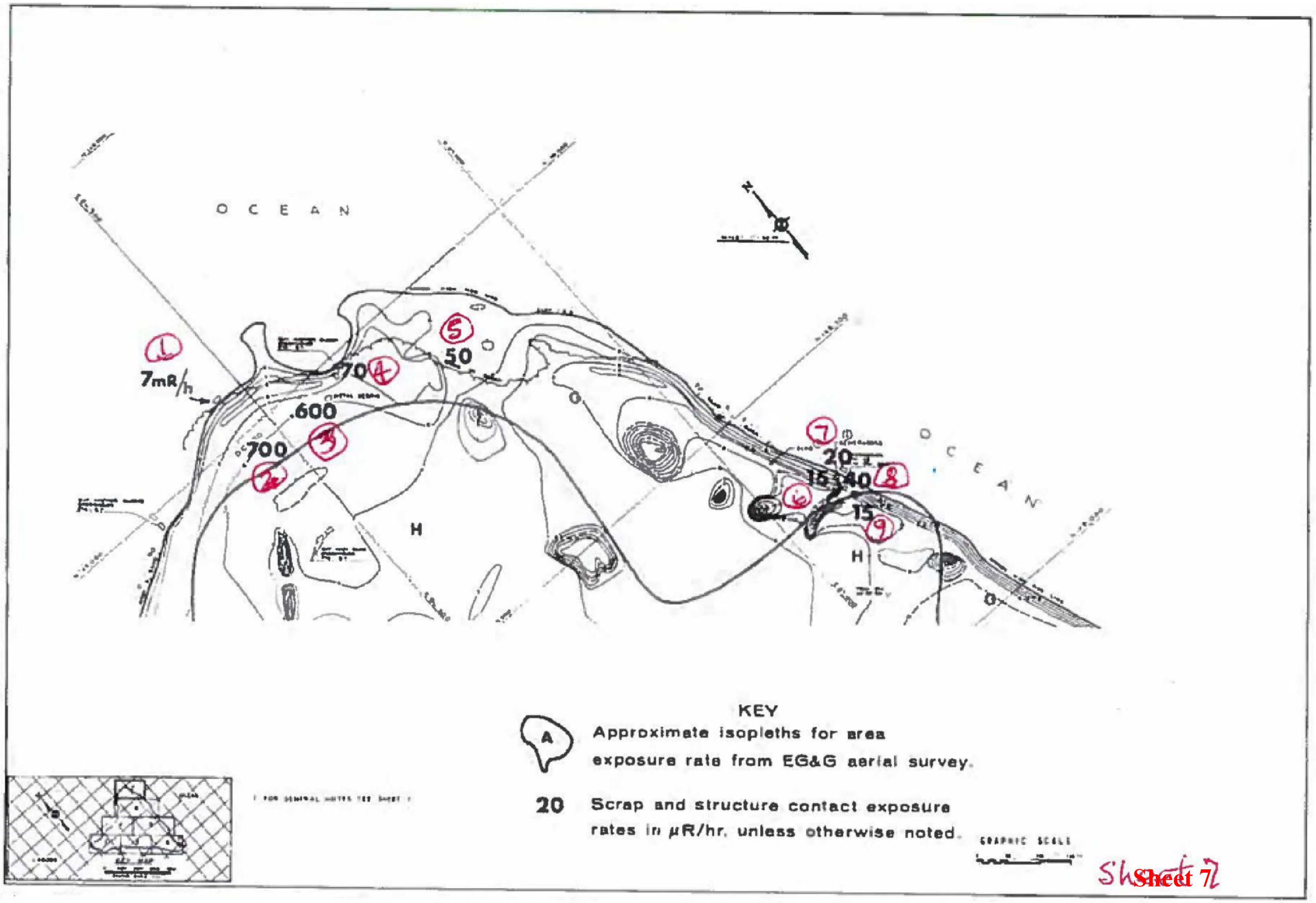

Figure I-17. Measured radiation exposure rates on Janet No. 7

Attachment II.

Exposure Rate Measurements on Islands where Contaminated Debris was Removed during ECUP

Table II-1 to Table II-5 list the debris radiation exposure rate contact measurements and map locations for the islands of Ruby, Sally, Pearl, Yvonne, and Janet. The measurements were extracted from maps in AEC (1973a). The map sheet and sequence numbers in the tables in this attachment crosslink to the exposure rates shown on the maps in Attachment I. Additional debris description information is available in H&N (1973).

Table II-1. Radiation exposure rates on Ruby

Map*	Sequence Number (See Map)	Exposure Rate ($\mu R\ h^{-1}$)	Location Number/ Station Number
Island: Ruby			
Figure I-1 (Sheet 1 of Ruby/Sally Map)	1	6	8
	2	12	9
	3	20	9
	4	20	12
	5	120	1
	6	15	Greenhouse Station 12

* Maps and exposure rates from AEC (1973a) and Attachment I.

Table II-2. Radiation exposure rates on Sally

Map *	Sequence Number (See Map)	Exposure Rate ($\mu R\ h^{-1}$)	Location Number/ Station Number
Island: Sally			
Figure I-2 (Sheet 2 of Ruby/Sally Map)	1	200	Slightly north of road way
	2	8	2
	3	60	3
	4	8	Redwing Stations 2221.01/02/03
	5	8	Loading Dock north of Redwing Station 2211
	6	8	12
	7	8	13
Figure I-3 (Sheet 3 of Ruby/Sally Map)	1	70	Redwing Stations 1 and 3011
	2	30	5 (Concrete slab)
	3	3,000	6

* Maps and exposure rates from AEC (1973a) and Attachment I.

Table II-3. Radiation exposure rates on Pearl

Map*	Sequence Number (See map)	Exposure Rate ($\mu R\ h^{-1}$)	Location Number/ Station Number
Island: Pearl			
Figure I-4 (Sheet 1 of Pearl Map)	1	1,000	3
	2	1,000	slightly south of location 3
	3	800	1 (central point on map)
	4	5,000	6
	5	80	1 (northernmost point on map)
	6	400	slightly NE of location 2
	7	2,000	2
	8	250	5
	9	3,000	1 (southernmost point on map)
	10	150	East of location 5
Figure I-5 (Sheet 2 of Pearl Map)	1	11	8
	2	3	3
	3	7	4
	4	7	Castle Station 120.22
	5	7	7

* Maps and exposure rates from AEC (1973a) and Attachment I.

Table II-4. Radiation exposure rates on Yvonne

Map*	Sequence Number (See Map)	Exposure Rate ($\mu R\ h^{-1}$)
Island: Yvonne		
Figure I-6 (Sheet 1 of Yvonne Map)	1	2
	2	150
	3	200
	4	15
	5	200
	6	70
	7	400
	8	240
Figure I-7 (Sheet 2 of Yvonne Map)	1	40
	2	50
	3	200
	4	80

Map[*]	Sequence Number (See Map)	Exposure Rate (µR h^{-1})
Island: Yvonne		
	5	60
	6	40
	7	40
	8	30
	9	60
	10	15
	11	25
	12	30
	13	170
	14	30
	15	60
	16	3
	17	100
	18	12
	19	80
	20	120
	21	1,400
	22	12
	23	3,000
	24	15
	25	10
Figure I-8 (Sheet 3 of Yvonne Map)	1	3,000
	2	8
	3	30
	4	70
	5	15
	6	120
	7	110
	8	3
	9	70
	10	2
	11	3
	12	1
	13	2
	14	5
	15	2
	16	8
	17	10
	18	400
	19	1,000

Map*	Sequence Number (See Map)	Exposure Rate (μR h^{-1})
Island: Yvonne		
Figure I-9 (Sheet 4 of Yvonne Map)	1	200
	2	80
	3	200
	4	1,000
	5	1
	6	3
	7	40
	8	130
	9	60,000
	10	250
	11	1,000
	12	15
	13	80
	14	5
	15	120
	16	220
	17	230
	18	300
Figure I-10 (Sheet 5 of Yvonne Map)	1	2
	2	2
	3	2
	4	1
	5	3
	6	2
	7	2
	8	2
	9	3
	10	3
	11	2
	12	3
	13	2
	14	3
	15	1

* Maps and exposure rates from AEC (1973a) and Attachment I.

Table II-5. Radiation exposure rates on Janet

Map*	Sequence Number (See Map)	Exposure Rate (μR h^{-1})
Island: Janet		
Figure I-11 (Sheet 1 of Janet Map)	1	4
	2	4
	3	4
	4	4
	5	1,500
	6	20
	7	20
	8	150
	9	190
	10	90
	11	750
	12	2,000
	13	8,500
	14	900
	15	2,300
	16	8,000
	17	15
	18	15
	19	15
	20	20
	21	70
	22	130
	23	5
	24	12
	25	5
	26	60
	27	500
	28	50
	29	20
Figure I-12 (Sheet 2 of Janet Map)	1	120
	2	10
	3	25
	4	10
	5	6
	6	5
	7	10
	8	60
	9	30
	10	15
	11	13

Map*	Sequence Number (See Map)	Exposure Rate (μR h^{-1})
Island: Janet		
	12	10
	13	10
	14	8
	15	5
	16	50
	17	15
	18	20
	19	20
	20	25
	21	15
	22	8
	23	3
	24	3
	25	5
	26	3
	27	8
	28	6
Figure I-13 (Sheet 3 of Janet Map)	1	10
	2	6
	3	20
	4	18
	5	22
	6	17
	7	10
	8	10
	9	25
	10	45
	11	10
	12	5
	13	10
	14	14
	15	14
	16	12
	17	8
	18	12
	19	13
	20	4
	21	12
	22	8
Figure I-14 (Sheet 4 of Janet Map)	1	400
	2	60
	3	90

Map*	Sequence Number (See Map)	Exposure Rate (μR h^{-1})
Island: Janet		
	4	85
	5	80
Figure I-15 (Sheet 5 of Janet Map)	1	20
	2	20
	3	60
	4	40
	5	50
	6	150
	7	45
	8	30
	9	200
	10	30
	11	50
	12	20
	13	25
	14	10
	15	15
	16	15
	17	45
	18	45
	19	35
	20	25
	21	35
	22	30
	23	30
	24	40
	25	12
	26	18
	27	16
	28	18
	29	9
	30	12
	31	15
	32	10
	33	13
	34	16
	35	13
	36	10
	37	15
	38	10
	39	15
	40	15

Map*	Sequence Number (See Map)	Exposure Rate (μR h^{-1})
Island: Janet		
	41	16
	42	8
	43	10
	44	9
	45	8
	46	7
	47	16
	48	4
Figure I-16 (Sheet 6 of Janet Map)	1	600
	2	80
	3	150
	4	120
	5	100
	6	50
	7	40
	8	50
	9	70
	10	80
	11	10
	12	85
	13	45
	14	40
	15	3
	16	40
	17	30
	18	30
	19	15
Figure I-17 (Sheet 7 of Janet Map)	1	7,000
	2	700
	3	600
	4	70
	5	50
	6	15
	7	20
	8	40
	9	15

* Maps and exposure rates from AEC (1973a) and Attachment I.

Attachment III.

Estimated Sizes and Exposure Rates for Contaminated Debris Piles

The estimated average size of contaminated debris piles on each of the islands from which contaminated debris was removed are shown in Table III-1. An explanation of the derivation of these values is given in Section K-2.2 and Section K-2.3.

The calculated exposure rates at the representative distance of 10 ft from the average piles for each island, estimated using the equivalent disk radii shown in Table III-1, are compared with the island-average exposure rate in Table III- 2. The calculation of the mean exposure rates is described in Section K-2.3.

Table III-1. Estimated average sizes of contaminated debris piles

Island	Contaminated Debris Removed (yd^3)[*]	Number of Contaminated Debris Locations[†]	Average Pile Volume (yd^3)	Length of Idealized Cube Side (ft)[‡]	Facing Area of Cube (ft^2)	Equivalent Disk Radius (ft)[§]
Janet (Enjebi)	530	103	5.1	5.2	26.8	2.9
Yvonne (Runit)	4,120	52	79.2	12.9	166	7.3
Pearl (Lujor)	255	10	25.5	8.8	78.0	5.0
Ruby (Eleleron)	250	4	62.5	11.9	142	6.7
Sally (Aomon)	728	5	146	15.8	249	8.9

[*] From DNA (1981), Figure 5-34.

[†] Locations with contaminated debris are those where the measured contact exposure rate is greater than or equal to 15 $\mu R\ h^{-1}$ as reported in AEC (1973a).

[‡] This is the length of one side of a cube with a volume equal to the volume of the average pile.

[§] Radius of a disk with an area equal to the facing area of the assumed cube geometry.

Table III- 2. Comparison of calculated debris average and island-average exposure rates

Island	Mean Exposure Rate at 10-ft Distance ($\mu R\ h^{-1}$)[*]	Island-Average Exposure Rate ($\mu R\ h^{-1}$)[†]
Janet (Enjebi)	0.6	40
Yvonne (Runit)	2.3	33
Pearl (Lujor)	7.1	70
Ruby (Eleleron)	1.4	14
Sally (Aomon)	3.5	7

[*] Geometric mean of the exposure rates calculated using a disk source model with a radius as shown in Table III-1. See also Section K-2.3.

[†] From the 1972 aerial survey, estimated at 1 meter from the ground (AEC, 1973a).

Appendix L.

Development of Beta-Gamma Dose Ratios for Skin Dose Assessments for Participants in the Enewetak Cleanup Project

L-1. Introduction

This appendix describes the development, applicability, and use of beta-gamma dose ratios for skin dose assessments for ECUP participants.

L-1.1. Background

Beta-gamma dose ratios are used to estimate beta skin doses from direct non-contact radiation when gamma doses are available. Estimates of ratios of beta and gamma doses at Enewetak Atoll based on measurements made in 1976 at Enewetak Atoll are available (Crase et al., 1982). The contributions of beta and low-energy gamma radiations to the total external doses from these presumably free-in-air measurements were determined for a height of 100 cm. From these measurements, minimum, median, and maximum "Crase ratios" of 0.19, 0.41, and 1.44, respectively, were calculated. The median value of these Crase ratios was recommended as an interim beta-gamma dose ratio in ECUP assessments for all skin sites in the original (2018) version of this technical report. Because beta-gamma dose ratios vary according to the distance of the skin site from the source, additional beta-gamma dose ratios are necessary to better estimate beta skin doses for sites at various heights.

L-1.2. Purpose and Objectives

The purpose of this appendix is to provide information and analyses to support and update the skin dose assessment methodology for ECUP participants. This purpose is accomplished via the two primary objectives described below:

- Describe a method used to independently derive a beta-gamma dose ratio for comparison with the interim beta-gamma dose ratio previously recommended for ECUP skin dose assessments
- Describe the development and results of additional beta-gamma dose ratios based on the interim ECUP beta-gamma dose ratio, for a range of heights above the ground.

L-2. Methodology

The methodologies for accomplishing the two primary objectives are discussed in the following subsections. Results of the described methodologies are contained in Section L-3.

L-2.1. Interim Beta-gamma Dose Ratio

An interim ECUP beta-gamma dose ratio was estimated using the measurements made in 1976 on the islands of Enjebi (site Janet) and Bokombako (site Belle) (Crase et al., 1982), hereafter referred to as "Crase ratios." The relevant measurements were made with LiF thermoluminescent dosimeters (TLDs) placed on crossbars mounted 100 cm above the ground on wooden stakes. The relative contributions of beta and low-energy gamma radiations to the total measured external doses from these presumably free-in-air measurements were determined and documented (Crase et al., 1982). Using the measured relative contributions[14], Crase ratios were estimated for the measurement height of 100 cm above the ground. The minimum and maximum derived Crase ratios are 0.19 and 1.44, with a median value of 0.41. The median Crase ratio was recommended as an interim beta-gamma dose ratio for use in ECUP assessments for all skin sites in the original version of this technical report.

Several features of the measurements underlying the Crase ratios presented uncertainties and possible issues with regard to using them as beta-gamma dose ratios for ECUP. These items include the following:

- Inclusion of low-energy gamma radiation in the Crase ratios
- Measurements made at only one height above the ground surface
- Unknown amounts of vegetation possibly affecting the measurements.

Therefore, an effort was undertaken to derive beta-gamma dose ratios independently for comparison with the Crase ratios. To accomplish this, several approaches were explored to produce new ratios that could be used for comparison with the Crase ratios. The approach described in this appendix involves modification of the existing beta-gamma dose ratios developed for the NTPR Program (DTRA, 2017) to produce ratios for comparison. The NTPR ratios have previously been calculated for post-detonation times out to 2 y. Because fission product beta-gamma dose ratios vary with time after a detonation, the approach involved extending the NTPR ratios out to the post-detonation period appropriate for ECUP (20-30 y). In addition, the NTPR ratios were calculated for fallout deposition on an impenetrable surface. Therefore, the approach also required a method to incorporate weathering of deposited fallout (i.e., infiltration of fallout into the soil).

L-2.1.1 Time-Extension of NTPR Beta-Gamma Dose Ratios

The NTPR beta-gamma dose ratios are based on dose factors that describe the emission, transport, and absorption of radiation for radionuclides in soil. More specifically, they relate the concentrations of contaminants in soil to the free-field radiological conditions, at specific heights above the soil. Correlations have been observed between beta and gamma dose factors and their respective mean particle energies for times out to the 2-y post-detonation time limit of the NTPR beta-gamma dose ratios. These correlations are based on the emission rates of beta and gamma particles from mixed fission products, together with their respective mean energies, as obtained from Finn et al. (1979) over decay times out to 70 y post-detonation. It was observed that the gamma dose factors are directly proportional to mean gamma energies, whereas beta dose factors are proportional to a simple power-law scaling of mean beta energies over time. The exponent used for the power-law scaling of beta dose factors varied from 0.16 to 1.8 for heights from 1 cm to 200 cm, respectively.

[14] Crase et al. (1982) contains values of 16%, 29%, and 59% for the minimum, median, and maximum measured contribution, respectively, of beta or low-energy gamma radiation to the total external exposure rate. Crase ratios were derived from these contributions, assuming that they were due entirely to beta radiation.

Based on the observed correlations of beta and gamma dose factors and their respective mean particle energies for times out to 2 y post-detonation, it was assumed that the relationships would also exist for times greater than 2 y. Using these proportionalities, the NTPR beta-gamma dose factors were extended to various times out to 70 y post-detonation. The calculated time-extended values for times from 1 y to 70 y are shown in Table L-1. The power-law exponent (*n*), that resulted in the best fit for each height was determined and is shown for each height in Table L-1.

Table L-1. Time-extended NTPR beta-gamma dose ratios

	Height *h* above a plane source (cm)							
	1	**20**	**40**	**80**	**100**	**120**	**160**	**200**
Time (y)	**n=0.16***	**n=0.5**	**n=0.9**	**n=1.2**	**n=1.3**	**n=1.4**	**n=1.7**	**n=1.8**
1	176	78	48	32	27	24	18	14
2	517	240	155	105	92	80	63	50
3	436	195	120	79	68	59	45	35
4	334	144	85	54	46	39	29	22
5	270	113	64	40	33	28	20	16
6	232	95	53	32	27	23	16	12
10	180	74	41	25	21	18	13	10
30	155	66	38	24	20	17	13	10
70	147	63	36	23	19	16	12	9

* For each height *h*, the power-law exponent *n(h)* used to calculate the set of beta-gamma dose ratios is given.

L-2.1.2 Incorporating the Effects of Weathering

To compare the Crase ratios derived from TLD measurements with the time-extended values developed from the NTPR program, environmental weathering – the infiltration of fallout into the ground – must be taken into account in the time-extended values. Weathering modifies the profiles of contaminants within the soil by moving them to greater depth where there is additional shielding. Assuming that beta-emitters and gamma-emitters move together with no vertical fractionation, weathering acts to decrease the beta-gamma dose ratio over time.

The algorithm developed to model the effects of weathering involved the coupling of a weathering factor with a conventional fallout distribution model to estimate the vertical profile of radioactive contaminants in the soil as a function of time. Radiation transport methods were then used to calculate the aboveground beta dose contribution from this profile. This allowed for the calculation of a "weathering reduction factor" that quantifies the time-dependent effects of weathering on the beta-gamma dose ratios.

Key aspects of the development of weathering reduction factors are described below. A full description of the development of the weathering reduction factors will be published at a later date.

The weathering factor used here was developed by the U.S. Nuclear Regulatory Commission to estimate a weathered gamma dose rate. Specifically, it models the reduction of the gamma dose rate above a weathered deposition of mixed fission products compared to a similar deposition on an impenetrable surface (i.e., a deposition with no weathering). This factor is expressed as the sum of two exponential terms, shown in Equation L-1 (Till and Meyer, 1983).

$$F_w(t) = 0.63 \times e^{-1.13t} + 0.37 \times e^{-0.007St} \tag{L-1}$$

where

$F_w(t)$	=	Weathering factor for gamma dose rate (unitless)
t	=	Time after deposition (y)

The vertical distribution of fallout assumed for contaminants in soil was taken from the work of Beck and de Planque (1968) and Beck (1980). As expressed in Equation L-2, the concentration of radionuclides (volumetric activity density) at time *t* after detonation is exponentially distributed with depth *x*:

$$C(x, t) = C_0 \times e^{-a(t)x} \tag{L-2}$$

where

C(x, t)	=	Volumetric activity density at depth *x* and time *t* (Ci cm^{-3} or Ci g^{-1})
C_0	=	Volumetric activity density at the air-soil interface (Ci cm^{-3} or Ci g^{-1})
α(t)	=	Depth profile parameter at time *t* (cm^2 g^{-1})
x	=	Depth in soil (g cm^{-2})

Starting with the above equations, a lengthy series of equations and assumptions were used to describe time-dependent features such as the relationship of areal density of contaminants to the volumetric activity density, and to estimate depth profile parameters for beta and gamma radiation sources. The Sandia National Laboratory radiation transport code CEPXS/ONEDANT (Lorence et al., 1989) was used to calculate beta dose factors for a range of soil overlay thicknesses *x* and various times *t* after detonation. The results of these calculations were used to estimate beta-gamma dose ratio reduction factors for various post-detonation times and heights. The calculated weathering reduction factors for post-detonation times from 1 y to 70 y are shown in Table L-2.

Weathering reduction factors derived for various post-detonation times and heights were then applied to the time-extended beta-gamma dose ratios from Section L-2.1.1. Specifically, the time-extended beta-gamma dose ratios in Table L-1 were multiplied by the corresponding reduction factors in Table L-2 to produce the time-extended and weathered beta-gamma dose ratios shown in Table L-3.

Table L-2. Weathering reduction factors

Time (y)	Weathering reduction factors at various heights above the surface (cm)							
	1	**20**	**40**	**80**	**100**	**120**	**160**	**200**
1	0.098	0.131	0.156	0.172	0.175	0.178	0.180	0.180
2	0.052	0.071	0.084	0.092	0.093	0.094	0.094	0.094
5	0.042	0.057	0.062	0.074	0.075	0.076	0.076	0.076
10	0.040	0.055	0.059	0.071	0.072	0.073	0.073	0.073
30	0.036	0.048	0.053	0.063	0.064	0.065	0.064	0.064
70	0.030	0.041	0.044	0.053	0.054	0.054	0.054	0.054

Table L-3. Time-extended and weathered beta-gamma dose ratios

Time (y)	Beta-gamma dose ratios at various heights above the surface (cm)							
	1	**20**	**40**	**80**	**100**	**120**	**160**	**200**
1	16.3	10.6	7.8	5.5	4.9	4.6	3.6	2.7
2	25.7	17.9	13.5	9.6	8.7	8.0	6.4	4.9
5	11.3	6.4	4.0	2.9	2.5	2.1	1.5	1.2
10	7.2	4.0	2.4	1.8	1.5	1.3	0.9	0.7
30	5.5	3.2	2.0	1.5	1.3	1.1	0.8	0.6
70	4.4	2.5	1.6	1.2	1.0	0.9	0.6	0.5

L-2.1.3 Comparison with Crase Beta-gamma Dose Ratios

To make a valid comparison of the Crase ratios with the 100-cm time-extended and weathered ratios described above, an adjustment was first made to the Crase ratios to convert them to Crase beta-gamma dose ratios. The adjustment accounts for the use of body self-shielding factors in the formulation of the NTPR ratios, from which the time-extended and weathered ratios were calculated. Self-shielding factors of 0.5 (beta) and 0.7 (gamma) are incorporated into the NTPR beta-gamma dose ratios. Therefore, the time-extended and weathered beta-gamma dose ratios incorporate these factors. Since the Crase ratios are presumably based on free-in-air measurements, self-shielding factors must be included in them in order to produce beta-gamma dose ratios for comparison. This is done by multiplying the Crase ratios by 0.5/0.7 = 0.71. Minimum, median, and maximum Crase beta-gamma dose ratios of 0.14, 0.29, and 1.03, respectively, were thus calculated.

L-2.2. Additional Beta-gamma Dose Ratios

The Crase beta-gamma dose ratios are based on measurements made at a height of 100 cm. They can be extrapolated to other heights using ratios of the beta-gamma dose ratios at height *h* to the ratio at 100 cm, as shown in Equation L-3.

$$RR_{\beta/\gamma}(t, h) = \frac{R_{\beta/\gamma}(t, h)}{R_{\beta/\gamma}(t, 100)} \quad \text{(L-3)}$$

where

$RR_{\beta/\gamma}(t, h)$	=	Ratio of the beta-gamma dose ratios at time *t* and height *h* to the ratio at time *t* and *h* = 100 cm
$R_{\beta/\gamma}(t, h)$	=	Beta-gamma dose ratio at post-detonation time *t* and height *h* (unitless)
$R_{\beta/\gamma}(t, 100)$	=	Beta-gamma dose ratio at post-detonation time *t* and height 100 cm (unitless)

The rationale for the use of $RR_{\beta/\gamma}(t, h)$ values ("ratios of ratios") to make height adjustments is based on the observation that when these ratios of ratios are plotted as a function of time, they tend to reach relatively constant values. This was observed for the NTPR ratios of ratios over the time period from about 0.5 y out to 2 y. The flattening of the NTPR ratios of ratios towards the end of the NTPR time period suggests that relatively constant values of these ratios may exist beyond 2 y. This was confirmed by examining the ratios of ratios for the time-extended and weathered dose ratios. The curves for most heights are relatively flat from about 2 y to 70 y, as shown in Figure L-1.

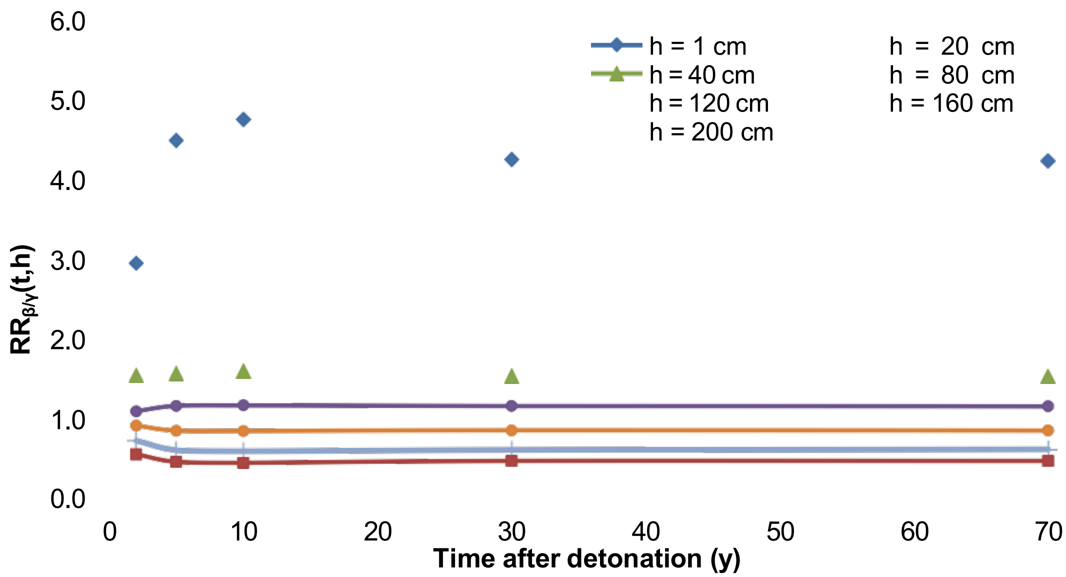

Figure L-1. Values of $RR_{\beta/\gamma}(t,h)$ for the time-extended and weathered beta-gamma dose ratios as a function of time

The values of the 30-y ratios of ratios ($RR_{\beta/\gamma}(30,h)$) for the time-extended and weathered beta-gamma dose ratios ($RR_{\beta/\gamma}(30,h)$) are shown in Table L-4.[15] The time of 30 y post-detonation was selected from the available times as appropriate because it is close to the post-shot time of the Crase measurements, which were made in 1976, 18 to 28 y after the period of the Enewetak Atoll detonations (1948–1958).

[15] The values in Table L-4 may differ slightly from those derived using the $R_{\beta/\gamma}$ values from Table L-3 due to rounding.

Table L-4. Values of $RR_{\beta/\gamma}(30,h)$ for the time-extended and weathered beta-gamma dose ratios

Time after Detonation	Distance *h* from Source Plane (cm)							
	1	20	40	80	100	120	160	200
30 y	4.27	2.46	1.55	1.17	1.0	0.864	0.619	0.483

The $RR_{\beta/\gamma}(30,h)$ values in Table L-4 were then used with the minimum, median, and maximum beta-gamma dose ratios estimated from the Crase measurements to calculate beta-gamma dose ratios at seven heights from 1 cm to 200 cm using Equation L-4.

$$R_{\beta/\gamma\,ECUP}(h) = R_{\beta/\gamma\,Crase} \times RR_{\beta/\gamma}(30,h) \quad \text{(L-4)}$$

where

$R_{\beta/\gamma\,ECUP}(h)$	=	ECUP beta-gamma dose ratio at height *h* (unitless)
$R_{\beta/\gamma\,Crase}$	=	Beta-gamma dose ratio calculated from Crase et al. (1982) (unitless)
$RR_{\beta/\gamma\,ECUP}(30,h)$	=	Ratio of the 30-y time-extended and weathered beta-gamma dose ratio at height *h* to the beta-gamma dose ratio at 100 cm (unitless)

L-3. Results and Discussion

The results of the methodologies described above are discussed in the following subsections.

L-3.1. Interim Beta-gamma Dose Ratio

The minimum, median, and maximum Crase beta-gamma dose ratios of 0.14, 0.29, and 1.03, respectively (from Section L-2.1.3), were compared to the 30-y 100-cm beta-gamma dose ratio of 1.3 from Table L-3. The beta-gamma dose ratio of 1.3 exceeds the maximum Crase beta-gamma dose ratio by about 25 percent and exceeds the median by a factor of about 4.5. Given these comparisons, the Crase beta-gamma dose ratios are found to be in reasonable agreement with the time-extended and weathered beta-gamma dose ratio of 1.3. This conclusion includes acknowledgement of several differences between the two sets of beta-gamma dose ratios. Those differences include the omission of Co-60 from the time-extended and weathered beta-gamma dose ratios, and the inclusion of low-energy gamma radiation in the Crase ratios. Preliminary results from other approaches indicate that inclusion of Co-60 would yield beta-gamma dose ratios within the range of the Crase beta-gamma dose ratios.

L-3.2. Additional Beta-gamma Dose ratios for ECUP

The 30-y values of the ratios of ratios ($RR_{\beta/\gamma}(30,h)$) from Table L-4 were applied to the minimum, median and maximum Crase beta-gamma dose ratios to estimate height-dependent beta-gamma dose ratios for ECUP. The resulting beta-gamma dose ratios are shown in Table L-5 and the medians are plotted in Figure L-2. The beta-gamma dose ratios calculated based on the median 100-cm Crase beta-gamma dose ratio are proposed for use in radiation dose assessments for skin for ECUP participants.

Table L-5. Beta-gamma dose ratios calculated for ECUP skin dose assessments

	ECUP Beta-gamma Dose Ratios at Various Heights (cm)*							
	1	20	40	80	100	120	160	200
Minimum	0.58	0.33	0.21	0.16	0.14	0.12	0.084	0.066
Median	1.2	0.72	0.45	0.34	0.29	0.25	0.18	0.14
Maximum	4.4	2.5	1.6	1.2	1.0	0.89	0.64	0.50

* Values are rounded to 2 significant digits.

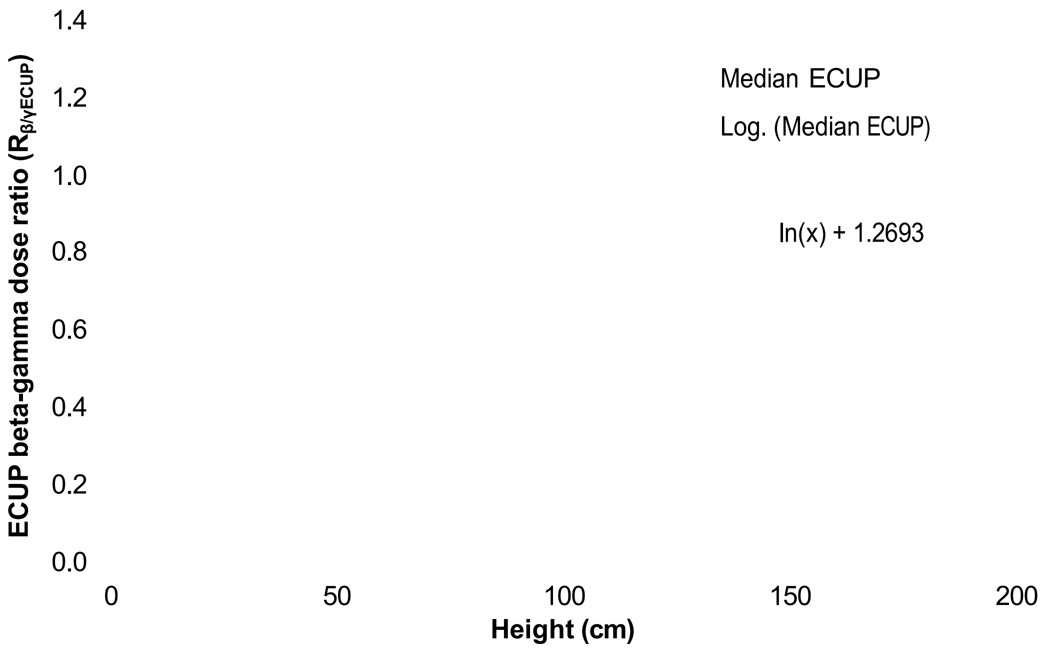

Figure L-2. Calculated ECUP beta-gamma dose ratios

The median ECUP beta-gamma dose ratios in Table L-5 can be used as reasonable estimates of beta-gamma dose ratios above contaminated soil for ECUP skin dose assessments. In using these values, it is assumed that on average, the conditions of exposure of ECUP participants in 1977–1980 were similar to the conditions under which the Crase TLD measurements were made. This is a necessary assumption because local conditions on Enewetak Atoll at the time of the Crase measurements (e.g., extent of vegetation, degree of soil moisture, nearby structures) would have affected the TLD measurements from which the beta contributions were determined.

The median beta-gamma dose ratios from Table L-5 are plotted as a function of height in Figure L-2 together with a fitted logarithmic function. The fitted equation is shown in the figure and is reproduced in Equation L-5.

$$R_{\beta\text{-}\gamma\ ECUP}(h) = -0.212 \times \ln(h) + 1.2693 \qquad \text{(L-5)}$$

where

$R_{\beta\text{-}\gamma\ ECUP}(h)$	=	Calculated ECUP beta-gamma dose ratio at height *h* (unitless)
h	=	Height above the surface (cm)

If the height above ground of a required skin site dose is not one of the heights given in Table L-5, Equation L-5 can be used to estimate the beta-gamma dose ratio for the specific height, i.e., for any skin site on a veteran. Alternatively, interpolation techniques can be used to estimate ratios between the values listed in Table L-5 . To aid in estimating ratios for a specific skin site, reference heights from the ground for 11 anatomical locations and three configurations (standing, sitting in a chair, sitting on the ground) are provided in Table L-6.

Table L-6 Reference heights of body locations from surface

Anatomical Location	**Reference Heights for Three Positions*,† (cm)**		
	Standing	**Sitting (chair/bench)**	**Sitting (ground/deck)**
Foot and ankle	1.0	1.0	5.1
Shin	20.3	20.3	15.2
Knee	40.6	40.6	15.2
Mid-thigh	71.1	53.1	15.2
Waist	99.1	56.4	14.0
Forearms	99.1	56.4	20.3
Stomach	119	76.7	34.3
Mid-chest	140	97.0	54.6
Neck	150	107	64.8
Face and head/eyes	160	117	74.9
Top of head	173	130	87.6

* Reference heights are for a veteran stature of 173 cm (68 inches) (DTRA, 2017).

† To estimate values for veteran heights other than 173 cm, multiply the appropriate reference height (except foot/ankle) by the ratio of veteran height to the reference height. For foot and ankle sites, the reference heights are used without modification for all veteran heights.

L-4. Conclusions

A beta-gamma dose ratio of 1.3 was estimated for a height of 100 cm at a post-detonation time of 30 y by modifying the NTPR beta-gamma dose ratios. The modified beta-gamma dose ratio was estimated using the flux and energy emission characteristics of decaying fission products over time to extend the NTPR beta-gamma dose ratios out to 70 y post-detonation, and incorporating environmental weathering reduction factors. The estimated value of 1.3 compares sufficiently well with the range of beta-gamma dose ratios of 0.14–1.03 calculated from the Crase TLD measurements. Preliminary results from other approaches produce beta-gamma dose ratios in the range of Crase beta-gamma dose ratios. Therefore, it can be concluded that both methods and results for estimating beta-gamma dose ratios are credible.

Additional beta-gamma dose ratios at various heights other than 100 cm were calculated using the time-extended and weathered 30-y beta-gamma dose ratio estimates to modify the minimum, median, and maximum 100-cm Crase et al. beta-gamma dose ratios. In the absence of specific measurements, the calculated beta-gamma dose ratios based on the median Crase beta-gamma dose ratios, shown in Table L-5, are recommended in skin dose assessments for ECUP participants and for all islands at Enewetak Atoll. A function was fitted to a plot of these ratios that can be used to estimate the beta-gamma dose ratio for the distance above the surface of any ECUP veteran skin site. Reference heights for specific anatomical skin sites are also provided, including a method for modifying these heights when necessary.

Appendix M.

Assessment of Internal Doses from Local Food Consumption by Participants in the Enewetak Cleanup Project

M-1. Introduction

The most likely local foods that ECUP participants may have consumed during their participation are identified and a standardized dose assessment methodology is described in this appendix. A dose calculation tool based on the methodology is developed to estimate internal radiation doses from the potential consumption of local foods by ECUP participants. This appendix provides the details of the dose estimation from the consumption of local foods presented in Section 7.

M-1.1. Background

Given the possible contamination from previous nuclear testing in foods obtained from Enewetak Atoll, it is expected that personnel who cleaned up the islands during ECUP would refrain from eating local foods. However, anecdotes from ECUP veterans indicate that participants did consume both local marine and terrestrial foods. As the veterans recounted, cleanup personnel caught, prepared, and ate lobsters, fish, coconut crabs, or clams as recreational activities while off-duty (Cherry, 2018b; Fitzgerald, 2017; Tupin, 2018). Other local foods commonly eaten by the Marshallese people that might have been occasionally consumed by ECUP personnel are coconut meat and coconut milk.

M-1.2. Purpose and Objectives

The purpose of this appendix is to document the technical basis for estimating radiation doses from the potential consumption of local foods by ECUP participants. To achieve this goal, the following objectives are pursued:

- Collect data and information to develop appropriate assumptions and select high-sided parameter values for calculating doses from the possible consumption of local food
- Develop calculation tools based on a standardized local food dose assessment methodology to ensure timely and accurate calculations when handling veteran claims.

M-2. Methodology

This section presents the data, methods, assumptions, and parameter values used to estimate doses to internal organs and committed effective doses to the whole body that result from the potential consumption of local foods by ECUP personnel.

M-2.1. Dose Calculation Method

The internal radiation dose accrued from the ingestion of potentially contaminated foods is quantified as the committed equivalent dose per serving for organ exposures, or committed effective dose per serving for whole body exposures. In this appendix, the term "dose per serving" is also used to describe these internal organ and effective doses from the ingestion of local foods. The organ dose per serving from eating local foods is calculated using Equation M-1 as follows:

$$D_{food} = \sum_{i=1}^{n} q_{food} \times \frac{C_{food,i}}{R_{w/d}} \times DC_{ing,i} \qquad \text{(M-1)}$$

where

D_{food}	=	Dose per serving from consumption of local food (rem per serving)
q_{food}	=	Food consumption rate, i.e., amount consumed per serving (g, wet weight per serving)
$C_{food,i}$	=	Average activity concentration of radionuclide *i* in edible part of the food (pCi g^{-1}, dry weight)
$R_{w/d}$	=	Wet-to-dry weight ratio [(g, wet weight) (g, dry weight)$^{-1}$]
$DC_{ing,i}$	=	Ingestion dose coefficient for radionuclide *i* for the organ of interest (rem pCi^{-1})
n	=	Total number of relevant radionuclides

The average activity concentrations, $C_{food,i}$, over the entire atoll for key radionuclides in the edible part of each local food are reported in Section M-2.2. The values for the wet-to-dry weight ratios, $R_{w/d}$, and the food consumption rates, q_{food}, along with the rationales, are presented and discussed in Section M-2.3. The ingestion dose coefficients, $DC_{ing,i}$, which convert activity intake to 50-year committed equivalent dose for 25 organs and 50-year committed effective dose to the whole body, are shown in Table C-3. The calculated results for organ and effective doses per serving and the corresponding upper-bound doses are presented in Attachment I of this appendix.

M-2.2. Activity Concentrations in Edible Parts of Local Foods

Local marine and terrestrial foods were collected during the radiological surveys conducted at Enewetak Atoll from October 1972 to February 1973 (DNA, 1981; AEC, 1973a). The averages of measured concentrations of radionuclides in the edible parts of local foods from samples collected over the entire atoll are calculated from data reported in AEC (1973a) and are listed in Table M-1. Activity concentration data from AEC (1973a) are presented in Section 4.7. Because of their relatively long half-lives, activity concentrations in foods, and potential contribution to internal doses, Co-60, Sr-90, Cs-137, and Pu-239/240 are considered the key radionuclides for the ingestion of local food. In addition, Am-241 was identified in fish so this additional radionuclide is included in the dose assessment for fish consumption (AEC, 1973a).

Two data analysis methods are used in AEC (1973a) to develop high-sided radionuclide average concentrations in the edible parts of the foods, thus overestimating doses from consumption of local foods. First, the arithmetic means of measured concentrations in food tissue are used as the values to estimate internal doses. This assumption overstates the doses because, for example, the distributions of the measured concentrations of Sr-90, Cs-137, Co-60, and Pu-239/240 in the marine samples are quite skewed, and the medians are about 3 to 20 times lower than the arithmetic means (AEC, 1973a). Second, when calculating average concentrations, non-detectable concentrations of relevant radionuclides in the samples were set to the respective detection limits. The average concentrations calculated using this data treatment produce high-sided dose contributions from some of these radionuclides because actual concentrations in the non-detect samples are frequently far below the analytical detection limits. This was verified, for example, in the case of Am-241, where the concentrations detected in a few fish samples using wet-chemistry analysis were found to be significantly lower than the detection limits previously established by gamma spectroscopy (AEC, 1973a).

Furthermore, Am-241 was not detected in 372 out of 410 marine samples by gamma counting (AEC, 1973a). This indicates that Am-241 was undetectable in the majority of fish samples and the concentration shown in Table M-1 is an overestimate. As a result of setting concentrations of Am-241 to the detection limit for such a large number of non-detect samples, the average concentration of this radionuclide in fish is about two orders of magnitude higher than when concentrations in non-detects were set to 0 pCi g^{-1}. Specifically, the reported average concentration is 0.00277 pCi g^{-1} with non-detect samples set to 0 pCi g^{-1}, and 0.114 pCi g^{-1}, shown in Table M-1, when the non-detects were set to the detection limit (AEC, 1973a). However, for the average concentrations in fish of the other four radionuclides listed in Table M-1, when non-detects are set to 0 pCi g^{-1} rather than the detection limit, the average concentrations are not significantly affected.

Table M-1. Average activity concentration of key radionuclides in the edible part of local foods at Enewetak Atoll

Food	Average Activity Concentration (pCi g^{-1}, dry weight)[*,†,‡]				
	Co-60	**Sr-90**	**Cs-137**	**Pu-239/240**	**Am-241**
Fish	2.00	0.075	0.39	0.248	0.114
Lobster	0.29	0.020	0.018[§]	0.0060	–
Coconut Meat	0.12	0.80	7.5	0.030	–
Coconut Milk	0.053	0.058	4.71	0.0030	–
Coconut Crab	0.629	0.759	3.93	0.0016	–
Clams (Giant)[**]	9.33	0.091	–	0.24	–

[*] Averages are based on data reported in AEC (1973a), except as noted otherwise. For fish, average concentrations are reported in Table 158 except for Sr-90, the average concentration is for muscle only and is taken from Table 159; for lobster, average concentrations are reported in Table 41, except Cs-137 (see note below); for coconut meat, see Table 164; for coconut milk, see Table 165; for coconut crab, see Table 169; for clams, concentrations are from Table 39. (AEC, 1973a)

[†] The concentrations are in pCi g^{-1} dry weight except they are pCi g^{-1} wet weight for coconut milk.

[‡] The averages are calculated with non-detect sample concentrations set equal to the detection limits.

[§] Concentrations of Cs-137 in spiny lobster muscle were not reported in AEC (1973a). The value shown is the highest value in samples collected in 1978–1979 reported in Table 6 of Ebert and Ford (1986).

[**] Cs-137 and Am-241 were not detected in the vast majority of the analyzed clam samples, so these radionuclides are not included for clams.

"–" indicates not detected or not considered as a key radionuclide (AEC, 1973a).

M-2.3. Parameter Values and Assumptions

The wet-to-dry ratio is the ratio of the fresh tissue weight to the dried tissue weight obtained following a drying process described in AEC (1973a). The food consumption rate, q_{food}, is expressed as edible tissue (wet) weight consumed per serving. Values of the wet-to-dry ratio and the suggested consumption rates of local foods are presented in Table M-2. The rationale for each suggested consumption rate for ECUP participants is discussed in the following sub-sections.

Table M-2. Parameter values for estimating ingestion doses from eating local foods

Edible Part of Local Food	Wet-to-Dry Ratio*	Consumption Rate (g per serving)
Fish muscle	3.5	300
Lobster muscle	4.3	500
Coconut Meat	2	400
Coconut Milk	20	300
Coconut Crab muscle	4.1	500
Clams (Giant)	6.4	500

* Values are taken from AEC (1973a), except that the ratio for muscle of the common shore crab is used for coconut crab muscle (Bjerregaard and Depledge, 2002).

M-2.3.1 Fish Consumption Rate

A serving of fish can be based on the body weight of the person eating the fish. For example, 8 ounces (227 g) of uncooked fish muscle is one serving for a 150-pound person in the United States. To adjust the serving size for a person with a different weight, 1 ounce (28 g) of fish is added or subtracted for every 20 pounds of body weight over or under 150 pounds, respectively (MDH, 2020). Using the average weight of military personnel in the United States of about 180 pounds (USMC.net, 2018), a consumption rate of approximately 10 ounces (rounded up to 300 g) of fish per serving for ECUP participants is a reasonable assumption.

M-2.3.2 Lobster Consumption Rate

The tail is assumed to be the portion of the lobster potentially consumed by ECUP participants. The weights of the tails of a sub-set of lobsters sampled in 1978–1979 were approximately 135–195 g (Ebert and Ford, 1986). The average of the values in this range is approximately 160 g, which corresponds to a lobster with a total weight of 550 g according to Ebert and Ford (1986). Assuming that an ECUP participant ate three 160 g tails in one meal, and further assuming that the weight of the tail is entirely from muscle, this would result in approximately 500 g of muscle consumed in a serving. This serving size is considered a high-sided estimate.

M-2.3.3 Coconut Meat Consumption Rate

The consumption of the meat from an entire coconut, which is about 400 g wet weight on average, is considered a high-sided assumption. This is because the consumption of the meat of an entire coconut all at once is considered unlikely. Nevertheless, the 400 g serving size from an entire coconut is used in this analysis to estimate internal doses for ECUP veterans. However, this should be considered an infrequent occurrence.

M-2.3.4 Coconut Milk Consumption Rate

A drinking coconut is fully grown but still green. It contains about 250–350 ml of liquid (AEC, 1973a). It is reasonable that an ECUP veteran may have consumed all the liquid from a green coconut. Therefore, a serving size of all the milk from one coconut, 300 ml or approximately 300 g, is used as a conservative consumption rate for ECUP veterans.

M-2.3.5 Coconut Crab Consumption Rate

The edible part of a coconut crab is the fresh muscle of the legs. Due to the lack of data on the weights of the legs, a serving of the muscle of coconut crab legs is assumed to be 500 g, which is based on the estimated serving size for lobster (Section M-2.3.2). Because the number of coconut crabs at Enewetak Atoll was limited and this food is considered a delicacy (AEC, 1973a), a 500 g serving size of coconut crab muscle is considered a high-sided estimate for ECUP personnel.

M-2.3.6 Clams (Giant) Consumption Rate

A typical amount of clams consumed as a main dish for a meal is about 1 pound of unshelled clams per person, which should yield around 125 g (4 oz) of actual meat per person (Cook's Info, 2018). This estimate is for clams of common sizes served on, for example, dinner tables. Thus a consumption rate of 500 g per serving is assumed as a high-sided estimate for clams consumed by ECUP participants.

M-2.4. Uncertainty

As discussed in Section 7 and following the standard procedures and methods used in the NTPR Program radiation dose assessments, an uncertainty factor of 10 is applied to the internal dose calculated using Equation M-1 to obtain an upper-bound dose (DTRA, 2017, SM UA01). This uncertainty factor accounts for all uncertainties applicable to high sided parameter values used in internal dose calculations for the consumption of local foods.

M-3. Results and Discussion

The average radionuclide activity concentrations in six local foods potentially consumed by ECUP participants are given in Table M-1 and the consumption rates are given in Table M-2. Using these parameter values, the doses per serving of the six local foods are estimated using Equation M-1. The two highest estimated organ doses per serving along with the corresponding organs and the whole-body committed effective dose per serving are shown in Table M-3 for each local food potentially consumed by ECUP participants. Calculated doses for all organs resulting from consumption of the six local foods are tabulated in Table I-1 of this appendix.

Table M-3. Estimated doses per serving from the consumption of local foods

Local Food	Estimated Dose (rem per serving)		
	Highest Organ Dose (Organ) (Radionuclide Contributing Largest Dose)	Second Highest Organ Dose (Organ)	Committed Effective Dose (Radionuclide Contributing Largest Dose)
Fish	9.8×10^{-4} (Bone surface) (Pu-239/240)	1.6×10^{-4} (Liver)	3.1×10^{-5} (Pu-239/240)
Lobster	2.5×10^{-5} (Bone surface) (Pu-239/240)	5.0×10^{-6} (Liver)	1.4×10^{-6} (Pu-239/240)
Coconut Meat	5.0×10^{-4} (Bone surface) (Sr-90)	1.9×10^{-4} (Red marrow)	9.5×10^{-5} (Cs-137)
Coconut Milk	1.3×10^{-4} (Bone surface) (Cs-137)	9.1×10^{-5} (LLI wall)	7.1×10^{-5} (Cs-137)
Coconut Crab	1.7×10^{-4} (Bone surface) (Sr-90)	8.6×10^{-5} (Red marrow)	3.4×10^{-5} (Cs-137)
Clams (Giant)	5.8×10^{-4} (Bone surface) (Pu-239/240)	1.3×10^{-4} (Liver)	2.7×10^{-5} (Pu-239/240)

Based on the parameter values described above, the bone surface receives the highest dose from each of the selected local foods potentially consumed by ECUP participants. The estimated doses to the bone surface range from 2.5×10^{-5} rem per serving of lobster to 9.8×10^{-4} rem per serving of fish. The much lower dose from consuming lobster than in fish is mainly due to the difference in concentrations of the highest contributor to dose in lobster and fish, Pu-239/240, being a factor of about 40. The estimated whole-body committed effective doses range from 1.4×10^{-6} to 9.5×10^{-5} rem per serving, where coconut meat consumption results in the highest effective dose. This is mainly due to the relatively high concentrations of Sr-90 and Cs-137 found in coconut meat. Except for coconut meat and lobster, whole-body effective doses for the other foods are similar in magnitude.

Furthermore, fish consumption produces the highest dose to the bone surface because the average Pu-239/240 concentration in fish was consistently higher than that in other foods as can be seen in Table M-1. In addition, Am-241 was detected only in fish, and the average concentration shown in Table M-1 was calculated by setting all non-detects equal to the detection limit. However, additional laboratory analyses showed that for non-detects, concentrations in fish samples were much lower than the detection limits. The dose to the bone surface from fish consumption drops to 6.7×10^{-4} rem per serving, or about 30 percent lower, if the average concentration of 0.00277 pCi g^{-1} is used for Am-241, which is obtained by assigning a value of 0 pCi g^{-1} for all non-detects.

The ranges of upper-bound organ and upper-bound committed effective doses per serving from the consumption of the selected local foods are presented in Table M-4. Upper-bound doses for all organs included in the ICRP Database of Dose Coefficients (ICRP, 2011) are tabulated in Table I-2 of this appendix. The upper-bound doses are obtained by applying an uncertainty factor of 10 to the doses shown in Table M-3 and Table I-1.

Table M-4. Upper-bound doses per serving from the consumption of local foods

Local Food	Upper-Bound Dose (rem per serving)	
	Organ Dose Range	Committed Effective Dose
Fish	$3.8 \times 10^{-5} - 9.8 \times 10^{-3}$	3.1×10^{-4}
Lobster	$2.9 \times 10^{-6} - 2.5 \times 10^{-4}$	1.4×10^{-5}
Coconut Meat	$6.2 \times 10^{-4} - 5.0 \times 10^{-3}$	9.5×10^{-4}
Coconut Milk	$5.8 \times 10^{-4} - 1.3 \times 10^{-3}$	7.1×10^{-4}
Coconut Crab	$2.0 \times 10^{-4} - 1.7 \times 10^{-3}$	3.4×10^{-4}
Clams (Giant)	$4.5 \times 10^{-5} - 5.8 \times 10^{-3}$	2.7×10^{-4}

Based on the upper-bound doses summarized above, the total internal dose accrued by an ECUP participant who consumed local foods can be estimated. Using fish as an example, a veteran who was deployed for six months may have consumed one serving of locally caught fish per month for a total of six servings. Given the limited opportunity to acquire and eat locally caught fish, this consumption rate is considered high-sided (Tupin, 2018). Using these assumptions, the estimated total upper-bound doses to internal organs range from less than 0.001 to 0.06 rem, the lowest dose being to the breast and the highest to bone surface. The estimated upper-bound committed effective dose is 0.002 rem. If the concentrations of Am-241 in non-detect fish samples are set to 0 pCi g^{-1}, the upper-bound organ doses would be about 35 percent lower overall, ranging from less than 0.001 rem to 0.04 rem.

M-4. Conclusions

The results show that the internal dose per serving to bone surface resulting from the consumption of local fish is higher than the dose from the consumption of any other local foods investigated. This results primarily from the relatively high concentration of Pu-239/240 in fish, which produces the highest contribution to internal dose.

For an ECUP participant that consumed local foods, the internal doses for some organs (e.g., bone surface and liver), may be the dominant overall dose components as compared to external doses or other internal doses due to inhalation and incidental ingestion of soil and dust discussed in Sections 6 and 7. However, estimated total internal doses from the ingestion of local foods depend on the assumed quantity consumed and how frequently local foods were consumed. The default values and assumptions presented in Section M-2 were carefully estimated and selected. They are default values that should be used in dose assessments for veterans who cannot recall the type, quantity, or frequency of the foods consumed. However, to perform individualized dose assessments for ECUP veterans, specific information on the consumption of local foods can be collected by means of a questionnaire. The veteran's input should then be used instead of the default parameter values to estimate doses from the consumption of local foods.

Attachment I.

Internal Organ and Effective Doses from Local Food Consumption

Committed internal organ doses per serving from the consumption of five local foods were calculated using the methods and assumptions described in Section M-2. These doses are shown in Table I-1. Doses were estimated for all organs included in ICRP Database of Dose Coefficients (ICRP, 2011). Table I-2 presents corresponding upper-bound organ doses per serving obtained by applying an uncertainty factor of 10 to the doses shown in Table I-1.

Table I-1. Total internal organ doses from potential local food consumption by ECUP participants

Organ/ Tissue	Ingestion Doses (rem per serving)					
	Fish	Lobster	Coconut Meat	Coconut Milk	Coconut Crab	Clam
Adrenals	4.98×10^{-6}	4.60×10^{-7}	7.87×10^{-5}	7.34×10^{-5}	2.57×10^{-5}	7.67×10^{-6}
Bladder Wall	5.06×10^{-6}	4.80×10^{-7}	7.92×10^{-5}	7.35×10^{-5}	2.61×10^{-5}	7.96×10^{-6}
Bone Surface	9.83×10^{-4}	2.49×10^{-5}	5.00×10^{-4}	1.26×10^{-4}	1.71×10^{-4}	5.76×10^{-4}
Brain	4.03×10^{-6}	3.08×10^{-7}	6.75×10^{-5}	6.29×10^{-5}	2.19×10^{-5}	4.73×10^{-6}
Breast	3.84×10^{-6}	2.88×10^{-7}	6.20×10^{-5}	5.77×10^{-5}	2.01×10^{-5}	4.46×10^{-6}
Esophagus	4.35×10^{-6}	3.53×10^{-7}	7.31×10^{-5}	6.81×10^{-5}	2.37×10^{-5}	5.53×10^{-6}
Stomach Wall	4.97×10^{-6}	4.57×10^{-7}	7.33×10^{-5}	6.82×10^{-5}	2.41×10^{-5}	7.75×10^{-6}
SI Wall*	6.41×10^{-6}	6.83×10^{-7}	7.92×10^{-5}	7.35×10^{-5}	2.64×10^{-5}	1.24×10^{-5}
ULI Wall*	9.77×10^{-6}	1.05×10^{-6}	8.25×10^{-5}	7.40×10^{-5}	2.87×10^{-5}	1.98×10^{-5}
LLI Wall*	1.82×10^{-5}	1.98×10^{-6}	1.10×10^{-4}	9.12×10^{-5}	4.11×10^{-5}	3.73×10^{-5}
Colon	1.33×10^{-5}	1.43×10^{-6}	9.29×10^{-5}	7.99×10^{-5}	3.35×10^{-5}	2.69×10^{-5}
Kidneys	7.40×10^{-6}	4.89×10^{-7}	7.36×10^{-5}	6.82×10^{-5}	2.40×10^{-5}	8.70×10^{-6}
Liver	1.58×10^{-4}	5.02×10^{-6}	1.10×10^{-4}	7.38×10^{-5}	2.57×10^{-5}	1.28×10^{-4}
Muscle	4.35×10^{-6}	3.70×10^{-7}	6.76×10^{-5}	6.29×10^{-5}	2.20×10^{-5}	6.07×10^{-6}
Ovaries	1.93×10^{-5}	9.30×10^{-7}	8.10×10^{-5}	7.38×10^{-5}	2.63×10^{-5}	1.91×10^{-5}
Pancreas	5.04×10^{-6}	4.72×10^{-7}	7.87×10^{-5}	7.34×10^{-5}	2.58×10^{-5}	7.94×10^{-6}
Red Marrow	4.91×10^{-5}	2.90×10^{-6}	1.88×10^{-4}	8.08×10^{-5}	8.55×10^{-5}	3.70×10^{-5}
ET Airways*	4.35×10^{-6}	3.53×10^{-7}	7.31×10^{-5}	6.81×10^{-5}	2.37×10^{-5}	5.53×10^{-6}
Lungs	4.41×10^{-6}	3.65×10^{-7}	7.31×10^{-5}	6.81×10^{-5}	2.38×10^{-5}	5.80×10^{-6}
Skin	3.84×10^{-6}	2.88×10^{-7}	6.20×10^{-5}	5.77×10^{-5}	2.01×10^{-5}	4.46×10^{-6}
Spleen	4.60×10^{-6}	4.03×10^{-7}	7.31×10^{-5}	6.82×10^{-5}	2.39×10^{-5}	6.60×10^{-6}
Testes	1.74×10^{-5}	6.04×10^{-7}	6.97×10^{-5}	6.32×10^{-5}	2.21×10^{-5}	1.24×10^{-5}
Thymus	4.35×10^{-6}	3.53×10^{-7}	7.31×10^{-5}	6.81×10^{-5}	2.37×10^{-5}	5.53×10^{-6}
Thyroid	4.35×10^{-6}	3.53×10^{-7}	7.31×10^{-5}	6.81×10^{-5}	2.37×10^{-5}	5.53×10^{-6}
Uterus	5.29×10^{-6}	5.22×10^{-7}	7.88×10^{-5}	7.34×10^{-5}	2.59×10^{-5}	9.01×10^{-6}
Effective dose	3.13×10^{-5}	1.40×10^{-6}	9.46×10^{-5}	7.08×10^{-5}	3.38×10^{-5}	2.69×10^{-5}

* Abbreviations used in this table: SI Wall = Small Intestine Wall; ULI Wall = Upper Large Intestine Wall; LLI Wall = Lower Large Intestine Wall; ET Airways = Extra-thoracic Airways.

Table I-2. Total upper-bound internal organ doses from potential local food consumption by ECUP participants

Organ/ Tissue	Upper-Bound Ingestion Doses (rem per serving)					
	Fish	Lobster	Coconut Meat	Coconut Milk	Coconut Crab	Clam
Adrenals	4.98×10^{-5}	4.60×10^{-6}	7.87×10^{-4}	7.34×10^{-4}	2.57×10^{-4}	7.67×10^{-5}
Bladder Wall	5.06×10^{-5}	4.80×10^{-6}	7.92×10^{-4}	7.35×10^{-4}	2.61×10^{-4}	7.96×10^{-5}
Bone Surface	9.83×10^{-3}	2.49×10^{-4}	5.00×10^{-3}	1.26×10^{-3}	1.71×10^{-3}	5.76×10^{-3}
Brain	4.03×10^{-5}	3.08×10^{-6}	6.75×10^{-4}	6.29×10^{-4}	2.19×10^{-4}	4.73×10^{-5}
Breast	3.84×10^{-5}	2.88×10^{-6}	6.20×10^{-4}	5.77×10^{-4}	2.01×10^{-4}	4.46×10^{-5}
Esophagus	4.35×10^{-5}	3.53×10^{-6}	7.31×10^{-4}	6.81×10^{-4}	2.37×10^{-4}	5.53×10^{-5}
Stomach Wall	4.97×10^{-5}	4.57×10^{-6}	7.33×10^{-4}	6.82×10^{-4}	2.41×10^{-4}	7.75×10^{-5}
SI Wall*	6.41×10^{-5}	6.83×10^{-6}	7.92×10^{-4}	7.35×10^{-4}	2.64×10^{-4}	1.24×10^{-4}
ULI Wall*	9.77×10^{-5}	1.05×10^{-5}	8.25×10^{-4}	7.40×10^{-4}	2.87×10^{-4}	1.98×10^{-4}
LLI Wall*	1.82×10^{-4}	1.98×10^{-5}	1.10×10^{-3}	9.12×10^{-4}	4.11×10^{-4}	3.73×10^{-4}
Colon	1.33×10^{-4}	1.43×10^{-5}	9.29×10^{-4}	7.99×10^{-4}	3.35×10^{-4}	2.69×10^{-4}
Kidneys	7.40×10^{-5}	4.89×10^{-6}	7.36×10^{-4}	6.82×10^{-4}	2.40×10^{-4}	8.70×10^{-5}
Liver	1.58×10^{-3}	5.02×10^{-5}	1.10×10^{-3}	7.38×10^{-4}	2.57×10^{-4}	1.28×10^{-3}
Muscle	4.35×10^{-5}	3.70×10^{-6}	6.76×10^{-4}	6.29×10^{-4}	2.20×10^{-4}	6.07×10^{-5}
Ovaries	1.93×10^{-4}	9.30×10^{-6}	8.10×10^{-4}	7.38×10^{-4}	2.63×10^{-4}	1.91×10^{-4}
Pancreas	5.04×10^{-5}	4.72×10^{-6}	7.87×10^{-4}	7.34×10^{-4}	2.58×10^{-4}	7.94×10^{-5}
Red Marrow	4.91×10^{-4}	2.90×10^{-5}	1.88×10^{-3}	8.08×10^{-4}	8.55×10^{-4}	3.70×10^{-4}
ET Airways*	4.35×10^{-5}	3.53×10^{-6}	7.31×10^{-4}	6.81×10^{-4}	2.37×10^{-4}	5.53×10^{-5}
Lungs	4.41×10^{-5}	3.65×10^{-6}	7.31×10^{-4}	6.81×10^{-4}	2.38×10^{-4}	5.80×10^{-5}
Skin	3.84×10^{-5}	2.88×10^{-6}	6.20×10^{-4}	5.77×10^{-4}	2.01×10^{-4}	4.46×10^{-5}
Spleen	4.60×10^{-5}	4.03×10^{-6}	7.31×10^{-4}	6.82×10^{-4}	2.39×10^{-4}	6.60×10^{-5}
Testes	1.74×10^{-4}	6.04×10^{-6}	6.97×10^{-4}	6.32×10^{-4}	2.21×10^{-4}	1.24×10^{-4}
Thymus	4.35×10^{-5}	3.53×10^{-6}	7.31×10^{-4}	6.81×10^{-4}	2.37×10^{-4}	5.53×10^{-5}
Thyroid	4.35×10^{-5}	3.53×10^{-6}	7.31×10^{-4}	6.81×10^{-4}	2.37×10^{-4}	5.53×10^{-5}
Uterus	5.29×10^{-5}	5.22×10^{-6}	7.88×10^{-4}	7.34×10^{-4}	2.59×10^{-4}	9.01×10^{-5}
Effective dose	3.13×10^{-4}	1.40×10^{-5}	9.46×10^{-4}	7.08×10^{-4}	3.38×10^{-4}	2.69×10^{-4}

* Abbreviations used in this table: SI Wall = Small Intestine Wall; ULI Wall = Upper Large Intestine Wall; LLI Wall = Lower Large Intestine Wall; ET Airways = Extra-thoracic Airways.

Abbreviations, Acronyms and Symbols

AAQS	ambient air quality standards
ADC	Army Dosimetry Center
AEC	Atomic Energy Commission
AFRRI	Armed Forces Radiobiology Research Institute
ALARA	as low as reasonably achievable
Am	americium
AMAD	Activity Median Aerodynamic Diameter
APF	assigned protection factor
AR	Army Regulation
Ba	barium
Bi	bismuth
Bq	becquerel
CDR	Commander
CaF_2:Mn	calcium fluoride manganese doped
CFR	Code of Federal Regulations
CJTG	Commander, Joint Task Group
CI	confidence interval
Ci	curie
cm	centimeter
Co	cobalt
COL	Colonel (US Army)
cpm	counts per minute
Cs	cesium
d	day
DA	Department of Army
DD	Directives Division
DARWG	Dose Assessment and Recording Working Group
DLF	decontamination laundry facility
DNA	Defense Nuclear Agency
DOE	Department of Energy
DoD	Department of Defense
DOI	Department of Interior, or Date of Issue
DOR	Date of return
dpm	disintegration per minute
DTRA	Defense Threat Reduction Agency
EAI	Enewetak Atoll Instruction
ECUP	Enewetak Cleanup Project
ED	external dose
EIS	Environmental Impact Statement
EOD	Explosive Ordnance Disposal
ERDA	Energy Research and Development Administration
ERSP	Enewetak Radiological Support Project
Eu	europium
F_B	film badge conversion factor

FCDNA	Field Command, Defense Nuclear Agency
fCi	femtocurie
FCRR	Headquarters, Joint Task Group, Radiation Records
FIDLER	Field Instrument for Detecting Low Energy Radiation
FRST	Field Radiation Support Team
g	gram
GB	gross beta
GM	geometric mean
Gy	gray
GZ	Ground Zero
H&N	Holmes and Narver, Inc.
HPS	Health Physics Society
h	hour
ID	internal dose
IMP	in situ measurement of plutonium
ICRP	International Commission on Radiological Protection
JTG	Joint Task Group
K	potassium
keV	kiloelectron volt
kg	kilogram
km	kilometer
kt	kiloton
L or l	liter
LARC	lighter, amphibious, resupply craft
LBDA	Lexington-Blue Grass Depot Activity
LCM	landing craft, mechanized
LCDR	Lieutenant Commander
LCU	landing craft, utility
LTC	Lieutenant Colonel (U.S. Army)
m	meter
mCi	millicurie
MDA	minimum detectable activity
MDL	minimum detectable level
min	minute
μCi	microcurie
μg	microgram
μR	microroentgen
ML	mass loading
mL	milliliter
μm	micrometer
μrem	microrem
MEDEVAC	medical evacuation
MPC	maximum permissible concentration
mR	milliroentgen
mrem	millirem
MSC	Medical Service Corps

MSTS	Mission Support and Test Services
Mt	megaton
N	number of years of age
n	nano or number
NaI	sodium iodide
nCi	nanocurie
NAS	National Academy of Sciences
NAS-NRC	National Academy of Sciences-National Research Council
NCO	non-commissioned officer
NCOIC	non-commissioned officer in charge
NCRP	National Council on Radiation Protection and Measurements
NDC	Naval Dosimetry Center
NIOSH	National Institute of Occupational Safety and Health
NTPR	Nuclear Test Personnel Review
NVO	Nevada Operations Office
OEHL	Occupational and Environmental Health Laboratory
OPLAN	operations plan
oz	ounce
pCi	picocurie
PM_{10}	particulate matter 10 micrometer or less in diameter
PMEL	Precision Measurement Equipment Laboratory
POI	population of interest
PPE	personal protective equipment
Pu	plutonium
R	roentgen
RADSAFE	radiation safety
RCC	Radiation Control Committee
RDA	radiation dose assessment
RECA	Radiation Exposure Compensation Act
rem	roentgen equivalent man
RPO	radiation protection officer
RSAIT	radiation safety audit and inspection team
SAR	search and rescue
Sb	antimony
SCUBA	self-contained underwater breathing apparatus
SI	Système International d'Unités (International System of Units)
SITREP	situation report
SM	standard method
SOP	standing operating procedures
SPARE	Scenario of Participation and Exposure
Sr	strontium
Sv	sievert
TLD	thermoluminescent dosimeter
TM	technical manual
TRU	transuranic
TTPI	Trust Territory of the Pacific Islands

UA	uncertainty analysis
UB	upper-bound
UDT	underwater demolition team
UF	uncertainty factor
UK	United Kingdom
USA	United States Army
USAF	United States Air Force
USEPA	United States Environmental Protection Agency
USN	United States Navy
USNRC	United States Nuclear Regulatory Commission
USUHS	Uniformed Services University of the Health Sciences
USSR	Union of Soviet Socialist Republics
VA	United States Department of Veterans Affairs
WBC	water beach cleanup
WBCT	water beach cleanup team
wk	week
y	year
Y	yttrium