HEADQUARTERS
AIR FORCE SAFETY CENTER

Radiation Exposures to Air Force Personnel Supporting the Enewetak Atoll Cleanup (1977 – 1980) and Assigned to the Atoll (1959 – 1973)

Steven E. Rademacher

FINAL

6 March 2019

Headquarters, Air Force Safety Center
Weapons Safety Division
9700 Avenue G, Southeast
Kirtland Air Force Base, NM 87117-5670

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
06/03/2019	FINAL	July 2016 - February 2019

4. TITLE AND SUBTITLE
Radiation Exposures to Air Force Personnel Supporting the Enewetak Atoll Cleanup (1977 - 1980) and Assigned to the Atoll (1959 - 1973)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Steven E. Rademacher, GS-14, DAF

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Headquarters, Air Force Safety Center
Weapons Safety Division
9700 Avenue G, Southeast
Kirtland AFB, NM, 87117-5670

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Headquarters, Air Force Safety Center
Weapons Safety Division
9700 Avenue G, Southeast
Kirtland AFB, NM, 87117-5670

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A: Approved for Public Release. Distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
From 1977 to 1980, a Department of Defense Joint Task Force, with the Depts of Energy and Interior rehabilitated the Enewetak Atoll to allow safe re-settlement of the Enewetak peoples. The primary field efforts involved the removal of debris and radiologically-contaminated soils that were residuals from atmospheric tests of nuclear weapons conducted at the Atoll between 1948 and 1958. Some veterans are concerned that radiation exposure radiations received during the cleanup is the cause of current health effects. This report details an assessment of exposure received by veterans and concludes that exposures were low, well below standards, and consistent with conclusions of a 1981 Defense Nuclear Agency report.

15. SUBJECT TERMS
Enewetak Atoll Defense Nuclear Agency nuclear testing Runit entombment Cactus Crater atmospheric testing Veterans Administration radiation exposure assessment fission products Air Force Marshall Islands Joint Task Force Atomic Energy Commission Department of Energy Department of Interior

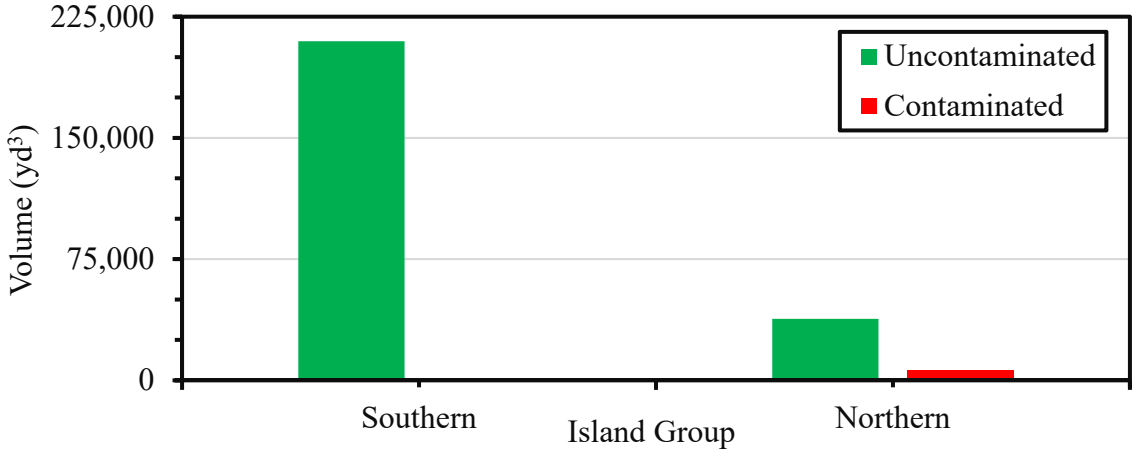
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Steven E. Rademacher
Unclass	Unclass	Unclass	Unclass	417	19b. TELEPHONE NUMBER *(Include area code)*

Executive Summary

Between 1977 and 1980, a Department of Defense (DoD) Joint Task Force (JTF) rehabilitated the Enewetak Atoll to allow safe re-settlement of the Enewetak peoples, whom were displaced in 1947. The Departments of Energy and Interior [DOE and DOI] also provided important support to this effort. The fieldwork was the culmination of many years of planning conducted by the DoD and predecessors to the DOE – Energy Research and Development Administration (ERDA) and the Atomic Energy Commission (AEC). The benchmark data source for the planning was the *Enewetak Radiological Survey* conducted between 1972 and 1973 by the AEC and its contract laboratories, and multiple commercial and government radioanalytical laboratories.

Recently, veterans who supported the cleanup effort have expressed their concerns to the DoD. They have concerns their work on the Atoll and the associated radiation exposures may be responsible for current health conditions. This report is designed to better understand the radiation exposure potential for personnel assigned to duties on the Atoll.

One primary purpose of the cleanup was removal and entombment of soils with the greatest concentrations of plutonium and removal of radiologically-contaminated debris that were residuals from 43 nuclear weapons tests conducted by the US on the Atoll between 1948 and 1958. While this primary purpose received much of the attention, removal of uncontaminated debris and structures entailed a significant amount of effort. In addition, due to impacts of WWII on the Atoll, significant work was dedicated to removing unexploded ordnance. The figure enclosed illustrates the volumes of debris removed and disposed among islands in the northern and southern parts of the Atoll during the cleanup. Only 2.3% of the debris was contaminated. As well, 83% of the debris removal was from southern islands of the Atoll, where none of the debris was radiologically contaminated.

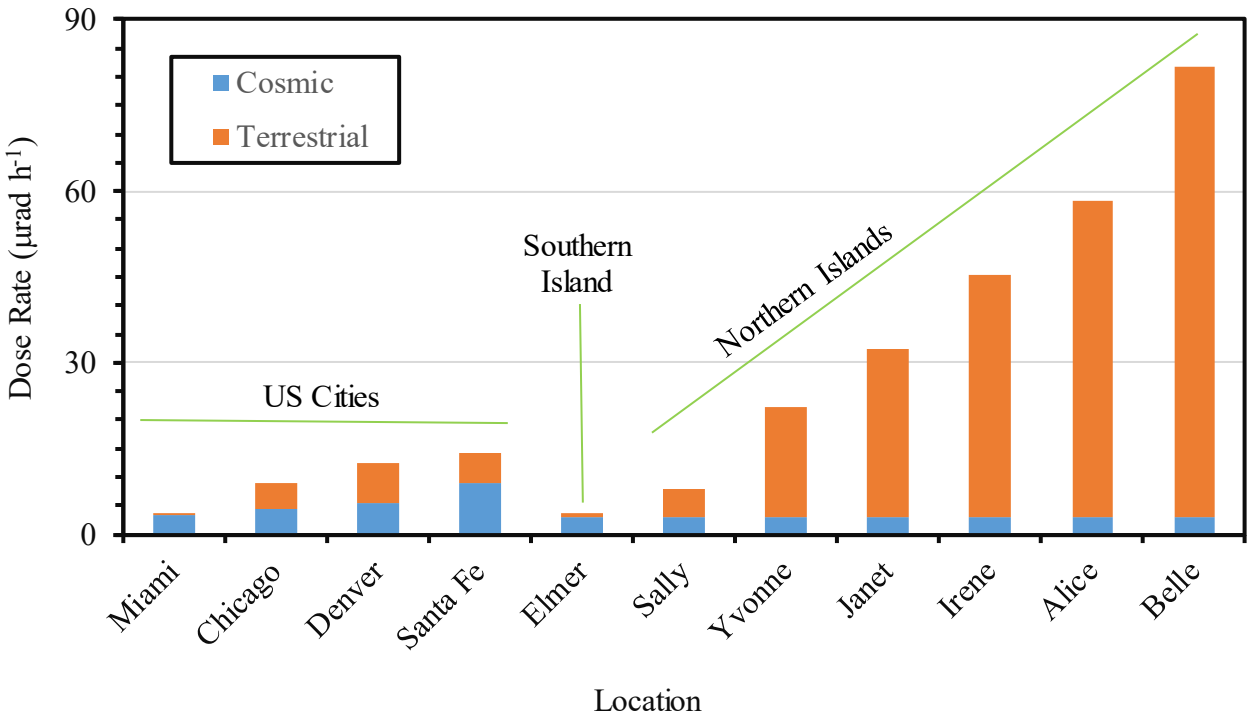


Debris Removal and Disposal Breakdown

The cleanup involved over 8,000 personnel serving at the Atoll, with numbers usually exceeding 1,000 personnel at any one time. About 5,600 were members of the DoD, with about 1,000 from the DOE, including its contractors, about 1,000 from other organizations, and 49 journalists. This report

supports the Air Force (AF) Safety Center's role in assessment of radiation exposures to its workers from nuclear weapons-related work environments. Though limited in scope to AF personnel, information contained in this report may be useful to other organizations that had personnel supporting this project.

This report provides an expansion of information on radiation exposures from the cleanup contained in the 1981 Defense Nuclear Agency (DNA) report, *The Radiological Cleanup of Enewetak Atoll*. The 1981 report provided extensive information on radiation exposures. The report concluded that radiation control measures implemented during the cleanup were effective, with radiation exposures being very low, a small fraction of the radiation exposure standards of the time. These conclusions were drawn based on the external dosimetry monitoring results, nasal swab and urine bioassay results, and air sampling results. Importantly, these conclusions were within expectations based on radiological conditions that existed prior to the rehabilitation effort, as detailed by the AEC 1972 – 1973 survey. The 1981 DNA report was primarily focused on workers performing work on the northern islands of the Atoll. This was because southern islands had external exposure rates well within those rates common to many locations in the continental US, as shown in the figure below. The key island representing exposure rates on southern islands is typified by the island Elmer, while key islands on the northern parts of the Atoll had higher exposure rates: Sally through Belle. Terrestrial sources of external dose are primarily from radioactive materials in surface soils, while cosmic radiation is from the Sun and galactic sources. This distinction in exposure potential is an important factor in assessment of exposure potential for individuals that supported the cleanup. A large fraction of workers never left the southern islands of the Atoll, as a large amount of work was dedicated to debris removal on southern islands. With only few exceptions, radiation safety practices enforced for individuals that worked on northern islands would not have been applied.



Based on review of historical radiological monitoring data in preparation of this report, the conclusions of the 1981 DNA report remain unchanged. The most important area of expanded information is for internal dose assessment, where the primary concern existed for inhalation of radioactive aerosols, and secondarily incidental ingestion of dust and soil. Information is also provided for dose to skin, from the build-up of contamination on the skin during work periods. Although the primary radiological contaminants that existed in soil during the period of the 1977 – 1980 cleanup project included varied isotopic mixtures of weapons grade plutonium (WGP), ^{137}Cs, ^{90}Sr, and ^{60}Co, this report will provide additional information on other radiological contaminants for completeness sake. Some of the additional review is dedicated to a 1995 DOE letter listing radionuclides not considered by the 1972 – 1973 AEC characterization. Still, for other radionuclides, a review was performed because of their expected presence, yet not included in AEC analyses due to a lack of photon emissions. Overall, while some of the radionuclides examined in closer detail had only negligible impacts to workers in the 1977 – 1980 cleanup, this report provides exposure estimates for personnel assigned to southern base islands between 1959 and 1973. The AF Safety Center receives many inquiries by veterans assigned to the Atoll during this period. For evaluation of exposures for earlier times, a more detailed assessment of some short-lived radionuclides was necessary. This detailed assessment concluded that personnel assigned to the southern base islands between 1959 and 1973 were exposed to low-level external radiation, well within levels typical to continental US (CONUS) locations from background radiation sources in the environment. The exposure rates, however, were higher than those observed during the cleanup, which is logical considering radioactive decay processes. The predicted internal exposures for personnel on the southern islands between 1959 and 1973 were only a small fraction of the external exposure source. Defense Threat Reduction Agency (DTRA) in 2017 published an upper-bound dose assessment report for Enewetak cleanup personnel (DTRA 2017). DTRA's report had a similar conclusion as this report, though this report has expanded detail on radiological and other data. DNA is a predecessor organization to DTRA.

The use of personal protective equipment (PPE) by personnel supporting the cleanup was a common issue raised by veterans supporting the cleanup. This report provides an extensive evaluation of PPE use by personnel supporting the cleanup. In review of historical documents, it is clear that there was varied application of PPE. Some changes were implemented over the course of the clean-up effort. Initially, very conservative specifications were implemented, which in many cases were reduced based on personnel contamination screening and air monitoring results experienced during the course of the clean-up. PPE specifications were also island-specific and varied among tasks being conducted on a given island. The most important task that specified an air-purifying respirator use with PPE was soil excision. This activity was associated with the highest concentrations of airborne α-radiation, based on historical air sampling results, yet also accompanied by air-purifying respirator use. Overall, PPE specified for personnel during the project were very conservative, which afforded very low estimated internal exposure estimates for activities where air-purifying respirators were used.

This report provides a detailed evaluation of radiation protection standards implemented during the period of the cleanup versus more current standards. The standard used for the project was promulgated in 1959. Though health effects knowledge of ionizing radiation protection have greatly expanded since 1959, there have not been major changes in protection standards since that time. Internal radiation exposures from WGP was a primary concern for personnel supporting cleanup at

the Atoll. The maximum permissible concentrations (MPC) for WGP established in 1959 are lower in many cases than derived air concentrations (DAC) established in updated international standards that have been adopted in the US. Historically, in the development of safety standards for radiation, lack of knowledge was often supplemented by a degree of prudent conservativism. This was indeed the case for radionuclides of concern on the Atoll.

This report concludes that internal radiation exposures potentially received by cleanup workers were low compared to external radiation exposures, based on conservative assumptions. The combined sources of external and internal radiation were well below radiation exposure standards implemented for the cleanup and current radiation standards used in the US and internationally. This report supports conclusions drawn by the 1981 DNA report.

Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

α	alpha
ACS	American Cancer Society
AEC	Atomic Energy Commission
AF	Air Force
AFRRI	Armed Forces Radiobiology Research Institute
ALI	annual limit of intake
AMAD	activity median aerodynamic diameter
β	beta
Bq	Becquerel, Système International unit, one disintegration per second
BS	bone surfaces
CEDE	committed effective dose equivalent
CFR	Code of Federal Regulation
Ci	Curie, Traditional unit or radioactivity, 3.7×10^{10} disintegrations per second
d	day
DAC	derived air concentration
DC	dose coefficient
DCF	dose conversion factor
DNA	Defense Nuclear Agency
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of Interior
DTRA	Defense Threat Reduction Agency
DU	depleted uranium
EG&G	Edgerton, Germeshausen & Grier
E	effective dose
EIC	Eberline Instrument Corporation
EPA	Environmental Protection Agency
ERDA	Energy Research Development Administration
E-T	extra-thoracic
f_1	gastro-intestinal tract uptake factor
fCi	femptoCurie, one-quadrillionth of a Curie, 3.7×10^{-5} disintegrations per second

FGR	Federal Guidance Report
FIDLER	field instrument for the detection of low energy radiation
FRC	Federal Radiation Council
FRST	field radiation support team
γ	gamma
GI	gastro-intestinal
h	hour
ha	hectare, unit of area, 10,000 m^2
HE	high explosives
HEU	highly-enriched uranium
HPS	Health Physics Society
keV	kilo electron volt
kg	kilogram
kt	kiloton
ICRP	International Commission on Radiological Protection
JTF	Joint Task Force
JTG	Joint Task Group
keV	kiloelectron Volts
km	kilometer, 1,000 meters
kT	kiloton
LFE	Laboratory for Electronics, Environmental Analysis Laboratories Division
LLL	Lawrence Livermore Laboratory
LLNL	Lawrence Livermore National Laboratory
mCi	milliCurie, $1/100^{th}$ of a Curie, 3.7×10^7 disintegrations per second
MT	megaton
μCi	microCurie, one-millionth of a Curie, 3.7×10^4 disintegrations per second
MCL	McClellan Central Laboratory
MCLs	maximum contaminant concentration levels
MDC	minimal detectable concentration
MeV	megaelectron Volts
mg	milligram, $1,000^{th}$ of a gram
MPBB	maximum permissible body burden

MPC	maximum permissible concentration
MPOB	maximum permissible organ burden
MT	megaton
NAS	National Academy of Sciences
NBS	National Bureau of Standards
nCi	nanoCurie, one-billionth of a Curie, 37 disintegrations per second
NCRP	National Committee on Radiation Protection and Measurements
NDET	non-detect
NRC	Nuclear Regulatory Commission
NTPR	Nuclear Test Personnel Review
OEHL	Occupational and Environmental Health Laboratory
OSHA	Occupational Safety and Health Administration
PAC	portable alpha counter
pCi	picoCurie, one-trillionth of a Curie, 0.037 disintegrations per second
PIC	pocket ion chamber
PPE	personal protective equipment
RBM	red bone marrow
RCC	radiation control committee
RBE	relative biological effectiveness
RPG	radiation protection guide
RPO	radiation protection officer
RSAIT	radiation safety audit and inspection team
SOP	standard operating procedure
T	ton
TLD	thermo-luminescent dosimetry
TTPI	Trust Territory of the Pacific Islands
US	United States
USAF	US Air Force
USTUR	U.S. Transuranium and Uranium Registries
VA	Department of Veterans Affairs
WGP	weapons grade plutonium
WWII	World War II
y	year

Acknowledgements

Dr. Byron Ristvet, retired/consultant. Appreciation for historical insights of nuclear weapons testing in the Pacific Proving Grounds, and assistance in evaluation of tracer materials used in testing. Dr. Ristvet, prior to his retirement from civil service at DTRA, provided valuable assistance in assessment of archived documents in the DTRA archives. Dr. Ristvet had many decades of experience in underground testing of nuclear weapons and scientific studies on the Pacific Proving Grounds.

Dr. Edward T. Bramlitt, CHP (American Academy of Health Physicists). Appreciation for his experience as the lead Defense Nuclear Agency (DNA) health physicist during the project and insights into radiation safety aspects implemented during the Enewetak cleanup provided to the author in completion of this report. Dr. Bramlitt also has extensive experience at the Johnston Atoll and remediation of plutonium contamination.

Dr. Robert Cherry, CHP, US Installation Management Command. Appreciation for historical aspects of radiation safety program implemented on the Atoll. Dr. Cherry served on Enewetak Atoll as a radiation protection officer during the cleanup and retired from active duty service in the Army at the rank of Colonel. Dr. Cherry provided valuable technical review of the manuscript.

Mr. Theodore Simmons, CHP, Staff Health Physicist, Sandia National Laboratories (SNL). Mr. Simmons had on-site experience during the Enewetak Atoll cleanup supporting the Department of Energy. Mr. Simmons provided valuable insights into operations during the cleanup. Mr. Simmons has over 40 years of experience at SNL and provided valuable technical review of the transcript.

Lt Col (Dr.) Scott Nemmers, QMP (American Association of Physicist in Medicine), Medical Physics Consultant, Office of the AF Surgeon General. Lt Col Nemmers provided valuable review of the manuscript.

Lt Col Alan C. Hale, CHP, Chief, Radiation Health, Office of the AF Surgeon General. Lt Col Hale provided valuable review of the manuscript.

Dr. Jason Cezeaux, CHP, Chief, Radiation Dosimetry Laboratory, USAF School of Aerospace Medicine. Dr. Cezeaux is an expert radiation dosimetrist on both external and internal radiation sources. Dr. Cezeaux provided valuable review of the manuscript.

Maj Ryan Eiswerth, Program Manager, Directed Energy Weapons, AF Safety Center. Major Eiswerth provided assistance in database development in support of dose reconstructions for personnel supporting the cleanup, bioassay data analysis included in this report, and valuable technical review of the manuscript.

Ms Joy Morris, Environment and Occupational Health Manager, AF Technical Applications Center, Patrick AFB, FL. Ms. Morris has extensive experience in evaluating veteran exposure claims. Ms. Morris provided valuable review of the manuscript.

Section 1.

Introduction

1.1 Overview

The Department of Defense (DOD) has recently received greater interest by veterans in the radiation exposures received by them during rehabilitation (cleanup) of the Enewetak Atoll[1] between 1977 and 1980. The DOD, involving a Joint Task Force (JTF) staff and numerous units from the Army, Navy, and Air Force (AF), executed the field portion of the cleanup. Planning the rehabilitation was initiated in 1972 and involved close cooperation with the Department of Energy (DOE), and its previous organizations: the Atomic Energy Commission (AEC) and Energy Research and Development Administration (ERDA). The resettlement of the Enewetak peoples to the Atoll was accomplished by the Department of the Interior (DOI), in part, during the field portion of the rehabilitation, and required close cooperation with the JTF and DOE.

The field portion of the rehabilitation involved a number of major activities to include: removal of undesired debris and infrastructure from AEC's use of the Atoll for atmospheric testing of nuclear weapons; removal of undesired infrastructure used by the Japanese and US military prior to, during, and after World War II (WWII); search and removal of suspected unexploded ordnance remnants from WWII battles on the Atoll; translocation of radiologically-contaminated soil and debris to the Cactus Crater on Runit (Yvonne) Island; construction of the Cactus Crater containment; verification of radiological conditions on the Atoll; construction of facilities to support the rehabilitation; and extensive interisland transportation. This effort involved about 1,000 personnel on the Atoll at any one time, with over 8,000 personnel serving at the Atoll during the cleanup (DNA 1981). As expected, a reasonable fraction of these personnel did not perform these primary tasks, but executed important support functions – lodging, dining, sanitation, equipment repair, supply and fuel distributions, etc. A detailed description of the scope of the 1977 – 1980 fieldwork is provided in a 1981 Defense Nuclear Agency (DNA) report, *The Radiological Cleanup of Enewetak Atoll* (DNA 1981).

1.2 Marshall Islands and Atmospheric Testing of Nuclear Weapons

Enewetak Atoll is a small ring of islands on the northwestern part of the Marshall Islands, as shown in Figure 1-1. The Atoll is about 2,500 miles west-southwest of Honolulu, Hawaii. The Atoll is comprised of about 40 islands, as shown in Figure 1-2, with the associated site names assigned by US Government personnel during the nuclear testing period. Table 1-1 contains a listing of the area of the majority of the islands and the names applied to the individual islands by the Enewetak peoples. It is approximately 20 nautical miles (37 km) from Janet (one of the northernmost islands) to Fred, the most southern island of the Atoll. Fred is the largest island in area and was the primary support island of the Atoll used during the atmospheric testing period at the Atoll. It also has an airfield that supports passenger jet service today, expanded from the runway that was built by the Navy during WWII. The island of Janet had a runaway and supporting facilities for military aircraft during WWII and is the second largest island of the Atoll.

During the period of 1946 (Operation Crossroads) through 1958 (Operation Hartack I), the US conducted 67 nuclear weapon tests in the Marshall Islands (DOE 2015). Forty-three of these

[1] The Atoll has also been historically spelled Eniwetok.

tests were conducted at Enewetak Atoll (1948 – 1958), 23 at Bikini Atoll, with one test conducted between these two Atolls at high altitude, supported by a balloon (DOE 2015). Table A-2 (Appendix A) contains a listing of the tests conducted at Enewetak Atoll, along with some details on each test. The total yield of each test is based on the latest update to DOE/NV-209, Revision 16 (DOE 2015). Many of the previous published reports on the rehabilitation of Enewetak Atoll, i.e., the 1981 DNA report and Nevada Operations Office, AEC Report NVO-140, *Enewetak Radiological Survey* (AEC 1973), only contained a partial listing of yields, as some yields remained classified when those reports were published. The yields of the tests ranged from zero (Tests Quince and Scaevola) to 10.4 megaton (MT) for the Mike Device in Operation Ivy. Scaevola was a Los Alamos

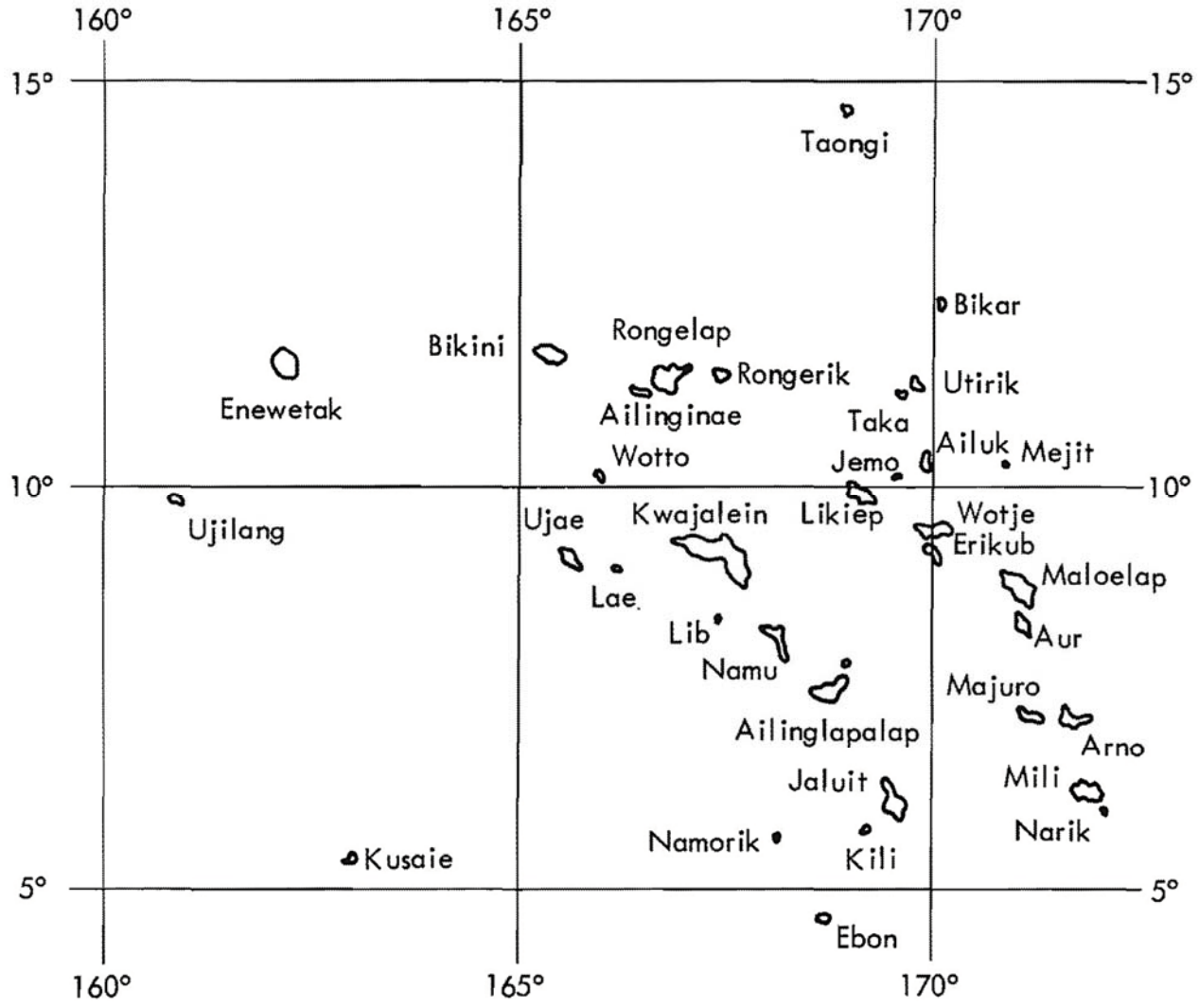


Figure 1-1. Marshall Islands [Figure 5, AEC (1973)].

Scientific Laboratory (LASL) safety test conducted on a barge, in the lagoon just west of Yvonne. Test Quince involved only the detonation of the conventional explosives component in the test device on the island of Yvonne, and subsequently had no nuclear yield. Some information in Table A-2 is provided only for reader interest. For example, noting the first thermonuclear test explosion, the first test of the boosting principle, and the largest fission device were among the tests at

Enewetak Atoll. Figure 1-3 provides a graphical depiction of individual test locations on the Atoll, corresponding to the information in Table 1-1. It is clear from the figure that with the exception of two underwater tests, Umbrella and Wahoo, all other tests were conducted in the northern portion of the Atoll. Only six of the islands of the Atoll were ground zero (GZ) for a test: Yvonne, Sally, Janet, Ruby, Pearl, and Irene. The island of Yvonne supported eight tests, the highest number among the islands. The location of tests along with weather conditions during and after the tests were very important in defining the short- and long-term radiological impacts the Atoll. In general, the southern islands of the Atoll had relatively insignificant impacts compared to islands in the northern half of the Atoll. Prior to atmospheric testing, the northern islands were inhabited by the Dri-Enjebi, with the Dri-Enewetak inhabiting the southern islands.

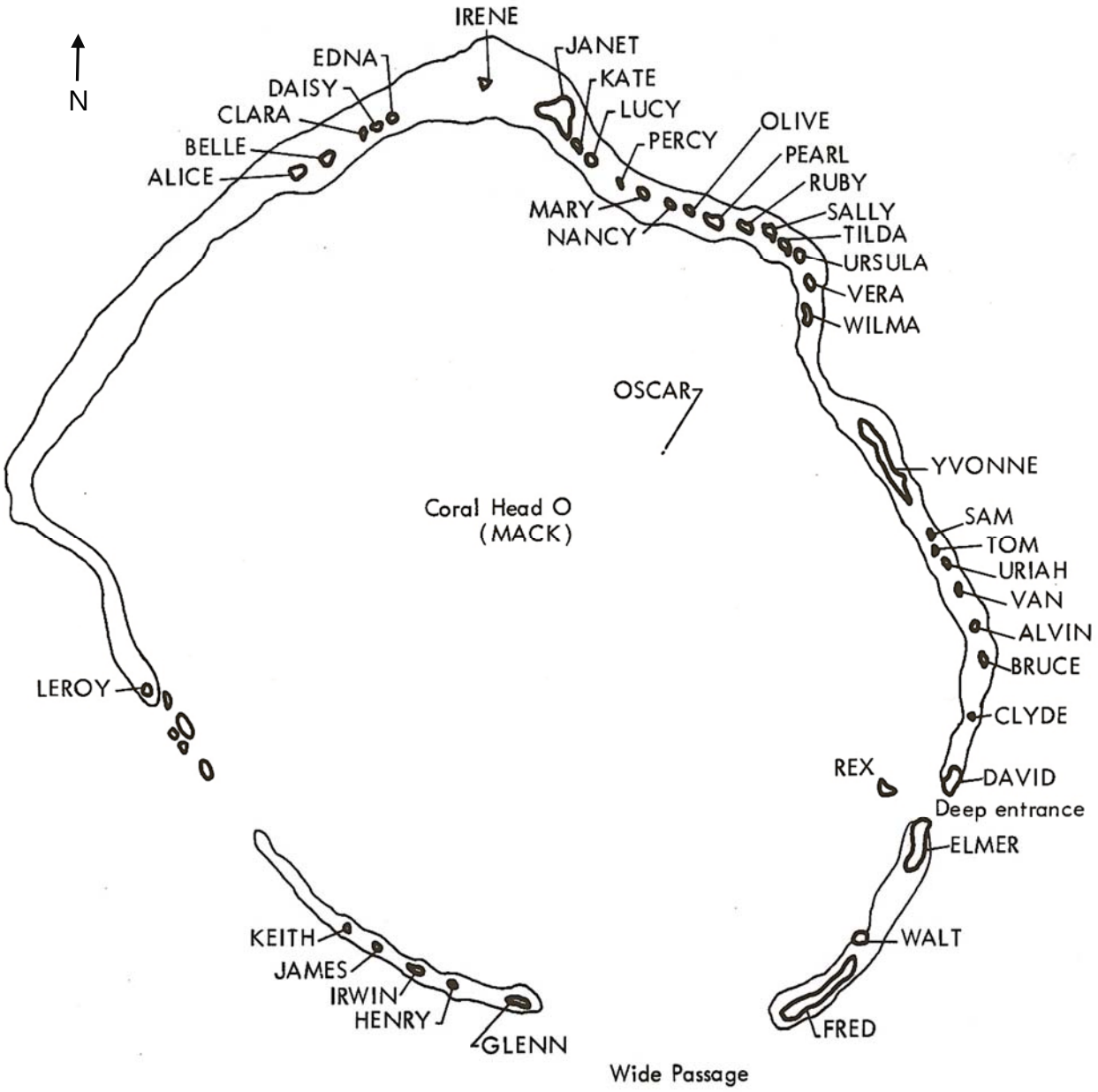


Figure 1-2. Enewetak Atoll [AEC (1973)].

TABLE 1-1. Island Code Names, Local Names, Island Areas, and Number of Ground Zero Locations for Nuclear Tests.

Group	Island Code Name	Local Name	Land Area (hectares†)	Ground Zero Tests
Southern Islands	Sam	Boko	0.5	0
	Tom	Munjor	1	0
	Uriah	Inedral	2	0
	Van	--	3	0
	Alvin	Jinedrol	1	0
	Bruce	Ananij	10	0
	Clyde	Jinimi	1	0
	David	Japtan	32	0
	Rex	Jedrol	2	0
	Elmer	Medren	89	0
	Walt	Bokandretok	0.5	0
	Fred	Enewetak	130	0
	Glenn	Ikuren	17	0
	Henry	Mut	16	0
	Irwin	Boken	12	0
	James	Ribewon	8	0
	Keith	Kidrenen	10	0
	Leroy	Biken	5	0
Northern Islands	Vera	Alembel	15	0
	Wilma	Billae	6	0
	Mack	Unibor	NL	0
	Ursula	Lojwa	16	0
	Tilda	Bijire	21	0
	Nancy	Elle	4	0
	Olive	Aej	16	0
	Edna	Bokinwotme	4	0
	Alice	Bololuo	9	0
	Belle	Bokombako	12	0
	Clara	Kirunu	3	0
	Daisy	Louj	9	0
	Percy	Taiwel	2	0
	Helen*	Bokaidrikdrik	NL	0
	Irene	Boken	16	1
	Janet	Enjebi	118	3
	Kate	Mujikadrek	6	0
	Lucy	Kidrinen	8	0
	Mary	Bokenelab	5	0
	Pearl	Lujor	22	1
	Ruby	Elleron	2	2
	Sally	Aomon	40	3
	Yvonne	Runit	37	8

NL = Not Listed * Mostly destroyed by Test Seminole, remainder considered part of Irene

† One hectare equals 10,000 m^2 or 1.47 acres

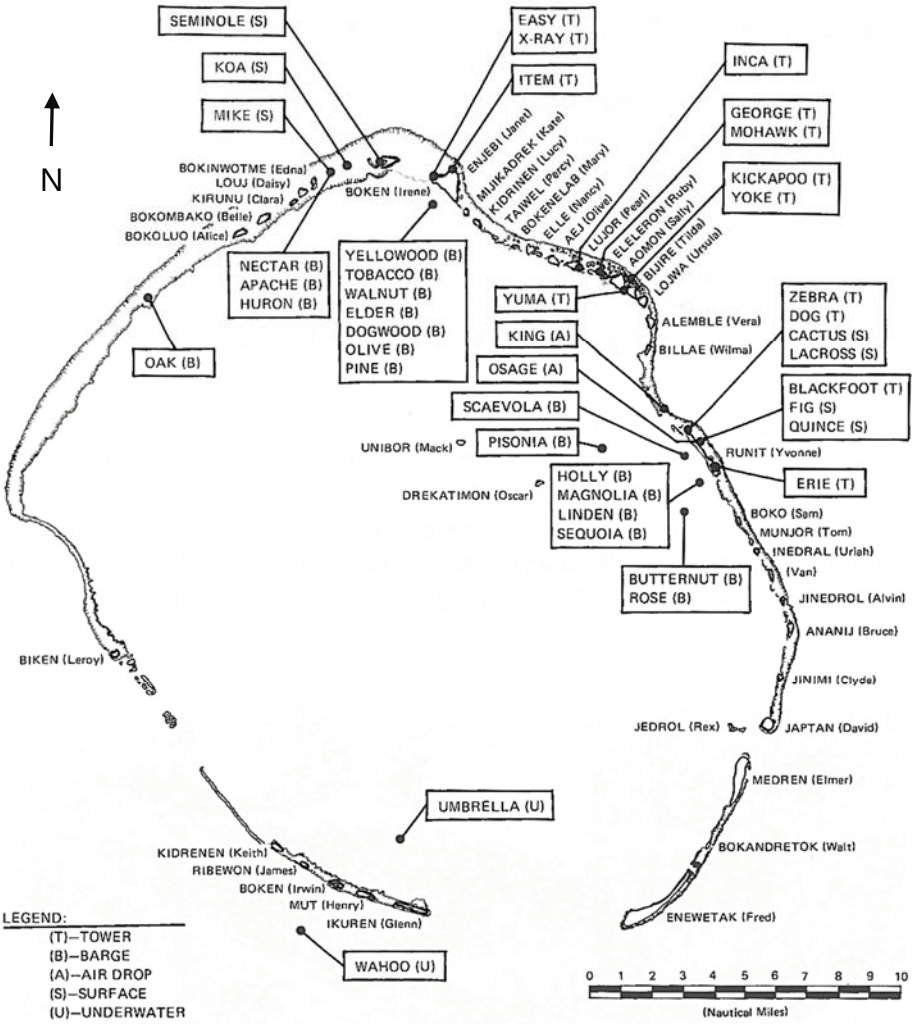


Figure 1-3. Nuclear Detonation Sites on Enewetak Atoll [Figure 1-53, (DNA 1981)].

This was due to limited tests by number (and type of tests) on the southern islands and careful planning of tests around weather conditions that were favorable to carry fallout contamination away from locations inhabited by test support personnel. Greater information on these factors will be discussed later in this report.

1.3 Scope and Emphasis

The primary purpose of this report is to provide details on the radiation exposures received by AF element members that were on the Atoll during the 1977 – 1980 cleanup effort. In this vein, this report provides an expansion on information already detailed in the 1981 DNA report (DNA 1981). The 1981 report concluded that radiation exposures to personnel on the Atoll during the cleanup were very low and well below radiation safety standards established for the project. These conclusions were drawn based on the external dosimetry monitoring results, nasal swab and urine bioassay results, and air sampling results. Importantly, these conclusions were within expectations based on radiological conditions that existed prior to the rehabilitation effort, as detailed extensively in Nevada Operations Office, AEC Report NVO-140, *Enewetak Radiological Survey* (AEC 1973). Based on review of historical radiological monitoring data in preparation of this report, the

conclusions remain unchanged. The most important area of expanded information is for internal dose assessment, where the primary concern existed for inhalation of radioactive aerosols, and secondarily incidental ingestion of dust and soil. Although the primary radiological contaminants that existed in soil during the period of the 1977 – 1980 cleanup project included varied isotopic mixtures of weapons grade plutonium (WGP), ^{137}Cs, ^{90}Sr, and ^{60}Co, this report will provide additional information on other radiological contaminants for completeness sake. Some of the additional review is dedicated to a 1995 DOE letter (Robison et al. 2001) listing radionuclides not considered by the 1972 – 1973 AEC characterization. Still, for other radionuclides a review was provided due the known presence of a radionuclide, yet not included in analysis due to a lack of photon emissions[2]. Overall, while some of the radionuclides examined in closer detail had only negligible radiation health implications to workers in the 1977 – 1980 cleanup, this report does provide exposure estimates for personnel assigned to southern islands of the Atoll between 1959 and 1973. Hence, some of the short-lived radionuclides had greater importance for individuals on the Atoll at earlier periods.

A secondary emphasis of this report it to provide discussion of personal protective equipment (PPE) use. This discussion is motivated in part by comments provided by veterans to the Defense Threat Reduction Agency (DTRA) office responsible for managing the Nuclear Test Personnel Review (NTPR) – DTRA/J9NTSN, offices in the DOD components that evaluate radiation health claims, and the Department of Veterans Affairs. Similarly, veterans have had their concerns published in a March 2016 *The American Legion Magazine* (Raughter 2016) and a 28 January 2017 New York Times article (Philipps 2017). A common issue raised by veterans was the varying levels of respiratory protection – some activities were specified for the use of air purifying respirators, while other activities were not or only specified the use of dust masks. Some veterans noted that dust masks were unavailable for some periods of their work. In review of historical documents, it is clear that there was varied application of PPE. Some variance was implemented over the course of the clean-up effort. Initially very conservative specifications were implemented, which in many cases were reduced based on personal contamination screens and air monitoring results experienced during the course of the clean-up. PPE specifications were also island-specific and varied among tasks being conducted on the island. In fact, for some islands of the Atoll, over the course of a few weeks, PPE specified ranged from no protection (Level I) to Level IV (full-face air purifying respirator, rubber boots, gloves, anti-contamination clothing, and tape-secured openings). Health concerns from heat stress associated with the use of higher levels of PPE also contributed to the re-evaluation of PPE requirements.

A third emphasis of this report is discussion on the applicability of the standards and protection provided to veterans during the cleanup in light of increased knowledge of the effects of ionizing radiation and changes in protection standards that have occurred over the past 50+ years. The recent concerns raised by veterans regarding their participation in the cleanup are primarily related to their current health conditions: "brittle bones, cancer, and birth defects in their children" (Philipps 2017) and "estimates that the cancer rate among [these veterans] is about 35%" (Raughter 2016). The exposure standards implemented for the cleanup were based on 1959 recommendations of the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection (NCRP). Though health effects knowledge of ionizing radiation protection have greatly expanded since 1959, there have not been major changes in protection standards since

[2] Gamma radiation spectrometry was performed on all soils samples. This analysis method is well suited for detection of photon emissions emitted during radiological decay. Some radionuclides do not have any photon emissions or only insignificant emissions on a frequency basis. For these radionuclides, more suitable methods are warranted for laboratory assessment.

that time. Historically, in the development of safety standards for radiation, lack of knowledge was often supplemented by a degree of prudent conservativism. Internal radiation exposures from WGP was a primary concern for personnel supporting cleanup at the Atoll. The maximum permissible concentrations (MPC) for WGP established in 1959 are lower in many cases than derived air concentrations (DAC) established in updated ICRP recommendations. The recent concerns expressed by veterans of health effects, most importantly incidence of cancer induction, is not unexpected. The mostly male population of veterans supporting the cleanup would have been born between about 1928 and 1961, and if currently alive, would be between 56 and 89 years old. As risk of cancer induction generally becomes much more prominent as individuals age, the rate referenced by Raughter (2016) does not appear abnormal. The American Cancer Society (ACS) estimates a lifetime probability of developing cancer of 42%[3] for males (ACS 2016). Table A-1 (Appendix A) provides a detailed listing by cancer site.

This report's scope is directed primarily to exposures received by the 740 AF element members that were part of the 5,617 DOD service member participants, as listed in Table 1-2, and other participants. The DOE and its contractors provided another large group of participants by number, as did the DOI and members of the Trust Territory of the Pacific Islands (TTPI). Information in this report may be useful in the assessment of exposures to these other groups of individuals, however, exposures to these groups are outside the AF's authority. A substantial amount of information archived by DNA also contains information on non-DOD participants. For example, during the 1977 – 1980 rehabilitation, northern islands of the Atoll had controlled access. The JTG maintained logs of individuals, by surname, SSN, island being accessed, and date. These logs contain all individuals that obtained access. As noted, this report extends exposure assessment to individual's assigned duties on the southern islands from 1959 to 1973. Many of these individuals were AF personnel, which falls under the AF responsibility. The data nevertheless could be applied to personnel that were supporting missions of other organizations.

TABLE 1-2. Participants in Enewetak Rehabilitation Project by Affiliation [Table B, pp. 645-646, (DNA 1981)].

Affiliation	Number	Affiliation	Number
Army Element[4]	2670	DOI & Trust Territory of the Pacific Islands (TTPI) Participants	597
Navy Element	2207		
AF Element	740	Journalists	49
DOE & its Contractors	1011	Others	513

1.4 Format and Style

This report is organized in a manner common to technical documents. However, it is anticipated that information in this document will be of interest to veterans that supported the

[3] 23 sites for cancer induction, 2010 – 2012, for those whom are initially cancer free, excluding basal and squamous cell skin cancers.
[4] HQ JTF members were all Army members and included in the total for Army personnel, yet these members did not conduct Army Element functions.

cleanup. For this reason, in some places there will be expanded details on some topics. Some readers may not have a technical background in the area of radiation safety. As a technical document, it is common to reference previously published articles, books, and reports as supporting information. This document is largely based on historical information from these types of sources. In most technical documents, it is commonly left to the reader to research these original sources for additional information and detail. In contrast, this document will provide excerpts of some of the materials as an aid to the reader. Much of this information is placed in Appendices. For those that desire even more detail, the most pertinent documents are available for free download on the internet.

This report also provided some technical information on the processes for formation of radiological contaminants. This information is also provided as an aid for the reader interested in understanding the basis for the residual contaminants from the tests conducted on the Atoll.

The majority of the historical radiological data used in compilation of this report and the historical safety standards referenced for the period of the rehabilitation work are reported in traditional units, i.e., rad (for radiation absorbed dose), curies (for quantity of radioactivity), roentgen (for exposure). To retain integrity of the historical units used, yet meet National goals of adopting to the International System of units (NAS 2017), in some places in this document, both types of units will be displayed, and unit conversions noted.

Section 2.

Radiological Source Term

2.1 Overview

Nuclear weapons are fundamentally designed around the fission of heavy elements induced by their bombardment by neutrons, as illustrated in Figure 2-1 below. In this example, the heavy element is split into two large fragments with three neutrons (depicted by the red spheres) and two gamma rays. A substantial amount of energy is released in the fission process, with distribution listed in Table 2-1. Fundamentally, all of the energy released is equivalent to the mass difference between the atom being fissioned, e.g. ^{235}U (or others), and the fission fragments. The majority of the energy released is prompt and in the form of kinetic energy of the fission fragments, neutrons, and gamma (γ)-radiation. Prompt energy release contributes to the heat and blast of the detonation.

The production of neutrons in the fission process is important to the sustainment of the fission process in other heavy elements, more commonly termed a nuclear chain reaction. Though many heavy elements are susceptible to fission under the bombardment of neutrons, only a small number of heavy elements, and specific isotopes of those elements, are suitable for use as a fission fuel in a nuclear weapon due to their greater susceptibility to fission by neutrons across a broad range of energies. These isotopes are referred to as fissile isotopes, and are capable of supporting a self-sustaining chain reaction, commonly referred to as a critical mass. The important fissile isotopes suitable for use are ^{239}Pu, ^{233}U, and ^{235}U. Other isotopic compositions of uranium have also been used in nuclear weapons: depleted and natural uranium (DU and U-nat) [DOD (2005); DOE (1982)], though neither are fissile. Both of these are predominantly comprised of ^{238}U on a mass basis.

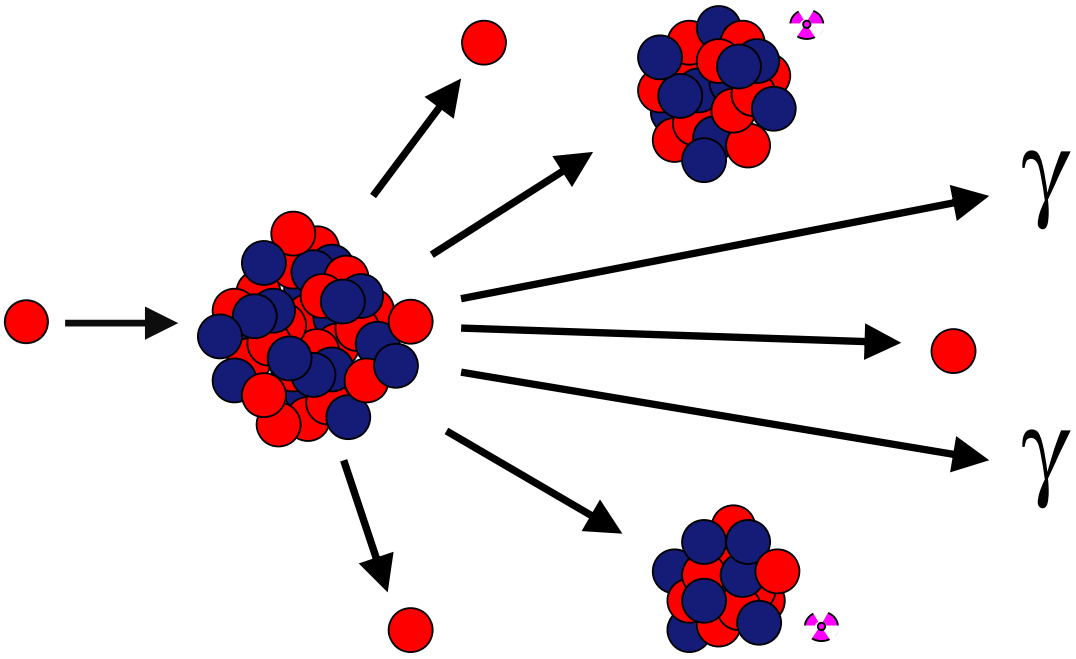


Figure 2-1. Conceptual Diagram of the Fission of a Heavy Nucleus by Neutron Bombardment, Producing Fission Fragments, Neutrons, and Gamma Rays (γ).

TABLE 2-1. Distribution of Fission Energy, from Glasstone and Dolan (1977).

Source	Energy Released	
	MeV	% of Total
Kinetic energy of fission fragments	165 ± 5	82.5
Instantaneous gamma-ray (γ-ray) energy	7 ± 1	3.5
Kinetic energy of fission neutrons	5 ± 0.5	2.5
Beta-radiation from radioactive decay of fission products	7 ± 1	3.5
Gamma-rays (γ-rays) from radioactive decay of fission products	6 ± 1	3
Neutrinos from fission products	10	5
Total	200 ± 6	100

This isotope of uranium is susceptible to fission, predominantly from fast neutrons only, while ^{235}U is susceptible to fission over a broad range of incident neutron energies. Isotopes are different forms of an element which have an identical number of protons in the nuclear, but a varied number of neutrons.

Thermonuclear weapons will also contain very light elements that will undergo the fusion process to form a heavier element and other particle(s). This process liberates kinetic energy to products of the reaction, with four important reactions shown below using tritium (^{3}H), deuterium (^{2}H), or a combination of the two elements as fuel. Both of these are isotopes of hydrogen. Deuterium, possessing only one neutron, is stable, while tritium, having two neutrons in its nucleus, is radioactive. Another reaction of thermonuclear weapon interest is that of ^{6}Li with a neutron

$$D + D = {}^3H + n + 3.2\ MeV$$

$$D + D = T + {}^1H + 4.0\ MeV$$

$$T + D = {}^4He + n + 17.6\ MeV$$

$$T + T = {}^4He + 2n + 11.3\ MeV$$

(Glasstone and Dolan 1977), as show below.

$$^6Li + n = {}^4He + {}^3T + 4.8\ MeV$$

2.2 Residuals from Weapon Detonations

2.2.1 General

Nuclear weapon detonations leave residual radioactive materials that are distributed to the environment by the blast wave and fallout from the debris cloud. The debris cloud produced from a nuclear weapon detonation is highly dependent on the type of test configuration. As listed in Table A-2, there were a variety of configurations for nuclear weapon tests on Enewetak Atoll – test towers at heights of 200 or 300 feet (ft) above ground level (AGL), ground surface, barge, underwater, and airdrop (1,500 ft). For surface or tower detonations on land, the debris cloud will incorporate materials in the vicinity of the detonation to include soil, rock, test support structures, etc. Detonations conducted underwater or on barges will incorporate water and water vapor into the debris pattern. Detonations at low altitudes, like Event King (15 Nov 52), that was detonated at 1,500 ft AGL will incorporate ground material in the debris cloud, but will have substantially less disruption of the terrain as compared to a surface or tower burst on land, and have a much lower level of debris. Many of the tests conducted on the Atoll left residual craters, with some of the tests completely destroying individual islands. This was the case for the Events Mike (31 Oct 52) and Koa (12 May 58) that destroyed the islands of Flora and Gene, respectively. The crater from Event Cactus on Yvonne (Runit) created a basin for the entombment structure that was one part of the executed cleanup activities.

The extent of nuclear fallout to the environment from an individual nuclear weapon test is influenced by a number of factors, with key ones being total yield of the test, existing weather and atmospheric conditions, and location of the test, e.g., surface, tower, air drop, underwater. An underwater test will have a significantly smaller amount of nuclear fallout distributed through an airborne debris cloud as compared to a test conducted on the surface of a land area, barge on a water surface, tower on land, or at low altitude. The amount of radioactive debris from a test is typically related to the total yield of the test, but is affected by the relative contribution of fission and fusion to the total yield of an individual test. For the non-underwater tests, total yield is an important factor in determining the extent of the nuclear fallout, as related to the height of the debris cloud. Greater debris cloud heights afford a larger fraction of the nuclear debris to regional and global dispersal, rather than primarily to the local area of the Atoll, which dominates the deposition for the lower yield devices. Some of the nuclear weapon tests conducted at Enewetak Atoll had only localized debris distributions, due to the very low nuclear yield of the test, i.e., the 190 ton (T) [TNT-equivalent] yield from Event Yuma (27 May 56) and 1.49 kiloton (kT) from Event Kickapoo (13 Jun 56) detonated on Sally, and the 20 T Event Fig (18 Aug 58) conducted on Yvonne. Two tests, Events Scaevola (14 Jul 58) and Quince (6 Aug 58) had no nuclear yield, with conventional high explosives (HE) providing the only source of energy for the dispersal of debris from the devices. Among the events, these two had the lowest degree of dispersal to the environment through the air. Since Event Scaevola was conducted on a barge, west of Yvonne, debris from this detonation would have largely deposited in surface waters of the lagoon. Event Quince caused the scattering of plutonium over a large area on Yvonne, with characteristics similar to the plutonium residue left on Johnston Island after two aborted nuclear weapons tests (DNA 1981). Some similarities would exist also with the residuals from the nuclear weapons accident that occurred at Palomares, Spain[5].

[5] The 17 Jan 66 nuclear weapons accident at Palomares, Spain involved HE-induced dispersion of WGP when the conventional HE detonated upon impact of two weapons with the groumd.

The degree of fallout debris depositing on any one island of the Atoll is dependent on a number of factors. First, a key factor is whether or not a nuclear test was conducted on an Island. Islands that supported tests will have areas of localized contamination near the GZ of a test. Residual contamination near the GZ will be higher than locations at greater distance from the GZ. In contrast, all islands within the Atoll would have had local fallout debris deposition from tests conducted on other islands in the Atoll. Contamination deposited in this manner is generally more uniform for any specific island. The relative impact to each island is primarily dependent on the local weather conditions that existed during a test. In general, the southern islands of the Atoll had very limited impact from local fallout of Enewetak tests, as compared to the northern island of the Atoll. To illustrate this point, the predicted radiation exposure rate contours of fallout deposits from Event Mike detonated on Flora is displayed in Figure 2-2. Event Mike had a 10.4 megaton (MT) yield, the highest among tests conducted on Enewetak. Clear from the plot is the drastic variation in predicted exposure rate, based on distance from GZ, as well as minimal impact to the key support southern islands of the Atoll: Elmer, David, and Fred. Figure 2-3 displays the predicted radiation exposure rate from fallout deposition of Event Nectar, as detonated on a barge over the crater created by the Mike device. Figure 2-3a is a close-in view of the predicted fallout, while Figure 2-3b illustrates the predicted deposition pattern on a larger scale. For all of these plots, it is important to note that the predicted patterns are for fallout deposition on land. Debris deposited on the ocean is subject to be dispersed from the surface and from the area of original deposition by ocean and lagoon currents. As well, the plots are normalized to one-hour post detonation. For many locations with fallout deposition, this is not possible due to the time required for wind transport. A key difference between the fallout from Events Mike and Nectar is the relative magnitude of the exposure rates. Event Mike had a total yield about six-fold higher than Event Nectar, which is evident in the much higher ground-deposited fallout exposure rates from Event Mike. For example, Janet was near the 2,000 R h^{-1} exposure rate contour for fallout from Event Mike, while only at about the 15 R h^{-1} contour for fallout from Event Nectar. Figure 2.3b provides a better overall picture of the area of heaviest predicted fallout deposition to the north of the Atoll – an area of Open Ocean.

For reader interest, Appendix A (Figure A-1 through A-8) provides a number of radiation exposure plots from other tests conducted at Enewetak Atoll. Some caution should be borne in the interpretation of some of these plots. For exposure rates listed on some plots, nearby islands may have higher exposure rates listed than those for the island that supported the test. In these cases, a previous test had been conducted within a short period prior to the test under consideration. Naturally, the test conducted just prior to the test under consideration would of necessity have been of much higher yield. In these cases, it is clear that residuals from a prior test are influencing the total reported exposure rate.

2.2.2 Radioactive Debris from Nuclear Weapon Tests

The debris produced by a nuclear weapon detonation is comprised of a highly-varied mixture of fission fragments (also commonly called fission products), activation products, fusion products, and unburned nuclear fuel. The characteristics of the radioactive debris are unique to each test device, and to some degree how the weapon was tested: land surface, water surface, underwater, low altitude, or high altitude burst. The characteristics of the radioactive debris from a detonation can be altered during transport of the debris cloud. Some radioactive elements produced in a detonation exist in gaseous form, i.e., noble gases, and will not be a part of fallout deposition on ground or water surfaces. For elements that are solids or liquids at ambient atmospheric temperatures will have some observed preferential fallout from the debris cloud earlier than other

elements, dependent on the melting point. Elements with higher melting points will be observed in fallout deposition at higher fractions in the total fallout inventory at earlier times than for fallout occurring at later times (Hicks 1982). The opposite is true for those elements with lower melting points. These elements will form a greater fraction of the fallout debris at later times rather than the early fallout deposition. This phenomenon is termed "fractionation." Observation of this effect for

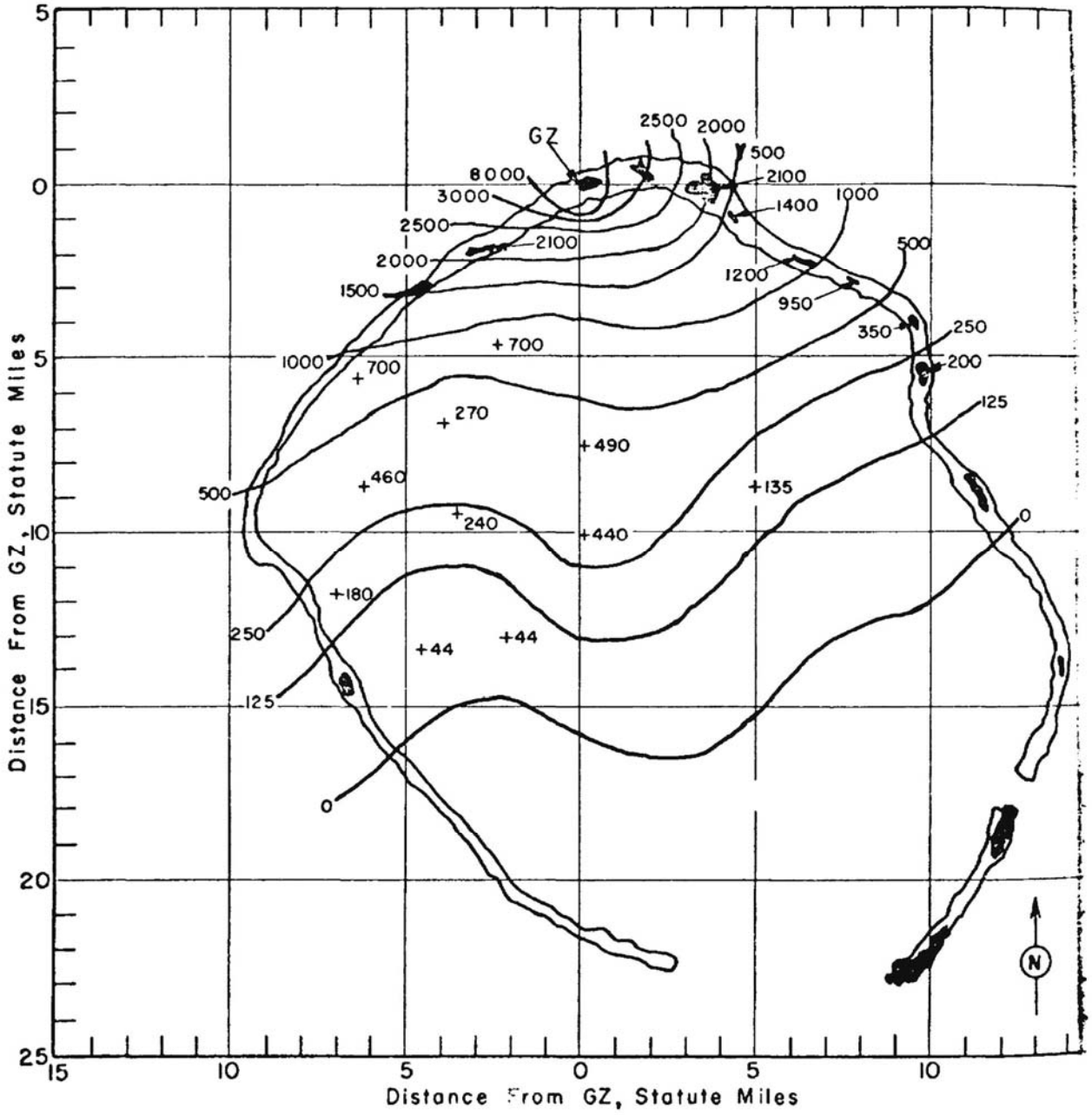
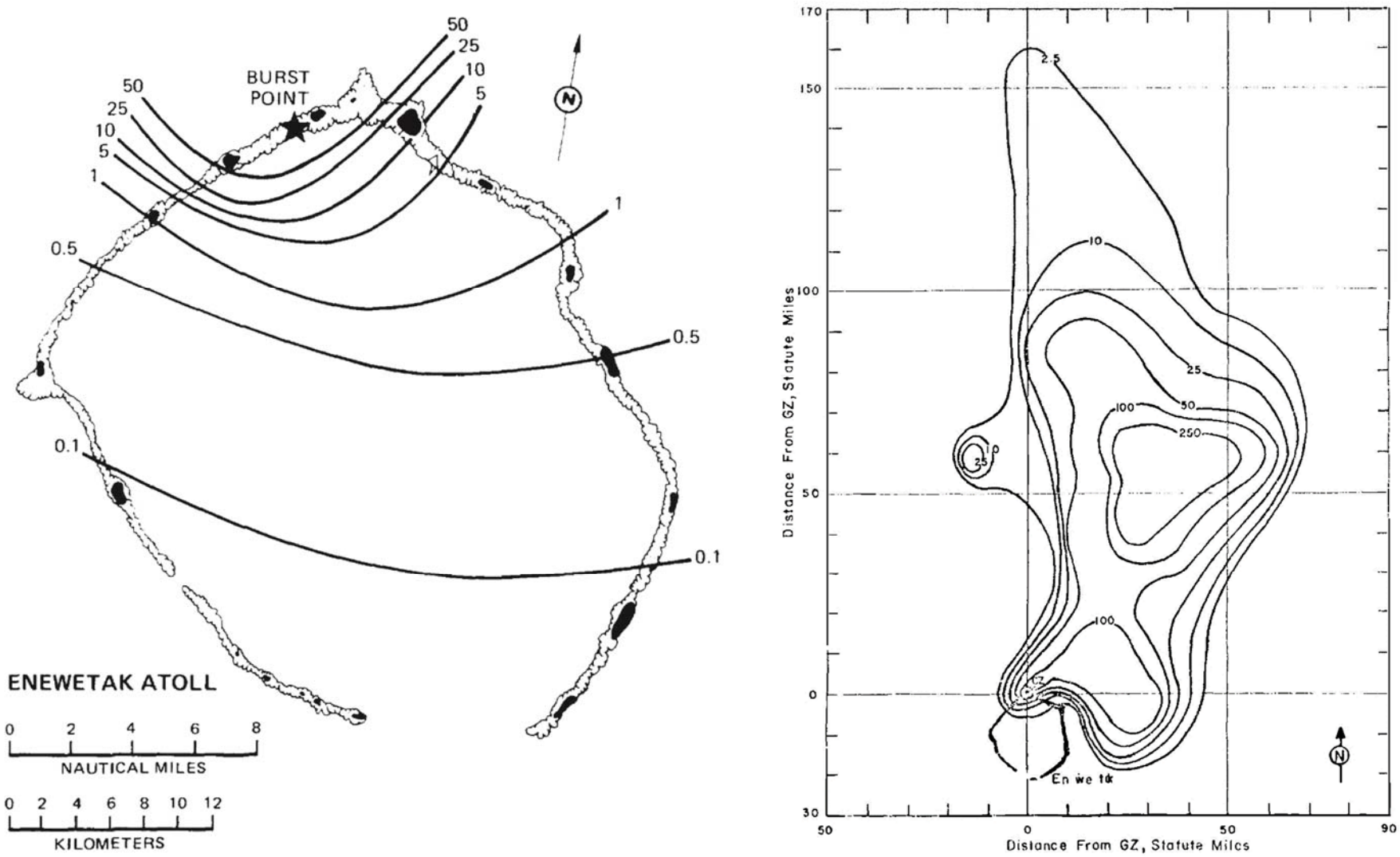


Figure 2-2. Estimated Radiation Exposure Rate Contours (R h^{-1}) at One-Hour Post Detonation of Event Mike on Island Flora, Enewetak Atoll, 31 October 1952 [Figure 31, (DNA 1979)].



a. Close-In Fallout Pattern.

b. Overall Deposition Pattern.

Figure 2-3. Estimated Radiation Exposure Rate Contours (R h^{-1}) at One-Hour Post Detonation of Event Nectar on Barge Over Mike Crater, Enewetak Atoll, 13 May 1954 [Figures 57 and 58, (DNA 1979)].

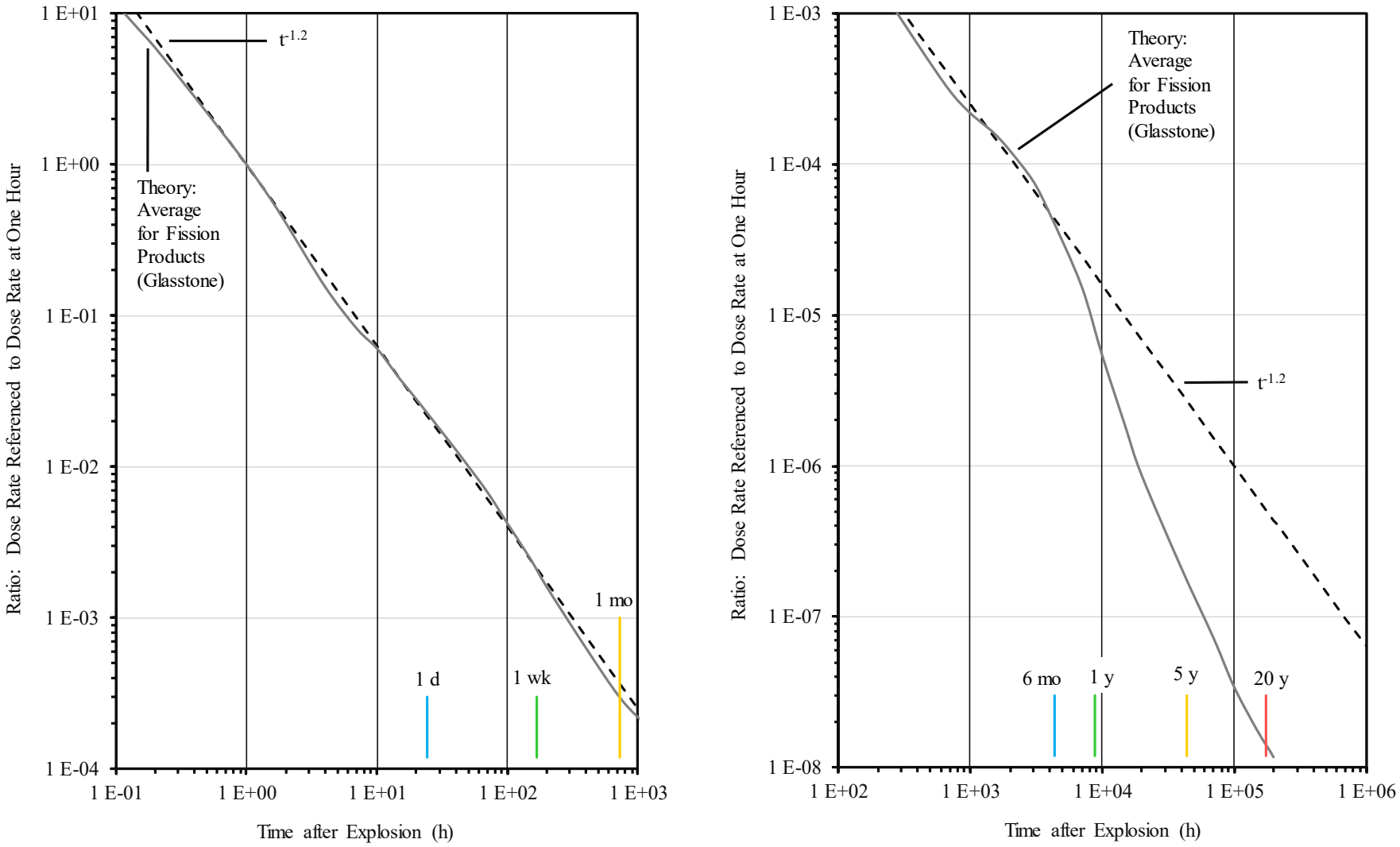
local deposition of fallout in Enewetak Atoll is not that significant, as most of the local deposition occurs shortly after the detonation. However, for regional fallout deposition from tests conducted at the Bikini Atoll and with deposition of fallout at Enewetak Atoll and for global fallout this effect could be observed. In general, for the northern islands of Enewetak Atoll, while fallout from nuclear testing deposited on these islands could have some contributions from regional and global fallout from tests conducted elsewhere, local fallout for tests conducted on the Atoll are the dominant source term. For the southern islands of the Atoll, there is a reasonable fraction from regional and global sources in addition to that from local nuclear tests.

In August 2010, the Health Physics (HPS) Journal published a series of articles on radiation doses and cancer risks to inhabitants on the Marshall Islands, excluding Bikini and Enewetak Atolls. Table A-3 lists Enewetak Atoll tests that contributed to measurable regional fallout for that study. This list included both a number of high and low yield test events, which illustrates the importance of atmospheric conditions at the time of a test on fallout intensity in addition to the total yield of a test event. Contrary to the scope of the study covered by the 2010 HPS Journal, primary impact to Enewetak Atoll were from tests conducted on Enewetak Atoll, and one test conducted on Bikini Atoll.

2.2.3 Fission Products

Fission products are commonly the most important source of external radiation exposure from ground-deposited fallout. Fission products from nuclear detonations are a complex mixture of over 300 different isotopes among 36 elements (Glasstone and Dolan 1977), with some subtle differences among fission product mixtures from the fission of ^{239}Pu, ^{235}U, ^{238}U, and other isotopes. Differences in the design of one weapon from another could also alter the fission product mixture for the same fission fuel, due primarily to the differences in the distribution of energies among neutrons produced in the detonation. Most of the fission products are radioactive, but have relatively short radioactive half-lives, affording a drastic reduction in external exposure rates over a short time periods after a detonation. Figures 2-4a and b, adapted from Glasstone and Dolan (1977), show the dose rate over time post detonation, as normalized to the dose rate at one-hour post detonation. The solid (gray) line is the average for a fission product mixture expected among varied weapon designs, with the dashed (black) line representing a power function fit to the data. This function fits reasonably well for time up to six months post detonation. After one day, the external dose rates from fission products drops to less than 3% of that at one hour, while at one month, over 3,000-fold lower. These early times were important to radiation safety considerations for work conducted on the Atoll shortly after the completion of a test and preparation for later tests. As applied to work conducted 20 to 25 years after detonation and within the context of this report, exposure rates from fission products are expected to be nearly 100-hundred million-fold lower (10^{-8}), assuming no environmental weathering processes.

Environmental weathering processes would distribute the fallout contaminants to greater depths in soils and involve an even greater reduction in the external exposure rates. Bouville et al. (2010) developed a time-dependent weathering correction factor for assessments of long-term doses to Marshallese populations. A five-fold reduction factor was recommended for 10^5 h (11.4 y) post detonation, the longest period covered by the model.



a. Early Fallout Times

b. Late Fallout Times

Figure 2-4. External Dose Rate at Various Times After Detonation of Fission Products Reference to One-Hour After Detonation [Adapted from Glasstone and Dolan (1977)].

As a practical illustration of this concept, the reduction of exposure from early fallout is considered for the island of Irene, as impacted by Event Mike on 31 October 1952. As shown in Figure 2-2, Irene falls around the 2,500 R h^{-1} one-hour, post-detonation external exposure rate contour. Applying a 10^{-8} decay factor, according to Figure 2-4b for 25-y post detonation, this exposure rate would have dropped to about 25 microroentgen per hour (μR h^{-1}). Migration of these fission products to greater depths in soils by weathering processes would involve an even further reduction.

Table A-4 contains a listing of important radionuclides expected in Enewetak soils from nuclear weapons testing. The list is compiled, in part from NVO-140 (AEC 1973) and Simon et al. (2010), and is applicable for periods of time shortly after testing, extending to substantially long periods of time after testing. The list separates the radionuclides into three primary groups: fission products, nuclear fuel, and activation products. Some of the radionuclides can fit into two of these categories. For example, tritium (^{3}H) is a fusion fuel, a fusion product, and an activation product. As well, isotopes of uranium and plutonium can be used as nuclear fuel in a test weapon, but are also produced in a nuclear detonation. A couple of additional isotopes are listed in the notes section of Table A-4, as they were noted for detection in soil samples analyzed by γ-spectrometry in NVO-140 (AEC 1973), yet were not in the list of expected radionuclides in the same report. The list of Table A-4 contains only about 60 fission-product related isotopes. The majority of these have very-short radiological half-lives, and based on the notes to the Table are most applicable to exposures to individuals from external radiation exposure, and internal radiation exposures from ingestion and inhalation for early periods after a detonation (notes 1 and 2). Exposures from these early periods are of interest in the evaluation of doses to veterans with on-site participation in nuclear weapons tests and considered under the Nuclear Test Personnel Review (NTPR) by DTRA. Table A-5 contains a listing of historical DNA reports that supports evaluation of claims under NTPR, as applicable to nuclear weapons tests in the Marshall Islands. Some information from these reports will be referenced later in this report.

Table A-6 contains a subset of radionuclides from Table A-4 that are long-lived fission products, along with a listing of their key β-particle emissions, electrons, and x- and γ-rays (combined as photon emissions). The primary long-lived fission products of concern for this project are ^{90}Sr-^{90}Y and ^{137}Cs. Though other isotopes listed in Table A-4 were observed in analyses of soils, sediments, and biological samples collected by the AEC in the 1972 radiological survey of the Atoll, their contribution to total activity is much lower. Due to the fact that ^{90}Sr-^{90}Y does not have any photon emissions, special laboratory methods are required for the assessment of this radionuclide in soil samples. In addition, due to decades of weathering since its predominant deposition in the 1950's from testing, the radionuclide had negligible contributions to external radiation exposures in the 1970's. Additional details will be provided later in this report on the relative contribution of other fission products.

2.2.4 Activation Products

The high neutron fluence existing during the detonation of a nuclear weapon also creates the potential for neutron-induced reactions in materials within the weapon, and the environment to include air, soils, water, and nearby structures. The common neutron activation reactions are capture reactions where an incident neutron is absorbed by the nucleus, and a γ-ray is emitted in the process, as shown below for ^{59}Co, an element commonly in ferrous alloys:

$$^{59}Co + n \rightarrow {}^{60}Co + \gamma$$

The product of the reaction, ^{60}Co, is radioactive and has a half-life of 5.3 y. Ferrous alloys are common to some parts used in nuclear weapons, weapon test towers, ground buildings and other items incorporated into weapon damage effect evaluations, i.e., test structures, vehicles. Among many activation products listed in Table A-4 are those also commonly produced by activation of stable precursors in steel: ^{55}Fe, ^{63}Ni, and ^{65}Zn. In the past, isotopes were added to some nuclear weapon test items, a practice termed "salting," to provide induced radioactivity tracers for the study of fallout (Glasstone and Dolan 1977). Though specific details remain classified for US tests, these isotopes, by design, would have provided detectable photon radiations, and therefore readily detectable in soil samples and in-situ photon radiation scans of the islands that were conducted by the AEC in 1972. A more recent review of these radionuclides and their current impact to the Marshall Islands is provided by Robison et al. (2001).

Fissionable fuel isotopes are also subject to activation, as shown in the examples below.

$$^{239}Pu + n \rightarrow {}^{240}Pu + \gamma \qquad ^{240}Pu + n \rightarrow {}^{241}Pu + \gamma \qquad ^{238}U + n \rightarrow {}^{239}U + \gamma$$

In the latter reaction, upon two successive β-particle decays, ^{239}Pu is the long-lived decay product. In some cases, the amount produced in a detonation can outweigh the mass initially in fuel (Noshkin et al., 1974). While isotopes of plutonium and uranium are produced and altered by nuclear weapon detonations, for the remainder of this report, isotopes of plutonium and uranium will be considered as part of unburned nuclear fuel. Tritium is also present in nuclear weapon debris due to its potential use as a fusion fuel, but also as an activation product by neutron capture reactions in deuterium and is a fission product in a small minority of fission events. For the convenience of this report, tritium isotopes will be summarized as an activation product. A number of additional neutron interaction, activation products are shown in Table A-4 which are favorable in fast neutron environments, common to thermonuclear weapon detonations. For example:

$$^{239}Pu + n \rightarrow {}^{238}Pu + 2n \qquad ^{238}U + n \rightarrow {}^{237}U + 2n.$$

Table A-7 contains a subset of radionuclides from Table A-4 that are long-lived activation products, along with a listing of their key β-particle emissions, electrons, and x- and γ-rays (combined as photon emissions). A number of activation products were detected in soil samples collected in the 1972 AEC radiological survey of the Atoll, however, the predominant activation product was ^{60}Co. This radionuclide undergoes radioactive decay through the emission of a β-particle, but more importantly emits two high-energy γ-rays. The 5.27 y radioactive half-life would have reduced the concentrations in half by 1977 when the rehabilitation efforts were initiated. The α-emitting radionucliudes of ^{242}Pu, ^{244}Pu, ^{237}Np, ^{236}Np produced through activation processes only exist as trace amounts, and are unimportant compared to the primary α-emitter of $^{238+239+240}$Pu and ^{241}Am (DOE 1982). As such, none of these are listed in Table A-7.

2.2.5 Nuclear Fuel

The primary fission fuels used for nuclear weapons tests are WGP and weapons grade uranium (WGU). As well, as noted above, some tests devices are also expected to contain DU and

U-nat [DOD (2005); DOE (1982)]. Table 2-2 contains an assumed WGP composition as listed in Nevada Operations Office, DOE Report NVO-213, *Enewetak Radiological Support Project* (DOE 1982). The fissile element of importance is ^{239}Pu, and for this example, comprises 93.4%, by mass. Some variability will exist among the test devices that contained WGP. For example, WGP debris from the Bluegill Prime launch failure that occurred on 25 July 1962 at Johnston Island had an average estimated ^{239}Pu mass content of 94.2% (Rademacher 2016). Other isotopes of plutonium in WGP, by mass, are dominated by ^{240}Pu, with relatively insignificant amounts of ^{238}Pu, ^{241}Pu, and ^{242}Pu. From a radiation health standpoint, under most environmental exposure circumstances, isotopes of plutonium primarily present an internal radiation hazard, with the most important radiological emission being α-particles, and generally negligible photon emission. Table A-8 lists the primary radiological emissions of these isotopes of plutonium and ^{241}Am. Among the five isotopes listed, all but ^{241}Pu, undergo α-particle decay. Due to the shorter half-life of ^{240}Pu compared to ^{239}Pu, ^{240}Pu contributes almost 19% of the α-particle contribution. Although ^{241}Pu has a negligible internal radiation hazard compared to the other isotopes of plutonium in WGP, it has a relatively short half-life and decays to ^{241}Am, which is also an α-particle emitter. Over time, ^{241}Am will have an ingrowth of activity compared to ^{241}Pu, as shown in Figure 2-5. The ^{241}Am in WGP is an important constituent, having the only significant photon emission which affords in-situ quantification of WGP in the environment by radiological survey instruments. Assessment of WGP by this method, however, requires knowledge of the relative quantities of isotopes of plutonium and ^{241}Am in the environment. Complicating this matter, these relationships are altered by the nuclear detonation process. Details of this effect will be described later in this section.

TABLE 2-2. Isotopic Composition of WGP Assumed for Enewetak Rehabilitation, from NVO-213, (DOE 1982).

Isotope	Composition Fractions (Unburned)		Radiological Half-life (y)
	Mass	α-Particle Activity	
Pu-238	0.00012	0.028	87.8
Pu-239	0.934	0.783	24,131
Pu-240	0.0606	0.189	6,563
Pu-241	0.0055	0.00018*	14.4
Pu-242	0.0002	0.000011	376,000

* 99.998% β-particle decay, ~0.002% α-particle decay

Table 2-3 contains an assumed composition of WGU, with ^{235}U enriched to 93.3%, by mass. For comparison, natural uranium in ore is only about 0.72% ^{235}U, by mass, with most of the balance to ^{238}U, as shown in Table 2-4. The ^{234}U and ^{238}U in this mixture have near equal activities, with ^{235}U, having an overall much lower contribution to total α-particle activity, as is also the case for the WGU example. In the production of WGU (i.e., enrichment) by a gaseous diffusion or centrifuge, the undesired byproduct which is depleted in its ^{235}U and ^{234}U content is called depleted uranium (DU). The isotopic content for an example of moderately-depleted uranium is listed in Table 2-5. In test nuclear weapon test devices, DU or U-natural could have been used interchangeably. The radiation emissions of these three isotopic compositions of uranium are contained in Table A-9,

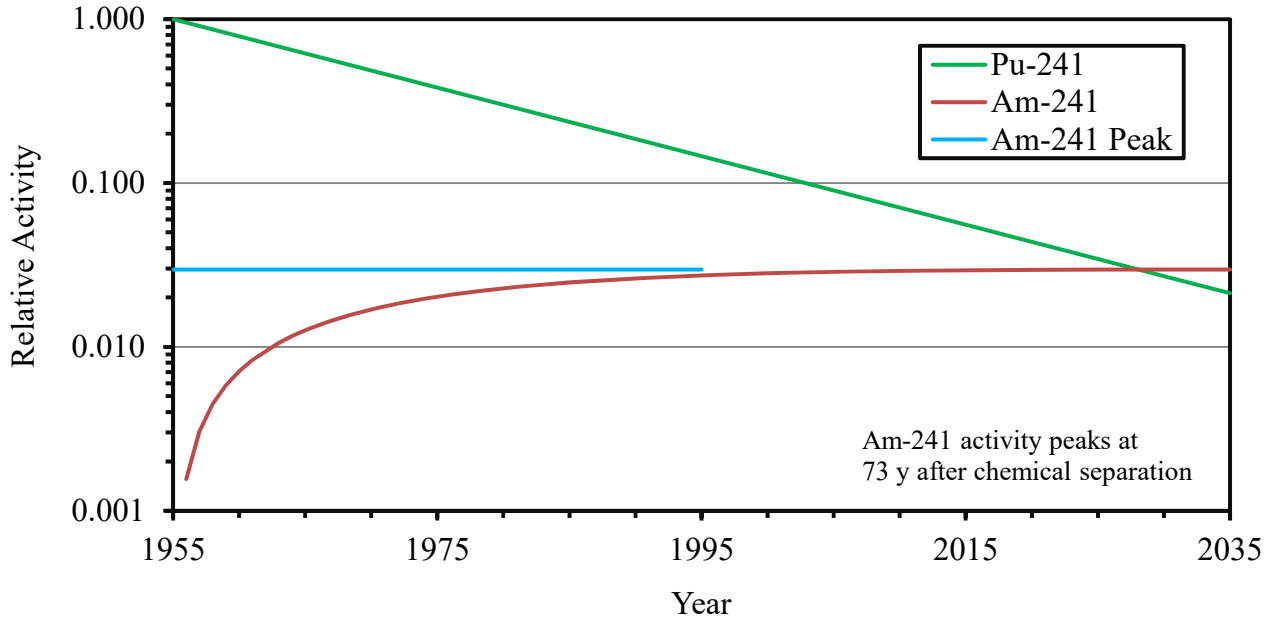


Figure 2-5. Relative Activity of ^{241}Am to ^{241}Pu after Chemical Separation in 1955.

which incorporate emissions from short-lived daughter products. The emissions are normalized to a single α-particle decay. As was the case for WGP, the α-particle emission is commonly the most important emission from uranium dispersed to the environment, and is due to internal exposure pathways. Photon emissions are relatively low, but of particular interest is the 185.7 kiloelectron volt (keV) γ-ray emission from ^{235}U. This γ-ray emitted by ^{235}U is commonly the most readily detectable, and forms a basis for estimation of the other isotopes of uranium likely to be present in samples. Due to the relatively-low health hazard of uranium compared to WGP for the Enewetak environment, isotopes of uranium assessed in samples collected in the 1972 AEC radiological survey were only afforded screening by high-resolution γ-spectrometry – no chemical separations and isotopic analyses were accomplished.

Overall, among materials described in this section, the most prominent radiological hazard is presented by WGP, due to its substantially higher specific activity than the other nuclear materials, as illustrated in Figure 2-6. The specific activity is the quantity of radioactivity per unit mass. The example WGP is over three orders of magnitude (1,000-fold) higher than WGU and over five orders of magnitude higher than U-natural (100,000-fold).

TABLE 2-3. Generic WGU Composition.

Isotope	Composition Fractions (Unburned)		Radiological Half-life (y)
	Mass	α-Particle Activity	
U-234	0.0106	0.97	244,500
U-235	0.933	0.0294	7.038×10^8
U-236*	0.00031	0.000293	2.342×10^7
U-238	0.0562	0.000275	4.468×10^9

* Found in spent and reprocessed fuel, but possibly not in all WGU

TABLE 2-4. Natural Uranium Composition.

Isotope	Composition Fractions		Radiological Half-life (y)
	Mass	α-Particle Activity	
U-234	0.000054	0.4888	244,500
U-235	0.007205	0.0225	7.038×10^8
U-238	0.992741	0.4887	4.468×10^9

TABLE 2-5. Example Moderately-Depleted Uranium Composition.

Isotope	Composition Fractions		Radiological Half-life (y)
	Mass	α-Particle Activity	
U-234	0.00001	0.153	244,500
U-235	0.0020	0.011	7.038×10^8
U-238	0.9980	0.836	4.468×10^9

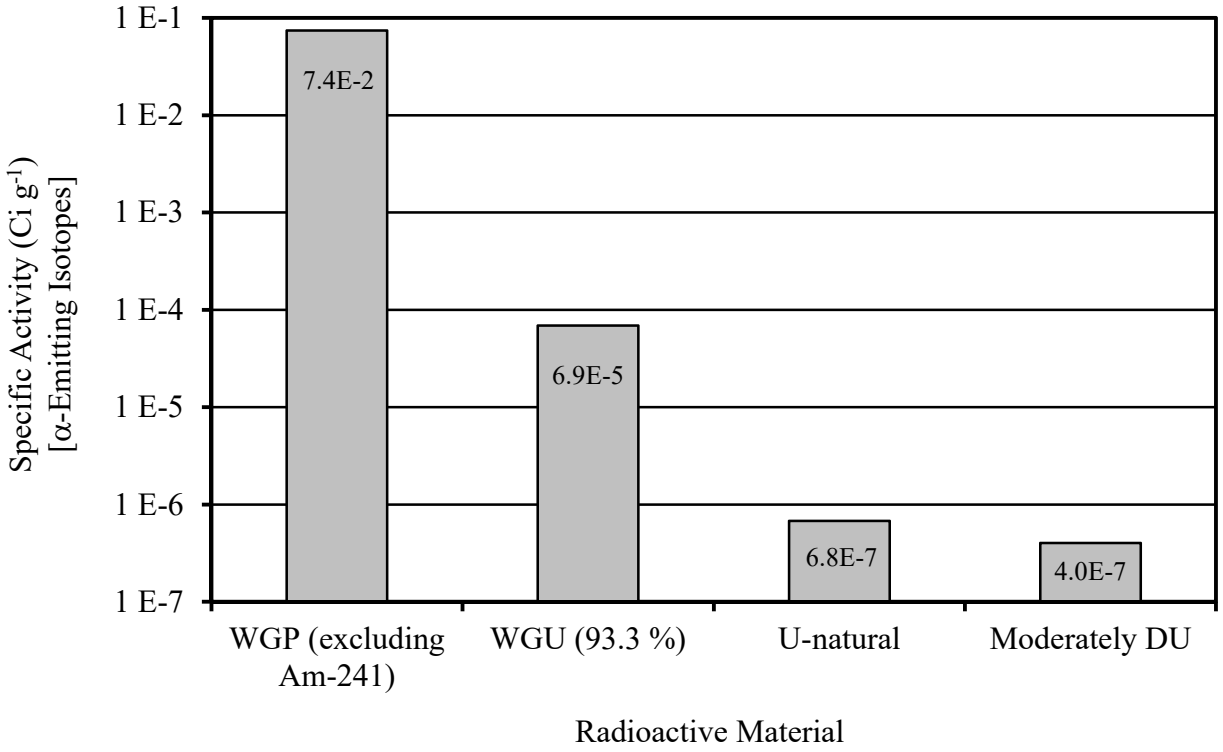


Figure 2-6. Comparison of Specific Activity of α-Particle Emitting Radionuclides in Materials Potentially Used in Nuclear Test Devices. [Multiply by 3.7×10^{13} for Bq kg^{-1}].

The composition of nuclear fuels are altered by the nuclear detonation process, except for test Events Scaevola and Quince that did not have any nuclear yield. While the alteration in isotopic mixtures of nuclear fuels is primarily considered for the materials that are contained in the device

being tested, some alteration could be expected for unburned fuel from a previous test that happens to be deposited on land surfaces in close proximity to a subsequent test. Among the nuclear tests conducted at Enewetak Atoll, there is expected to be a wide range of fuel burn fractions, which represents the fraction of fuel undergoing fission. Table 2-6 illustrates the alteration of the WGP isotopic composition for the case where 20% of the fuel undergoes fission in a detonation. For this example, the composition from Figure 2-2 is used and it is assumed that fast neutron activation of ^{238}U is only minor. For this simplified evaluation, thermal neutron interaction cross-sections for fission and (n,γ) capture reactions are assumed to be the primary reaction types. This simplified approach is applicable to fission weapons, but much less applicable to thermonuclear weapons due to additional fast neutron interactions in a plutonium nuclear fuel. The (n,γ) capture reactions for this example are important for the production of ^{240}Pu from ^{239}Pu and ^{241}Pu from ^{240}Pu, due to the

TABLE 2-6. Isotopic Composition of WGP from TABLE 2-2 Before and After 20% Fission Burn.

Isotope	Composition Fractions (Unburned)		Radiological Half-life (y)	Thermal Neutron Interaction Cross-Section (barns) †		Composition Fractions After 20% Thermal Neutron Fission Burn	
	Mass	Alpha Activity		Fission	(n,γ)	Mass (Normalized to Unburned)	Alpha Activity
Pu-238	0.00012	0.028	87.8	18	540	0.010	0.024
Pu-239	0.934	0.783	24,131	748	269	0.662	0.572
Pu-240	0.0606	0.189	6,563	0.06	290	0.127	0.404
Pu-241	0.0055	0.00018*	14.4	1011	358	0.858	0.0003
Pu-242	0.0002	0.000011	376,000	19	< 0.2	0.080	0.00004

† Table of Isotopes, 8th Edition, Firestone, Richard B., John Wiley and Sons, 1996.

* Primary emission is a low-energy β-particle, not listed in this Table.

large mass fractions for both of these isotopes in WGP. These capture reactions and fission alter the isotopic composition of WGP. For example, as shown in Table 2-6, ^{240}Pu comprises about 40% of the α-particle activity, as compared to about 19% prior to detonation. The one key aspect of this alteration is the ratio of α-emitting isotopes of plutonium compared to ^{241}Am which is produced in the decay of ^{241}Pu. This is important if ^{241}Am is used to estimate plutonium activities in samples or surface soils from in-situ measurements. ^{241}Am is the most significant source of photons in aged WGP. Figure A-9 contains a plot of the α-radiation activity fractions for isotopes of plutonium and ^{241}Am over time based on the example composition listed in Table 2-6 after a 20% fission burn. The ^{239}Pu and ^{240}Pu fractions remain fairly consistent over time, due to their long radiological half-lives. The $^{239+240}Pu$ to ^{241}Am activity concentration ratio is high initially, but reaches a near plateau of about 2.6 for later periods. Figure A-10 contains a plot of the ratio of $^{239+240}Pu$ to ^{241}Am for other assumed fission burn fractions using the same simplified approach applied to the values in Table 2-6, and also for debris collected after Event Mike. This event was commonly termed the 'Mike Device' since it was an experimental thermonuclear device beyond the physical dimensions of a typical bomb. Isotopic ratios for the Mike Device plutonium debris are from Hoff (1978). All of the examples assume fresh fuel and a fission burn in 1955, except the Mike Device, which was detonated in 1952. The two extremes of this plot: the dispersal of an unburned fuel and the Mike

device should provide practical bounding expectations for plutonium debris from Enewetak tests. A truncated portion of Figure A-10 for time period between 1970 and 1980 is provided in Figure 2-7, as an aid for the review of Enewetak data produced in the 1970's and most applicable to the scope of this project.

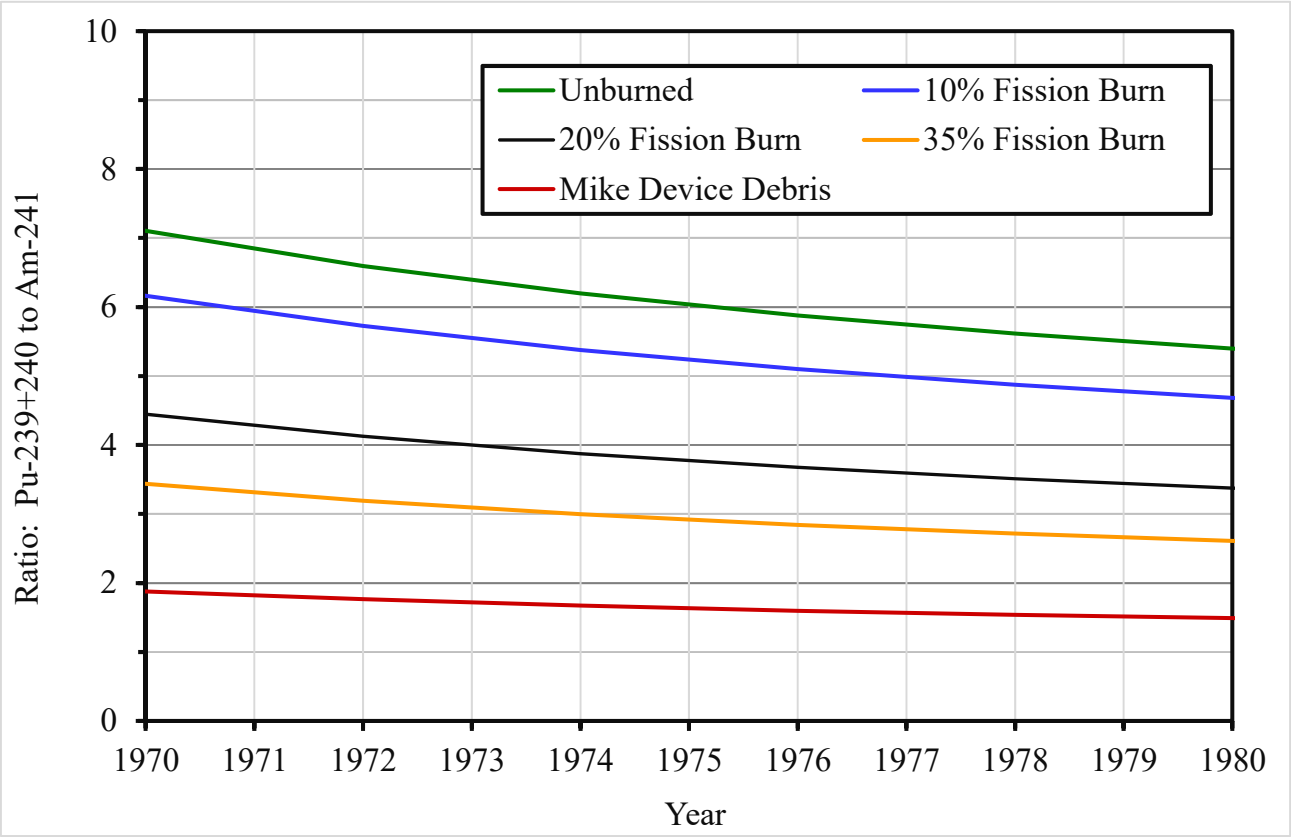


Figure 2-7. $^{239+240}$Pu to ^{241}Am Activity Concentration Ratios for Various Isotopic Forms of WGP Over Time, Based on a Nuclear Detonations in 1955 (except Mike, 1952) [Truncated Version of Figure A-10 for Period 1970 – 1980].

Table 2-7 contains an assessment of the isotopic composition of WGU from Table 2-3, as modified by a 20% fission burn. For this example, the initial ^{236}U mass fraction is assumed zero, and fast neutron reactions are not included. The primary reaction is the fission of ^{235}U, with radiative neutron capture (n, γ) in ^{234}U and ^{235}U being much less. Mass fraction values are listed for a 20% fission burn only, while activity fractions are shown for both 20% and 30% fission burn rates. Though the α-radiation activity levels from uranium isotopes in the Enewetak environment are expected to be low, as compared to those from WGP, the ^{234}U to ^{235}U activity ratio values are provided as an aid in estimating ^{234}U activities from measurements that only include ^{235}U[6]. The activity ratio ranges from 32.7 (unburned WGU) to 49.5 for the 30% fission burn rate.

[6] ^{234}U has only negligible photon emissions. It's presence in soils is commonly assessed by chemical separation and α-particle spectrometry.

TABLE 2-7. Isotopic Composition of WGU from TABLE 2-2 Before and After 20% and 30% Fission Burn [Initial ^{236}U Mass Activity Assumed Zero].

Isotope	Composition Fractions (Unburned)		Radio-logical Half-life (y)	Thermal Neutron Interaction Cross-Section (barns) †		Composition Fractions After Thermal Neutron Fission Burn		
	Mass	Alpha Activity		Fission	(n,γ)	* Mass Fraction (20% Burn)	Activity Fraction 20% Burn	Activity Fraction 30% Burn
U-234	0.0106	0.9701	244,500	< 0.6	99.8	0.0102	0.9424	0.9283
U-235	0.9330	0.0297	7.04×10^8	582.6	98.3	0.6975	0.0224	0.0187
U-236	0.0000	0.0000	2.34×10^7	0.07	5.11	0.0361	0.0350	0.0527
U-238	0.0562	0.0003	4.47×10^9	0.004	2.68	0.0561	0.0003	0.0003
Ratio: $^{234}U/^{235}U$		32.7	Not Applicable				42.0	49.5

* Normalized to unburned fractions † Table of Isotopes, 8th Edition, Firestone, Richard B., John Wiley and Sons, 1996

2.3 Summary of Results from AEC Report NVO-140, *Enewetak Radiological Survey*, 1973

2.3.1 General

The radiological survey conducted on the Enewetak Atoll by the AEC in 1972 provided important data to determine the extent of adverse environmental impacts primarily from residual contamination and physical hazards from atmospheric nuclear weapons tests, and provided a technical basis for estimating radiological exposures to the Enewetak peoples under a plan for resettlement to the Atoll. This document provided the technical basis for the Environmental Impact Statement (EIS), *Cleanup, Rehabilitation, Resettlement of the Enewetak Atoll – Marshall Islands* (DNA 1975). This data was also very important in developing appropriate radiation protection measures and monitoring methods for personnel that participated in cleanup activities on the Atoll from 1977 – 1980. It is important to understand some very important differences in radiation exposure potential to the Enewetak peoples resettling the Atoll and those individuals participating in the cleanup. The key difference in exposure potential is related to the exposure pathways. Participants in the cleanup work had exposure potential from inhalation of resuspended radiological contaminants in soil, incidental ingestion of soil, and external radiation while working on contaminated land areas. However, sources of exposure from dietary sources are expected to be very low or non-existent for workers, as compared to individuals resettling the Atoll. These sources would include plants, land animals, aquatic life from the lagoon, and drinking water. During the cleanup, a distillation plant on the island provided fresh water, and the dining facilities relied upon food transported to the Atoll primarily from the continental US (CONUS), with some fresh produce from Hawaii. While the Atoll during the time of the cleanup effort did not have established agriculture, as this had not been maintained since the Enewetak people left the Atoll in 1947, it is possible that some foodstuffs were acquired from the Atoll by workers. Reasonable sources may have been aquatic life from the lagoon and perhaps coconuts, although coconut trees had suffered significant destruction by bombardment during WWII (DNA 1981). Nevertheless, consumption of these items would have been substantially lower than that assumed by the AEC under the resettlement plan for the Enewetak people.

2.3.2 External Radiation Assessments

External radiation levels on islands of the Atoll were measured or estimated by a number of methods. The most extensive set of measurements were those conducted by a helicopter fitted with a multi-detector, thallium-drifted sodium iodide [NaI(Tl)] spectrometry system. The results of these scans were analyzed to produce total estimated γ-radiation isoexposure contour maps, and contour maps specific to photon emissions from ^{137}Cs and ^{60}Co, and ^{241}Am for some islands where this isotope provided a more significant contribution to total exposure rate. ^{125}Sb and ^{152}Eu also had some minor contributions. The altitude of the flights ranged from 1,000 to 10,000 feet above ground level (AGL). Static ground measurements were collected with a man-portable NaI(Tl) system at 1 m AGL, which provides better spatial resolution of exposure rates than the aerial surveys, and aided in the calibration of an aerial measurement to a ground-equivalent measurement. Thermoluminescent dosimeters (TLDs) were also used to characterize exposure rates at static measurement locations.

Soil sampling and laboratory analysis was conducted on over 3,000 soil samples collected from the surface: 0 – 2, 0 – 5, 0 – 10, and 0 – 15 centimeters (cm) in depth, and depth profiling, combining surface samples with additional ones from greater depths, up to 1.9 meters (m). Soil samples provided additional information on external exposure rates, based on known relationships between activity concentrations of specific radionuclides in surface soils and external exposure rates. Soil sampling was also necessary for the analysis of some radionuclides, which provided limited photon emissions, or none, in the case of ^{90}Sr. This data set is an important supplement to external exposure measurements in characterizing external exposure rates. It was also beneficial in better identifying those radionuclides with only a minor contributions to external exposure, as laboratory analyses provided better sensitivity for identification of these radionuclides, as compared to in-situ measurements with NaI(Tl) spectrometry systems.

Table B-1, Appendix B, contains a listing of average exposure rates for islands in the Enewetak Atoll from NVO-140 (AEC 1973), Table 9. The total exposure rates are listed for each island along with a breakout of rates due to ^{137}Cs and ^{60}Co. Clear from the Table is the distinct difference between islands in the northern and southern portions of the Atoll. For most of the southern islands of the Atoll, the measurements by the aerial system were below the sensitivity of the system, in which case, the exposure rates derived from soil sample data are listed in parentheses. The disparity in fallout deposition between the southern and northern islands of the Atoll by the number of test events responsible for fallout on an individual island and the H + 1 h exposure rate data is also included in the Table. Both of these columns were integrated from Table 11 of NVO-140 (AEC 1973). Leroy, included in the group of southern islands, had external exposure rates much higher than others in this group, with exposure rates more in line with those of some in the northern group of islands. Similarly, a few of the islands in the northern group had relatively minor residual fallout levels, i.e., Vera, Wilma, Ursula, Percy, Mary. For most of the islands, the total exposure rate, as measured by the aerial surveys was comprised of mostly ^{137}Cs and ^{60}Co. Among these, Pearl, Percy, and Mary had the greatest fraction attributed to other radionuclides, about 20%. For Mary and Percy, the average total exposure rate was only 5 μR h^{-1}, with ^{125}Sb providing the majority of the balance to the ^{137}Cs and ^{60}Co. The average total exposure rate on Pearl was much higher, 70 μR h^{-1}. The majority of the balance, however, for this island was from ^{152}Eu. As noted in the Table for Yvonne, the primary additional contribution to the average total exposure rate was from ^{241}Am. This is due to the non-nuclear detonation of Event Quince and low-nuclear yield of Event Fig, which were responsible for the greater degree of WGP residuals than that left on other islands. As noted earlier, ^{241}Am provides the majority of photon emissions from aged WGP.

For individuals present on the islands, the source of the external radiation is not important to the individual receiving the exposure. However, in order to predict the exposure for other periods, knowledge of the specific radionuclides mixture is important for properly correcting for radioactive decay. For example, ^{60}Co has a half-life of 5.26 y and ^{125}Sb 2.8 y. An appreciable decay in the activity of each of these radionuclides occurred between the surveys conducted in support of NVO-140 and the cleanup conducted between 1977 and 1980. This is reflected in the addition of an estimate of total average exposure rate in 1978 column in Table B-1. The estimated rates for this column have decay-corrected for ^{60}Co and ^{137}Cs radiological losses between 1972 and 1978. The islands with the greatest change in total mean exposure rate between 1972 and 1978 were Irene (80 → 43.9 μR h^{-1}), Belle (115 → 80 μR h^{-1}), and Pearl (70 → 44 μR h^{-1}).

The range of exposure rates within an island were highly varied, dependent on the island. To help illustrate this variability, example isoexposure contour plots from NVO-140 are provided in Appendix B. Figures B-1 to B-3 contain isoexposure contours for Irene, respectively for contributions from gross (total), ^{137}Cs, and ^{60}Co. In review of the three contours, it is clear that the highest contour band of total exposure, 130 – 260 μR h^{-1} is primarily influenced by ^{60}Co content in soils. The area encompassed by this band, however, is only about 5,000 m^2, a small fraction of the island's total land area. The fixed radiation measurements displayed in Figure B-4 shows the location of the highest measured exposure rate, 560 μR h^{-1}. This fixed measurement location is within the highest isoexposure band displayed in Figure B-1. The source of the high external exposure rates due to ^{60}Co in this area are from high concentrations of the radionuclide dispersed in top soils, and in metal debris and concrete blocks in the area. Figure 2-8 contains a magnified section of Figure 96 from NVO-140 showing details of a radiological survey of this land area, north of the Event Seminole crater. The external exposure measurements shown on the figure range from 40 to 1,200 μR h^{-1}, with the lower measurements representing debris with only minor to no radiological impacts. This area also contain a depth profiling soil sample, as annotated in blue ("x SOIL PROFILE") in Figure 2-8. The results of the soil sample analysis for the isotopes of ^{60}Co, ^{90}Sr, ^{137}Cs, $^{239+240}$Pu, and ^{238}Pu are contained in Figure 2-9. ^{60}Co had highest activity concentration among the radionuclides, with the peak concentration in the 10 – 15 cm sampling depth at 1,260 pCi g^{-1}. As averaged over the top 15 cm, the ^{60}Co concentration was 508 pCi g^{-1}, the highest ^{60}Co concentration among surface samples collected on this island. Table 2-8 contains a summary of radioactive scrap conditions by island. The majority of the information is from Table 108, NVO-140, with information for Irene added by the author of this report. With the exception of Edna, the islands listed on the Table were among those islands of the northern part of the Atoll with the highest levels of external exposure measurements. For many of the islands, the debris was a source of the higher levels of external exposure. However, for Alice, Belle, Clara, and Daisy, the debris did not appear contaminated.

Figures B-5 through B-7 contain isoexposure contours for Janet, respectively for contributions from gross (total), ^{137}Cs, and ^{60}Co. Though the Island had a much larger quantity of contaminated debris than Irene, the exposure contours from the aerial survey did not extend to the same level as observed on Irene. As well, the areas of higher exposure rate have somewhat consistent contributions from ^{60}Co and ^{137}Co as those areas with lesser total average exposure. The fixed radiation measurements for Janet are displayed in Figure B-8. The levels correlated well with the aerial survey results. The location with the highest measured exposure rate, 150 μR h^{-1}, is only a little higher than the high isoexposure contour shown in Figure B-5 of 66 – 130 μR h^{-1}. NVO-140 contains seven separate plots of scrap and structure radiation measurements, due to the size of the

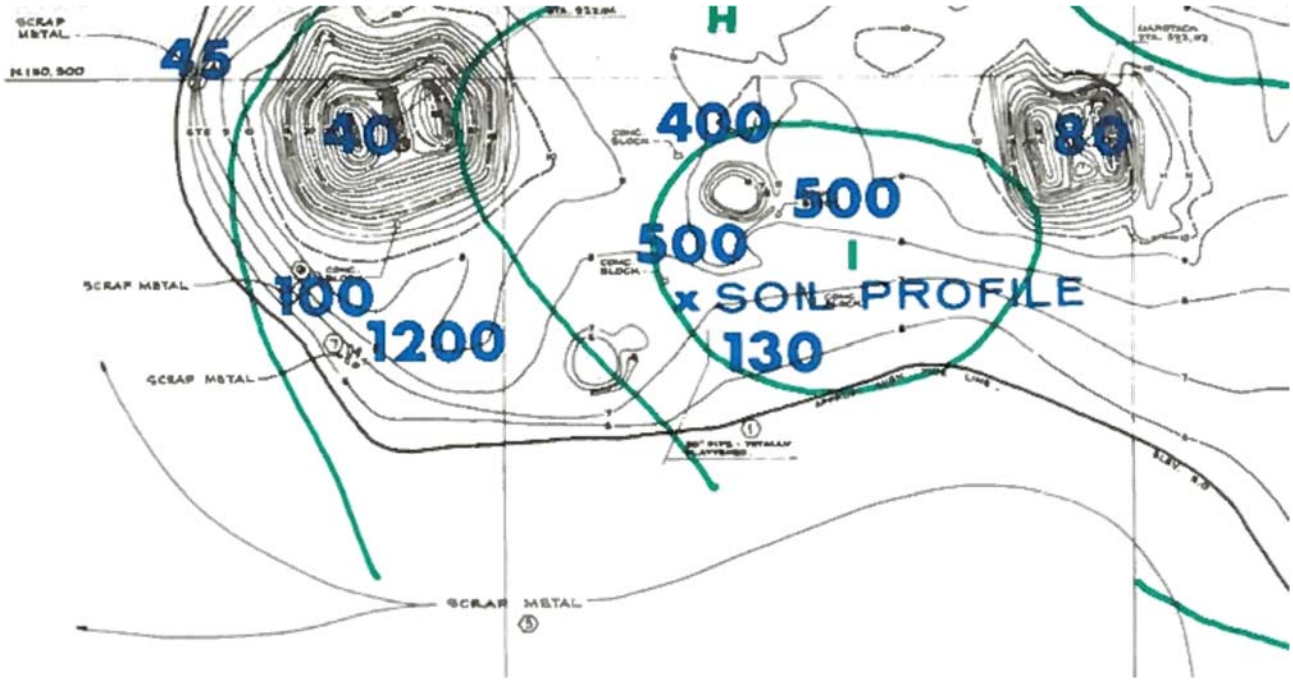


Figure 2-8. Truncated Portion of Figure 96 from NVO-140, *Scrap and Structure Radiation Measurements, Helen and Irene* (AEC 1973). [Blue Numbers are Contact Exposure Measurements on Scrap and Structure, in μR h^{-1}, Green Lines Approximate Aerial Survey Exposure Contours].

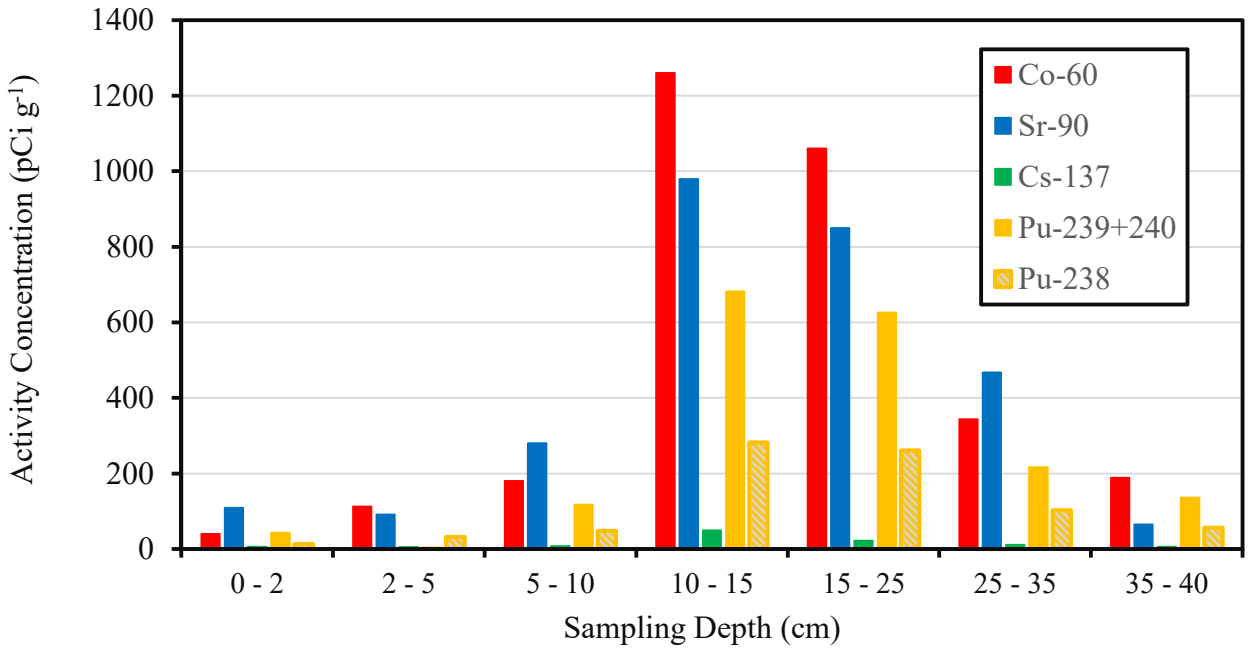


Figure 2-9. Bar Graph of Activity Concentrations of Key Radionuclides in Soils at Sampling Location 100, Island Irene, Data from NVO-140 (AEC 1973).

TABLE 2-8. Radioactive Scrap Conditions by Island, from Table 108 NVO-140 (AEC 1973).

Island	Scrap Characteristics		Remarks
	Relative Quantity	Radioactivity	
Alice	Significant	Apparently not contaminated above background.	Background is up to 170 μR/h. An M-boat wreck on beach reads 8 mR/h.
Belle	Insignificant	Apparently not contaminated above background.	Background exposure rates up to 250 μR/h.
Clara	Insignificant	Apparently not contaminated above background.	Background exposure rates up to 100 μR/h.
Daisy	Insignificant	Apparently not contaminated above background.	Background exposure rates up to 140 μR/h.
Edna	None	Not applicable.	Sandbar
Helen & Irene*	Small	Up to 1.2 mR/h.	Most scrap is apparently not contaminated. Some activated concrete slabs and metals.
Janet	Large	Up to 8.5 mR/h.	Activated scrap metal in all sizes can be found in piles or individual pieces scattered over the island.
Pearl	Small	Up to 5 mR/h.	Confined to GZ area.
Sally	Large	Scrap metal up to 120 μR/h; concrete surfaces, alpha up to 1,000 dpm/cm^2 and 3 mR/h.	Most scrap metal is apparently not contaminated. Several structures contain plutonium-contaminated debris.
Yvonne	Large	Activated/contaminated up to 60 mR/h.	Most scrap metal is activated or contaminated. Also, much plutonium contamination.

* Island pair surveyed, yet not summarized in Table 108 of NVO-140

island. Two of the plots are provided in Figures B-9 and B-10, Appendix B. Among the seven these two highlight the more important areas on Janet with high, contact exposure rates, as the majority of metal debris and structure was not activated or contaminated to a significant degree. The northeast (NE) segment is shown in Figure B-9. Along the northern ocean shore, there are a number of small structural features and debris piles with contact exposure rates between 190 μR h^{-1} and 8.5 mR h^{-1}. Many of the locations though are within the exposure rate range, of 2 and 150 μR h^{-1}, as listed in Table B-1. B-10 contains annotation of metal debris and structural features with exposure rates between 600 μR h^{-1} and 7.5 mR h^{-1}. These were also near the northern ocean shore of the island.

Figures B-11 through B-13 contain isoexposure contours for Pearl, respectively for contributions from gross (total), ^{137}Cs, and ^{60}Co. Similar to Irene, the area of higher exposure rate, contour J on Figure B-11, is largely due to contributions from ^{60}Co, based on review of Figures B-12 and B-13. The external exposure rates from the fixed radiation measurements on Pearl range from 1 to 400 μR h^{-1}, as detailed in Figure B-14 and summarized in Table B-1. They correlated well with the aerial survey results. The single test conducted on Pearl was Event Inca, detonated on a 200-foot tower. NVO-140 contains two separate plots of scrap and structure radiation measurements. One

plot is provided in Figure B-15, for the western portion of the island. A number of locations where contact exposure measurements were collected exceeded the range of fixed in-situ measurements, 1 – 400 μR h^{-1}, displayed in Figure B-14. A number of locations were at or above1 mR h^{-1}, with the highest at 5 mR h^{-1}. This area also contained two depth profiling soil sampling locations, as annotated in blue in Figure B-15. The results of the soil sample analysis for the isotopes of ^{60}Co, ^{90}Sr, ^{137}Cs, $^{239+240}Pu$, and ^{238}Pu are contained in Figure 2-9 for the western sampling location. ^{60}Co, $^{239+240}Pu$, and ^{238}Pu were the dominant radionuclides detected in the upper layers of soil. Due to the relatively low photon emissions from the plutonium and associated ^{241}Am, ^{60}Co dominated the external exposure emissions.

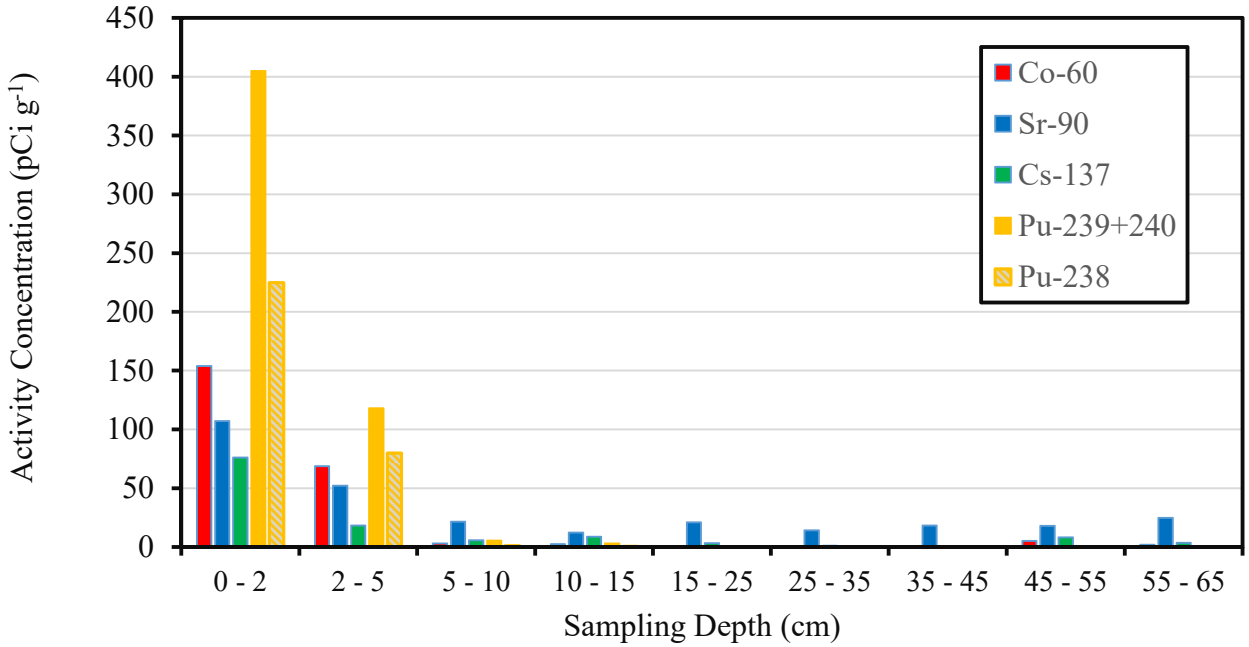


Figure 2-10. Bar Graph of Activity Concentrations of Key Radionuclides in Soils at Sampling Location 101, Island Pearl, Data from NVO-140 (AEC 1973).

Figures B-16 through B-18 contain isoexposure contours for Sally, respectively for contributions from gross (total), ^{137}Cs, and ^{60}Co. In comparison to Janet, Irene, and Pearl, this island had more uniform distribution of contaminants. The areas of higher external exposure had similar contributions from ^{137}Cs and ^{60}Co, as areas of lower exposure rates. The external exposure rates from the fixed radiation measurements on Sally range from 3 to 110 μR h^{-1}, as detailed in Figure B-19 and summarized in Table B-1. The highest fixed radiation measurement, 110 μR h^{-1}, was on the western tip of the island, and was located in an area of contaminated scrap metal and concrete debris. The contact exposure measurement in this location only produced a little higher reading, 120 μR h^{-1}, as shown in Figure 106 of NVO-140 (AEC 1973). This plot is not reproduced in this report for brevity sake, though two other segments of scrap and structure measurements plots, Figures 107 and 108 are combined in Figure B-20, Appendix B. Prominent features noted in these plots are plutonium contamination sealed in concrete on the northern tip of the island (open ocean), as well as at a location on the southern shoreline (lagoon). One contaminated metal and concrete debris location had a contact exposure reading of 3 mR h^{-1}, also on the northern tip of the island.

Similar to the other islands that had contaminated debris, these locations of elevated exposure were small is overall area.

Figures B-21 and B-22 contain isoexposure contours for Yvonne, composited from four image segments from NVO-140 (AEC 1973). B-21 contains the image segments from the northern portion of the island (A & B), while B-22 is for the image segments from the southern region (C & D). Four tests were conducted on the northern portion of Yvonne. Events Cactus and Lacrosse produced craters, as they were surface shots, while Events Dog and Zebra were tower tests. Blackfoot and Erie were tower tests, and detonated in more central areas of Yvonne. Quince and Fig were surface shots detonated on the central segment, but had only conventional explosives and a low-nuclear yield, respectively. Event Osage was an airdrop, detonated at altitude, but had a low yield. Overall, the highest residual exposure levels were observed on the northern part of the island, near the Cactus Crater. The southern segment of the island that contained the greatest amount of infrastructure had very-low exposure levels. Based on the review of the ^{137}Cs, and ^{60}Co contributions for the northern segments of the island, Figures B-23 and B-24, respectively, there was a somewhat equivalent contribution from each radionuclide to external exposure rates. During the cleanup conducted between 1977 and 1980, the ^{60}Co contribution would be about one-half, with total exposure rates about 75% of that displayed for the northern part of Yvonne. The north-central segment of Yvonne has areas of equivalent contributions of ^{137}Cs, and ^{60}Co to total external exposure, as evidenced by Figures B-25 and B-26, though the isoexposure contour H on Figure B-26 illustrates a significantly higher contribution from ^{60}Co to the total external exposure. A similar condition exists for the central-south segment of Yvonne. There is a fairly uniform contribution of the two radionuclides for the area, except for the isocontour G on Figure B-28, where the ^{60}Co has a significantly higher contribution than the ^{137}Cs, shown in Figure B-27.

Figure B-29 contains a plot of fixed external radiation measurement on the northern region of Yvonne. The highest external radiation measurement 750 μR h^{-1} shown on the plot was the highest among this type of measurement conducted on the Yvonne, and is noted on Table B-1. ^{241}Am provided a sizeable contribution to external exposure rates in parts of the north-central region of Yvonne, due to the WGP dispersed from Events Quince and Fig. The greatest impact was likely due to the dispersal from Event Fig, as the surface soils in the regions with the highest WGP concentrations were scraped and placed in the lagoon just adjacent to the test site (DNA 1982). Figure B-30 contains ^{241}Am isocontours, based on the aerial survey conducted over this area. Mean $^{239+240}$Pu activities in surface soil samples are contained in the plot in Figure B-31. As there is expected to be a fixed relationship between the $^{239+240}$Pu and ^{241}Am, the two plots should provide a similar pattern, except for the effect of heterogeneity in the assessment of $^{239+240}$Pu in soil samples. Only small aliquots of soil were analyzed by chemical separation and α-particle spectrometry for isotopes of plutonium. None of the other areas on Yvonne had ^{241}Am concentrations that provided an important contribution to external radiation as was the case for the area around the Events Quince and Fig GZ.

Figures B-32 through B-36 contain plots with annotation of scrap and structures on Yvonne with details on contact exposure readings. For the plot of the north segment, Figure B-32, the highest measurement was on a metal debris pile to the east of the Cactus Crater, with an exposure reading of 400 μR h^{-1}. Other metal debris piles surveyed had exposures ranging between 2 (non-contaminated) to 240 μR h^{-1}. The north-central segment had some metal and concrete debris with external exposure rates ranging from 10 to 3,000 μR h^{-1}. The 3,000 μR h^{-1} reading was on scattered debris near the high-tide ocean shoreline, while a 1,400 μR h^{-1} reading was on scattered debris near

the high-tide lagoon shoreline. Most debris, from inspection of Figure B-33, however, did not appear to be contaminated. The central segment, Figure B-34, also displayed the same 3,000 μR h^{-1} reading, as discussed for the north-central segment. A number of other metal and concrete debris had contact exposure measurements ranging from 1 to 1,000 μR h^{-1}, though most appeared uncontaminated or only to a mild degree. The south central segment had a number of contaminated metal and concrete debris locations documented on Figure B-35. These appear to be related to Event Erie, and are contained on the eastern portion of this land segment. The highest reading was 60 mR h^{-1}, attributed to a metal and concrete debris pile off the eastern coast, in an area submerged during high tide. The highest contact exposure measurements on land areas was 1,000 μR h^{-1}. Later in this report, it will be noted that field measurements during the clean-up phase only yield about 25 mR h^{-1} at the location that yielded 60 mR h^{-1} during the AEC survey. The decrease in exposure rate is directly related to the decay of ^{60}Co.

The fifth segment plot is contained in Figure B-36, and is for the southern portion of Yvonne. All locations with contact exposure measurements had reading between 1 and 3 μR h^{-1}. Exposure levels in this range, as will be discussed below, are largely attributable to naturally existing cosmic radiations. This portion of the Yvonne was an important work area for materials support for construction of the Cactus Crater entombment, yet with negligible levels of radiological impact.

Appendix B contains isoexposure contours for three islands of the Enewetak Atoll that only had minimal residual radiological impacts. Two islands in the northern group of island are shown: Ursula and Tilda, respectively Figure B-39 and B-40. Ursula is particularly germane to this report, as it was the support island for individuals that worked on the northern islands of the atoll. This island was fitted with billeting, a mess hall, and recreation facilities for a large duration of the cleanup. One southern island, Elmer, is displayed in Figures B-37 and B-38. Elmer was the major support island in the southern portion of the atoll. In review of the aerial survey isoexposure contours, it is clear that these islands had only negligible impacts from radiological fallout. This is also reflected in the average exposure rates listed in Table B-1, Ursula – 5 μR h^{-1}, Tilda – 6 μR h^{-1}, and Elmer - < 0.9 μR h^{-1}.

2.3.3 External Radiation Exposure Rates in CONUS

Figures B-41 and B-42 are plots of dose rates in CONUS and parts of Canada and Alaska from terrestrial γ-radiation and cosmic-ray sources, respectively. These plots provide a basis for comparison of exposure for individuals assigned to CONUS base duties to those at the Enewetak Atoll during the restoration. The plots are in units of nGy h^{-1}. Dividing by a factor of 10, converts the values into units of μrad h^{-1}. The cosmic radiation dose rates exclude contributions from neutrons. To convert the exposure rates generated in NVO-140 to absorbed dose in air, the following conversion is recommended (Cember 1996):

$$D\ (air) = Exposure\ (air) \times 0.875 \frac{rad}{R}$$

The cosmic ray dose component to background radiation dose was not included in the aerial survey measurements conducted and documented in NVO-140, as cosmic ray interaction events in the detectors used for these surveys excluded events with energy deposition greater than 3,000 keV (3 MeV), as shown in Table 2-9 below. Only a negligible fraction of cosmic ray interactions would have deposited energy below this threshold. The cosmic ray dose rate at Enewetak Atoll is about

3 μrad h^{-1}. This level is a little lower than the exposure rates in coastal areas of CONUS that are near sea level, as shown in Figure B-42. Cosmic ray exposure rates are influenced by altitude and latitude. This is clearly illustrated by the correlation of cosmic ray dose rates (Figure B-42) and an elevation plot in Figure B-43. Miami, FL has a cosmic ray exposure level about 3.2 μrad h^{-1}, while Chicago, IL, Denver, CO, Santa Fe, NM about 4.3, 5.3, and 9.0 μrad h^{-1}, respectively. The in-situ γ-radiation exposure measurements conducted at 1-meter heights above ground level and contact exposure measurements on debris described in NVO-140 were made with a 1 x 1.5 inch thallium-drifted NaI(Tl) detector. This instrument was calibrated to photon emissions from ^{137}Cs, but did not have a defined response to cosmic radiations. Many of the key measurements collected with this instrument were in areas of elevated exposure. In these cases, the contribution from cosmic radiations was of only minor influence to the total measured exposure.

TABLE 2-9. Exposure Rate Measurements on Enewetak Atoll from NVO-140 (AEC 1973).

Measurement Type	Instrument Response	
	Terrestrial γ-Rays	Cosmic Rays
Aerial Survey [2 x 5 inch NaI(Tl) Arrays]	0 – 3,000 keV	negligible
In-situ @ 1-meter [1 x 1.5 inch NaI(Tl)]	calibrated to ^{137}Cs	constant, but not defined
Contact exposure [1 x 1.5 inch NaI(Tl)]	calibrated to ^{137}Cs	constant, but not defined

The terrestrial exposure rates are due to radioactive materials in the surface soils. The primary radioactive materials in soils contributing exposure in CONUS are ^{40}K, and ^{232}Th and ^{238}U and their decay products. Similar to the plot of cosmic radiation in CONUS, there is a considerable range of dose rates from terrestrial sources, as shown in Figure B-41. Miami, FL has a rate of 6 nGy h^{-1} (0.6 mrad h^{-1}), while Chicago, IL, Denver, CO, Santa Fe, NM have rates of about 4.8, 7.3, and 5.2 mrad h^{-1}, respectfully. In contrast, the coral-based atolls, like Enewetak, Bikini, and Johnston have negligible levels of these isotopes, with virtually all terrestrial radioactivity due to fallout from nuclear weapons testing. Figure 2-11 contains the contribution of cosmic and terrestrial sources to external dose at various locations in CONUS and example islands of Enewetak, based on average estimated exposure rates in 1978 from Table B-1. Elmer is an example of expected dose rates for the southern islands, except Leroy. Most of the work performed on the southern island was conducted on Elmer, David, and Fred. Fred contained the airport. Individuals assigned to duties on the southern islands of the Atoll were billeted on these islands. The dose rates for Elmer were similar to Miami, FL, but lower than many other locations in the CONUS. Hence, for individuals assigned to duties on the southern islands of Enewetak, their external radiation dose potential was at or below that for a CONUS duty location. For some islands in the northern part of the Atoll, external dose rates were a little higher, e.g., Sally, Ursula, yet similar to the exposure potential in Chicago, IL, but less than Denver, CO, and Santa Fe, NM. Key islands on the northern group of island – Yvonne and Janet, where a significant amount of work was conducted during the restoration had exposure rates above those in the example CONUS cities. Irene, Alice, and Belle are examples of islands with higher average exposure rates than others in the northern group of islands. These islands, in contrast to Yvonne and Janet, did not have much occupancy by workers during the restoration. This is because these islands did not have significant amounts of debris requiring removal. As well, Alice and Belle did not have any soil removal activities.

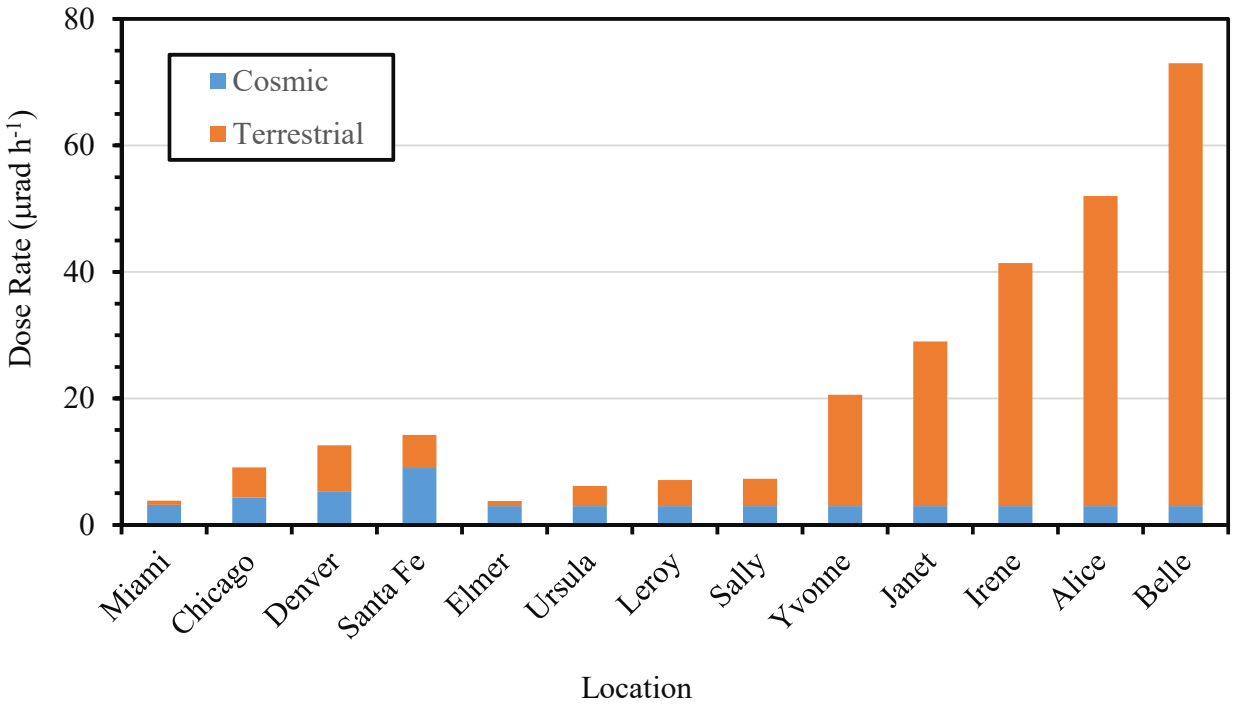


Figure 2-11. Cosmic and Terrestrial Dose Rates at Various Locations in CONUS and Islands of Enewetak Atoll for 1978 (Mean), based on AEC (1973).

2.3.4 Exposure Rate Measurements Post Cleanup

During the cleanup, a primary responsibility of the DOE was verification of radiological conditions on the island. For islands with soil excision activities, DOE measurements also guided these activities. As expected, due to soil activity removals by the soil excisions, radioactive decay, and environmental dilution processes, the mean measured exposures were lower in 1978/1979 during the DOE survey (DOE 1982), as compared to 1972 when the AEC collected the measurements (AEC 1973) for most islands. Figures B-44 and B-45 illustrate in scatterplots the relationships for ^{137}Cs, and ^{60}Co for select northern islands. Each plot contains a light-blue line representing the ideal relationship for losses from radioactive decay alone. Linear regressions are also contained on each plot to show total loss in exposure due to all three effects. Annotations are also contained on each plot the data points for Irene, Janet, and Pearl. For each plot, these three islands had the greatest ratios in exposure for 1972 compared to 1978/1979. This is reasonable since these islands had soil excision, while the other islands with plotted exposure rates did not have any soil excision. It is also clear that environmental dilution processes also caused reduction in exposure rates. The ratio of the regression analysis slope to the ratio of exposure reduction from radioactive decay-only was about 1.4 for both ^{137}Cs and ^{60}Co. Figures B-46 and B-47 contain the same regression analyses, except with omission of islands with soil excision. The ratio of the regression analysis slope to the ratio of exposure reduction from radioactive decay-only was 1.31 and 1.14, respectively for ^{137}Cs and ^{60}Co. Calculated annual reduction factors were 0.96 and 0.98, respectively for ^{137}Cs and ^{60}Co. This is a reasonable finding - cesium is expected to have greater mobility than cobalt in soils of the Atoll environment and lead to a greater reduction from environmental dilution.

2.3.5 Radionuclides in Soils

2.3.5.1 General

The AEC collected a vast number of soil samples in support of the preparation of NVO-140. The primary purpose of the effort was support of exposure assessment calculations for potential future use scenarios of the Enewetak peoples on the islands. Radionuclides in soils create exposure potential to individuals from a multitude of exposure pathways to include inhalation of surface soils suspended in the atmosphere, incidental ingestion of surface soils, ingestion of food grown in soils with radionuclides, ingestion of animals that graze on plants grown in soils with radionuclides, and external radiation emissions. Some of the exposure pathways can also be assessed by other methods. For example, plants were also assessed for radionuclide content, as well as animals, and aquatic life from the Atoll's lagoon. For the latter, concentrations of radionuclides in water and sediment samples from the lagoon can be used as predictors of radionuclides in aquatic life, though the direct measurements are preferred. Radionuclide concentrations in soils can be used as a predictor of external radiation exposure. However, due to the extensive external radiation measurements conducted on the Atoll, radionuclide data is a supporting source of data for this exposure pathway.

Inhalation of air-suspended radionuclides and incidental ingestion of radionuclides in surface soils are key exposure pathways that can be predicted from this data, though air sampling is a more direct assessment method for the inhalation pathway. As there are some reasonable limitations to the collection of air samples for a multitude of potential occupied areas, there is a practical necessity to pair air sampling data and surface soil concentrations for assessment of exposure potential. While all of the exposure pathways noted above were deemed important for assessment in the resettling of the Atoll by the Enewetak peoples, the only pathways of exposure important for individuals supporting the restoration between 1977 and 1980 were external exposure, inhalation of air-suspended radionuclides, and incidental ingestion of radionuclides in surface soils. Purified water was provided for drinking and food was transported into the Atoll for workers. It has been noted by some veteran's assigned to Atoll for duty during this period that occasionally fish and shellfish acquired from the lagoon were consumed. This exposure pathway is expected to be low, but estimates of dose can be made, based on data in NV0-140.

2.3.5.2 Soils Data from NVO-140

The AEC collected two primary types of soils samples for NVO-140: surface soil samples from the top 5 or 15 centimeters (cm) and profiling samples with vertical sampling increments as small as 2 cm and depth to nearly two meters. The vertical profiling depths were varied dependent on the island and the history of surface soil disturbances that occurred during and after use for atmospheric tests. The majority of the samples were collected at randomly selected locations, while some biased samples were collected at locations of higher contamination, termed "hot spots." External exposure measurements guided the selection of sampling at hot spots. A little over 3,000 soils samples were analyzed, while about 1,500 samples were analyzed on lagoon sediments, aquatic and terrestrial animals and vegetation, water, and air, as well (AEC 1973). The soils samples were analyzed by high-resolution, γ-spectrometry, and analyzed for isotopic plutonium and ^{90}Sr by chemical separation and subsequent α-particle and β-particle spectrometry, respectively. Lawrence Livermore Laboratory (LLL) performed γ-spectrometry analyses, while Laboratory for Electronics, Environmental Analysis Laboratories Division (LFE), Richland WA, Laboratory of Radiation Ecology (LRE), Eberline Instrument Corporation (EIC), Santa Fe, NM, and McClellan Central Laboratory (MCL), McClellan AFB, CA split the isotopic plutonium and ^{90}Sr analyses.

This report will discuss three separate analyses of the NVO-140 soils data.

1) This report provides an analysis of the data contained in the microfiche supplement to NVO-140 (AEC 1973). Since the internal pathways of concern for personnel supporting the restoration activities was inhalation and incidental ingestion of surface soils, this report concentrates primarily on concentrations of radionuclides in surface soils.

2) Tables 13, 14, and 15 of NVO-140 summarize soil sampling data, though NVO-140 also contains an extensive number of depth distributions plots of radionuclides among depth profile samples, and overlay plots of radionuclide concentrations on aerial images. Some of these will be reproduced in this report as a convenience to the reader.

3) NVO-213 (DOE 1982) also summarizes NVO-140 surface soil sample analyses along with results from additional sampling of soils conducted by the DOE in 1979. The number of soil samples collected by the DOE varied by island. Many islands had a similar number of samples collected as was the case for preparation of NVO-140. Overall, ^{90}Sr analyses of samples was lower for NVO-213, compared to NVO-140. Except for Leroy, no samples were collected on the southern islands. The soil sampling performed on Janet and Sally by the DOE were substantially more extensive than for NVO-140. For Janet this was attributable to a continued interest in the evaluation of the potential for future residence on this island. This was an important issue for the Enewetak people then and continues today.

While all three assessments of NVO-140 soil data are believed to have been performed on the same data set, there were similarities and differences in the summary descriptive statistics among the three analyses performed.

2.3.5.3 Descriptive Statistics of Soils Data from NVO-140 for Primary Radionuclides

A summary of activity concentrations of primary radionuclides from soils in the northern islands are provided in Table 2-10, as compiled primarily from microfiche-archived soil data from NVO-140 (AEC 1973). Figure 2-12 contains a graphical depiction of the mean concentrations for the primary radionuclides. Table 2-11 contains similar data for two of the southern islands of the Atoll. Since the archived data did not detail which soil samples were deemed from the beach versus interior of the island[7], the data from Tables 13 and 15 of NVO-140 is only listed without a separate assessment from archived data. The red print in Table 2-10 denotes datum that deviates from that contained in the Tables 13 or 15 of NVO-140, while datum printed in black matched data in the two tables. Table C-1 contains a copy of Table 15 from NVO-140 for the reader's convenience. Some of the deviations in data are inherent to additional granularity provided in Table 15 from NVO-140 for samples collected from sparsely versus densely vegetated areas. NVO-140 used this reporting convention for Belle, Daisy, Kate, Olive, and Tilda islands. However, for Pearl, it distinguished between samples collected at a hot spot versus the remainder of the sampling locations on this island. The mean radionuclide activity concentrations in surface soils were generally higher in the densely vegetated areas over the sparsely vegetated ones. The presumption was sparsely vegetated areas were subjected to a greater degree of erosion than the densely vegetated areas. This was supported by the comparisons provided in Table 15 of NVO-140. In a similar vein, NVO-140

[7] The plots of soil sampling location overlaid on aerial images provides some indication of whether a sample was on or near a beach.

summarized the results from samples collected on beach areas of the northern Atoll islands, and overall the concentrations of the primary radionuclides on the beaches was much lower than the mean for the same radionuclides on many of the islands. Exceptions existed for Wilma and the southern portion of Yvonne for ^{90}Sr, and Ursula for $^{239+240}$Pu.

There was some deviation in sample numbers listed in Table 2-10 versus that contained in Table 13 of NVO-140. In general, the differences were only a sample or two between the two summaries, with the exception of Irene. For Irene the data summary in Table 2-10 is based on the soil concentrations in 46 random samples, while Table 13 of NVO-140 only lists 34 (AEC 1973). Nine additional samples were collected along the beach area of the Seminole Crater. While these samples were collected to gather additional clarity on the distribution of radionuclides in surface soils of this island, they were not included in the calculation of the mean concentration in surface soils for this island in Table 2-10, as these samples were deemed biased. Table 13 of NVO-140 appeared to list all samples planned for sampling, while the numbers listed in Table 2-10 of this report contains only those with results reported in the microfiche enclosed in NVO-140. NVO-140 (AEC 1973), p. 426, notes that more than 5,000 samples were collected during field operations, though about 4,500 were selected for analysis. It was clear that some locations were planned for sampling, though the sequence of sample number omitted some numbers in the listing of results. This was also reflected by the omission of these sample location postings on plots in NVO-140.

NVO-213 (DOE 1982) contains results from sampling conducted in 1979. The primary purpose of this sampling was to assess significant differences between pre- and post-remediation radiological conditions. This was most important for islands of the Atoll that had soil excisions, though some reduction in concentrations of long-lived radionuclides are expected due to erosion. NVO-213 contained results for soil analysis of samples collected in 1979 paired against results from soil sampling conducted for NVO-140. Tables C-2 through C-4 contains these results for ^{137}Cs, ^{90}Sr, and $^{239+240}$Pu, respectfully. The NVO-213 soil sampling summary of data for soil samples collected for NVO-140 was reported in similar manner to that in Table 2-10. As such, mean concentrations were not distinguished for samples collected among dense and sparsely vegetated areas. Some of the directly comparable parameters of the NVO-140 soil data, as reported in Tables 13 and 15 of NVO-140 and NVO-213: maximum and mean soil concentration, and sample number did not match. The summary of NVO-140 soils data analyzed by this report (summarized in Table 2-10) and NVO-213, in general, were in better agreement than either of these with that contained in Tables 13 and 15 of NVO-140. The bar graphs in Figures C-1, C-2, and C-3 contain a comparison of mean ^{90}Sr, ^{137}Cs, and $^{239+240}$Pu activity concentrations in surface soils as listed in Table 2-10 of this report, Table 15 of NVO-140 (AEC 1973) and Table 7-1, 7-2, and 7-3 of NVO-213, respectively. As noted above, mean radionuclide concentrations listed in Table 15 of NVO-140 are not displayed on the bar graphs due to the greater granularity of data summaries for Belle, Daisy, Kate, Olive, Pearl, and Tilda. For the data displayed, among the three analyses, the mean surface soil concentrations listed in Table 15 of NVO-140 were more commonly lower than the mean concentrations listed by the other two analyses. With a few exceptions, the mean soil concentrations of primary radionuclides were very similar, as analyzed for this report and NVO-213. For mean soil concentrations, it was noted in NVO-140 that beach areas were excluded in the calculation of mean activity concentration, except for samples in that category (AEC 1973). Naturally, differences in listed mean concentrations are more of a concern for the islands with greater overall concentrations of radionuclides. For mean concentrations of ^{90}Sr on Edna, there was a significant difference among all three analyses. Another source of the difference is believed to be due to the method of calculation of the mean. For NVO-140 and NVO-213, it appears that the minimal detectable concentration (MDC) was used as a surrogate for a reported concentration, if the activity concentration of a sample was reported as a

Table 2-10. Soils Data for Northern Islands, from Archived Data Soils Data of NVO-140 (AEC 1973)
[Red-highlighted Data is Not Consistent with Data in Tables 13 and 15 of NVO-140].

Island	Random Sampling Location Type		§Descriptive Statistics for Random-Selected Surface Soil Samples – Top 15 cm (pCi g^{-1})							
			^{90}Sr		^{137}Cs		$^{239+240}Pu$		^{60}Co	
	Surface	Profile	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Alice	19	4	117	5.8 - 480	42	0.9 - 134	16	0.08 - 71	7.9	0.2 - 30
Belle	32	4	140[1]	9.8 - 660	42	0.45 - 120	28[†]	4.2 - 105	10	0.22 - 31
Clara	9	3	100	13 - 311	37	0.77 - 110	32	3.5 – 88	8.5	0.3 - 20
Daisy	15	4	94	3.4 - 295	9.4	1.0 - 33	31	3.8 - 98	5.5	0.35 - 26
Edna	6	2	32[2]	30 - 83	4.7	2.7 - 6.4	20	13 - 25	0.46	0.33 - 0.63
Irene	27	19	35[1]	5.1 - 100	5.2	0.16 - 21	12	2 - 95	12	0.43 - 150
Janet	127	13	66	0.34 - 301	27	0.57 - 180	16[1]	0.08 - 180	3.4[1]	0.09 - 28
Kate	22	3	45[1]	1.4 - 200	13	0.08 - 38	11[1]	0.2 - 50	2.0[2]	0.04- 5.8
Lucy	22	3	30	4.4 - 83	10	0.1 - 25	7.8	1.5 - 23	1.4[3]	0.04 - 3.8
Mary	22	3	52	1.2 - 140	8.8[4]	0.1 - 26	14	0.92 - 53	2.1[5]	0.09 - 4.8
Nancy	21	4	39	1.8 - 160	12[2]	0.11 - 56	10	0.12 - 42	1.8[2]	0.09 - 8.0
Percy	5	1	36[1]	7.0 - 47	7.2	0.12 - 17	9.0	1.5 – 23	1.5	0.08 - 2.9
Olive	22	4	22[1]	2.0 - 69	7.7	0.07 - 30	8.4	1.9 - 30	1.3[2]	0.08 - 3.9
Pearl	45	5	27	2.3 - 140	11[1]	0.17 - 55	39	0.34 - 530	9.7[1]	0.05 - 70
Ruby	4	1	24	7.1 - 63	3.2	0.71 - 7.2	11	1.8 - 24	6.6[1]	0.3 - 16
Sally	23	9	17	0.87 - 140	6.3[1]	0.06 - 37	14[†]	0.21 - 130	2.9[4]	0.01 - 69
Tilda	28	4	19	2.2 - 54	4.1[1]	0.15 - 20	5.7	0.64 - 34	0.86[2]	0.05 - 2.0
Ursula	28	3	8.3	0.93 - 19	2.6[1]	0.13 - 7.8	1.8	0.23 - 7.3	0.46[4]	0.04 - 1.7
Vera	22	3	14	1.1 - 59	4.6	0.03 - 13	16	0.6 - 300	0.58[3]	0.02 - 2.2
Wilma	19	4	5.8	0.26 - 15	2.0	0.31 - 7.2	13	0.1 - 260	0.18[5]	0.05 - 0.7
Yvonne (south)	51	5	3.2[2]	0.092 - 20	0.97[7]	0.02 - 3.6	12	0.08 - 210	2.4[7]	0.031 - 20
Beaches (north)[‡]	51	9	6.4	1.2 – 30	0.3	0.03 - 9.0	2.7	0.34 - 18	0.13	0.03 - 1.6

§ Values displayed in red differed from data in Table 13 or Table 15
[1] One sample non-detect [2] Two samples non-detect [3] Three samples non-detect [4] Four samples non-detect [5] Five samples non-detect [7] Seven samples non-detect
[†] One sample with un-reported $^{239+240}Pu$, estimated value based on ^{241}Am and median ratio: $^{239+240}Pu/^{241}Am$ [‡] Data from Table 13 and 15 of NVO-140

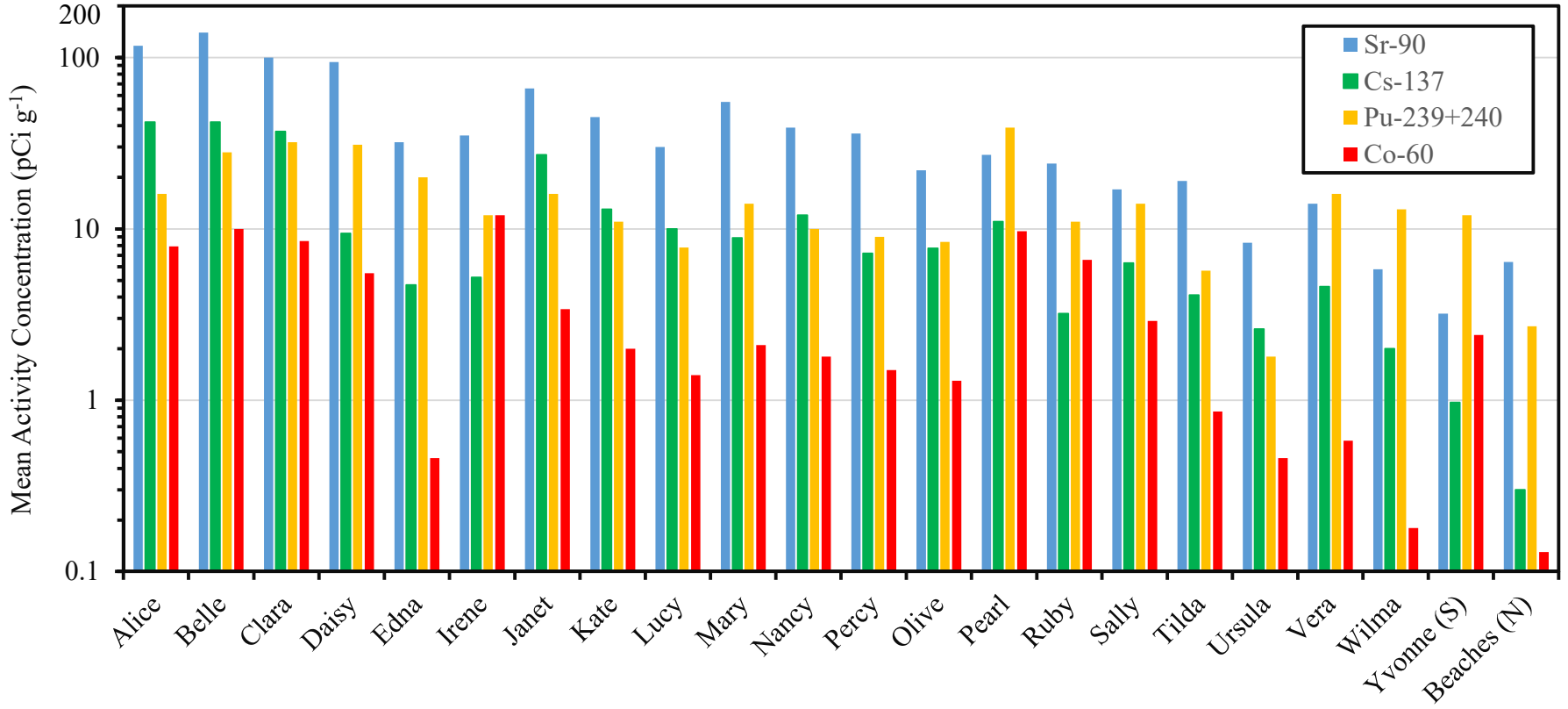


Figure 2-12. Histogram of Mean Primary Radionuclide Concentrations on Northern Islands from Data in TABLE 2-10.

Table 2-11. Soils Data for Two Southern Islands, Data from NVO-140 (AEC 1973).

Island	Random Sampling Location Type		Descriptive Statistics for Random-Selected Surface Soil Samples – Top 15 cm (pCi g^{-1})							
			^{90}Sr		^{137}Cs		$^{239+240}Pu$		^{60}Co	
	Surface	Profile	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Elmer	53	8	0.72[4]	0.02 - 5.1	0.36[9]	0.09 - 1.2	0.38[9]	0.008 - 5.6	0.038[†]	0.06 - 0.73
Sam	4	1	0.73	0.3 – 0.81	0.36	0.2 - 0.52	0.10	0.06 - 0.18	0.002[4]	0.01

[4] Four samples non-detect [9] Nine samples non-detect [†] Fifty-one samples non-detect

non-detect (NDET). Two samples, EDN-002 and -004, had abnormally-high MDA concentrations for ^{90}Sr – 44.4 and 218 pCi g^{-1}, respectively. Only a few surface samples collected on the northern islands had ^{90}Sr below the MDC. In fact, most samples collected from the southern islands had reported activity concentrations less than 1 pCi g^{-1}. Table 15 of NVO-140 and Table 7-2 of NVO-213 both list 220 pCi g^{-1} as the maximum activity concentration among the eight samples from Edna.

For mean $^{239+240}Pu$ activity concentrations in surface soils, Table 2-10 of this report was fairly similar to NVO-213, with the exception of Vera and Wilma. The range of activity concentrations among the samples for these two island are identical, as reported in Table 15 of NVO-140 and Table 7-3 of NVO-213, though the mean concentrations are different. Table 2-10 lists the maximum concentration for a sample from each of these islands which is substantially higher than listed in Table 15 of NVO-140. For Vera and Wilma, the maximum activity concentration among the samples was 300 and 260 pCi g^{-1}, respectively. The reported $^{239+240}Pu$ activity concentrations for both of these samples does not appear consistent with each data set as a whole based on scatterplots of the $^{239+240}Pu$ to ^{241}Am activity concentrations displayed in Figure C-4 and C-5. For each plot, the sample of interest are solid red circles, while other data are open black circles. The linear regression analyses displayed in red, clearly demonstrate poor correlation when all data are considered, while the regression analyses in green demonstrate excellent correlation when the sample with the high $^{239+240}Pu$ is omitted. Since neither of these islands supported a test detonation, the fallout contamination is expected to have a fairly uniform $^{239+240}Pu$ to ^{241}Am relationship. The data included in Figures C-4 and C-5 contain all samples – surface and depth profile, while only surface soil samples were included in the estimate of mean concentration in Table 2-10. The reason NVO-140 and NVO-213 omitted the two samples with high $^{239+240}Pu$ was not documented in either of the reports. Nevertheless, these samples are clearly outliers. It is speculated that the samples may have been cross-contaminated. Both samples had their wet chemistry conducted at the same laboratory. Overall, some differences may exist in the treatment of $^{239+240}Pu$ activity concentrations among this report, NVO-140 and NVO-213. Table 7-3 of NVO-213 notes that $^{239+240}Pu$ activity concentrations were estimated from ^{241}Am data, though the relationship between $^{239+240}Pu$ and ^{241}Am was not specified.

Descriptive statistics for soil concentrations on the southern island were only compiled for two islands, as summarized in Table 2-11. In review of the primary radionuclide activity concentrations, they are significantly lower than those observed in soil samples from the northern islands. Due to this circumstance, an analysis of soil sample concentrations from other southern islands was not performed for this report. Table 16 of NVO-140 provides a summary of mean concentrations of primary radionuclides for soils collected from southern islands among three groups of islands. A copy of this table is contained in Table C-5.

2.3.5.4 Soils Data from NVO-140 for Primary Radionuclides on Northern Yvonne

Table 2-10 descriptive statistics for radionuclide in soils for Yvonne was limited to the southern portion of the island because the northern portion of the island had a much more complex distribution of radionuclides (AEC 1973). As shown in Figures B-21 and B-22, eight nuclear tests were conducted on Yvonne, with another detonated in by airdrop over the island (Event Osage, 16 Jun 56), and Event King conducted 2,000 feet north of the island at 1,500 feet AGL. As discussed above in relation to external radiation, $^{239+240}Pu$ activity concentrations in soils was of prominent interest to Yvonne due to its dispersal in Event Quince and re-distribution by remedial actions conducted after this Event, but prior to Event Fig. ^{241}Am isocontours were displayed in

Figure B-30, which correspond to surface soil concentrations of $^{239+240}$Pu. Table C-6 provides $^{239+240}$Pu activity concentrations depth profile samples corresponding to the region surface samples results (0 – 10 cm) displayed in Figure B-31, encompassed by the red-lined polygon. In general, the average $^{239+240}$Pu activity concentration level is highest in the soil lifts closer to the surface, but considerable spatial heterogeneity exists among samples in each identical depth layer and those at varied depth from each sampling location.

Table 2-12 contains surface soil data for land segments of Yvonne for primary radionuclides, according to the sample locations shown in Figures C-6, C-7, C-8, and C-9. Sample locations 134 through 139 were designated segment A/B for the purpose of this report and are in part displayed in both segments A and B. The mean activity concentrations of ^{90}Sr, ^{137}Cs, and ^{60}Co are highest in segments A, with concentrations in the other segments much lower. Proximity to the GZ's of Events Lacrosse, Cactus, Dog and Zebra (see Figure B-21) are key to this characteristic. The only ground or near-ground level tests with significant yield conducted on other segments of Yvonne were Events Blackfoot (8 kT, segment A/B) and Erie (14.9 kT, segment C). In contrast, $^{239+240}$Pu activity concentrations in surface soils were greatest in segment B and much lower in the other segments. This condition is due to the dominant local deposition of $^{239+240}$Pu from Events Quince and Fig.

Table 2-12. Soils Data for Northern Segments of Yvonne, from Archived Data Soils Data of NVO-140 (AEC 1973).

Island Segment	Sample Locations	Parameters	Activity Concentration Top 10 or 15 cm (pCi g^{-1})			
			^{90}Sr	^{137}Cs	$^{239+240}$Pu	^{60}Co
A	7	Mean	110	19	31	28
		Range	1.4 – 520	0.3 – 70	3.8 – 120	1.2 – 120
A/B	6	Mean	11	3.5	34	5.6
		Range	2.8 – 23	0.78 – 7.3	1.8 – 160	0.35 – 16
B	32	Mean	5.3	2.3	140	1.9
		Range	0.44 – 23	0.34 – 9.5	0.26 – 730	0.05 – 10
C	39	Mean	4.2	1.3	12	3.3
		Range	0.09 – 20	0 – 3.6	0.71 – 50	0.05 – 20
D	17	Mean	1.3	0.42	14	0.75
		Range	0.23 – 2.3	0.02 – 2.3	0.083 – 210	0 – 5.8

2.3.5.4 Soils Data from NVO-140 for Other Radionuclides

2.3.5.4.1 General. In addition to the primary radionuclides identified in soil samples, the activity concentrations of other radionuclides were assessed in detail. Due to the limited number of internal exposure pathways of concern for individuals supporting the restoration of Enewetak Atoll, a reasonable approach to the description of secondary radionuclides is in relation to concentrations of the primary radionuclides. Among other radionuclides, the most important to the purpose of this report are: ^{241}Am, ^{238}Pu, ^{155}Eu, and ^{125}Sb. Table 2-13 contains median values of the ratios of primary and a number of other radionuclides detected in soil samples. The use of median values is convenient, but also a parameter that is robust to the influence of outlier data. In addition, for many paired radionuclide data sets, scatterplots were produced, reviewed, and afforded regression analysis. A number of these plots will be provided in this report. As noted in Table 2-13,

for all paired radionuclide comparisons, samples from the top 15 cm were used, with the exception of paired analysis of transuranic-only isotopes, i.e., $^{239+240}$Pu, ^{241}Am, ^{238}Pu. This protocol was adopted because surface soils were generally of interest for incidental ingestion, and airborne suspension of radioactive materials for evaluation of inhalation exposures. Limiting assessment to surface soils alleviates the undue influence of differences in the migration rates of radionuclides to greater depths in the soil profile, which is a concern for many of the fission and activation products. Due to the general refractory nature of the transuranic elements considered here, and the fact that three of the four are isotopes of the same element, the relationships among these was expanded to include samples at depth for profile sampling locations. In this case, the expanded sample numbers improved the confidence in median and regression parameters. Samples that were NDET for one or both of the radionuclides being compared were not included. This protocol eliminated assessment of the relationship of some of the radionuclides listed in Table 2-13 for some of the islands due to a limited number of samples with positive detects for the two radionuclides being considered. This was observed for the assessment of ^{152}Eu, ^{207}Bi, and ^{102m}Rh regressed against ^{137}Cs for a majority of the islands, and $^{239+240}$Pu to ^{238}Pu for one-third of the islands listed in Table 2-13.

2.3.5.4.2 ^{137}Cs to ^{90}Sr. ^{137}Cs and ^{90}Sr are the two key long-lived fission product residuals from nuclear detonations. The median values listed among the northern islands in Table 2-13 ranged from 0.097 (Irene) to 0.49 (Sally). The relationship in activity of these radionuclides produced in nuclear weapon detonations is varied dependent on the weapon design. For ^{235}U fission weapons, the production ratio of ^{137}Cs to ^{90}Sr is near unity, while a little greater than two for a ^{239}Pu fission device (Sherrill et al. 1975). For thermonuclear weapons, the ratio is expected to be closer to 1.5 (Sherrill et al. 1975), due to the expected dominance of the fast neutron fission of ^{238}U. The local ground deposition of these fission products will be substantially different due to fractionation, where ^{90}Sr is expected to be preferably retained in local fallout compared to ^{137}Cs, which is preferably carried to greater heights in the atmosphere, where it provides a greater contribution to global fallout than the ^{90}Sr. This condition is readily supported by the data for the islands on the Atoll. The varied ratios among the islands are attributed to the greater mobility of ^{137}Cs in the coral soil environment than ^{90}Sr. This effect is exacerbated for the smaller islands, and especially those sparsely vegetated. Figure 2-13 contains a scatterplot of ^{137}Cs to ^{90}Sr for samples collected from the top 15 cm on Alice. The regression analysis had a slope close to the median value when the y-intercept was set at 0. Figure C-10 contains a similar scatterplot for surface samples from Sally. For this data set, the median ratio was 0.49, but the slope of the regression was 0.33.

2.3.5.4.3 ^{137}Cs to ^{60}Co. The distribution of median values listed among the northern islands in Table 2-13 ranged from 0.28 (Yvonne south) to 11 (Edna). Since ^{60}Co is an activation product, its production is not strongly related to that of ^{137}Cs, but rather to the abundance of steel in proximity of the detonation. Figure 2-14 contains a scatterplot of ^{137}Cs to ^{60}Co for samples collected from the top 15 cm on Irene. Due to the broad scatter of the data, the plot does not contain a regression analysis. Figure C-11 contains a similar scatterplot for surface samples from Janet. Janet had GZ for three tests and had the greatest amount of debris removal among the northern islands. The island, however, had proportionately much lower concentrations of ^{60}Co compared to ^{137}Cs content. Due to the 5.27 y radiological half-life, and the sample analysis conducted in 1972, the median ^{137}Cs to ^{60}Co ratios listed in Table 2-13 would have been about 50% lower during the cleanup.

2.3.5.4.4 ^{137}Cs to ^{125}Sb and ^{155}Eu. ^{125}Sb and ^{155}Eu are the next two important residual fission products after ^{137}Cs and ^{90}Sr. Like ^{60}Co, due their short half-lives, significant decay occurred between sample analysis and cleanup activities. As such, the range of

Table 2-13. Relationships between Primary and Other Radionuclides for Soil Sample Data of NVO-140 (AEC 1973a).

Island	Sample Locations			Median Values of Ratios of Radionuclides in Soils									
				Samples within Top 15 cm								All Samples	
	Random		Hot Spot	$\frac{^{137}Cs}{^{90}Sr}$	$\frac{^{137}Cs}{^{60}Co}$	$\frac{^{137}Cs}{^{125}Sb}$	$\frac{^{137}Cs}{^{152}Eu}$	$\frac{^{137}Cs}{^{155}Eu}$	$\frac{^{137}Cs}{^{207}Bi}$	$\frac{^{137}Cs}{^{102m}Rh}$	$\frac{^{239+240}Pu}{^{90}Sr}$	$\frac{^{239+240}Pu}{^{241}Am}$	$\frac{^{239+240}Pu}{^{238}Pu}$
	Surface	Profile											
Alice	19	4	1	0.35	4.5	23	170	7.8	3.1	120	0.18	3.2	14
Belle	32	4	1	0.33	4.4	7.7	71	7.7	101	110	0.19	3.6	9.3
Clara	9	3	1	0.35	4.4	19	67	7.1	93	120	0.31	4.9	6.0
Daisy	15	4	1	0.10	2.5	4.9	16	1.4	11	36	0.26	3.3	12
Edna	6	2	0	0.10	11	25	19	1.4	5.0	50	0.40	3.4	NA[1]
Irene[†]	27	19	2	0.097	0.78	3.1	5.4	1.3	5.2	NA[2]	0.31	5.7	3.4*
Janet	127	13	1	0.41	8.6	22	23	9.5	52	92	0.20	3.1	15*
Kate	22	3	0	0.37	7.0	21	NA[2]	6.8	62	NA[2]	0.23	2.8	NA[3]
Lucy	22	3	2	0.35	9.3	14	NA[2]	6.6	85	NA[2]	0.24	2.6	11.5[4]
Mary	22	3	0	0.20	4.8	15	NA[2]	4.1	30	NA[2]	0.30	2.8	NA[3]
Nancy	21	4	0	0.35	8.8	15	NA[2]	6.4	NA[2]	NA[2]	0.24	2.5	103[5]
Percy	5	1	0	0.18	3.7	14	NA[2]	3.7	18	76	0.23	2.9	220
Olive	22	4	0	0.26	4.4	13	NA[2]	3.9	4.9	NA[2]	0.38	3.0	9.8[4]
Pearl	45	5	3	0.38	2.0	8.5	0.20	3.0	NA[2]	NA[2]	0.39	5.0	3.5[6]
Ruby	4	1	0	0.14	1.9	3.1	1.4	0.46	NA[2]	NA[2]	0.43	7.5	9.5
Sally	23	9	2	0.49	7.1	16	7.4	7.4	NA[2]	NA[2]	0.31	3.3	45
Tilda	28	4	0	0.32	4.1	4.1	NA[2]	4.0	NA[2]	NA[2]	0.22	2.5	17.8[5]
Ursula	28	3	0	0.29	5.8	13	NA[2]	4.6	NA[2]	NA[2]	0.21	3.0	NA*
Vera	22	3	0	0.41	8.6	13	NA[2]	6.2	NA[2]	NA[2]	0.31	2.7	215[5]
Wilma	19	4	0	0.25	6.2	7.0	NA[2]	4.7	NA[2]	NA[2]	0.28	3.0	NA[3]
Yvonne (south)	51	5	0	0.28	0.28	3.0	2.4	0.62	NA[2]	NA[2]	2.3	7.9	2.6[6]

[†] Nine Seminole Crater samples, collected from 0 – 5, 0 – 10, and 0 – 15 cm depths. Samples in addition to others listed. * Majority of samples apparently did not have Pu-238 content assessment by isotopic Pu method [1] All samples non-detect for Pu-238 [2] All or vast majority samples non-detect for Eu-152, Rh-102m, or Bi-207 [3] About half samples non-detect for Pu-238, other half apparently did not have Pu-238 content assessment by isotopic Pu method [4] Only few samples with detect for Pu-238, about one-third apparently did not have Pu-238 content assessment by isotopic Pu analysis [5] Only few samples with detect for Pu-238, about one-half apparently did not have Pu-238 content assessment by isotopic Pu method [6] About one-third apparently did not have Pu-238 content assessment by isotopic Pu method

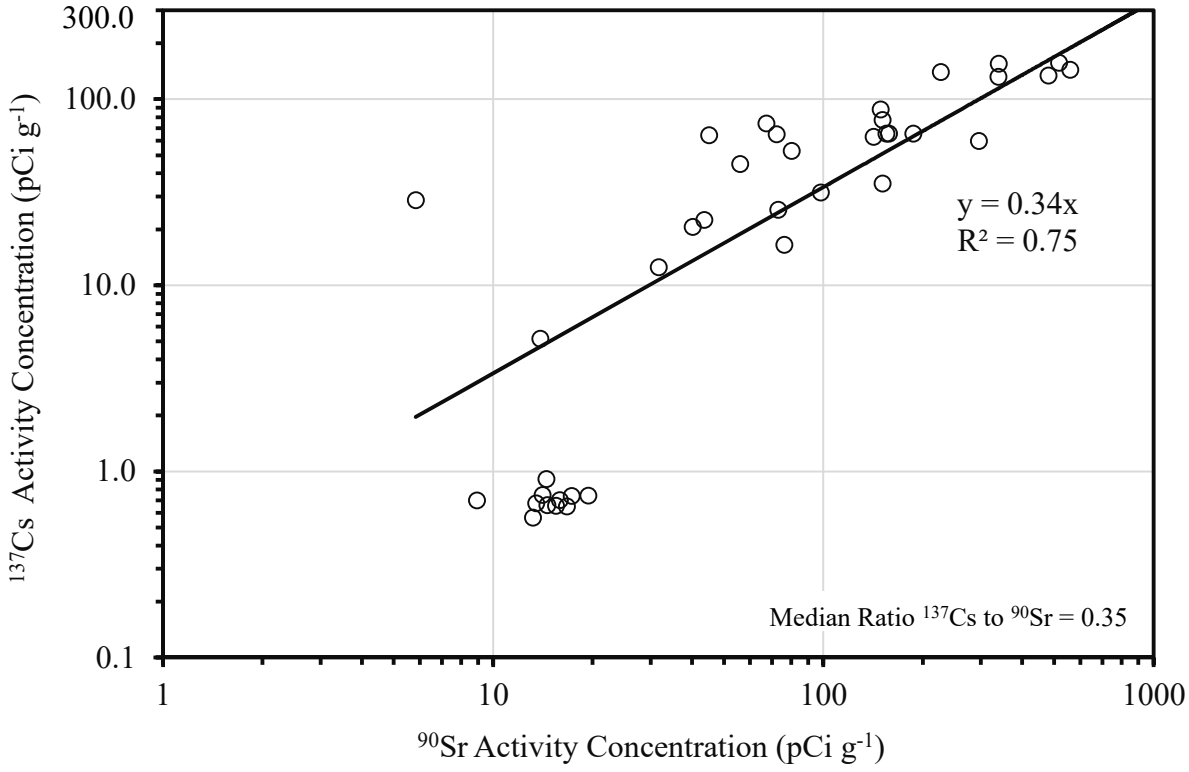


Figure 2-13. Scatterplot of ^{137}Cs to ^{90}Sr for NVO-140 Soil Samples from Top 15 cm on Alice.

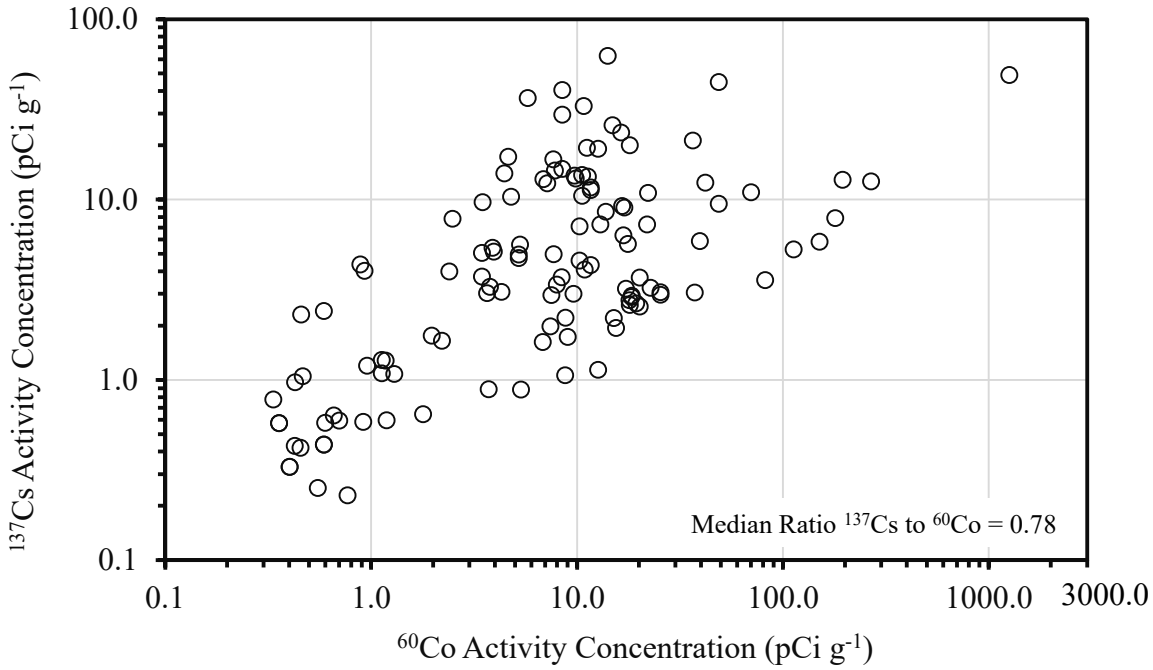


Figure 2-14. Scatterplot of ^{137}Cs to ^{60}Co for NVO-140 Soil Samples from Top 15 cm on Irene.

median ratios of ^{137}Cs to ^{125}Sb, 3.0 (Yvonne south) to 25 (Edna) would be close to 12 to 100 during the cleanup. The median ratios of ^{137}Cs to ^{155}Eu during the restoration would be about twice those

listed in Table 2-13, 0.46 (Ruby) to 9.5 (Janet). Figure 2-15 contains a scatterplot of ^{137}Cs to ^{125}Sb for samples collected from the top 15 cm on Irene. The median ratio for this data set was 3.1, though the slope of the regression was 1.1. Clear from the plot, the data does not hold a strong linear relationship. The regression analysis is dominated by the data point with the highest concentration of ^{137}Cs and ^{125}Sb. The ^{125}Sb activity concentration for this sample, 50.6 pC g^{-1}, was the highest among soil samples for the Atoll reported in NVO-140. It was more common for scatterplot of fission products to have better correlation on islands that were impacted by fallout from tests, yet did not have a test GZ on the island. Irene had Event Seminole. A similar plot in Figure C-12 is shown for soil sample data from Belle, where the highest activity concentration of ^{125}Sb was 23.5 pC g^{-1}. A scatterplot of the ^{137}Cs to ^{155}Eu for samples collected from the top 15 cm on Irene is in Figure 2-16. The plot has a similar characteristic to Figure 2-15 – a weak linear correlation. The sample with the highest ^{155}Eu, 169 pC g^{-1}, was the highest among surface soil samples for the Atoll reported in NVO-140. The scatterplot of ^{125}Sb to ^{155}Eu shown in Figure C-13 has a linear correlation. It is possible that these fission products behave more similarly in the environment than either of them with ^{137}Cs. Europium is noteworthy for being less mobile than cesium in the environment. Naturally, some of the variability is also related to differences in the fission production rates, e.g., thermal neutron induced fission of ^{239}Pu or ^{235}U, fast neutron induced fission of ^{238}U, and fractionation of the fallout. Figure C-14 contains a scatterplot of ^{137}Cs to ^{155}Eu for surface soil samples on Pearl. Similar to the scatterplot of the same radionuclides for Irene, a good linear correlation did not exist. The regression line shown on the plot has a high y-intercept value. Samples with the higher concentrations have a ^{137}Cs to ^{155}Eu ratio closer to unity, while the lower activity concentrations samples have a much higher ratio. Pearl had GZ for Event Inca.

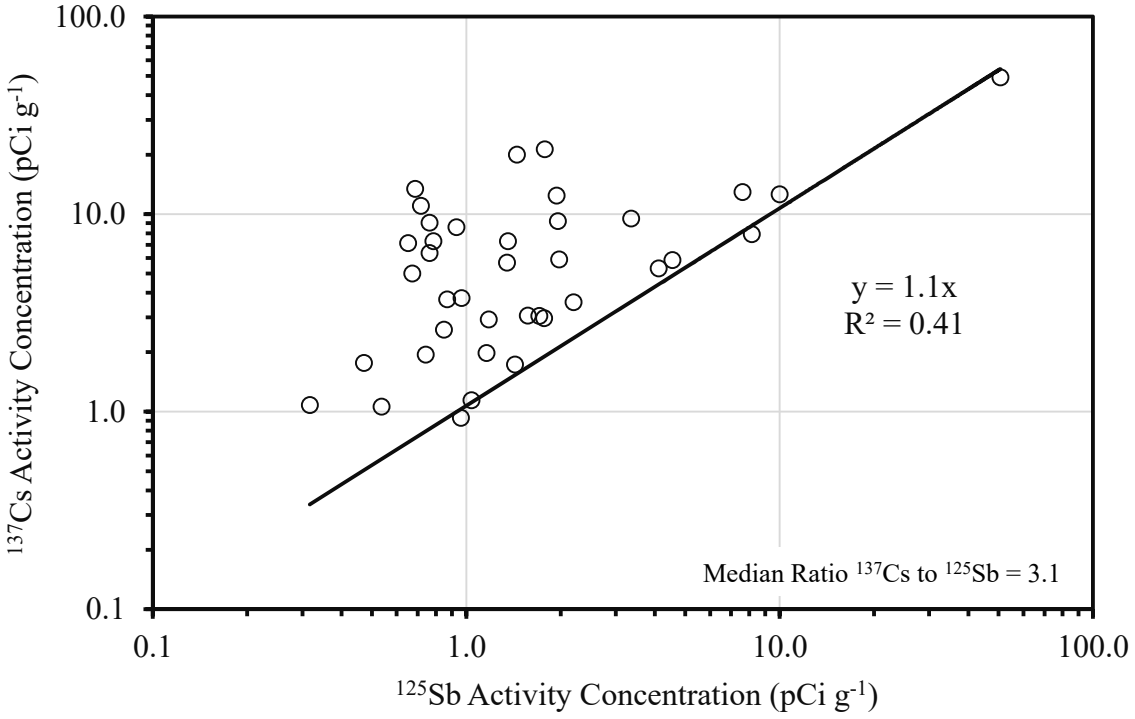


Figure 2-15. Scatterplot of ^{137}Cs to ^{125}Sb for NVO-140 Soil Samples from Top 15 cm on Irene.

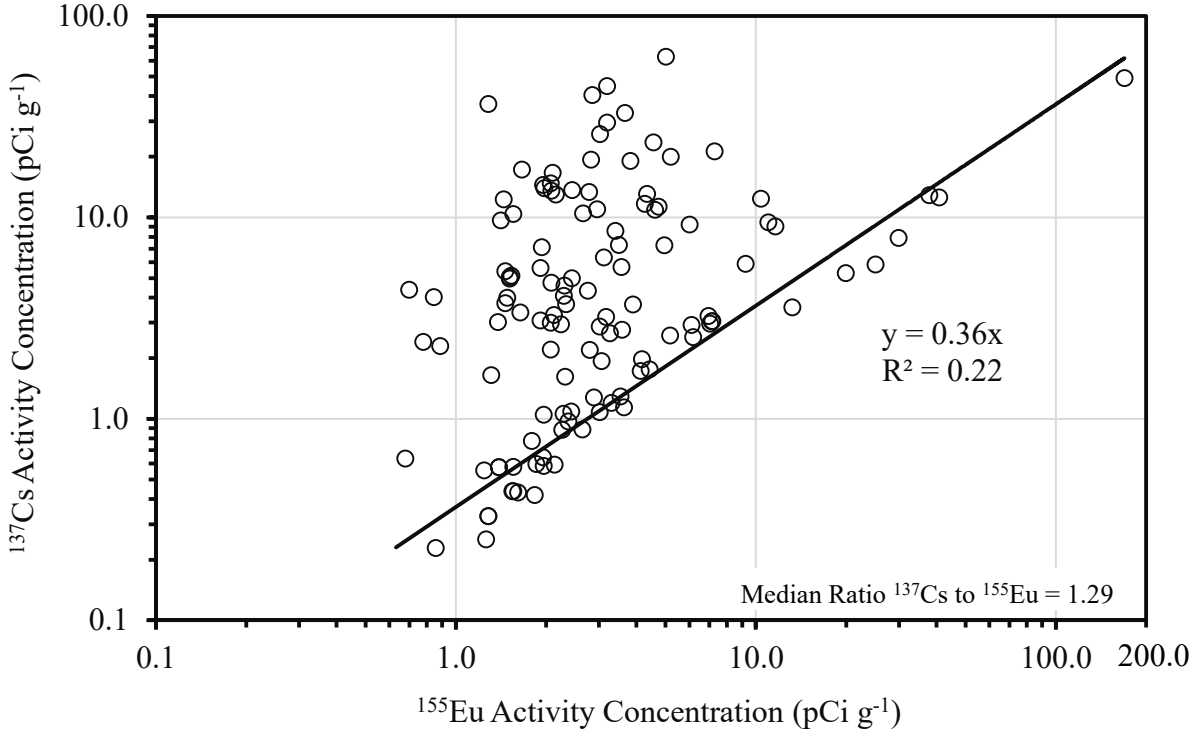


Figure 2-16. Scatterplot of ^{137}Cs to ^{155}Eu for NVO-140 Soil Samples from Top 15 cm on Irene.

2.3.5.4.5 ^{137}Cs to ^{152}Eu

^{152}Eu is produced from neutron activation of ^{151}Eu, which comprises about 48% of the stable element. While the formation of ^{60}Co is primarily due to the neutron activation of ^{59}Co in steel, trace amounts of ^{151}Eu in soils is the source for production of ^{152}Eu. As shown in Table 2-13, for many of the islands, ^{152}Eu was a NDET for all or the vast majority of samples. The exceptions are for Alice, Belle, Clara, Daisy, and Edna due to their proximity detonation of the Mike Device detonation (10.4 MT), and other islands that had GZ for surface or tower tests. The other thermonuclear weapon tests conducted on Enewetak were barge tests, and did not afford the dispersal of coral as was the case of the Mike Device detonation. For these islands, though ^{152}Eu was detected in a reasonable number of samples, the average concentrations in surface soils was much lower than the fission products ^{137}Cs, ^{90}Sr, and ^{155}Eu. Pearl and Ruby had the highest average ^{152}Eu concentrations in surface soil samples (0 – 15 cm), 2.2 and 2.0 pCi g^{-1}, respectively. A scatterplot of ^{137}Cs to ^{152}Eu for surface soil samples from Pearl is in Figure 2-17. The two radionuclides do not have any apparent correlation, which is reasonable considering the differences in the source of contamination. The majority of ^{152}Eu was produced from the in-situ activation of surface soils from the tower shot conducted in the vicinity of the sampling location, while the ^{137}Cs was deposited from fallout from airborne debris clouds. A scatterplot for Clara demonstrates a linear correlation, as both radionuclides are the result of fallout deposition. The average ^{152}Eu concentrations in surface soil samples (0 – 15 cm) on Clara was only 0.59 pCi g^{-1}.

The histogram plots contained in Figures 2-19 and 2-20 for the ^{137}Cs, ^{152}Eu, and ^{155}Eu at sampling locations 100 on Pearl and Belle further illustrate this concept. Belle has a similar deposition fallout deposition pattern to Clara, dominated by the detonation of Event Mike. The ^{137}Cs and ^{155}Eu have similar relationships at each sampling depth for both sampling locations, with each

radionuclide having a similar general reduction in concentration with depth. Whereas, in the case of ^{152}Eu, it is only seen in the top sampling depth profile for Belle, but much more prominent than the ^{137}Cs at all sampling depths at the Pearl sampling location.

2.3.5.4.6 ^{40}K. A reasonably high number of soil samples had positive detection of ^{40}K. Table 2-14 lists the number of samples with positive detects for ^{40}K on the northern islands among a group of other radionuclides with limited detection. ^{40}K is a long-lived, naturally-occurring radioactive material (NORM) that is present to a varying degree in rocks, as summarized in Table 2-15 for the primary NORM radionuclides found in rock. Coral-based soil is noteworthy for having low concentrations of ^{40}K, as compared to common surface soils that are derived from the rock types listed in Table 2-15. NVO-140 (p. 438) notes that the origin of the ^{40}K in the soils is not related to the weapons tests (AEC 1973). However, in our review of the soil sampling data, positive detections of the radionuclide were more common in soil samples from the northern islands of the atoll than those from the southern portion. It is suspected that the ^{40}K is from a combination of both pre-existing natural sources and neutron activation of ^{39}K in soils. Nevertheless, the average concentrations in surface soils is much less than those typical to CONUS soils.

2.3.5.4.7 ^{65}Zn. Only one soil sample collected on the northern islands of the Atoll (Irene) had a positive detect for ^{65}Zn. Due its short radiological half-life, 244 days, its presence is likely due to Chinese tests conducted in the early 1970s.

2.3.5.4.8 ^{101}Rh. Only detected in 18 soil samples from northern islands of the Atoll, as listed in Table 2-14. Among these samples, the activity concentration was negligible to the concentrations of other fission products detected in samples.

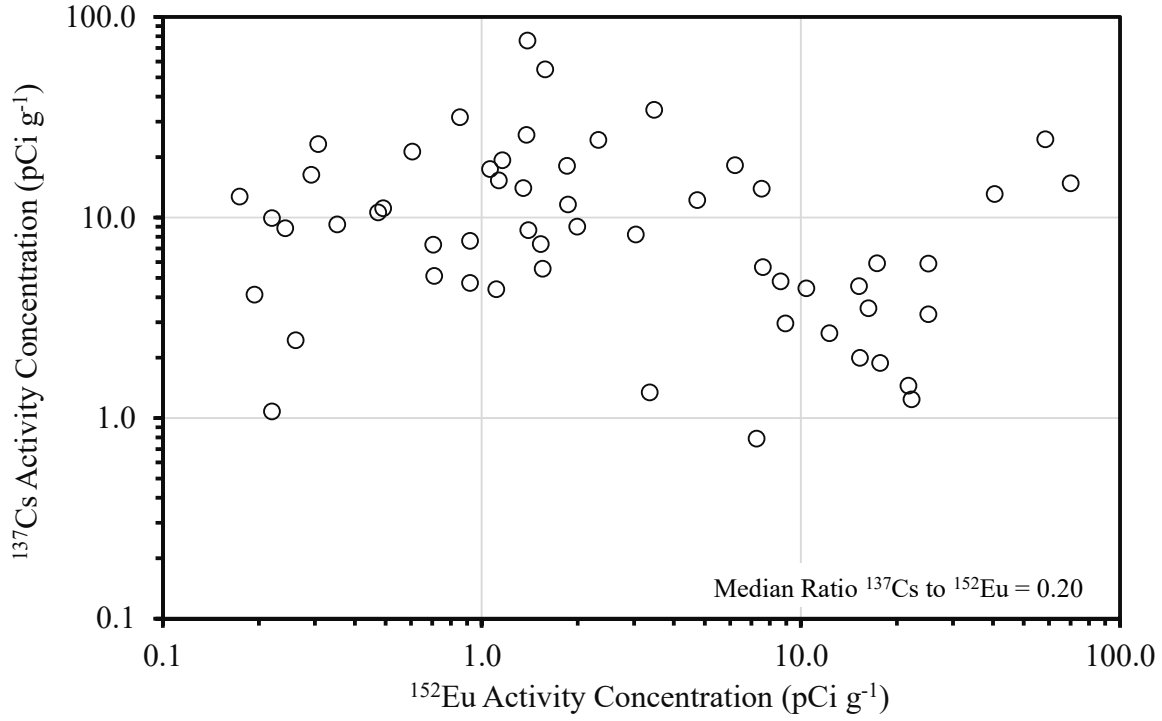


Figure 2-17. Scatterplot of ^{137}Cs to ^{152}Eu for NVO-140 Soil Samples from Top 15 cm on Pearl.

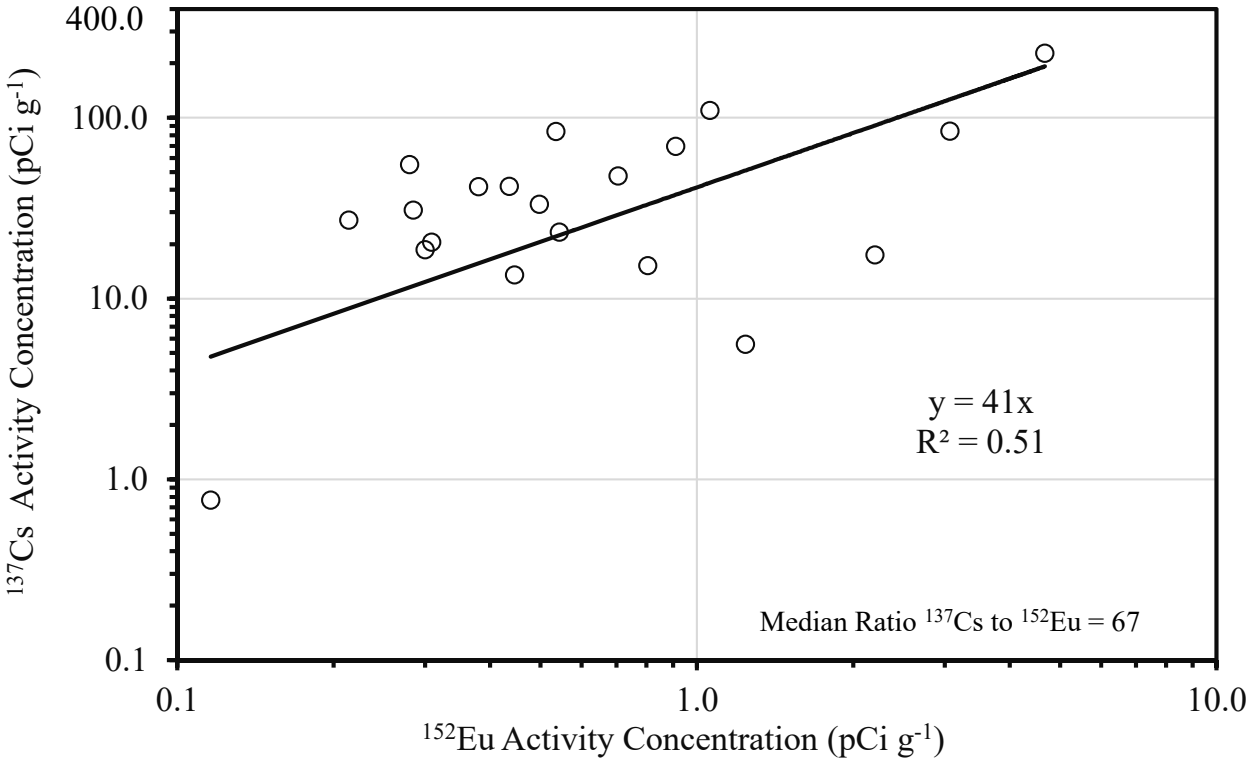


Figure 2-18. Scatterplot of ^{137}Cs to ^{152}Eu for NVO-140 Soil Samples from Top 15 cm on Clara.

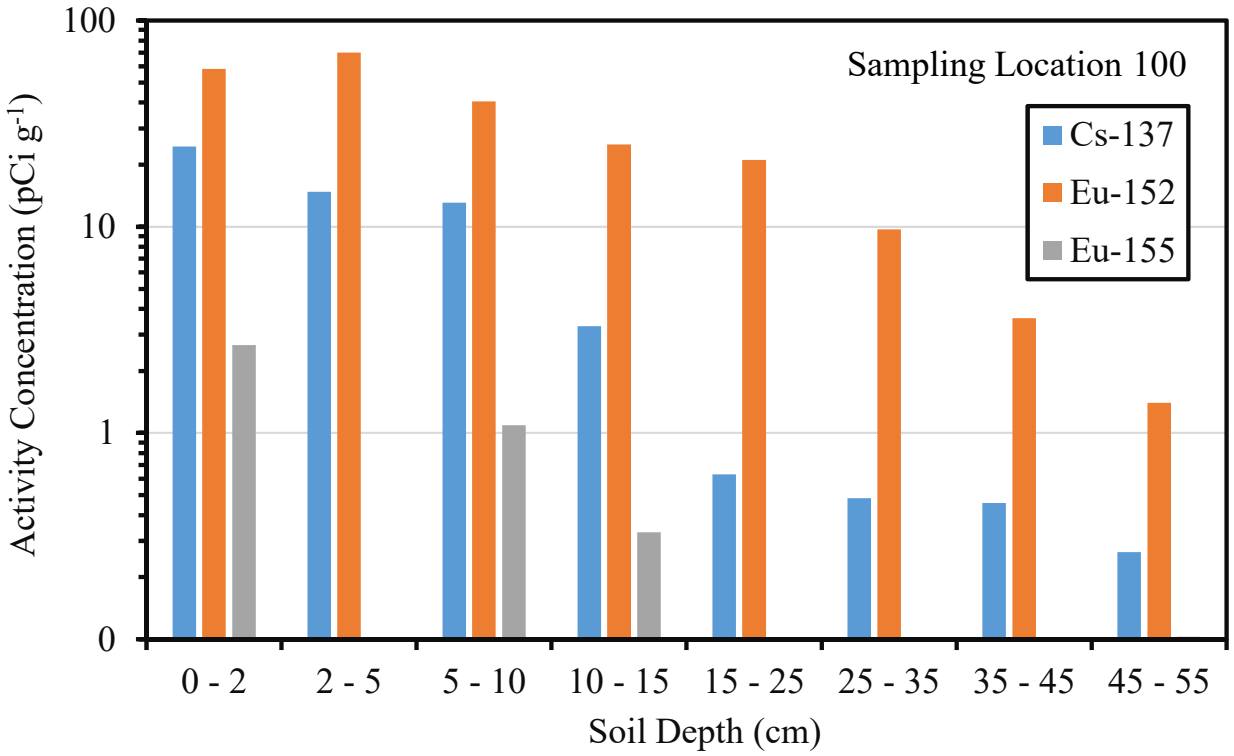


Figure 2-19. Histogram of ^{137}Cs, ^{152}Eu, and ^{155}Eu Concentrations at Depth for Sampling Location 100 on Pearl.

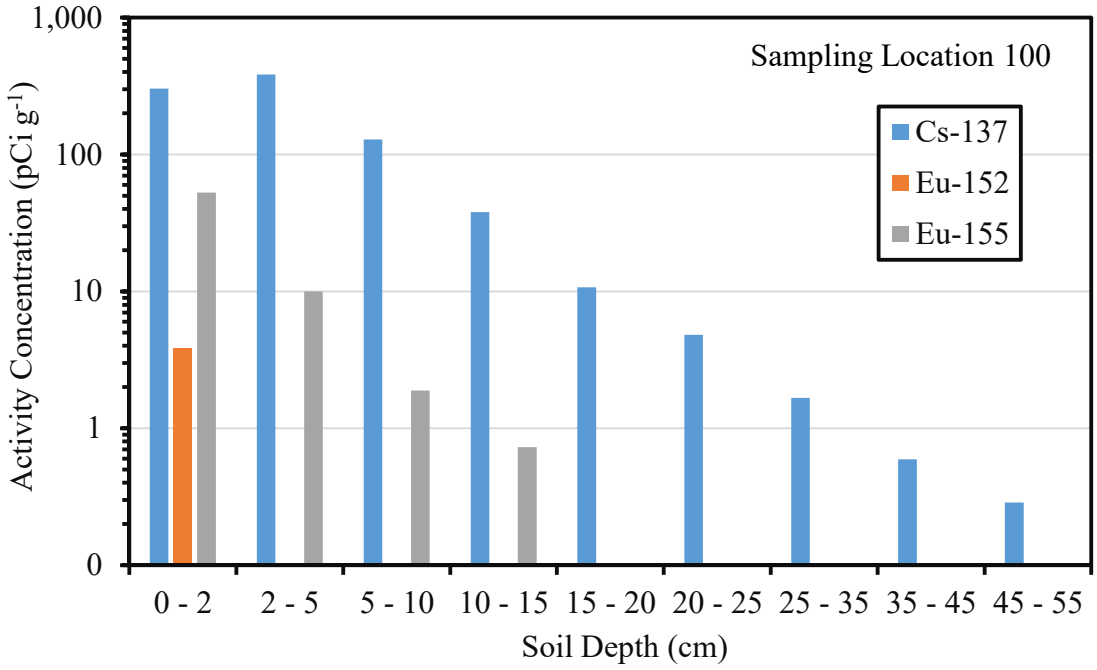


Figure 2-20. Histogram of ^{137}Cs, ^{152}Eu, and ^{155}Eu Concentrations at Depth for Sampling Location 100 on Belle.

2.3.5.4.9 ^{134}Cs. ^{134}Cs was only detected in four soils samples from northern islands of the Atoll, as listed in Table 2-14. This radionuclide is produced in very low abundance compared to ^{137}Cs as a fission product in nuclear reactors and nuclear detonations. As a nuclear reactor effluent, its presence is dominated by its production via neutron activation of stable ^{133}Cs. Due to its 2.05 year radiological half-life, its presence in soil samples is due to French and/or Chinese tests conducted in the early 1970s. This radionuclide was also detected in a soil sample from each of two southern islands in the Atoll. Among these samples, the activity concentration was negligible compared to the concentrations of other fission products detected in samples.

2.3.5.4.10 ^{133}Ba. Thirty-five samples from the northern islands had detectable levels of ^{133}Ba, spread among samples from Janet, Pearl, Sally, and Yvonne. The production of ^{133}Ba is from neutron activation of trace amounts of ^{132}Ba in soils. As such, due to the limited detection among samples, it was only observed in a small number of samples from islands that had tests conducted on towers. Since the samples were found within close proximity to the location of tower tests, the contaminant was likely produced in-situ, with little disturbance between the time of the test and sample collection. For the island with the highest number of samples having positive detections (n = 13), Sally, there was good correlation between ^{133}Ba and ^{152}Eu on an activity basis. The relationship, however, was not linear across the range of activity concentrations. Figure 2-21 show a scatterplot of the activity concentrations for samples with positive detections for both radionuclides. The median ratio of ^{133}Ba to ^{152}Eu among the samples was 0.021. For a plot of similar data for Pearl, as contained in Figure 2-22, the relationship between the two radionuclides is not well correlated as was the case for data from Sally. As noted in Table 2-14, a sample collected from Pearl had the highest activity concentration for this radionuclide among samples with positive detections, 46 pCi g^{-1}. The activity concentration of ^{133}Ba in this sample is somewhat high, compared to the ^{152}Eu activity concentration, and the range of ^{133}Ba activity concentration levels

observed in other samples with positive detects for ^{133}Ba. For Yvonne, there was an excellent linear relationship between ^{133}Ba and ^{152}Eu, as displayed in Figure 2-23. For Janet, the activity concentrations of the ^{133}Ba was so low among the eight samples with positive detects (0.08 – 0.98 pCi g^{-1}) such that a meaningful relationship with ^{152}Eu was difficult to establish.

2.3.5.4.11 ^{144}Ce. This radionuclide was detected in only three soil samples from those collected from the northern islands of the Atoll. As listed in Table 2-14, the activity concentrations ranged from 0.70 to 0.92 pCi g^{-1}. Due to its 280 d radiological half-life, this radionuclide would have underwent over six half-lives between the radiological sampling conducted by the AEC in the preparation of NVO-140 and the work conducted between 1977 and 1980. As such, the activity concentrations of this radionuclide would have been about 100-fold lower than reported in NVO-140 during the cleanup period covered by this report. This radionuclide is considered for exposures to personnel working on southern islands between 1959 and 1973.

2.3.5.4.12 ^{154}Eu. Similar to the production of ^{152}Eu, ^{154}Eu is produced by neutron activation of ^{153}Eu, which comprises about 52% of the stable element. The thermal neutron absorption cross-section for the production of ^{152}Eu is about 17-fold higher than that of ^{154}Eu. As well, the radiological half-life of ^{154}Eu is only 8.8 y, while 13.6 y for ^{152}Eu. Similar to the analysis of ^{152}Eu, ^{154}Eu was observed in a small fraction of the samples for islands in proximity to the Mike Device detonation (Alice, Belle, Clara, and Daisy), and other islands that had GZ for surface or tower tests. For the islands with GZ's, Yvonne, Sally, and Pearl had enough positive detects for ^{152}Eu and ^{154}Eu on each island to evaluate their relationship. Figure 2-24 contains a scatterplot of the ^{154}Eu to ^{152}Eu activity concentrations among samples from Pearl that had positive detections of each radionuclide. The ^{154}Eu is only about seven to eight percent of the ^{152}Eu on an activity basis,

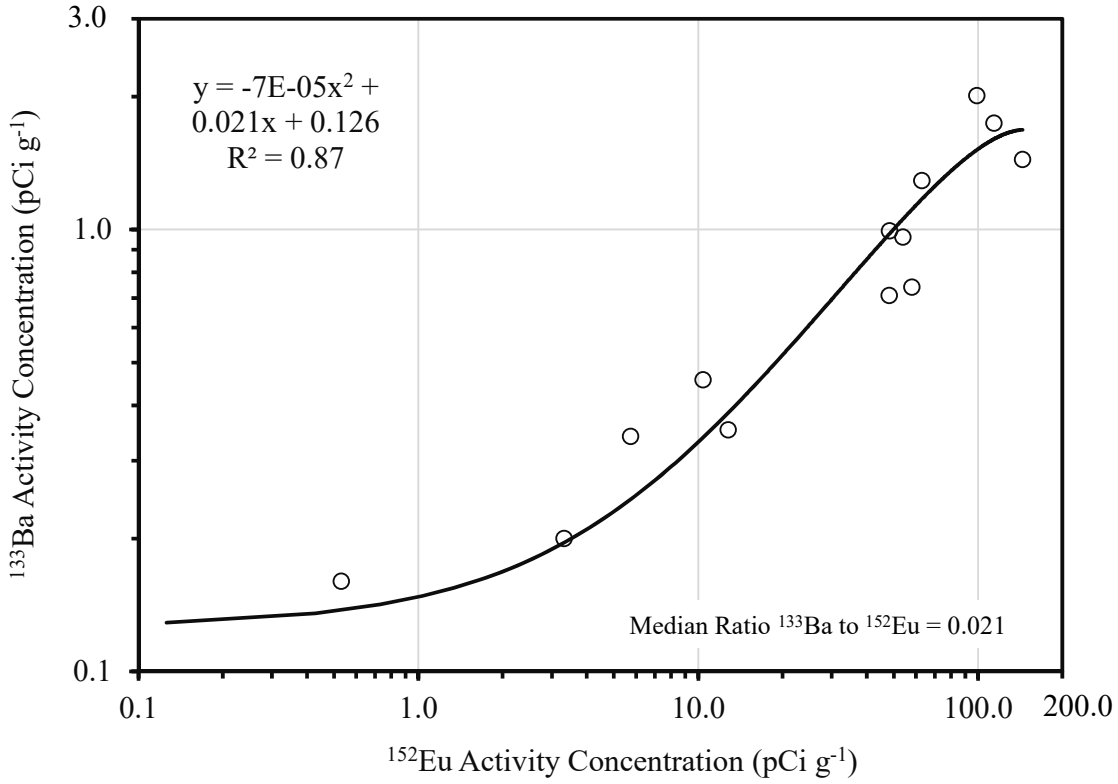


Figure 2-21. Scatterplot of ^{133}Ba to ^{152}Eu for NVO-140 Soil Samples on Sally.

Table 2-14. Other Radionuclide Detected in Northern Island Soils.

Island	Parameters for Samples	Radionuclide Detected									
		K-40	Zn-65	Rh-101	Cs-134	Ba-133	Ce-144	Eu-154	Ra-226	Th-228	U-235
Alice	No. Samples with Detect	9	0	1	0	0	0	7	8	0	10
	Max Conc (pCi g^{-1})	5.0	NA	0.23	NA	NA	NA	0.44	0.1	NA	0.091
Belle	No. Samples with Detect	4	0	1	1	0	1	14	1	0	2
	Max Conc (pCi g^{-1})	2.0	NA	0.14	0.21	NA	0.72	0.76	0.2	NA	0.078
Clara	No. Samples with Detect	5	0	2	0	0	0	4	1	0	1
	Max Conc (pCi g^{-1})	1.4	NA	0.23	NA	NA	NA	0.69	0.02	NA	0.027
Daisy	No. Samples with Detect	7	0	5	0	0	0	2	5	0	6
	Max Conc (pCi g^{-1})	1.70	NA	0.30	NA	NA	NA	0.74	0.17	NA	0.25
Edna	No. Samples with Detect	0	0	0	0	0	0	0	5	0	2
	Max Conc (pCi g^{-1})	NA	NA	NA	NA	NA	NA	NA	0.12	NA	0.06
Irene	No. Samples with Detect	11	1	1	0	0	0	8	2	0	4
	Max Conc (pCi g^{-1})	2.0	2.7	0.07	1	NA	NA	2.3	0.02	NA	0.04
Janet	No. Samples with Detect	21	0	3	0.14	8	0	5	5	0	14
	Max Conc (pCi g^{-1})	2.6	NA	0.12	NA	0.98	NA	0.56	0.05	NA	0.30
Kate	No. Samples with Detect	8	0	1	0	0	0	0	1	0	1
	Max Conc (pCi g^{-1})	7.4	NA	0.10	NA	NA	NA	NA	1.6	NA	0.12
Lucy	No. Samples with Detect	6	0	0	0	0	0	0	2	0	4
	Max Conc (pCi g^{-1})	1.4	NA	NA	2	NA	NA	NA	0.02	NA	0.04
Mary	No. Samples with Detect	0	0	0	0.13	0	0	0	0	0	1
	Max Conc (pCi g^{-1})	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.03
Nancy	No. Samples with Detect	1	0	0	0	0	0	0	0	0	0
	Max Conc (pCi g^{-1})	2.1	NA	NA	NA	NA	NA	NA	NA	NA	NA
Olive	No. Samples with Detect	3	0	0	0	0	0	0	4	0	5
	Max Conc (pCi g^{-1})	1.7	NA	NA	NA	NA	NA	NA	0.03	NA	0.06
Pearl	No. Samples with Detect	7	0	1	0	6	0	26	0	0	1
	Max Conc (pCi g^{-1})	2.2	NA	0.36	NA	46	NA	7.1	NA	NA	0.10
Percy Daugh	No. Samples with Detect	0	0	0	0	0	0	0	1	0	3
	Max Conc (pCi g^{-1})	NA	NA	NA	NA	NA	NA	NA	0.02	NA	0.03

Table 2-14. Other Radionuclide Detected in Northern Island Soils, continued.

Island	Parameters for Samples	Radionuclide Detected									
		K-40	Zn-65	Rh-101	Cs-134	Ba-133	Ce-144	Eu-154	Ra-226	Th-228	U-235
Ruby	No. Samples with Detect	0	0	0	0	0	0	0	0	0	0
	Max Conc (pCi g^{-1})	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sally	No. Samples with Detect	4	0	0	0	13	0	12	0	0	4
	Max Conc (pCi g^{-1})	3.0	NA	NA	NA	2.0	NA	9.6	NA	NA	0.075
Tilda	No. Samples with Detect	1	0	1	0	0	0	0	0	0	1
	Max Conc (pCi g^{-1})	1.8	NA	0.03	NA	NA	NA	NA	NA	NA	0.03
Ursula	No. Samples with Detect	2	0	0	0	0	1	0	0	0	2
	Max Conc (pCi g^{-1})	1.6	NA	NA	NA	NA	0.7	NA	NA	NA	0.019
Vera	No. Samples with Detect	4	0	0	0	0	1	0	1	0	4
	Max Conc (pCi g^{-1})	2.2	NA	NA	NA	NA	0.92	NA	0.03	NA	0.090
Wilma	No. Samples with Detect	2	0	0	0	0	0	0	1	0	5
	Max Conc (pCi g^{-1})	1.7	NA	NA	NA	NA	NA	NA	0.03	NA	0.050
Yvonne	No. Samples with Detect	33	0	2	0	8	0	25	19[1]	32[2]	24[1]
	Max Conc (pCi g^{-1})	2.4	NA	0.77	NA	0.46	NA	5.5	0.054	13	0.064

[1] Primarily samples from Test Quince and Fig GZ [2]Samples from northern portion of island

Table 2-15. Average Radium, Uranium, Thorium, and Potassium Contents in Various Rocks [from Eisenbud (1987)].

Rock Type	Activity Concentration (pCi g^{-1})			
	^{226}Ra	^{238}U	^{232}Th	^{40}K
Igneous	1.3	1.3	1.3	22
Sandstones	0.71	0.4	0.65	8.8
Shales	1.08	0.4	1.1	22
Limestones	0.42	0.4	0.14	2.2

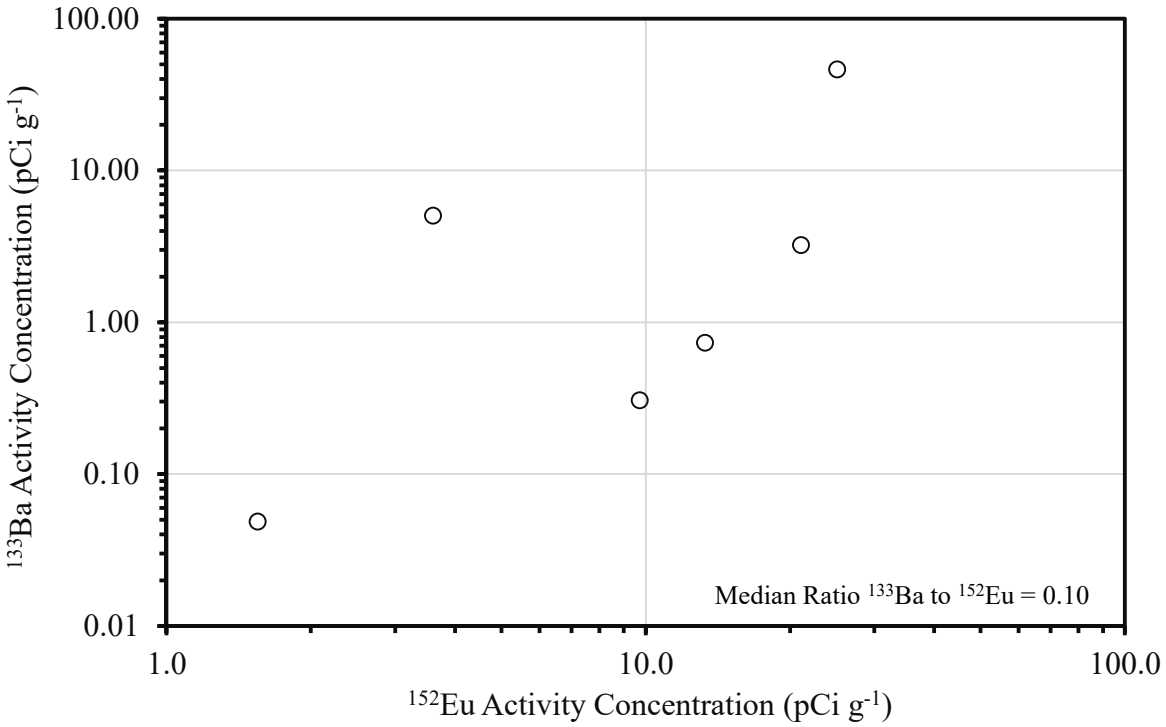


Figure 2-22. Scatterplot of ^{133}Ba to ^{152}Eu for NVO-140 Soil Samples on Pearl.

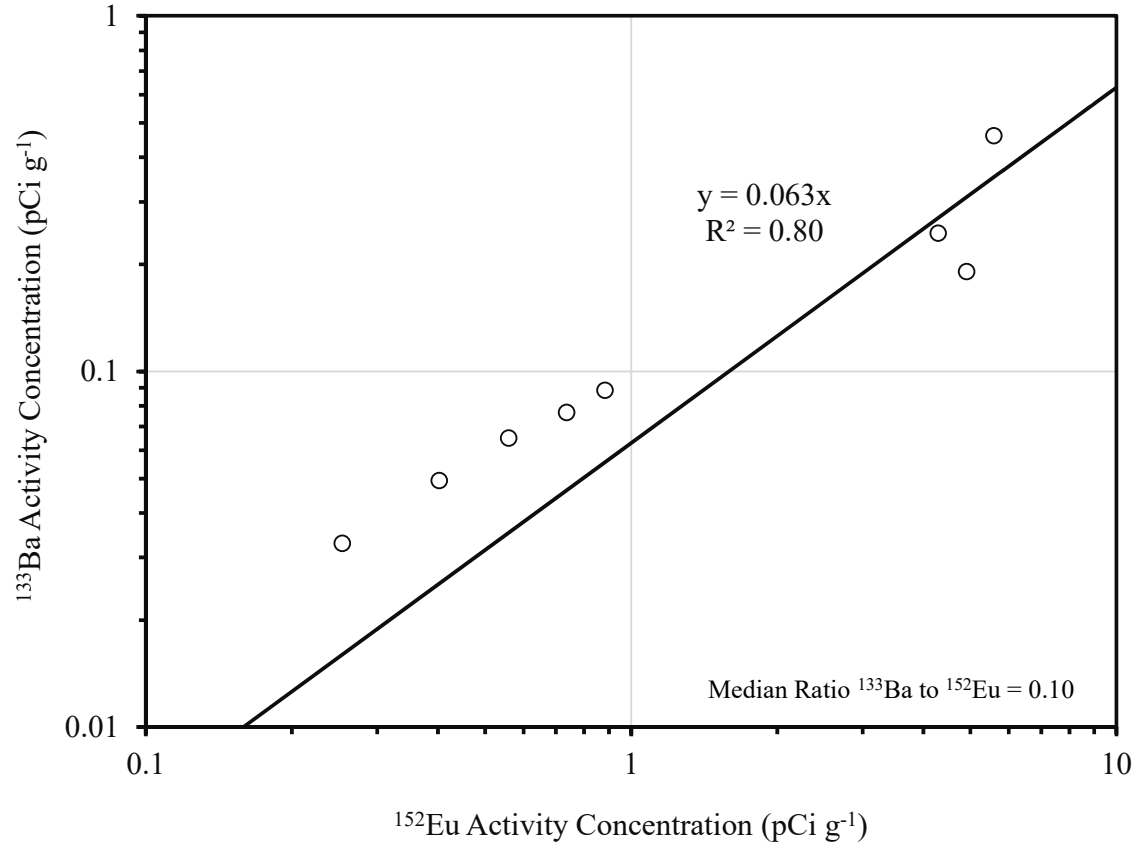


Figure 2-23. Scatterplot of ^{133}Ba to ^{152}Eu for NVO-140 Soil Samples on Yvonne.

dependent on use of the slope of the regression analysis or the median value. Similar findings existed for evaluation of these isotopes on Yvonne and Sally. The activity concentrations of the samples with positive detects for ^{154}Eu on Janet and Irene were fairly low, as compared to those on Yvonne, Sally, and Pearl. As a result, a regression analysis of ^{154}Eu against ^{152}Eu did not provide good insight into the relationship between these radionuclides. Similarly, the activity concentrations of the samples with positive detects for ^{154}Eu on Alice, Belle, Clara, and Daisy were low. For these islands, the mean ^{154}Eu in surface soils was substantially lower than the mean ^{152}Eu, and deemed of negligible significance. A similar relationship between the ^{154}Eu and the ^{152}Eu likely exists on these islands, but due to the low activity concentrations of ^{154}Eu, it was not possible to demonstrate through regression analysis the relationship, as was done for Yvonne, Sally, and Pearl.

2.3.4.4.13 ^{226}Ra. ^{226}Ra is a naturally-occurring radioactive material in the ^{238}U decay chain. ^{238}U has a radiological half-life of 4.5×10^9 y, whereas that of ^{226}Ra is 1,600 y. As noted in Table 2-14, ^{226}Ra was detected in numerous soil samples on the northern islands of the Atoll. Similarly, it was also observed in soil samples on the southern islands of the Atoll. Coral-based soil is noteworthy for having low concentrations of ^{226}Ra, as compared to common surface soils that are derived from the rock types listed in Table 2-15. This is clearly demonstrated in the relatively low activity concentrations of ^{226}Ra detected in the soil samples. Yvonne had an unusually high number of samples with positive detects for ^{226}Ra, as compared to other islands. As noted in Table 2-14, these were primarily in the Test Quince and Fig GZ area. This artifact is likely due to the importation of 130 tons of soil from the Nevada Test Site (NTS) and its emplacement in a conical plug beneath the GZ planned for Event Fig (Gladeck et al. 1982). While the imported soil would have had mean ^{226}Ra concentrations substantially higher than the coral-based soil on Enewetak, its dispersal by the Fig detonation would have caused some dilution, with the end result

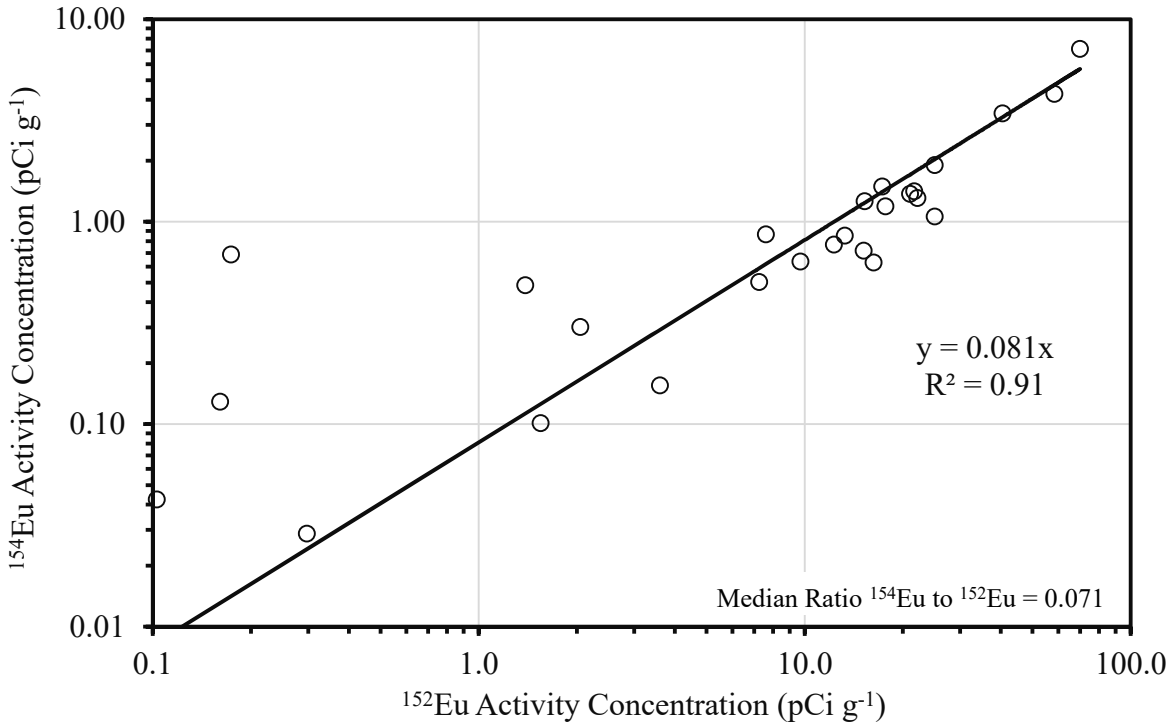


Figure 2-24. Scatterplot of ^{154}Eu to ^{152}Eu for NVO-140 Soil Samples on Pearl.

of soils in this area having average ^{226}Ra activity concentrations higher than other parts of the Atoll, yet well below the undiluted concentration of ^{226}Ra in the NTS soil.

2.3.5.4.14 ^{228}Th, ^{230}Th, and ^{232}Th.

^{228}Th is a naturally-occurring radioactive material in the ^{232}Th decay chain. ^{232}Th has a radiological half-life of 1.4×10^{10} y, whereas that of ^{228}Th is 1.9 y. Coral-based soil is noteworthy for having low concentrations of ^{232}Th (and subsequently also ^{228}Th), as compared to common surface soils that are derived from the rock types listed in Table 2-15. In the Lawrence Livermore Laboratory (LLL) γ-spectrometry analysis of samples, the spectral analysis library only included photon emission lines from ^{228}Th and its decay-chain progeny [Table 111 (AEC 1973)]. Therefore, it is not possible to determine definitively if the ^{228}Th is in equilibrium with ^{232}Th, though this is reasonable for natural sources of thorium in soil and rock. Lawrence Livermore National Laboratory (LLNL) more recently evaluated impacts to the Bikini and Enewetak Atolls from tracer elements (Robison et al. 2001). This was noted above under the practice of "salting" weapons being tested for the purpose of better assessment of weapon performance. Based on information provided by the DOE, Robison et al. (2001) reported the mass of materials associated with the 67 tests at Enewetak and Bikini. A copy of Table 1 from this report is displayed in Table C-7, modified with calculated radioactivity levels. Although ^{228}Th has an activity level about 16-fold higher than ^{232}Th, assumed at time of use in testing, due to the interceding period of time between testing and soil sampling in 1972 for preparation of NVO-140, the activities of the two radionuclides would be almost equal. Figure C-15 provides a plot of ^{232}Th activity concentrations and other daughters after chemical purification for thorium from a potential source, e.g., likely uranium- or thorium-rich ores. ^{228}Th was only detected in samples collected from the northern part of Yvonne, and distinctly north of the Test Quince and Fig GZ which exhibited a number of positive detects for ^{226}Ra. Due to these facts, the ^{228}Th is likely related to testing rather than from a natural environmental source. Among the 32 samples with positive detects for ^{228}Th, the highest concentration was 13.1 pCi g^{-1} [sampling location number 143, sampling depth 10 – 20 cm]. Among the seven sampling locations designated in this report for segment A of Yvonne [sampling locations 140 – 146, see Figure C-6], the mean ^{228}Th concentration was 3.3 pCi g^{-1} for samples in the top 10 cm, while for segment A/B of Yvonne [sampling locations 134 – 139, see Figure C-6 and C-7] it was only 0.9 pCi g^{-1}. In comparison, igneous and shale rock types have mean concentrations of 1.3 and 1.1 pCi g^{-1}.

Of particular interest with respect to thorium are activity concentrations of ^{230}Th in soils. This isotope of thorium is within the decay chain of ^{238}U and has a half-life of 77,000 y. ^{230}Th undergoes α-particle decay to ^{226}Ra, but since it has negligible photon emissions, it is usually quantified in soils by chemical separation and α-spectrometry. ^{230}Th analysis was not performed on samples analyzed by the AEC for its 1973 report. The total activity of ^{230}Th involved with tests at Enewetak and Bikini was about 30% higher than the ^{238}U activity, based on data from Robison et al. (2001), whom believed that detonations would disperse thorium, ^{238}U, and ^{233}U diffusely to the environment. One question not answered by Robison et al. (2001) was the relationship among the isotopes of thorium. Was the ^{230}Th integral to the other isotopes of thorium in its use in tests, and consistent in isotopic fractions? If this was the case, one would be inclined to assume that the mean ^{230}Th in surface soils in segment A/B was 252-fold higher than the ^{232}Th (assumed to be equal activity concentration to the ^{228}Th in 1973). Under this assumption, the ^{230}Th would be estimated at 830 pCi g^{-1} for surface soils in segment A/B of Yvonne. The activity concentration is much higher than the $^{239+240}$Pu for segments A, A/B, and B of Yvonne: 31, 34, and 140 pCi g^{-1}, respectfully. If this is the case, ^{230}Th would need assessment as a radiological contaminant of concern.

Contrary to this interpretation, it is possible that the DOE estimates of ^{228}Th and ^{230}Th masses were mistakenly calculated, as listed Table 1 of Robison et al. (2001). Credence to this conclusion is drawn from the equally unusual observation of a high ^{228}Th to ^{232}Th activity concentration ratio, ~ 16:1. ^{228}Th is normally in secular equilibrium with ^{232}Th in soils, and thorium- and uranium-rich ores. This is due to the short radiological half-lives of ^{228}Ra (6.7 y) and ^{228}Ac (6.1 h), β-particle emitters preceding ^{230}Th in the ^{232}Th decay chain. As noted above and displayed in Figure C-15, shortly after chemical separation of thorium from any of these sources, the ^{228}Th will be depleted compared to the ^{232}Th on an activity basis, but will recover to near equilibrium conditions after about 20 y. The production of material with ^{228}Th about 16-fold higher than ^{232}Th is unusual. It suggests that the majority of ^{228}Th was introduced independent of the ^{232}Th. Pure ^{228}Th could have been extracted from a radium source, which would normally contain ^{228}Ra and ^{226}Ra, and ingrowth of ^{228}Th from the ^{228}Ra decay, but no ^{232}Th. An industrial-scale isotopic separation of the isotopes of thorium in the 1950's is not known to the author of this report. Another method for the production of ^{228}Th is through neutron bombardment of ^{226}Ra, which had been conducted on a small-scale at Mound Laboratory in the mid-1950's when ^{227}Ac was contemplated for use as a neutron initiator (DOE 1992) and in the later 1950's when a variety of radionuclides were considered for heat sources on space platforms (Hanford 1959). In the case of ^{228}Th use as an initiator, there would not have been any ^{232}Th or ^{230}Th, unless thorium metal was used for another purpose in a test.

Thorium metals used in testing on Bikini and Enewetak would have some ^{230}Th co-contaminant, as a metal derived from thorium- and/or uranium-rich ores. If derived from thorium-rich ores, the ^{230}Th activity will typically be equivalent or less than the ^{232}Th activity, dependent on the relative content of ^{232}Th and ^{238}U in the ore. On the other hand, mill tailings from the extraction of uranium from uranium-rich ores will have ^{230}Th activity much higher than the ^{232}Th, perhaps 10 to 15-fold higher, dependent on the ore. Either of these sources were viable during the early 1950's. In the mid-1950's Mound Laboratory studied the refining process for Brazilian Monazite sludge (a thorium-rich ore, which also contains ^{238}U and its decay progency) during a period when the US contemplated the use of thorium in breeder reactors designed to produce ^{233}U.

Another plausible explanation is that the ^{230}Th is a co-contaminant with ^{238}U. In most ore sources of ^{238}U, ^{230}Th will be in equilibrium with the ^{238}U, on an activity basis, though only about 17 parts per million on a mass (ppm) basis. Some chemical separation processing methods designed to extract uranium metals from ore may not exclude thorium from the extraction, essentially leaving the ^{230}Th in near equilibrium concentration with ^{238}U. In review of Table C-7, the total ^{230}Th activity is a little higher than the ^{238}U, lending support to this explanation as one source of the ^{230}Th. Thus, the positive detects for ^{228}Th on Yvonne may be unrelated to a large fraction of the ^{230}Th. Overall, due to the discussions above, it is reasonable to assume that in 1972, the ^{228}Th detected on Yvonne was in near equilibrium with ^{232}Th, and the ^{230}Th in this area of Yvonne was likely on par with ^{232}Th or less if derived from thorium-rich ore, or up to 15-fold higher if derived from uranium-rich ore. As well, for every α-particle decay of ^{232}Th, five other α-particles are emitted by daughters in the chain (in secular equilibrium). For the purposes of this report, it is assumed that the ^{230}Th is 10-fold higher than the ^{232}Th. This is a relatively conservative balance between the two potential extreme cases. This relationship could be modified if better information becomes available.

2.3.5.4.15 ^{235}U and ^{234}U.

The concentrations of naturally-occurring uranium in coral from global locations have been summarized by Robison et al. (2001). The largest constituent of naturally-occurring uranium is ^{238}U (see Table 2-4) Natural uranium in soils have a ^{238}U to ^{235}U activity concentration ratio of 21.7.

Table C-8 contains a listing of referenced ^{238}U concentrations in coral from the work of Robison et al. (2001) and previous researchers. As discussed above, uranium metal incorporated into weapons contained varied compositions of ^{238}U and ^{235}U, with ^{234}U having a negligible mass fraction. On an activity basis, however, ^{234}U contributes to total α-particle emission rates ranging from about 15 to 97%, dependent on the uranium composition (see Tables 2-3 to 2-5). The analytical methods implemented in evaluation of soil samples for preparation of NVO-140 only targeted the ^{235}U. A number of soil samples collected from the northern island of the Atoll had positive detects for ^{235}U, as summarized in Table 2-14 by number of sample per island and the maximum concentration. A number of soils samples from the southern islands also had positive detects for ^{235}U, though the maximum concentrations per island were not as high as those observed in some samples from the northern island. Yvonne had an unusually large number of positive detects, especially within the Fig/Quince test area. Similar to the unusually high number of positive detects for ^{226}Ra in this area, some of the ^{235}U is likely due to NTS soils brought into this area. The ^{235}U content for an individual sample is comprised of that from natural sources (pre-atmospheric testing), and global, regional, and local fallout from atmospheric tests. The southern islands of the Atoll are expected to have to have contributions primarily from natural sources with lesser contributions from fallout sources. Northern islands of the Atoll are expected to have a greater contribution from fallout source, though it is difficult to precisely assess the relative contributions to the average concentrations in surface soils due to the generally low concentrations of ^{235}U in samples, and lack of paired analysis of ^{238}U. Due to the generally low activity concentrations of ^{235}U in soils, modelled doses to individuals occupying areas contaminated from this radionuclide are negligible. Interest in this radionuclide for this report is based on its use in predicting ^{234}U activity concentrations, which under some weapons testing scenarios described above can be about 50-fold higher than the ^{235}U in fallout debris (see Table 2-7).

Concentration of ^{238}U in coral analysis summaries listed in Table C-8 ranged from 1.4 to 3.9 $\mu g\ g^{-1}$ (0.47 – 1.3 pCi g^{-1}). Robison et al. (2001) noted that ^{238}U concentrations in soils of the northern islands of the Marshall Islands were indiscriminate from concentrations in southern islands. Overall, the authors concluded that atmospheric testing of nuclear weapons had no discernable impact on activity concentration of ^{238}U in surface soils on islands in the Marshall Islands. The average ^{238}U among the 1,375 soil samples collected and analyzed by Robison et al. (2001) was 1.8 $\mu g\ g^{-1}$ (0.59 Ci g^{-1}). As such, under the assumption that ^{235}U is assimilated and retained in coral in a similar manner to ^{238}U, the average ^{235}U in Enewetak soil from natural sources is 0.027 pCi g^{-1}.

Among the samples with positive detects from the northern islands, only a small handful of samples were notable for being substantially higher than the expected mean from natural sources of 0.027 pCi g^{-1}. A sample from Janet had the highest activity concentration among the samples with positive detects for ^{235}U, 0.3 pCi g^{-1}, about 11-fold higher than the expected mean from a natural source. Among the other thirteen samples from Janet with positive detects, the next highest was only 0.06 pCi g^{-1}, with others ranging between 0.02 and 0.05 pCi g^{-1}. The sample with the highest activity concentration was a surface sample, while a large fraction of the other positive detects were from depth, and had concentrations on par with those samples with positive detects for ^{235}U, as collected on Midway and Ujelang Island, with results for ^{235}U in Table C-9. These islands were chosen as background sampling islands in preparation of NVO-140. The sample with the second highest detected activity concentration was from Daisy, with ^{235}U at 0.25 pCi g^{-1}. Among the other five, the next highest was 0.09 pCi g^{-1}, while the other four ranged between 0.028 and 0.047 pCi g^{-1}. Only one positive detect for ^{235}U was observed each on Kate and Pearl, with activity concentrations of 0.12 and 0.10 pCi g^{-1}, respectively. The sample with the highest ^{235}U from Alice was 0.091 pCi g^{-1}, though the other nine with positive detects ranged between 0.030 and 0.048 pCi g^{-1}. Overall, samples with the highest concentration of ^{235}U observed in samples from the northern

islands of the Atoll were from the surface, and of activity concentration greater than activity concentrations for samples with positive detects from southern islands of the Atoll. Among the 389 samples (surface and profile sampling locations) for David, Elmer, and Fred in the southern part of the Atoll, 86 samples (22%) had positive detects for ^{235}U, with the highest having an activity concentration of 0.11 pCi g^{-1}.

Average concentrations of ^{235}U in surface soils are difficult to accurately estimate due to the limited number of positive detects, which makes it difficult to correlate with other radionuclides detected in a large fraction of the samples. Overall, the northern islands of the Atoll had higher ^{235}U concentrations among samples with the highest ^{235}U concentrations compared to a similar group of samples collected from southern islands[8]. While this observation alone is insufficient to demonstrate statistically that the northern islands of the Atoll have a higher average ^{235}U concentrations than the southern islands, it does qualitatively lend support to this conclusion, and is reasonable considering the fallout pattern dominating northern islands vice that on the southern part. From professional judgement, the mean concentration of ^{235}U in the northern islands of the Atoll are perhaps at most 50% higher than that on the southern islands, $\leq$ 0.041 pCi g^{-1}. Table 2-16 lists estimated concentrations of uranium isotopes for different location/condition. The first row is based on an estimate of concentrations in natural background, while the second row is an estimate of the maximum average on the northern islands of Enewetak Atoll. As noted, the excess ^{234}U is conservatively assumed to be 49.5-fold higher than the ^{235}U, based on a 30% burn of fissile uranium (Table 2-7). The same calculation method was applied to the soil sample with the highest ^{235}U, observed on Janet, with estimated isotopic activities in row three of the Table. For this sample, the estimated total uranium activity concentration is 15 pCi g^{-1}.

Table 2-16. Estimated Activity Concentrations for Uranium Isotopes on Enewetak.

Location/Condition	Activity Concentration (pCi g^{-1})			
	U-234	U-235	U-238	Total
Average Northern & Southern Islands (Natural Background)	0.59	0.027	0.59	1.2
Maximum Average Northern Islands (Natural Background + Estimated Testing Impacts)	1.3*	0.041	0.59	1.9
Soil Sample with Highest ^{235}U (Janet)	14*	0.30	0.59	15

* Assumes ^{235}U in excess of natural background, 0.0273 pCi g^{-1}, has ^{234}U concentration 49.5-fold higher than ^{235}U.

The estimates of residual uranium concentrations appear conservative with respect to residual $^{239+240}Pu$ activity concentrations. From Figure 2-6, the ratio of specific activity of WGP (α-particle, excluding ^{241}Am) to 93% HEU is about 1,000:1. Although the total mass and mass ratios of these fissile materials used in testing at Enewetak remains classified, a simple comparison of residuals under the premise of equal use of each fissile material is made here for illustration. The maximum estimated average residual concentration of uranium from testing on the northern islands of the Atoll is about 0.68 pCi g^{-1}, dominated by excess ^{234}U. For an equivalent mass of WGP, the residual concentration would be about 68 pCi g^{-1} $^{239+240}Pu$. The levels of average $^{239+240}Pu$ in northern islands ranged from 1.8 (Ursula) to 39 pCi g^{-1} (Pearl). For an equivalent mass of WGP, scaled to the soil sample with the highest ^{235}U, the residual concentration would be about 1,400 pCi g^{-1} $^{239+240}Pu$. The

[8] Samples with positive detections for ^{235}U only considered

highest $^{239+240}$Pu among samples was 843 pCi g^{-1} in the Events Quince/Fig GZ on Yvonne (see Figure C-7). The high levels of $^{239+240}$Pu in this area were primarily related to the Quince explosion. Excluding soil samples from Yvonne, the highest $^{239+240}$Pu was for a sample on Pearl, 530 pCi g^{-1}.

In summary, among the key isotopes of uranium, ^{234}U is expected to have the highest residual activity concentration related to atmospheric testing on the northern islands of the Atoll. The activity concentrations, however, are expected to be a very small fraction of other α-particle emitters.

2.3.5.4.15 ^{238}Pu

This isotope of plutonium was expected to have a low activity concentration compared to $^{239+240}$Pu based on its insignificant mass in WGP of generic composition listed in Table 2.2. This composition only yields an initial α-particle activity concentration of 2.8% among the other plutonium isotopes. Table 14 of NVO-140 listed median activity concentrations for pertinent radionuclides measured in soil samples (AEC 1973). An excerpt of median ratios are listed for ^{238}Pu/^{239}Pu in Table C-10. The text notes that the median ratio for [^{238}Pu/^{239}Pu] was essentially constant at 0.10 [p. 97, AEC (1973)]. However, for many of the northern islands of the Atoll, a median ratio was not listed. It is our assumption that the footnote in the Table, "^{238}Pu activities were measured only in a few samples," was deemed a factor that limited an analysis for all islands.

In review of the data in preparation of this report, some agreement was found with listed median ratios in NVO-140, some contradictions were found in the median values reported in NVO-140, and sufficient ^{238}Pu data was found to estimate ^{238}Pu/^{239}Pu median ratios for some islands that were omitted for analysis in NVO-140. Fundamentally, the shortcoming in ^{238}Pu analysis in NVO-140 was rooted in a lack of reporting this isotope by some laboratories performing wet chemistry. The lack of reporting by the individual laboratories was not consistent for all samples. An example of ^{238}Pu reporting for Irene is provided in Figure C-16. The three laboratories that performed wet chemistry for Irene soil samples were: LFE, EIC, and MCL. For these samples, three samples did not list the performing laboratory(s), with the annotation, NL. For two groups of samples, the wet chemistry was split between two laboratories: LFE and EIC (2 samples), and MCL and EIC (24 samples). It is our assumption that one laboratory performed strontium analysis and the other plutonium. In the case of the samples with wet chemistry by MCL and EIC, it is reasonable to conclude that MCL performed the plutonium analysis, based on the ^{238}Pu reporting convention observed when a single laboratory had responsibility for all wet chemistry on a sample. A small fraction of the samples analyzed by MCL used mass spectrometry. For these samples, quantification of ^{238}Pu was not expected due to its negligible mass fraction.

A scatterplot of the $^{239+240}$Pu to ^{238}Pu activity concentrations for soil samples on Alice is in Figure 2-25. In contrast to median ratio values listed in Table 2-13 for most radionuclides, the median ratios for this radionuclide combination and $^{239+240}$Pu to ^{241}Am included all samples, not just those in the top 15 cm. For the 52 samples, 38 that had positive detection for $^{239+240}$Pu and ^{238}Pu. For the other fourteen samples, 12 were reported as non-detects, while two did not have a reporting for ^{238}Pu. The slope of the regression, 13.0, and median $^{239+240}$Pu to ^{238}Pu ratio, 13.8, were in good agreement. The median ratio of ^{238}Pu to $^{239+240}$Pu, 1/13.8 = 0.072, is a little lower than reported in Table 14 of NVO-140, 0.1. The median ratio of ^{238}Pu to $^{239+240}$Pu, 1/9.3 = 0.11 and 1/6.0 = 0.17, for soil samples from Belle and Clara, respectively, agree better with Table 14 of NVO-140, 0.11 and 0.14. Scatterplots of the $^{239+240}$Pu to ^{238}Pu activity concentrations for soil samples from these islands are in Figures C-17 and C-18. Daisy had a median $^{239+240}$Pu to ^{238}Pu ratio of 12, as listed in Table 2-

13, which is similar to Alice and Belle. Table 14 of NVO-140 did not list a ratio. For this island, among the 48 samples, only 20 had reported detects for both $^{239+240}$Pu and ^{238}Pu. For Edna, NVO-140 reported a median ^{238}Pu to $^{239+240}$Pu ratio of 0.06, yet in review of soil data for this report, none of the samples analyzed for plutonium by MCL had detects for ^{238}Pu. A plot of the minimum activity concentration ratio $^{239+240}$Pu to ^{238}Pu versus is plotted in Figure C-19 using the reported MDC. The lowest minimum ratio is 7.9, while most are much higher, indicative of only a small potential contribution from ^{238}Pu to radioactivity in soils. As noted in Table 2-13, about half the samples for Edna did not have any reported information on ^{238}Pu. Data from sampling and analysis of soils conducted during the cleanup and reported in NVO-213 supports the conclusion that ^{238}Pu activity concentrations were very low in comparison to $^{239+240}$Pu for Edna. A scatterplot of the $^{239+240}$Pu to ^{238}Pu activity concentrations for soil samples from Edna is in Figure C-20.

The $^{239+240}$Pu to ^{238}Pu activity concentration ratios for Kate, Lucy, Mary, Nancy, Wilma, and Ursula were low for the few samples with ^{238}Pu detection values reported. Since these islands did not support GZ for any tests and were at substantial distance from large yield devices detonated to the western part of the Atoll, the $^{239+240}$Pu concentrations in surface soils were relatively low compared to many other islands. A scatterplot of the $^{239+240}$Pu to ^{238}Pu activity concentrations for soil samples collected during the remedial action on Kate is in Figure 2-27. The median $^{239+240}$Pu to ^{238}Pu activity concentration ratio was 220, while the minimum was 17, as displayed as the red data point in the scatterplot. Similar conclusions were drawn for samples on the other island in this group, based on NVO-213 data. Due to these facts, the ^{238}Pu is of negligible interest for these islands. Ursula had the lowest average $^{239+240}$Pu activity concentrations in surface soils among northern islands of the Atoll, 1.8 pCi g^{-1} (Table 2-10). Another group of islands: Olive, Percy, Sally, Tilda, and Vera had large number of samples with non-detects or lack of assessment for ^{238}Pu. For these islands, a sufficient number of samples existed to estimate the median $^{239+240}$Pu to ^{238}Pu. With the exception of Olive, the median ratios $^{239+240}$Pu to ^{238}Pu for the islands were high. A scatterplot of the $^{239+240}$Pu to ^{238}Pu activity concentrations for soil samples on Percy is in Figure C-21. Olive and Ruby had median $^{239+240}$Pu to ^{238}Pu activity concentrations, 9.8 and 9.5, respectively, and similar to that observed on Belle, 9.3. The majority of the samples for Ruby had positive detects for ^{238}Pu and good correlation between the $^{239+240}$Pu and ^{238}Pu. The scatterplot of the $^{239+240}$Pu to ^{238}Pu activity concentrations for soil samples on Olive is in Figure 2-26. The data displayed in blue and green circles was poorly correlated as a set, with the regression line and statistics in black. The data is blue as a set, is more similar in $^{239+240}$Pu to ^{238}Pu ratios observed in soils samples from Percy, Sally, Tilda, and Vera, while the green data is more similar to the ratios observed on Pearl, a neighboring island. Nevertheless, outside of academic interest, the ^{238}Pu activity concentrations were low on Olive.

Relatively low, median $^{239+240}$Pu to ^{238}Pu activity concentrations ratios were exhibited for soils on Irene, Pearl, and the Yvonne. A scatterplot of the $^{239+240}$Pu to ^{238}Pu activity concentrations for soil samples on Irene is in Figure 2-28. The median $^{239+240}$Pu to ^{238}Pu activity concentration ratio of 3.4 is somewhat similar to that from sampling and analysis of soils conducted during the remedial action (DOE 1982) effort, as displayed in Figure C-22. The two data sets have a similar characteristic in higher $^{239+240}$Pu to ^{238}Pu ratios for samples with lower activity overall plutonium concentrations, based on the high fraction of samples laying above the regression line. The plutonium contaminant appears to have two dominating sources – each with a varied $^{239+240}$Pu to ^{238}Pu ratio. However, the lower ratio is a better estimator of the ratio that exists for the mean

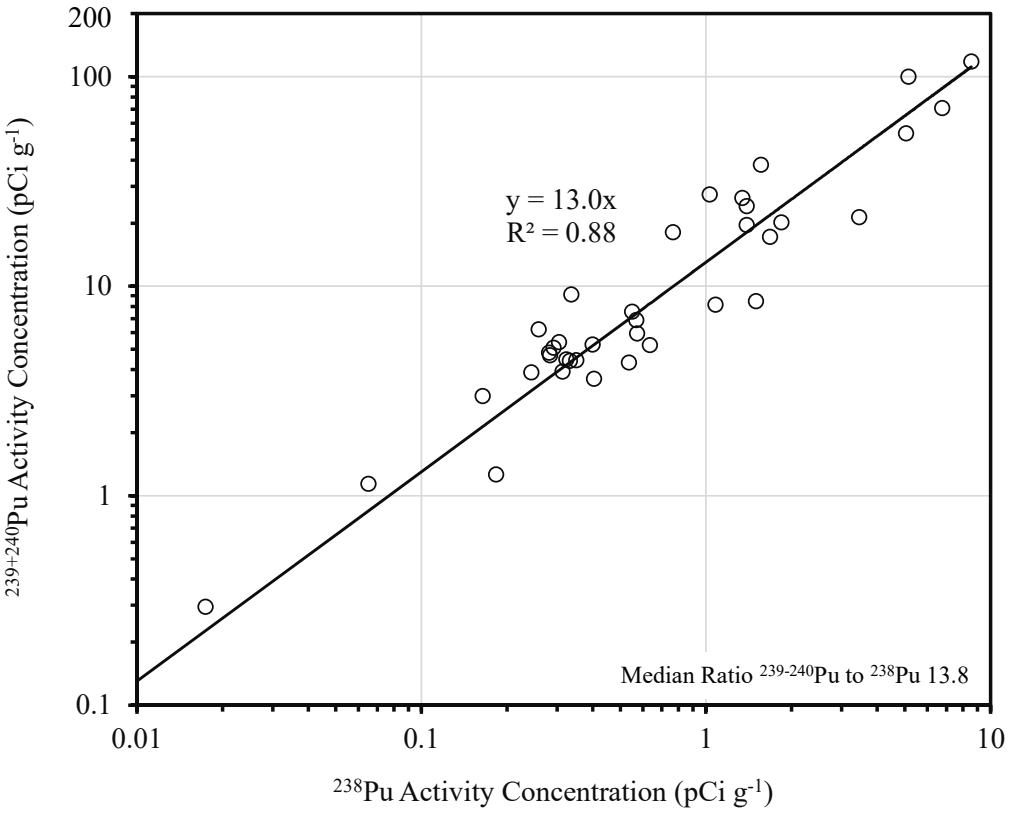


Figure 2-25. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for NVO-140 Soil Samples on Alice, Data from AEC (1973).

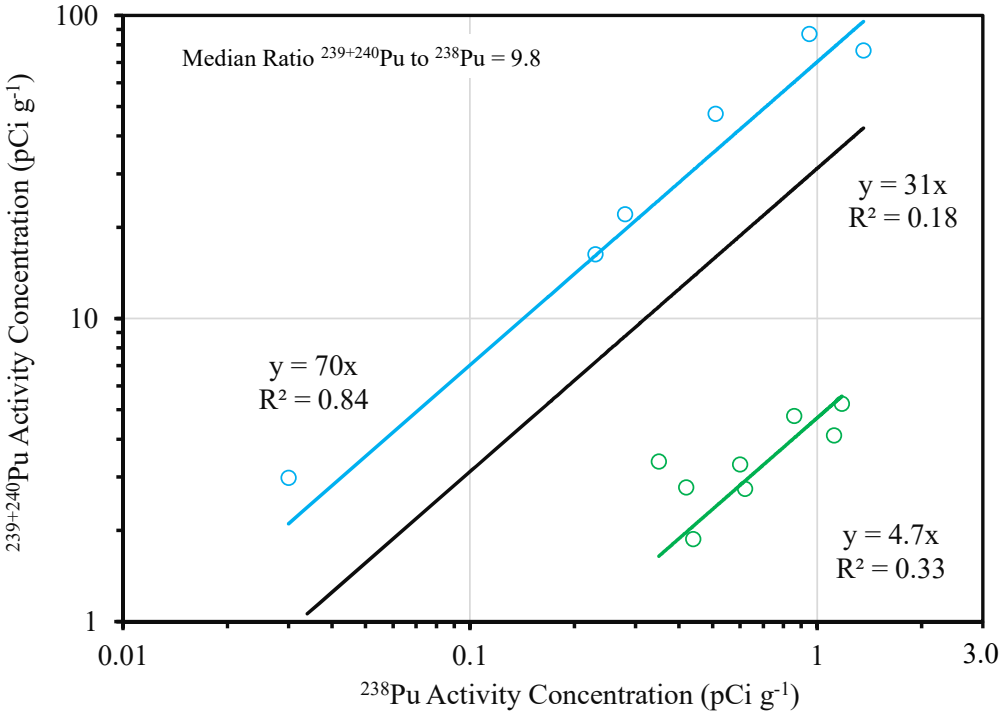


Figure 2-26. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for NVO-140 Soil Samples on Olive, Data from AEC (1973).

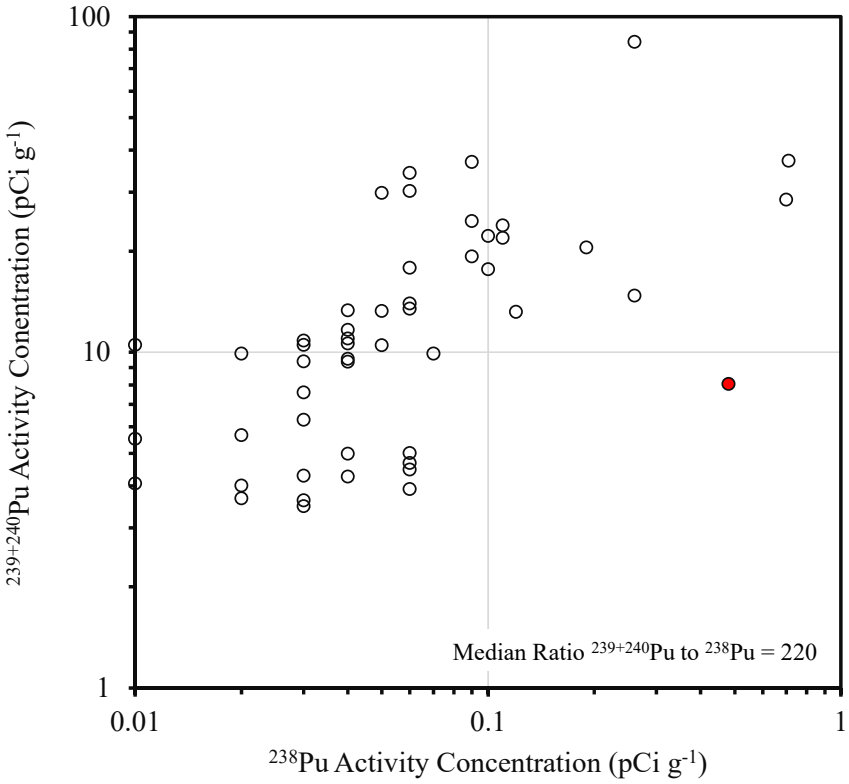


Figure 2-27. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for NVO-140 Soil Samples on Kate, Data from DOE (1982).

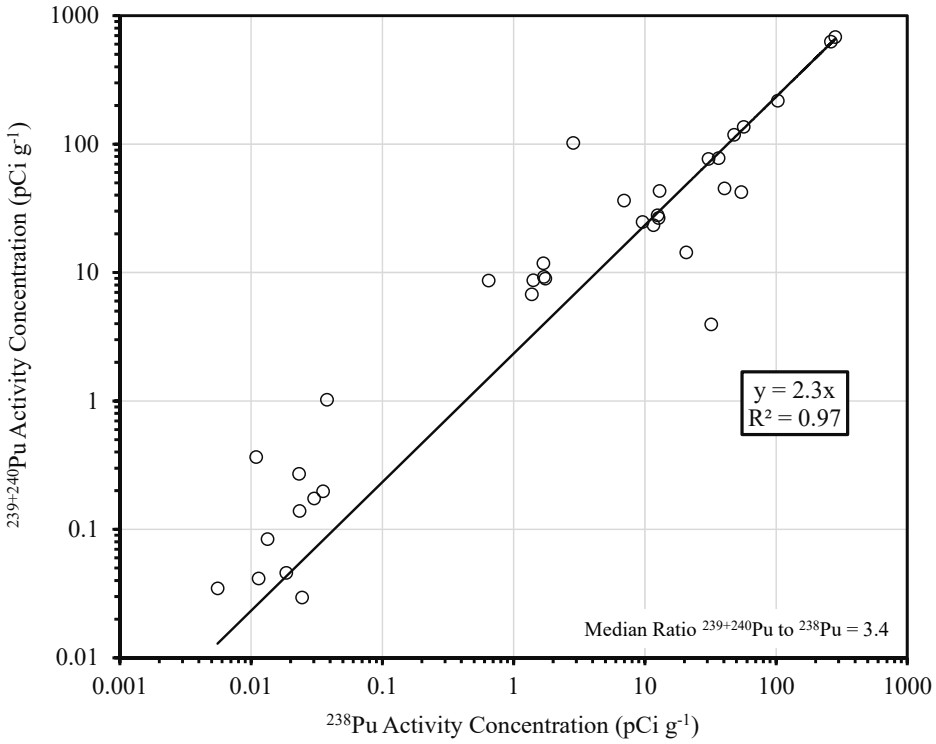


Figure 2-28. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for NVO-140 Soil Samples on Irene, Data from AEC (1973).

plutonium concentration on the island. Although a majority of samples analyzed for preparation of NVO-140 did not have ^{238}Pu assessment accomplished, it is important to note that the analysis of the relationship between $^{239+240}$Pu to ^{238}Pu was ably accomplished with a lesser number of samples. A scatterplot of the $^{239+240}$Pu to ^{238}Pu activity concentrations for soil samples on Pearl is in Figure C-23, based on NVO-140 data, while Figure C-24 contains a similar plot for data from NVO-213. Similar to the data for Irene, samples with lower concentrations of plutonium tended to have a higher $^{239+240}$Pu to ^{238}Pu activity concentration ratios than the samples with higher concentration. Similar to the discussion of the $^{239+240}$Pu to ^{238}Pu activity concentration ratio for Irene, the ratio for the higher activity concentration samples provides the best estimate of the ratio for the mean plutonium concentrations on this island. Between the two sets of data, a $^{239+240}$Pu to ^{238}Pu activity concentration ratio of 2.0 seems reasonable. Yvonne was notable for having highly varied patterns of fallout. Due to this, summary statistics are listed for separate segments, as done above in Table 2-12 for primary radionuclides, and below in Table 2-17 for transuranics (TRU). For samples from segments A and D of Yvonne, ^{238}Pu activity concentrations were either not reported or reported as non-detects. The median $^{239+240}$Pu to ^{238}Pu activity concentration ratio for samples with detects for both isotopes of plutonium was 3.9, 5.4, and 2.6, respectively, for segments A/B, B, and C of

Table 2-17. TRU Soils Data for Yvonne, from Archived Soils Data of NVO-140 (AEC 1973).

Segment (Sample Number)*	Parameter	Activity Concentration (pCi g^{-1}) [Top 10 or 15 cm]		Activity Concentration Ratios $^{239+240}$Pu:X [All Samples]	
		$^{239+240}$Pu	^{241}Am	^{238}Pu	^{241}Am
A (7)	Min	3.8	0.37	^{238}Pu not Reported for Any Samples	4.4
	Max	120	14		22
	Median	9.9	1.1		12
	Mean	31	3.9		13
A/B (6)	Min	1.8	0.27	0.63	5.6
	Max	160	9.5	12	22
	Median	11	1.0	3.9	14
	Mean	34	2.8	4.2	13
B (32)	Min	0.26	0.17	0.41	0.082
	Max	730	57	49	55
	Median	61	4.4	5.4	12
	Mean	140	11	8.8	13
C (39)	Min	0.71	0.05	1.4	0.54
	Max	50	7.4	33	150
	Median	8.9	1.1	2.6	8.1
	Mean	12	1.6	5.4	12
D (17)	Min	0.083	0	^{238}Pu not Reported for Some Samples, All Others Non-Detects	5.6
	Max	210	1.6		8.7
	Median	0.32	0.20		7.2
	Mean	14	0.40		7.2

* Surface samples, top 15 cm.

Yvonne. A scatterplot of the $^{239+240}$Pu to ^{238}Pu activity concentrations for soil samples from segment B of Pearl is in Figure 2-29, based on archived NVO-140 data. A scatterplot of data for segment C is in Figure C-25. The median ratio of 2.6 is similar to the observation of the relationship between these two isotopes on Pearl and Irene. For this segment of Yvonne, however, due to the relatively low mean $^{239+240}$Pu activity concentration in surface soils, the impact of ^{238}Pu activity concentrations are relatively minor. For segment B, the mean $^{239+240}$Pu activity concentration in surface soils is much higher, 140 pCi g^{-1}. Use of the median ratio as a scaling factor, would provide an estimated ^{238}Pu activity concentration of 26 pCi g^{-1}. The EPA in assessment of soil on Bikini Atoll island Eneman (Tare) in 1972, found soils with similarly high ^{238}Pu activity concentrations in relation to $^{239+240}$Pu, as contained in Table C-11.

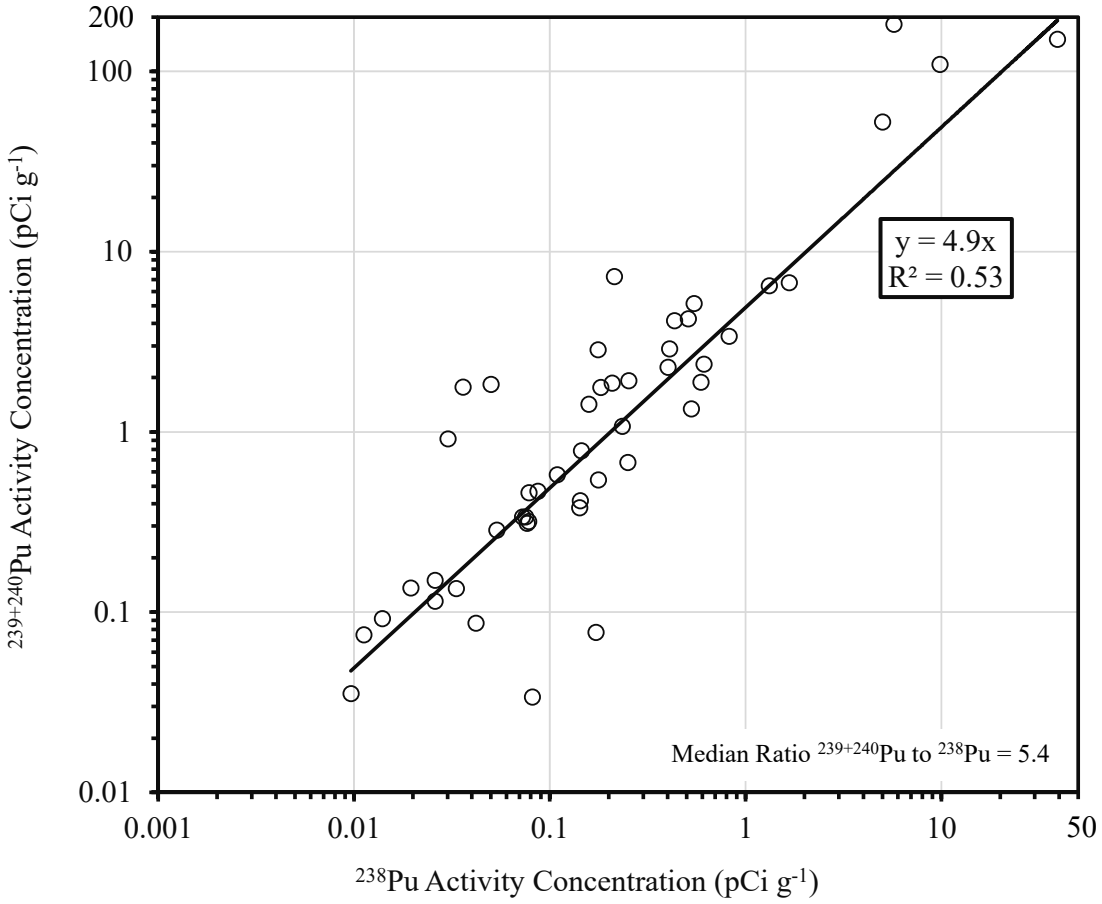


Figure 2-29. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for NVO-140 Soil Samples on Segment B of Yvonne, Data from AEC (1973).

2.3.5.4.16 ^{241}Am and $^{239+240}$Pu. Activity concentrations of ^{241}Am were included by DOE in assessment of total transuranics in soils. DOE γ-radiation surveys of land areas relied on detection of the 60 keV photon emitted by ^{241}Am with their in-situ van (IMP). With this in mind, in preparation of NVO-140, the ratio of $^{239+240}$Pu to ^{241}Am was an important index. By early 1978, concerns for exposures to future residents from $^{239+240}$Pu was expanded to include ^{238}Pu and ^{241}Am. From the NVO-140 soils data, the median $^{239+240}$Pu to ^{241}Am activity concentration ratios ranged from 2.5 (Nancy and Tilda) to 14 (Yvonne, segment A/B). As discussed in section 2.2.5 this

ratio is expected to have some variability, dependent on the isotopic mixture of the plutonium fuel in a weapon test, the fuel burn efficiency, and non-fission neutron interactions with plutonium and uranium in a test. As well, soils were likely influenced by the impacts of a number of separate tests, and to some degree world-wide fallout. The islands with the lower observed ratios likely have a dominant influence from Event Mike and other high-yield detonations conducted on the Atoll. A scatterplot of the $^{239+240}$Pu to ^{241}Am activity concentrations for soil samples from Belle is shown in Figure 2-30. Good agreement existed between the isotopes, with a median $^{239+240}$Pu to ^{241}Am ratio of 3.6 and slope of the regression at 3.2. A scatterplot of the $^{239+240}$Pu to ^{241}Am activity concentrations for soil samples from segment B of Yvonne are shown in Figure 2-31. Similar to the data in Figure 2-29, a good correlation existed between the isotopes. In comparison to expected ratios from an isotopic composition of WGP listed in Table 2-2 from NVO-213 (DOE 1982), the original ^{239}Pu WGP mass content for the contamination in this area appears much higher.

2.3.5.4.17 TRU Content of Soils. Table C-12 contains a summary of estimated mean concentrations of the TRU in surface soils on the individual islands of the Atoll. The totals ranged from 2.5 (Ursula) to 180 (Yvonne, segment B) pCi g^{-1}. With only a few exceptions, ^{241}Am activity concentrations were based on soil sampling, which also formed the basis for the average $^{239+240}$Pu activity concentrations listed in the table. Clarifying comments are added to provide additional detail for the reader. Most of the comments detail the method used to estimate the ^{238}Pu. In many cases, the median $^{239+240}$Pu to ^{238}Pu activity concentration was used, as listed in Table 2-13. For a few islands, median $^{239+240}$Pu to ^{241}Am activity concentration or slope of a regression analysis was used instead of actual ^{241}Am activity concentrations in soil. These indices were commonly used because they provided higher estimates of the ^{241}Am activity concentrations.

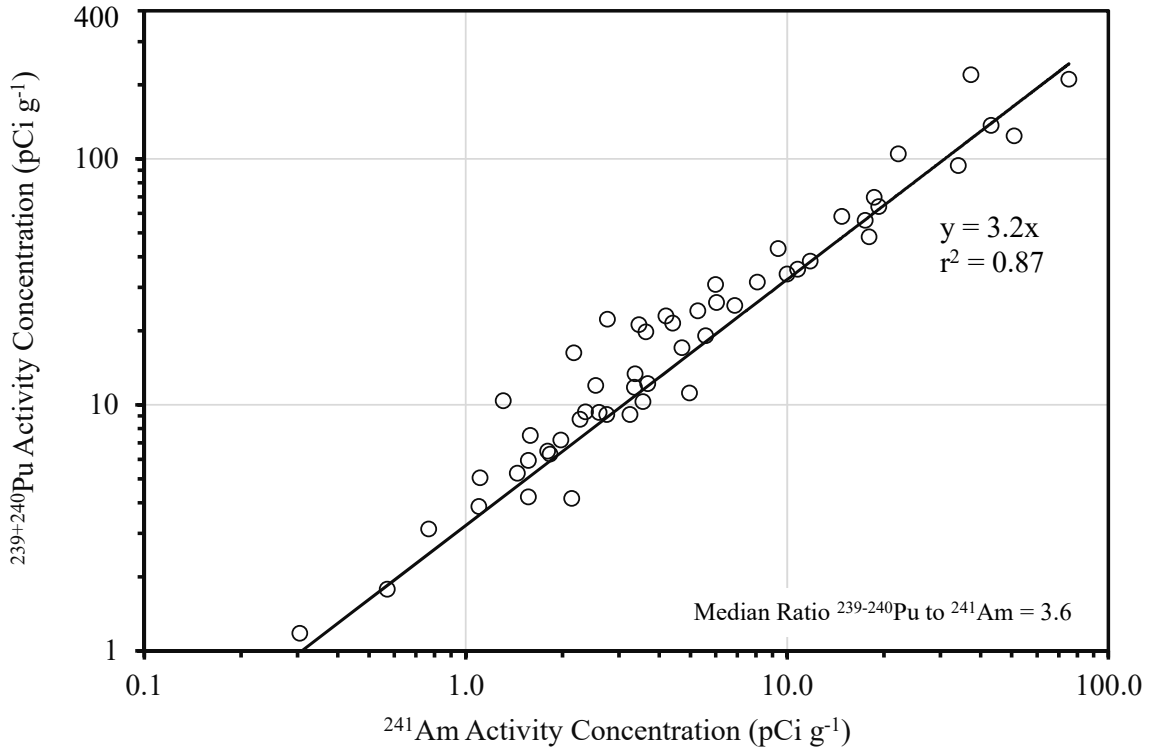


Figure 2-30. Scatterplot of $^{239+240}$Pu to ^{241}Am Activity Concentrations for NVO-140 Soil Samples on Belle, Data from AEC (1973).

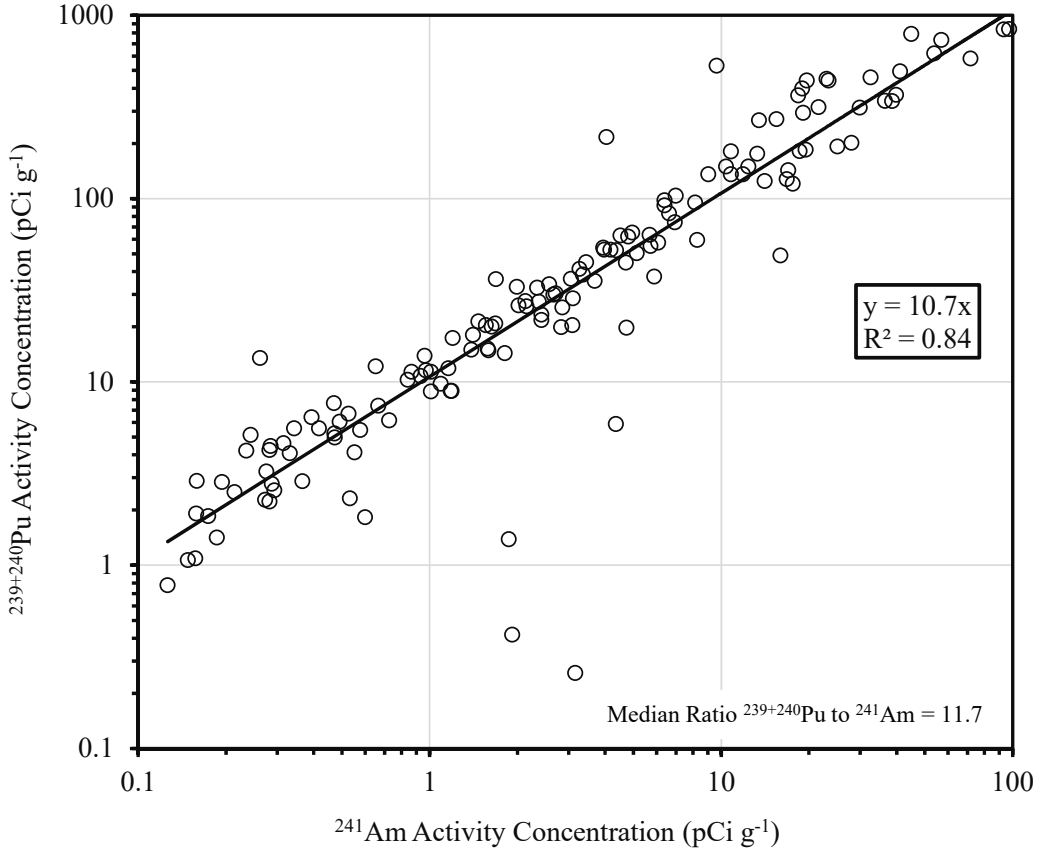


Figure 2-31. Scatterplot of $^{239+240}$Pu to ^{241}Am Activity Concentrations for NVO-140 Soil Samples on Segment B on Yvonne, Data from AEC (1973).

For many cases, however, there was very little practical difference in the estimated ^{241}Am concentration. For a number of the islands, the ^{238}Pu activity concentrations are listed as negligible, as discussed in the text above. For Edna, an estimated ^{238}Pu activity concentration of 0.23 pCi g^{-1} is listed in Table C-12, based on the slope of the $^{239+240}$Pu to ^{238}Pu regression analysis. Clearly, however, the contribution is negligible compared to the total TRU. There was one case where the slope of the $^{239+240}$Pu to ^{238}Pu regression analysis was used for estimation of the ^{238}Pu activity concentration, and the slope had a noticeable difference from the median value. This was for Pearl with the applicable data in Figure C-23. For this case, a polynomial trendline was fitted to the data, with the slope being displayed in green. For the average $^{239+240}$Pu activity concentration of 39, the $^{239+240}$Pu to ^{238}Pu ratio was about 1.9. For three cases, the $^{239+240}$Pu activity concentration is noted for being biased high due to an outlier sample. The cases for Vera and Wilma were discussed above. Segment B of Yvonne had one sample with a $^{239+240}$Pu activity concentration of 210 pCi g^{-1}, though non-detect for ^{241}Am (see Table 2-17). For all three of these cases, the calculated mean $^{239+240}$Pu concentration included the concentration of the outlier sample, though the sample population data justified use of a much lower mean concentration.

2.3.5.4.18 ^{151}Sm

^{151}Sm is produced in insignificant quantities by fission of ^{235}U, ^{238}U, or ^{239}Pu, but is the decay product of the short-lived ^{151}Pm, as show below, which has a reasonable fission production cross-

section. Hence, due to the short half-life, within a week after its production in a nuclear detonation, virtually all decays into ^{151}Sm, which has a 90-year half-life.

$$^{151}_{61}Pm \rightarrow {}^{151}_{62}Sm + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\upsilon}, \tau_{\frac{1}{2}} = 28\ hours$$

In Table 10 of the *Enewetak Radiological Survey* report (AEC 1973), ^{151}Sm is listed as a radionuclide expected in soils at the Atoll, however, due to its lack of significant photon emissions, it was not detectable by γ-spectrometry analyses. An isotopic-specific analysis for this radionuclide was not accomplished on any samples.

For completeness, an estimate of activity concentrations of this radionuclide is provided here. A reasonable method is based on correlation of ^{151}Sm as the daughter of a fission product with respect to other prominent long-lived fission products, namely ^{90}Sr and ^{137}Cs. A listing of cumulative percent atom yield for thermal, fast and 14 MeV neutrons fission of ^{235}U, ^{238}U, and ^{239}Pu are provided in Table 2-18 from IAEA data (IAEA 2008) for ^{137}Cs, ^{90}Sr, and ^{151}Sm. In addition, the Table contains the atom percent values normalized to activity, with these values then related to ^{90}Sr and ^{137}Cs normalized activity. A number of factors affect the accurate assessment of ^{151}Sm in relation to ^{90}Sr and ^{137}Cs. First, the fission product fractions are varied by energy of the incident neutron and the fissionable material. All combinations are deemed possible among the 41 tests[9] conducted at Enewetak, though the relative contribution of each remains classified and with varied local deposition. Since the fission cross-section of ^{238}U from thermal neutrons is negligible, it is not listed. Also, the IAEA report did not contain cross-sections for 14 MeV neutrons incident on ^{239}Pu. Second, there is expected to be some variability among the islands, due to the varied contribution to fallout on each island and the effects of fractionation. ^{137}Cs and ^{90}Sr are primarily produced as decay products of short-lived noble gas fission products, ^{137}Xe ($\tau_{1/2}$ = 3.8 min) and ^{90}Kr ($\tau_{1/2}$ = 32 s), respectively. Third, due to the varied test dates and different radiological half-lives of fission products, some differences in relationships among fission products is expected over time. There will be only minor differences in the ^{137}Cs/^{90}Sr ratios over time, considering only radioactive decay, due to the similar half-lives, though the half-life of ^{151}Sm is three-fold higher. Fourth, there is expected to be some varied retention in surface soils among fission products. ^{137}Cs, is notably more mobile in soils on coral atolls than other prominent fission products.

Considering the factors discussed above, the following assumptions and simplifications were made in estimation of ^{151}Sm. Since the precursor of ^{90}Sr has a shorter half-life than the precursor for ^{137}Cs, in effect, ^{90}Sr is expected to have a lesser degree of fractionation compared to refractory elements. As well, ^{90}Sr is likely to have an environmental mobility closer to Sm. For these reasons, the ^{151}Sm relationships to ^{90}Sr were deemed more appropriate for assessments on northern islands. For conservativeness, it is assumed that concentrations of ^{151}Pm was favored for local deposition by a factor of two over ^{90}Sr. The ^{151}Sm to ^{90}Sr activity ratio from Table 2-18 is assumed to be from fast fission of ^{238}U, 0.084. This value was the median among the ratios for fission of ^{235}U, ^{238}U, and ^{239}Pu, and deemed to be a reasonable estimate of the combined contribution from all fission sources. Decay correction of the ^{151}Sm to ^{90}Sr activity ratio from production to 1978 assumes a production date of 1953. This year is a reasonable central estimate of production time for the total yield of tests, with exception of underwater tests that had negligible impacts on fallout deposition on the northern islands. Overall, due to these considerations, the estimated ^{151}Sm to ^{90}Sr activity ratio in surface soils in 1978 is 2 x 0.126 = 0.25.

[9] Two detonations did not produce any nuclear yield, and therefore did not produce any neutrons.

Table 2-18. Cumulative Percent Atom Yield and Scaled Activity for Thermal, Fast, and 14 MeV Neutron Fission of ^{235}U, ^{238}U, and ^{239}Pu, and Activity Ratios of ^{137}Cs and ^{90}Sr to ^{151}Sm [Data from IAEA 2008].

Fission Product	Neutron Energy	U-235		U-238		Pu-239	
		Atom	Activity	Atom	Activity	Atom	Activity
Sr-90	Thermal	5.73	0.197			2.013	0.0692
	Fast	5.22	0.179	3.11	0.107	2.031	0.0698
	14 MeV	4.41	0.152	3.07	0.105		
Cs-137	Thermal	6.22	0.206			6.588	0.218
	Fast	5.89	0.195	6.02	0.199	6.35	0.210
	14 MeV	5.60	0.185	5.62	0.186		
Sm-151	Thermal	0.420	0.00467			0.776	0.00862
	Fast	0.431	0.00479	0.81	0.00900	0.796	0.00884
	14 MeV	0.388	0.00431	0.8	0.00889		

Fission Product	Neutron Energy	U-235		U-238		Pu-239	
		Ratio to Sr-90	Ratio to Cs-137	Ratio to Sr-90	Ratio to Cs-137	Ratio to Sr-90	Ratio to Cs-137
Cs-137	Thermal	1.05	1			3.15	1
	Fast	1.09	1	1.87	1	3.01	1
	14 MeV	1.22	1	1.76	1		
Sm-151	Thermal	0.024	0.023			0.12	0.040
	Fast	0.027	0.025	0.084	0.045	0.13	0.042
	14 MeV	0.028	0.023	0.084	0.048		
Sm-151 (25 y decay)	Thermal	0.036	0.033			0.19	0.058
	Fast	0.040	0.036	0.126	0.066	0.19	0.062
	14 MeV	0.043	0.034	0.126	0.070		
Sm-151 (6 y decay)*	Thermal	0.026	0.025			0.137	0.043
	Fast	0.029	0.027	0.093	0.050	0.140	0.046
	14 MeV	0.031	0.026	0.093	0.052		

* For use in next section of report.

2.3.5.5 Soils Data from NVO-213. Summary statistics for samples collected as part of the remedial actions are listed in Table C-13, as adapted from Table 7-1 through 7-3 of NVO-213 (DOE 1982). The data presented in this table differed from Table 15 of NVO-140. NVO-140 had ^{60}Co data, while the NVO-213 table did not contain ^{60}Co. NVO-213 contained sampling data from a few of the very small islands omitted from sampling in preparation of NVO-140: Mary's Daughter, Pearl's Daughter, and Sally's Child. For many of the islands, the sampling was more extensive in NVO-140 than NVO-213. Notable exceptions are for Janet and Sally for γ-spectrometry and isotopic plutonium. Three-hundred sixty four samples were collected on Janet and 137 on Sally for NVO-213. The impetus for extensive sampling on Janet was the continued interest in a future use of Janet (Enjebi) as a village island. In general, activity concentrations of radionuclides in surface soils were greater based on soil data from NVO-140 compared to NVO-213. The reasons for this general observation are likely attributed to the effects of contaminant migration over time and soil removals

on some islands which provide an overall reduction in residual TRU. NVO-213 used ^{241}Am concentrations multiplied by standard $^{239+240}$Pu to ^{241}Am ratios for estimation of the $^{239+240}$Pu.

2.3.5 Radionuclides in Soils Data Prior to 1973, Southern Support Islands

2.3.6.1 Background. Some military members and contractor personnel were assigned duties on Enewetak Atoll after the completion of testing in 1958. In general, most personnel assigned duties to the Enewetak Atoll between 1948 and 1958 were related to atmospheric tests. After 1958, military members assigned duties to the Atoll were part of base support and a weather squadron, which was also operated by the US Weather Bureau. Access to northern islands of the Atoll would not have been required. Hence, it is the assumption here that all work was performed from the southern support islands of Fred (Enewetak), Elmer (Medren), and David (Japtan). Assessment of external radiation exposure and internal radiation exposure requires extrapolation of the 1973 AEC data back in time, since detailed radiological survey data on surface soils prior to the 1973 is limited. The activity of individual radionuclides in soils were higher in 1959 as compared to 1973. As well, some dilution by weathering effects occurred during the interceding period. Therefore, to appropriately estimate the conditions that existed back in 1959, extrapolation of the 1973 AEC data includes both of these factors. In addition, it was necessary to determine if any key radionuclides generated from tests which impacted the southern islands contained radionuclides with radioactive half-lives sufficiently long to be present in 1959, yet of half-lives sufficiently short to decay to undetectable levels by 1972, when most of the AEC survey was conducted.

2.3.6.2 Tests Impacting the Southern Support Islands. With the exception of two tests, all other tests were conducted on the northern part of the Atoll. Due to this, the southern islands were expected to have only minor impacts from fallout of tests. The Wahoo and Umbrella tests, both underwater type test conducted on the southern part of the Atoll had very little airborne fallout compared to the other tests that impacted the southern islands. The test with the largest yield on Enewetak was the Mike device, detonated 31 October 1952 with a yield of 10.4 MT. Six other tests with yields in excess of 1 MT were detonated on Enewetak Atoll, with test dates between 13 May 1954 and 26 July 1958. Four of the test were conducted on barges, while Oak (8.9 MT) and Koa (1.37 MT) were respectively detonated on a reef and island (Gene). A number of factors determined the potential impact of the southern support islands from tests conducted on the northern portion of the Atoll. Among these are the yield, distance between the GZ of a test and the southern support islands, and wind direction and speed. Table 2-19 contains a summary of key test with fission and activation product fallout deposition on southern support island, with a listing of associated predicted H+1 fallout exposure rate contour plots. The two tests conducted in the closest proximity of the southern support island were Dog and King on Yvonne. Though test Dog had a substantially lower yield than King, the wind patterns were favorable on the day of the Test Dog for some reasonable fallout deposition on the southern support islands. This was also the case for Test Item, which was even farther from the southern support islands. Two of the thermonuclear tests, Mike and Nectar, did not have as favorable atmospheric conditions as Tests Dog and Item for fallout deposition on the southern support islands, but the yield of these tests provided substantially greater fission product production and injected debris to higher altitudes. Test Apache, based on its fallout pattern was also expected to have some deposition on the southern support islands. In the review of fallout patterns from other tests, the impact on fallout to the southern support islands was of much lower impact than these six tests. Test Tewa, conducted on barge anchored near a reef west of Iroji island on Bikini Atoll, had some fallout observed on Enewetak Atoll. Figure C-26 shows the fallout

pattern, up to 150 miles to the west of Bikini, with the eastern edge of Enewetak Atoll being about 200 mile from the GZ of this test. For this assessment, exposure and soils data for Elmer will be used as a conservative estimation of dose for all three of the southern support islands. Among the three southern support islands, this island had the highest number of tests noted for impact from

TABLE 2-19. Summary of Key Test Events Impacting the Southern Support Islands of Enewetak Atoll.

Test Event	Test Date	Island	Type and Height of Burst	Yield (MT)	Fallout Contour Figure Listing
Dog	7 Apr 1951	Yvonne	Tower 300 feet	0.081	A-4
Item	24 May 1951	Janet	Tower 200 feet	0.0455	A-5
Mike	31 Oct 1952	Flora	Surface	10.4	2-2
King	14 Nov 1952	2,000 feet North of Yvonne	Airdrop 1500 feet	0.5	A-6
Nectar	13 May 1954	Mike Crater	Barge	1.69	2-3
Apache	8 Jul 1956	Mike Crater	Barge	1.85	A-2
Tewa	21 July 1956	Reef (Bikini)	Barge	5	C-29

fallout, five, as summarized in Table B-1. Only one of the southern islands was impacted by fallout from more tests, 13 on Leroy. This island, however, encompasses only 5 acres and is 20 miles to the west of Elmer.

2.3.6.3 Fallout Radionuclides in Soil

The concentrations of radionuclides in soils is the key to estimation of potential internal intakes to individuals and the extrapolation of external radiation exposure levels to years prior to 1973 when the AEC conducted extensive external exposure assessments, similar to the importance for estimation of exposure potential on the northern islands of the Atoll. Table C-14 contains a summary of isotopes of concern, similar to those in surface soils discussed in extensive detail above, but with important exceptions. While ^{106}Ru, ^{144}Ce, and ^{147}Pm were only observed in a few of the AEC 1973 soil samples and deemed of negligible consequence for current and future exposure potential, these radionuclides would have had much higher activities at prior times. As noted in Table C-14, soil data was sufficient for assessment of surface soils concentrations of $^{239+240}$Pu, ^{137}Cs, ^{90}Sr on Elmer. These radionuclides are deemed prime radionuclides for assessment of surface soil concentrations on Elmer in 1973, as they were detected in the vast majority of surface soil samples. Due to the concentrations of other radionuclides and the sensitivity of the laboratory methods used by the AEC in 1973, the mean activity for other radionuclides were based on relationships with key radionuclides on Elmer and other islands of the Atoll. For example, ^{238}Pu was based on the regression of $^{239+240}$Pu to ^{238}Pu for Elmer soils, as displayed in Figure C-27 and noted in Table C-14. Though 145 soil samples from Elmer were analyzed, ^{238}Pu was detected in only 10 samples. In this case, it was deemed more reasonable to estimate the mean ^{238}Pu concentration based on its relationship established with $^{239+240}$Pu among samples with higher activity concentration. Similarly, this was also accomplished for ^{241}Am (Figure C-28), where only seven samples had positive detects for ^{241}Am.

^{241}Pu was not analyzed by the AEC in 1973. ^{241}Pu has 14.4 y half-life and is found in WGP in low-mass fractions. For this assessment, it is assumed that its initial mass fraction was 0.437, with respective ^{239}Pu and ^{240}Pu mass fractions of 0.933 and 0.062. These mass fractions match generic Hanford Production Burn-up rates for a 700 MWd/t (megawatt-day per ton) fuel removed from irradiation and an assumed chemical separation in 1954. A plot of respective plutonium and ^{241}Am activity fractions, and isotopic ratios are displayed in Figure C-29, based on this assumed composition. The ^{238}Pu, however, was based on the relationship with $^{239+240}$Pu in 1973, as shown in Figure C-27. The $^{239+240}$Pu to ^{241}Am ratios on Elmer, inferred from Figure C-28, match the expectation for this mixture. In contrast to fission and activation product deposition on Elmer, the plutonium deposited on Elmer is believed to be influenced more by plutonium dispersed from tests in 1958, conducted on or near Yvonne than the tests listed in Table 2-19. Two of these such tests had no fission yield, while the other only a very small yield.

For activity concentrations of other radionuclides, relationships were established with ^{137}Cs on northern islands: Alice, Belle, Clara, and Daisy. These islands had relatively consistent relationships between ^{137}Cs and the radionuclides of interest: ^{60}Co, ^{125}Sb, ^{152}Eu, ^{155}Eu, and ^{102m}Rh. Example regression plots for these radionuclides are in Figure C-30, C-31, C-32, C-34, and C-35. Due to the effects of fractionation of deposition between volatile elements (i.e., the production and fate of ^{137}Cs) and more refractory elements (Co, Sb, Eu, and Rh), the relationships inferred for these radionuclides on Elmer are expected to be high-sided (conservative). ^{154}Eu was inferred from the relationship with ^{152}Eu on Belle, as shown by the regression analysis in Figure C-33.

Due to the relatively long half-life of ^{207}Bi, 32.2 y, relatively low concentrations detected on Elmer, and its relatively low radiotoxicity compared to plutonium isotopes, no effort was expended to better estimate its activity concentration in Elmer soils - only the mean soil concentrations among surface samples, including 0's for non-detect samples.

Estimated soil concentrations in 1959 for most radionuclides listed in Table C-14 are based on extrapolation to 1959, assuming environmental dilution effects. For ^{137}Cs, the estimated half-value concentration time of 12 y was based on data in Beck *et al.* (2010). The 12 y figure from Beck *et al.* was an estimated environmental half-life, which included radioactive decay and dilution effects of ^{137}Cs being distributed to greater depths in the soil column. For this work, a 12 y environmental dilution factor for stable Cs was assumed, with radiological decay considered separately, providing a combined effective half-value concentration of 8.6 y. This approach is conservative in nature, and expected to produce high-sided estimates of radiological concentrations in 1959[10]. Plutonium and americium are assumed to have a half-value concentration time of 20 y, based on their much lower expected environmental mobility. All other isotopes are assumed to have half-value concentrations of 16 years for stable isotopes, with radioactive decay considered separately. The concentrations of ^{241}Pu and ^{241}Am are related to the environmental dilution-adjusted concentration estimated for $^{239+240}$Pu in 1959 according to Figure C-29. Due to the relatively long half-life of other plutonium isotopes, no decay correction was used. As noted in Table C-14, the concentrations of ^{106}Ru, ^{144}Ce, ^{147}Pm, and ^{151}Sm are based on fission yield ratios to ^{137}Cs in 1953 from IAEA (IAEA 2008). Similar to the assessment of ^{151}Sm concentration for the northern islands in 1978 above, fast neutron fission product production rates in ^{238}U were assumed. This provided a reasonable balance in the varied fission production rates among all potential reactions. More details of the calculations are listed in Table C-15. The year 1953 was chosen due to this year being in the middle of the key tests

[10] The environmental half-value concentration (radioactive decay & environmental dilution) from data evaluated in Figure B-46 provided a value of 16 y for ^{137}Cs.

depositing fission products on the southern support islands. The relationships in activity concentration of the three radionuclides to ^{90}Sr in 1953 were decay-adjusted to 1959. Due to fractionation, ^{144}Ce, ^{147}Pm, and ^{151}Sm are expected to be observed in lower concentrations than the ^{90}Sr in the southern support islands, as compared to the unfractionated relationships. As a result, the estimated surface soil concentrations for these radionuclides are expected to be high-sided (conservative). Table C-15 contains the activity concentration values of radionuclides in 1973 and 1959 that are part of this assessment. For each year, the most important radionuclides have an associated concentration reported. Figure 2-32 contains a histogram of the soil concentrations listed in Table C-15 for 1959 and 1973. Clear from the plot, all radionuclides with displayed activity concentrations in both years have a net decrease in concentration between 1959 and 1973, due to environmental dilution processes. For $^{239+240}$Pu and ^{238}Pu, there is negligible radioactive decay between 1959 and 1973, but it is important for many of the fission and activation products displayed in the Figure. It is important to note that the implications of the relative concentrations of these radionuclides is dependent on the exposure pathway being considered: external exposures, internal exposure via inhalation of re-suspension, or incident ingestion of soil.

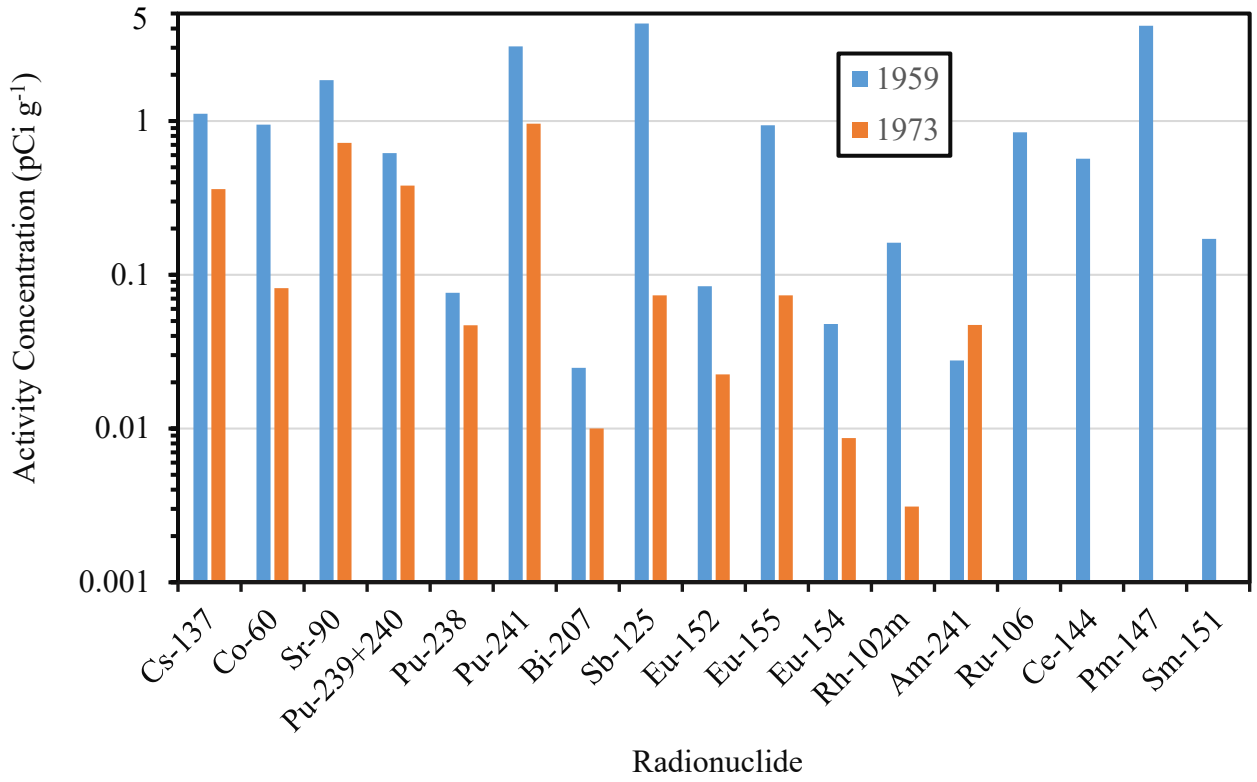


Figure 2-32. Summary of Estimated Radionuclide Activity Concentrations from Table C-15 for 1959 and 1973 on Elmer Island.

2.3.6.4 ^{102}Rh in Soil. ^{102}Rh was listed in Table A-4 as a radionuclide expected in Enewetak soils. Similar to ^{102m}Rh, it is produced in fission, though in trace quantities. Bush (1991) estimated the production rate of 6.6 and 3.7 ng per kg ^{235}U fission, respectively for ^{102}Rh and ^{102m}Rh. These radionuclides are also produced by fast neutron activation of ^{103}Rh. As noted in Table C-7, stable rhodium was used as tracer for some tests. The fast neutron production cross-section is about 0.6 and 0.24 millibarns (mb), respectively for ^{102}Rh and ^{102m}Rh (Francois et al. 1973). Due to the

short half-life of ^{102}Rh, 284 d, compared to that of ^{102m}Rh, 2.9 y, the ^{102}Rh is less than 10% of the ^{102m}Rh on a relative activity basis five years after production, as displayed in Figure C-36. Therefore, since the fallout expected on Elmer was modelled for tests around 1953, ^{102}Rh is expected to be much lower in proportion to ^{102m}Rh for periods of 1959 and later. For this reason, ^{102}Rh was omitted from estimated soil activity within the scope of this report.

2.3.6.5 External Exposures from Radionuclides in Soils on Elmer

The extensive external radiation measurements conducted for preparation of the AEC 1973 report has been discussed above, with a summary of exposure levels for the islands in Table B-1. For most of the islands with measureable exposure related to fallout radionuclides, ^{137}Cs and ^{60}Co provided the greatest contributions to total exposure, about 82%. As noted in Table B-1, ^{241}Am provided important secondary contributions for some areas of Yvonne. From Table B-1, exposures were too low to be quantifiable for all but two of the southern islands. To estimate the exposure for Elmer in 1973, and allow for extrapolation of exposure to earlier periods, as supplemented by soils data, a relationship between measured exposure for ^{137}Cs and ^{60}Co was developed for northern islands, which had quantified levels of exposure for these two radionuclides, and well established average surface soil concentrations of both radionuclides from soil analysis.

Figure C-37 and C-38 contain the regression analysis for mean exposure and mean surface soil activity concentration of ^{137}Cs and ^{60}Co, respectively. There was some expected variability of the two respective regressed data sets, but the squared correlation coefficient (R^2) for the regressions were 0.80 and 0.85, respectively for ^{137}Cs and ^{60}Co. Some of the variability is likely associated with varied distribution of contaminants in surface soils, inhomogeneity in areal deposition, etc. The mean and median exposure to soil concentration ratios were also annotated on each plot. While exposure values used for each regression analysis were from Table B-1, mean surface soil sample concentrations were from Table 2-10. A summary of descriptive parameters for each regression analysis is summarized in Table 2-20. For each radionuclide, among the mean, median, and regressed slope (measures of central tendency), the median value was highlighted, and deemed an appropriate best estimate of the true value. These values were compared to effective dose (ED) coefficients from Federal Guidance Report (FGR) 15 (EPA 2018) for soil contaminated to a depth of 15 cm (Table 4-4). The ratio of the median value to the FGR coefficient are: 2.46 and 2.36, respectively for ^{137}Cs and ^{60}Co. The two ratios were similar, with a mean of 2.41 between them. The similarity is attributable the strength of a large data set. The 2.41-fold higher value of free-air measured exposure as compared to computed values for a phantom, as listed in FGR 15 is well recognized. Measured values of exposure in free air are expected to be higher than modelled exposure, due to reduction of incident photon fields by attenuation of body tissues, and orientation of the phantom in relation to a plane surface source. Additionally, dose to tissue is not the same as exposure in air, but related by the following relationship:

$$D\ (tissue) \approx Exposure\ (air) \times 0.875 \frac{rad}{R} \times \overline{S}_a^{\,t},$$

where $\overline{S}_a^{\,t}$ is the ratio of the mean stopping power of secondary electrons produced in tissue compared to air. A value of 1.1 is a reasonable estimate of this ratio.

The scaling factor of 2.41 was used to scale ED coefficients from FGR 15 to soil concentration in surface soils on Elmer. ED coefficients for other radionuclides were also taken from Table 4-4 of

TABLE 2-20. Summary Parameters from Regression Analysis of Relationship Between Exposure Rates (1 meter above ground) vs. Mean Activity Concentration of ^{137}Cs and ^{60}Co in Surface Soils.

Radionuclide	Descriptive Parameters for Exposure vs. Soil Concentration (μR g h^{-1} pCi^{-1})				
	Minimum	Maximum	Mean	Median	Slope
^{137}Cs	0.23	2.69	0.84	0.67	0.98
^{60}Co	0.95	5.56	3.42	3.48	4.1

FGR 15. Figure 2-33 contains a plot of estimated exposure in air on Elmer from 1959 to 1973. The primary contributions to the estimated exposure of 0.71 μR h^{-1} in 1973 is contributed in a near equal fraction from ^{137}Cs and ^{60}Co. The contribution from each of these radionuclides was below the approximate sensitivity of the measurement system and method used for the 1973 surveys. From Table B-1, sensitivity for assessment of ^{137}Cs and ^{60}Co were about 0.3 and 0.6 μR h^{-1}. About 17% of the estimated exposure in 1973 is from ^{125}Sb, ^{152}Eu, ^{207}Bi, ^{154}Eu, ^{102m}Rh combined. Distribution of radionuclides contributing to external exposure in 1959 and 1973 are illustrated in Figures 2-34 and 2-35. Some radionuclides are not included in the plots. ^{151}Sm and ^{241}Pu have negligible photon emissions, as they essentially emit only low-energy β-particles. ^{144}Ce and ^{147}Pm are omitted from the 1973 plot, as they were assumed to have negligibly presence is soils; though they had greater estimated presence in 1959, their impact on external exposure was very low. For either time, the contribution to external dose from $^{239+240}$Pu was negligible, as neither isotope has significant photon emissions. The same is true for ^{238}Pu, but display of this isotope was omitted from both plots. ^{90}Sr has no photon emissions, though some external photon emissions exist due to bremsstrahlung radiation produced from high-energy β-particle interactions in soil. Nevertheless, the contribution remains negligible. ^{106}Ru has no external photon emissions, but its short-lived daughter, ^{106}Rh, is expected to exist in secular equilibrium. ^{106}Rh does have photon emissions, with an estimated contribution of 3% to external exposure in 1959. The largest contributions to estimated exposure rate in 1959 is from ^{125}Sb and ^{60}Co, 75%, with ^{137}Cs, ^{102m}Rh, and ^{106}Ru/^{106}Rh summed about 21%.

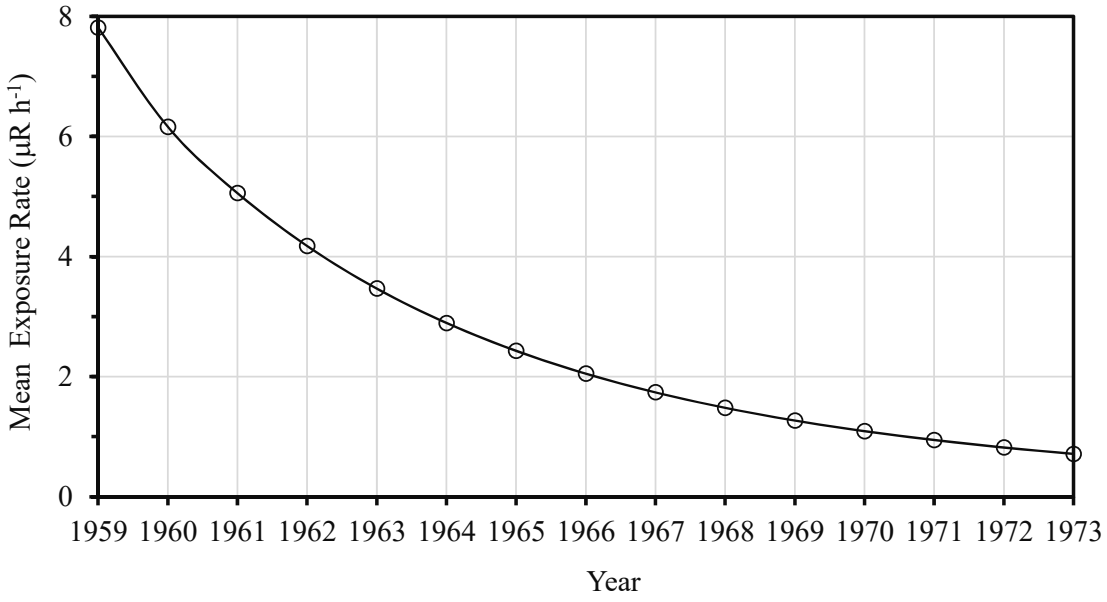


Figure 2-33. Estimated Exposure in Air from 1959 to 1973 on Elmer.

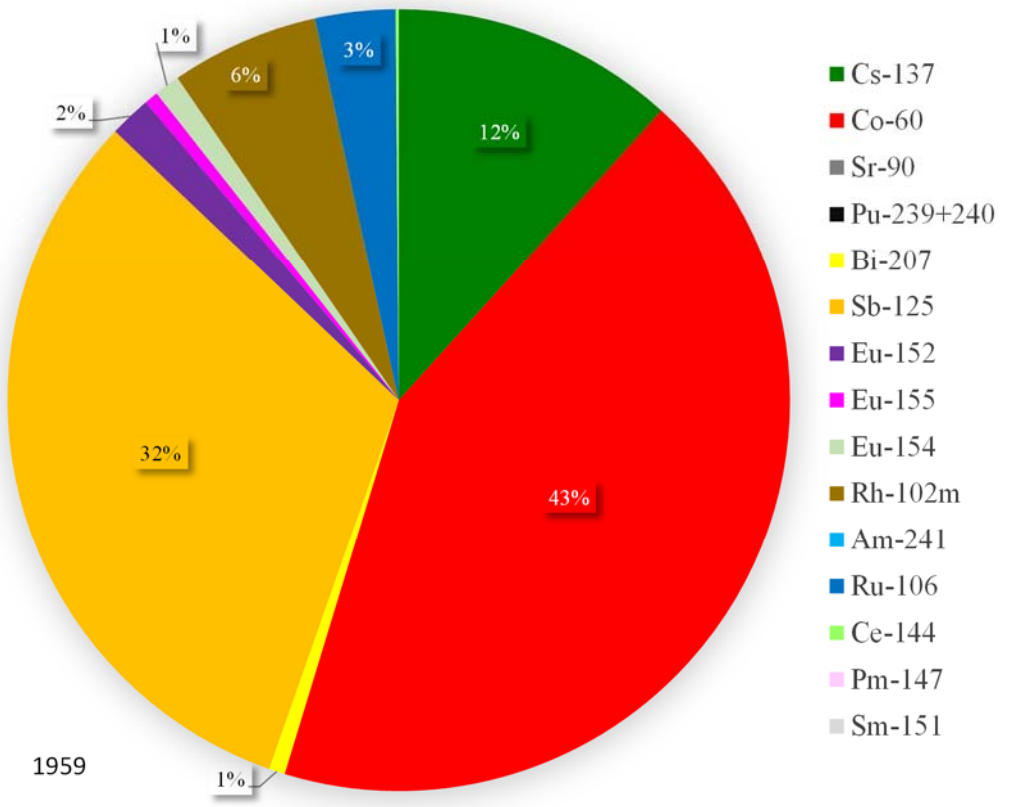


Figure 2-34. Distribution of External Exposure Radiological Sources for 1959.

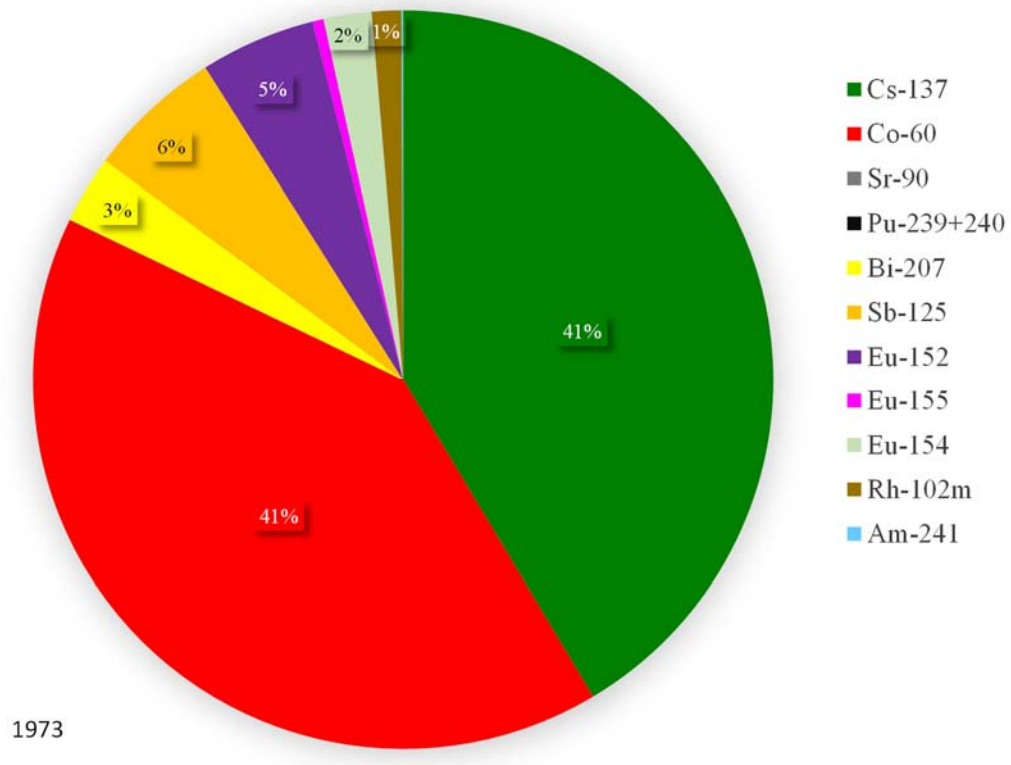


Figure 2-35. Distribution of External Exposure Radiological Sources for 1973.

Section 3

Radiation Safety Standards

3.1 Brief History

Radiation protection guidance issued in the United States has evolved over nearly 90 years since the first recommendations were released in National Bureau of Standards (NBS) Handbook No. 15, *X-Ray Protection,* in 1931. Early exposure guidance was designed to protect against observable radiation effects, i.e., reddening and desquamation of the skin, abnormal changes in blood counts, and others. Early guidance focused on protection from external radiation exposures from machine-produced x-rays and radium sources. The first US radiation protection guidance for internally-deposited radionuclides was issued in NBS Handbook No. 27, *Safe Handling of Luminous Compounds,* in 1941. The primary focus of this guidance was protection from ingestion and/or inhalation of dangerous amounts of radium and secondarily protection from inhalation of hazardous levels of radon gas and its daughters. This guidance continued to provide recommendations for protection from the readily observable short-term effects of radiation exposure, but added new guidance to protect from the delayed effects of radiation due to the accumulation of radium in the skeleton and exposure to the lung from radon daughters. At this time, important recognized delayed effects were bone necrosis, leucopenia, anemia, and increased risk of osteosarcomas. It was also speculated that increased frequency of workers developing lung carcinomas could occur from continuous exposure to radon gas. NBS Handbook No. 42, *Safe Handling of Radioactive Isotopes,* issued in 1949 expanded recommendations for safety in handling of radioactive materials to a multitude of radionuclides that had garnered much greater use after World War II and the advent of atomic energy. This handbook noted the possible genetic change effective in later generations of exposed individuals, but noted its importance to exposures had not yet been established. The mutagenic effects of x-ray exposures on fruit flies had been proposed by Hermann Muller 23 years earlier (Muller 1927).

Radiation exposure guidance published in the US by the National Committee on Radiation Protection and Measurements (NCRP) in Report No. 22 in 1959, *Maximum Permissible Body Burdens (MPBB) and Maximum Permissible Concentrations (MPC) of Radionuclides in Air and in Water for Occupational Exposure* had a long-lasting influence on radiation protection standards in the US. This report was published as NBS Handbook No. 69, and similar to many previously NBS-published radiation protection handbooks was developed by the NCRP with input from numerous US radiation protection experts and in parallel with international experts, most notably those associated with the ICRP. The MPBB and MPC values contained in NCRP Report No. 22 were the same as those published in ICRP Report 2 (ICRP 1959), with only minor exceptions. These reports met the underlying exposure guidance and objectives of ICRP Report 1 (ICRP 1958). The stated objective of the guidance was "to prevent or minimize somatic injuries and to minimize the deterioration of the genetic constitution of the population." The common exposure guidance from these reports formed the basis for AEC exposure standards promulgated in 10 Code of Federal Regulation (CFR) Part 20, 1960, which remained largely unchanged until the Nuclear Regulatory Commission (NRC) adopted an updated set of ICRP recommendations in the early 1990s. The Occupational Safety and Health Administration (OSHA) in 1971 adopted 10 CFR 20 radiation exposure limits that were established in 1969. OSHA has not updated these standards since.

3.2 Exposure Standards and Guidance Evaluated for Enewetak Exposures

3.2.1 Occupational Exposure Standards

Occupational exposure standards applied to the Enewetak Cleanup project followed U.S. Army Regulation (AR) 40-14, 20 May 1975. A tabular summary of the key criteria are contained in Table D-1. Exposure limits for individuals under the age of 18 are not listed as well as special limits for females known to be pregnant. The primary criteria applied to exposures cleanup workers at Enewetak was the dose equivalent limit to the whole-body, head and trunk, blood-forming organs, and lens of eye, which was 1.25 rem per calendar quarter and 5 rem in a year, but with a provision for higher exposures for adults older than 19 when lifetime occupational exposure history was considered. External radiation dosimetry monitoring results are traditionally used to estimate the deep tissue dose to a monitored individual. While for some individual workers it was possible to receive up to 12 rem in a calendar year, it is generally impractical to design a practical radiation safety program for large groups of workers with varied annual limits. Higher dose levels were acceptable to the skin of the whole-body, cornea of the eye, and bone – 30 rem in a calendar year. A source of unshielded β-particle emission or low-energy x-rays generally are important considerations for evaluation against this criterion. For radiation exposures to workers in the Enewetak cleanup, this was not a key exposure type. Higher exposure limits are designated for the extremities: hands, wrists, feet, ankles, and forearms. In general, most external radiation exposures for Enewetak cleanup personnel were expected to be uniform across organs/tissues of the body. A few individuals were responsible for the removal of small plutonium fragments on Yvonne in the early period of the cleanup. For this unique exposure circumstance, the hands, wrist, and forearms of individuals performing this task, was likely higher than the dose recorded on the monitoring device generally placed on the trunk of the body. Some consideration for these exposures will be discussed later.

The exposure standards in AR 40-14 were identical to the OSHA standard and 10 CFR 20 that existed at that time, with the exception of the limit for the forearm, bone, and thyroid. For the forearm, OSHA and 10 CFR 20 allowed 18.75 rem per calendar quarter, while the AR 40-14 limit was lower. OSHA and 10 CFR 20 do not explicitly list exposure limits for the thyroid, and "other organs, tissues, and organ systems" as was the case in the AR 40-14. These limits were implicitly followed through application of the maximum permissible body burden (MPBB) and maximum permissible organ burden (MPOB) specifications for exposures to internal exposure emitters. Dose limits were not established for the bone in ICRP 2 (similarly in NCRP 22 and NBS 69). Rather, limits for bone-seeking radionuclides were based on equivalence with the MPBB for ^{226}Ra. MPOB limits for the thyroid for radionuclides with specificity for deposition and retention in the thyroid, i.e., radioiodines, was based on a 30 rem annual limit to this organ under ICRP 2, NCRP 22, and NBS Report No. 69. The AR 40-14 annual limit was lower at 15 rem. Radioiodines are not key radionuclides of interest for the Enewetak cleanup.

3.2.2 Occupational Exposure Standards for Internal Emitters, NBS Report No. 69

AR 40-14 did not specifically address internal radiation emitters, and as noted by Defense Nuclear Agency (DNA 1981). Internal exposure potential was assessed against MPC values listed in the prevailing 10 CFR 20, which were consistent with NBS Report No. 69. Due to projected weekly

work periods of up to 60 hours for the Enewetak cleanup, the airborne MPC values were modified to a level of 2/3 of those established in NBS Report No. 69 for a standard 40-hour workweek. The 60- hour work week assumed 10 hours per day and six days a week. In reality, due to requirement for boat transport of many individuals that both worked on the northern islands and were billeted on Ursula, presence on a controlled islands was more likely limited to about 8 hours per day. Some individuals periodically travelled to the northern islands for a portion of their work, but since the majority of their work was conducted on the southern islands, the assumption of a 60-hour work week in a contamination zone was also conservative. This is because radiological exposure potential on the southern support islands was negligible, and well within typical environmental background rates found in CONUS.

Effective control of radiation exposure to individuals from internally-deposited radionuclides is more complicated than external exposures due varied exposure routes, deposition, and retention in the organs and tissues of the body. Typically, the most important exposure routes are inhalation and ingestion, though in some cases skin absorption and exposure through wounds can be important. Inhalation was the most important internal exposure pathways for workers supporting the Enewetak cleanup, with incidental ingestion of dusts and soils being of secondary importance. For future residents of the Atoll, the ingestion of locally grown food, seafood, and water were carefully considered by the AEC as well. Among the residual radionuclides in the Enewetak Atoll environment: isotopes of plutonium, ^{241}Am, ^{137}Cs, ^{90}Sr, ^{60}Co, ^{125}Sb, ^{151}Sm, isotopes of europium, and others, there are differences in the deposition and retention in the organs and tissues. To account for these differences, the ICRP addressed internal exposures using the critical organ concept, as defined,

> "A critical organ is defined as that organ of the body whose damage by a given radiation source results in the greatest impairment to the body. Criteria appropriate to the determination of critical organs for external or internal exposure are: (1) the radiosensitivity of the organ, i.e., the organ damaged by the lowest dose; (2) the essentialness or indispensability of the organ to the well-being of the entire body; (3) the organ that accumulates the greatest concentration of the radioactive material; and (4) the organ damaged by the radionuclide enroute into, through, or out of the body."

This terminology was developed in radiation exposure guidance issued by the NCRP and ICRP in the early 1950's, and was effectively the basis for the internal radiation exposure standard for radium issued in in 1941. Table D-2 contains a listing of MPC values in air from NBS Handbook No. 69 for many of the radionuclides identified in soil samples at the Enewetak Atoll. The MPC values are listed for both soluble and insoluble compounds of the listed radionuclide, and the critical organ that forms the basis for the limit. Because the guidance is developed for individuals with potential for radiation work over an entire lifetime, these limits were developed to ensure that the annual dose to the critical organ did not exceed the acceptable annual limit, cumulated over a 50 y working lifetime. For cases of exposure to bone seeking radionuclides, MPCs could be based on the MPBB due to accumulations in the bone. In the case of all example insoluble radionuclides listed in Table D-2, the lung is the critical organ, providing the basis for MPC in air. The fundamental limit to lung as a critical organ is 15 rem annual dose. Among the radionuclides listed in Table D-2, the MPC is lowest for the isotopes of plutonium. For inhalation of soluble chemical forms, the bone is the critical organ for isotopes of plutonium, ^{241}Am, ^{154}Eu, and ^{90}Sr, while it is the lower large intestine

for ^{60}Co, the kidney for ^{152}Eu, ^{155}Eu, ^{144}Ce, and ^{207}Bi. For ^{137}Cs, the dose to the total body is limiting, due to its generally uniform distribution throughout the body. For ^{241}Am and ^{154}Eu, the bone and kidney are both limiting critical organs, while for ^{144}Ce, it is both the bone and liver. Table D-2 also provides MPC values for other organs that provide an MPC $\leq$ 3-fold higher than that provided by limiting dose to the critical organ. This was provided for informational purposes.

Figures 3-1 and 3-2 provide an illustration of the accumulation of lung and bone burdens of ^{239}Pu from inhalation of insoluble and soluble forms, respectively. The solid black line in the plots represents the accumulation in the respective organ over a 50-y occupational exposure period at an inhalation level equal to the MPC in air. The MPOB for the lung is 0.016 μCi (16 nCi), while it is 0.04 μCi (40 nCi) for the bone. For inhalation exposures of insoluble ^{239}Pu, a near steady-state equilibrium lung burden is achieved in about nine years, while for the bone, a steady-state equilibrium is not achieved within the 50-y occupational exposure timeframe. The ramifications of these metabolism characteristics are interesting from a practical exposure standpoint for Enewetak cleanup workers, where support of this project may have been the only occupational exposure potential for many workers. Each plot contains also the accumulation of lung and bone burdens of ^{239}Pu for a six-month and 12-month exposure period, but after the respective periods, no additional exposure is received. With the exceptions of some Enewetak cleanup personnel that only visited the Atoll for brief period of duty, most were assigned for six-months of duty. For inhalation exposures of insoluble ^{239}Pu for six- and 12-months, the lung only accumulates about 29 and 50%, respectively of the MPOB. For inhalation exposures of soluble ^{239}Pu for six- and 12-months, the bone only accumulates about 1.1 and 2.2%, respectively of the MPOB. The bar graph illustrates how the dose from the lung is distributed from a six-month inhalation exposure at the MPC to insoluble ^{239}Pu, but no additional exposure. In the year of exposure, the total lung dose is about 3 rem, 20% of the annual limit to the lung. The total dose summed over the eight years is nearly 7.5 rem.

3.3 Radiation Protection Guide for Enewetak Inhabitants

Table D-3 contains a summary of radiation protection guidelines that were adapted to the future Enewetak inhabitants as a restoration goal, summarized by DNA (DNA 1981). These guidelines were separated into six distinct exposure categories and displayed in the Table with their bases from Federal Radiation Protection Guides (RPGs) of 1960 issued by the Federal Radiation Council (FRC). Among the six criterion, the most important were dose to bone and bone marrow, due to the importance of residual plutonium in surface soils and its propensity for deposition and retention in the bone. These goals were met by establishing restrictions on islands planned for residential use and those for agriculture, and the control of transuranics, e.g., plutonium and americium. Concentrations of transuranics in surface soils were controlled through soil excavation, and transport to and disposal in the Cactus Crater on Yvonne. Table 3-1 lists the threshold concentrations of transuranics in surface soils for each planned use scenario, and the number of islands that met the specific criterion upon project completion.

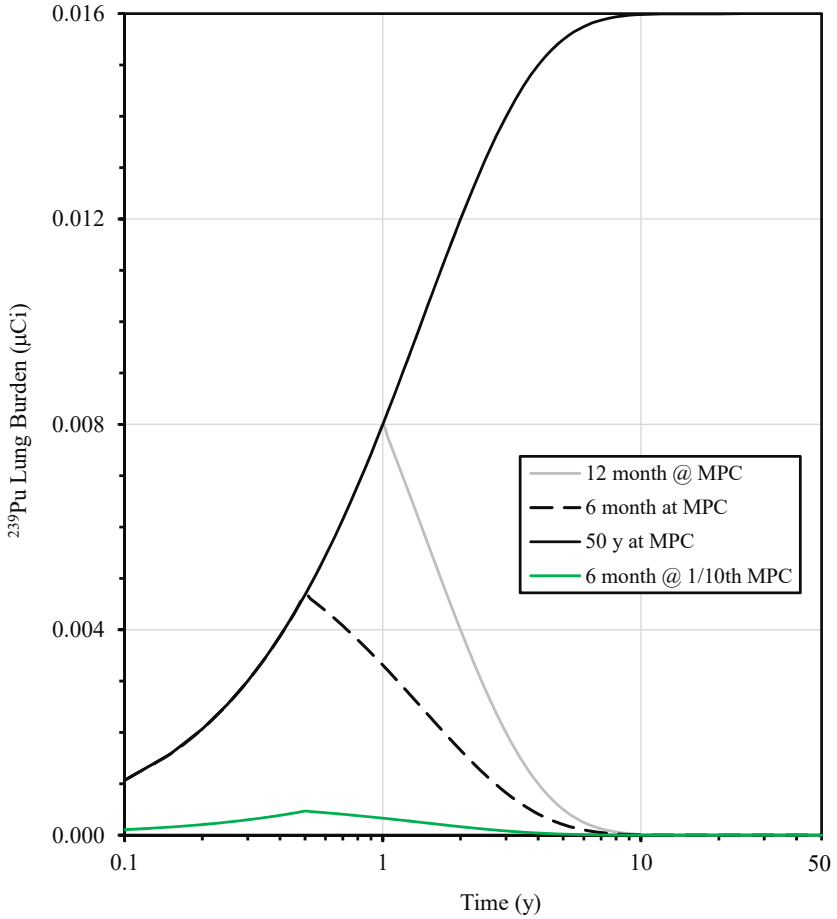


Figure 3-1. Lung Burdens for Various Inhalation Exposures to Insoluble ^{239}Pu using NBS Report No. 69 Metabolism.

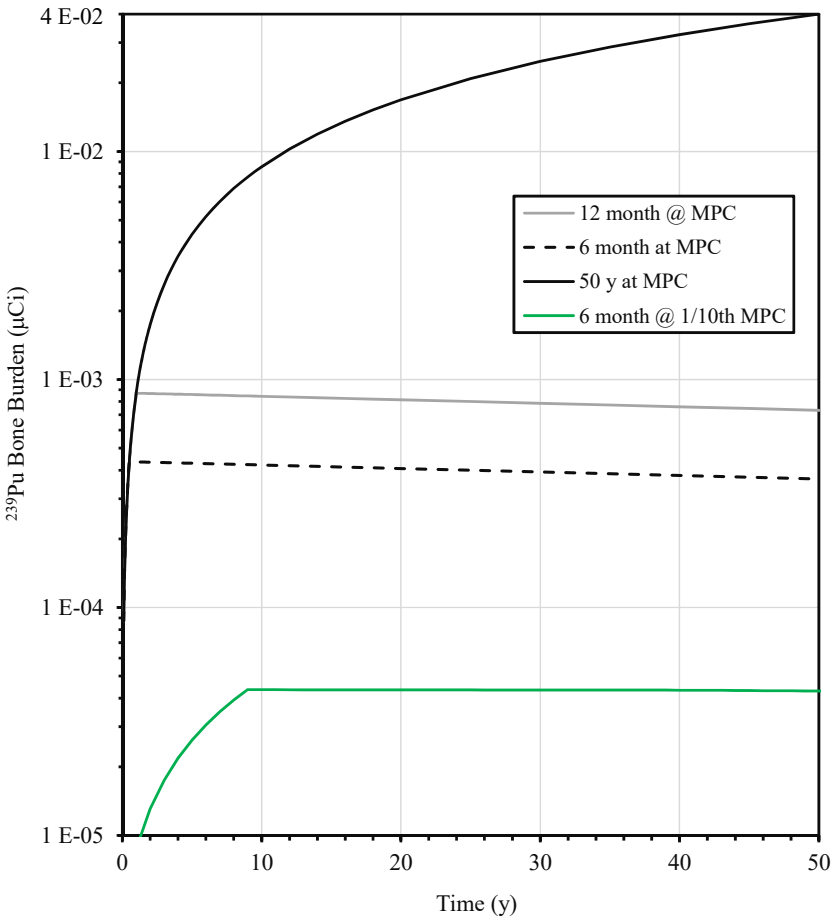


Figure 3-2. Bone Burdens for Various Inhalation Exposures to Soluble ^{239}Pu using NBS Report No. 69 Metabolism.

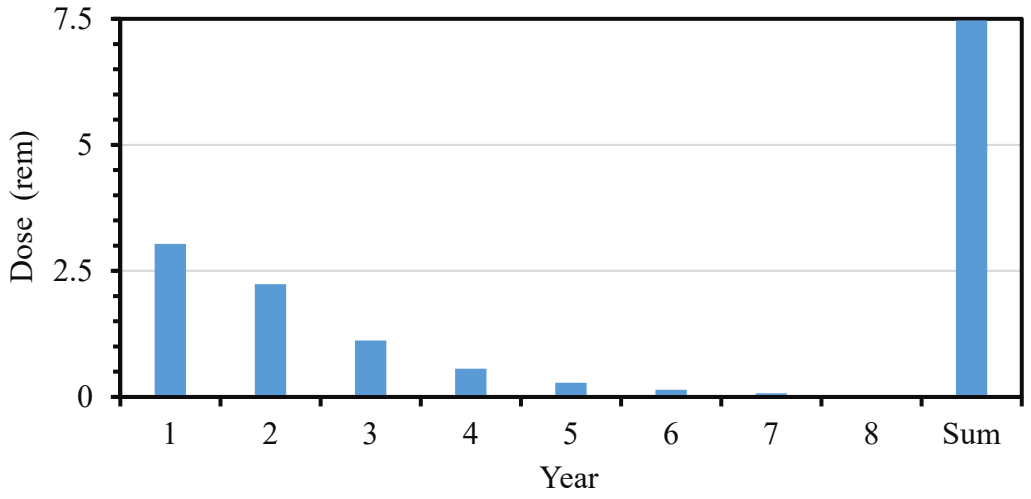


Figure 3-3. Annual Lung Doses from 6-month Inhalation Exposure in Year 1 at MPC for Air to Insoluble ^{239}Pu Using NBS Report No. 69 Metabolism.

TABLE 3-1. Average Concentration in Surface Soils* of Transuranics Established for Enewetak Restoration and Number of Islands Meeting Goal (DNA 1981).

Future Intended Use	Concentration Criteria (pCi g^{-1})	Notes	Project Completion Status, Number of Islands
Residential	40	Concentrations of transuranics averaged over one-quarter acre	30
Agricultural	80	Commercial crops of coconuts, pandanus, and breadfruit	7
Food Gathering	160	Infrequent visits to gather food such as coconut crabs, birds, and eggs	2
Quarantine	-	Yvonne	1

* Surface average defined as top 3 cm, as averaged over one-half acre, except for residential

During the restoration, the Environmental Protection Agency (EPA) drafted proposed guidance on dose limits for members of the public exposed to transuranium elements in the environment (EPA 1977). The draft guidance was initially prompted by the State of Colorado out of interest for exposures to the public in the vicinity of the Rocky Flats site. In contrast to the Federal RPGs of 1960 and their adaptation to Enewetak inhabitants, the EPA guidance was limited to transuranics. A summary table of the guidance is in Table D-4. Some concerns were raised during the Enewetak restoration that this proposed guidance would be applied to the Enewetak cleanup, as derived soil screening levels were equivalent to 13.3 pC g^{-1} of transuranic in surface soils, a value one-third the criterion established for residential islands (DNA 1981). Use of the newer proposed guidance, if implemented could have affected soil volumes planned for excavation and burial in the Cactus Crater. Nevertheless, the majority of the islands that were planned for future residential use had concentrations of transuranics in surface soils below the EPA guideline.

Two separate exposure criterions were contained in the EPA proposed guidance, both to underlying exposure to critical organs: the lung for inhalation of insoluble transuranium elements

and the bone for the ingestion exposure pathway. Similar in approach to the internal dose control methodology of NBS Report No. 69, dose limits were applied to the accumulated dose after a chronic lifetime exposure. In this case, 70 years. It is important to note that the EPA dose limits are in units of rad, while the dose limits used in NBS Report No. 69 are RBE dose, where the dose is modified by the relative biological effectiveness (RBE)[11] of the radiation type. In Report No. 69, the RBE for α-particle radiations was 10.

While this guidance was not implemented for Enewetak, it did provide a basis for the restoration of Johnston Atoll (Rademacher 2016).

3.4 Occupational Exposure Standards for Internal Emitters Under Later ICRP Guidance

In 1977, the ICRP updated their guidance for occupational exposures to ionizing radiation in Report 26 (ICRP 1977). The objectives remained largely unchanged from those made in 1959:

- the prevention of detrimental non-stochastic (dose threshold for occurrence) effect on the exposed individual,
- limitation of stochastic (probability of effect related to dose) effects on the exposed individual to acceptable levels, and
- limitation of stochastic effects on descendants of the exposed individual (hereditary).

The ICRP introduced the dose equivalent term to describe modification of dose with a unitless quality factor, Q, which varied by radiation type. This factor was applied in a similar manner to the RBE used in NBS Report No. 69 and ICRP Report 2. X-rays, γ-rays, and electrons have a Q of one, while for α-particles the factor was 20. Quality factors were developed for stochastic effects, most importantly to limit increased risk of cancer induction. In NBS Report No. 69, the RBE for α-particles was 10, and one for X-rays, γ-rays, and electrons (of moderate to high energy).

The 1977 ICRP recommendations limited exposure to the whole body, by applying an organ-specific weighting factors, w_T, for the dose equivalent received by the various organs of the body and limiting the summation of the product for the organs. Table D-5 contains a listing of the dose equivalent limits and weighting factors for specified organs. Although the critical organ approach for dose limitation was no longer used by ICRP, the factors used in this approach were incorporated into the organ weighting factors. The higher dose equivalent limits 15 and 50 rem, as applied to individual organs, extremities, and the lens of eye is specified to prevent detrimental non-stochastic effects.

Doses from internal radiation sources were managed by a new method. The committed effective dose equivalent (CEDE) was the accumulation of dose equivalent incurred over 50 y after an intake of a radionuclide within a year. For radioactive materials with short half-lives and/or short effective biological half-lives in the body after an intake, there will be relatively little difference in the committed effective dose equivalent and the actual dose equivalent incurred in the year an intake incurred. For radionuclides with long effective biological half-lives in the body after an intake, a few years to decades may be required to realize the dose from an intake. This is very important for long-lived actinides, e.g., ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Am, that have prolonged retention in the body after an intake.

[11] RBE a ratio of dose of a reference radiation (commonly γ-rays) to the dose from another radiation type to produce the same biological endpoint.

The primary criteria of ICRP 26, the total effective dose equivalent (TEDE), which is comprised from the sum of the deep dose equivalent from external radiation sources and the CEDE from internal dose from intakes, has an annual limit of 5 rem. This limit is the same as the 5 rem annual limit to the whole body under NBS Report No. 69, with the exception for the allowance of 12 rem for individuals of greater age and limited occupational exposure history.

In 1990, the ICRP again updated their guidance for occupational exposures to ionizing radiation in Report 60 (ICRP 1990a). The primary criteria of ICRP, the effective dose (ED), was compiled in a little different manner than the TEDE in ICRP 26, but had the same annual limit guidance of 5 rem, as summarized in Table D-6. For five consecutive years, however, the guidance recommended a 2 rem per year average. The organ weighting factors were modified over the guidance in ICRP 26, as summarized in Table D-7. The red bone marrow and lung tissues had the same tissue weighting factors, while the bone surfaces, breast, and gonads were lower under ICRP 60. The colon and stomach had higher weighting factors under ICRP 60.

The US NRC did not implement the updated ICRP guidance of 1977 for licensees until 1994, but has not adopted ICRP 60. The Department of Energy (DOE) adopted the provisions of ICRP 60 in 2007. The ICRP in 2007 updated the 1990 recommendations of the ICRP in Publication 103 (ICRP 2007). Some changes were afforded to the organ weighting factors over those provided in ICRP 60. Two of the key changes were an increase of the weighting factor for the breast from 0.05 to 0.12 and a decrease in the factor for the gonads from 0.2 to 0.08. ICRP 60 replaced the use of the quality factor with radiation weighting factor, w_R. For the radiation types of concern for this report, w_R are the same as Q.

3.5 Impacts of ICRP Changes on Radiation Safety

Although recommended guidance for radiation safety in the US and internationally has had some important changes since the recommendations in 1959 to present day, from a practical standpoint, the changes would have had only a minor impact on operations conducted at Enewetak Atoll in 1977 – 1980. Exposure to external radiation are limited by the 5 rem limit to the whole-body that has remained consistent since 1959, though there were differences in limits to the skin, extremities, and allowance for 12 rem in a year for some individuals. The latter allowance, as noted earlier, was difficult to implement in a radiation safety program with varied age and radiation exposure histories of employees.

Potential internal exposures were normally protected by concentrations of radionuclides in air and water, respectively for inhalation and ingestion exposure pathways. Table D-8 contains a listing of annual limits on intake for ingestion and inhalation exposures, and derived air concentrations (DAC) for a 2,000 hour work year for occupationally exposed individuals from Federal Guidance Report (FGR) 11 (EPA 1987). The FGR was based on ICRP Reports 26, 30, and 48 as noted in the Table. Effluent concentrations that were intended to be applied to members of the public from NRC-licensed activities are also included for informational purposes. These were based on a 0.1 rem CEDE. For exposures on Enewetak, since natural water sources were not used by workers, the key exposure criteria was the in Table D-8 was the DAC for air. These were similar in application to the MPC_{air} values presented in Table D-2, from NBS Report No. 69. The differences between the MPC and DAC values are based on a combination of the dose limitation methodology (ICRP 2 versus ICRP 26) and the metabolic data in use within each of these sets of guidance.

Over time the ICRP metabolic models have become more sophisticated in their modelling of transport of radionuclides in the body. The improvements were based primarily on human physiology research, animal studies with exposure to radioactive materials, and the study of humans exposed to radioactive materials. The inhalation model used in ICRP 2 allowed for either soluble or insoluble forms of the radioactive materials listed in Table D-2, while ICRP 30 (ICRP 1979) provided for three different inhalation classes: D, W, and Y, which were based on the relative rate of transport/mobility days-D, weeks-W, and years-Y. The more recent lung model described in ICRP Report 66 (1994) provides for three different inhalation types: F, M, and S for radionuclides of concern for Enewetak cleanup personnel. The types are very similar to ICRP 30 inhalation classes: F ~ D, M ~ W, and S ~ Y. In spite of the advancements in knowledge since 1959, the acceptable concentrations of key radionuclides of concern for exposure at Enewetak Atoll are not substantially different in the most recent ICRP recommendations compared to those issued in ICRP 2. Figure 3-4 contains a bar graph of MPC or DAC concentrations for ^{239}Pu from a range of ICRP (and other US compatibles) occupational exposure recommendations. For the higher lung-transportable compounds of plutonium, there is a gradual increase in acceptable airborne concentration from ICRP 2 to the ICRP 26/30 combination, and the later ICRP 60/68 combination, which uses the ICRP 66 lung model. For the lower lung-transportable compounds of plutonium, the DAC under ICRP 26/30 dropped by a factor of nine from the ICRP 2 MPC value, but under a later version of ICRP 26/30 with ICRP 48 updates and the later ICRP 60/68 provisions, the DACs were increased back to higher levels. The changes over the various sets of recommendations are primarily due to modifications of the lung models applied to inhalation exposures, but also due to changes in the partitioning of plutonium deposition and retention half-lives among the internal organs. The changes in the ICRP 26/30 DAC values from ICRP 30, Part 1 to ICRP 30, Part 4 was due to these changes introduced by ICRP 48 for systemic distribution and retention of plutonium (ICRP 1986). Under ICRP 30, a 1 μm activity median aerodynamic diameter (AMAD) particle distribution for aerosols was the default for occupational exposures. ICRP 68 recommended the use of 5 μm AMAD particle distribution for aerosols as the default for occupational exposures. The DOE uses 5 μm AMAD particle distribution as the default for internal radiation exposure under 10 CFR 835. In dose reconstructions, a 1 μm AMAD particle distribution is commonly used because it typically provides higher dose estimates.

Figure 3-5 contains a bar graph of MPC or DAC concentrations for ^{137}Cs from a range of ICRP occupational exposure recommendations. Though ICRP 2 recognized MPC values for an insoluble chemical form, the more recent ICRP recommendations only recognized high lung-transportable chemical forms of cesium. Very minor changes in acceptable airborne concentration of ^{137}Cs have been made among the three sets of recommendations. This is due to the rather uniform distribution of ^{137}Cs throughout the whole body and the common whole body dose limit of 5 rem in ICRP 2, 26, and 60. Additionally, the metabolism of this radionuclide was well studied as it is a prominent fission product. It is interesting to point out that the DAC under ICRP 60/68 is lower for the 5 μm AMAD aerosol particle size distribution exposure case than that for the 1 μm AMAD case. This is more common for inhalation of high lung-transportable chemical forms of compounds. In these cases, there is generally a high overall transport of the radionuclide to systemic circulation, regardless of where the radionuclide is initially deposited in the respiratory tract. As well, for inhaled material that is cleared from the respiratory tract, swallowed, and enters the gastro-intestinal tract, there is also very high uptake into systemic circulation. Dose to organs in the whole body are the limiting factor, vice dose to the lung. Hence, the key factor in derivation of the DAC for inhalation exposures is the fraction of the aerosol deposited in the respiratory tract. For the 5 μm AMAD aerosol particle size distribution exposure cases, the ICRP 66 respiratory model assumes about 82% of the aerosol inhaled is deposited in the respiratory tract, 28% is exhaled. For the 1 μm

AMAD aerosol particle size distribution exposure cases, the ICRP 66 model assumes that almost 49% is exhaled.

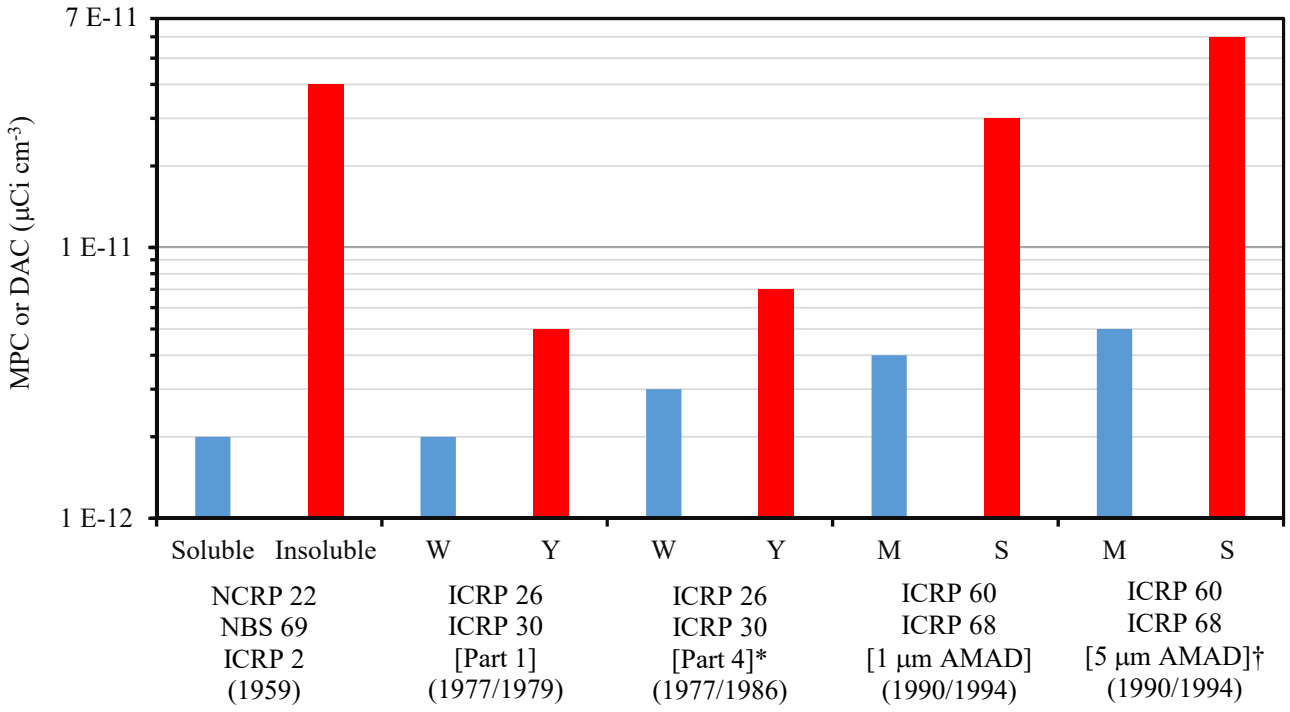


Figure 3-4. ICRP MPC or DAC Values for ^{239}Pu for Occupational Exposures. [* Updated from ICRP 48, †5 µm activity median aerodynamic diameter (AMAD) deemed more appropriate for occupational exposures].

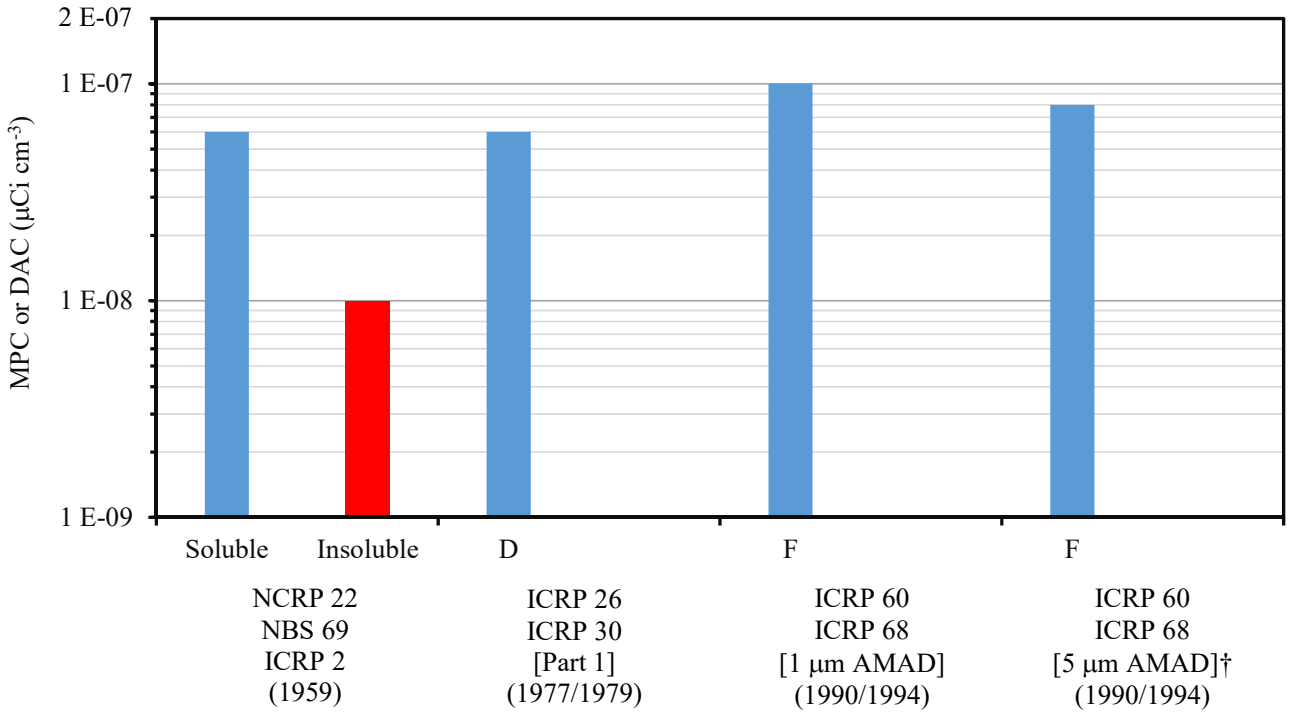


Figure 3-5. ICRP MPC or DAC Values for ^{137}Cs for Occupational Exposures. [†5 µm activity median aerodynamic diameter (AMAD) deemed more appropriate for occupational exposures].

Figure 3-6 contains a bar graph of MPC or DAC concentrations for ^{90}Sr from a range of ICRP occupational exposure recommendations. The ICRP, under Reports 26/30 and 60/68, provided recommendations for either a low or high lung-transportability chemical forms for strontium. In review of the ICRP recommended MPC and DAC values, there are some similarities to the evolution of acceptable airborne concentrations of ^{137}Cs and ^{239}Pu. Like ^{239}Pu, the acceptable airborne concentrations of soluble forms have increased between successive sets of ICRP recommendations. For insoluble forms, the DAC under ICRP 26/30 dropped a little, but in the ICRP 60/68 set, it is very similar to the MPC under ICRP 2: one lower and the other higher, dependent on the aerosol particle size distribution. Under ICRP 60/68, the difference in DACs for the 1 and 5 µm aerosol particle size distributions are similar to ^{239}Pu for the Type S, but similar to ^{137}Cs for Type F.

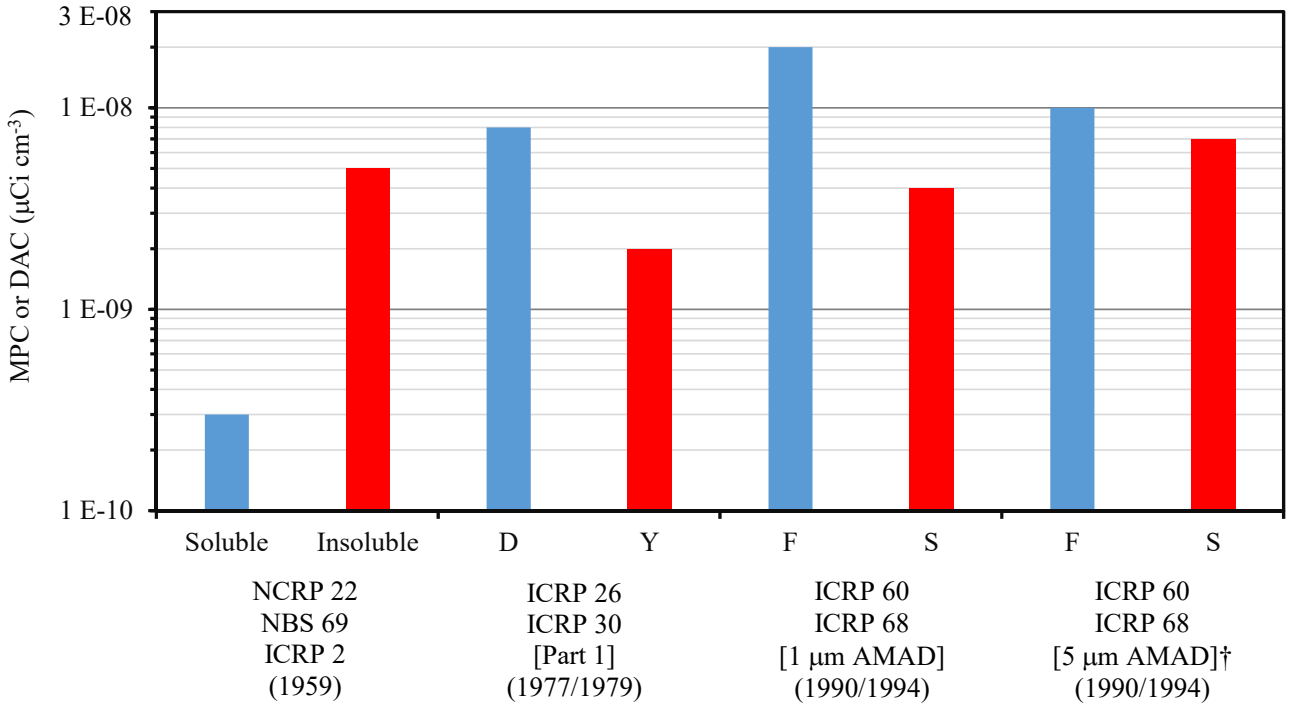


Figure 3-6. ICRP MPC or DAC Values for ^{90}Sr for Occupational Exposures. [†5 µm activity median aerodynamic diameter (AMAD) deemed more appropriate for occupational exposures].

Overall, the acceptable airborne concentrations of these three key radionuclides has not changed substantially since 1959 in spite of the growth over the many decades in radiological health science knowledge. The standards development process incorporated conservative margins of safety as a compensatory measure for knowledge gaps that may have existed.

3.6 Dose Conversion Factors

The MPC and DAC values are used as a radiation protection tools to assess airborne concentrations of radioactive materials in relation to acceptable annual intakes. In the process of determining DAC values, the 50-y integrated dose to tissues and organs are compiled, as referenced to unit intake values. In a similar manner, the same calculations are accomplished to determine the annual limits of intake by the ingestion pathway. These values are referred to as dose conversion factors (DCF) for ICRP 26/30, though under ICRP 60/68 they are termed dose coefficient (DC).

These factors are used to estimate tissue/organ doses for individuals with known or estimated intakes of radioactive materials. For the purposes of individual tissue/organ dose estimates made in this report, dose conversion factors based on ICRP 68 methods will be used. Tables D-9 and D-10 contain inhalation and ingestion DC values, respectively, from a number of ICRP reports. A bar graph of DC values from ICRP 68 for inhalation exposures to 1 µm AMAD, Type S material is shown in Figure 3-7, while ingestion of the same material is in in Figure 3-8. The plots clearly

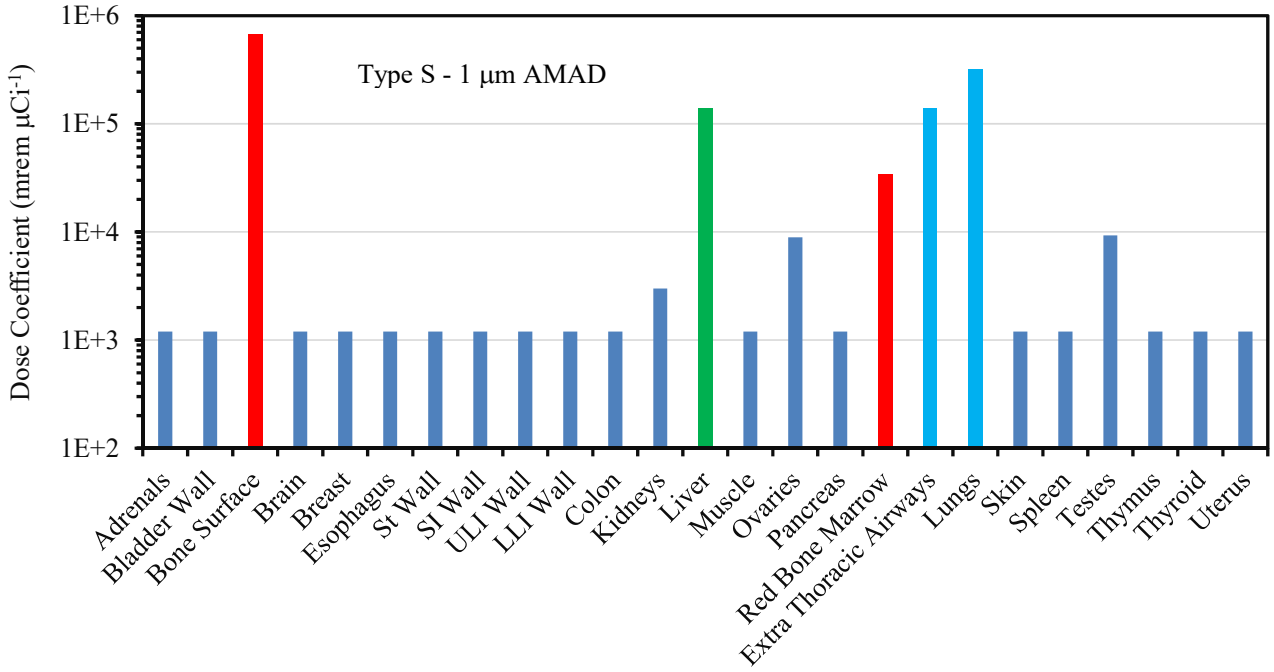


Figure 3-7. Dose Coefficients for Inhalation of Type S ^{239}Pu under ICRP 68.

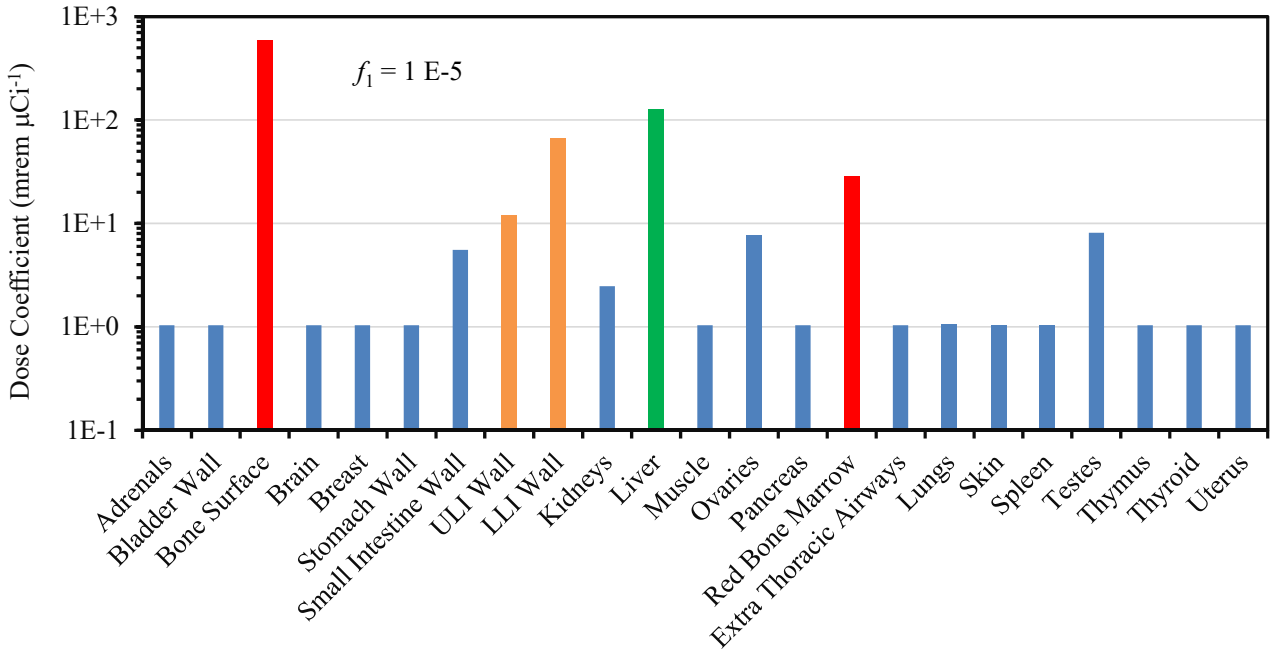


Figure 3-8. Dose Coefficients for Ingestion of $^{239}PuO_2$ under ICRP 68.

illustrate the organs with the greatest estimated dose from respective inhalation and ingestion exposures. For inhalation, the lungs, extra thoracic airways, bone surfaces, liver, and red bone marrow receive the greater cumulative dose over 50 years after an intake. For ingestion, of $^{239}PuO_2$, the organs receiving the greatest cumulative doses are the bone surfaces, red bone marrow, liver, and the large intestines, for the gastro-intestinal tract uptake factor, f_1, is 1×10^{-5}. The upper and lower large intestines (ULI and LLI) receive dose from two sources: during transport of content through the tract as feces, and material deposited by through blood stream transport to the organ.

The chemical form of the material either inhaled or ingested affords different distributions of dose to the organs and tissues, and therefore is an important factor in radiation protection programs and assessing doses after an exposure has occurred, "dose reconstruction," which is one purpose of this report. For the Enewetak cleanup, the MPC_{air} for insoluble forms of plutonium was used for radiation protection purposes. It is a common dose reconstruction practice to use DCFs (and DCs) that provide the highest CEDE (under ICRP 26) or committed effective dose (CED) under ICRP 60. For some exposures, however, it is likely that radionuclides are in a chemical form that supports the use of a DCF (or DC) that does not provide the highest CEDE or CED. The choice of a conservative DCF (or DC) for one organ can in some cases can be contradictory for other organs. Figure 3-9 illustrates this concept for ^{239}Pu. For Type M aerosols, the bone surfaces, liver, and red bone marrow have higher doses than for the Type Y aerosol, while the opposite is the case for the lungs and the extra thoracic airways (nasal cavity, pharynx, larynx). This bar graph also illustrates the effect of the aerosol particle size distribution. For internal organs, 1 µm AMAD Type M provides the highest committed equivalent dose to the bone surface, liver, and red bone marrow, while 5 µm AMAD Type S provides the highest dose to the extra thoracic airways and 1 µm AMAD Type S to the lungs.

The appropriate choice of chemical form for ingestion is dependent on the types of ingestion being modelled for an exposure assessment. The common ingestion pathways are ingestion of food grown on contaminated land, ingestion of contaminated water, incidental ingestion of contaminated soil, and ingestion of animals grazing on contaminated land. The chemical form of radionuclides

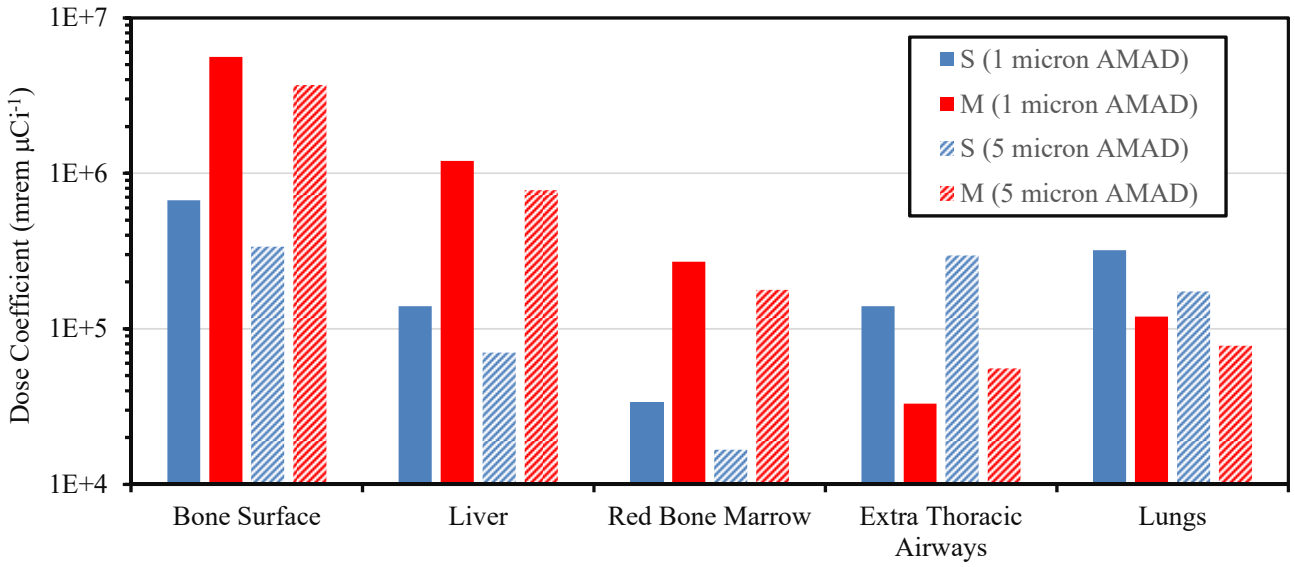


Figure 3-9. Dose Coefficients for Inhalation of ^{239}Pu to Key Organs under ICRP 68.

among these pathways could be varied. The chemical form of the radionuclides involved in the incidental ingestion of soil should be very similar to that suspended in air and available for inhalation exposure. In contrast, radionuclides in the commonly consumed portions parts of plants, e.g., foliage, fruit, seed pods, and water, would normally be associated with chemical forms having higher mobility in soil and plants. ICRP (1992) noted that many elements incorporated into food may be more readily absorbed from the GI than inorganic forms. Subsequently, ICRP in their default assumptions for environmental exposures to members of the public from radionuclides recommends the use of a high GI tract uptake factor, f_1, which is often equivalent to the highest f_1 value among those listed for chemical forms of radionuclides ingested by workers. For ingestion intakes by residents of Enewetak Atoll, this may be a reasonable assumption due to the importance of locally grown food to diet. However, for individuals that were part of the Enewetak cleanup, where incidental ingestion of soil was the only ingestion pathway of importance, use of f_1 values consistent with the f_1 used for inhalation exposures is deemed more appropriate. As well, environmental studies on transuranics in Pacific Atoll soils have shown that the vast majority of transuranics remains in relatively insoluble chemical forms (Rademacher 2016). Figure 3-10 shows DC values for key organs from ingestion of ^{239}Pu for the f_1 values listed in ICRP 68. For most organs impacted by systemic deposition, the DC values for the organ are directly proportional to the f_1. For the organs displayed in Figure 3-10, the exceptions to this rule exists the ULI and LLI walls. This is due to the contribution of dose from the transport of material through the tract, and material deposited in the tissues via gut uptake and distribution by the blood stream.

3.7 Internal Metabolism

Some characteristics of the plutonium metabolism in the human body are clear from the dose coefficients illustrated in Figures 3-8. For plutonium that makes it to the blood stream, the bone surfaces (BS) and the liver have preferential deposition and retention. The important characteristics that influence biological behavior were discussed in early research by Durbin (1960), among these: oxidation state stability at body pH, solubility of the stable state, tendency to be incorporated into organic compounds, and tendency to associate with specific proteins. Table D-11 provides a generalized summary of internal biokinetic characteristics of elements, as summarized by chemical

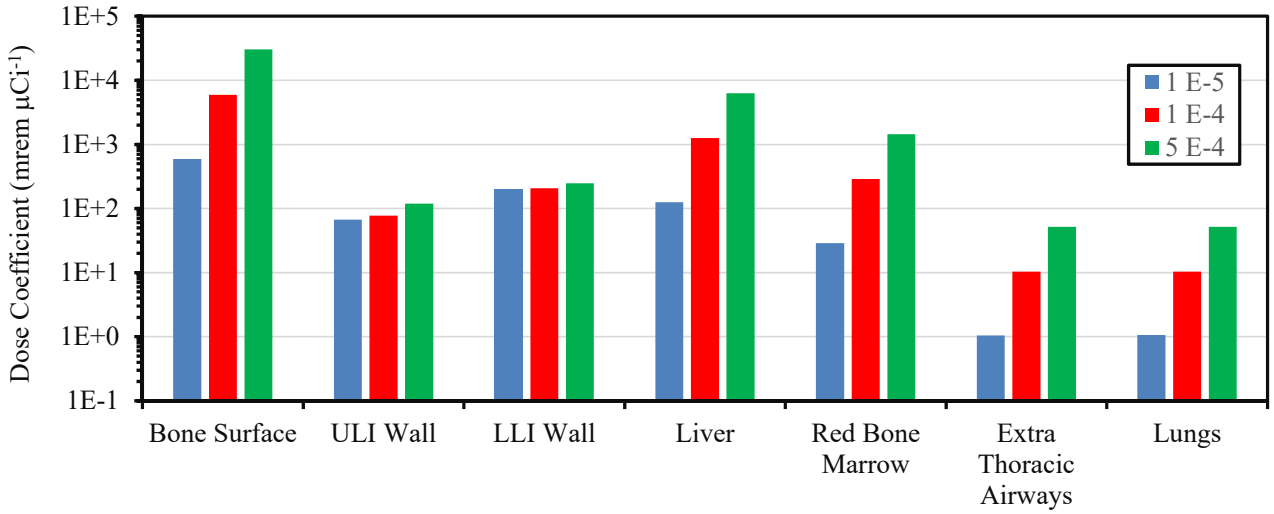


Figure 3-10. Dose Coefficients for Ingestion of $^{239+240}$Pu to Key Organs under ICRP 68 with Different GI Tract Uptake Factor, f_1.

group. In general, there is much similarity in the biological metabolism of elements within a chemical group. For example, like potassium, cesium has preferable deposition and retention in the skeletal muscle. In spite of this, there is a uniform distribution of dose among all organs and tissues of the body, as evident from the DC's for ^{137}Cs contained in Table D-10. This condition is due to the prominence of the energy of the γ-ray emitted by ^{137}Cs, and its deposition of energy in adjacent tissues. Cobalt, ruthenium, and rhodium, transition metals, have fairly uniform distribution in tissues. The lanthanides and actinides have preferable deposition on the BS and liver. Though the materials are assumed to be deposited on the surfaces, over time there is redistribution to the volume of the bone. In contrast, strontium, as an alkaline earth is metabolized in a similar manner to calcium, being deposited in mineral bone. Strontium, however, does not have preferable deposition in the liver. The deposition of radionuclides on the BS and mineral bone also provide dose to the red bone marrow (RBM). For radionuclides with the energy release primarily from α-particle emission, DC factors for RBM are about 20-fold lower than the DC for BS, while for ^{90}Sr, the DC factor for RBM is only about 2.4-fold lower. The difference is due to the much greater penetration range in tissue of the β-particles emitted by ^{90}Sr/^{90}Y, as compared to that of an α-particle. Because its β-particle emissions and its deposition in bone, it has a reasonably high dose to the RBM.

Uranium has some deposition and retention characteristics similar to the alkaline earths in its deposition in mineral bone, but as a heavy metal, it also has preferable retention in the kidney, similar to mercury and bismuth. Bismuth (Bi), however, does not have preferable deposition and retention in the bone. Antimony (Sb), also a metalloid, has preferable deposition in the skeleton and liver, similar to the lanthanides.

Another important factor defining the relative magnitudes of DCs among organs and tissues of the body for inhalation pathway exposures is the f_1 value. This factor defines the fraction of inhaled material cleared by the respiratory tract and entering the gastrointestinal (GI) tract that is transported into the blood stream from within the GI tract. Table D-12 lists the factors for the elements in Tables D-9 and D-10. There is some consistency among chemical groups. For examples, the lanthanides and actinides have low GI tract uptakes, as compared to other elements. An exception is uranium, which has a much higher assumed f_1. For some elements, there is some difference among inhalation type compounds, while for others the factors remains the same. Cesium has the highest f_1, of one, while soluble forms of strontium have a value of 0.3.

Overall, among all radionuclides listed in Tables D-9 and D-10, the DCs are higher among heavy elements that decay by α-particle emission, due to their much higher radiation-weighting factor, as compared to that of β-particles and γ-rays.

3.8 α-Particle Emitters

Due to the importance of the α-particle emitters as a potential source of internal exposure, it is useful to provide a comparison of DC values for these radionuclides. Figures D-1 and D-2 contain bar graphs comparing the DC values for $^{239+240}$Pu, ^{241}Am, ^{238}Pu, ^{234}U, and ^{232}Th. In Figure D-1, the most insoluble ICRP 66 inhalation type is listed for each radionuclide, while for D-2, Type M is assumed, which is the most soluble option under ICRP 66, except for uranium. For each radionuclide, the DC is shown for the BS, liver, RBM, extra-thoracic (E-T) airways, lungs, kidneys, and the overall effective dose (ED). For the BS, liver, and RBM, the DC is highest for ^{241}Am among the isotopes compared in Table D-1. This is logical due to the greater uptake of ^{241}Am to the blood

stream through the lung tissue than for the other radionuclides. On the other hand, due to the greater retention of the other radionuclides in the respiratory tract the DCs the lung and E-T airways are for the other radionuclides, as compared to ^{241}Am. Notable is the nearly identical DC for $^{239+240}$Pu and ^{238}Pu, due to their identical metabolism and similar α-particle energies. For inhalation of Type M compounds shown in Table D-2, there is somewhat similar DC values for $^{239+240}$Pu, ^{241}Am, ^{238}Pu, and ^{232}Th, while ^{234}U is notably lower.

For this work, a mixture of inhalation types was assumed for each radionuclide to appropriately assess the internal exposure, as listed in Table 3-2. For isotopes of plutonium, 80% is assumed to be Type S, dioxide chemical forms, with the balance to Type M, which represents other potential chemical forms. Though ^{241}Am is most commonly associated with plutonium, and is assumed to have similar metabolism in the lung, ^{241}Am is more commonly assigned an inhalation Type M. For this report, all ^{241}Am is assigned to Type M. For ^{234}U, it is assumed that the majority exists in a moderately lung-transportable Type M, with about 30% in less transportable oxide types. A small fraction is assumed to be in a readily transportable Type F. ^{232}Th is assumed to be 90% Type S and 10% Type M, where the Type S typifies environmental thorium. A comparison of DCs for this mixture is in Figure 3-11. Similar to the discussion above for the two histograms contained in Figure D-1 and D-2, ^{241}Am has the highest DC for BS, liver, RBM, kidneys and effective dose. Overall, the DC for ^{234}U is lower than DCs of other radionuclides.

TABLE 3-2. Inhalation Types Assumed for This Report.

ICRP 66 Inhalation Type	Fraction of Inhalation Intake				
	$^{239+240}$Pu	^{241}Am	^{238}Pu	^{234}U	^{232}Th
F	-	-	-	0.05	-
M	0.2	1.0	0.2	0.65	0.1
S	0.8	-	0.8	0.3	0.9

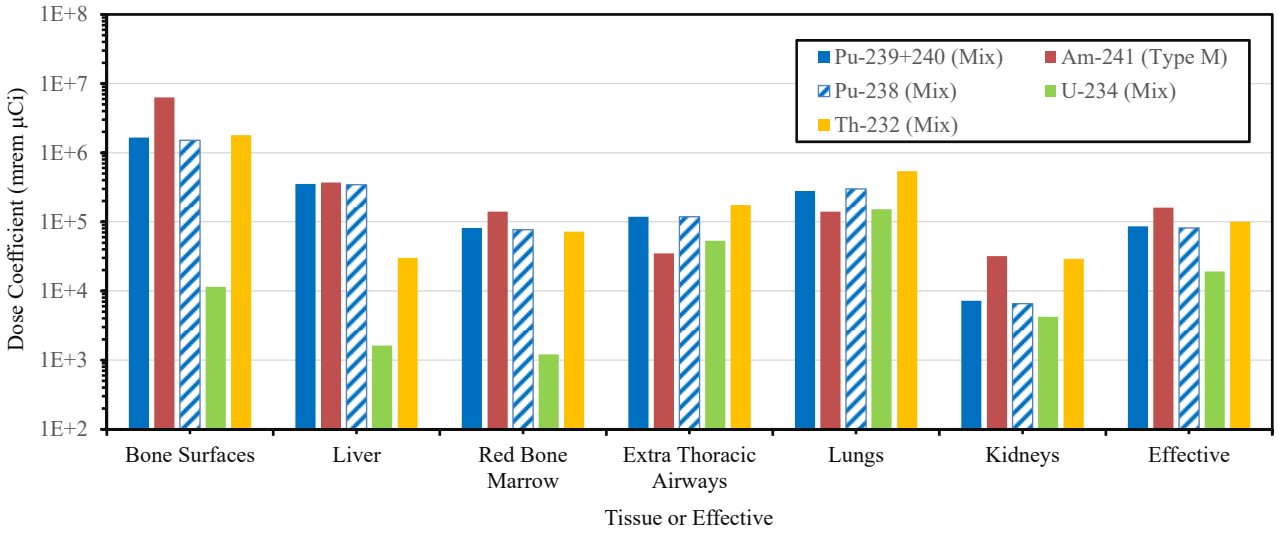


Figure 3-11. Inhalation Dose Coefficients for α-Particle Emitting Radionuclides in Soil, Based on Mixtures Specified in Table 3-2.

Under the premise that the inhalation types assumed were reasonable for the radionuclides in soils, some important conclusions can be drawn. First, the DCs for ^{238}Pu are reasonably close to those of $^{239+240}$Pu, such that $^{239+240}$Pu DCs could be used for $^{238+239+240}$Pu. Second, the DCs for ^{232}Th are similar enough to those for ^{241}Am and $^{239+240}$Pu to allow evaluation of ^{232}Th with respect to the activity concentration of these radionuclides in soil. As discussed above, ^{228}Th was detected only in samples in segments A and A/B of Yvonne. Due to the intervening time between testing and the restoration activities, it is a reasonable assumption that the daughter radionuclides are in serial equilibrium with the ^{232}Th primordial radionuclide (Figure C-15). DC's for inhalation of ^{232}Th and daughter decay-chain radionuclides are listed in Table D-13. From the table, it is apparent that DC's for the two isotopes of thorium dominate the total effective dose DCs. ICRP does not provide DCs for radionuclides with very short half-lives, e.g., ^{222}Rn, ^{216}Po and ^{208}Tl. For these radionuclides, tissue dose are only deemed important as provided by the biokinetic behavior of parent radionuclides. Overall, the sum DC values listed are 1.8- and 3.3-fold higher than the respective DCs for ^{232}Th. With a 90:10 partition between inhalation Types S and M, the mix has a DC of 3.1E+5 mrem μCi^{-1}, 3.1-fold higher than the DC for the same mix of ^{232}Th alone. The mean residual ^{228}Th observed in the top 10 cm of segments A and A/B were 3.3 and 0.9 pCi g^{-1}. Therefore, for approximate equivalence with ^{232}Th and $^{239+240}$Pu, these residuals can be scaled by a factor of 3.1, e.g., 10.2 and 2.8 pCi g^{-1}, respectively. For segment A, with a mean $^{239+240}$Pu of 31 pCi g^{-1} in surface soils (Table 2-17), the residuals from ^{232}Th and its daughters effectively increase the internal radiation exposure hazard by a factor of 1/3. For segment A/B, the impact of the same residuals is only a factor 1/12 of the $^{239+240}$Pu. ^{230}Th is also likely present in Sections A and A/B as a co-contaminant; its impact is dependent on its relative abundance with ^{232}Th. Its metabolism is similar to ^{232}Th.

The third important conclusion from the comparison of DCs for α-emitting radionuclides is for ^{234}U. As discussed above and summarized in Table 2-16, the mean ^{234}U in surface soils on the northern island is assumed to be less 1.3 pCi g^{-1}, with the excess ^{234}U from testing (i.e., above pre-existing background) only 0.69 pCi g^{-1}. Clearly, due to the lower ^{234}U DCs, as compared to those for $^{239+240}$Pu, and the low estimated activity concentrations of ^{234}U compared to $^{239+240}$Pu, it is a negligible residual contaminant.

Section 4

Radiation Safety Program

4.1 Organization and Implementation

The radiation safety program developed for the Enewetak Cleanup was integrated into the Joint Task Group (JTG) structure, as shown in Figure 4-1. The joint task group commander was an Army Corps of Engineers colonel who reported to a brigadier general who commanded Field Command, DNA at Kirtland AFB. Staff officer in the JTG divisions were all Army personnel, with a number of subordinate divisions and teams filled with personal primarily from the individual services. The largest team was the engineer supported by the Army to carry out the removal and disposal of debris and contaminated soil, and construction of the entombment structure. While radiation safety practices were exercised by all personnel assigned to duties where access controls were emplaced, the radiation-specific tasking were delegated to all services and DNA, as summarized in the upper portion of Table 4-1. The tasks listed in the bottom portion of the Table list

the other actions of the service elements, which will be discussed later in this report. The Army had 2,670 personnel supporting the Enewetak cleanup, the largest among all services. Three levels of radiation control administration were accomplished on the Atoll (DNA 1981). An Army field grade officer (colonel, lieutenant colonel, or major) was assigned as the radiation protection officer (RPO), with a staff of Army company grade officers (captains) and enlisted technicians. A radiation control committee (RCC) was chaired by the Deputy Commander JTF and consisted of a number individuals on the JTF. The RCC met at least every calendar quarter (DNA 1981). Hands-on radiation safety was accomplished by a 33 person field radiation support team (FRST) comprised of USAF enlisted technicians under staff supervision of the RPO. These personnel provided hot-line control, air sampler operation, dosimetry issue/collection/reading, radiation control procedure supervision, and contaminated personal and equipment designations. Radiation safety specifications were contained

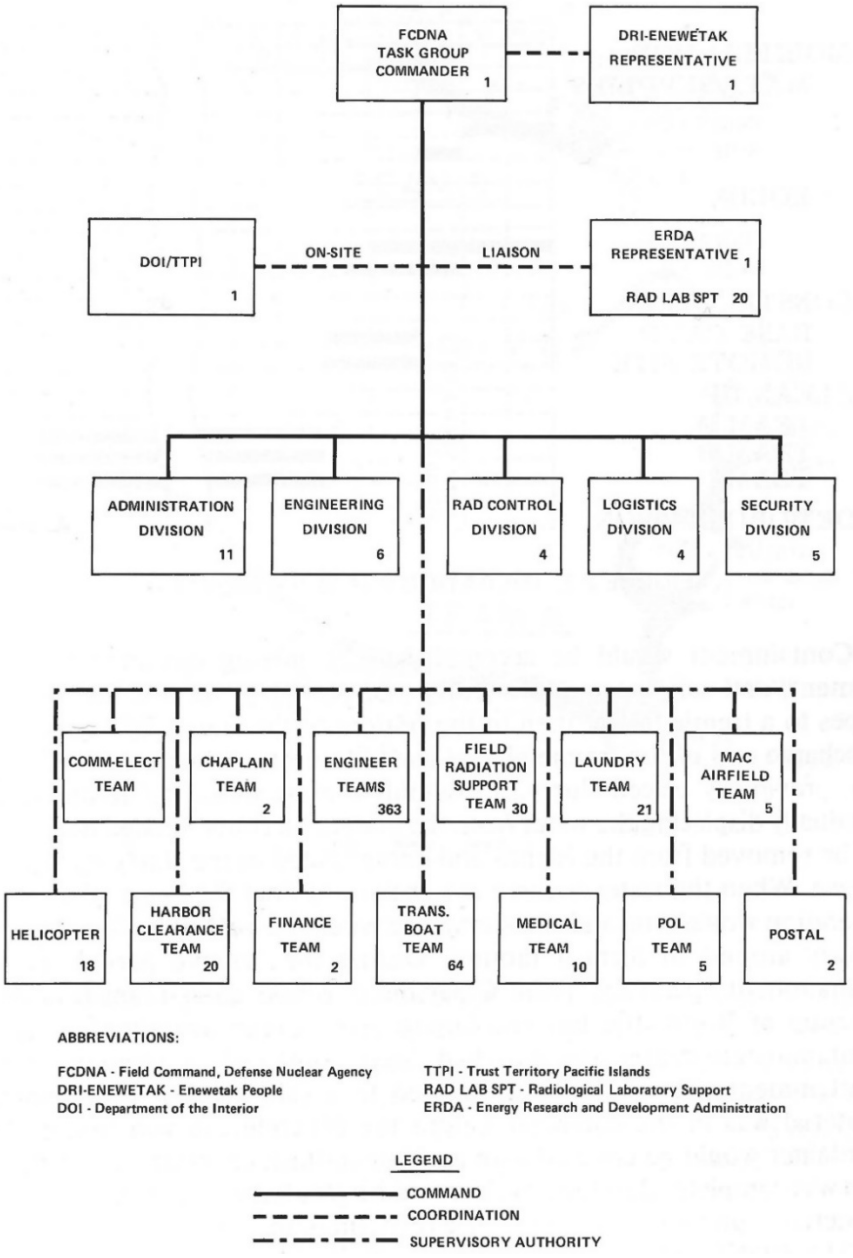


Figure 4-1. Joint Task Group Organization [Figure 2-6, DNA (1981)].

in 18 standard operating procedures (SOPs) and 12 instructions documents (DNA 1981). In addition to the three levels of radiation control, DNA chartered a radiation safety audit and inspection team (RSAIT), with the chairperson of this team headed by the Director of the Armed Forces Radiobiology Research Institute (AFRRI). AFRRI during the Enewetak Cleanup was a part of DNA. The team conducted 10 visits to the Atoll and one to DNA's Field Command office in Albuquerque, NM.

Table 4-1. Military Service Element Organization for Enewetak Cleanup [from DNA (1981)].

Army	Navy	Air Force	DNA
n = 2,670	n = 2,207	n = 740	n = 246
- On-site radiation safety planning and oversight* - On-site health physics support - Site radiation protection officer (RPO) - Radiation safety audit and inspection team members	- Radiological and laboratory technicians - Radiation safety audit and inspection team members (RSAIT)	- Field radiation support team - Radiological and laboratory technicians - Radiation safety audit and inspection team members	- Radiological safety oversight and review - Chairperson radiation control committee (RCC) - RSAIT taskings
- Chaplain team - General laundry team - Decontamination laundry - Engineering units - Helicopter team - LARCs and amphibious vehicle - Financial team	- Intra-atoll transportation - Harbor clearance teams - Beach cleanup - Submerged debris cleanup	- Airfield operations - Postal team - POL team - Medical teams - Communications & electronic support teams	- Command, Joint Task Group - Logistics - Security - Project administration - Engineering support

* Command, JTG

4.2 Radiation Exposure Controls, Protective Measures, and Monitoring Methods

4.2.1 Controlled Island Access. The northern islands of the Atoll were controlled during the remediation to the protocols established by the radiation protection officer (RPO). Access control included a number of specific actions that were common to entry on all islands, though some actions were islands specific. One common item for all was the mandate to wear external radiation dosimetry, whether it was a film badge, pocket dosimeter, thermoluminescent dosimeter (TLD), or a combination of these. Another requirement was the maintenance of a log listing access to controlled islands on an individual and daily basis. Dosimeter numbers were also specified on logs as a RPO protocol. Although not a specified protocol, it became a practice to also annotate the level of

personal protective equipment (PPE) used by individuals on a daily basis, and island-specific. In preparation of this report, the Air Force Safety Center digitally compiled a spread-sheet type controlled island access log. An access log to the southern islands of the Atoll were not specified in a radiation safety protocol, as radiation safety controls were only applied to a minor contaminated area on one southern island. DNA did log entry and exits onto Enewetak Atoll for individuals that participated in the cleanup. A large fraction of individuals that supported the projects, however, never worked on the controlled access islands on the northern part of the Atoll. As such, no radiation safety protocols would have been prescribed for their work.

4.2.2 Hot-line Controls. For some islands and specific work, hot-lines were established. In some cases hot-lines were established to control worker access to areas with external radiation exposure rates much higher than the average for an island. A number of examples of these areas on some islands were discussed in Section 2.3.2, with isoexposure contour examples in Appendix B. Many of these areas were associated with activated metallic debris, as summarized in Table 2-8. DNA (1981) noted that hot-lines were established in areas where the external exposure rates were below 50 $\mu R\ h^{-1}$. From Table B-1, only two islands were projected to have mean external exposure rates in excess of 50 $\mu R\ h^{-1}$ during the cleanup – Alice and Belle. FRST members controlled access and support to personnel conducted removal actions in areas of higher exposure rate. FRST activities were supported with portable radiation survey instruments. Hot-lines were also used to control access to areas where entry required the use of respiratory protections and/or protective clothing. In these cases, hot-lines were established up-wind of the controlled area. It was noted by DNA (1981) that it was fairly easy to establish hot-lines for this purpose, due to the relatively consistent direction of the trade winds. Hot-lines were the location where personnel wearing PPE were screened upon leaving the controlled area, in addition to the screening of equipment. FRST members performed contamination monitoring and access to work areas through hot-lines. It was a common practice to conduct air sampling at the hot-line entry control point. Additional air samplers were typically placed at multiple location downwind and within work zones, with the number of samplers dependent on the scope of dust-generating operations. According to the air sampling procedures, nominally it was recommended to use a single sampler for areas of 100 ft^2 or less, two for areas between 100 and 1,000 ft^2, and three for areas between 1,000 and 10,000 ft^2. Air sampling was a FRST function. One of the most notable activities that was strictly controlled by the hot-line controls was soil removal and loading operations. Greater attention to controls for this activity is concern for greater levels of air-suspended surface soils.

4.2.3 Attention to Upwind Areas. Personnel were indoctrinated to adhere to simple habits that minimized exposure (DNA 1981). As an example, for pedestrian activity near a road, personnel would walk on the windward side of the road to limit presence in an area of elevated air-suspended soil by vehicle traffic. During soil removal operations, unnecessary activities were not accomplished in downwind locations. Necessary activities, however, mandated the use of air purifying respirators, and varied additional PPE.

4.2.4 Water Spray Application. During and operation that was anticipated to increase soil resuspension, lagoon water was sprayed over the area where work was being conducted. Operations that dictated this procedure was used prior brush removal and all soil movement operations, from excision, stockpiling, loading, and off-loading (DNA 1981).

4.2.5 PPE Protection Levels

Personal protective equipment specifications are listed in Table 4-2. There were four primary levels: I, II, III, and IV, with two sub-level specifications for levels II and III. Action levels are specified for various levels of contamination on personnel, in air samples, and ground surfaces. For protection from inhalation, the most important PPE item was positive-pressure, air-purifying respirators. Levels III and IV specified positive-pressure, air-purifying respirators. Level IV required a full-face respirator, while level III either a half- or full-face respirator. For assessment of airborne activity, DNA (1981) noted that the first action level was set at 10% of the adjusted

TABLE 4-2. Personnel 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="5">α: < 60 cpm
β: < 200 cpm
γ: < 15 μR h^{-1}</td><td rowspan="3">α: < 55 cpm h^{-1}
β: < 3,250 cpm h^{-1}</td><td>α: < 300 cpm
β: < 540 cpm
γ: < 2,000 μR h^{-1}</td></tr>
<tr><td>IIA</td><td>Rubber boots</td><td rowspan="2">Above plus arms and legs</td><td rowspan="4">α: < 3,000 cpm
β: < 7,200 cpm
γ: < 2,000 μR h^{-1}</td></tr>
<tr><td>IIB</td><td>Rubber boots and surgical mask*</td></tr>
<tr><td>IIIA</td><td>Rubber boots, gloves (as appropriate), and positive-pressure air-purifying respirator</td><td rowspan="2">Whole body</td><td rowspan="3">α: < 5,500 cpm h^{-1}
β: < 325,000 cpm h^{-1}</td></tr>
<tr><td>IIIB</td><td>Same as IIIA & anti-contamination clothing</td></tr>
<tr><td>IV</td><td>Same as IIIB, plus mandatory gloves, full-face respirator (vice half-face option), and openings in clothing taped</td><td>Whole body</td><td>α: < 300,000 cpm
β: < 7,200 cpm
γ: < 2,000 μR h^{-1}</td><td>α: < 300,000 cpm
β: < 7,200 cpm
γ: < 2,000 μR h^{-1}</td></tr>
</table>

* Although surgical masks are shown as minimum level of "respiratory protection," they served other purposes. See Section 4.2.6 for more information.

Notes: 1. Alpha (α) and beta (β) action levels refer to measurements taken over the area of the appropriate probe.
2. Action levels for air refer to samples taken using the Roots M102 air sampler. For Staplex air samplers multiply the α-values by 2.8 and multiply the β-values by 4. For RAS-1 samplers, divide the α-values by 2 and multiply the β-values by 2. Filters should be monitored every two hours.
3. Table assumes the following probes are used: α – AC-3 (Eberline PAC-1S); for β – HP-210 (Eberline Pancake G-M)

MPC for controlled access islands, while the second action level was set at 50% of the adjusted MPC. As noted above, with an MPC of 40 pCi m^{-3} for ^{239}Pu and a maximum work period of 60 h in a week, the action levels were respectively 2.7 and 13.5 pCi m^{-3}. If airborne concentrations exceeded the lower action level, it was necessary for the attending FRST to collect nose swipe samples from all personnel that were within the air sampling zone and not wearing a respirator (DNA 1981). Table 4-2 does not list this monitoring action. If the second action level was reached, nose swipe were collected from all personnel in the work zone, and personnel not wearing respiratory protection would be mandated to don an appropriate respirator, along with other PPE. Portable instrument response indices for the action levels in air are listed in Table 4-2. The first α-radiation criterion listed, < 55 cpm h^{-1}, is approximately equivalent to the count rate observed by an Eberline PAC-1S with an AC-3 α-scintillation probe, for a typical air collection flow rate[12], as normalized to the total sampling period in hours, and equivalent to 50% of the MPC. The second set of action levels listed for air are 100-fold higher than the first set, and for α-radiation represent airborne concentrations less than 50-fold higher than the ^{239}Pu MPC. DNA (1981) did not note the basis for this criterion, however, it is speculated that this criterion is rooted in the minimum 100-fold assigned protection factor for some types of respiratory protection. Of note: some full-face respirators have assigned protection factors of 1,000. Since none of the air samples were near this second set of action levels, the requirement to implement more protective respiratory protection was not required. On Ursula, the MPC for a 168-h exposure week was used as the exposure limiting criterion, which was 1×10^{-11} μCi cm^{-3} (pCi m^{-3}), four-fold lower than the MPC for 40 h[13].

In spite of the actions levels delineated for air, decisions on respiratory protections were very conservative. This approach is best summed-up by a statement from Dr. Edward Bramlitt, the DNA civilian health physicist,

> *"The Radiation Safety Audit team described the Enewetak air samples as 'insignificant' and 'well below acceptable concentrations.' On the other hand, Director, DNA [Admiral Monroe] is known to be concerned about low-level radiation, and taking steps to insure exposures are not only low but lowest."* (DNA 1978)

This was very much the case in the early stages of the project, where air sampling history was limited. Prior to initiation of work, there was only a limited amount of air sampling data collected for preparation of the 1973 AEC report. Airborne concentrations were fairly low, however, it was understood that these samples were collected under mostly quiescent conditions. Operations involving surface soil disturbances were expected to increase suspended aerosol concentrations. In April and May 1977, Field Command, DNA evaluated air samples collected in both up- and down-wind locations during aggregate hauling operations on Janet and Ursula (DNA 1977). The results of this sampling will be discussed later along with all air sampling conducted during the cleanup.

The very conservative approach in application of PPE did require some practical modifications. For example, in early work by the 84th Engineering Battalion in preparation for the batch plant on Yvonne, full protective gear was worn by personnel in trenching conducted near the

[12] The Roots-Tecumseh air sampler was assumed to have a typical flow rate of 17 ft^3 min^{-1} and open filter area of 231 cm^2 (DNA-OALG 1 Aug 78 MSG). The Staplex TF-1A air sampler had a typical flow rate of 50 ft^3 min^{-1} and open filter area of 406 cm^2.

[13] The conversion factor between the 40-h and 168-h MPC values is 3.0 [Due to single digits, range of ratio of MPC values listed in ICRP 2 are between 2.5 and 4.]

Test Erie GZ (DNA 1981), as shown in Figure B-22. The heat and humidity made work conditions unbearable, greatly impacting the number of hours personnel were able to work in a day, due to the necessity to provide rest breaks. In this circumstance, a high degree of protection from one potential hazard - airborne radioactivity, had a potential to compromise worker health. Hourly breaks had to be instituted due to the fatigue introduced by level IV PPE. PPE can also negatively impact productivity and in some cases increase risks of other injuries due to reduced vision, mobility, dexterity, etc. Hence, the application of PPE for the remainder of the cleanup was varied dependent on the type of work and existing conditions, based on DNA's evaluation of work in the Test Erie GZ (DNA 1981). Of note: between 27 June and 31 December 1977 on Yvonne, FRST collected 242 air samples, with a total volume of 31,800 m^3 and an average of 131 m^3 per sample. Among the samples, none had a mean activity concentration greater than 1% of the MPC. The sample with the highest activity concentration was only 0.07 pCi m^{-3} (0.26% MCL). While concerns existed for high levels of activity buried in the Test Erie GZ prior to work, surface concentrations of $^{239+240}Pu$ were about 24 pCi g^{-1} in the top 30 cm (DNA 1981), well within expectation of AEC data (see Table 2-12, segment C). Some sub-surface soils had activity concentrations between 150 and 282 pCi g^{-1}.

Another example of the conservative approach in assignment of respiratory protection was the widespread requirement for positive pressure air purifying respirator use, in spite of the fact that none of the air samples analyzed had detection of α-particle activity concentration greater than 10% of the adjusted MCL. From Table 4-2, positive-pressure air purifying respirators were not required unless the action level of 50% of the MPC was exceeded. It is very clear from review of controlled island access logs that this type of respiratory protection was specified at much lower levels of airborne α-particle activity concentration.

The other criterion listed in Table 4-2 were less important in designation of PPE levels. For example, because airborne α-particle activity was the primary concern for internal exposure concerns, airborne β-particle activity did not affect PPE decisions. The ground contamination γ-radiation notes a consistent < 2,000 $\mu R\ h^{-1}$ (2 mR h^{-1}) across all PPE levels. This criterion is somewhat misleading. Some areas with debris had external exposure rates in excess of this level. The 2 mR h^{-1} criterion was used primarily as a basis for FRST monitoring support in these areas of elevated exposure. This exposure level has been a long-standing threshold level in 10 CFR Part 20 for delineating unrestricted from restricted areas, though the exposure is traditionally defined over any one hour period of exposure time. As discussed in Section 2 and listed Table 2-8 only a few areas on Janet, Pearl, Sally, and Yvonne had exposure rates this high based on the AEC survey (AEC 1973). Due to the dominant contribution of ^{60}Co in producing the exposure and its 5.26 y half-life, many of these areas may have been below the 2 mrem h^{-1} exposure rate during the cleanup.

4.2.6 Dust Masks (Surgical Masks)

In general, dusk masks do not remove particulates from air to the same degree as air purifying respirators and are not generally considered, then or today, a form of PPE, except for low hazard levels. Air purifying respirators generally have much superior effectiveness in the removal of very small and large suspended particles compared to masks that are most effective at primarily the larger particles. Dust masks also have varied levels of venting dependent on the type of mask and it's mating to the individual wearer, which can allow air to circumvent the filter. While this is also a concern for air purifying respirators, this issue is much less significant.

The use of the masks in this project likely reduced the inhalation of nuisance dusts by individuals. The Occupational Safety and Health Administration (OSHA) recognizes that these types of particulate respirators are the least protective types available, but may be appropriate for low hazard level environments. However, their use was not a critical PPE element of the radiation safety program. Subsequently, no credit was assumed in the reduction of airborne radiological contaminants if individuals wore a dust mask for their work or not.

4.2.7 External Exposure Monitoring

Film badges were initially the primary dosimetry monitoring device planned for use, supplemented by direct-reading dosimeters. The latter were small pocket ion chamber (PIC) type of detectors. Initially, visitors to the Atoll were provided PICs during their visits to the controlled islands. The film badges were supplied by the US Army Lexington-Blue Grass Depot. Due to the high heat and humidity encountered at the Atoll, some damage was observed in these dosimeters. As a solution, the detectors were placed in plastic bags with a desiccant which reduced incidence of the problem, though not completely (DNA 1981). In May 1978, dosimetry needs were supplemented by US Navy thermoluminescent dosimeters (TLDs). The TLDs were not affected by the heat and humid conditions of the Atoll. These devices were worn in parallel with film badges and replaced the use of PIC self-reading dosimeter issue for visitors.

For exposure cases, where a film badge was damaged or lost, and a supplemental TLD was not worn, administrative doses were calculated based on occupancy times and dose rates established for specific islands. This method was reasonable since exposure rates were fairly uniform with the exception of areas of contaminated debris that provided enhanced exposure in isolated areas. Due to the close attention paid to control of personnel exposures in these areas by FRST, cases of individuals with damaged or lost badges could have their exposures appropriately calculated if they worked in any of these areas. As discussed in Section 2, these areas were limited in number. While PICs were issued and read daily for visitors to controlled islands, TLD issuance to visitors was for the period of the visit. Based on review of controlled island entrance logs, visitors to the Atoll generally had only a day to a few days on controlled islands.

Most military members assigned to long-term duties on the Atoll were deployed for six-month periods (179-day temporary duty tours), while JTG were assigned to one year tours. Personnel assigned to long-term duties on controlled islands typically were assigned film badges and/or TLDs for monthly periods. Therefore, individuals' assigned to long-term duties typically had five to seven dosimetry monitoring periods. Though DOE and their contractors are not the primary focus of this report, the monitoring provided to these personnel was handled in a similar manner as for the DoD personnel. Some DOE civilians and contractor personnel supported operations on the Atoll numerous times over the period of the project, but for periods of only a few days to a week. Many of these visits were for management oversight or specialized technical work. Some DOE contractor personnel supporting the Enewetak Radiological Support Project (ERSP) function had more routine presence on the Atoll, i.e., with a common six-week rotation. Most of these individuals would have had only on a few dosimetry records. Personnel supporting the ERSP were typically on-site technical representatives, radiation measurement support personnel, or laboratory personnel.

Collective dosimetry records were monitored very closely by JTG. Radiation protection staff investigated readings that appeared anomalous. A few unique cases will be discussed later. JTG established an electronic database to maintain record of all individuals visiting or deployed for duty to the Atoll. The database noted arrival and departure dates, dosimetry monitoring periods and

results, nose swipe and urine bioassay results, and controlled island access dates. The portion of the records for DOE and their contractor personnel remain available in portable document format (pdf). Unfortunately, the portion of the records for military members and DoD civilian members were not found in a search of DTRA archived records. A substantial number of external dosimetry, nose swipe, and urine bioassay records for military and DoD civilians are contained in DTRA archived records, though most are not compiled on an individual basis. Controlled access entrance logs, however, have been digitized and compiled on an electronic spreadsheet by the Air Force Safety Center. Some exposure records have been added to this record. Dosimetry records for military members were sent to the individuals and DoD components upon completion of their assignments to the Atoll. As such, this information may be in archived medical records of veterans and/or in military service dosimetry databases.

Dosimetry monitoring was primarily issued for individuals that worked on controlled access islands. Dosimetry monitoring was also provided for some individuals that may have worked only on the southern islands of the Atoll. The most notable cases were for individuals that worked in the radiological laboratory due to the potential for handling radiological samples. As well, some individuals that worked on Ursula, yet did not perform work on other northern islands were provided dosimetry. This applied primarily to clinic personnel.

4.2.8 Air Sampling Results

4.2.8.1 General

DNA (1981) provided a simple summary of air sampling data. During the cleanup, a total of 5,204 air filters were analyzed, with a total sampled air volume of 866,227 m^3 and an average of 166 m^3 per sample. Figure 4-2 contains a bar graph of α-particle activity concentration on air filters. About 51% of the samples had non-detect α-particle activity concentrations, displayed as 'zero

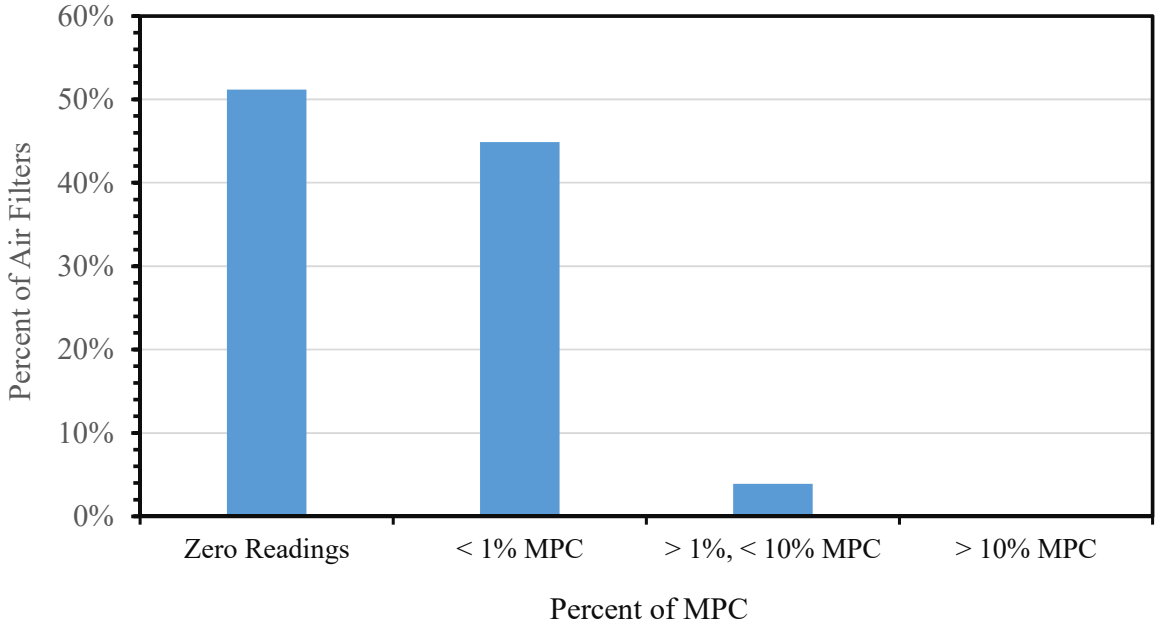


Figure 4-2. Distribution of α-Particle Activity Concentration Among Air Samples [MPC = 27 pCi m^{-3}].

reading' in the bar graph, while about 45% of the samples had detectable activity, yet below 1% of the MPC. Only 3.9% of the samples had activity concentrations greater than 1% of the MPC. All were less than 10% of the MPC, with the sample with the highest activity concentration at 2.07 pCi m^3, 7.7% of the MPC. Air sampling was accomplished to varying degrees across the northern islands of the Atoll. The greatest amount of air sampling was performed during operations involving soil excision, loading, and transport for disposal in the Cactus Crater. With the exception of some soil excavated from Janet, soil removal was specifically dictated due to levels of plutonium in excess of the final endpoint desired for an individual island.

Since Ursula was being used as a residence island for workers with assigned duties on the northern islands during the restoration, air sampling was conducted on this island between April 1977 to September 1979. Islands where soil removal was not accomplished only had a limited number of air samples. For example, among Alice, Belle, Daisy, Kate, Lucy, Nancy, Olive, Ruby, and Tilda, only 62 air samples were collected. However, only 24 of these samples had a positive detect for α-radiation, none had α-radiation concentrations above 1% of the MPC, and the sample with the highest activity concentration was only 0.12 pCi m^{-3} (Belle). No air sampling was conducted on Clara, Edna, Mary, Vera, or Wilma. These islands had similarities to the others discussed immediately above with regard to concentrations of plutonium in surface soils and the type and scope of restoration activity. Hence, similar air sampling results would have been observed.

Air sampling was also conducted during the transport of soil on water transport vessels. This activity was not initiated until spring 1978. Airborne α-radiation concentrations of samples were unremarkable in 1978 – not a single sample had α-radiation concentrations above 1% of the MPC. However, between February and September 1979, a number of samples had concentrations greater than 1% of the MPC. The majority of these samples were collected in April and May. This condition dictated the use of respirators for personnel assigned soil transport duties on watercraft. More details of the air sampling data will be discussed below.

4.2.8.2 Airborne Resuspension Tests Conducted on Janet and Ursula

In April and May 1977, DNA conducted resuspension studies for plutonium on Janet and Ursula during aggregate hauling operations – an activity that was expected to create higher airborne activity levels than quiescent conditions. For most air sampling actions, samplers were placed in areas both upwind and downwind of the aggregate hauling operations. Three air samples collected in the beach area of Janet on 6, 7, and 8 May were only collected downwind of the aggregate hauling operations. Table E-1 contains a summary of the air samples collected during these measurements. Overall, with the exception of one paired-set of samples, 20 April on Janet, the downwind air samples had higher $^{239+240}$Pu activity concentrations than their paired upwind sample. Due to the low activity concentration for eight upwind air samples, the values are listed as less than the minimal detected concentration (MDC). Though accurate ratio assessments cannot be assessed due to this data limitation, the median ratio of upwind to downwind activity concentration is estimated to be about 0.056. Estimated resuspension factors listed in Table E-1 are based on mean surface soil concentrations of $^{239+240}$Pu on the respective islands, as noted in the table. In comparison of the resuspension factors for aggregate handling operations on Ursula and Janet, it appears that the $^{239+240}$Pu concentrations assumed for Janet should be much lower than the mean $^{239+240}$Pu in soils. The soil samples for these work were analyzed by MCL for isotopic plutonium through chemical separation and α-particle spectrometry (DNA 1977). In contrast, the majority of air samples collected during the cleanup were analyzed for gross α-particle activity.

4.2.8.3 Modelling Airborne Resuspension

A number of methods are available to estimate inhalation exposures. Air sampling is one of the preferred methods, since it directly measures airborne concentrations subject to inhalation. Airborne concentrations can also be predicted from the concentrations of contaminants in surface soils. During the cleanup, the relationship between measured airborne α-particle activity concentrations and soils concentrations closely evaluated by health physics staff members at DNA.

Two common resuspension models are used to predict resuspension: a mass loading model and a resuspension factor model. In the mass loading model, the airborne activity is predicted from the mean surface soil activity concentration, S_o, the total suspended particulate mass loading, M, in units of mass per volume of air, and the enhancement factor, E_f, which relates the average activity concentration in the suspension to that in soils. As described by Shinn (1998), the product of these terms is equivalent to the airborne activity concentration, C_{Air}:

$$C_{Air} = E_f S_o M.$$

The mass loading can be characterized for a site, and soil concentrations can be established through sampling and analysis. Shinn (1998) lists the top 5 cm for determining mean surface soil concentrations, though other authors may recommend different averaging thicknesses. Shinn (1998) noted that enhancement factors were "usually less than unity, typically 0.7, for non-fissioning types of accidents [i.e., the Palomares, Spain nuclear weapons accident, and nuclear weapon safety experiments conducted in the Pacific, and the Nevada Test Site and Tonopah Test Range in Nevada] and at large distances from fission events [Bikini and Enewetak Atolls, Maralinga Australia (British nuclear weapon tests)]." Shinn (1998) noted that traffic and bulldozer blading temporarily increased enhancement factors between 2.5 and 6.5. In theory, these activities are better able to resuspend soil particles than wind alone. Shinn (1998) noted that for radiologically-impacted sites caused by nuclear fission, near ground-zero, a substantial amount of the Pu was contained in small glass beads that were too large for resuspension, with enhancement factors estimated near 0.01. At Enewetak Atoll, Test Scaevola was a weapon safety experiment test and effectively so was Test Quince, since it did not have a yield. The area around Test Quince GZ was well noted for the existence of discrete WGP particles.

Figure E-1 displays the annual mean mass concentrations of airborne particulate in non-urban air monitoring stations in the continental US by the EPA (EPA 1977). In February 1977, LLNL also conducted some preliminary air sampling studies within a vegetated site on Janet, though more extensive studies were conducted on Bikini Atoll in May 1978 (Shinn et al. 1997). They measured a mass loading of 56 μg m^{-3} under quiescent conditions on Janet. The AEC (1973) estimated the quiescent condition from air samples collected during site characterization about 40 μg m^{-3}. Table E-2 lists some of the aerosol characteristics from the LLNL work on Janet and Bikini Atoll. The broad range of enhancement factors were characteristic of Shinn's findings for a broad survey of sites (Shinn 1998).

The resuspension factor model predicts airborne concentrations based on the product of areal deposition, D, and a resuspension factor, S_f, which has the dimension of the reciprocal of length:

$$C_{Air} = S_f D.$$

Areal deposition, D, for a freshly deposited contaminant is readily assessed by measurements or modelling. Adaptation of this factor to aged surface deposits is performed by substituting D with the product of S_o, soil density, ρ, and the surface soil thickness subject to resuspension, t:

$$D = S_o \rho t.$$

As noted in Table E-1, S_f values were based on a t = 1 cm and a ρ of 1.5 g cm^{-3}. Anspaugh et al. (1974) summarized some early models for temporal changes in resuspension factors, as summarized in Figure E-2. The Kathren and Anspaugh et al. models is based on an initial resuspension factor of 10^{-4} m^{-1}, while the model described by Smith et al. (1982) used an initial resuspension factor of 10^{-5}, based on Nuclear Regulatory Commission (NRC) use. The Smith and Anspaugh (1975) models restrict the resuspension factor to a minimum of 10^{-9} m^{-1}. Also shown is the case of the Anspaugh model without the 10^{-9} m^{-1} minimum restriction. At the time the Anspaugh et al. (1975) model was described, only 15 - 17 y of field data was available. The Langham and Kathren models were developed from short-term studies of fallout from nuclear experiments at NTS, and were not intended for long periods of time after initial deposition. The NTPR uses a standard assumption of a 10^{-5} m^{-1} resuspension factor for most dose reconstruction applications when individuals entered areas with freshly-deposited fallout, though higher values are assumed for some activities that notoriously generate dust, i.e., helicopter landings (NAS 2003). Due to the long period between the test period and cleanup, resuspension factors developed for early period after deposition are not applicable to airborne contaminants during the cleanup.

The variability in the models results from differences in the periods after deposition data was collected and differences in the types of contamination and their circumstances for initial deposition. The reduction in resuspension over time is primarily due to attachment of contaminants to soil particles, which presumably have lower potential for resuspension from wind and surface disturbances than the contaminant alone, migration to greater depths by chemical and physical processes, and redistribution on the horizontal plane. These processes are primarily controlled by soil conditions, weather conditions, ground cover, and land use.

Shinn, a co-author of the Anspaugh et al. (1975) paper, in evaluation of post-accident inhalation exposure potential from plutonium noted that extensive empirical data from accident sites involving the dispersal of plutonium exhibited reductions in airborne plutonium by five orders of magnitude in the first 20 to 30 days after initial deposition (Shinn 1998). Shinn further noted that the 1975 Anspaugh et al. model was too conservative and over-predicts resuspended plutonium and that long-term steady-state resuspension would be in the 10^{-10} to 10^{-9} m^{-1} range. Anspaugh et al. (2002) provided an update on resuspension, along with information on the interception of airborne and waterborne radionuclides, and the weathering of radionuclides from soil surfaces into deeper soil layers. The authors proposed a predictive model to cover the vast range of data on resuspension to date with an upper and lower bound vs. time, as shown in Figure E-3. This model predicts significantly greater reduction in the resuspension rate in the early periods than the 1975 Anspaugh et al. model but retains a range of 10^{-8} to 10^{-10} m^{-1} for later periods, consistent with the Smith et al. (2002) model and the Anspaugh et al. (1975) model.

Stephens' (1995) best estimate of the expected value of respirable fraction from plutonium dispersed from high-explosive (HE) detonations was 20% of the total dispersal. The impact of this condition varies over time for resuspension of this material is not well characterized, but is assumed to be incorporated into the basis for the $10^{\pm 1}$ factor and the many sources of variability between sites discussed above. In this regard, it is also important to note that it is assumed that all of the aerosol sampled by the air sampling method used for the cleanup is within the range of aerodynamically respirable particle size. Due to the varied sources of contamination on the Atoll, there is expected to be

considerable variability in the accuracy of this assumption. Nevertheless, the assumption is conservative, providing high-sided exposure estimates.

The two models for resuspension are related by the following equality:

$$E_f M = S_f \rho t \text{ or } S_f = {}^{E_f M}/_{\rho t}.$$

Figure E-4 displays the resuspension factor for mass loading values from 40 to 600 μg m^{-3} and enhancement factors from 0.01 to 6. Soil density and the surface soil thickness subject to resuspension were assumed to be 1.5 g cm^{-3} and 1 cm, respectively. The upper value of mass loading was set at a value used by DTRA in their upper-bound assessment of doses to cleanup personnel for heavy dust generating tasks (DTRA 2017), while the low value was based on AEC measurements during quiescent conditions. DTRA noted a value of 100 for areas with truck traffic. The ratio of the upper and lower mass loading value is 15, which is similar to the median ratio of downwind to upwind activity concentration, 1/0.056 = 18. The range of enhancement factors is based on a range of values discussed by Shinn (1998) for numerous sites evaluated. For the combinations considered, the resuspension factors ranged from 2.7×10^{-11} to 2.4×10^{-7}, about four orders of magnitude.

The estimated resuspension values listed in Table E-1 ranged from 8.3×10^{-11} to 9.2×10^{-8} m^{-1}, spanning three orders of magnitude, yet fairly centered by a factor of three from the high- and low-range of Figure E-3. Note: due to limited sensitivity in the analysis of some upwind samples, the lower end of resuspension factors could be lower.

4.2.8.4 Air Sampling Results on Individual Islands

4.2.8.4.1 Ursula. Among northern island with relatively minor radiological impacts from atmospheric tests, air sampling was deemed important due to its use as a residence island for workers with assigned duties on the northern islands during the restoration. Among the 866,227 m^3 of air sampled during the cleanup, about one-fourth was dedicated to this island, though only about $1/7^{th}$ by total filter number; sampling performed on Ursula was for generally a longer duration than on other islands. Over two-thirds of the samples were non-detects, and among the filters with some detected activity, none had activity concentrations greater than 1% of the adjusted MPC. The filter with the highest activity concentration was only 0.09 pCi m^{-3}, only about 0.33% of the adjusted MPC (60-h workweek), and 0.9% of the 168-h MPC developed specifically for Ursula. Most of the samples with a positive detection for α-radiation activity were only 0.01 – 0.03 pCi m^{-3}. The air sampling was conducted between April – November 1977 covered the period of the camp construction and preparation for residence and between December 1977 and 14 October 1979 when it was used as a residence. By mid-October 1979, the limited number of workers with remaining work on the northern islands were billeted on Fred, one of the southern islands. There were no remarkable characteristics of the air sampling data over the duration of the sampling period.

4.2.8.4.2 High Sample Results

During the course of the cleanup, on occasion an air sample would have a concentration of α-particle activity that was higher than expected for an island based on previous air sampling results, expectations for the type of work being conducted, and/or the levels of plutonium in soils. This concern was expressed in spite of the low activity concentrations observed (DNA 1978). DNA suspected, among many potential causes of an occasionally higher than expected result, that other

radionuclides on the Atoll, including natural uranium, may have an influence due to the non-specific nature of the gross α-particle assessment method. Figure 4-3 is a histogram of mean activity concentration of expected α-particle emitters in surface soils of Ursula. For this plot, ^{238}Pu activity concentrations are expected to be negligible[14], while it is assumed that test-related uranium is a small fraction of the natural source. Clear from the mean values, the natural uranium and ^{241}Am combined are a greater source of α-particle activity than the $^{239+240}$Pu. Therefore, provided these radioactive materials all have similar resuspension characteristics, the α-particle activity concentration of these air samples will have only a 48% contribution from $^{239+240}$Pu and 32% from natural uranium within the Atoll environment. For islands with much higher mean levels of $^{239+240}$Pu, the influence of natural uranium on total sampled α-particle activity will be much less.

Another phenomenon not considered by DNA in the artifact of an occasionally higher than expected air sampling result is heterogeneity. The effect is due to the discrete nature of contaminants released to the environment by the nuclear weapons test, and the stochastic nature of the resuspension of soils particles and their sampling in air. To illustrate this concept, consider the one high air sample collected on Ursula in the week 25 February to 3 March 1979. Ten air samples were collected over this period, with an average of 147 m^3 per filter. Therefore, for an estimated

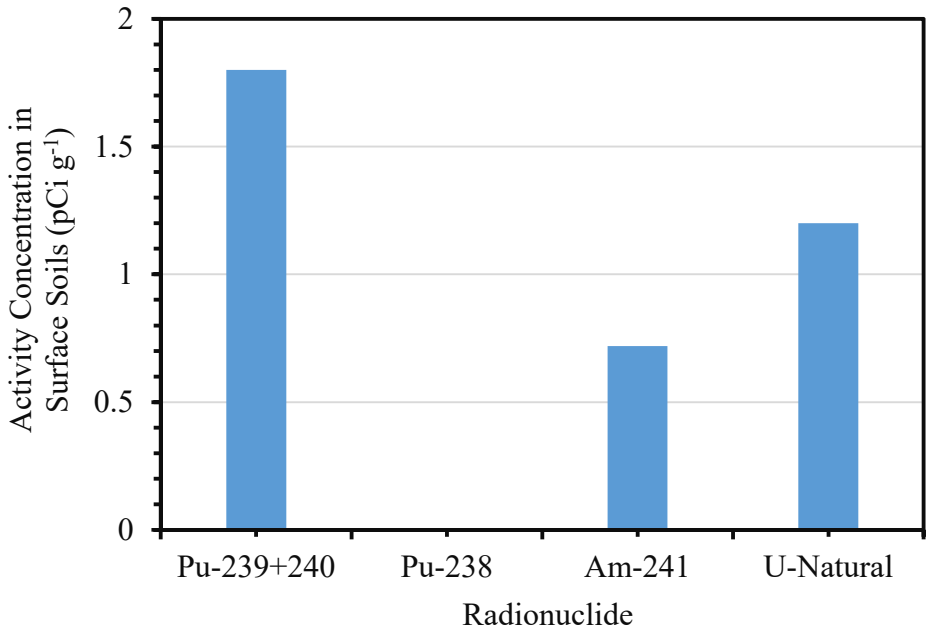


Figure 4-3. Histogram of Mean Activity Concentration of α-Emitters Expected in Surface Soils of Ursula (From Tables 2-16 and C-11).

average activity concentration of the filter, the total α-particle activity on this filter is only 13 pCi (0.48 Bq). Figure E-5 contains a plot of maximum particle activities and volume equivalent diameters for $^{239+240}PuO_2$ particles. Though the plot is for particles of pure dioxide, it is readily applied to particles with only a fraction of $^{239+240}PuO_2$ and inert material. Assuming that only about one-quarter of a filter was analyzed, the aliquot being analyzed would have an activity 3.25 pCi. If all (or the majority of the sample activity) was comprised of a single particle, it would have

[14] This is not a good assumption for some islands of the Atoll.

aerodynamic equivalent diameter (spherical) of about 7 μm. Particles of this higher range of aerodynamic equivalent diameters are a relatively small fraction of an aerosol by particle number, but represent a substantial fraction of the aerosol mass. As such, it is easy to appreciate the variability in activity concentrations of airborne $^{239+240}$Pu when a single particle can have a large influence on the total sampled activity where generally low activity airborne conditions exist. This was common for the islands where residual $^{239+240}$Pu activity concentrations were low in soils. The majority of air samples were non-detect for α-particle activity, yet for the small fraction of samples with positive detections, some had α-particle activities greater than expected for the average. Nevertheless, the samples with positive detections were very small in comparison to the adjusted MPC established for the cleanup.

4.2.8.4.3 Air Sampling on Alice, Belle, Daisy, Kate, Lucy, Nancy, Olive, Ruby, and Tilda

Among the 62 air samples collected on these islands, the total volume was only about 1% of the total air sampled. Due to the limited cleanup activities conducted on these islands, there was not an expectation for significant airborne radiological contamination with respect to the established MPC. As noted above, other northern islands did not have any air sampling conducted, though the radiological conditions on these islands were similar to islands within this group. For example, the conditions on Clara and Edna are similar to Alice, Belle and Daisy. The conditions on Mary are similar to Kate, Lucy, Nancy, and Olive, while those on Vera and Wilma are similar to Tilda. Appendix F contains details on debris and soil removal activities in a number of tables and figures, as summarized in Table 4-3. Since these islands did not have any soil removal actions, all key actions are summarized in Table F-7. For example, on Belle, debris survey and removal operations were conducted between March and June 1978. Some air sampling was conducted in January, February and May of that year, based on information in Table E-2. Among the samples collected on Belle, only one had a positive detect for α-radiation, though the α-radiation concentration was only 0.12 pCi m^{-3}. This sample was collected in February 1978, a period when IMP surveys and soil sampling were being conducted on the island. AF, Army, and DOE contractor personnel conducted work only on six days of this month. Air samples were collected on Alice in January, April, and May 1978. Alice had substantially more debris removed than was the case for Belle, however, like Belle, all of it was uncontaminated. Survey and removal actions were accomplished between February and June 1978. One air sample had a positive detect for α-radiation, but the average concentration was only 0.01 pCi m^{-3}, only 0.04% of the adjusted MPC.

Kate had a large amount of uncontaminated debris surveyed and removed between April and June 1978, with some air sampling conducted in December 1977 and April to June 1978. Among the 12 samples, five had positive detects for α-radiation, though the sample with the highest activity concentration was only 0.07 pCi m^{-3}, only 0.26% of the MPC. In spite of the negligible levels of airborne α-particle activity, two Army and one AF personnel wore level IIIA PPE on 25 May, while a lone Army individual wore level IIIA PPE on 26 May. Lucy had a lessor amount of uncontaminated debris removed than in the case of Kate, but with operations conducted over the same period. Similar to air samples collected on Kate, most samples had negligible levels of α-particle radiation. As well, in spite of the negligible levels of airborne α-particle activity, 20 man-days of work in May 1978 was conducted by personnel wearing level IIIA PPE of the total 187 man-days of work. Of the 61 individuals that worked on Lucy in this month, this level of PPE was only worn by 10 Army personnel. It is clear that only certain work conducted on Lucy in this month had this level of PPE specified. It is interesting to note that the 10 Army personnel that wore level IIIA

PPE, wore level I PPE on other work days in this month on Lucy. Nine AF FRST members worked on Lucy in May, but only one wore level IIIB PPE (on two days). With the exception of one workday wearing level IIA PPE, other FRST workdays were in level I PPE.

TABLE 4-3. Appendix F Tables and Figures Detailing Debris and Soil Removal Operations.

Table/Figure	Title
Figure F-1	Histogram of Debris Volumes on Southern Islands of Atoll
Figure F-2	Histogram of Debris Volumes on Northern Islands of Atoll
Table F-1	Volume and Transuranic Activity of Soil Excised during the Radiological Cleanup of Enewetak Atoll, from DOE
Table F-2	Soil Plowing and Excision Details for Janet, from DNA
Table F-3	Soil Excision Details for Pearl, from DNA
Table F-4	Soil and Debris Excision Details for Sally, from DNA
Table F-5	Soil Excision Details for Irene, from DNA
Table F-6	Soil and Debris Excision Details for Yvonne, from DNA
Table F-7	Debris Survey and Excision Details for Other Northern Islands, from DNA
Table F-8	Summary of Work Performed on Southern Islands, NVO-213
Figure F-3	Plowing Experimental Testing Sites on Janet
Figure F-4	Plow Test X-1 Area on Janet
Figure F-5	Initial Characterization of Surface Transuranic Activity on Island Janet
Figure F-6	Areas of Soil Removal for Surface Cleanup on Island Janet
Figure F-7	Island Pearl Cleanup Areas
Figure F-8	Final Estimated Transuranic (TRU) Activity Isopleths (pCi g^{-1}) for Island Pearl
Figure F-9	Areas of Island Sally Designated for Soil Excision
Figure F-10	Area Cleared by Sand Dredging on Island Sally and Details of Soil Stockpiles and Aomon Crypt Excavation Area
Figure F-11	Surface Soil Areas of Island Irene with Estimated TRU Activity > 40 pCi g^{-1}
Figure F-12	Sub-Surface Sampling Locations on Island Irene with Notation of TRU Activity Concentrations
Figure F-13	Final Estimated Transuranic Activity Isopleths (pCi g^{-1}) for Island Irene, with Annotation of Total TRU to ^{241}Am Ratios

Among the islands being discussed in this section, the debris on Ruby was largely contaminated, though the total volume was not that large. The debris was assessed and removed between 1 June and 10 July 1978. Among the five air samples collected over a portion of this period, only negligible levels of airborne α-particle activity were found, with the two samples with positive detects having α-particle activity concentrations of 0.01 pCi m^{-3}. Tilda had a reasonably high volume of uncontaminated debris removed between in June/July 1978. The air sampling conducted on this island was between September and November 1977 when debris survey and brush clearing work was being accomplished. Only negligible air sampling results were observed. While the brush clearing operation may be expected to produce increased soil resuspension over quiescent condition, the application of lagoon water over areas planned for brush clearance would have reduced this potential.

4.2.8.4.4 Air Sampling on Janet

Among the northern islands, Janet had the greatest amount of debris planned for removal, with almost 16,550 yd^3 removed during the cleanup. In spite of the large volume, only 3% of the volume was categorized as contaminated (Table F-7). Although the debris survey for this island was initiated in July 1977, the removal action was accomplished over 16 months January 1978 to May 1979) due the large volume and the necessity in demolishing a large, three story concrete structure, the "Enjebi Hilton," constructed for Operation Greenhouse to test impacts of nuclear detonations on structures. The island also had a significant amount of soil removed and disposed in the Cactus Crater, ~ 53,000 yd^3. The volume from Janet was half of the total volume of soil excised, as noted in Table F-1, however, its mean transuranic concentration was much lower than that in soils excised from the other islands. About 38% of the volume removed targeted soils with transuranic concentrations only between 40 and 45 pC g^{-1}. Soil excision was conducted between July 1978 and May 1979, coinciding with a portion debris removal operation timeline. Figures F-5 and F-6 show the areas on Janet initially planned for soil excision and where it actually. Figures F-3 and F-4 show the areas subjected to Plow Test experimental areas. As noted in Table F-2, this experiment was conducted in June 1978, while soil from these areas excised in May 1979.

Air sampling was conducted on Janet between April 1977 and May 1979, accounting for about one-eighth of the total volume sampled during the cleanup. A distribution of the air sampling results are displayed in Figure 4-4. The distribution of zero reading and those is similar to the distribution observed overall for all air samples (Figure 4-2). The fraction of samples with activity concentration greater than 1% of the adjusted MPC, however, was only 0.5% (n = 3), compared to 3.9% for all air samples. The three air samples with activity concentration, 0.30, 0.39, and 0.33 pCi m^{-3}, were only a little over 1% of the adjusted MPC. Only one of the three samples was collected during a period of soil excision, 3 – 9 September 1978, while the other two were collected in September 1977.

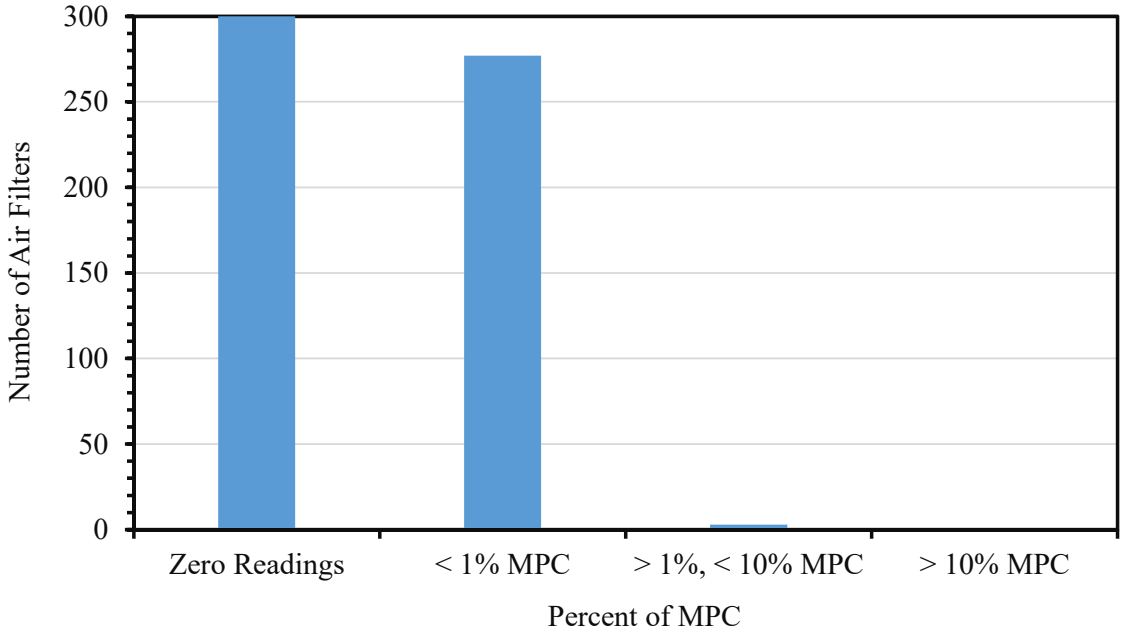


Figure 4-4. Distribution of α-Particle Activity Concentration Among Air Samples Collected on Janet [Adjusted MPC = 27 pCi m^{-3}].

In spite of the relatively low airborne α-particle concentrations observed on air samples from Janet, there were many work periods where a sizeable fraction of the workers were required to wear PPE that specified a positive pressure full or half-face respirator (PPE levels IIIA or higher). Appendix G contains some example controlled island access log summary data and distributions of PPE worn on individual islands. For example, during April 1979, Figure G-2, some man-days of work was accomplished with PPE levels IIIA and IIIB, though soil removal operations had not been initiated. Respiratory protection was likely specified as a precautionary measure for some debris removal. The majority of personnel were in level I for this month. In June 1978, only a few man-days of work was accomplished in level IIIA, though by August 1978, 320 man-days of work was accomplished in level IIIA or IIIB out of the total 1,483 man-days for that month. Noteworthy is the fact that work on Janet with non-radioactive debris was much more labor intensive than the soil removal activities. Level IIIA PPE was applied to work on Janet for 411 man-days in October 1978 (Figure G-10), 381 man-days in December 1978 (Figure G-12), 260 man-days in March 1979 (Figure G-14), and 179 man-days in April 1979. By June 1979, there was little worker presence on Janet – only eight man-days was accomplished by AF FRST personnel, with only level I PPE. Overall, negligible levels of airborne α-radiation was detected on Janet. The level of PPE for many workers exceeded the requirements of the project for the observed airborne levels of contamination.

4.2.8.4.5 Air Sampling on Pearl

The volume of soil removed from Pearl was about one-fourth of that removed from Janet, though the concentrations of the transuranics in the excised soil were estimated to be over twice the activity concentration of the soil excised from Janet (Table F-1). In contrast to Janet, there was only a small volume of debris (271 yd^3) removed from the island, though most was radioactive. Air sampling was conducted between September 1977 and February 1978, during the period of debris removal, and again between April and July 1979 during the period of soil excision work. The blue bars in Figure 4-5 contain the distribution of α-particle activity concentration in all air samples collected on Pearl. Among the 57 samples that had activity concentrations between one and 10% of the MPC, they accounted for 28% of the samples in this range of activity concentration among all samples. However, with the exception of one sample, as shown in Figure 4-5, all in this activity concentration range were collected within a six-week period in April/May 1979 when the initial soil excision work was being accomplished. For the group of air samples collected within this period, there was also a dis-proportionately high fraction of samples with positive detects, but with activity concentration less than the MPC than for the samples collected during other periods. Among the 57 samples collected during this six-week period, the sample with the highest activity concentration was 1.71 pCi m^{-3}, 6% of the adjusted MPC.

Figure 4-6 displays the PPE worn, by month, between April and June 1979 on Pearl. Overall, for the six weeks of time when elevated concentrations of α-particle activity were observed, the majority of personnel assigned duties to the Island were wearing level IIIA PPE. The majority of individuals in level I PPE were designated as visitors or provided support upwind of the hot-line. Figure 4-7 shows the distribution of number of days with access to Pearl. It is clear from the plot, a large fraction of the man-days spent on this island was from a large number of personnel with only a few days of presence, while a large fraction of man-days was from a much small number of personnel that spent a large fraction of the work days in the month on Pearl. Use of level IIIA PPE was disproportionately associated with the latter individuals. Figure F-7 and F-8 show, respectively, the cleanup areas and the final surface soil transuranic isopleths. Due to the trade wind dominance from the east-northeast, the upwind region of the island coincided with the least contaminated land.

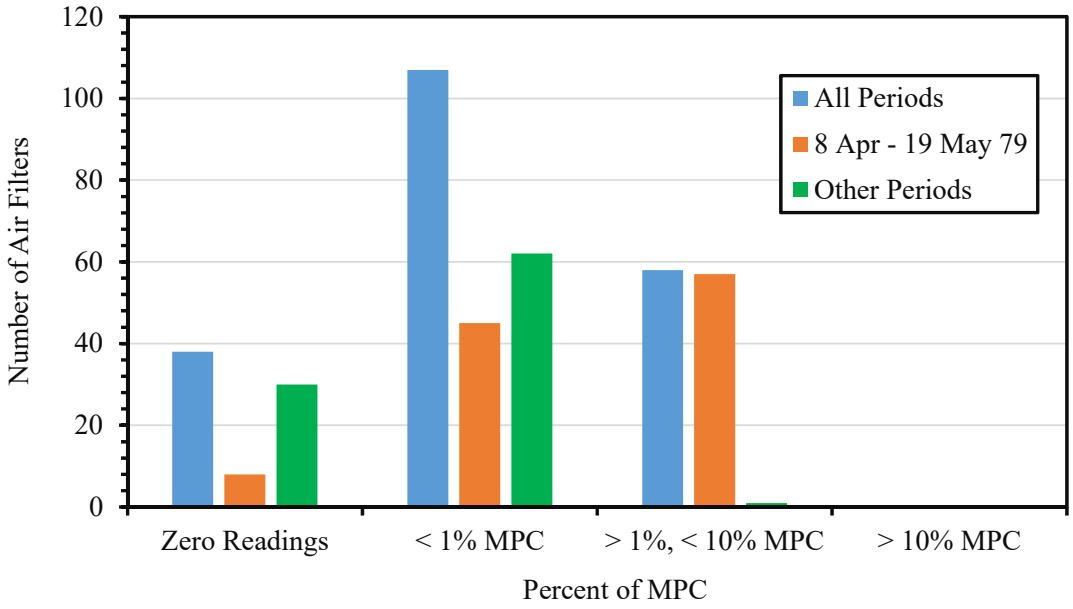


Figure 4-5. Distribution of α-Particle Activity Concentration Among Air Samples Collected on Pearl [Adjusted MPC = 27 pCi m^{-3}].

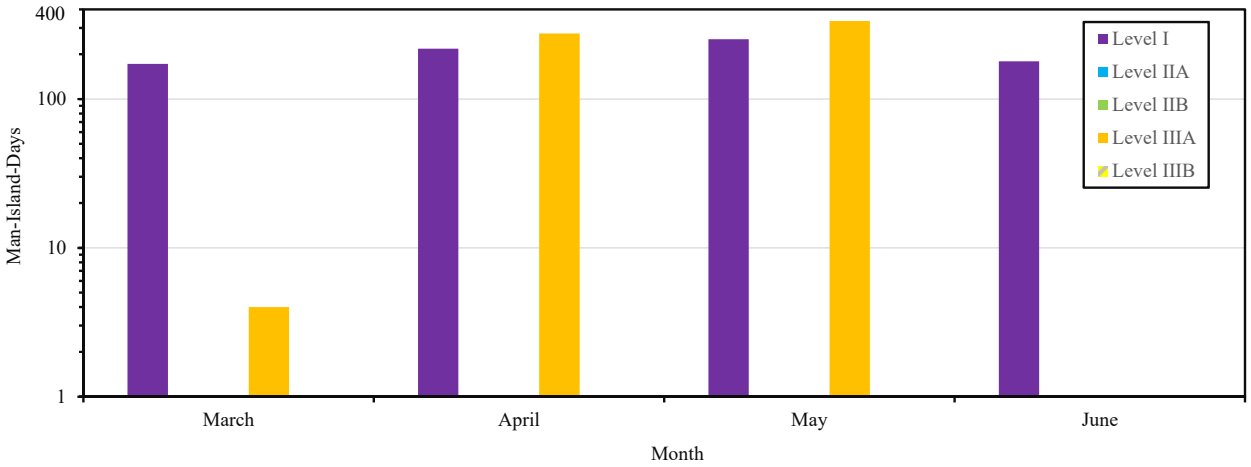


Figure 4-6. Distribution of PPE for Work Conducted on Pearl between April and June 1979.

4.2.8.4.6 Air Sampling on Sally

Sally had about 50% more soil excised than that removed from Pearl, as detailed in Table F-4. The mean concentration of the soil was similar to that for Pearl. Sally had the second largest volume of debris removed, about 2,900 yd^3, though only a quarter of the volume was contaminated. Contaminated soil was removed from four areas: the three test GZ zones Kickapoo, Yuma, and Hustead, and the Aamon (Sally) Crypt, shown in Figures F-9 and F-10. Seven-hundred fifty-two air samples were collected, with a distribution of activity concentrations, as shown in Figure 4-8. The samples were collected over the period of October 1977 to June 1979, encompassing debris surveys and removal, and soil excision and transport. The six samples with activity concentration greater than 1% of the adjusted MPC were collected in March and April 1978, coinciding with the period

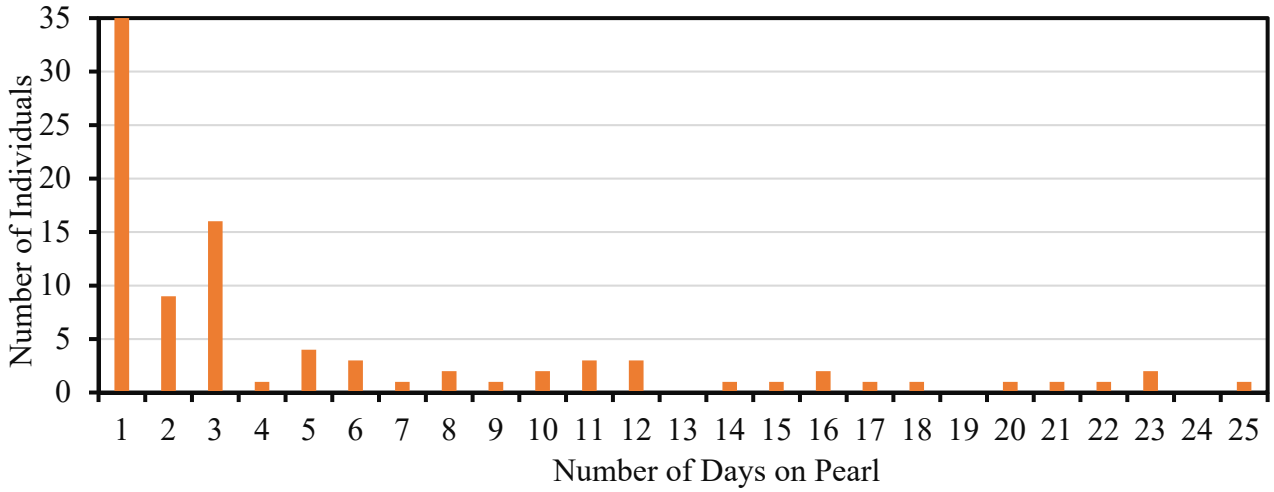


Figure 4-7. Distribution of Access Days to Pearl by Individual April 1979.

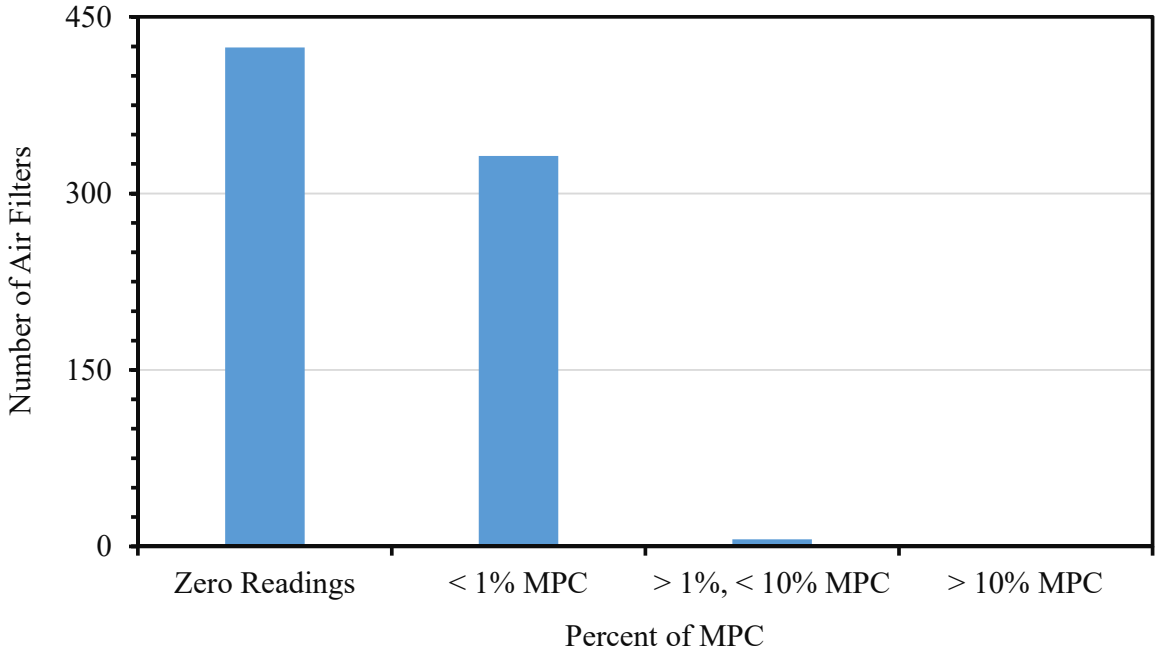


Figure 4-8. Distribution of α-Particle Activity Concentration Among Air Samples Collected on Sally [Adjusted MPC = 27 pCi m^{-3}].

soil excision was initiated. It is logical that higher concentrations of airborne activity concentrations were observed at this time, as soils with higher concentrations are generally removed early in the excision process. Nevertheless, the concentrations of the air samples were negligible, with the air sample with the highest activity concentration about only about 3% of the adjusted MPC.

From review of PPE histograms in Figures G-2 (April 1978), G-4 (May 1978), G-6 (June 1978), and G-8 (August 1978), a large fraction of man-days of work on Sally was accomplished in PPE levels IIIA of higher. All four of these monthly periods were during the soil excision of the Kickapoo, Yuma, and Hustead areas. For the August 1978 controlled island access PPE distribution

bar graph, four man-days of work were conducted in level IV PPE. This level of PPE was worn by two DOE-affiliated and two Army personnel. Level III PPE during August on Sally was worn by a number of individuals from the 84th Engineering Battalion, with other users of this level of PPE limited to an individual from the Desert Research Institute (DOE support contractor) and an AF FRST member. This was very common for soil excision work – the majority of personnel in the zones designated for air-purifying respirator use were Army personnel.

The Aamon crypt soil excision was conducted from mid-January to the end of April 1979. During this period, none of the air samples were in excess of 1% of the adjusted MPC, two were near this value: 0.13 pCi m^3 (0.5% adjusted MPC) and 0.21 pCi m^3 (0.8% adjusted MPC). Similar to the period, previous soil excisions were being conducted on Sally, PPE levels requiring air-purifying respirators were worn by personnel in this work zone. The distribution of PPE levels worn on Sally in the spring of 1979 are displayed in Figure 4-9. Apparent from the distribution, the greatest number of personnel in the work zone requiring air-purifying respirator use was in January and February. By May, the soil excision work had been completed and level I PPE-only was specified for work on this island. The conservative nature of PPE specifications are evident: air-purifying respirator use was specified for this in the soil excision area, though the air sampling α-radiation concentration levels did not require this level of protection according to Table 4-2 from DNA (1981).

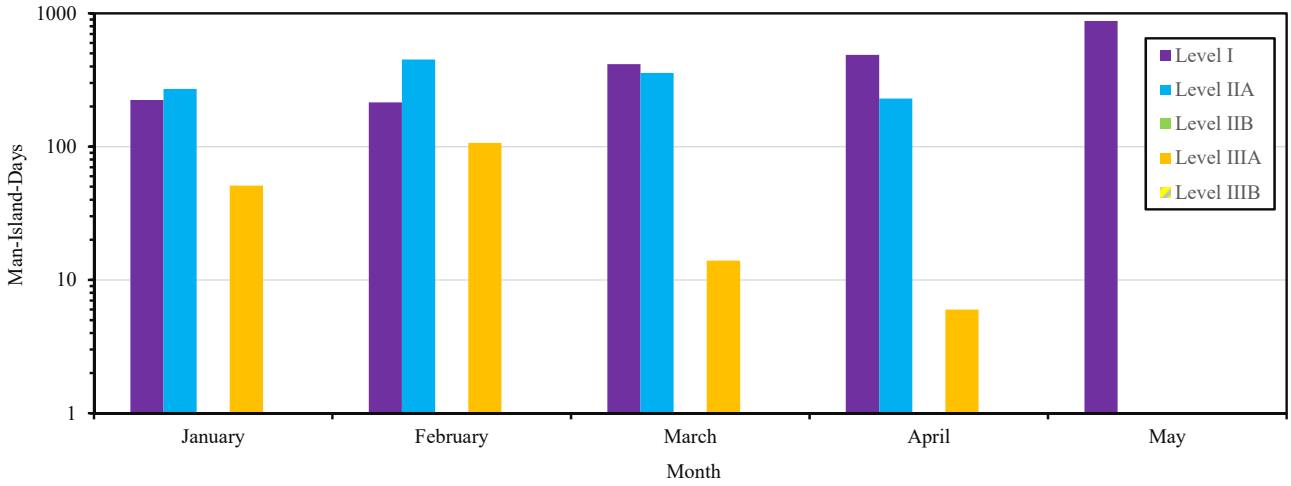


Figure 4-9. Distribution of PPE for Work Conducted on Sally between January and May 1979.

4.2.8.4.7 Air Sampling on Irene

Among the islands with soil excision, Irene had the smallest volume, 4,937 yd^3. The mean transuranic concentrations of the excised soils was 180 pCi g^{-1}, much higher than the mean concentrations excised from Janet, Pearl, and Sally. Soil excision was accomplished between December 1978 and July 1979, though no excision was accomplished between the end of April to early June 1979. A substantial amount of debris was removed from Irene, 1,905 yd^3, but it was all uncontaminated. Debris removals were conducted between January and July 1978. Air sampling was conducted between October 1977 and March 1978, and between January and July 1979. The distribution of α-radiation activity concentrations for the 110 filters is contained in Figure 4-10. Only a single filter had an α-radiation activity concentrations greater than 1% of the adjusted MPC,

a sample collected the end of January. The activity concentration was only 0.5 pCi m^{-3}, about 2% of the adjusted MPC. Among the other filters with positive detects, the next highest concentration was only 60 fCi m^{-3}, about 0.2% of the adjusted MPC. In general, the distribution of activity concentrations among the air filters were fairly low considering the fact that the soil excised from this island had greater transuranic activity concentrations than the other islands already discussed with excised soil.

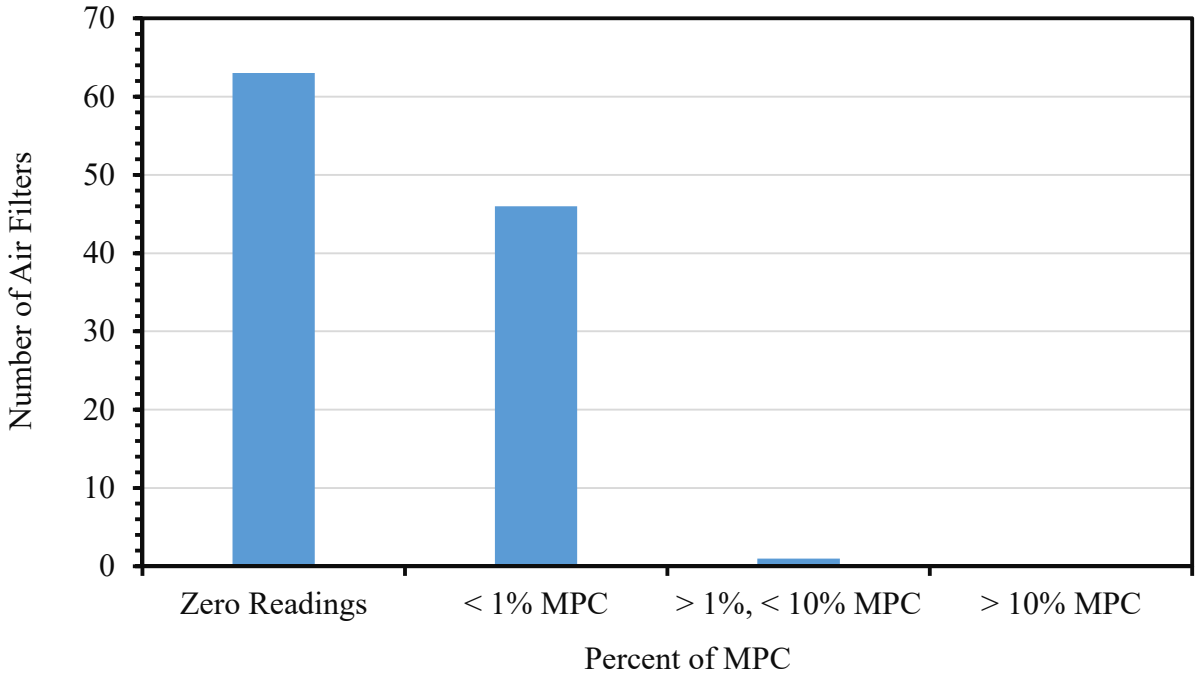


Figure 4-10. Distribution of α-Particle Activity Concentration Among Air Samples Collected on Irene [Adjusted MPC = 27 pCi m^{-3}].

The areas planned for surface soil excision are shown in Figure F-11, a region north of the Test Seminole Crater. Figures F-12 and F-13, respectively, provide information on sub-surface transuranics and final estimated transuranic activity concentration isopleths. Similar to Pearl, the areas planned for excavation were on the lee-ward side of the island, effectively providing a large regions of undisturbed areas upwind of the areas planned for excision. From example distributions of PPE shown for March and April 1979 (Figures G-14 and G-16), it is clear that a reasonable fraction of man-days of work conducted during soil excision on Irene was performed with level IIIA PPE. In December 1978 (Figure G-12) and June 1979 (Figure G-18), months before and after the soil excision work was being conducted on Irene, levels I and IIB PPE were used. PPE requiring air-purifying respirators were used during some periods of time where soil excision was not being accomplished. For example, in June 1978 (Figure G-6) some man-days of work was accomplished with level IIIA PPE on Irene. Uncontaminated debris removal operations were being conducted during this month.

4.2.8.4.7 Air Sampling on Landing Craft, Utility (LCU), Landing Craft, Mechanized (LCM), YC-Barge, and Lighter Amphibious Resupply Cargo (LARC) Vessel

LCU and LCM water vessels were used to transport excised soils from Janet, Pearl, Sally, and Irene to Yvonne for ultimate containment in the Cactus Crater entombment. The craft were also used for equipment and debris transport. The YC-Barge was used for transport of debris, while the LARC was used as an aid in debris collection in shallow areas, as well as some debris transport. Air sampling was performed on these transport operations beginning in May 1978 and ending in October 1979. The approximately 130,000 m^3 of air sampled on these vessels accounted for about 15% of all sampled air volume during the cleanup. Over 1,300 air filters were analyzed. The distribution of activity concentration among filters is displayed in Figure 4-11, as separated between samples collected in 1978 and 1979. The α-radiation activity concentration of samples collected in 1978 were negligible, with the sample with the highest activity concentration only 0.22 pCi m^{-3}, about 0.8% of the adjusted MPC. In spite of the low activity concentrations of air samples in 1978, the PPE levels requiring air-purifying respirators were implemented in June 1978, as seen from Figure G-6. LCM vessels were coded, "Maggie," while LCU were designated Mesh. With few exceptions, Maggie 9, had almost uniform use of level IIIA PPE in June 1978. It became a standard practice to

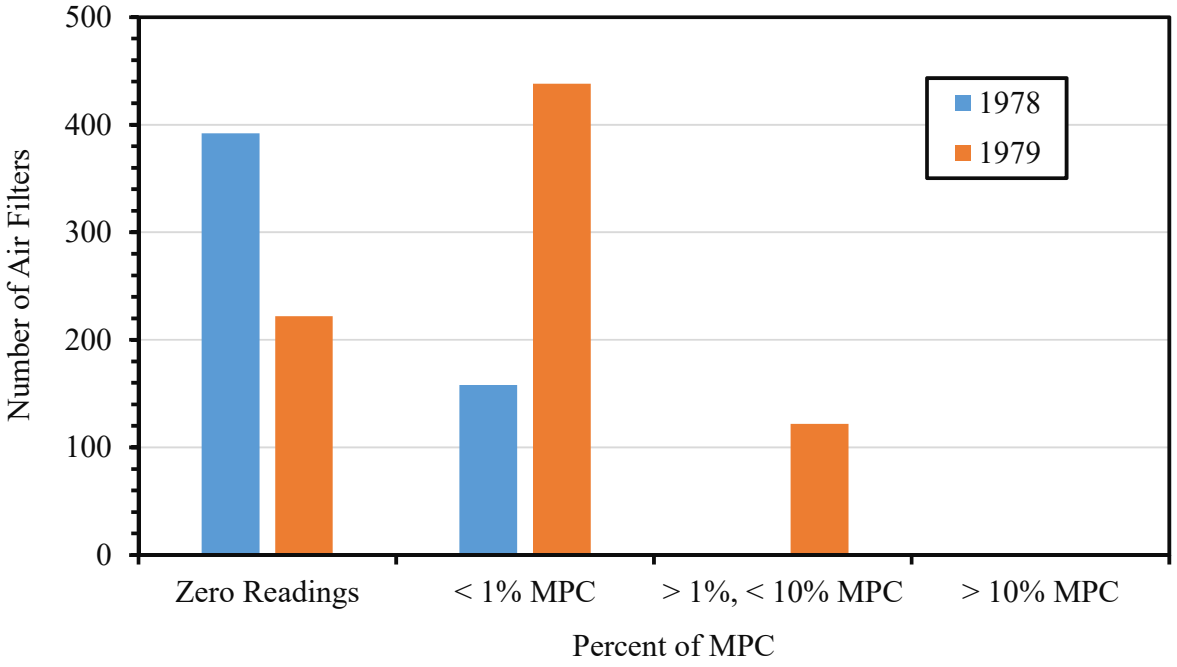


Figure 4-11. Distribution of α-Particle Activity Concentration Among Air Samples Collected on Water Vessels [Adjusted MPC = 27 pCi m^{-3}].

wear either level IIIA or IIIB for personnel on water vessels carrying soil and debris. For work days where only equipment or personnel were being transported, levels I, IIA, or IIB PPE may have been worn, based on review of controlled island access logs.

During 1979, a substantially larger fraction of the air samples had detectable levels α-radiation activity, as well as a large fraction of samples above 1% of the adjusted MPC. The 122 samples with α-radiation activity concentration above 1% of the adjusted MPC represented 61% of

the total number of samples in this concentration range among all air samples. All of the samples with α-radiation activity concentration above 1% of the adjusted MPC were collected during work periods on LCM and LCUs. The sample with the highest α-radiation activity concentration was 2.07 pCi m^{-3}, 8% of the MPC. With the exception of two air samples, all samples above 1% of the MPC were collected between April and June 1979. With the exception of one air sample, all samples above 1% of the adjusted MPC were collected on LCMs. During this period , almost all man-days of work on the LCM's were accomplished with personnel in level IIIA PPE. The exceptions would have been for non-soil cargo uses. During this three-month period, soils were transported from Janet, Pearl, Sally, and Irene to Yvonne.

DNA expressed surprise at the higher levels of airborne α-particle activity concentrations for some samples collected during water vessel transport, due in part to the fact that soils were covered by tarps during transports over water. As noted earlier, some opined that other sources of α-particle radiation at Enewetak may have influenced the measurements. The analysis provided above demonstrated that there was a possibility that other sources could have an influence on air samples collected on islands with very-low levels of plutonium. The influence of these other sources of α-radiation, however, become much less important for northern islands where soil was removed, as these islands had much higher total transuranic concentrations. Nevertheless, PPE levels specifying air-purifying respirators were used for soil transports, though none of the air filters had α-radiation in excess of 10% of the adjusted MPC.

4.2.8.4.7 Air Sampling on Yvonne

Air sampling was conducted on Yvonne between June 1977 and March 1980, with a total volume of about 240,000 m^3, 28% among all islands. The distribution of activity concentration among filters is displayed in Figure 4-12. Thirteen samples had activity concentrations greater than 1% of the adjusted MPC, most were among the samples collected in March and June 1979, during the period soil excision operations were being accomplished in the Fig-Quince Test Area, 13 March to 26 July. The activity concentration of the sample with the highest concentration was 1.2 pCi m^{-3}, about 4% of the adjusted MPC. Most notable about the soil excised from the Fig-Quince Test Area was its higher mean transuranic activity concentration than soils excised from the other islands. The air sampling results are logical with respect to soil removal operations on Yvonne. About one-half of the soil removed from the Fig-Quince Test Area, 5,720 yd^3 (see Table F-6 for total volume) was removed by the end of March; additional soil would be excised from the Fig-Quince Test Area of Yvonne after soil excision goals from other islands were met (DNA 1981). By mid-May soil excision goals were met on Irene, Janet, and the Aomon Crypt on Sally. Additional soils were planned for excision from the Fig-Quince Test Area to meet volume availability in the Cactus Crater containment dome. One-quarter hectare areas were selected for excision from the Fig-Quince Test Area, based on IMP survey assessments to maximum transuranic activity reduction within available volume limits. In June and July an additional 5,015 yd^3 was excised from the Fig-Quince Test Area. During this period, only three air samples had activity concentration greater than 1% of the adjusted MPC, with the highest at 0.62 pCi m^{-3}, about 2% of the adjusted MPC.

PPE use, as detailed in the Figures G-14 (March 1979), G-16 (April 1979), and G-18 (June 1979), match soil excision activities in the Fig-Quince Test Areas. In March and June when soil excision activities were occurring on Yvonne, varied levels of PPE (IIIA to IV), requiring air-purifying respirators were used in March and June, while during April when soil excision operations were suspended on Yvonne only levels I and IIB were used. After the additional volume of soil from Yvonne was added to the crater, capping operations on the dome were initiated. PPE levels in

August 1979 were primarily limited to levels I and IIB, with the exception of a couple of man-days of work on Yvonne. The large amount of man-days of work occurring on Yvonne was primarily dedicated to the concrete cap construction. During August 1979, 373 individuals had accessed Yvonne. About a third of the individuals were only on the island three days or less. Eighty-percent of the man-days of work were accomplished by 160 individuals working 15 days or more in this month. Many of the individuals with only a few days of access to Yvonne during this month were either visitors to the Atoll or senior leadership monitoring progress on the containment.

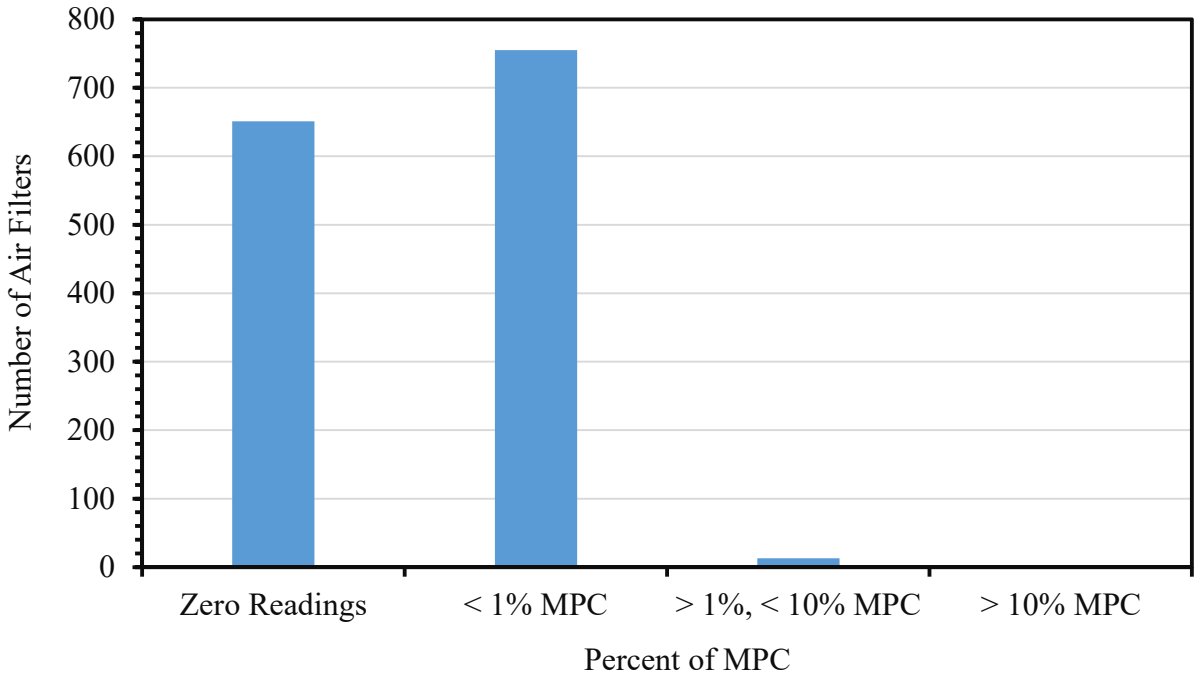


Figure 4-12. Distribution of α-Particle Activity Concentration Among Air Samples Collected on Yvonne [Adjusted MPC = 27 pCi m^{-3}].

Although the concrete cap on the Cactus Crater was completed by 6 August 1979, additional work was accomplished on Yvonne up to April 1980. About 120 yd^3 of contaminated debris from land and reef areas of Yvonne were added to an extension of the dome in September 1979. Surveys of the Fig-Quince Test Area were accomplished by the DOE in the fall of 1979. In addition, another small volume of debris was located in reef areas in the fall of 1979 and spring 1980. This additional volume of debris was contained in an extension to the Cactus Crater which was completed in March 1980 (DNA 1980). Between the end of July and December 1979, air sampling was continued for work on Yvonne. Among the 160 air samples collected, only one had an activity concentration greater than 1% of the adjusted MPC, 0.32 pCi m^{-3}, about 1.2%. Over 60% of the air samples were non-detects during this period. No air sampling was conducted on Yvonne in 1980.

4.2.9 Air Sampling Data from 1972 AEC Radiological Survey

Table E-4 provides a summary of results from air sampling conducted during the 1972 AEC radiological survey (AEC 1973). The sampling was limited to only a few islands: Fred, David, Janet, Sally, and Yvonne. Three different type of air sampling were accomplished: ultra-high

volume (samples ID UH X X), low volume (samples ID VC X X), and cascade impactors (samples ID A X X X). Samples collected from the ultra-high sampler had volumes ranging from 16,500 to 101,000 m^{-3}, while low volume sampling had volumes ranging from 1,640 to 2,100 m^{-3}. The four cascade impactor samples had volumes ranging from 5,700 to 9,900 m^{-3}. For these samples, the last letter in the sample ID (ranging from A to E), corresponded to aerodynamic equivalent diameters ranges of 0.01 - 1.1, 1.1 - 2.0, 2.0 - 3.3, 3.3 - 7.0, > 7.0 μm, respectively. Samples were collected from a central to western area on Fred, a central location on David, a northern location on Janet (but centered from east-to-west), a southern location on Sally (but centered from east-to-west), and at two different locations on Yvonne. Sample UH28 was collected about 80 m south of the Cactus Crater southern rim, while all other samples were collected within the Quince/Fig GZ.

^{7}Be and ^{40}K are naturally-occurring radioactive materials, while the other radionuclides listed in the results are expected in local and global fallout from nuclear weapons testing. ^{95}Zr and ^{54}Mn, due to their relatively-short radiological half-lives, 64 d and 313 d, were likely associated with recent (in relation to 1972) French and/or Chinese tests. One high volume air sample collected on Fred, UH27, also had detectable quantities of ^{241}Am, ^{103}Ru, and ^{125}Sb. Since ^{103}Ru has a 39 d radiological half-life, its presence in the sample is attributed to recent (in relation to 1972) French and/or Chinese tests.

Activity concentrations of the isotopes of plutonium: $^{239+240}$Pu and ^{238}Pu are the most pertinent to airborne radiological concerns on the Atoll. Among the samples collected, airborne plutonium concentrations were unremarkable, except a few samples collected on Yvonne. For comparison purposes, activity concentrations of airborne $^{239+240}$Pu at a number of global locations is provided in Figure E-6 from 1963 to 1977. The mean activity concentrations were below 0.1 fCi m^{-3} for all sampling locations in 1972. Monitoring at the Mauna Loa, HI location is the closest in latitude to Enewetak Atoll and had an average $^{239+240}$Pu of 0.048 fCi m^{-3} in 1972. The sample with the highest $^{239+240}$Pu activity concentration was UH27, 2.6 fCi m^{-3}. This airborne concentration would be expected for an area contamination with an average surface soil $^{239+240}$Pu activity concentration of 52 pCi g^{-1} and a mass loading of 50 μg m^{-3}. For comparison purposes, Figure B-30 contains the ^{241}Am isocontour plot for the area surrounding the Fig-Quince GZ, while Table C-6 contains $^{239+240}$Pu activity concentrations in surface soils. For the 27 samples in the 0 – 10 cm depth profile of Table C-6, the average $^{239+240}$Pu activity concentration is 157 pCi g^{-1}. One plausible explanation for the lower than expected resuspension is heterogeneity, where a reasonably high fraction of the plutonium contamination is contained in particles with aerodynamic properties too large for re-suspension. Another plausible explanation is suppressed dust loading due to precipitation.

4.2.10 Controlled Island Entrance Logs

4.2.10.1 General. One of the radiological safety protocols established for the cleanup was logging personnel entries on controlled-access islands. Personnel logs were initiated in June 1977, a couple months after the initial mobilization of limited staff to the Atoll on 15 March 1977. Personnel logs were maintained on all personnel entries on controlled islands through use of a FC DNA Form 290. AF communications personnel arrived on 16 March, though their initial two months on the Atoll was dedicated to upgrading communication systems on the Fred, the base camp on the southern part of the Atoll. The first group of personnel conducting operations on controlled-access islands were a small group of personnel to conduct aggregate removal from Janet and transport to Ursula in April – May 1977. The personnel consisted of four Army equipment operators, five Navy boat operators, with radiological support from Captain Day, USA, and two

Holmes & Narver (H&N) personnel (DNA 1981). The air sampling conducted during this operation was discussed above. Because training and deployment of FRST was not started until the end of June 1977, Captain Day, an Army Health Physicist, implemented radiation safety protocols for the members of the team. The deployment of 12 personnel for this operation was prior to use of the logs during the cleanup. Work being performed in the development of the northern camp on Ursula began on 19 May 1977, though similar to access on Janet, these entries were not recorded until June 1977.

4.2.10.2 Ursula. Although maintenance of logs for access to Ursula were not initially made until June 1977, the island was considered safe by ERDA for construction and earth moving (DNA 1981). Based on external exposure and air sampling data provided above, the radiological conditions on this island were well within radiological conditions of many CONUS locations. The mean $^{239+240}$Pu concentrations in surface soils were also only 4.5% of the goal for residential islands of 40 pCi g^{-1}. Some personnel were assigned duties to support the camp operations at Ursula, while others that performed work on other northern islands were billeted on Ursula. Access to Ursula was maintained on FC DNA Form 290's in June and July 1977, during the period the island was being prepared as the northern base camp, and between January and August 1978. It appears that the decision was made to no longer record these accesses. Therefore, for individuals that performed work on northern islands of the Atoll, except Ursula, it is reasonable that they were billeted on Ursula for periods between 15 November 1977 and 14 October 1979. This case would be apparent from record of their access to other northern islands. For individuals that supported camp operations on Ursula, yet did not perform duties on other northern islands, the currently available records maintained at DTRA may not have details of all individuals working on Ursula. For the purposes of this report, it is not important from a radiological exposure standpoint since the conditions on Ursula were very similar to the southern islands of the Atoll. One important group of AF personnel that worked on Ursula, yet had limited travel to other islands of the Atoll were medical personnel assigned to the clinic on Ursula, as well as some FRST members. H&N contractors also performed camp support functions. Medical personnel were not deployed from Ursula to other northern islands except in the case of emergencies. For example, the AF attending physician on Ursula was deployed to a life-threatening injury on Sally on 14 Aug 78 (DNA 1981). The injured individual died on Sally (DNA 1981). The record of the physician's access to Sally was made on a FC DNA Form 290, though his presence on Ursula was not in the archived logs. This was also the case for the individual that died in the accident – his access to Irene, Janet, Sally, the Warp Tug, and a barge was logged, yet not his billeting on Ursula. There are many similar cases of AF clinic personnel assigned to camp support duties on Ursula, with infrequent access to other northern islands. One FRST team member was assigned precision measurement electronics laboratory (PMEL) duties on Ursula, yet had seven days of duties on Yvonne and Sally.

4.2.10.3 Database Maintenance. During the cleanup, an electronic database was maintained with radiological exposure information, i.e., film badge/TLD monitoring results, urine bioassay, controlled-island access information, deployment dates to Enewetak, etc. Data from FC DNA Form 290's were used for the controlled island access data. In the past two decades, DTRA has attempted to ascertain if an electronic version of this database was still in existence. These searches were prompted by Veterans Administration. Their search of computer system at DTRA and within boxed archives were unsuccessful. The only remnants of the database found was a printout of the data for DOE-associated participants. A similar printout of data for DoD personnel was not found in archived records. In preparation of this report, an Excel™-based spreadsheet was compiled for controlled island access from archived FC DNA Form 290's. Four months of controlled island access data on FC DNA Form 290's, September to December 1979, was not found

in DTRA boxed archives. The Safety Center's Excel™-based spreadsheet was populated for DOE-affiliated personnel from the archived printout. During this period, a limited amount of work on the northern islands was still being conducted, and exclusively on Yvonne. In August 1979, about 350 DoD members accessed Yvonne, while in February 1980, only 51 DoD personnel accessed Yvonne. Only 24 of the 51 personnel had three or more days of access. Due to the rapid decrease in personnel strength needs for work in the northern islands of the Atoll in the fall of 1979, use of the camp on Ursula ceased on October 14. Hence, there were a limited number of DoD workers present on Yvonne during these four months. Access to Yvonne can be inferred for individuals with presence on Yvonne in August 1979 and/or January 1980, in conjunction with arrival/departure date records maintained for personnel supporting the cleanup. In review of access logs to Yvonne, a number of personnel with presence on Yvonne in 1980 also had presence prior to September 1979 on this island. For these individuals, it is logical that they had some presence in September to December 1979. Dosimetry monitoring reports also exist for this period. The dosimetry monitoring logs have consistency with controlled island access logs. The number of personnel on dosimetry monitoring was in the range of a few hundred personnel in September and early October 1979, but rapidly declined from latter October to January 1980. The listing of dosimetry monitoring can be used to assess presence on Yvonne during this period under the assumption that if an individual was issued dosimetry monitoring, they had access to Yvonne over this period. The Safety Center populated an Excell™-based spreadsheet with this data, which provides another source of personnel access to Yvonne from September to December 1979.

4.2.10.4 PPE. Most of the initial controlled island access logs only contained presence of individuals in controlled islands and water transport vessel in the northern part of the Atoll. While not part of the instructions for completion of the FC DNA Form 290's initially, in spring 1978, it became a standard practice to annotate the level of PPE worn on a daily basis on FC DNA Form 290's. From a practical standpoint, the critical activity of concern for enhanced suspension of soil were the excision operations on Irene, Pearl, Janet, Sally, and Yvonne. These operations did not begin until March 1978, but by established practice included levels of PPE that required air-purifying respirators and wetting of soil with lagoon water to suppress suspension of dusts. A discussion was provided above on the early use of level IV PPE during exploratory excavations of the Test Erie GZ on Yvonne in June 1977. As well, unique contaminated areas were excavated on Elmer from 7 – 10 February 1978. The contaminated areas were due to low-levels of ^{60}Co in soils, suspected to be due to a previously leaking calibration source. As documented by DNA (1981), excavation of soils from two contaminated soil areas was conducted with level IV PPE by the individual operating the bucket loader, with the soil planned for excavation being saturated with seawater prior to removal[15]. This was the only area on a southern Atoll location where contaminated soils were removed during the cleanup. The excavation generated 110 yd^3 of soil for disposal in the Cactus Crater.

4.2.10.5 Double Listings. Some individuals performed duties on different northern islands of the Atoll and/or on a Navy vessel on the same day, as noted on FC DNA Form 290's, though this was not very common for most personnel performing duties on the northern islands. These double listings did increase the number of man-days displayed in Appendix G histograms. In some cases, the level of PPE varied by location. For example, an Army enlisted member in support of work on Pearl on 14 July 1979 wore level I PPE, while on the same day was required to wear level IIIA PPE on Maggie 9. Soil excision operations on Pearl were completed by 8 July 1979 on Pearl, thereby not necessitating a level of PPE requiring an air-purifying respirator based on a

[15] ^{60}Co on an activity concentration basis is a significantly lower inhalation hazard than $^{239+240}$Pu.

radiological safety practices established. Yet, the veteran on the same day was on Maggie 9, and if it was carrying soil for transport to Yvonne, it was a standard practice to wear level IIIA PPE by this time in the cleanup. Some individuals in leadership positions had many double and triple listings for access to multiple islands on the same day. This was necessitated by a need to periodically supervise operations on the many islands.

4.2.10.6 Examples of Controlled Island Access for Individuals

Appendix G provides example histograms of PPE levels for veterans serving on northern islands of Enewetak Atoll. These examples are provided to illustrate the varied degree of PPE among individuals, but also provide illustrations of the varied levels of PPE on an individual basis. The issue of PPE use was one concern expressed by veterans that served on Enewetak Atoll - air purifying respirators were supplied to some veterans, while not others. As clearly discussed and illustrated above, air purifying respirator use was primarily used for workers within work zones where soil excision actions were being accomplished. Other activities also dictated their use – transport and loading of excised soils, and some debris removal actions.

The first example histogram, Figure G-22, is for an AF FRST member that performed work between mid-February and late-June 1979 on Sally, with one day of presence on a Navy vessel, L3. During this period, the most prominent soil or debris removal action was excision of soil from the Aomon Crypt. This veteran wore level I and IIA PPE for all work days, but one, where level IIIA was worn. While FRST personnel commonly supported activities at the hot-line, there wasn't a requirement for use of air purifying respirators in this role. Some FRST members had duty requirements within work zones where soil excision actions were being accomplished, most notably radiological survey in support of soil excision operations. In the case of this FRST member, this was the case for only one day in February during his assignment to Enewetak. Overall, for the veteran's 19 weeks on the Atoll, he was on controlled islands for an average of six days per week. The one day of presence on L3, the veteran was also on Sally.

The second example histogram, Figure G-23, is also for an AF FRST member. In contrast to the FRST member that worked on Sally, this individual worked on a number of islands, and had numerous work days on Navy watercraft. Among the 119 work days, 27 were duplicates, with duties split between work on Janet and Irene on the same day, and in some cases work on these islands and Mesh 1, a Navy watercraft. In contrast to the other FRST member, with PPE levels listed in Figure G-22, this FRST member had 33 work days in level IIIA PPE, which required air purifying respirator use. With the exception of a single day of work on Janet in January, level IIIA PPE was worn for work on Pearl and Mesh 1. The work on Pearl was in support of soil excision work in April and May, while the work on Mesh 1 was for contaminated soil transports in May and June.

The third example histogram, Figure G-24, is also for an AF FRST member. Out of 102 work days, 17 were duplicates where work was conducted on a northern controlled access island and Navy vessels on the same day. Most of the work days for this individual were accomplished in level IIIA PPE, and with the exception of three work days on Pearl, all others were due to work on Navy vessels transporting contaminated soil.

The fourth example histogram, Figure G-25, for an AF FRST member on a number of the northeast, northcentral, and northeast islands of the Atoll. Of the 159 work days, 48 were duplicates due to entries on multiple islands on the same day, and/or islands and naval vessels on the same day.

The use of level IIIB PPE by this individual was limited to only eight days, five on Yvonne in September, two on Lucy in May, and one on Clara in April. From Figure G-4, the use of level IIIA and IIIB PPE was common for a number of man-days of work on Lucy in May 1978. On the two days that the veteran wore level IIIB PPE, nine Army personnel from the 84th Engineering Battalion wore level IIIA. The use of PPE on these days was highly precautionary, as the work being conducted was debris removal according to Figure F-7. None of the debris was determined to be contaminated, upon completion of the removal process. As well, the activity concentration of the air samples collected on Lucy over these days were negligible (Table E-3) – none were above 1% of the MPC. A similar condition existed for the work on Clara. On a few days during the debris removal process, primarily Army personnel wore level IIIA or IIIB PPE, with support by a few AF FRST members in similar protection, as detailed in Figure G-2. However, as was the case for Lucy, none of the debris was contaminated. The veteran's days of level III PPE use on Yvonne were in September. Besides construction activities on the tremie and keywall for the Cactus Crater, debris removal activities were being conducted on the southern portion of the island. Air sampling conducted during these operations, however, were unremarkable. Only one sample among 55 collected in September had an activity concentration greater than 1% (but only 1.1%). The fifth example PPE histogram of another AF FRST member during a similar period of the fourth example histogram has similar PPE wear use, as shown in Figure G-26. Between April and August 1978, there were 46 duplicates among 160 days. Level III PPE was worn for a few days on Alice and Clara during debris removal in April and a single day on Mesh II. Levels IIB and IV were worn for five days on southern Yvonne. Level IV PPE was worn on Yvonne primarily by Army personnel during some debris removal actions. The sixth example of PPE wear for an AF FRST member is summarized in Figure G-27 for a veteran with work on Yvonne and naval vessels. Besides a few days on Navy vessels, most of the work days were on Yvonne. This FRST member only had one day of work specifying level III or higher PPE.

Though this report is primarily focused on AF veterans support to the Enewetak cleanup, some examples for other personnel are provided. The seventh example is contained in the histogram in Figure G-28 for an Army veteran that performed work on a number of islands between January and June 1979. Among the 90 days, only one was a duplicate, work on Pearl and Maggie 9, a naval LCM. For this veteran, only 19 days of work was performed in level IIIA, with the other 70 in levels I or IIA. Level IIIA PPE was used for four days of work on Sally in February, four days on Janet in April, nine days on Pearl in April, and a day on Maggie 9, during soil transport. These days coincided with soil excision activities on each of these islands. It is important to note that for some work days on these islands, lesser levels of PPE were specified. It is clear that some days of work on these islands were conducted by this veteran in the presence of soil excision work, while for other days, soil removal work was not being accomplished or the veteran was not in the hot zone.

An example for another Army veteran is contained in Figure G-29. This individual only worked on Yvonne for the first six months of 1979. Among the 75 work days, only 9 required use of level IIIB PPE, in January and February. During these months, no soil excision operations were being conducted on Yvonne, though contaminated soil stockpiled from other islands was being mixed with dry concrete in the Cactus Crater. Personnel performing this operation used a grader to spread soil, a disc harrow to mix the material in-situ, a water truck to spray water, and a soil compactor (DNA 1981). Personnel conducting this work wore air purifying respirators. Figure G-30 provides another example of PPE wear for a veteran that worked on Yvonne for six months between April and September 1978. Among the 116 days of work, the majority used PPE levels I and IIB, which did not require an air-purifying respirator. It is notable that for the 37 days where PPE requiring use of an air-purifying respirator was required, about a third were for level IV. For

the other Army veteran, with a PPE histogram shown in Figure G-29, level IV PPE was not worn, though a number of days of work were conducted with level IIIB. This observation is consistent with a general trend in PPE specifications during the cleanup. As the project progressed, overly-conservative PPE specifications dictated early in the project were gradually modified. While both level IIIB and IV PPE required the use of an air-purifying respirator, the additional burden of protective clothing (level IV PPE) limited the amount of productive work time due to concerns for heat stress on workers. It became clear from experience gained during the project that the additional level of protection afforded by protective clothing was unnecessary. Levels of contamination detected on protective clothing of workers was very low. As well, air sampling conducted on Yvonne during the period of April to September 1978 was unremarkable. Among the 259 air samples collected on Yvonne during this period, only one sample had an activity concentration greater than 1% (but only 1.1%). Over 60% were non-detects.

The last example for an Army veteran is contained in the histogram in Figure G-31. This is a unique example included to illustrate a number of points regarding controlled islands access and duration of deployment to the Atoll. The example is for one of the JTG Commanders assigned to the Atoll. In contrast to most military members which were assigned to the Atoll for six month deployments, this Army Colonel served on the Atoll for 13 months. Of the 156 man-days on controlled islands, 83 were duplicates, many of which were multiple islands visited on a single day. Over the Colonel's deployments, he was on controlled islands 73 days, or an average of 5.5 days per month. The visits to controlled islands were for management oversight, and in some cases to escort visitors. For a number of the Colonel's access to controlled islands, the access logs also contained an extensive list of visitors. Most controlled island visits did not specify PPE requiring an air-purifying respirator. Only one day of level IV PPE (Yvonne) and three days of level IIIA (Mesh II, Sally, and Janet) were listed in access logs. It is assumed that hot zones were accessed on these days. The days that the Colonel escorted visitors, however, level IIIA or IV PPE was not worn. Visitors generally wore only level I or IIA PPE, and only a small number of days spent on controlled access islands. The JTG Commander's presence on controlled access was similar to other personnel with assigned duties primarily on the southern islands. An Army health physicist that was assigned to the Atoll between August 1978 and June 1979 performed duties on both southern and northern islands of Atoll averaged about 5 days per month on the northern islands.

Figures G-32, G-33, and G-34 contain histograms of PPE levels for three Navy veterans. Each of these veterans served approximate six-month deployments to the Atoll. Navy veterans served three primary roles during the cleanup: cleanup of debris on beaches and sub-merged, harbor clearance, and intra-Atoll transport. Among these three example Navy veterans, the veteran with PPE listed in Figure G-32 was involved primarily with soil transport operations when performing duties on within northern islands of the Atoll on Maggie 7 and Maggie 9. All of the man-days of work on these Navy vessels required level IIIA PPE. This veteran had only 69 days of access to controlled islands in their six-month deployment. Some days were apparently involved with work in the southern islands of the Atoll or intra-island transport of perhaps personnel, which would not have been maintained on controlled island access logs. The veteran with PPE listed in Figure G-33 was on the WBCT. Of the 91 man-days listed on controlled island access logs, all were with either level I or IIA PPE. There were four duplicate man-days for this veteran. Similar to the other Navy veteran, discussed above, some man-days were apparently involved with work in the southern islands of the Atoll or intra-island transport. The last example of a Navy veteran is in Figure G-34. Of the 90 man-days, 20 were duplicates. The majority of duplicates were associated with access to islands and Navy vessels on the same day in support of soil transport from Sally to Yvonne. This work activity was responsible for all of the man-days where level IIIA PPE was worn. The veteran's

work on Irene, Janet, and Kate, however, only listed level I PPE. The veteran was apparently associated with WBCT work on these islands.

Figure G-35 contains a histogram for PPE levels worn by a Holmes and Narver (H&N) contract employee. This individual worked on Sally between November 1978 and May 1979, with no presence on the island in December 1978 and February 1979. Controlled island access logs had records for 134 H&N employees accessing northern islands during the cleanup. This employee only wore level IIIA on two days in March and one day in April. During this period, the Aomon Crypt was being surveyed, with the removal of debris and soil. Table 4-4 contains a summary of the number of individuals listed on controlled island access logs that were contractor employees separated by employer. H&N had the largest number of individual employees. DOE prime contractors also had a number of employees. These individuals were largely responsible for island surveys and technical consulting for the DOE. Eberline Instrument Corporation operated the on-site radioanalytical laboratory. The laboratory, however, was located on Fred, a southern island of the Atoll.

TABLE 4-4. Summary of Controlled Island Access Logs for Contractor Employees.

Employer	Number of Individuals	Employer	Number of Individuals
Holmes & Narver	134	EG&G	16
Battelle Pacific Northwest Lab	3	Desert Research Institute	4
Eberline Instrument Corporation	23	Los Alamos Scientific Laboratory	5
Lovelace Inhalation Toxicology Research Institute	1	Lawrence Livermore Laboratory	18
		Oak Ridge National Laboratory	5
Mid-Pacific Marine Laboratory	51	Stanford Linear Accelerator	1

4.2.10.7 Summary of PPE Use. As discussed and noted in histograms of PPE requirements, there was a general reduction in PPE requirements over time for the various tasks being accomplished. The most important reduction was much more judicious use of protective clothing, especially suits, which were required for levels IIIB and IV. From a practical standpoint, due to the overwhelming concern for internal radionuclides intakes, protection for the inhalation pathway was mitigated by air-purifying respirator use. Throughout the duration of the project, the key tasks of brush removal by bull dozers, soil excision, soil loading and unloading, and soil moving operations in the Cactus Crater all required use of air-purifying respirators. The degree of accompanying protective clothing, suit, gloves, booties, etc. did receive modification over time. One important point regarding soil transport on Navy vessels, if trucks loaded with dirt and a protective tarp were transported in whole, level I PPE was allowed once the truck was on the loaded on the vessel. For soils directly loaded into Navy vessels, air-purifying respirator use was specified for all phases of the operation (loading, unloading, transport) (DNA 1981). In addition, it was clear that PPE requiring air-purifying respirators were required for other activities, i.e., some debris removals.

4.3 External Dosimetry Results

4.3.1 Summary. Figures 4-13 and 4-14 contain a summary of film badge and TLD monitoring by device, respectively. As discussed above, initially film badge dosimetry was used, but due to some problems encountered by humidity and heat, TLD monitoring was added to augment the monitoring provided by film badges. As noted in DNA (1981), the two monitoring methods were worn in parallel by workers, though TLDs alone were used by visitors beginning in May of 1978. Prior to this time, visitors were monitored with PIC self-reading dosimeters. A total of 12,248 film badges were issued and processed during the cleanup, while 7,519 for TLDs (DNA 1981). In cases where film badges were damaged and dose information was deemed unreliable, administrative doses were estimated based on the nature of work conducted and the islands in which the work was conducted. The latter criterion was very important, due to the varied external exposure rates observed among the islands. Figure H-1 shows the timeline of dosimeter use on Enewetak.

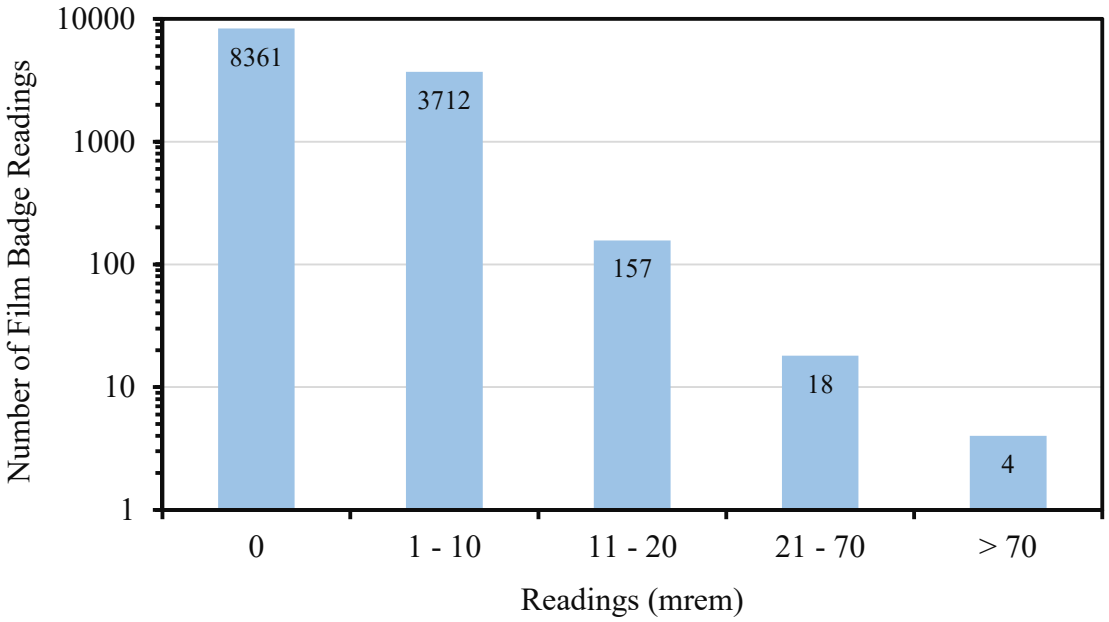


Figure 4-13. Summary of Film Badge Dosimetry Results.

4.3.2 Archiving External Dosimetry Data

Individual monitoring data was recorded on DD Form 1141's, a DoD form that was developed in the 1950's for recording occupational exposure to radiation. The need for a central repository for personnel exposure records was noted by numerous DNA senior personnel (DNA 1977b). As noted above, this same archived data is available for DOE-affiliated personnel, as it was retained in DTRA archived files. While a similar database was generated for DoD personnel, an archived copy of this data could not be located in DTRA archives. The archives did contain a substantial number of film badge and TLD summary documents, and in a number of cases individual DD Form 1141's. In addition, the archives contain a substantial monthly record of individual film badge and TLD monitoring documents. The data from these documents were transferred to DD Form 1141's on an individual basis. Figure H-2 contains an example DD Form 1141 with the name and social security number masked. DTRA cross-referenced personnel-specific data in Excel™

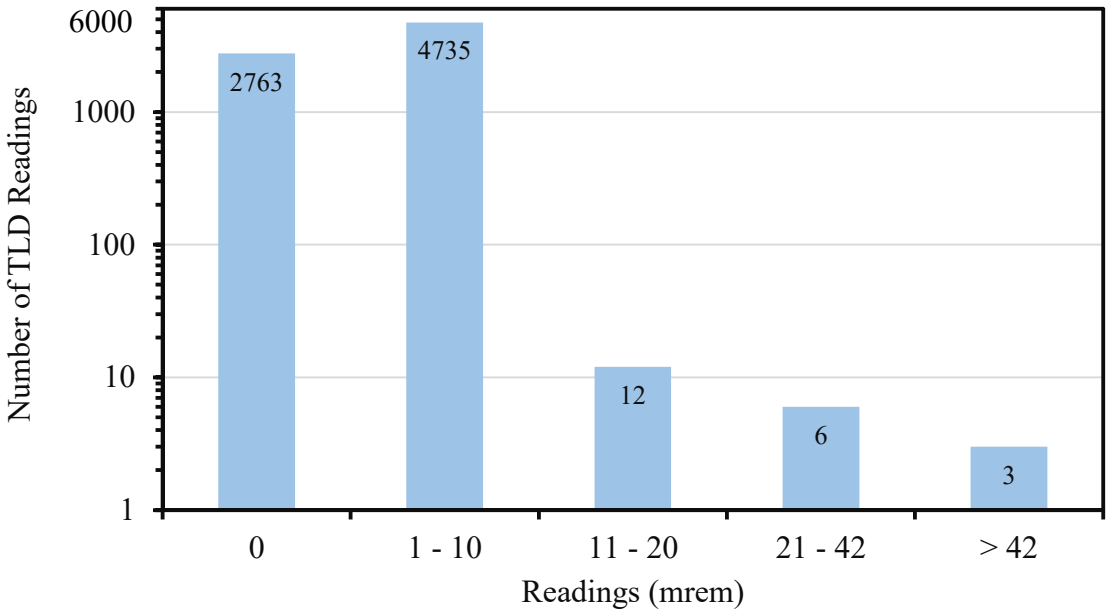


Figure 4-14. Summary of TLD Results.

files for many of the Enewetak cleanup veterans, however, DTRA archives files are not complete for all DoD personnel. DNA dedicated an extensive amount of time forwarding copies of DD Form 1141 to military member organizations for inclusion in their medical records. The historical files have extensive archive documenting this effort, especially in the case of veterans that changed duty locations. Therefore, it is reasonable to expect that the medical records for many veterans will contain a DD Form 1141 for their participation. The medical records of individuals was the primary location for radiation exposure documentation in the DoD during the time of the Enewetak cleanup.

DNA recognized the existence of the AF's Master Radiation Exposure Repository (MRER), a computer-based repository for radiation dosimetry records of individuals monitored by the AF. The MRER has provisions for the addition of dosimetry data from other sources, however, based on a review of MRER records of AF personnel that participated in the cleanup, monitoring data from DD Form 1141's from this project were not added to the database. Due to the fact that most of the AF individuals that accessed controlled islands were FRST members, they consisted of individuals that may have performed radiological-related tasks in their regular duties. For this reason, many of these individuals already had records in the MRER from their regular AF work. Though the MRER existed in the latter 1970's, it was still a common practice in the AF to file dosimetry records in medical records.

4.3.3 Review of Dosimetry Results

4.3.3.1 General

Overall, the film badge and TLD program documented very low exposures for personnel monitored under the program, as illustrated in the histograms displayed above. This was a result of two primary factors. First, external exposure rates on the northern islands of the Atoll were fairly low by the time the cleanup was accomplished between 1977 and 1980. Second, in spite of some

debris areas causing locally-elevated exposure rates, the practice of controlling access to these areas during debris removals also reduced exposure potential.

Evaluation of exposures is more readily accomplished by exception, due to the fact that virtually all film badges or TLDs had recorded doses less than 20 mrem. Dosimetry was issued on a monthly basis, though for some individuals the monitoring period may have been less. Visitors were issued badges for the duration of a visit, which could have been a single day or perhaps a few days. As well, for some individuals with dosimetry assigned for multiple months, which was common for individuals that were assigned work on the controlled access islands for a typical six-month deployment, dosimeters at the beginning and end of a deployment would have been only a fraction of a month. As an aid to the reader, Table 4-5 was provided to illustrate estimated monthly radiation doses for individuals that worked on controlled islands. The estimates used average island doses from either DOE exposure measurements conducted during the cleanup or AEC (AEC 1973) decay-corrected exposure rates to 1978. A small exposure rate of 1 $\mu R\ h^{-1}$ was assumed for individuals while on naval vessels, assuming that debris or soil was being transported. The off-duty exposure rate is for the terrestrial exposure rate estimate for Ursula, the island most personnel that worked in the northern islands of the Atoll were billeted during off duty hours. Cosmic radiation was estimated to provide an exposure rate of 3 $\mu R\ h^{-1}$ from directly ionizing radiations and photons. It is important to understand that these exposure rates are for averages on the respective islands. Some individuals conducted work closer to interior regions of an island, where exposures would have been higher than the average, while others, most notably Navy veteran's on the WBCT and FRST members providing some support to these teams, exposure rates encountered during work periods would have been lower, especially for work in the water. Work conducted in the water would have been comprised primarily of cosmic radiation alone, due to the high degree of attenuation provided by water in shielding photon emissions by radionuclides in sediments. The assumption of a 10-hour work day on the island would have been higher than the average, as some days may have included more time spent on naval vessels. For the example islands, the highest was for Belle, which is in general, representative of the other islands in this area, e.g., Alice, Clara, Daisy, Edna. It is important to note that very little work was accomplished on these islands, as compared to Janet, Pearl, and Sally. The two islands among the northern controlled islands of the Atoll requiring the greatest levels of manpower were Janet and Yvonne. The pie charts are provided as an aid to the reader to illustrate the fractional dose from each source for four of the cases listed in Table 4-5. The average radiation exposure conditions on Sally and Vera are within the range of typical background conditions in CONUS, where cosmic and terrestrial exposures are about 3 $\mu R\ h^{-1}$.

From the data in Table 4-5, it is readily apparent why the vast majority of individual dosimeters had doses reported less than 10 mrem. In the case of film badges, only 1.5% were greater than this levels, while for TLDs 0.28%. For the 20 mrem criterion, only 0.18% of the film badge results were greater, while 0.12% for TLDs. As noted earlier, upon introduction of TLDs to augment radiation monitoring, TLDs were issued with film badges for workers, while they replaced PICs for visitors. Therefore, for the film badges and TLDs issued in tandem, a device with a higher reading could be evaluated against the result of the other device worn by the worker. This capability was important for evaluation of a few dosimeters that had readings well beyond expectations for the work being conducted on the Atoll. These will be discussed specifically below. An important point to be made regarding the estimated monthly dose, similar to the discussion in Section 2.3.6.5, free air measured exposure will be higher than equivalent dose to tissue due to attenuation of photons and the 0.875 conversion factor between exposure and dose to tissue.

TABLE 4-5. Estimated Monthly Doses for Personnel with Presence on Various Northern Islands for 26 Work Days per Month, 10 hours per Day, 2 hours per Day on Transport Boats, and Residence on Ursula during Off-Duty Hours [Based on Either DOE Exposure Measurements in 1978 or AEC 1973 Measurements Decayed-Corrected to 1978].

Island	Exposure Rates (μR h^{-1})				Estimated Monthly Dose (mrem)
	Work	Boat	Off-Duty	Cosmic	
Belle	51	1	1.4	3	16.0
Janet	13.5	1	1.4	3	6.3
Pearl	26	1	1.4	3	9.5
Sally	3.5	1	1.4	3	3.7
Vera	1.5	1	1.4	3	3.2
So. Yvonne	3.1	1	1.4	3	3.6
No. Yvonne	7.6	1	1.4	3	4.8

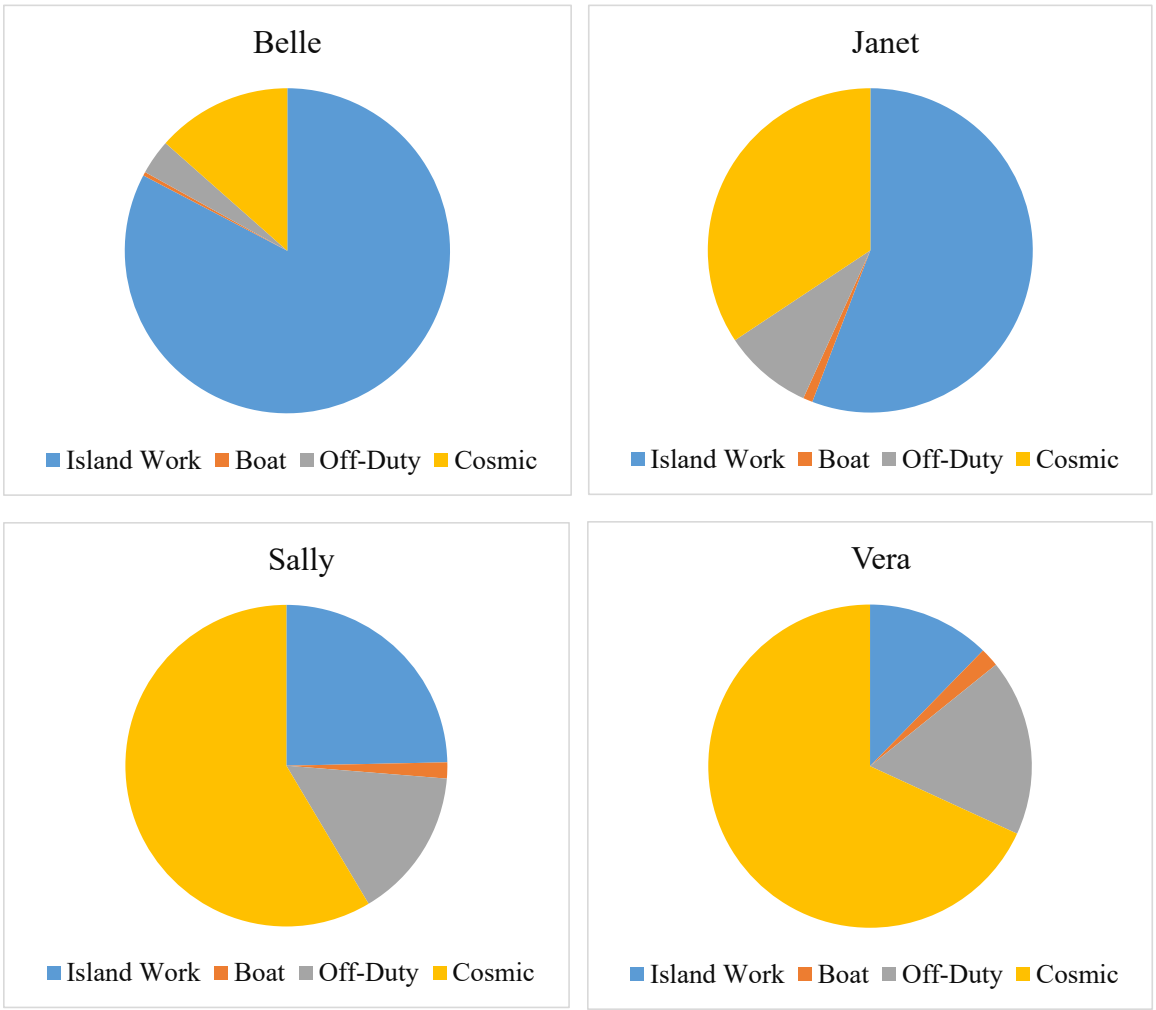


Figure 4-15. Distribution of Estimated Contributions to Dose from Various Sources of Exposure.

4.3.3.2 Higher Dosimeter Readings

Due to the relatively small fraction of samples with reported dose in excess of 20 mrem, it is much more informative to review these cases to understand the circumstances for higher than typical exposure rates, as compared to the vast majority of samples. Nevertheless, none of the workers received an external exposure in their work that approached a concern with regard to exposure limits established for the project. There were 1,011 DOE and contractors involved with the project (DNA 1981), although archived exposure data for this group included 945 individuals. Among the 945 individuals, only one individual had a film badge or dosimetry recording in excess of 20 mrem. The case was for an Eberline Instrument Corporation (EIC) civilian with a film badge issued for a period covering mid-May to mid-June 1978 having a dose of 43 mrem. During the monitoring period, the individual had work on Janet, Yvonne, Irene, and Sally. This individual had a total of four separate external dosimetry entries in their record, covering the period: 14 April 1978 to 14 June 1978. For one month, separate entries were made for duplicate coverage by a TLD and film badge. Besides the 43 mrem recorded dose, the other three dose recordings were zero.

Two of the high TLDs and film badge dose recordings covered an abnormal circumstance for two veterans working on Yvonne. Each of the individuals was wearing both a film badge and TLD. Both were AF FRST members involved in the debris survey team on Yvonne. One of the members had a TLD reading of 559 mrem and a film badge reading of 400 mrem; the other had a TLD reading of 550 mrem with a film badge reading of 430 mrem. This single event generated a significant amount of investigation. Seven other members of the survey team had their dosimetry read with all zero mrem readings. The investigation revealed that these individuals in all likelihood left clothing with their dosimetry attached in an area where external exposure rates were about 25 mrem h^{-1}. This area on Yvonne had a reported external exposure rate of 60 mrem, as documented by AEC (1973) (see Figure B-35), but due to the likely dominance of ^{60}Co and its 5.3 y radiological half-life, it had decayed to 25 mrem h^{-1} by 1978. The DTRA archives contained the DD Form 1141 for one of these FRST members. Besides the one TLD with a recording of 550 mrem, the other dosimetry monitoring results were well within expectations: a 23, 19, 10, and 5 mrem recordings, three 2 mrem and four zero recordings. Excluding the 550 mrem recording, the total from the other recordings was 63 mrem. The result of the investigation of the two high TLD readings was a recommendation to provide an administrative dose for the two individuals for the reporting period.

With exception of the TLDs that had 559 and 550 mrem, the next high TLD result was 67 mrem, read in mid-April 1978. Among the 418 other TLDs turned-in for processing this week in April, none were in excess of 10 mrem. Among all TLDs readings, six had readings between 21 and 42 mrem, which were spread-out among a number of individuals. Three of the six were among 350 TLDs processed in early October 1978, while single TLDs within this range of dose were read for three other TLD turn-in periods. In review of work being conducted, the exposures were to individuals assessing and removing contaminated debris. Due to the relatively small fraction of debris that was contaminated on the a few northern islands of the Atoll, the potential for a dosimeter reading in excess of 20 mrem was very low. The islands containing this debris were Janet, Pearl, Sally, and Yvonne. Due to the spread of these higher dosimetry monitoring values over a number of individuals, the sum of external dosimetry results for individual workers were below 100 mrem, based on review DD Form 1141's in the archives. The rare exceptions were the two individuals discussed above that had readings in excess of 500 mrem. One AF veteran had a film badge dosimetry recording of 36 mrem for one monthly monitoring period, 13 and 10 mrem for two others,

and five zero mrem readings for other months, totaling 59 mrem for a duty period a little over six months. A Navy veteran had one of the TLDs in reading range of 21 and 42 mrem - a reading of 24 mrem for the period of 15 July to 18 August 1979. Other dosimetry recordings were 19, 4, and 1 mrem, with two zero recordings for a total of 48 mrem for a six-month deployment.

An AF veteran that worked in the clinic had a reading of 42 mrem for a TLD over the monitoring period 24 December 1979 to 7 Janurary 1980. He was also issued a film badge. This individual was monitored for three other periods with respective recordings of 3 mrem and two zeros. This individual did not have any unique duties that would have justified an exposure of 42 mrem, since his duties were on the Ursula Clinic. One location of potential evaluated for the other AF members with unusually higher readings was the locker that stored check source used for the IMP, as stored by FRST on Ursula.

In addition to the two abnormally high TLD readings for the AF FRST members with duties on Yvonne, there was a Navy veteran that had a 27 mrem TLD reading. The reading for this individual was suspicious due to the fact that most reading for Navy veterans assigned duties on Navy vessels were typically below 10 mrem. An investigation determined that the high reading for the monitoring period was due to the TLD being in close proximity to a self-illuminating gauge containing ^{226}Ra on the boat. Apparently, the veteran placed his shirt with the dosimeter attached near the dial for prolonged periods of time during transport operations.

4.3.3.3 Total Doses for Deployment

Overall, although there is not a complete archive of DD Form 1141's for military participants in the Enewetak cleanup, based on the overall distribution of individual film badge and TLD dosimetry records and review of dosimetry records for some the limited number of individuals with a higher dosimetry recordings, total individual external doses were less than 100 mrem. This conclusion is independent of assignment duration. One may be inclined to assume that individuals assigned to duties for a year may have a total dose for their deployment twice this value. This is not the case, however, as the higher doses received by a small number of individual's was not based on their total deployment period, but rather on the amount of time they spent working in areas with contaminated debris. Overall, this type of work was very limited in duration and limited in the number of personnel involved. Veterans that were assigned to the Atoll for longer periods of time were commonly in leadership positions where potential for higher exposure was limited due to very little presence in areas with contaminated debris.

In summary, archived DD Form 1141's supports an upper level recorded dose of 100 mrem from external exposures to individuals assigned to the Atoll. The two AF veterans with dosimeter readings in excess of 500 mrem are identified by name in archived documents. Nevertheless, administrative doses were recommended for each of these individuals, which would have placed their total external dose less than 100 mrem.

4.3.4 Uncertainties in Dosimetry Monitoring Results

Dosimetry monitoring devices have inherent source of bias and uncertainties, which can arise from variability in the laboratory methods used to evaluate a film badge or TLD, how the device are worn by individuals in the working environment, how devices are stored during non-use periods, and environmental factors. The evaluation of dosimetry data was an important issue in assessment of veterans and other personnel that participated in atmospheric testing of nuclear weapons due to

variability of exposure conditions these individuals were subjected to under these test programs (NAS 1989; DTRA 2003). Assessment of historical dosimetry methods used during atomic tests remains an important issue for assessment of atomic veteran exposure cohorts. In contrast, exposure conditions on Enewetak Atoll were well understood due to the extensive monitoring conducted by the AEC (1973) prior to restoration and the DOE (1982) after the completion of restoration work. Furthermore, for atmospheric testing, doses for some personnel were based on a film badge issued to one individual in a group. This was not done for work at Enewetak, except in the cases where a dosimeter was damaged. In these cases, dosimetry results from other individuals in the similar work detail were evaluated for determination of an appropriate administrative dose.

DTRA (2017) estimated that the minimal detectable level (MDL) of radiation exposure from the film badge type dosimetry used by the Army in support of the Enewetak cleanup was about 20 mrem for the moderate to higher energy photons emitted by residual radionuclides. The MDL for TLDs used during the cleanup was much lower, ~ 10 mrem. Clear from the estimated average monthly exposures for individuals with full-time work on controlled islands contained in Table 4-5, almost all exposures received by a dosimetry device whether it was recorded by a film badge or TLD would have been below the MDL. In essence, this leads to conditions where an actual received dose, for example 10 mrem, could be recorded as a zero, 5, 10, or perhaps 15 mrem, or a zero dose is recorded as a 0, 5, or 10 mrem. The histograms containing the summary of reported film badge and TLD results in Figures 4-13 and 4-14 illustrate this issue. Although there are about 60% more film badge results than TLD results, which was due to the fact that TLDs use was not initiated until April 1979, the relative distribution of dose to individuals wearing the devices over the monitoring period are expected to be similar. The one key range of recorded dose for each histogram of interest are those between 11 and 20 mrem. For film badges, 0.16% had reported dose within this range, while for TLD's it was only about 0.10%. Under the reasonable premise that almost all dosimetry devices received less than 10 mrem of actual dose, it understandable that this range of recorded dose would have a higher frequency for film badge recordings than that for TLDs. It is likely due to the greater degree of uncertainties inherent to assessment of low-level doses for film badges over TLDs – low-level doses received by film badges were distributed over a greater range than their TLD counterpart.

One concern over the distribution of recorded film badge and TLD results is the number of zero recordings. In evaluation of this concern, it is important to understand a number of factors that contributed to this condition. First, a large number of dosimeters were issued to individuals that had presence on controlled islands for a limited period, in some cases only a single or a few days. Second, dosimetry was issued for individuals that were assigned duties on Ursula, though they had limited or no duties on other controlled access islands. Since control badges were established on Ursula, it is reasonable to understand why this group of individuals would have an expected net dose of zero. A number of the other northern islands had external exposure rates very similar to Ursula, i.e., Vera, Wilma, and many parts of Southern Yvonne. Third, many personnel had expected net doses less than zero, though they were assigned duties on controlled islands. For example, Navy personnel that spent a large portion of their duties on Navy vessels would have received radiation doses less than the control badge maintained on Ursula, as doses received are primarily from cosmic radiation alone. Similarly, Navy personnel that were part of the WBCT, would likely have net doses less than that of control badges, due to the attenuation of photon emissions from water.

The NAS (1989) in review of dosimetry method applied to participants in atmospheric testing, discussed assessment of dose to individuals with doses reported less than the MDL. The NAS committee suggested using a value half-way between zero and the MDL "for determining the upper limits in a consistent manner for exposures reported below the MDL." This would imply a

recommended dose of 10 mrem for film badge results reported less than the MDL and 5 mrem for TLDs. The committee cautioned, ". . . that this does not imply a recommendation to modify existing records of exposures recorded below the MDL."

Use of this principle could have some mixed outcomes in accurate prediction of doses to workers. For individuals that were deployed to the Atoll for the typical six month period and performed work on key controlled access islands, e.g., Janet, Yvonne, Sally, etc., their total dose would be about 60 mrem, if they were provided film badge dosimetry, and didn't have any individual dosimetry device recordings above 20 mrem. For the minority of individuals that had one film badge result between 11 and 20 mrem, and the remaining five less than the MDL, their dose would between 61 and 70 mrem. For those with a single film badge result between 21 and 70 mrem, and five less than the MDL, their dose would be between 71 and 120 mrem. Based on the fact that the higher recorded doses were spread out among many individuals, only a few individuals would have total doses higher than 120 mrem. These few individuals, based on follow-up, had suspected anomalous readings based on actual exposure conditions. These cases can be managed on an individual basis, due to the limited number of cases, and the fact that they were well documented. For many individuals with very low exposure potential, it is possible to have an estimated dose in excess of 120 mrem, though in reality their exposures are likely to be substantially lower. A good case in point is an individual in leadership, with only intermittent duties on controlled islands, e.g., perhaps 5 days a month, yet a deployment period of 15 months. If this individual had 15 film badges issued, all with recorded doses less than the MDL, their estimated dose would be 150 mrem. In reality, however, if dose estimates are made based on actual occupancy, their doses would be a small fraction of that estimated for individuals that had only six-month deployments, but prolonged work periods on controlled islands. This example provides some practical constraints on this method.

The practice of substitution of recorded doses with values less than the MDL with a value one-half of the MDL can create complications in attempting to provide more accurate dose estimates. This process is complicated by the fact that for many individuals, TLD results are used for a portion or all of some individuals' dosimetry monitoring. For TLD results less than or equal to 10 mrem, a value of 5 mrem could be assigned as an estimated dose.

4.3.5 External Dose Recommendations for AF Veteran Inquiries

External dosimetry records for many veterans are likely to exist in their service records due to the efforts conducted by DNA to forward DD Form 1141's to veteran's installation of assignment. For some veterans' DNA archived data contains completed DD Form 1141's. For cases where an archived DD Form 1141 is no longer available, individual TLD and/or film badge monitoring results can be compiled from archived DNA documents for many of the individuals assigned to duties at the Atoll. For some individuals, however, a complete record of dosimeter readings may not be available. Controlled island access logs in conjunction with documented external dose rates can be used to augment archived monitoring results, as illustrated in Table 4-5. Nevertheless, based on the review of archived dosimetry results in comparison to individual island exposure rates, individuals are expected to have total doses from a deployment less than 100 mrem.

For AF members deployed to the Atoll, 120 mrem is a reasonable upper-bound estimate for external dose where dosimetry monitoring data is unavailable. This is based on the discussion provided in Section 4.3.4. Estimates of external dose using a combination of occupancy on controlled access islands compiled from archived access logs and average external exposure rates for the islands would provide estimated doses less than this value, based on a review of controlled island

access characteristics. Regardless of the values of external dose for individuals, whether they are based on DD Form 1141 data, DD Form 1141 data modified for reported doses less than the MDL, or 120 mrem upper-bound external dose estimate, all values are well below the annual occupational exposure standard of 5,000 rem that was applied to this project and remains a current DoD occupational exposure limit.

4.3.6 External Exposure to Skin

For most occupational exposures to external radiation sources, absorbed dose to the skin is commonly similar to deep tissue dose when the source of radiation is from penetrating photon radiations. For exposures of low-energy photons, mixed β- and γ-radiation fields, and pure β-radiation fields, dose to the skin can in some cases be much higher than dose to deep tissue. Film badge and TLD dosimetry monitoring devices used during the cleanup did not incorporate shallow dose measurement elements.

In 1976, prior to the cleanup, LLNL assessed this issue with measurements on Janet and Fred using TLDs and portable survey instruments (Crase et al. 1982). In their work they found that 29% of the total dose rate in air (at a height of 1 m above ground) was due to the contributions of β-radiation and low-energy photons. This provides an estimated β-radiation and low-energy photons dose to deep dose ratio of 0.41 [0.29/(1 - 0.29)]. The relative contribution of β-radiation and low-energy photons to total dose rate was affected by ground cover, with some reductions observed in vegetated areas, compared to areas with bare soil only.

Skin doses are generally only a concern in cases where individuals have a medical condition affecting the skin, i.e, basal or squamous cell carcinomas. For these cases, it is recommended that a shallow dose of 1.41-fold times the recorded or estimated external dose be used.

4.3.7 Environmental TLDs

Environmental TLDs were placed at numerous locations on northern islands of the Atoll during the 1977-1980 cleanup. These TLDs were read periodically in a similar manner to TLDs worn by individuals. TLD results provide similar information on exposure potential in the area of placement as do external dose measurements performed in preparation of the 1973 AEC Radiological Survey Report and by the DOE during the cleanup. Similar to the discussion provided above for external dose measurements collected by portable survey instruments, free air measurements of dose with TLDs will be higher than equivalent dose to tissue due to attenuation of photons afforded by the body. Because the TLD measurements do not provide additional benefit in assessment of external exposure to workers, the results of these measurements are not detailed in this report.

4.4 Urine Bioassay Results

Urine bioassay samples were collected from all individuals that were present for more than 30 days on northern islands of the Atoll that had controlled island access. Individuals collected a 24-h urine void upon completion of duties on the Atoll. A total of 2,338 samples were submitted by personnel, about 29% of the total number of individuals (8,033) that were present on the Atoll based on Appendix B of DNA (1981). This is a reasonable number of individuals under consideration of the fact that many individuals assigned to duties on the Atoll did not perform work on the controlled islands and many individuals that were present on controlled islands during the cleanup were only

present for a few days. Urine samples were sent to the USAF Occupational and Environmental Health Laboratory (OEHL) for analysis. Samples were analyzed for isotopic plutonium, gross β-radiation, and ^{40}K through γ-spectrometry (DNA 1981). ^{40}K is a naturally-occurring radionuclide in the environment and due to its relatively good solubility, it is found in most foodstuffs. As a result, all individuals have a body burden of ^{40}K which provides a presence routinely in urinary excretions. It is generally the largest source of β-radiation emissions observed in urine samples of individuals from background sources in the environment. The gross β-radiation was in the analysis protocol to evaluate potential intakes ^{137}Cs, ^{60}Co, and/or ^{90}Sr, the most prominent radiological contaminants in Enewetak Atoll that emit β-particle radiation. Since the laboratory analyzed samples through γ-spectrometry, they were prepared to report positive detections of ^{137}Cs and ^{60}Co. The laboratory planned to conduct isotopic analyses of activation and fission products in the event the gross β-radiation analyses yielded a result indicative of a significant intake. Two criterion used were: 1) a gross β-radiation concentration greater than five nanoCuries per liter (nCi/L) and 2) a ratio of the gross β-radiation to ^{40}K activity concentrations for an individual urine sample greater than three (DNA 1981).

Plutonium content of urine samples were compared to a Health Physics Society (HPS) Plutonium Bioassay Committee proposed 0.2 pCi plutonium[16] activity per 24-h void sample criterion, which recommended a re-sampling for verification (DNA 1981). Among the 2,338 urine samples, all but six had $^{239+240}$Pu less the minimum detectable activity (MDA) for the method. The six samples had respective $^{239+240}$Pu activities of 0.05, two at 0.06, two at 0.08, and one at 0.11 pCi. None were greater than the 0.2 pCi criterion for re-sampling. In spite of this, these six individuals were requested to submit an additional 24-h void urine sample. The second sample for each individual was below the MDA. The six positive detections from initial samples submitted were likely false positives. This is very reasonable for a sample population of 2,338. The likelihood for a true positive detection of plutonium in the urine samples of Enewetak workers was negligible due to the relatively low activity concentration of plutonium in soils, relatively low activity concentration of plutonium observed in the 5,000+ air samples, the conservative implementation of air-purifying respirator use, and the practice of wetting soils being excised, transported, and disposed.

The gross β-radiation and ^{40}K activity concentration assessments of urine samples were within expectations for individuals with only typical intakes and urinary excretions from background radiation sources. ^{40}K activity concentrations ranged from non-detect (~ 0.05) to 4.1 nCi L^{-1}, while gross β-radiation ranged from non-detect (~ 0.3) to 4.2 nCi L^{-1}. One sample had a ratio of the gross β-radiation to ^{40}K activity greater than three, 3.05. This sample was reviewed, but since the gross β-radiation activity of the sample was very small, further investigation was not pursued. A regression of the gross β-radiation to ^{40}K activity concentrations for 182 samples submitted by AF veterans supporting the cleanup is provided in Figure 4-16. For this plot, the ^{40}K activity concentrations were modified by the β-particle emission branching fraction of 0.893. Eighteen samples had gross β-radiation activity concentrations below the MDA of 0.3 nCi L^{-1}, while three of these also had ^{40}K below the MDA. The 15 samples with a value for ^{40}K are displayed by red squares, with the value of the MDA for gross β-radiation plotted for each of these samples. This sub-set of samples for AF workers is 7% of the total number of urine samples, but does represent the general characteristic for the data set of all urine samples. The correlation between gross β-radiation and ^{40}K activity concentrations is very good, with a regressed slope of 1.07 $\pm$ 0.014. Thus, β-particle emissions from ^{40}K contribute about 93% of the gross β-radiation. The small fractional

[16] It is inferred that only the α-particle emitting radionuclides are of importance.

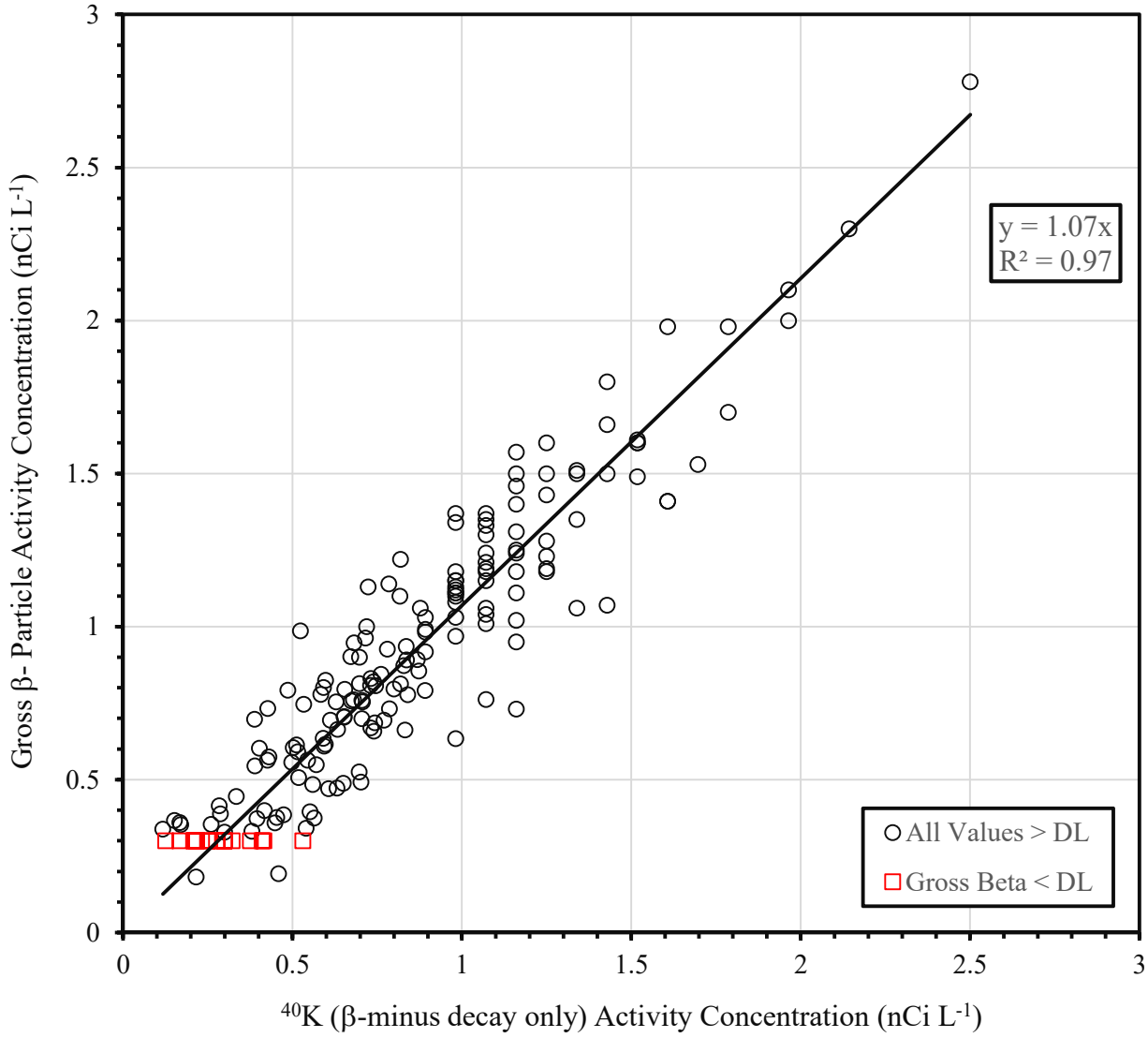


Figure 4-16. Regression of Gross β-Particle Activity Concentration to ^{40}K Activity Concentration (β-Emission Branching Fraction Only) for AF Member Urine Samples.

balance of β-particle emissions in urine is primarily due to radionuclides in the naturally-occurring ^{232}Th and ^{238}U decay chains. Regressions of gross β-radiation to ^{40}K activity concentrations and relative percent difference (RPD) of these two entities vs. ^{40}K activity concentration are contained in Figures H-3 and H-4. Both of these plots use the value of 0.3 nCi L^{-1} for samples with gross β-radiation activity below the MDA. Both plots display the common characteristic of evaluations of this type: at low activity concentrations, uncertainties in activity concentration of analytes in the low activity concentration range contribute to a large spread in the data, as compared to the samples of high concentration. The shape reasonably follows the expectation for the Poisson distribution for random uncertainties for samples with low total counts. Understandably, the ratio of the gross β-radiation to ^{40}K activity concentrations is not a key indicator of the potential for an intake if the ratio is dominated by high uncertainties for samples in the low activity range. For the one sample with a ratio of gross β-radiation to ^{40}K activity concentrations about 2.9, it had a ^{40}K activity concentration of 0.132 nCi L^{-1}, seven-fold lower than the average of 0.94 nCi L^{-1}. This was a similar conclusion

drawn by DNA (1981) in the decision for no additional investigation of the one sample with a gross β-radiation to ^{40}K activity concentration of 3.05. The evaluation of a population of urine samples, as was done in Figures 4-15, H-3, and H-4, provides a better perspective on the results of the gross β-radiation and ^{40}K analyses than a review conducted on single samples. Overall, the same conclusion can be drawn on potential intakes of prominent β-particle emitters of ^{60}Co, ^{90}Sr, and ^{137}Cs as was the case for plutonium, only negligible intakes were possible due a number of factors, including PPE use. Only a few urine samples had positive detects for ^{137}Cs, based on the γ-spectrometry screening method used to assess the ^{40}K. Among the positive detects, the highest ^{137}Cs activity concentration was only 0.107 nCi L^{-1}, a concentration deemed negligible (DNA 1979).

4.5 Nose Swipes

Nose swipes[17] were collected periodically from cleanup personnel as another method to assess the adequacy of radiation safety procedures at protecting personnel from unacceptably-high inhalation exposures. In contrast to urine bioassay samples, which were submitted be personnel upon completion of their assignment to the Atoll, nose swipes were collected from personnel at hotline control points on controlled access islands by FRST members. Swipes were collected for a number of reasons. In the initial months of work (June – August 1977) all nose swipes were collected on a random monitoring basis. The practice of periodically collecting random samples continued until July 1978. It was discontinued because it tended to irritate the mucous membrane of workers. If an individual entered an area requiring respiratory protection, yet did not have the appropriate level of respiratory protection or it was worn improperly, a nose swipe was collected on the worker. If defects were noticed in a protective mask or filter, or if dirt was observed on the interior indicating a potential breech in protection, a nose swab was collected on the wearer. As well, if an individual broke a procedure, for example unauthorized smoking in a work area, a nose swipe was collected on the violator. When an airborne concentration on an air filter exceeded one-tenth of the adjusted-MPC for unprotected workers, nose swipe were collected on personnel in the work zone. This criterion was based on field screening measurements of air filters, as none of the 5,204 air filters exceeded 10% of the adjusted-MPC from a laboratory analysis.[18] Figure 4-17 provides a pie-chart breakdown of the number of nose swipes collected during the project, while Table H-1 provides a more detailed summary over the course of the project. Upon review of some of the periods where high numbers of nose swipes were collected due to high field measurements of air filters, none correlated with some of the periods where higher air sampling results were recorded, based on laboratory analysis of filters. Hence, it appears likely radon daughter interferences were the likely cause of concern. Radon daughter interference was a notable interference in the field assessment of air filters that the radiation safety staff dealt with throughout the project. A 17-day period, 2 – 18 December 1978 had 184 nose swipes collected alone, one-half of the total collected for this reason. Nevertheless, not a single air filter had an activity concentration in excess of 1% of the adjusted MPC for this period. During this period, air sampling was being conducted on Janet, Sally, Yvonne, Ursula, and a number of the Navy vessels. Among 66 air samples collected on Yvonne during this period, over half had positive detects for airborne activity, though the highest activity concentration was only 0.6% of the MPC. A sizeable fraction of man-days of work was performed in PPE requiring air-purifying respirators, as shown in Figure G-12. Another example of the very conservative nature of nose swipe collection was for six veterans assigned to duties on the Navy vessels Maggie 8 in February 1979. Nose swipes were collected from all six individuals due to an action level exceedance on a field assessment of an air filter. Nevertheless, all those assigned

[17] These samples are also commonly referred to as "nasal swabs."
[18] Radon daughters were believed to be responsible for some of the high-sided field assessments of air filters.

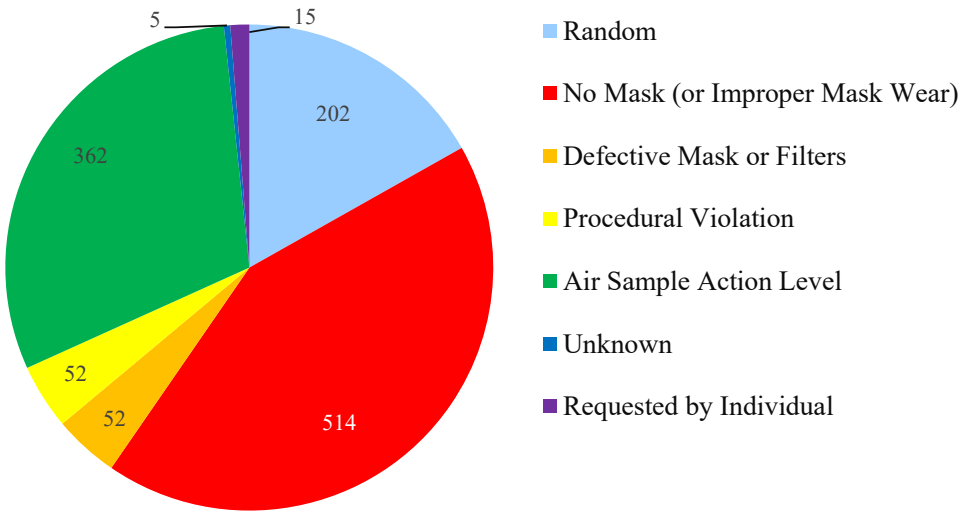


Figure 4-17. Piechart of Bases for Nose Swipes.

duties on Maggie 8 during this period donned level IIIA PPE when soil was being transported. The highest activity concentration from an air filter from Maggie 8 during this month was 0.03 pCi m^{-3}, about 0.1% of the adjusted MPC.

About 40% of the nose swipes were collected due to individuals violating a requirement to wear respiratory protection in a work area or a mask was being worn improperly. As an example, during the period of 2 to 28 June 1979, 38 individuals had nose swipes collected for this reason. During the month of June 1979, 425 individuals had access to controlled islands for a total of 2,662 total man-days. The estimated infraction rate was about 1.4% per work-day for this example period.

The summary results of nose swipe data is displayed in Table 4-6, as reported from DNA (1981). The total number of nose swipes listed by DNA (1981), 1145, is a little lower than from a listing found in DTRA archives, 1227. The highest nose swab activity was only 1.64 pCi (3.6 dpm). Activity levels observed on swipes were commonly below the MDA for the method, but all were well below screening levels established. DNA (1981) notes two separate action levels. On page 199, it references 100 dpm as the action level, while on page 200, it references the action level of 50 dpm, a value one-tenth the allowable level established for the project. Regardless, all swipes were well below both levels listed. The maximum activity of 3.6 dpm is a very low-level of activity. Nose swipe logs were maintained on an individual basis and are part of the DTRA archives.

TABLE 4-6. Nose Swipe File Summary Data from DNA (1981).

Descriptor	Number
Number Taken	1145
Range of readings	< MDA – 1.64 pCi [3.6 dpm]
< MDA*	439 (38.3%)
Zero	317 (27.7%)
> MDA	389 (34.0%)

Section 5. Internal Dose Assessment.

5.1 General

The issue of internal exposures was one concern expressed by some veteran comments in regard to their service in support of the Enewetak cleanup. This issue was inter-related with other concerns expressed by veterans – why was there varying levels of PPE provided to veteran's during the cleanup?, why was air sampling conducted during some operations while not others?, was it because air sampling equipment suffered failures?, etc. Internal exposures to radiation are also more difficult to comprehend for many individuals, because the exposures are not simply recorded by a dosimeter, as is the case for external radiation. Most internal radiation exposures are estimated based on levels of radioactive materials in soils, air, food, and water, coupled with inhalation or ingestion intakes. The levels of radioactive materials in air are normally inferred from concentration in soils. Inhalation and ingestion intakes are then converted into doses with use of dose coefficients discussed in extensive detail above. One important point regarding internal dose estimates for this project, internal doses may or may not be correlated to external radiation exposures. The higher levels of external exposure potential were related to individuals removing contaminated debris, with elevated external exposures primarily from ^{137}Cs and ^{60}Co. These areas, however, were not necessarily associated with higher concentrations of transuranics (e.g., $^{239+240}$Pu, ^{238}Pu, or ^{241}Am) in soils.

Because internal exposure potentials are intrinsically-linked to concentrations of radioactivity in soils and air, this report provided an extensive review of the radiological source term. The internal dose assessment considered all key radionuclides, but also radionuclides that were deemed of little impact to total internal dose. This was accomplished to demonstrate completeness in the assessment of internal dose.

5.2 Internal Dose Pathways

5.2.1 Key Internal Exposure Pathways. The key internal exposure pathways assessed in detail in this report are inhalation of suspended soil particles and incidental ingestion of soil particles. Both of these exposure pathways are intrinsically related to the concentrations of radioactive materials in soils. A number of other internal exposure pathways were possible, however, for reasons to be explained below, these pathways were not evaluated in detail for this report.

5.2.2 Unimportant Internal Exposure Pathways

5.2.2.1 Ingestion of Potable Water. Potable water for cleanup personnel assigned to the residence islands of Fred and Ursula was produced by desalination of ocean water. This process was effective at removal of minerals, which would have included fission products and activation products, e.g., ^{137}Cs, ^{90}Sr, and ^{60}Co, potentially existing in ocean waters, as well as key transuranics ^{238}Pu, $^{239+240}$Pu, and ^{241}Am. Samples of water from the distillation plant were analyzed by γ-spectrometry and isotopic plutonium by α-spectrometry. Concentrations of ^{137}Cs and isotopes of plutonium were many orders of magnitude below maximum contaminant levels (MCLs) specified in the current Safe Drinking Water Act (SDWA) [40 Code of Federal Regulations, Part 141.77]. As such, since the levels of radionuclides were well below SDWA levels, an assessment of dose is not deemed necessary; SDWA MPC levels are set to ensure very low radiation exposures.

5.2.2.2 Incidental Ingestion of Natural Waters Around Enewetak Atoll Islands

Individuals performing work on the Atoll had the potential for incidental intakes of lagoon and ocean water during their work. This was likely realized to a greater degree by WBCT and Navy vessel operators than individuals that worked primarily on land areas. Water sampling and analysis was conducted in 1972 and 1973 by the AEC at a number of locations throughout the Atoll (AEC 1973). Figure I-1 shows the sampling locations with accompanying information on the sampling depth. Samples collected at locations with craters created from test are annotated on the Figure: Mike, Koa, Seminole, Cactus, and Lacrosse. All of the sample results are below SDWA MCL's. The MCLs for ^{137}Cs, ^{60}Co, ^{90}Sr, ^{155}Eu, ^{207}Bi, and transuranics (^{238}Pu, $^{239+240}$Pu, and ^{241}Am) are 200, 100, 8, 600, 200, and 15 pCi L^{-1}, respectively. For β-/γ-emitters, MCLs are designed to limit either total body or a critical organ annual dose to 4 mrem from the daily consumption of 2 liters of water using ICRP 2 methodology. For ^{137}Cs, dose to the total body is limiting. Whereas, for $^{239+240}$Pu, the MCL is based on the gross α-particle MCL limit, which was derived from the toxicity equivalence of ^{210}Po to ^{226}Ra[19]. Among the samples collected at a depth of 3 feet, the activity concentrations were fairly low with respect to SDWA MCLs. A summary of descriptive statistics for this data is contained in Table I-2. Water samples at this depth are more appropriate for review for incidental ingestion, as compared to samples collected at much greater depths. Samples collected near bottom surfaces are more likely to contain suspended sediments, as compared to this collected from the surface. Among surface samples, one in particular, sample number 611, had an unusually high concentration of ^{137}Cs, ^{238}Pu, and $^{239+240}$Pu. This sample was collected near the edge of the Seminole Crate on Irene. Due to its collection location near the edge of a crater, inclusion of suspended sediments are likely the cause of the higher concentrations, as compared to other surface samples. High sediment concentrations are likely attributed the high activity concentrations of water samples collected near bottom surfaces of the lagoon. Overall, activity concentrations are a small fraction of the SDWA MCLs.

While plutonium and ^{137}Cs analyses were deemed the most important radionuclides for assessment, γ-spectrometry analyses of samples was also performed, though as clear from data summarized in Table I-1, only a few positive detections were made on γ-emitting radionuclides. Nine samples had positive detects for ^{60}Co, three samples for ^{155}Eu, 10 for ^{207}Bi, and only three for ^{241}Am. Due to the low activity concentrations in comparison to SDWA MCLs and the small intakes of ocean water, dose estimates for this pathway was also deemed unnecessary. Similarly, it is readily apparent why drinking water produced on Ursula and Fred through desalination had very low concentrations of radionuclides. As annotated on Table I-1, sample number 120 was for a location near Ursula. The ^{137}Cs and $^{239+240}$Pu activity concentrations of the sample at this location were 0.11 and 0.05% of their respective SDWA MCLs.

5.2.2.3 Ingestion of Locally-Derived Food

Food provided for cleanup personnel was comprised of food transported from CONUS. It did not contain any locally-derived supplement. Prior to the Enewetak people's relocation to another island in the Marshall Islands before atmospheric testing of nuclear weapons at the Atoll, they derived sustenance from marine life, coconuts, pandanus, breadfruit, and arrowroot (tacca). Due to the impacts of use for atmospheric testing, the islands had very limited presence of terrestrial plants

[19] ^{210}Po was deemed the next most radiotoxic α-particle emitter in the ^{226}Ra decay chain, with a concentration of 10 pCi l^{-1} being equivalent to 5 pCi L^{-1} of ^{226}Ra. The gross α-particle MCL included ^{226}Ra, which had its own limit of 5 pCi L^{-1}.

for consumption by personnel during the cleanup and for sampling by the AEC in 1972. As such, consumption of locally-derived food is deemed a low frequency event, though some veterans noted consumption of fish and shellfish procured from recreational activities. Tables I-3 through I-6 contain summaries of radionuclide concentrations from AEC (1973) for coconut, crabs, breadfruit, and tacca.

One notable radionuclide included in the analyses of potential food source samples which was not included in soil sample analyses was ^{55}Fe. From Table A-4, ^{55}Fe has a 2.7 y half-life and is produced from the activation of steel. As this radionuclide only has low-energy x-ray and electron emissions, it presents only a negligible external radiation exposure potential. Analysis for ^{55}Fe in foodstuffs is of interest primary due to the potential for bioaccumulation in organisms and its relatively high solubility within ecosystems.

Due to the expected low frequency of consumption of locally-derived food, assessment of doses are considered on a case-by-case basis.

5.2.3 Inhalation Exposure Pathway

5.2.3.1 General

There are a variety of methods of estimating intakes of radioactive materials by workers and members of the general public. In some cases, these methods are not designed to be an accurate assessment of an intake, but rather as a screening tool to demonstrate compliance with an exposure standard. There are some variances in approach, dependent on the exposure conditions and the radionuclide involved. In this clean-up project, there were a number of approaches applied to estimation of inhalation intakes. First, in the decision-making process for rehabilitation of the Atoll for future inhabitance by the Enewetak peoples, air sampling and dose-modelling were conducted to predict inhalation intakes, which were used to predict dose consequence to inhabitants. During the cleanup, this knowledge was used to guide PPE use by workers, though air sampling was also conducted to confirm that airborne concentrations were within expectations. However, because the primary objective was demonstration of compliance with the adjusted-MPC, a gross α-radiation assessment method was used by the laboratory. Accuracy in assessment of samples with low activity concentrations of α-emitting radionuclides was limited. Second, most of the air sampling conducted during the cleanup was conducted in areas where higher concentrations of α-emitting radionuclides were expected, e.g., during excision, transport, and loading of contaminated soil. A complicating factor is that many workers present in the areas that air sampling was conducted were wearing air-purifying respirators.

Bioassay samples can be a useful indicator of estimating inhalation intakes for some radionuclides. For intakes of tritium, urine bioassay is a very effective assessment method. In the case of plutonium exposures to cleanup personnel in this project, however, no bioassay method is very effective at quantifying intakes. This is due to the very low exposure potential that existed at the Atoll – the combination of relatively low concentrations of plutonium in soil, limited occupancy in these areas compared to a member of the public with long-term residence potential, the use of PPE (especially air-purifying respirators), and the soil wetting mitigation practice implemented. In the case of the prominent fission and activation products present at the Atoll during the cleanup: ^{60}Co, ^{137}Cs, and ^{90}Sr, some bioassay methods are effective at quantifying small intakes. However, due to the relatively low internal dose potential from these radionuclides in inhalation exposures compared to the transuranics present ($^{239+240}$Pu, ^{238}Pu, ^{241}Am), gross β-radiation and γ-radiation screening

methods were used. As discussed above, from review of urine samples submitted by AF personnel, the gross β-radiation results were consistent for urine excretions dominated by contributions from dietary ^{40}K. As well, only a few of the urine samples submitted by cleanup personnel had positive detects for ^{137}Cs, based on the γ-spectrometry screening method used to assess ^{40}K.

Therefore, modelling is a reasonable method of estimating intakes from the inhalation pathway. Due to the many assumptions necessary in this method, estimated airborne concentrations will be augmented with actual air sampling results to ensure that assumptions are reasonable for the many exposure conditions considered.

5.2.3.2 Modelling of Inhalation Intakes

The basic inhalation intake model is enclosed below:

$$I_{Inh,i} = \frac{IR \; x \; C_{Air,i} \; x \; ED}{RPF},$$

where

$I_{Inh,\,i}$ = inhalation intake of radionuclide *i*
$C_{Air,\,i}$ = activity concentration of radionuclide *i* in air
IR = inhalation rate
ED = exposure duration
RPF = respiratory protection factor.

This model is common for use when air sampling data is being used as the source of airborne activity concentration. This model, as used in radiation protection, normally adopts standard inhalation rates. ICRP Report 66 (ICRP 1994a) lists rates for various activities, as listed in Table 5-1. For this report, during work periods, an inhalation rate assuming light exercise will be used. The RPF is included to account for protection afforded by air-purifying respirators. Table J-1 lists RPFs for a variety of respiratory protection from Occupational Safety and Health Administration (OSHA) guidance (2009). Three separate types of respiratory protection were worn by personnel, as specified by DNA (1981), and summarized in Table 4-2. For dust masks, no credit is taken for

Table 5-1. Activity-Based Inhalation Rates (ICRP 1994a).

Activity	Inhalation Rate ($m^3\ h^{-1}$)
Sleeping	0.45
Sitting	0.54
Light exercise	1.5
Heavy exercise	3

protection, with a RPF assigned as 1.0. Level III PPE specified either a half- or full-face positive pressure respirator, while level IV required a full-face positive pressure respirator. Therefore, from Table J-1, assigned RPF could range from 50 to 1,000. Controlled islands access logs do not specify

the type of respiratory protection worn for those individuals wearing level III PPE. Therefore, without additional information from the individual worker, the conservative assumption for those wearing level III PPE would be a RPF of 50.

The basic inhalation intake equation can be modified if airborne concentrations of radionuclides are estimated from soil concentrations, by one of two methods discussed above. First, the mass loading approach:

$$C_{Air} = E_f \, S_o M \ ,$$

where

E_f = enhancement factor
S_o = average surface soil activity concentration,
M = total suspended particulate mass loading

and second, using a resuspension factor:

$$C_{Air} = S_f D \ ,$$

where

D = areal deposition density
S_f = average surface soil activity concentration.

Inhalation intakes are converted into committed equivalent dose to individual tissues, $H_T(50)$, or committed effective dose, $E(50)$, as shown below.

$$H_T(50) \; or \; E(50) = \sum_{i=1}^{n} I_{Inh,i} \; x \; DC_{Inh,i}$$

where

$DC_{Inh,i}$ = Inhalation dose coefficient for radionuclide i

5.2.3.3 Inhalation Modelling: Assignment of Soil Concentrations, Enhancement Factors, and Mass Loading

5.2.3.3.1 General. Airborne contamination concentrations are fundamentally determined by the combination of these three factors – soil concentration, enhancement factor, and mass loading. All three have the potential for a variety of values, dependent on the island, the type of work being performed, and the characteristics of the contaminant. The quantities of radiological

contaminants were well known for surface soils, based on extensive evaluation by the AEC (1973). Sub-surface soils were not characterized as well. A couple of good examples are the Aomon (Sally) crypt and the Erie site, which was evaluated very early in the project as discussed above. Hence, for many work activities, the average concentration of surface soils provides a reasonable basis for predicting re-suspension. For work being conducted at interior locations, the mean soil concentrations will be higher than the average, while at beach locations, the concentrations would generally be lower than the average. Because soil excision work was focused in areas of higher levels of transuranics on some islands, the activity concentrations of these radionuclides would have been much higher than the average for an island.

5.2.3.3.2 Soil Concentrations

Table J-2 contains soil concentrations for use for estimates of inhalation and ingestion intakes. The primary source of the soil concentration data is from NVO-140 (AEC 1973), as summarized in Tables 2-10, 2-12, and 2-13, and discussed in extensive detail in Section 2 of this report. Some supplemental information for transuranics was provided by NVO-213 (DOE 1982) and analysis in Table C-11. Due to the greatest exposure impacts from inhalation and ingestion intakes of transuranics, the analysis of these radionuclides in soils was deemed most critical, with estimates of ^{241}Am and ^{238}Pu soil concentrations based on relationships with $^{239+240}$Pu. For more appropriate assignment of activity concentrations to actual work areas on each island, the $^{239+240}$Pu concentration is listed at the 25, 40, 70, 75, and 80th percentiles. Notionally, the 25th and 70th percentiles may better represent actual soil concentrations at beach and interior locations, respectively, based on better radionuclide retention characteristics of soil at interior locations that were generally more heavily vegetated than beach locations which are subjected to dilution effects of the ocean and lagoon water. For this work, the 40 and 80th percentiles will be used respectively for beach and interior locations. These values are expected to be conservative for general types of work being conducted. Due their prominent presence on an activity basis, ^{90}Sr and ^{137}Cs are the key fission products. Table J-2 has their estimated fractional relationship to $^{239+240}$Pu listed for each island. Most of these values were based on median radionuclide ratio values derived from Table 2-13, and in some cases, regression analysis. For some radionuclides and specific radionuclides on some islands, surrogate relationships were established by data for an adjacent island. For example, as listed on Table J-2, due to limited number of samples analyzed for ^{238}Pu on some islands, surrogates were used for Kate, Mary, Ursula, Wilma, and land segments A and D on Yvonne. A ratio established between ^{238}Pu and $^{239+240}$Pu on Edna was based on excellent NVO-213 data. Inclusion of a number of other radionuclides were also contained in the Table for completeness. ^{60}Co is a key activation product and source of external exposure, though it had lessor importance for internal exposures from inhalation and ingestion intakes. Among the radionuclides listed in Table 2-13, all were included in Table J-2, except ^{102m}Rh[20]. This radionuclide was omitted due to its limited presence in NVO-140 samples and its short half-life, 3 y. ^{154}Eu was not listed in Table 2-13, but was included for a few islands which had numerous positive detections in soils. In the case of ^{125}Sb, ^{152}Eu, and ^{154}Eu for Yvonne, the relationship to ^{137}Cs was based on samples combined from all land segments. This was due to limited number of samples with positive detects among a single segment. Estimates of ^{154}Eu were only made for Pearl, Sally, and Yvonne, as noted in Table 2-14, it was only detected infrequently in samples on other islands. Other radionuclides listed in Table 2-14 that were produced from Enewetak tests, i.e., ^{101}Rh, ^{133}Ba, and ^{235}U were omitted from internal dose assessment due to their expected insignificant contributions to internal doses, as compared to other

[20] ^{102m}Rh, ^{106}Ru-Rh, ^{144}Ce, and ^{147}Pm were included for internal dose estimates for individuals on southern islands of the Atoll between 1959 and 1965, maintaining consistency with their inclusion for external dose estimates.

radionuclides considered in Table J-2. ^{151}Sm was also expected to have an insignificant contribution to internal doses, but was included for benefit to the reader in recognition that all important radionuclides were incorporated into the analysis. ^{151}Sm is an example of a long-lived fission product that had a reasonably high estimated residual activity fraction compared to ^{90}Sr, 0.25.

^{241}Pu content in relation to other isotopes is based on its initial mass fraction and alteration from fission and activations processes of the detonations on the Atoll, as discussed earlier in this report. For the purposes of internal dose assessments, it is assumed that ^{241}Pu has an activity fraction to other α-emitting radionuclides of plutonium as displayed in Figure A-9. In 1978, the ^{241}Pu to $^{239+240}$Pu activity ratio is 4.22.

^{228}Th, as listed in Table 2-14 as an isotope only detected in samples on the northern land segments of Yvonne, was discussed in extensive detail in Section 2.3.5.4.14, and included other isotopes of thorium: ^{230}Th and ^{232}Th. Table J-3 provides details of the estimated inhalation exposure impacts of thorium isotopes for presence in land segments A and A/B of Yvonne. As noted in Section 2.3.5.4.14, isotopes of thorium have very similar metabolism in humans to plutonium. Due to the concerns for internal exposures to thorium isotopes (decay chain daughters), yet limited land areas of concern for exposures, its equivalence to $^{239+240}$Pu as an internal exposure emitter was deemed an appropriate method to manage estimates exposures. Equivalence was based on effective dose (inhalation) scaling, with details provided in Table J-3. For segment A, estimated equivalent activity concentrations of $^{230+232}$Th, 36 pCi g^{-1}, were a little higher than the $^{239+240}$Pu, 31 pCi g^{-1}. For segment A/B, the estimated equivalent activity concentrations of $^{230+232}$Th were 9.8 pCi g^{-1}, less than a third of the $^{230+232}$Th.

For the purposes of this report, fractional relationships of radionuclides to $^{239+240}$Pu as listed in Tables J-2 and J-3 are assumed to remain consistent for the various $^{239+240}$Pu sample percentiles. For ^{238}Pu and ^{241}Am, there were fairly consistent linear relationships for islands where the majority of work was being conducted. For ^{238}Pu, notable exceptions were Nancy and Olive (Figure 2-26), although ^{238}Pu had a low fractional relationship to $^{239+240}$Pu for each island. In the cases of Pearl (Figure C-24), there was only moderately good correlation in ^{238}Pu to $^{239+240}$Pu. The relationship between ^{238}Pu and $^{239+240}$Pu was dominated by samples with higher concentrations, which was of greater importance for assumptions used for inhalation exposures. In the case of fission and activation products, correlations were generally good and reasonable for the purposes of this report. Nevertheless, correlations were not as critical as for the case of ^{238}Pu and ^{241}Am, as the fission and activation products provided much smaller contributions to internal dose.

For soil excision work, workers would have been predominantly in areas of respective islands with higher activity concentrations of $^{239+240}$Pu, as this work specifically targeted these areas. Table F-1 contains average activity concentrations of soil excised from Janet, Pearl, Sally, Irene, and Yvonne for disposal in the Cactus Crater. The mean TRU concentrations specified in these soils will be used in conjunction with actual air sampling data to establish appropriate concentrations for inhalation and ingestion exposures for excision of these soils and their handling.

5.2.3.3.3 Enhancement Factors and Mass Loading

Many of the examples of air sampling conducted on Enewetak and Bikini Atolls had specific information on mass loading and enhancement factors, as detailed earlier in this report. Enhancement factors ranged from 0.41 to 4.41. As well, there was detailed air sampling at the early stages of the cleanup that compared upwind to downwind locations during mechanical disturbance

of soils. This latter data was useful at demonstrating the overall difference in the combined effect of mass loading and enhancement effect, but details of either parameter alone was not assessed by the method of air sampling used, unless one assumed that quiescent conditions existed upwind of the activity. For the purposes of this report, our review of air sampling data is based on the understanding that accurate details of mass loading and/or enhancement factors may not be established, but the overall combined effect of the two factors is important.

Airborne activity concentrations versus soil activity concentration plots for various mass loading values are provided in Figures J-1, J-2, and J-3, respectively, for E_f's of 1, 0.33, and 3. These plots cover the range of average TRU concentrations in Enewetak soils, though some individual soil samples had higher concentrations. Table J-4 contains the mean TRU activity of soils excised during the cleanup, excluding the soils on Fred, which had negligible levels of TRU. For each island, airborne α-particle activity concentrations are listed for a mass loading of 600 $\mu g\ m^3$, and E_f's of 0.33, 1, and 3. The mass loading value used is deemed a reasonable upper-bound for soil excavation activities. This is supported by air sampling conducted early in the project, discussed earlier in this report, where airborne $^{239+240}Pu$ activity concentrations were enhanced by a factor of about 11 in comparison of samples collected upwind and downwind of soil excavation activities. In the case of this sampling, the upwind quiescent conditions were expected to be about 40 $\mu g\ m^3$. For soil excision activities, Table J-4 contains recommended parameters for use in estimation of airborne activity concentrations of TRU. These values were based on a mass loading of 600 $\mu g\ m^3$, but varied E_f's and/or activity concentrations of TRU in soils, based on a review of air sampling results from samples collected during soil excision. This process was based on these principle considerations:

- airborne activity concentrations averaged over numerous filters is more representative of potential exposures to personnel rather than the concentration of a single air filter collected within a single day,
- estimated airborne activity concentrations will be greater than the airborne activity concentration averaged over numerous filters,
- those individuals working in airborne contamination zones where air sampling was conducted had exposures summed over numerous days of work, and
- due to the fact that airborne activity concentrations were expected to be less than 10% of the MPC and demonstrated to be below this level based on extensive air sampling, use of averaged airborne activity concentrations are reasonable for dose reconstruction.

Within these considerations, airborne activity concentrations during soil excision activities was estimated based on varying either the E_f and/or the activity concentration of TRU in soils. Varying the activity concentration of TRU was deemed necessary for certain time periods of soil excision on Janet, Pearl and Sally. This step ensured that estimated average airborne activity concentrations exceeded the average measured airborne concentrations during the reference time period. This was a reasonable measure for these islands, as it was logical that at the initiation of soil excision activities, soil areas with the greater TRU concentrations would have been excised first, with progressively lower concentrations during the excision process. In the case of Janet, only one week of soil excision activity, 3 – 6 September 1978, had a recommendation to use an average TRU concentration three-fold higher than the average for excised soils. For all other periods where soil excision activities were being performed, the average TRU concentration was recommended. For Pearl, a six-week period, 7 April – 19 May 1979 had a recommendation to use an average TRU concentration 4-fold higher than the average with an E_f of 3, while for other periods the average

TRU concentration in soils was recommended with an E_f of 2. Effectively, the average concentration between the two periods varied by a factor of six. The reason for the much higher airborne concentrations than expected, based on the average TRU in soils, is attributed in part to the reason noted above. But, it is speculated that TRU concentrations in excised soils may have been underestimated for some islands. Notably for Pearl, ^{238}Pu encompassed about one-third of the TRU concentration, the highest fraction observed among the islands (see Table J-2). For Sally, soil excisions during March to April 1978 have a recommended TRU soil concentration twice the average with an E_f of 3, though for soil excisions in May to August 1978, the average TRU soil concentration with an E_f of 2 is recommended. Effectively, the average concentration between the two periods varied by a factor of three. For excision of soils in the Crypt on Sally (Aomon), Irene, and Yvonne, the average TRU concentration is recommended.

Table J-5 contains estimated airborne α-particle activity concentrations for TRU activity concentrations in soils at either the 40th or 80th percentile values for northern islands on the Atoll. The values are listed for three combinations of mass loading and E_f values. A mass loading value of 300 μg m^3 is recommended for work involving soil handling (excluding soil excision) and brush removal. A mass loading value of 100 μg m^3 is recommended for work not involving heavy soil disturbances, e.g. debris removal, building demolition, soil sampling, radiological surveys. The middle column of airborne concentrations for the respective 40th and 80th percentiles has a mass loading of 100 μg m^3 and E_f of 3. The data in these columns is equivalent to a loading of 300 μg m^3 and E_f of 1. Due to limited concerns for airborne resuspension of radioactive materials in soils during these activities, air sampling data is less extensive than that accomplished during soil excision operations. Notable exceptions are for sampling on Yvonne, Ursula, and Janet, which had comprised about 53% of the air samples. These islands had the greatest worker presence among the northern islands.

Ursula was the residence island for workers performing duties on northern islands and did not have any restoration activities. As noted above in discussions of air sampling results, air sampling results were unremarkable in regard to the established airborne MPCs. Nevertheless, air samples collected between April 1977 to September 1979 had some samples with gross α-radiation activity concentration in excess of $^{239+240}$Pu activity concentrations for samples collected in April and May 1977 for resuspension studies. The airborne $^{239+240}$Pu activity concentrations from the resuspension studies were more consistent with estimated concentration in listed in Table J-5 for Ursula, 80th percentile, as ranging from 100 μg m^3 and E_f of 1 to 300 μg m^3 and E_f of 3. There are a number of reasonable explanations for this difference. First, due to heterogeneity, there is some natural variations in sampled activities among a large group of air samples. Second, almost all air samples analyzed during the cleanup used a gross α-radiation method, which would have included contributions from ^{241}Am, ^{238}Pu, natural uranium and it's α-emitting decay chain daughters, natural thorium and it's α-emitting decay chain daughters, contributions from isotopes of uranium used in nuclear tests, and contributions from thorium used in nuclear tests. Lastly, the gross α-radiation laboratory method included the use of a self-absorption factor. The effect of naturally-occurring α-emitting radionuclides is expected to provide the greatest amount of bias in estimation of TRU on islands with the lowest TRU concentrations in soils, e.g., Ursula, Vera, Wilma, and segment D of Yvonne. For the estimated airborne TRU concentrations listed in Table J-5 for segments A and A/B of Yvonne, $^{239+240}$Pu equivalent concentrations of thorium isotopes and decay chain daughters have been included, as detailed in Table J-3.

In summary, for activities conducted on the northern islands, except soil excision, the estimated airborne α-particle activity concentrations listed in Table J-5 will be used. For brush removal, it is recommended to use a mass loading of 300 μg m^3 and E_f of 3. Since brush removal was necessary for interior locations of the northern islands, the 80th percentile soil concentrations are applicable. For other activities, e.g. debris removal, building demolition, soil sampling, radiological surveys, hot-line management and control, it is recommended to use a mass loading 100 μg m^3 and an E_f of 3. For WBCT debris clearance work, it is appropriate to use the 40th percentile soil concentration values, while for work away from beaches, the 80th percentile concentration values are more important. For some work conducted on Yvonne, there are special considerations discussed below.

While some of the activities conducted on Yvonne are very similar to activities conducted on the other northern islands of the Atoll, e.g., soil excision, debris removal, building demolition, soil sampling, radiological surveys, hot-line management and control, some of the activities are unique to this island. For example, while soil excision activities were accomplished in the Fig-Quince GZ area, soils from excision from other islands were brought onto Yvonne for stockpiling and ultimate disposal in the Cactus Crater entombment. Similarly, contaminated debris from other northern islands of the Atoll was stockpiled on Yvonne prior to disposal. Many activities, however, were unique to Yvonne, namely construction of the concrete keywall for the entombment, quarrying and crushing rock for the Cactus Crater revetment on the ocean-bearing side, production of concrete/contaminated soil slurry, tremie placement of slurry, etc. To better appreciate the work conducted on Yvonne, Figure J-4 contains a plot of features on a map of Yvonne, adapted from Figure D-12 of DNA (1981). The segment notation was added for this report to correspond to Figures B-21 through B-36, and radiological contaminant concentrations delineated in Tables by segment. From Figure J-4, contaminated debris stockpiles are within segments A and A/B, while contaminated soil stockpiles are within segment B. Segment B is centered over the Fig-Quince GZ, which made it a logical location to stockpile contaminated soils from excision areas of other islands. The south quarry area, rock crusher, decontamination facility, concrete batch plant, and hot-line fence are contained in segment C, while D contains various other facilities that supported operations on this island. Radiological conditions in segment D are similar to Ursula – of negligible radiological impact. In a few cases, personnel were billeted overnight in this area of Yvonne, when it was critical to complete construction activities on Yvonne. This practice saved lost time in transport time between Ursula. Concrete ramps were located at two locations. The ramp in segment A/B was used for vessels involved with downloading debris and contaminated soils on the northern part of Yvonne, while the ramp in segment C served for transport of personnel and other logistics shipments. The helicopter pad was also located in segment C.

Figure J-5 provides a plot of the cleanup project status from DNA (1981) to help illustrate the activities that were conducted up to that point. Team A operations listed on the upper section of the figure are for southern island work. Team B operations were conducted among northern islands of the Atoll, except Yvonne (Runit), while Team C operations were conducted on Yvonne. Crushed coral rock was initially derived from an old aggregate pile on Janet. In November 1977, coral rock was obtained from the quarry site annotated on Figure J-4 in a reef area of segment C on Yvonne. Rock was crushed at the crusher complex on segment C of Yvonne. Crushed rock was used as aggregate for concrete foundations and the Cactus Crater revetment. Rock quarried from the north quarry supplemented rock requirements for the revetment. For activities involving crushing and handling crushed rock, it is recommended to use a combination of TRU concentrations from the

Janet[21] aggregate and the beach area of segment C of Yvonne, a mass loading of 300 μg m^3 and an E_f of 3. For the soil/concrete slurry used initially to fill the Cactus Crater with the tremie operations, the stockpiled soils were provided from Janet, Irene, Sally, and Fred. Contaminated soil were mixed with concrete, a clay additive (attapulgite), and water at the batch plant. The batch plant was located on the northern portion of segment C of Yvonne, just north of the hot-line. As noted earlier, for soil handling operations, it was recommended to use a mass loading of 300 μg m^3 and an E_f of 3. Due to the wide range of soils being incorporated into the concentrations of soil being used, a wide range of estimated airborne TRU concentrations would exist for this activity. With exception of air sampling conducted in the Fig-Quince GZ on Yvonne, air sampling during other periods did not warrant estimated airborne TRU concentrations commensurate with soil excision activities conducted initially on Pearl. These were noteworthy, as summarized in Table J-4 for providing the highest airborne TRU during soil excision work. Airborne concentrations limited by resuspension soil excised soil from Sally, 107 pCi g^{-1} and an E_f of 3 leads to a more reasonable conservative estimate, when compared to the higher air sampling results observed on Yvonne. An important point to note is that a sprinkler system was employed at the batch plant to suppress dust generation.

Placement of slurry onto the Cactus Crater was accomplished between mid-June 1978 and mid-February 1979, as shown in Figure J-5 (DNA 1981). During this period, contaminated debris was also added to the crater. For personnel working in the proximity to the Cactus Crater during tremie operations, suspended airborne contamination could be produced from rock emplacement operations for the crater revetment, resuspension of soils in segment A, or the contaminated soil/concrete slurry being deposited into the crate. Due to the high water content of the slurry, this is unlikely to be an important source of airborne contamination. Due to the source of crushed rock being from the reef area of segment C and/or Janet, the largest potential source of resuspension in the area surrounding the tremie operations was from resuspension of soil within segment A. However, inhalation potential for workers is highly dependent on their location. For individuals near the crater land boundaries or concrete pump location, their inhalation potential is better estimated by resuspension of soil in segment A, while individuals on the tremie barge will have much lower exposure potential. In the latter case, area surrounding the barge would largely be water and then slurry once deposition was greater than the height of the reef in the latter stages of this operation.

Once the tremie operations generated sufficient slurry to the Cactus Crater to a height three feet above the reef, additional contaminated soil was added directly to the Cactus Crater. Bags of concrete were added and mixed in-situ with a disc harrow towed by a bull dozer (DNA 1981). Water was sprayed over the mixture and a vibratory roller-compactor was used to compact the mixture (DNA 1981). This operation would have provided airborne contamination commensurate with the contaminated soil being spread in the crater entombment. Logically, the parts of this operation involving the deposition, spreading, and mixing of soil with concrete would have much higher resuspension potential than the phase when the mix was wetted and compacted. The majority of the contaminated soil deposited directly to the crater was from Pearl and Yvonne, with lesser volumes from Sally, Irene, and Janet. Under these considerations, it is recommended to use a mean soil concentration equal to twice the mean concentration of soil excised from Pearl, 198 pCi g^{-1}, with an E_f of 3. This recommendation maintains a high-sided estimate of airborne concentration from all contaminated soils added to the entombment, yet balances substantially lower resuspension for the time periods where wetted soil/concrete mix was being compacted. During this period, some continuing work on the keywall was being completed. For these workers, resuspension potential

[21] It was previously noted in this report from airborne resuspension studies that the aggregate appeared to have $^{239+240}Pu$ much less than the average for soils on Janet, perhaps more like expected concentrations or beach areas.

existed from the soil excavation associated with the keywall construction and soil emplacement. Use of the resuspension estimates associated with soil entombment provides a higher estimate of resuspension.

Table J-7 contains a summary of recommended airborne concentrations of TRU during key operations on Yvonne. Due to the vast range of radiological impacts on Yvonne, estimates for the activities are separated among the segments of the islands. Estimated mass loading follows recommendations already discussed in this report. Activities that have limited disruption of soil are assigned a mass loading of 100 μg m^3, while trenching and handling soils are assigned a value of 300 μg m^3 and 600 μg m^3 is used for soil excision in the Fig-Quince GZ and soil mixing in the Cactus Crater entombment. There is a vast range of estimated TRU airborne activity concentrations. For work and presence in segment D, estimated activity concentrations are the lowest, 0.0011 pCi m^3, while for soil excision work in the Fig-Quince GZ, 0.35 pCi m^3. The range between these is a factor of 320. While air-purifying respirators were required for workers during soil excision work in the Fig-Quince GZ, they were only used during construction in the early phases of the cleanup project on southern Yvonne (Level IV PPE). This issues was noted above based on detailed discussions in DNA (1981). The level of PPE for this work was unnecessary for the existing radiological conditions. Concentrations of radionuclides in soil are assumed to be consistent throughout the cleanup, with notable exceptions. Soil brought into the stockpiles and placed in the entombment were dependent on the source, and conditions in Fig-Quince GZ area were substantially lower in TRU activity concentration after the restoration and placement of clean soils in excised areas. Table J-6 provides estimated TRU activity concentrations in segment B for three separate time periods: prior to soil excision, after soil excision but prior to clean soil fill, and after clean soil fill. Besides the transport and storage of soil stockpiles in this area and the excision of Fig-Quince GZ soils, personnel presence in this area was primarily due to debris/soils surveys and soil sampling work by DOE and FRST, debris removals, and simply passing through the road in this segment enroute to work areas near the Cactus Crate entombment. Debris surveys were conducted in July and December 1977 by FRST crews and later in September 1978 (DNA 1981). The most substantial volumes of debris were located in segments A, A/B, C, and D off Yvonne (see Figures B-32, -33, -34, -35, and -36). Segment B contained a relatively small volume of debris. Table J-7 contains recommended TRU airborne activity concentration values for work involving debris.

Transport of contaminated soil on Navy vessels from Sally, Janet, Irene, and Pearl for entombment was performed primarily with LCM and LCU. Initially, soil was transported in dump trucks, though later in an effort to improve transport efficiency soils were transported in bulk with modifications to these vessels. Due to the concerns for airborne resuspension of contaminated soils during transport, air sampling was conducted during these operations. Based on a review of air sampling data for these transport operations, Table J-6 was generated with conservative estimates of TRU airborne activity concentrations. The Table is separated by the vessel and periods of operations. For a number of vessels, the recommended concentrations are uniform, regardless of time period. This was the case for the YC Barge, LARC 22, and LCUs. The concentrations ranged between 0.02 and 0.04 pCi m^{-3}. Transport of soil on the LCM's had a greater variability in airborne TRU activity concentrations than the other vessels. The highest concentrations of TRU airborne activity concentrations was observed from early-April to early-June 1979, and transport of contaminated soils primarily from Pearl. This finding also coincides with observations of higher TRU airborne concentrations for islands with soil excision.

5.2.3.4 Ingestion Intake Modelling

The EPA recommends use of a 50 mg per day ingestion rate of soil and dust, which is the average, based on review of numerous research studies (EPA 2011). The RESRAD computer-based modeling code assumes a daily ingestions rate of 100 mg, but modifies this value with an occupancy factor that has a default of 0.75, for an effective ingestion rate of 75 mg d^{-1} (Yu et al. 2001). Both of these modelling approaches are based on residential-type occupancies. In the case of workers on the Enewetak Atoll, precautionary measures were taken to limit radiological exposures on controlled islands of the northern group of islands. These measures would have greatly reduced potential ingestion intakes under certain circumstances. For example, when workers were wearing air-purifying respirators, there was limited potential for ingestion intakes. As well, protective clothing and monitoring of personnel at hot-lines would have been effective in the reduction of ingestion intakes over those assumed for residual-type occupancies. For the assessments covered in this report, a daily ingestion rate of 100 mg d^{-1} will be made for workers not wearing air-purifying respirators. It is assumed that intakes only occur during non-sleep hours, 100 mg $(16\ h)^{-1}$ = 6.25 mg h^{-1}. Therefore, for a 10-hour work period, it is assumed 62.5 mg of accidental ingestion occur. Surface soil concentrations in areas occupied by a worker forms the basis for the concentration of radionuclides in the estimate of ingestion.

For workers wearing air-purifying respirators, it is conservatively assumed that the worker has an ingestion rate one-fourth the rate of an unprotected worker. This provision was provided to simplify the dose estimation process. While it is reasonable that ingestion of only negligible amounts of nuisance dusts are possible during periods of work where an air-purifying respirator is worn, it is recognized that workers do spend a portion of those workdays without respiratory protection – in preparation for work, work breaks, clearance through hot-lines, and trouble-shooting failures in respiratory protection. Individuals evaluating internal exposures for workers, nevertheless, have the option to apportion a fraction of those work hours in a day (where air-purifying respirator use is noted) to estimates of inhalation and ingestion without protection afforded by respiratory protection.

5.2.3.5 Respiratory Protection Factors. An RPF of one is used for levels I and II PPE. For level III PPE, an RPF of 50 is assumed, unless other information is available to verify that a worker was wearing a full-face respirator. In these cases, a RPF of 1000 is recommended. For workers wearing level IV PPE, and RPF of 1000 is recommended.

5.3 Internal Dose Considerations

5.3.1 General. The process of internal dose estimation is complicated by the varied types of work, resuspension potential, concentrations of radionuclides in soils, and islands. The process of dose estimation is supplemented for individuals based on information contained on controlled island access logs: dates of presence on individual islands and PPE annotation. In addition, an individual's military service dictates the type of work being conducted by their members. The following sections describe additional factors for consideration of dose estimates.

5.3.2 Multiple Islands. It was noted prior in this report that many individuals had presence on one or more islands on the same days. This condition was most common for individuals that were a part of leadership, visitors to the Atoll, or individuals that were involved in soil or debris transport by Navy vessels. In the process of estimating internal doses, it is reasonable to split an individual's presence among the islands, or assign occupancy to the island with the greatest exposure potential.

5.3.3 Off-Duty Periods. Most of the individuals that had routine work on controlled-access islands were billeted on Ursula during the period of November 1977 to mid-October 1979. Outside this period, most workers would have been billeted on Fred, a southern island. In isolated cases, as noted previously in this report, some individuals were billeted on southern Yvonne, though the radiological conditions were similar to Ursula. For cases of billeting on Ursula or Yvonne, off-duty exposure conditions are based on presence on Ursula. It is assumed that during off-duty periods of work days, 37.5 mg d^{-1} of incidental soil ingestion occurs, while for non-work days 100 mg d^{-1}. Eightieth percentile $^{239+240}Pu$ concentrations of soil on Ursula are assumed. For the inhalation exposure pathway during off-duty periods on work days, the assumed inhalation volume is 6.84 m^3, comprised of 0.45 and 0.54 m^3, respectively for sleeping and sitting. For non-duty days, a composite inhalation volume of 19.9 m^3 is assumed with eight hours each to light exercise, sitting, and sleeping. This assumption is conservative for those individuals that participated in water-based recreation activities during a portion of their non-work days. It is important to note that exposure potential for those with duties on or billeted on Ursula were very low. Due to the fact that exposures on key southern islands of the Atoll during the cleanup were at or below exposure CONUS locations, no internal exposure estimates will be included, except for individuals that were assigned to the Atoll between 1959 and 1973.

5.3.4 Individuals Submitting to Nose Swipe. For a small fraction of workers on controlled islands, nose swipes were collected for a variety of reasons, as discussed above. While these individuals may have been noted on a controlled access log for wearing an air-purifying respirator on a given day, in some circumstances, it is reasonable to assume that the minimum protection level specified for a given respirator type was breached for some period, though nose swipe data was unremarkable. For the purposes of this report, it is deemed reasonable to assign two hours of unprotected inhalation exposures for those days where respiratory protection is noted for an individual on a controlled access log or nose swipe log. Notable exceptions are for random nose swipe collections that were common during the early periods of the project and when an air sample action level was exceeded. While the latter case seems counter-intuitive, it is important to note that all air sample action level exceedances were false positive events, effectively being unfounded based on further laboratory assessment. False air sample action level exceedances were attributed to radon-daughter interferences with field-portable screening measurements. Random and air sample action level exceedances accounted for about 47% of the nose swipe collections. Nose swipes collected for work without a mask, improper wear or a defective mask, or a procedure violation numbered 518 incidents (Table H-1).

5.3.5 Individuals Assigned Duties on Ursula. A number of individuals were assigned duties on Ursula, with very limited or no presence on controlled islands of the northern Atoll. This was the case for some AF FRST and most clinic personnel. As well, there was a number of contractor personnel that supported necessary functions for the base camp – food service, laundry, etc. As noted earlier, some access logs notations were made for personnel on Ursula, however, since the island did not have controlled access like the other northern islands, the logs were not complete. For cases of this nature, information from a participating veteran can be used to supplement data for presence on Ursula. Another method is review of dosimetry records. Individuals assigned to duties on Ursula were typically provided dosimetry monitoring.

5.3.5 Respiratory Protection Factors (RPF). For cases of air-purifying respirator use by a worker where either a half- or full-face respirator was possible, it is recommended to use a RPF of 50, which is specified for a half-face respirator. Cases of this nature could occur for level III PPE

where either respirator type was acceptable. Supplemental information from the worker could be used to rectify the uncertainty in respirator type use. Level IV PPE specified a full-face respirator.

5.4 Example Estimated Internal Doses

5.4.1 Work and Billeting on Ursula

Figure K-1 contains a histogram of effective and committed effective doses to bone surfaces, liver, and lung for a worker assigned duties on Ursula for six-months from inhalation and ingestion exposures. Based on the preceding discussions, the exposures are based only on exposures to soil due to resuspension and incidental ingestion. ICRP inhalation type combinations assumed for the inhalation and ingestion intakes are listed in Table K-1. These values are reasonable estimates based on discussions in Section 3.6. Due to the prominence of committed dose to the lung, liver, and bone surfaces from radionuclides of plutonium, americium, and thorium, committed dose to these organs are highlighted, along with the source of the internal exposure: inhalation, ingestion, or total. Overall, the effective dose total was 0.556 mrem, with committed effective dose to the bone surfaces the highest at 14.8 mrem. $^{239+240}$Pu intakes were 3.47 and 53.5 pCi, respectfully, for inhalation and ingestion exposure pathways. Intakes of other radionuclides are based on fractional relationships to $^{239+240}$Pu from Table J-2. A histogram of intakes for the six-month exposure is shown in Figure K-2. Note that intakes of ^{90}Sr, ^{137}Cs, and ^{151}Sm are higher than the intake of $^{239+240}$Pu.

Figure K-3 shows the distribution of individual transuranic radionuclides and the sum of fission and activation product contributions to effective dose for an individual with six-months of work duty on Ursula. $^{239+240}$Pu and ^{241}Am provide the largest overall contribution to effective dose, with lessor contributions (but nearly equal) from ^{238}Pu, ^{241}Pu, and the combined fission and activation products. While the ^{238,239,240}Pu had a larger contribution from the inhalation pathway than ingestion, ^{241}Am and the combined contribution from the fission and activation products had a larger contribution to effective dose from the ingestion pathway. Only 3% of the effective dose is from fission and activation product contributions. Figure K-4 shows the relative contribution from individual radionuclides. A majority contribution is from ^{90}Sr, with secondary contributions from ^{137}Cs. ^{151}Sm was added to illustrate the contribution of one long-lived radionuclide that was theoretically present, yet is not readily detected due to its lack of photon emissions. Though this radionuclide had a negligible contribution to effective dose, it contribution was projected to be higher than that from ^{60}C, ^{155}Eu, and ^{125}Sb, all pertinent radionuclides noted by AEC (1973)[22].

Overall, the internal dose levels projected for an individual working on Ursula during the Enewetak cleanup were very low, and much less than the external exposure attributable to terrestrial sources on Ursula projected for a six-month period, about 16 mrem[23].

5.4.2 Work and Living on Key Southern Islands, 1959 – 1973

Section 2.3.6.5 provided estimates of external exposures from radionuclides in soils on Elmer (Medren) from 1959 to 1973. The data was expected to be applicable to inhabitance by veterans and civilians working on this and the other key southern islands of the Atoll during this period, e.g., Fred (Enewetak) and David (Japtan). While Figure 2-33 displayed estimated external exposure rates over the period of 1959 to 1973, for brevity, this report will only provide estimated internal exposures

[22] Table 14, AEC (1973)
[23] Inferred from Table B-1, assuming equivalence in exposure and dose to tissue.

from inhalation of suspended soil and incidental ingestion of soil for 1959. Estimates for other years can be made on a case-by-case basis. Activity concentrations of radionuclides in soils are based on values displayed in Table C-14. These activity concentrations also formed a basis for the external exposure estimates.

The histogram in Figure K-5 contains effective and committed effective doses to bone surfaces, liver, and lung for a worker assigned duties on Elmer for one year from inhalation and ingestion exposures. One year would have been a common remote assignment period for a veteran. ICRP inhalation type combinations assumed for the inhalation and ingestion intakes listed in Table K-1 were also used for this example. Similar to the dose assessment for a worker assigned to Ursula, a mass loading of 100 μg m^{-3}, with an E_f of 3, was used for estimates of inhalation intakes, with the same inhalation rates used for various activities listed in Table 5-1. This combination provides a resuspension factor, S_f, of 2×10^{-8} m^{-1}, as shown in Figure E-4. The total internal dose estimates for this exposure are very low. The effective dose total is only 0.18 mrem, while the total for bone surfaces is only 3.6 mrem. For this case, the estimated effective dose from the internal exposure pathway is about 400-fold lower than the external exposure attributable to terrestrial sources on Elmer projected for a one year period, about 68 mrem.

Figure K-6 and K-7 contain the isotopic breakout for contributions to effective dose from internal exposures. $^{239+240}$Pu dominates, as was the case for occupancy on Ursula during the cleanup. The relative contribution of ^{241}Pu to internal doses in 1959 is much higher than its contributions in 1978. Fission and activation products have a larger contribution to effective dose, as was the case for Ursula exposures during the cleanup, though they are only about 5%. ^{90}Sr and ^{137}Cs are the largest contributors, though the short-lived radionuclides: ^{125}Sb, ^{60}Co, ^{106}Ru, and ^{144}Ce are more important than was the case for exposures in 1978.

5.4.3 Work on Janet

Among work being accomplished on controlled islands in the northern Atoll, Janet and Yvonne comprised the largest number of man-hours. The examples of work provided here are for six-month periods, though it must be understood that many of the personnel that worked on Janet during their deployments may have also performed work on other islands. As well, for many workers, as noted above in the report, performed work under a variety of PPE combinations.

The first example is for a hypothetical individual that worked on Janet for a six-month duration. For this case, it is assumed that the work was performed without an air-purifying respirator. The worker is assumed to be billeted on Ursula. Figure K-8 contains a histogram of effective and committed effective dose to bone surfaces, liver, and lung. The projected total effective dose is 2.75 mrem, with the bone surfaces receiving 73 mrem.

The second example is for a hypothetical individual that worked on Janet for a six-month duration, but with 75% of their work without PPE conducting general work and 25% wearing an air-purifying respirator supporting soil excision activities. Figure K-9 contains a histogram of effective and committed effective dose to bone surfaces, liver, and lung. The total effective dose is 2.23 mrem, with the bone surfaces receiving 59 mrem. It is clear from the comparison to first example that the higher airborne concentrations existing during soil excision were well mitigated by the respiratory protection.

5.4.4 Work on Pearl

The work conducted on Pearl was much more limited than that performed on either Yvonne or Janet. The most prominent activity from a radiological safety standpoint was the excision of soil, which occurred primarily in April and May 1979 (Table F-3). As noted above, airborne α-radiation concentrations, based on air sampling was highest during excision of soils from this island. During this period, the vast majority of work was conducted by Army personnel, with support by AF FRST personnel. The first example provided for work conducted in May, was for an Army enlisted member from the 84th Engineering Battalion. This individual worked 27 days on this island, all with level IIIA PPE. This individual did not have any nose swipes collected during his work. Figure K-10 contains a histogram of effective and committed effective dose to bone surfaces, liver, and lung. The projected total effective dose is 0.45 mrem for the month of work. For this example, an RPF of 50 was assumed for all workdays. Figure K-11 contains a similar plot, except in this case, it is assumed that the worker spends two hours within a 10-hour workday outside the soil excision area wearing no respiratory protection. In this case, the effective dose is about 30% higher than the case where respiratory protection is assumed to be worn for the entire workday. The latter case likely better estimates the actual exposure. For both of these examples, billeting on Ursula is assumed in the calculations of dose. Figure K-12 contains the isotopic breakout for contributions to effective dose from internal exposures for the effective dose from Figure K-11. The most prominent feature of the distribution of dose is the contribution from ^{238}Pu, which provides about 50% of the contribution provided by $^{239+240}$Pu. In previous exposure examples provided for Ursula, Elmer, and Janet, ^{238}Pu was of tertiary importance behind $^{239+240}$Pu and ^{241}Am. For work on Irene, Pearl, the northern portions of Yvonne, ^{238}Pu provides a greater contribution to internal doses than ^{241}Am. Fission and activation products only contribute about 2% to effective dose. Figure K-13 contains the relative contribution from individual radionuclides. Although of negligible dose consequence, it is interesting to note for Pearl, sufficient activity concentrations existed for all three isotopes of europium to include in the dose estimate. This characteristic is common to islands that contained a nuclear test GZ, and is due primarily from in-situ activation of stable europium in the soil.

The latter example of dose displayed in Figure K-12 was modified to include 4 hours of work in the soil excision area with a defective respirator. As described above, this simulates the duration of two events that could have prompted the collection of a nose swipes. For this modification, the total effective dose was 1.0 mrem for the month, about 1.7-fold higher. The simulated respirator failure incidents had a noticeable increase in effective dose, though the projected dose over the month was very low in comparison to expected external dose levels.

A fourth example of exposure on Pearl is considered for illustration. For this case, exposure is illustrated during a period where soil excision did not occur. For this case, a month of work is assumed, 27 work days, but no respiratory protection is worn for any of the work days. Figure K-14 contains a histogram of effective and committed effective dose to bone surfaces, liver, and lung. For this case, the effective dose is 1.2 mrem for the month of exposure. The projected internal dose for this case is higher than the previous cases. This illustrates an important point. The performance of work in areas with higher than quiescent soil resuspension, i.e., soil excision, brush removal, and the higher expected intakes, were more than compensated by the minimum RPF of 50.

5.4.5 Work on Yvonne

Among the islands of the Atoll, Yvonne had the most varied radiological conditions. The first example is for a working conducting trenching activities in segment A. This example is for an

individual that supported construction of the keywall, where trenching was performed by heavy equipment. For this example, it is assumed that no respiratory protection was worn, and the individual was billeted on Ursula. The example is limited to a month, as the total duration of the construction of the keywall was conducted over only a few months, but trenching was only a portion of this work. For the 27 days of work assumed for this example, the $^{239+240}$Pu intakes were estimated as 14 and 68 μCi, respectively for inhalation and ingestion pathways. Figure K-15 contains a histogram of effective and committed effective dose to bone surfaces, liver, and lung. The projected effective dose is 3.45 mrem, while committed effective dose to the bone surfaces is 72 mrem and 10 mrem to the lung. Since this work involved the excavation of soils in segment A, intakes for ^{230}Th, ^{232}Th and its decay products have been included. The inclusion adds a $^{239+240}$Pu equivalent of 16 and 74 μCi, respectively for inhalation and ingestion pathways. Figure K-16 contains the isotopic breakout for contributions to effective dose. Contributions from ^{230}Th, ^{232}Th and its decay products are included in the $^{239+240}$Pu (53%). As discussed above for exposures on Pearl, contributions from ^{238}Pu to effective dose are higher than that from ^{241}Am. Fission and activation products contribute less than 1% to effective dose, with a breakout displayed in Figure K-17.

During construction of the Cactus Crater and its filling, FRST members had a significant presence in segment C manning the hot-line. For an example of an individual that had prominent work duty in this area, exposures for a six-month exposure duration is modelled under the assumption that respiratory protection was not worn. Figure K-18 contains a histogram of effective and committed effective dose to bone surfaces, liver, and lung. The projected effective dose is 2.0 mrem, a little lower than similar exposure conditions for a worker on Janet for six months (Figure K-8).

5.4.6 Work on Alice, Belle, Clara, and Daisy. This group of islands had similar radiological impacts, being largely impacted by fallout from thermonuclear detonations. Work on these islands were largely comprised of radiological debris surveys, debris removal, brush removal, final status surveys, and soil sampling. No soil excision was accomplished. Therefore, two examples are provided for three-month work periods on Clara, the one among the four with the highest $^{239+240}$Pu activity concentrations. It is important to note that long-term work on any one of these islands did not occur, though collectively, some work was accomplished over a number of months on this group of islands. Figure K-19 contains a histogram of effective and committed effective dose to bone surfaces, liver, and lung for work in the interior. The projected effective dose is 2.4 mrem, a rate about 75% higher than similar exposure conditions for a worker on Janet for six months (Figure K-8). This is attributable to the much higher $^{239+240}$Pu concentrations on Clara compared to Janet. Only 2.2% of the effective dose is from fission and activation products, with a breakout by radionuclide in Figure K-20. The dominant contribution is from ^{90}Sr and ^{137}Cs. Though of negligible dose consequence, due to detection of ^{207}Bi in soil samples on these islands, a dose contribution from this radionuclide is listed. Figure K-21 contains a histogram of effective and committed effective dose to bone surfaces, liver, and lung for work in beach areas. The estimated doses are nearly one-half of those expected in for work in interior areas. Occupancy in beach areas was common for Navy personnel that were part of the WBCT.

5.5 Customized Internal Dose Estimates. In preparation of estimated doses for example exposure cases detailed above, the author prepared a spreadsheet to allow customized internal dose estimates for individuals, where any combination of occupancy on islands and work types can be used as an input. In general, based on the magnitude of the internal dose estimates provided in example cases detailed above, it may not be necessary. These examples could effectively serve as bounding

conditions. The spreadsheet also allows the ability to alter ICRP inhalation type combinations for the radionuclides considered in this report for internal doses.

5.6 Committed Effective Dose to Other Organs

Due to the dominant contribution of transuranic radionuclide to internal doses, this report only detailed effective dose and committed effective dose to the bone surface, liver, and lung. Among the three organs of primary concern for inhalation and ingestion exposures, committed effective dose to the bone surfaces was consistently much higher than other organs. Dose to the bone surfaces are important in assessment of risk of primary bone cancers. Among organs/tissues, committed effective dose to the bone surface from an internal exposures source is the only tissue with contributions from an internal source likely to exceed that from external exposure. Primary cancers to the lung and liver, are respectively evaluated by dose to these organs. For some exposure scenarios, the internal dose contribution may provide a reasonable fraction of combined dose from internal and external sources. For other organs/tissues, however, the internal dose contributions to total will be substantially lower, and of negligible contribution compared to the external exposure source. This is due to poor uptake and retention of transuranics in other tissues. The committed effective organ/tissue dose for other organs/tissues are a small fraction of the effective dose, with the only exception being the red bone marrow (RBM). For this case, the committed effective dose to the RBM is similar in magnitude to the effective dose.

Committed effective doses to other organs/tissues can be calculated on an individual case basis, however, their contributions will be very small compared to the external dose contribution.

Section 6. Direct Contact Skin Doses from Contamination

6.1 General

Some dose to skin is possible from the deposition and retention of contamination on the skin. Historically, in dose reconstructions, this was an important consideration for veterans with on-site participation in atmospheric testing of nuclear weapons, due primarily from β-particle radiations emitted from short-lived fission products. An in-depth treatment of the topic was compiled by Apostoaei and Kocher (2010) for DTRA. This document was developed as a technical aid in assessment of skin doses for veterans supporting atmospheric tests, but has applicability to other exposure scenarios, including personnel covered by this report. DTRA considered this exposure scenario in their evaluation report (DTRA 2017). For this report, a similar approach to assessment of skin exposures from this exposure pathway was conducted, with only minor differences.

In general, the importance of dose to skin for veterans working on Enewetak Atoll was much less than for veterans with on-site participation in atmospheric testing. In addition, due to the much higher energy released by α-particles than β-particles in nuclear transformations, and the radiation weighting factor, w_R, disparity between these particles: 20:1, in most exposure scenarios, the dose from α-particle radiation dwarfs that from β-particles. Some notable exceptions are for exposures to some skin locations on the body where the epidermal layer is sufficiently thick to preclude penetration of α-particles to the sensitive basal cells that are of concern for risk of skin cancer induction. Notably, these include the palm of the hand, sole of the foot, the back of the hand.

6.2 Methodology

6.2.1 Exposure Period

The methodology for assessing dose to skin within Apostoaei and Kocher (2010) incorporates detailed discussion of factors important to the exposure period. In contrast to the other exposure pathways considered in this report: external and internal, this exposure pathway is unique. Exposures to the skin is starts upon the initial deposition and retention of contamination on the skin, and continues until the contamination is removed by physical processes or by radioactive decay. Apostoaei and Kocher (2010) provide extensive detail on the radioactive decay process, which is important for dose from short-lived radioactive material. For the radionuclides important to this assessment, radioactive decay is not an important factor. While natural physical processes can be an important consideration for losses of contamination on the skin, for estimates of dose from deposition and retention, it is assumed that the contamination is removed by showering. Apostoaei and Kocher (2010) note that when density thicknesses of soils retained on skin exceed 2 mg cm^{-2}, the material becomes visible and *ad hoc* cleaning is likely. For soil build-up scenarios considered in this report, the maximum build-up is 2.6 mg cm^{-2}, for the case of a dusty environment having an airborne soil mass loading of 600 μg m^{-3}.

As noted in multiple examples above, work scenarios during a given day could be highly varied, and involve work on numerous islands. For simplicity sake, example calculations provided in this report will only consider a single exposure condition for a day. All examples provided in this report will consider single day exposure periods. Multiple days of exposure can be summed for an individual worker over their assignment period on the Atoll. Although 10-hour workdays, for six day a week were common for most personnel assigned to the Atoll, it is assumed that the period of contamination accumulation on the skin occurs over an eight-hour period. This provides two hours in a workday for transit between the Ursula and work sites on controlled islands on the northern part of the Atoll. Due to the negligible concentrations of radiological contaminants on Ursula and southern islands of the Atoll, no examples will be provided for skin exposure for occupancy on these islands. Each eight-hour work period will have an assumed delay period of four hours prior to the worker removing contamination from showering.

In contrast to external exposures, which are assumed to provide a uniform dose to tissues and organs of the body when penetrating radiations are the source of exposure, skin doses from this exposure pathway can be highly varied, dependent on a number of factors. Among these are deposition and retention which can be highly varied for skin locations on the body, whether or not the specific area of skin was covered by clothing (and possibly PPE), and the epidermal layer thickness. Due to these considerations, assessment of dose from this pathway will normally be accomplished for workers that have a radiogenic disease of the skin. And, the dose assessment will of necessity be tailored to specific disease location on the skin.

6.2.2 Radionuclides Considered for Skin Exposure

The primary α-particle emitters considered for this report are $^{239+240}Pu$, ^{238}Pu, and ^{241}Am. The only other α-particle emitters with important contributions to internal dose are ^{232}Th (and its

decay chain daughters) and ^{230}Th. As detailed above, these radionuclides were considered for personnel working in segments A and A/B of Yvonne (near the Cactus Crater). Due to this limited application, specific information will be provided separately below for these radionuclides.

The β-particle emitters considered for this report are: ^{60}Co, ^{90}Sr, and ^{137}Cs. These were used because of their prominent presence in soil samples and reasonably-high β-particle energies. Other β-particle emitters, e.g., ^{125}Sb, ^{152}Eu, ^{154}Eu, and ^{155}Eu, had much lower abundance. In the case of ^{151}Sm, it has a reasonably-high estimated abundance in soils, but emits only low-energy β-particles (see Table A-6). In addition, the contribution of dose to skin from this pathway is dominated by dose from α-particles in most exposure scenarios.

6.2.3 Parameters

Table L-1 summarizes some of the key parameters used for estimation of skin dose from contamination deposited and retained on skin. The interception and retention factor, *I/R*, is the key parameter defining the varied deposition and retention of contamination on skin surfaces. This factor varies by a range of 100: 0.015 to 1.5, and is based on values listed in Apostoaei and Kocher (2010). Most skin areas have values ranging from 0.015 to 0.06, while the scalp has a value of 0.23. Some unique areas have a factor of 1.5 – under the collar of a shirt for the back of the neck, under the belt line of trousers, under the boot edge on the lower leg, and behind the ears. The *I/R* for these unique locations is greater than one, and due to primary deposition and retention of contamination at the location plus losses of contamination from adjacent areas. Due the limited area encompassed by these unique locations compared to entirety of the skin, it is less likely this exposure condition will be evaluated.

The deposition velocity, V_d, was set at 3,600 m h^{-1}, as recommended in Apostoaei and Kocher (2010). The particulate loading, *M*, is varied among 100, 300, and 600 μg m^{-3}, dependent on the activity being conducted by workers. It is reasonable for these values to be similar to those selected for the inhalation exposure pathway. The loading approach has been selected for use in the assessments of this exposure pathway. It is possible to use resuspension factors, S_f, however, these values incorporate the enhancement factor, E_f, and can lead to varied levels of contamination build-up on the skin for identical exposure scenarios unless the E_f is constant for all exposures. When self-attenuation factors are not incorporated into the analysis of skin dose, use of resuspension factors will lead to consistent results. However, if self-attenuation factors are considered in the analysis of skin dose, use of the resuspension factors can lead to inconsistencies, due to the importance of density thickness of the contaminant in calculation of attenuation factors. In this report, self-attenuation of α-particles calculations are included for this exposure scenario. Due to the relatively small contributions of β-particles to skin dose from contamination on the skin, self-attenuation factors were not calculated.

Table L-1 contains β-particle dermal contamination dose coefficients, *DC*, for ^{60}Co, ^{90}Sr, and ^{137}Cs. These were set at levels consistent with DTRA (2017). Apostoaei and Kocher (2010) provided skin-dose modification factors for these β-particles emitters, as summarized in Table I-1. These values modify dose to account for the varied thickness of the epidermal layers of the various

locations skin on the body. Apostoaei and Kocher (2010) referenced the calculation of DC values from the work of Eatough (1997), according to the equation below:

$$DC\ (\mu Sv\ cm^2 Bq^{-1}) = 2.8\ \frac{E}{R^2}\ x_0\ \left[(2-f)\,e^f - (2+f)\right],$$

$$\text{where}\quad f = \frac{[q-(R+t)]}{x_0} \text{ and}$$

E = energy of the α-particle (MeV)

R = range of α-particle (mg cm^{-2})

t = half the thickness of the basal layer (mg cm^{-2})

x_o = shape factor for smooth function fit to step-function distribution of epidermal thicknesses

q = minimum density thickness for smooth function fit to step-function distribution of epidermal thicknesses

To convert DC from μSv cm^2 Bq^{-1} to rem cm^2 μCi^{-1} h^{-1}, the results are multiplied by 1.33×10^4. Dependent on the skin location, the following factors were recommended. While x_o is a shape factor for the smooth fit to the step function of epidermal thickness, q is the minimum density thickness of the smooth function fit.

Table 6-1. Values of q and x_o for Calculation of α-Particle Dose to Skin, from Apostoaei and Kocher (2010) for Use in Method of Eatough (1997).

Skin Location	q (mg cm^{-2})	x_o (mg cm^{-2})
Back of hand	5	2.4
Arms & legs	3.1	2.0
Trunk	2.0	1.35
Face	1.4	2.1

For this work, DC values were calculated for varied density thickness build-up of soil on the skin. This was accomplished by simply replacing the q value in the distribution with q', where this quantity is:

$$q' = q + h_{Eq} \text{ and}$$

h_{Eq} is the epidermis-equivalent contaminant thickness. Due to the disparities in stopping powers of α-particles in skin and coral sand, the density thickness of contaminated sand was converted into an epidermis-equivalent thickness. Eatough (1997) assumed the epidermis was comprised of a muscle equivalent liquid according to International Commission on Radiological Units (ICRU) Report 49 (ICRU 1993). Due to the dominant calcium composition of coral, we have assumed the soil had a composition equivalent to compact bone. This provides a scaling factor of about 0.91 to convert soil to an equivalent density thickness of epidermis.

Figure L-1 contains example calculations of the dose coefficients for $^{239+240}$Pu and ^{238}Pu:^{241}Am for the skin location categories listed in Table 6-1. Due to the near identical α-particle energies of ^{238}Pu and ^{241}Am, these radionuclides are combined, in a similar manner as the case for ^{239}Pu and ^{240}Pu, which have similar α-particle energies. Dose to back of hand was zero for radionuclides included in this plot. For each tissue location, the *DC* was higher for ^{238}Pu:^{241}Am than $^{239+240}$Pu, due to the greater α-particle energy. As well, dose was higher for skin locations with a lower average thickness of epidermis layer covering the sensitive basal cells than those with higher thicknesses. For contaminant thicknesses in excess of 3.4 mg cm^{-2}, zero dose rates were estimated for the radionuclides included in this plot.

6.2.4 Skin Dose Equation

Dose to skin from deposition and retention of contaminated soil is calculated by the equation below:

$$D_{Skin,i} = \int_{t=0}^{t=8\ h} I/R\ \ E_f\ \ S_o\ M\ \ V_d\ \ (T-t)\ \ DC(\rho_A)\ SDMF\ \ dt\ ,$$

where

$D_{Skin,\ i}$ = dose to skin for ith radionuclide
I/R = interception and retention factor
E_f = enhancement factor
S_o = mean surface soil activity concentration,
M = total suspended particulate mass loading
V_d = deposition velocity
T = total exposure period
$DC(\rho_A)$= dose coefficient, density thickness dependent for α-particles
SDMF = skin dose modification factor for β-particles, value of 1 used for α-particles

The integral is necessary for calculation of doses from α-particles due to the varied self-attenuation from the build-up of contaminated soil on skin over the exposure period. Since self-attenuation of β-particles is omitted for this work, calculations of β-particle dose could be accomplished without an integral. For example calculations made with this equation, and presented in this report, *T*, was set at 12 h. Hence, contaminated soil initially deposited at the beginning of the exposure period is assumed to provide dose to the skin over a period of 12 hours, while, at the end of the eight-hour work period, contaminated soil has an exposure period of only four hours. The dose coefficient, $DC(\rho_A)$, is effectively a time varying function in the h_{Eq} variable, which is assumed to have a linear increase over the course of a work day. For examples considered here, it is over eight hours.

6.3 Example Daily Skin Dose Calculations

Figures L-2 through L-19 provide plots of dose to skin from $^{239+240}$Pu and ^{238}Pu:^{241}Am versus activity concentration in soils for the five *I/V* values listed in Table L-1, three different skin

locations with respect to mean basal cell depth, and three different mass loading values for α-particles. For all of the example plots, an E_f of 3 was used. It is left to the user to perform simple calculations for exposure cases where other E_f values were recommended for use. While the plots show daily-integrated dose across the soil concentration range of 10 to 400 pCi g^{-1}, it is important to understand that the higher soil concentrations were applicable for some soil excision activities on Pearl, Yvonne, Sally, and Irene, while during other types of work, the assumed concentrations of these radionuclides are typically below 100 pCi g^{-1}. The notable exceptions is for work in segment B of Yvonne, the Fig/Quince GZ.

Some of the curves contained in Figures L-2 through L-19 may not be of practical use. For example, the *I/R* value of 0.23, listed for the scalp would be appropriate for assessment of a radiogenic disease on the scalp, using a face skin location for basal cell depth. The plots for basal cell depth for skin on the arms, legs, and trunk would not be applicable. In spite of these apparent discrepancies, all of the plots retain all five *I/R* combinations. There may be a future desire for use of some of these combinations. For example, an individual may have very thick hair on the trunk, arms, or legs of the body, and it may be desired to use a higher *I/R* value.

Figure L-20 through L-28 contain plots of dose to skin due to β-particles emitted from ^{60}Co, ^{90}Sr, and ^{137}Cs. Similar to the plots for α-particle dose, all five *I/R* values were evaluated with an E_f of 3. A mass loading value of 100 μg m^{-3} was used for all plots. Simple scaling factors can be used to calculate dose for other E_f and mass loading values.

A summary of example daily skin dose calculations are contained in Table L-2 for various exposure scenarios. The first group of examples are for exposures on Pearl during soil excision operations. This is reflected by the E_f of 3 and *M* of 600 μg m^{-3}. The period chosen for this work was between 7 April and 19 May 1979, when the more highly concentrations of soil were suspected for excision, based on air sampling results, and as reflected in Table J-4. Hence, the TRU activity concentration of 396 pCi g^{-1}, is comprised of the summation of the $^{239+240}$Pu, ^{238}Pu, and ^{241}Am, as shown in Table L-2 for each of the four skin tissue locations. The summation of doses from the five primary radionuclides are listed in the last column of Table L-2. The activity concentration of the ^{238}Pu, ^{241}Am, ^{60}Co, ^{90}Sr, and ^{137}Cs are based on the recommended relationships with $^{239+240}$Pu, listed in Table J-2. Figure 6-1 shows the break-out by primary radionuclide for exposure to skin locations on the chest and forearm. While the total dose for the example day of work was 0.0036 rem (3.6 mrem) for the chest, only 0.3% was from β-particle contributions. The contributions from $^{239+240}$Pu and ^{238}Pu:^{241}Am are partitioned about 0.55:0.45. Due to the greater mean epidermal thickness on forearms, the total dose was only 0.96 mrem, 3.6-fold lower. For skin at this location, contributions from β-particle contributions was about 1.5% of the total, and the $^{239+240}$Pu and ^{238}Pu:^{241}Am dose are partitioned about 0.45:0.55.

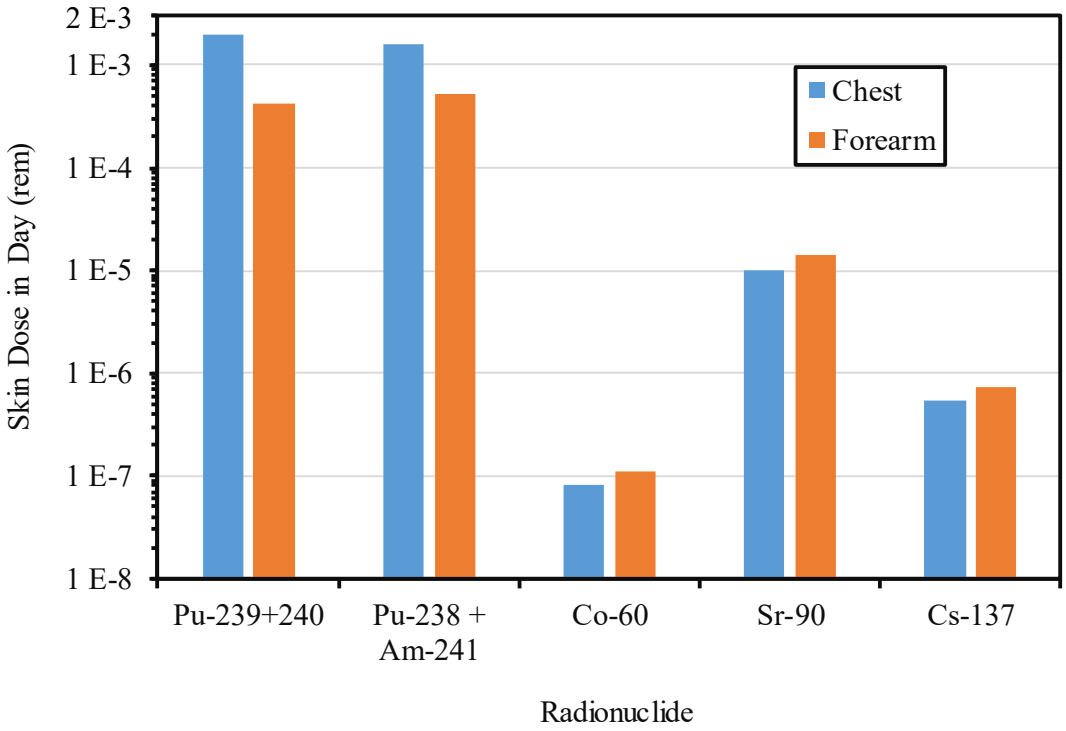


Figure 6-1. Histogram of Skin Doses in Day for Primary Radionuclides from Supporting Soil Excision Activities on Pearl between 7 April and 19 May 1979 (Values from Table I-2).

6.4 ^{232}Th and ^{230}Th Skin Dose Calculations

The calculation of skin doses from ^{232}Th and its decay daughter chain daughters requires an evaluation of the contribution from all α-emitters in the decay chain, since each radionuclide had a different mean α-particle energy, and hence range in tissue. Table 6-2 list mean α-particle energies and range in muscle-equivalent liquid values from ICRP Report 49. Figure L-29 contains dose coefficient curves for ^{230}Th and ^{232}Th and its decay chain daughters for the basal cells of skin of the trunk. These values were calculated by the same method used for $^{239+240}$Pu and ^{238}Pu:^{241}Am, as displayed in Figure J-1. The dashed red line is a summation of dose from ^{232}Th and its decay chain daughters. Figure L-30 contains a similar plot for ^{230}Th and the summation of dose from ^{232}Th and its decay chain daughters for basal cells within other skin locations. No value is listed for dose from ^{230}Th to the basal cells of the back of hand, as the dose is zero. Dose to skin for ^{232}Th and its decay chain daughters is dominated by the short-lived daughters in the decay chain, due to their much higher energy than the long-lived daughters in the decay chain.

Table 6-2. Mean α-Particle Energy and Range in Muscle-Equivalent Liquid from ICRU Report 49 (ICRU 1993).

Radionuclide	$^{239+240}$Pu	^{238}Pu:^{241}Am	^{230}Th	^{232}Th	^{228}Th	^{224}Ra	^{216}Po	^{212}Bi	^{212}Po
Energy (MeV)	5.15	5.48	4.66	3.99	5.40	5.67	6.78	6.06	8.78
Range (mg cm^{-2})	3.93	4.32	3.38	2.69	4.22	4.55	6.02	5.05	9.15

Tables L-3 and L-4 contain single day dose values from the deposition and retention of ^{230}Th and ^{232}Th and its decay chain daughters for exposure scenarios on segments A and A/B of Yvonne. Only two exposure conditions have been recommend for exposures assessment for soils native to this region of Yvonne: one with a mass loading of 300 µg m^{-3} (trenching) and 100 µg m^{-3} (quiescent). Other soil resuspension scenarios have been recommended for these segments of Yvonne, however, they involve the handling of soils from other locations on the Atoll. These other locations did not have detectable levels of ^{228}Th in soils. Values in these tables can be scaled to other concentrations levels of the contaminants, if desired.

Figure 6-2 shows the break-out by radionuclide for exposure to skin on the scalp for an individual assisting in trenching work on segment A of Yvonne. Values for the primary radionuclides are contained in Table L-2 for this example, while values for ^{230}Th and ^{232}Th and its decay chain daughters are from Table L-3. The total daily dose is 3.4 mrem, with ^{230}Th and ^{232}Th and its decay chain daughters providing about 48% of the skin dose for this scenario.

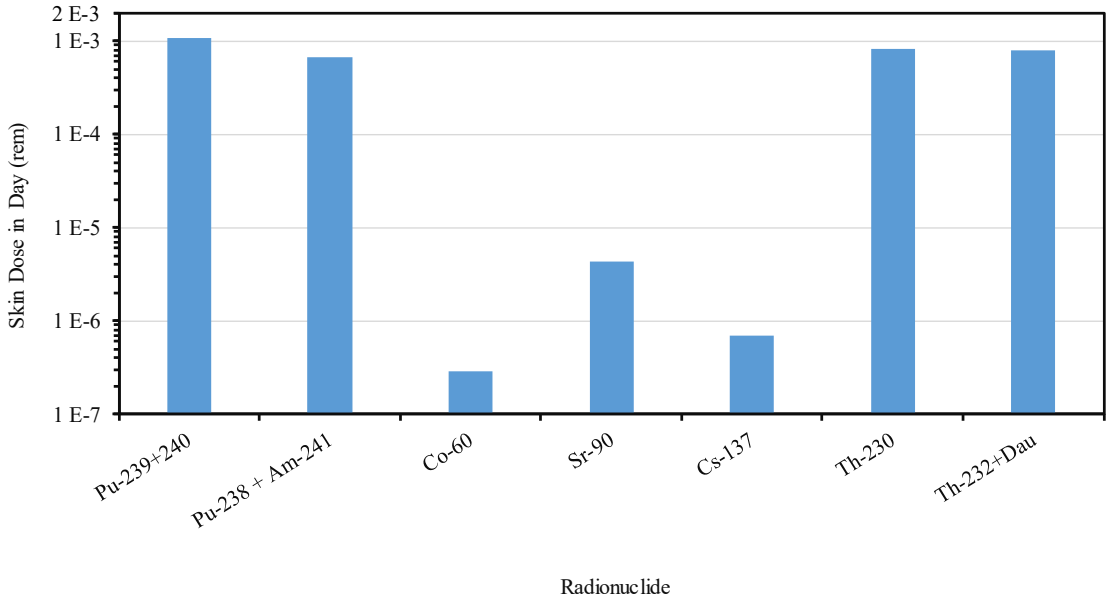


Figure 6-2. Histogram of Skin Doses in Day for Primary Radionuclides and Thorium from Trenching Activities in Segment A of Yvonne (Values from Tables L-2 and L-3).

Section 7

Extremity Dose from Discrete Plutonium Particle Removals on Yvonne

Extremity dose generally regard exposures to the limbs of the body, with special attention to the hands and feet. As discussed in this report, whole-body film badge dosimetry and/or TLDs were worn be individuals performing work on the northern islands of the Atoll during the 1977 – 1980 cleanup. The results of this monitoring data was expected to provide reasonable estimates of doses received by personnel from external sources. Special considerations were made for shallow doses to the skin from external sources, as discussed in Section 4.3.6. Some exposure scenarios justify monitoring and/or assessment of external exposures to extremities. For these cases, it is common to issue a finger film dosimeter or TLD. Cases where extremities of an individual may have been exposed to a significantly higher dose than the trunk of the body during the Enewetak cleanup are not apparent to this author. One example exposure scenario provided here is for individuals assigned the task in the summer of 1977 to remove discrete plutonium particles[24] from surface soils on Yvonne. This task was unique to AF FRST members (DNA 1981).

The JTG and DOE ERSP reviewed data provided by FRST and estimated that about 60 mCi of total TRU were collected and bagged by the FRST. FRST members performed the search with the field instrument for the detection of low-energy radiation (FIDLER) probes. It is an assumption that the majority of the FIDLER response was due to the 60 keV γ-ray emitted by ^{241}Am, with assessment of the $^{239+240}$Pu inferred from its estimated relationship with ^{241}Am. In 1977, JTG and DOE ERSP were not aware of the prominent activity contribution of ^{238}Pu to total TRU that existed on some islands, including Yvonne. As such, the estimate of 60 mCi of total TRU likely excluded ^{238}Pu. As well, Table 14 of NVO 140 (AEC 1973) did not list a median activity ratio of ^{241}Am to ^{239}Pu for locations on Yvonne. From Table J-2, the estimated $^{239+240}$Pu to ^{241}Am ratio Segment B of Yvonne was 10.8, though JTG and DOE ERSP may have assumed a different ratio. For purposes of this analysis, a conservative ratio of 3.0 is assumed. This provides an estimated total ^{241}Am activity of 20 mCi.

DNA (1981) notes that identified hot spots were excised with shovels and placed in plastic bags. A conservative estimate of the external dose to the extremity of an FRST technician assumes a separation distance of 15 cm (six inches) and distribution of the activity among 40 particles. Under these assumptions, the external dose rate is only about 7 mrem h^{-1}, using a specific γ-radiation dose constant of 8.5 mSv MBq^{-1} h^{-1} (at 1 m) from Unger and Trubey (1981). If particle number was increased, the mean activity per particle would decrease proportionately. DNA (1981) did not note the distribution of activity among the particles, not particle number excised during this special activity. Nevertheless, due to the relatively-low external exposure estimate provided in this example and the limited amount of contact time for the removal and bagging of an individual particle, the accumulated extremity dose by any one individual is deemed to be low.

In 1978, FRST personnel conducted a similar precautionary survey of fragments near the Kickapoo GZ on Sally. For these, the fragments had plutonium activities on the order of a few μCi (DNA 1981). This activity level is substantially lower than the example for Yvonne fragments.

[24] DNA (1981) noted that fragments identified and removed from Yvonne had the appearance of weathered metal, and in some cases attached to soil or concrete. The initial concern that the particles were high-graded plutonium was deemed unfounded after review of the field evidence. The attachment of particles to concrete may have influenced some individuals to refer to them as "fragments."

Section 8

Conclusions

This radiation exposure report was developed as an aid in the assessment of radiation exposures to AF personnel assisting in the Enewetak cleanup conducted between 1977 and 1980. In addition, the AF has also received many radiation exposure inquiries for its veterans assigned to the Atoll after atmospheric testing was completed in 1958 up to the time of the initial cleanup preparation in 1973. As such, this report also provides a comprehensive estimate of potential exposure received by AF veterans assigned to the Atoll during that period. Since the most extensive set of radiological measurements of the Enewetak Atoll were collected in a 1972 – 1973 survey by the AEC and its contractors, estimates of exposures for periods prior to this survey required a more extensive evaluation of the radiological source term than was necessary for evaluation of exposures to personnel supporting the 1977 to 1980 cleanup. This extensive evaluation of the source term also afforded a more accurate assessment of radiological conditions on the Atoll between 1977 and 1980. The primary radiological materials of concern were WGP, ^{137}Cs, ^{90}Sr, and ^{60}Co, though many additional radionuclides are considered in this report. The radionuclides of ^{238}Pu, ^{230}Th, and ^{232}Th (and its decay chain daughters) were some of the more important radionuclides included in the analysis of internal radiation exposures. The latter two were only deemed of importance for exposures on Yvonne. ^{125}Sb and ^{102m}Rh were important radionuclides for external exposures between 1959 and the early 1960s. While this report was developed as an aid to the AF in evaluation of doses to its personnel, other organizations may find information in this report useful. The report purposely enclosed a significant amount of support information in the Appendices. This was done as an aid to the reader. Some individuals that may read this report may not be accustomed to acquiring some of the referenced material.

Although more recent concerns expressed by veterans prompted the development of this report, the DoD in 1981 summarized radiation exposures to veteran's supporting this project in *The Radiological Cleanup of Enewetak Atoll* (DNA 1981). This report concluded that radiation exposures were very low, well below established radiation exposure standards. This report supports the findings of that report, though the evaluations provided in this report were more extensive in the assessment of internal exposures from the inhalation of contaminated soils and the incidental ingestion of soil. As well, this report provided an extensive review of the radiation exposure standards used during the cleanup with respect to more recently promulgated national and international standards. This report found that the standards used during the 1977 to 1980 cleanup were equivalent and in many cases more restrictive than current standards for protection, especially in the case of inhalation of WGP. This report concludes that internal radiation exposure potential was very low, commonly a small fraction of potential exposures received by external radiation sources, e.g., radionuclides in soil.

Due to the concern expressed by many veterans on PPE and its use in the project, this report provides extensive details on the use of PPE during the restoration. Overall, the PPE specified for personnel during the project were very conservative, and contributed to the very low internal exposures estimated from the inhalation pathway. This information was complied from controlled island access logs, documented during the cleanup and part of archived information from the cleanup.

Section 9

References

ACS American Cancer Society, *Lifetime Probability of Developing and Dying from Cancer for 23 Sites, 2010 – 2012,* Surveillance Research, 2016.

AEC Atomic Energy Commission, *Enewetak Radiological Survey*, Nevada Operations Office, Las Vegas, NV, Report NVO-140, Volume I, October 1973. Available at: http://www.dtra.mil/Home/Nuclear-Test-Personnel-Review/Enewetak-Atoll-Cleanup-Documents/

AEC Atomic Energy Commission, *Enewetak Radiological Survey*, Nevada Operations Office, Las Vegas, NV, Report NVO-140, Volume II, October 1973. Available at: http://www.dtra.mil/Home/Nuclear-Test-Personnel-Review/Enewetak-Atoll-Cleanup-Documents/

AEC Atomic Energy Commission, *Enewetak Radiological Survey*, Nevada Operations Office, Las Vegas, NV, Report NVO-140, Volume III, October 1973. Available at: http://www.dtra.mil/Home/Nuclear-Test-Personnel-Review/Enewetak-Atoll-Cleanup-Documents/

Anspaugh, L.R., Shinn, J.H., Phelps, P.L., Kennedy, N.C., *Resuspension and Redistribution of Plutonium in Soils*, Health Physics, Vol. 29, No. 4, 1975.

Anspaugh, L.R., Simon, S.L., Gordeev, K.I., Likhtarev, I.A., Maxwell, R.M., Shinkarev, S.M., *Movement of Radionuclides in Terrestrial Ecosystems*, Health Physics, Vol. 82, May, 2002.

Barnes, J. W., Lang, E.J., Potratz, H.A., *Ratio of Ionium to Uranium in Coral Limestone*," Science Vol. 124, 1956.

Beck, H. L., Bouville, A., Mozoz, B.E., Simon, S.L., *Fallout Deposition in the Marshall Islands from Bikini and Enewetak Nuclear Weapons Tests*, Health Physics, Vol. 99, No. 2, August 2010.

Bouville, A., Beck, H.L., Simon, S.L., *Doses from External Irradiation to Marshall Islanders from Bikini and Enewetak Nuclear Weapons Tests*, Health Physics, Vol. 99, No. 2, August 2010.

Broecker, W. S. and D. L. Thurber, *Uranium-Series Dating of Corals and Oolites from Bahaman and Florida Key Limestones*," Science Vol. 149, 1965.

Cember, H., *Introduction to Health Physics*, 3rd Ed, McGraw-Hill, New York, 1996.

Crase, K.W., Gudiksen, P.H., Robison, W.L., *β- and γ-Comparative Dose Estimates on Enewetak Atoll*, Health Physics, Vol. 42, No. 5, 1982.

DNA Defense Nuclear Agency, Environmental Impact Statement, *The Cleanup, Rehabilitation, Resettlement of Enewetak Atoll*, Volumes I – IV, Washington DC, 1975. Available at: http://www.dtra.mil/Home/Nuclear-Test-Personnel-Review/Enewetak-Atoll-Cleanup-Documents/

DNA Defense Nuclear Agency, *Enewetak Atoll Air Sampling*, Memorandum for Record, Field Command, FCLS, Dr. Edward T. Bramlitt, 30 June 1977.

DNA Defense Nuclear Agency, *Central Repository for Personnel Exposure Records,* Memorandum for Director, Defense Nuclear Agency, LaWayne R. Stromberg, M.D., Colonel, US Army, Defense Nuclear Agency, 12 Aug 77.

DNA Defense Nuclear Agency, *High Air Sample Concentration at Enewetak Atoll*, Memorandum for Record, Field Command, FCLS, Dr. Edward T. Bramlitt, 7 September 1978.

DNA Defense Nuclear Agency, *Enewetak Bioassay*, Telephone or Verbal Conversation Record, Field Command, FCLS, Dr. Edward T. Bramlitt (DNA) and Major David Case (OEHL), 19 December 1979.

DNA Defense Nuclear Agency, *Compilation of Local Fallout Data from Test Detonations 1945-1962 Extracted from DASA 1251*, Volume II – Oceanic U.S. Tests, General Electric-TEMPO, Report DNA 1251-2-EX, Washington DC, 1 May 1979. Available at: http://www.dtra.mil/Home/Nuclear-Test-Personnel-Review/NTPR-Radiation-Exposure-Reports/

DNA Defense Nuclear Agency, *The Radiological Cleanup of Enewetak Atoll*, Washington DC, 1981. Available at: http://www.dtra.mil/Home/Nuclear-Test-Personnel-Review/Enewetak-Atoll-Cleanup-Documents/

DNA Defense Nuclear Agency, *Operation Hartack I – 1958,* Washington DC, Report DNA 6038F, 1 December 1982.

DOE Department of Energy, *Enewetak Radiological Support Project*, Nevada Operations Officer, Las Vegas, NV, Report NVO-213, September 1982. Available at: http://www.dtra.mil/Home/Nuclear-Test-Personnel-Review/Enewetak-Atoll-Cleanup-Documents/

DOE Department of Energy, *Remedial Investigation/Feasibility Study, Operating Unit 9, Site Scoping Report, Volume 7 – Waste Management, Environmental Restoration Program, Mound Plant,* July 1992.

DTRA Defense Threat Reduction Agency, *Radiation Doses to Skin from Dermal Contamination*, DTRA-TR-09-16, Fort Belvoir, VA, October 2010.

DTRA Defense Threat Reduction Agency, *Radiation Dose Assessment for Military Personnel of the Enewetak Atoll Clean-up (1977 – 1980)*, DTRA-TR-2017, Fort Belvoir VA, 2017.

Durbin, P. W., *Metabolic Characteristics with a Chemical Family*, Health Physics, Vol. 2, 1960.

EPA Environmental Protection Agency, *Report of the Radiological Clean-up of Bikini Atoll*, Office of Dose Assessment & Systems Analysis, Western Environmental Research Laboratory, Report SWRHL-111r, January 1972.

EPA "Exposure Factor Handbook, Chapter 5 – Soil and Dust Ingestion," US Environmental Protection Agency, 2011.

EPA "Proposed Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment," US Environmental Protection Agency, Report 520/4-77-016, Sep 1977.

EPA "Response to Comments: Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment," US Environmental Protection Agency, Report 520/4-78-010, Washington, October 1978.

EPA *External Exposure to Radionuclides in Air, Water, and Soil*, Federal Guidance Report 12, US Environmental Protection Agency, September 1993.

Eatough, J.P., *Alpha-Particle Dosimetry for the Basal Layer of the Skin and the Radon Progeny ^{218}Po and ^{214}Po*, Physics in Medicine and Biology, Vol. 42, pp 1899 – 1911, 1997.

Gladeck, F.R.; Gould, K.G.; Hallowell, J.H.; Martin, E.J.; McMullan, F.W.; Miller, R.A.; Osborn, M.J.; Shelton, C.F.; Berkhouse, L.; Calhoun, F.S.; *Operation Hardtack I – 1958*; Defense Nuclear Agency, Report 6038F, Washington, 1 December 1982.

Glasstone, Samuel, and Dolan, Philip J., *The Effects of Nuclear Weapons*, 3rd Edition, US Department of Defense and US Department of Energy, 1977.

Hanford Laboratories, *Ionium (Thorium-230) for Radioisotope Preparation (Status Report),* Hanford Laboratories Operation, Hanford WA, 15 December 1959.

Harley, J.H., "Plutonium in the Environment – A Review," Journal of Radiation Research, Vol. 21, 1980.

Hicks, H. G., *Calculation of the Concentration of any Radionuclide Deposited on the Ground by Off-Site Fallout from a Nuclear Detonation*, Health Physics, Vol. 42, No. 5, May 1982.

Hoff, Richard W., Letter to Mr. John Stewart, Nevada Operations Office, Department of Energy, Lawrence Livermore Laboratory, Nuclear Chemistry Division, 31 January 1978.

ICRP International Commission on Radiological Protection, *The 2007 Recommendations of the International Commission on Radiological Protection,* ICRP Publication 103, 2007.

ICRP International Commission on Radiological Protection, *Age-Dependent Doses to Members of the Public from Intake of Radionuclides – Part 5 Compilation of Ingestion and Inhalation Coefficients,* ICRP Publication 72, 1995. (c)

ICRP International Commission on Radiological Protection, *Age-Dependent Doses to Members of the Public from Intake of Radionuclides – Part 5 Compilation of Ingestion and Inhalation Coefficients,* ICRP Publication 71, 1995. (b)

ICRP International Commission on Radiological Protection, *Age-Dependent Doses to Members of the Public from Intake of Radionuclides – Part 4 Inhalation Dose Coefficients,* ICRP

Publication 69, 1995. (a)

ICRP International Commission on Radiological Protection, *Dose Coefficients for Intakes of Radionuclides by Workers,* ICRP Publication 68, 1994. (b)

ICRP International Commission on Radiological Protection, *Age-Dependent Doses to Members of the Public from Intake of Radionuclides – Part 2 Ingestion Dose Coefficients,* ICRP Publication 67, 1992.

ICRP International Commission on Radiological Protection, *Human Respiratory Tract Model for Radiological Protection,* ICRP Publication 66, 1994. (a)

ICRP International Commission on Radiological Protection, *1990 Recommendations of the International Commission on Radiological Protection,* ICRP Publication 60, 1990. (b)

ICRP International Commission on Radiological Protection, *Age Dependent Dose to Members of the Public from Intake of Radionuclides: Part 1,* ICRP Publication 56, 1990. (a)

ICRP International Commission on Radiological Protection, *The Metabolism of Plutonium and Related Elements,* ICRP Publication 48, 1986.

ICRP International Commission on Radiological Protection, *Limits for Intakes of Radionuclides by Workers,* ICRP Publication 30, Part 1, 1979.

ICRP International Commission on Radiological Protection, *Limits for Intakes of Radionuclides by Workers,* ICRP Publication 30, Part 2, 1980.

ICRP International Commission on Radiological Protection, *Limits for Intakes of Radionuclides by Workers,* ICRP Publication 30, Part 3, 1981.

ICRP International Commission on Radiological Protection, *Recommendations of the International Commission on Radiological Protection,* ICRP Publication 26, 1977.

ICRP International Commission on Radiological Protection, *Report on Committee II on Permissible Dose for Internal Emitters,* ICRP Publication 2, 1959.

ICRP International Commission on Radiological Protection, *Recommendations of the International Commission on Radiological Protection,* ICRP Publication 1, 1958.

ICRU International Commission on Radiation Units and Measurements, *Stopping Powers and Ranges for Protons and Alpha Particles*, ICRU Report 49, Bethesda MD, 1993.

Mueller, H.J., "Artificial Transmutation of the Gene," *Science*, 1927.

OSHA Occupational Safety and Health Administration, *Assigned Protection Factors for the Revised Respiratory Protection Standard*, OSHA 3352-02, 2009.

NAS *Film Badge Dosimetry in Atmospheric Nuclear Tests*, Committee on Film Badge Dosimetry In Atmospheric Nuclear Tests, National Research Council of the National Academy of Sciences, National Academies Press, Washington, D.C., 1989.

NAS *A Review of the Dose Reconstruction Program of the Defense Threat Reduction Agency*, National Research Council of the National Academy of Sciences, National Academies Press, Washington, D.C., 2003.

NAS National Academies of Science, *Adopting the International System of Units for Radiation Measurements in the United States: Proceedings of a Workshop*, National Academies Press, Washington, DC, 2017. Available at: http://www.nap.edu/24645.

Nelson, V. A., *Radiological survey of Plants, Animals, and Soil at Five Atolls in the Marshall Islands,* University of Washington, College of Fisheries, Laboratory of Radiation Ecology, U.S DOE Report NVO-269, 1979.

Noshkin, V.E., et al., "Transuranics at Pacific Atolls, 1. Concentrations in Waters at Enewetak and Bikini," UCRL-51612, 1974.

NRC *Reactor Safety Study – An Assessment of Accident Risks in US Commercial Nuclear Power Plants*, Nuclear Regulatory Commission, Report WASH-1400, Washington, D.C., 1975.

Philipps, Dave, *Troops Who Cleaned up Radioactive Islands Can't Get Medical Care*, New York Times, NY, NY, 28 January 2017.

Rademacher, S.E., *Plutonium Exposures to Personnel Assigned to Johnston Atoll*, Revision 1, HQ Air Force Safety Center, Weapons Safety Division, Kirtland AFB, NM, 87117-5670, 11 August 2016.

Rademacher, S.E., "Boeing Michigan Aeronautical Research Center (BOMARC), Final Remedial Action Report for Site RW-01, McGuire AFB, N.J.," Headquarters, Air Force Safety Center, Kirtland AFB, NM, 17 May 2010.

Raughter, John, *Toxic Paradise*, The American Legion Magazine, Indianapolis, IN, March 2016.

Robison, W.L., Noshlin, V.E., Hamilton, T.F., Conrado, C.L., Bogen, K.B., *An Assessment of the Current Day Impact of Various Materials Associated with the U.S. Nuclear Test Program in the Marshall Islands*, Lawrence Livermore National Laboratory, Report UCRL-LR-143980, 1 May 2001.

Shinn, J.H., Homan, D.N., Robison, W.L., *Resuspension Studies in the Marshall Islands*, Health Physics, Vol. 73, No. 1, July 1997.

Shinn, Joseph H., *Post-Accident Inhalation Exposure and Experience with Plutonium*, Lawrence Livermore National Laboratory, Report UCRL-JC-131173, June 1998.

Simon, S.L., Bouville, A., Land, C.E., Beck, H.L., *Radiation Doses and Cancer Risks in the Marshall Islands from Associated with Exposure to Radioactive Fallout from Bikini and*

Enewetak Nuclear Weapons Tests: Summary, Health Physics, Vol. 99, No. 2, August 2010.

Simon, S.L., Bouville, A., Melo, D., Beck, H.L., Weinstock, R.M., *Acute and Chronic Intakes of Fallout Radionuclides by Marshallese from Associated from Nuclear Weapons Testing at Bikini and Enewetak and Related Internal Radiation Doses*, Health Physics, Vol. 99, No. 2, August 2010.

Smith, W.J., Whicker, F.W., Meyer, H.R., *Review and Categorization of Saltation, Suspension, and Resuspension Models*, Nuclear Safety, Vol. 23, 1982.

Stephens, D.R., *Source Terms for Plutonium Aerosolization from Nuclear Weapon Accidents*, Lawrence Livermore National Laboratory, Report UCRL-ID-119303, July 1993.

Tatsumoto, M. and Goldberg, E.D., *Some Aspects of the Marine Geochemistry of Uranium*, Geochimica et Cosmochimica Acta, Vol. 17, 1959.

Thurber, D. L., W. S. Broecker, R. L. Blanchard, H. A. Potratz (1965), *Uranium-Series Ages of Pacific Atoll Coral*, Science, Vol. 149, 1965.

Unger, Laurie and Trubey, D.K., *Specific Gamm-Ray Dose Constants for Radionuclides Important to Dosimetry and Radiological Assessment*, Oak Ridge National Laboratory, Report ORNL/RSIC-45, September 1981.

Veeh, H. H. and K. K. Turekian, *Cobalt, Silver, and Uranium Concentrations of Reef—Building Corals in the Pacific Ocean*," Limnology and Oceanology. Vol. 13, 1968.

Whitton, J.T., *New Values for Epidermal Thickness and Their Importance*, Health Physics, Vol. 24, January 1973.

Yu, C., Zeilen, A.J., Cheng, J.-J., Lepoire, D.J., Gnanapragasam, E., Kamboj, S., Arnish, J., Wallo III, A., Williams, W.A., Peterson, H., "User's Manual for RESRAD Version 6," Argonne National Laboratory Report ANL/EAD-4, Argonne IL, July 2001.

Appendix A.

Background Information on Atoll and Radionuclides

TABLE A-1. Lifetime Probability (Percents) of Developing* and Dying from Cancer for 23 Sites, 2010 – 2012, American Cancer Society, Surveillance Research (ACS 2016).

Site	Males		Females	
	Developing	Dying	Developing	Dying
All Sites †	42.1	22.6	37.6	19.1
Brain & ONS	0.7	0.5	0.5	0.4
Breast	0.1	< 0.1	12.3	2.7
Colorectal	4.7	2.0	4.4	1.8
Esophagus	0.8	0.8	0.2	0.2
Hodgkin lymphoma	0.2	< 0.1	0.2	< 0.1
Kidney & renal pelvis	2.0	0.6	1.2	0.3
Larynx	0.6	0.2	0.1	< 0.1
Leukemia	1.8	1.0	1.2	0.7
Liver & intrahepatic bile duct	1.3	0.9	0.5	0.5
Lung & bronchus	7.2	6.3	6.0	4.9
Melanoma of skin‡	3.0	0.5	1.9	0.2
Myeloma	0.9	0.5	0.6	0.4
Non-Hodgkin lymphoma	2.4	0.9	1.9	0.7
Oral cavity & pharynx	1.6	0.4	0.7	0.2
Ovary	--	--	1.3	1.0
Pancreas	1.5	1.4	1.5	1.3
Prostate	14.0	2.6	--	--
Stomach	1.1	0.5	0.7	0.3
Testis	0.4	< 0.1	--	--
Thyroid	0.6	0.1	1.7	0.1
Urinary bladder§	3.8	0.9	1.1	0.3
Uterine cervix	--	--	0.6	0.2
Uterine corpus	--	--	2.8	0.6

* For those who are cancer free.

† All sites excludes basal cell and squamous cell skin cancers and in-situ cancers except urinary bladder.

‡ Statistics are for whites.

§ Includes invasive and in-situ cancer cases.

TABLE A-2. Nuclear Events at Enewetak Atoll (Adapted from DNA 1981).

Operation	Event Name	Date (GMT)	Type and Height of Burst	Location	Total Yield*
Sandstone	X-ray	14 Apr 48	Tower 200 ft	Janet	37 kT
	Yoke	30 Apr 48	Tower 200 ft	Sally	49 kT
	Zebra	14 May 48	Tower 200 ft	Yvonne	18 kT
Greenhouse	Dog	7 Apr 51	Tower 300 ft	Yvonne	81 kT
	Easy	20 Apr 51	Tower 300 ft	Janet	47 kT
	George†	8 May 51	Tower 200 ft	Ruby	225 kT
	Item††	24 May 51	Tower 200 ft	Janet	45.5 kT
Ivy	Mike	31 Oct 52	Surface	Flora††††	10.4 MT
	King †††	15 Nov 52	Airdrop 1500 ft	2000 ft N. of Yvonne	500 kT
Castle	Nectar	13 May 54	Barge	Mike crater (Flora)	1.69 MT
Redwing	Lacrosse	4 May 56	Surface	Yvonne	40 kT
	Yuma	27 May 56	Tower 200 ft	Sally	190 T
	Erie	30 May 56	Tower 300 ft	Yvonne	14.9 kT
	Seminole	6 Jun 56	Surface	Irene	13.7 kT
	Blackfoot	11 Jun 56	Tower 200 ft	Yvonne	8 kT
	Kickapoo	13 Jun 56	Tower 300 ft	Sally	1.49 kT
	Osage	16 Jun 56	Airdrop	Yvonne	1.7 kT
	Inca	21 Jun 56	Tower 200 ft	Pearl	15.2 kT
	Mohawk	2 Jul 56	Tower 300 ft	Ruby	360 kT
	Apache	8 Jul 56	Barge	Mike crater (Flora)	1.85 MT
	Huron	21 Jul 56	Barge	Mike crater (Flora)	250 kT
Hardtack I	Cactus	5 May 58	Surface	Yvonne	18 kT
	Butternut	11 May 58	Barge	Lagoon	81 kT
	Koa	12 May 58	Surface	Gene††††	1.37 MT
	Wahoo	16 May 58	Underwater 500 ft	Ocean	9 kT
	Holly	20 May 58	Barge	Lagoon	5.9 kT
	Yellowwood	26 May 58	Barge	Lagoon	330 kT
	Magnolia	26 May 58	Barge	Lagoon	57 kT
	Tobacco	30 May 58	Barge	Lagoon	11.6 kT
	Rose	2 Jun 58	Barge	Lagoon	15 kT
	Umbrella	8 Jun 58	Underwater 150 ft	Lagoon	8 kT
	Walnut	14 Jun 58	Barge	Lagoon	1.45 MT
	Linden	18 Jun 58	Barge	Lagoon	11 kT
	Elder	27 Jun 58	Barge	Lagoon	880 kT
	Oak	28 Jun 58	Barge	Reef	8.9 MT

*DOE/NV-209-Revision 16, September 2015 † First thermonuclear test explosion

†† First test of boosting principle ††† Largest fission device †††† Island destroyed by test

TABLE A-2. Nuclear Events at Enewetak Atoll (Adapted from DNA 1981), continued.

Operation	Event Name	Date (GMT)	Type and Height of Burst	Location	Total Yield*
Hardtack I	Sequoia	1 Jul 58	Barge	Lagoon	5.2 kT
	Dogwood	5 Jul 58	Barge	Lagoon	397 kT
	Scaevola‡‡	14 Jul 58	Barge	Lagoon‡	Zero
	Pisonia	17 Jul 58	Barge	Lagoon	255 kT
	Olive	22 Jul 58	Barge	Lagoon	202 kT
	Pine	26 Jul 58	Barge	Lagoon	2 MT
	Quince	6 Aug 58	Surface	Yvonne	Zero
	Fig	18 Aug 58	Surface	Yvonne	20 T

*DOE/NV-209-Revision 16, September 2015 ‡ Near Yvonne ‡‡ LASL safety experiment test

TABLE A-3. Nuclear Tests Estimated to Have Deposited Measurable Fallout in the Marshall Islands [Adapted from Simon et al. 2010a for Tests Conducted at Enewetak Atoll Only].

Operation	Event Name	Date (GMT)	Cloud Top Height, Diameter (feet)†	Location	Total Yield (MT)*
Sandstone	Yoke	30 Apr 48	56k, 35k	Janet	0.049
Greenhouse	Dog	7 Apr 51	56k, 23.8k	Yvonne	0.081
	Item	24 May 51	40k, ND	Janet	0.046
Ivy	Mike	31 Oct 52	102k, 106k	Flora	10.4
	King	15 Nov 52	67k, 50k	2000 ft N. of Yvonne	0.50
Castle	Nectar	13 May 54	71k, 32k	Mike crater (Flora)	1.69
Hardtack I	Cactus	5 May 58	19k, ND	Yvonne	0.018
	Koa	12 May 58	72k, ND	Gene	1.37

*DOE/NV-209-Revision 16, September 2015 † DNA 1251-2-EX [diameters @ time peak height achieved]
ND = Not Documented

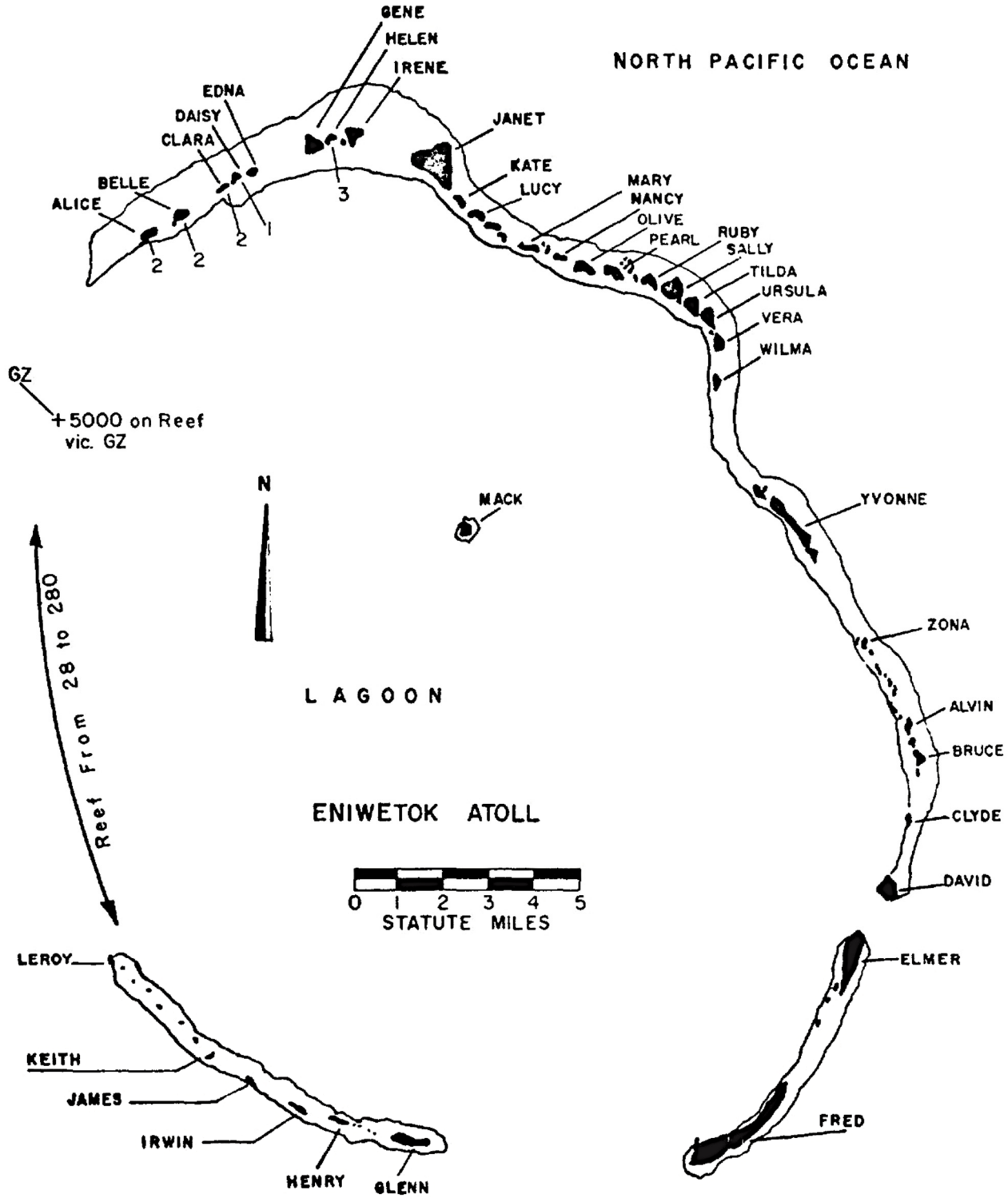


Figure A-1. Radiation Exposure Rates (R h^{-1}) on Selected Island at One-Hour Post Detonation of Event Oak on Reef (GZ), Enewetak Atoll, 28 June 1958 [Figure 155, (DNA 1979)].

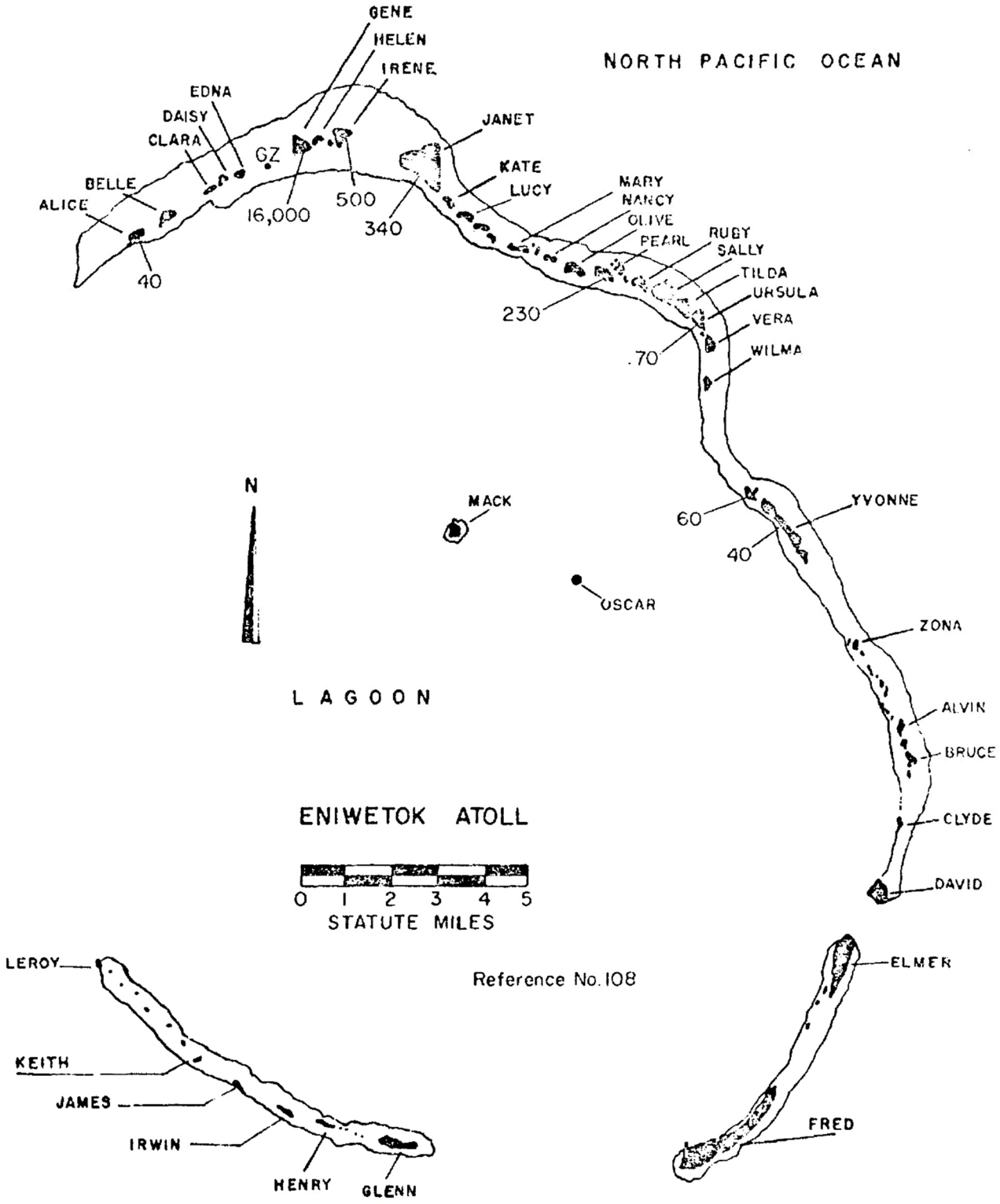


Figure A-2. Radiation Exposure Rates (R h^{-1}) on Selected Island at One-Hour Post Detonation of Event Apache on Barge (GZ), Enewetak Atoll, 8 July 1956 [Figure 100, (DNA 1979)].

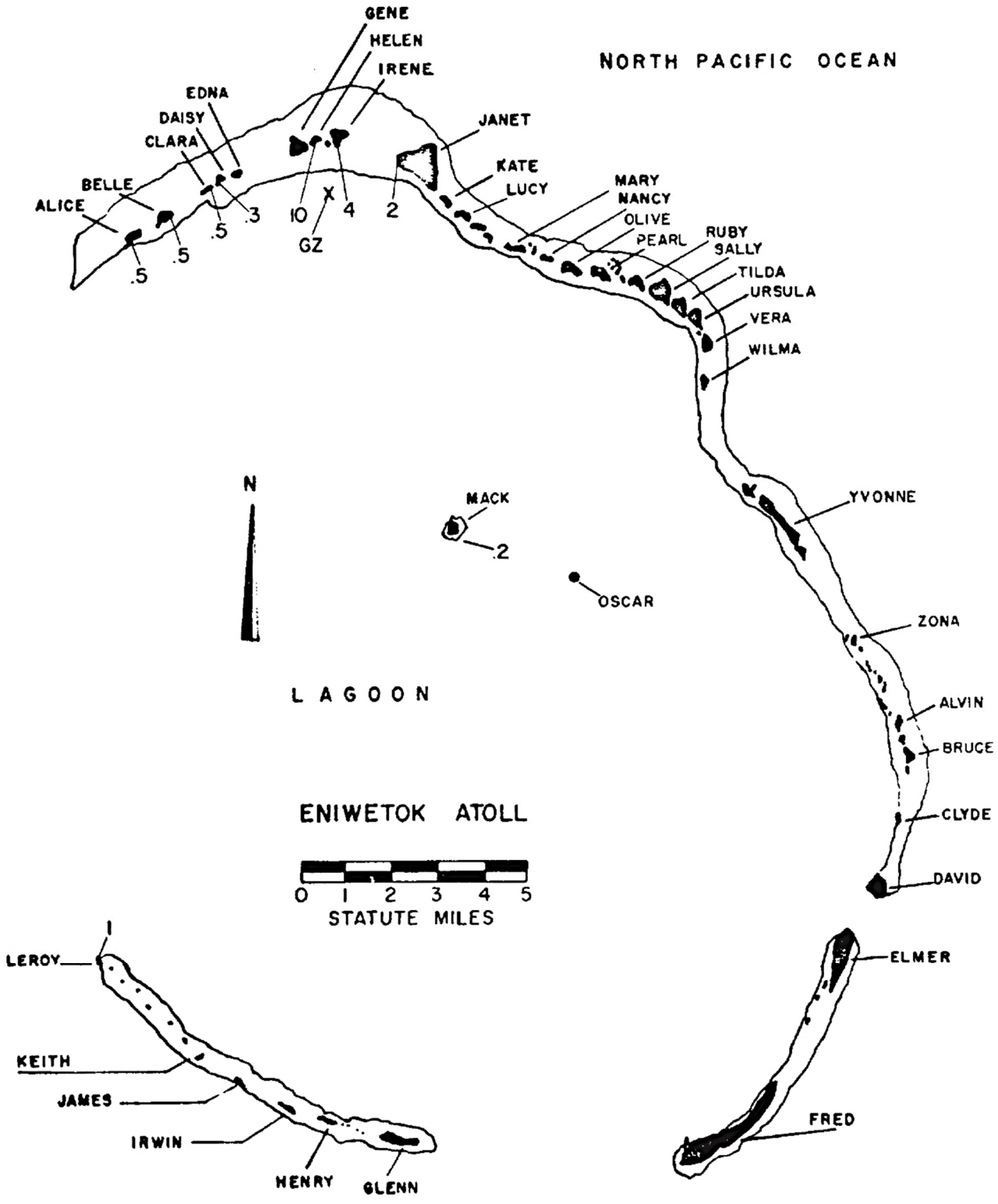


Figure A-3. Radiation Exposure Rates (R h^{-1}) on Selected Island at One-Hour Post Detonation of Event Pine on Barge (GZ), Enewetak Atoll, 26 July 1958 [Figure 173, (DNA 1979)].

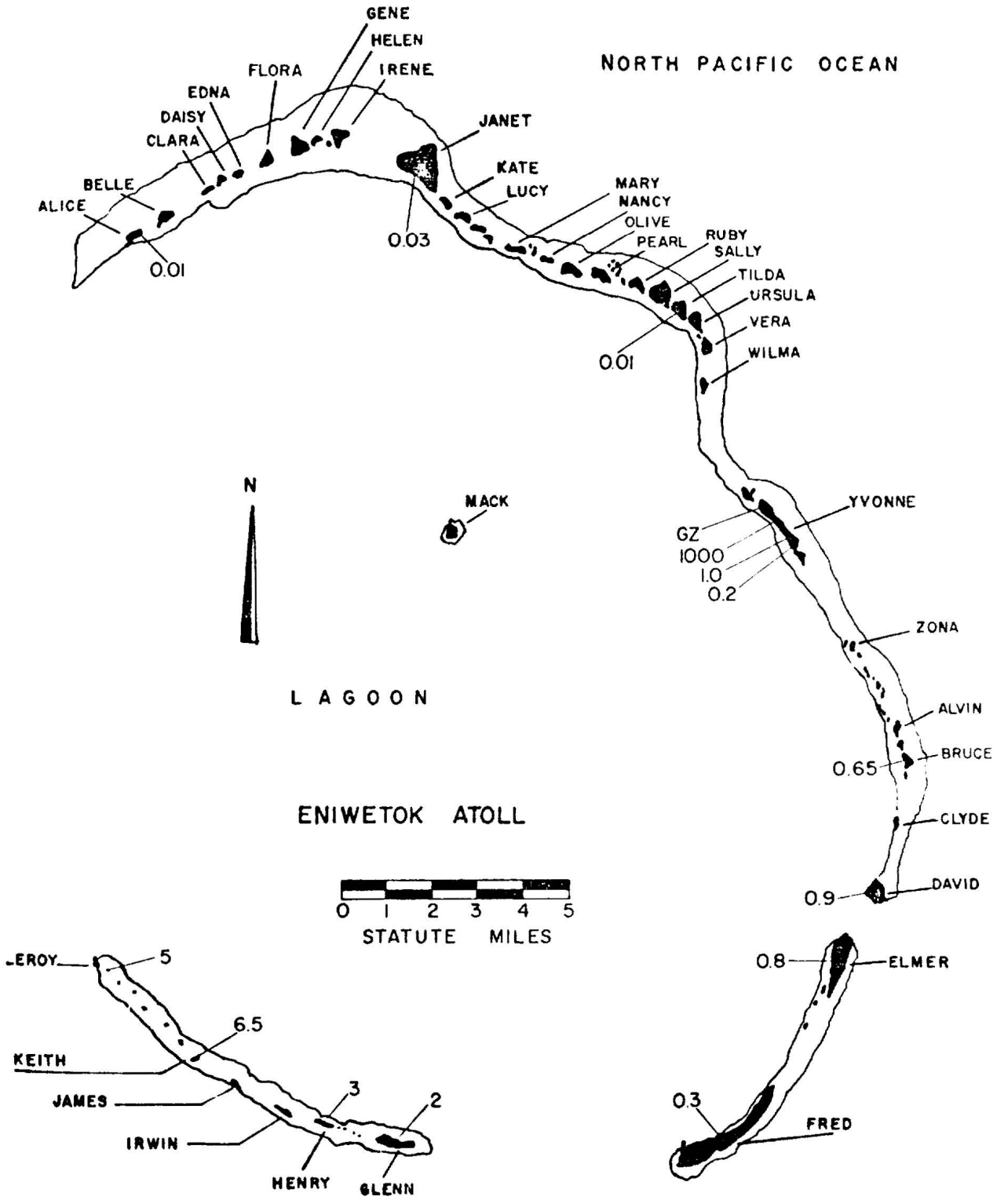


Figure A-4. Radiation Exposure Rates (R h^{-1}) on Selected Island at One-Hour Post Detonation of Event Dog on Yvonne (GZ), Enewetak Atoll, 7 April 1951 [Figure 16, (DNA 1979)].

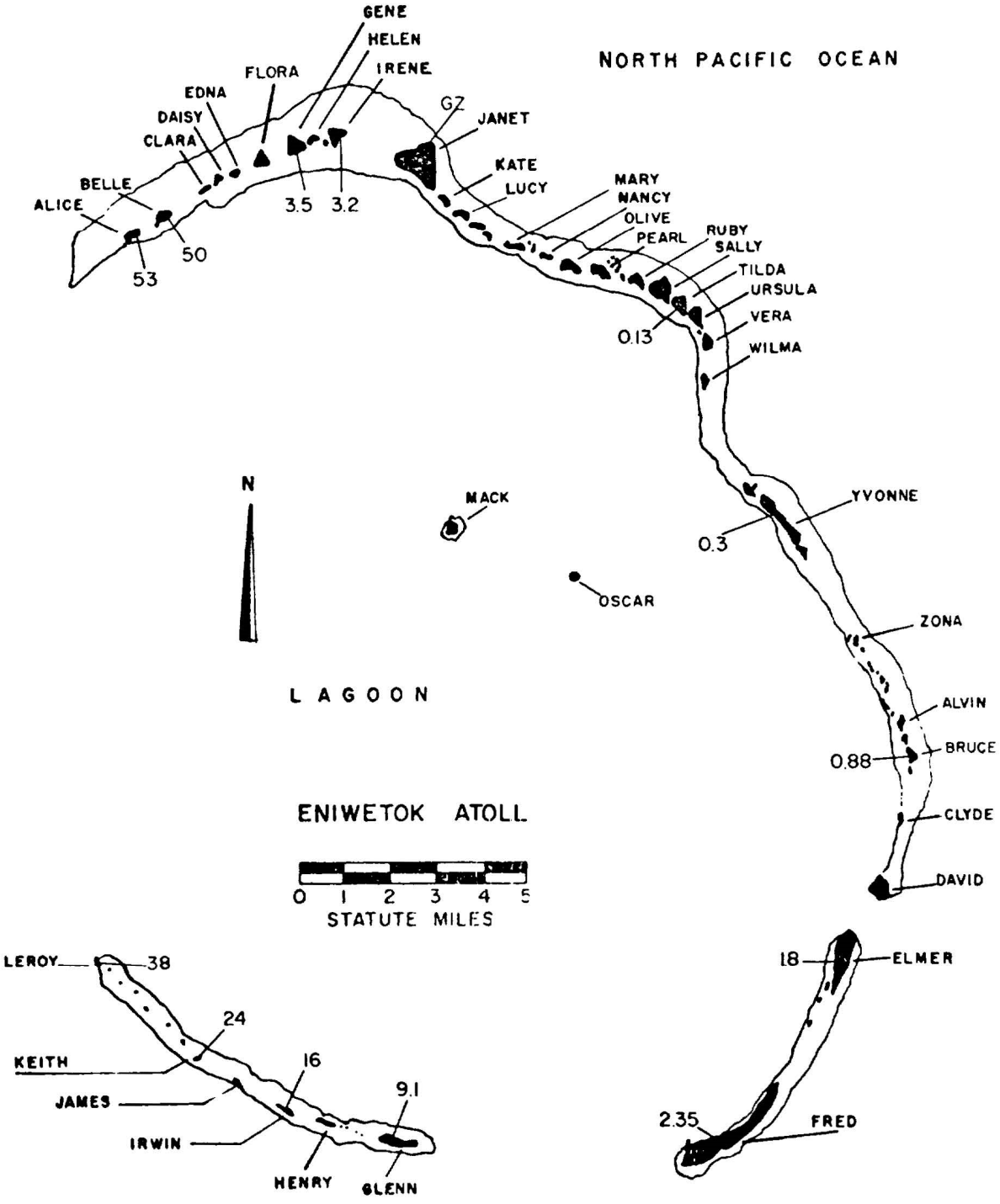


Figure A-5. Radiation Exposure Rate Contours (R h^{-1}) at One-Hour Post Detonation of Event Item on Island Yvonne, Enewetak Atoll, 25 May 1951 [Figure 27, (DNA 1979)].

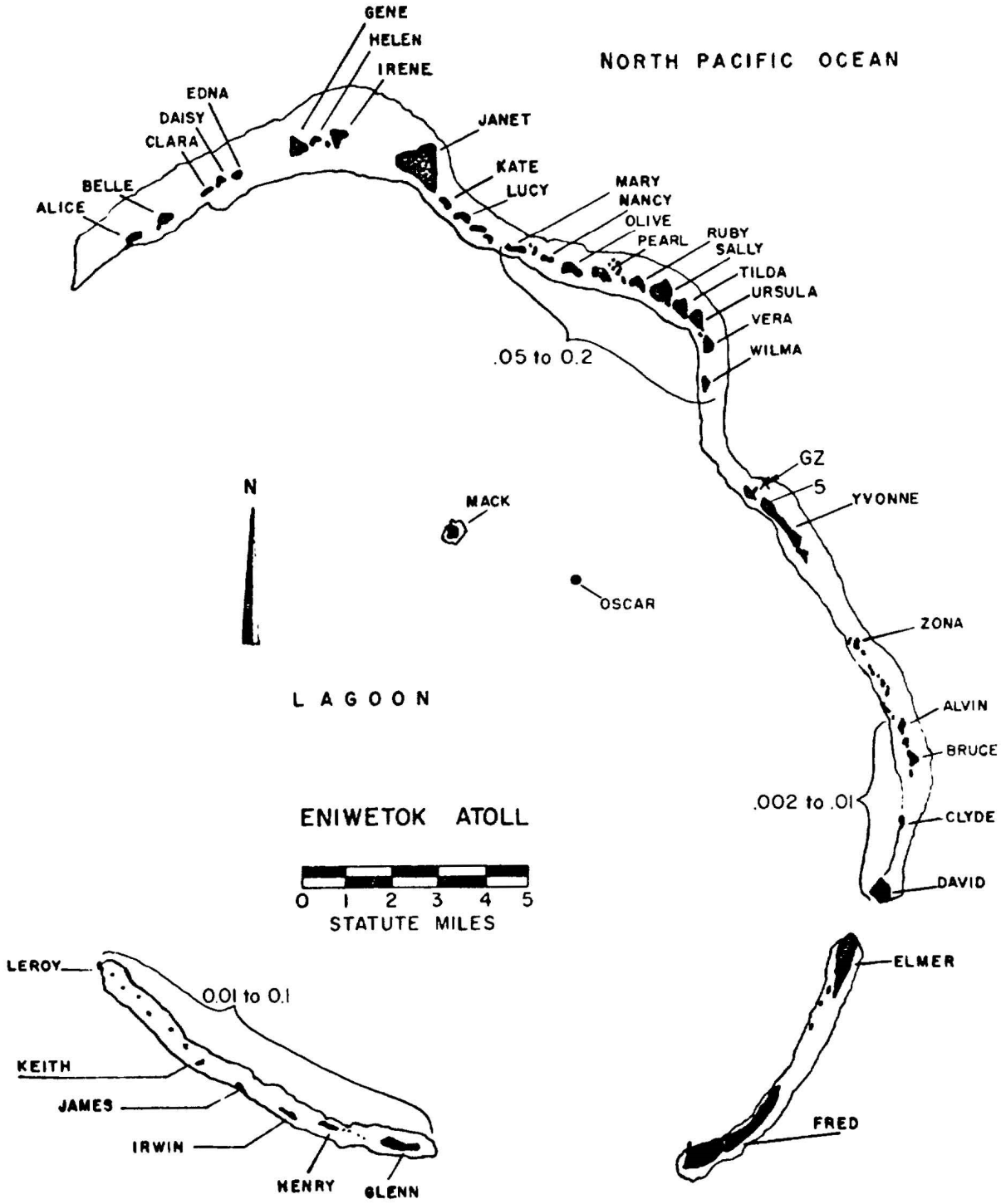


Figure A-6. Estimated Radiation Exposure Rate Contours (R h^{-1}) at One-Hour Post Detonation of Event King 2,000 feet North of Island Yvonne, Enewetak Atoll, 15 November 1952 [Figure 34, (DNA 1979)].

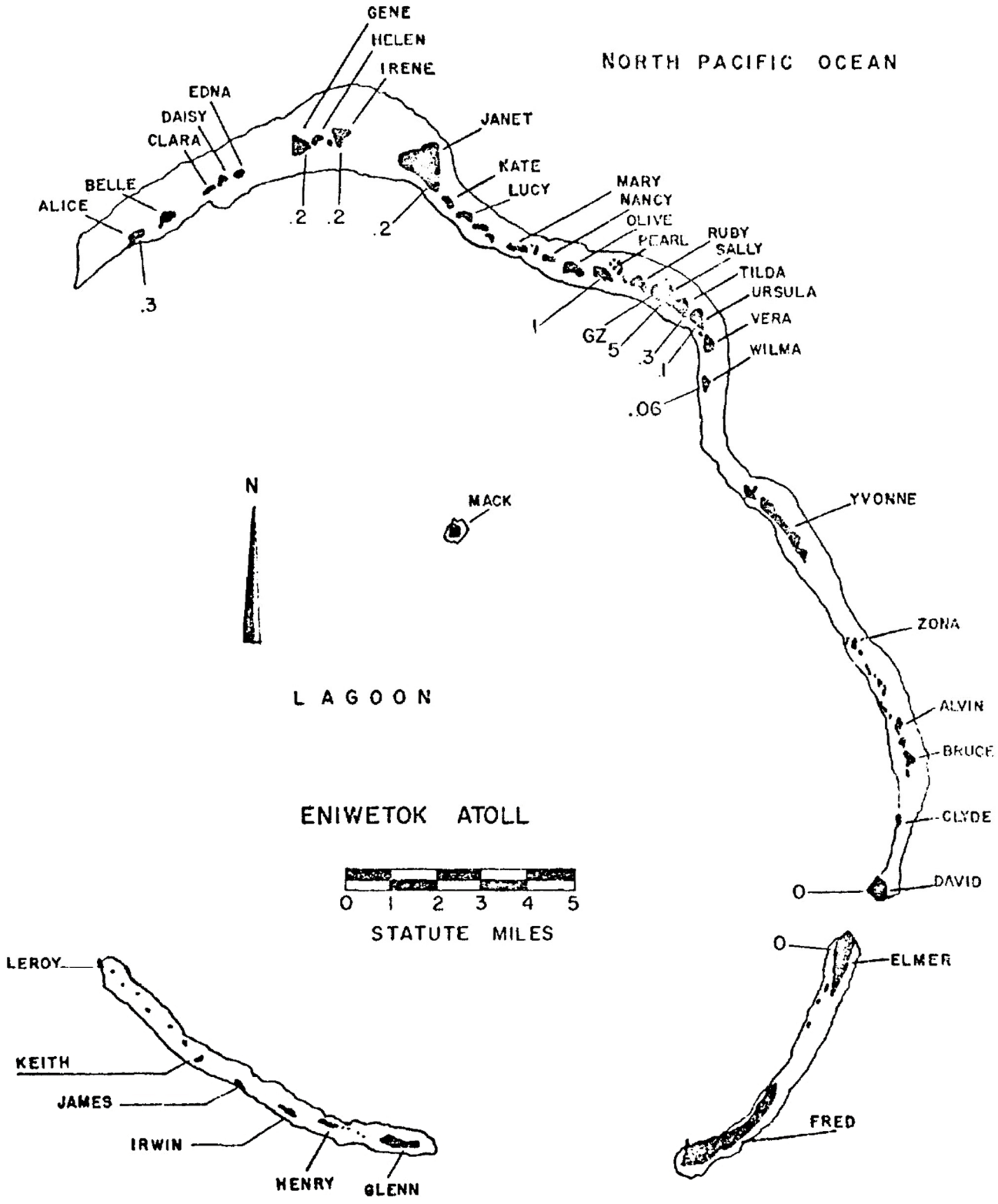


Figure A-7. Radiation Exposure Rates (R h^{-1}) on Selected Island at One-Hour Post Detonation of Event Yuma on Sally, Enewetak Atoll, 27 May 1956 [Figure 76, (DNA 1979)].

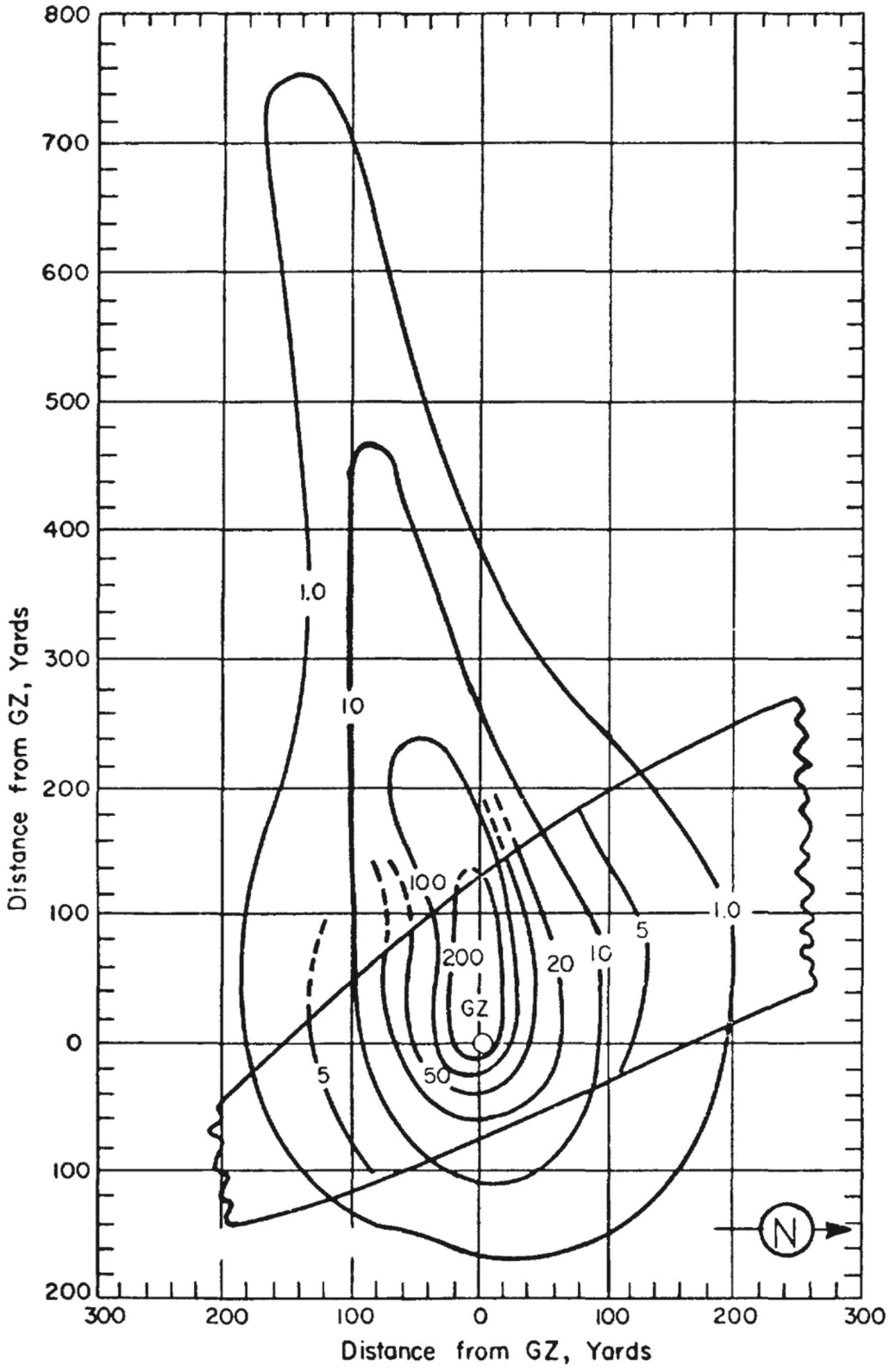


Figure A-8. Radiation Exposure Rates (R h^{-1}) on and near Yvonne at One-Hour Post Detonation of Event Fig on Yvonne, Enewetak Atoll, 18 August 1958 [Figure 177, (DNA 1979)].

TABLE A-4. Radionuclides of Importance Expected in Enewetak Soils.
[Compiled in Part from NVO-140, Volume 1 (AEC 1973) & Simon et al. (2010b)].

Radio-nuclide	Source		Half-life	Notes
	Primary	Other (Non-Fission Interactions)		
Pu-238	Unburned fuel	Fast neutron (n,2n) with Pu-239	87.8 y	8
Pu-239	Unburned fuel	Fast neutron (n,γ) with U-238 + decay	24,131 y	7
Pu-240	Unburned fuel	Thermal neutron capture with Pu-239	6,563 y	7
Pu-241	Unburned fuel	Thermal neutron capture with Pu-240	14.4 y	8
Am-241		Decay product of Pu-241	432 y	6
U-234	Unburned fuel		245,000 y	8
U-235	Unburned fuel		7.04×10^8 y	6, 7
U-236		Thermal neutron capture with U-235	2.34×10^7 y	8
U-237		Fast neutron (n,2n) with U-238	6.75 d	4
U-238	Unburned fuel		4.47×10^9 y	8
U-239		Fast neutron capture with U-238	23.5 min	4
Np-239		Decay product of U-239	2.4 d	1
H-3	Unburned fuel	Fusion and neutron activation product	12.4 y	10
C-14		Neutron activation of soil, concrete, air	5,730 y	10
Fe-55		Neutron activation of steel	2.7 y	2
Co-60		Neutron activation of steel	5.27 y	2, 5, 9
Ni-63		Neutron activation of steel	96 y	10
Cu-64		Neutron activation of copper	12.7 h	4
Zn-65		Neutron activation of steel	244 d	2
As-77	Fission		39 h	4
Br-83	Fission		2.4h	4
Rb-88	Fission		18 min	4
Sr-89	Fission		50.5 d	1
Sr-90	Fission		29.1 y	2, 9
Y-90		Serial decay product of Sr-90	64 h	2, 9
Sr-91	Fission		9.6 h	4
Y-91m	Fission		50 min	4
Sr-92	Fission		2.7 h	1
Y-92	Fission		3.5 h	1
Y-93	Fission		10 h	1
Zr-95	Fission		64 d	3
Nb-95	Fission		35 d	3
Zr-97	Fission		17 h	3
Nb-97m	Fission		53 s	3
Mo-99	Fission		66 h	1
Tc-99m	Fission		6.0 h	1
Rh-102m	Fission	Tracer [^{103}Rh(n, 2n)^{102m}Rh]	2.9 y	6
Rh-102	Fission	Tracer [^{103}Rh(n, 2n)^{102}Rh]	284 d	6
Ru-103	Fission		39 d	4
Rh-103m	Fission		56 min	4

TABLE A-4. Radionuclides of Importance Expected in Enewetak Soils, continued.

Radio-nuclide	Source		Half-life	Notes
	Primary	Other (Non-Fission Interactions)		
Ru-105	Fission		35 h	1
Ru-106	Fission		374 d	5
Pd-109	Fission		14 h	4
Ag-112	Fission		3.1 h	4
Cd-115	Fission		53 h	4
Cd-117	Fission		2.5 h	4
In-117m	Fission		2.0h	4
Sn-121	Fission		27 h	4
Sb-125	Fission		2.8 y	5
Sn-127	Fission		2.1 h	4
Sb-127	Fission		3.9 d	1
Te-129	Fission		70 m	4
Sb-129	Fission		4.4 h	1
Te-131m	Fission		30 h	1
I-131	Fission		8.0 d	1
Te-132	Fission		78 h	1
I-132	Fission		2.3 h	1
Te-133m	Fission		55 min	1
I-133	Fission		21 h	1
I-135	Fission		6.6 h	1
Cs-137	Fission		30.2 y	2, 5, 9
Ba-139	Fission		83 min	4
Ba-140	Fission		13 d	1
La-140	Fission		1.7 d	1
La-141	Fission		3.9 h	1
Ce-141	Fission		33 d	4
La-142	Fission		91 min	1
Ce-143	Fission		33 h	1
Pr-143	Fission		14 d	1
Ce-144	Fission		280 d	6
Pr-144	Fission		17 min	6
Pr-145	Fission		6.0 h	1
Nd-147	Fission		11 d	4
Pm-147	Fission		2.62 y	4
Pm-149	Fission		53 h	1
Nd-149	Fission		1.7 h	4
Pm-151	Fission		28 h	4
Sm-151	Fission		90 y	4
Eu-152	Activation		13.6 y	6
Sm-153	Fission		46 h	4

TABLE A-4. Radionuclides of Importance Expected in Enewetak Soils, continued.

Radio-nuclide	Source		Half-life	Notes
	Primary	Other (Non-Fission Interactions)		
Eu-154	Activation		8.8 y	6
Eu-155	Fission		5.0 y	6
Bi-207		Possible neutron activation of ^{209}Bi or (p,d,t,etc.) reactions with Pb [Noshkin et al. (2000)]	32.2 y	6

TABLE A-4. Radionuclides of Importance Expected in Enewetak Soils, continued.
[Compiled in Part from NVO-140, Volume 1 (AEC 1973) & Simon et al. (2010)]

Note	Applicable Radionuclides	Description
1	^{89}Sr, ^{92}Sr, ^{92}Y, ^{93}Y, ^{99}Mo, ^{99m}Tc, ^{105}Rh, ^{127}Sb, ^{129}Sb, ^{131m}Te, ^{132}Te, ^{133m}Te, ^{131}I, ^{132}I, ^{133}I, ^{135}I, ^{140}Ba, ^{140}La, ^{141}La, ^{142}La, ^{143}Ce, ^{149}Pm, ^{143}Pr, ^{145}Pr, ^{239}Np	Acute Intake: radionuclides providing the most significant dose to colon, red bone marrow, stomach, or thyroid from acute intakes to individuals shortly after detonation and fallout deposition in Marshall Islands [from Simon et al. (2010b)]
2	^{55}Fe, ^{60}Co, ^{65}Zn, ^{90}Sr-^{90}Y, ^{137}Cs	Chronic Intake: radionuclides providing the most significant dose to colon, red bone marrow, stomach, or thyroid from chronic intakes to residents of Marshall Islands [from Simon et al. (2010b)]
3	^{132}Te-^{132}I, ^{140}Ba-^{140}La, ^{95}Zr-^{95}Nb, ^{97}Zr-^{97}Nb, ^{97m}Nb, ^{131}I, ^{133}I, ^{135}I	Early Integrated External Dose: important radionuclides providing integrated external dose for individuals on Marshall Islands from fallout deposition within a few hours after detonation [from A. Bouville et al. (2010)] to a month
4	^{64}Cu, ^{77}As, ^{83}Br, ^{88}Rb, ^{91}Sr-^{91}Y-^{91m}Y, ^{103}Ru-^{103m}Ru, ^{109}Pd, ^{112}Ag, ^{115}Cd, ^{117}Cd, ^{117m}I, ^{121}Sn, ^{127}Sn-^{127}Sb, ^{139}Ba, ^{141}Ce, ^{147}Nd, ^{147}Pm, ^{149}Pm, ^{153}Sm, ^{153}Sm, ^{237}U	Short-Lived Radionuclides: radionuclides of short half-life with low exposure impact to individuals compared to other radionuclides described in notes 1, 2, and 3.
5	^{60}Co, ^{137}Cs	Important Contributors to External Dose from Long-Lived Radionuclides: radionuclides of long half-life providing the dominant exposure impact for external radiation to individuals occupying land areas impacted by fallout deposition many years after detonation
6	^{22}Na*, ^{101}Rh*, ^{102m}Rh*, ^{106}Ru-^{106}Rh, ^{125}Sb, ^{133}Ba*, ^{134}Cs*, ^{144}Ce-^{144}Pr, ^{147}Pm, ^{151}Sm, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{207}Bi, ^{226}Ra*, ^{228}Th*, ^{241}Am, ^{235}U	Minor Contributors to External Dose from Long-Lived Radionuclides: radionuclides of long half-life providing small to negligible exposure impact for external radiation to individuals occupying land areas impacted by fallout deposition many years after detonation
7	$^{239+240}$Pu, ^{238}Pu, ^{241}Am	Major Contributors to Intakes from Long-Lived Fissionable Materials: fissionable radionuclides of long half-life providing the dominant intake and dose consequence for individuals occupying land areas impacted by fallout deposition many years after detonation

TABLE A-4. Radionuclides of Importance Expected in Enewetak Soils, continued.
[Compiled in Part from NVO-140, Volume 1 (AEC 1973) & Simon et al. (2010)]

Note	Applicable Radionuclides	Description
8	^{234}U, ^{235}U, ^{236}U, ^{241}Pu	Minor Contributors to Intakes from Long-Lived Fissionable Materials: fissionable radionuclides of long half-life providing small to negligible intake and dose consequence for individuals occupying land areas impacted by fallout deposition many years after detonation
9	^{60}Co, ^{90}Sr-^{90}Y, ^{137}Cs	Primary Contributors to Intakes from Long-Lived Non-Fissionable Materials: activation and fission products of long half-life providing the dominant intake and dose consequence for individuals from fallout in environment many years after detonation
10	^{3}H, ^{14}C, ^{63}Ni	Unimportant Radionuclides: low-energy pure, β-particle emitters that provide insignificant intake and dose consequence and no external radiation exposure

* Identified in a few soil samples reported in NVO-140 (AEC 1973), yet not listed as a radionuclide of interest (^{226}Ra is a naturally-occurring radionuclide in the decay chain of ^{238}U, ^{232}Th is naturally-occurring radionuclide)

TABLE A-5. Nuclear Test Personnel Review Reports Applicable to
Atmospheric Nuclear Weapons Tests in the Marshall Islands.

Operation	Operation Year	Testing Locations	DNA Report	Publication Date
Crossroads	1946	Bikini Atoll	6032F	1 May 84
Sandstone	1948	Enewetak Atoll	6033F	19 Dec 83
Greenhouse	1951	Enewetak Atoll	6034F	15 Jun 83
Ivy	1952	Enewetak Atoll	6036F	1 Dec 82
Castle	1954	Enewetak & Bikini Atolls	6035F	1 Apr 82
Redwing	1956	Enewetak & Bikini Atolls	6037F	1 Aug 82
Hardtack I	1958	Enewetak & Bikini Atolls, Johnston Island, and between Enewetak & Bikini Atolls	6038F	1 Dec 82

Available at: http://www.dtra.mil/Home/Nuclear-Test-Personnel-Review/US-Atmospheric-Nuclear-Test-History-Documents/

TABLE A-6. Long-Lived Fission Products from Nuclear Weapons Tests and Their Decay Characteristics (Subset of Table A-4).

Radio nuclide	Half-Life	Key β-particles/electrons		Key photons (γ-, x-rays)	
		Energy (MeV)	Frequency	Energy (MeV)	Frequency
Sr-90	29.1 y	0.546 (β) max	1.0	None	NA
Y-90*	64 h	2.3 (β) max	~ 1.0	None	NA
Rh-101	3.3 y	0.105 (e^-)	Low	0.127	0.68
		0.124 (e^-)	Low	0.198	0.73
		0.176 (e^-)	Low	0.325	0.12
Rh-102m	3 y			0.475	0.95
				0.632	0.54
				0.698	0.41
				0.767	0.33
				1.047	0.31
Ru-106	370 d	0.039 (β) max	1.0	None	NA
Rh-106*	30 s	2.41 (β) max	0.098	0.512	0.206
		3.03 (β) max	0.082	0.621	0.098
		3.45 (β) max	0.787		
Sb-125	2.8 y	0.095 (β) max	0.136	0.027	0.239
		0.131 (β) max	0.181	0.428	0.293
		0.303 (β) max	0.400	0.463	0.104
		0.622 (β) max	0.135	0.601	0.178
Ba-133	10.5 y	0.044 (e^-)	0.44	0.031	0.96
		0.017 (e^-)	0.11	0.081	0.34
		0.075 (e^-)	0.07	0.276	0.07
				0.303	0.18
				0.356	0.62
				0.384	0.09
Cs-134	2.1 y	0.088 (β) max	0.27	0.569	0.154
		0.701 (β) max	0.66	0.605	0.98
				0.800	0.85
Cs-137	30.2 y	0.512 (β) max	0.95	0.662	0.90
Ce-144	280 d	0.185 (β) max	0.196	0.036	0.044
		0.238 (β) max	0.047	0.134	0.108
		0.318 (β) max	0.772		
Pr-144*	17.3 min	3.0 (β) max	0.98	0.696	0.015
Pr-147	2.62 y	0.225 (β) max	1.0	0.121	0.00003

TABLE A-6. Long-Lived Fission Products from Nuclear Weapons Tests and Their Decay Characteristics (Subset of Table A-4), continued.

Radio nuclide	Half-Life	Key β-particles/electrons		Key photons (γ-, x-rays)	
		Energy (MeV)	Frequency	Energy (MeV)	Frequency
Sm-151	90 y	0.076 (β) max	0.99	0.022	0.0003
Eu-155	5.0 y	0.141 (β) max	0.46	0.086	0.31
		0.159 (β) max	0.26	0.105	0.21
		0.246 (β) max	0.18	0.043	0.12

* In secular equilibrium with ^{106}Ru parent radionuclide

TABLE A-7. Long-Lived Activation Products from Nuclear Weapons Tests and Their Decay Characteristics (Subset of Table A-4).

Radio nuclide	Half-Life	Key β-particles/electrons		Key photons (γ-, x-rays)	
		Energy (MeV)	Frequency	Energy (MeV)	Frequency
H-3	12.4 y	0.0186 (β) max	1.0	None	NA
C-14	5,730 y	0.156 (β) max	1.0	None	NA
Na-22	2.6 y	0.546 (β) max	0.90	0.511	1.80
				1.27	1.0
Fe-55	2.7 y	0.005 (e^-)	0.6	0.006	0.29
Co-60	5.27 y	0.32 (β) max	1.0	1.17	1.0
				1.33	1.0
Ni-63	96 y	0.066 (β) max	1.0	None	NA
Eu-152	13.6 y	0.385 (β) max	0.024	0.040	0.58
		0.696 (β) max	0.136	0.121	0.28
		1.47 (β) max	0.08	0.344	0.26
		0.075 (e^-)	0.20	1.41	0.21
Eu-154	8.8 y	0.247 (β) max	0.28	0.123	0.405
		0.569 (β) max	0.37	0.723	0.197
		0.839 (β) max	0.17	1.00	0.179
		1.84 (β) max	0.11	1.27	0.355
Bi-207	32.2 y	1.05 (e^-)	0.02	0.570	0.98
		0.98 (e^-)	0.07	1.06	0.75
		0.008 (e^-)	0.54	1.77	0.069
				0.075	0.37
				0.073	0.22
				0.085	0.16

TABLE A-8. Primary Radiation Emissions from Plutonium Isotopes and ^{241}Am in WGP.

Radionuclide	Half-life (y)	α-particles		e^- & β-particles		photons	
		E (MeV)	frequency	E (MeV)	frequency	E (MeV)	frequency
^{238}Pu	87.8	5.46	0.28	0.022	0.21	0.014	0.12
		5.50	0.72	0.038	0.08		
^{239}Pu	24,131	5.10	0.12	0.030	0.05	0.014	0.04
		5.14	0.15			0.113	0.005
		5.16	0.73				
^{240}Pu	6,569	5.12	0.26	0.023	0.20	0.014	0.11
		5.17	0.74	0.039	0.07	0.054	0.005
^{241}Pu	14.4	None†		0.021*	1.00	None	
^{242}Pu	376,000	4.86	0.224	0.023	0.160	0.014	0.08
		4.90	0.775	0.039	0.045		
^{241}Am	432	5.39	0.01	0.021	0.15	0.014	0.43
		5.44	0.13	0.027	0.05	0.026	0.02
		5.49	0.85	0.037	0.35	0.060	0.36
				0.054	0.08		

* Maximum energy, average energy = 0.005 MeV † ~0.002% α-particle decay

TABLE A-9. Radiation Emissions from Various Isotopic Forms of Uranium.

Activity Percents			α-emissions		β-emissions		Photons	
U-234	U-235	U-238	Energy (MeV)	Frequency	Energy (MeV)	Frequency	Energy (MeV)	Frequency
15.3	1.1	83.6	4.20	66%	2.28*	82%	0.0926	4.4%
Specific Activity =	4.0 E-07	Ci/g	4.15	18%	0.189	59%	0.0633	3.2%
			4.78	11%	0.096	22%	0.1857	0.6%
Moderately-Depleted Uranium			4.72	4.4%	0.076	2.4%	1.001	0.5%
			4.40	0.6%	0.287	0.5%	0.1128	0.2%
							Th,U, Pa x-rays	> 10 %
							Brems. x-rays*	variable
U-234	U-235	U-238	Energy (MeV)	Frequency	Energy (MeV)	Frequency	Energy (MeV)	Frequency
97	2.94	0.0275	4.78	69%	0.287	1.4%	0.1857	1.6%
Specific Activity =	6.9 E-05	Ci/g	4.72	28%	0.304	1.0%	0.0256	0.4%
			4.22	2.0%	0.205	0.4%	0.143	0.30%
HEU (93.3 %)			4.40	1.7%			0.0915	0.30%
			Others	0.3%			Th,U, Pa x-rays	> 1%
U-234	U-235	U-238	Energy (MeV)	Frequency	Energy (MeV)	Frequency	Energy (MeV)	Frequency
48.9	2.3	48.9	4.20	39%	2.28*	48%	0.0926	2.5%
Specific Activity =	6.8E-07	Ci/g	4.78	35%	0.189	34%	0.0633	4.20%
			4.72	14%	0.096	13%	0.1857	1.22%
Natural Uranium Metal			4.15	10%	0.076	1.4%	0.0256	0.30%
			4.40	1.3%	0.287	1.1%	Th,U, Pa x-rays	> 7 %
			Others	0.7%	0.304	0.8%	Brems. x-rays*	variable

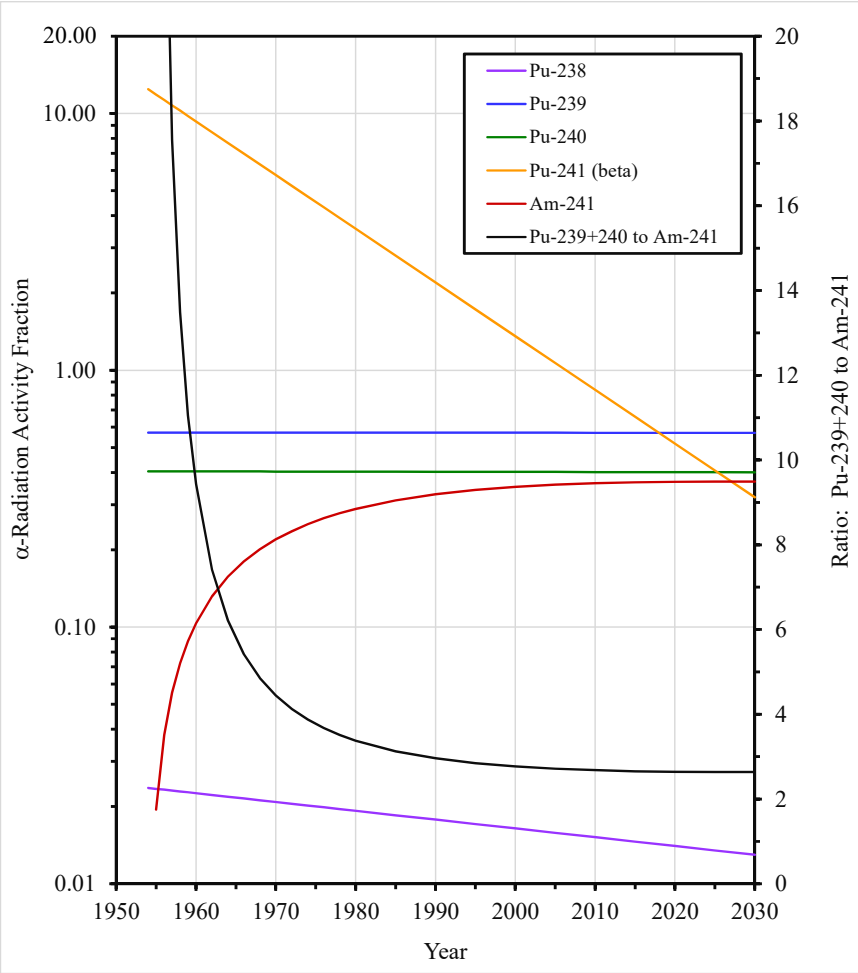


Figure A-9. α-Radiation Activity Fractions for Isotopes of Plutonium and ^{241}Am and the $^{239+240}$Pu to ^{241}Am Activity Concentration Over Time (20% Fission Burn in 1955)

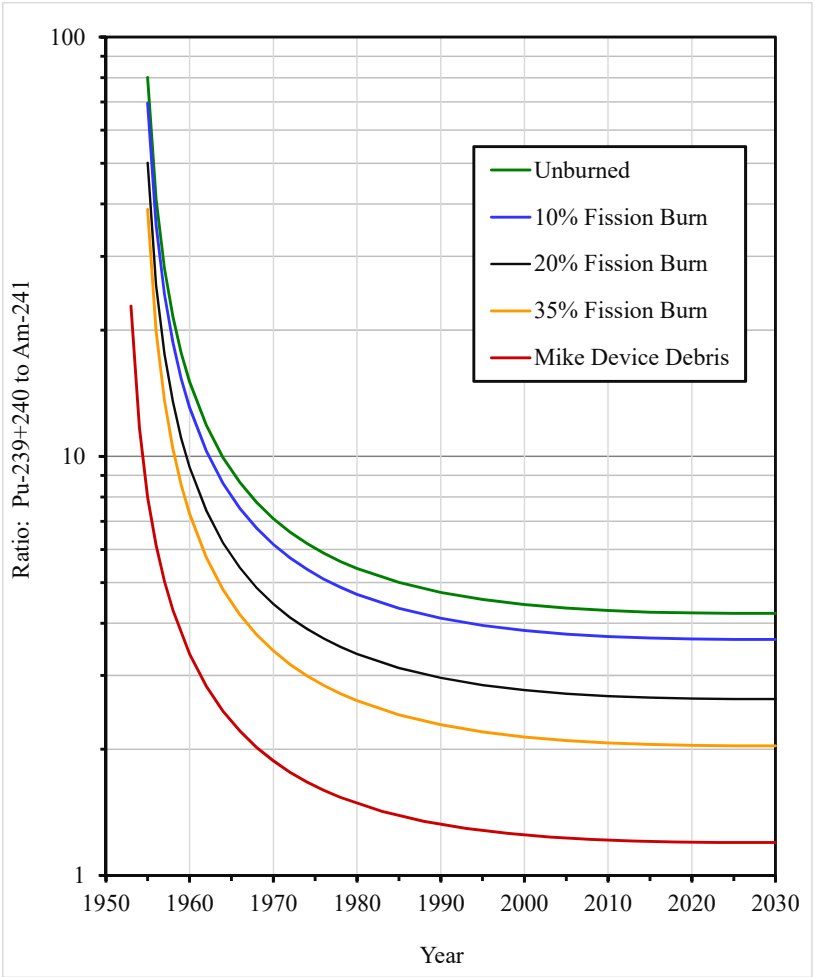


Figure A-10. $^{239+240}$Pu to ^{241}Am Activity Concentration Ratios for Various Isotopic Forms of WGP Over Time, Based on a Nuclear Detonation in 1955 (Mike, 1952).

Appendix B.

Background Information from NVO-140, External Exposure

TABLE B-1. Radiological Exposure Summary Data and Access Restrictions for Islands of Enewetak Atoll for 1977 – 1980 Restoration.

Group	Island Code Name	Local Name	Average Exposure Rate for Islands in Atoll (μR h^{-1} @ 1 meter) [NVO-140, Table 9‡, p. 80]					H+1 h Exposure Rate (R h^{-1})†	Total Events Causing Fallout†	Surface Ground Zero Events	Land Area (hectares)	Controlled Island Access during Restoration (Radiological)	
			^{137}Cs	^{60}Co	Total (0-3 MeV)		Range					Yes/No	Date Controlled Access Removed
					1972	1978§§							
Southern Islands	Sam	Boko	<0.3 (0.2)	< 0.6 (0.11)	< 0.9	< 0.6	0-1	0	--	0	0.5		
	Tom	Munjor	< 0.3 (0.18)	< 0.6 (0.13)	< 0.9	< 0.6	0-1	0	1	0	1		
	Uriah	Inedral	< 0.3 (0.06)	< 0.6 (0.43)	< 0.9	< 0.6	0-1	0	1	0	2		
	Van	--	< 0.3 (0.08)	< 0.6 (0.25)	< 0.9	< 0.6	0-1	0	1	0	3		
	Alvin	Jinedrol	ND (0.06)	< 0.6 (0.25)	< 0.9	< 0.6	0-1	0	2	0	1		
	Bruce	Ananij	0.4 (0.22)	0.8 (0.34)	1.2	0.8	0-1	1.5	4	0	10		
	Clyde	Jinimi	< 0.3 (0.04)	< 0.6 (0.11)	< 0.9	< 0.6	0-1	0	1	0	1		
	David	Japtan	ND (0.21)	ND (0.10)	< 0.9	< 0.6	0-5	1	3	0	32		
	Rex	Jedrol	< 0.3 (0.28)	< 0.6 (0.25)	< 0.9	< 0.6	0-1	0	1	0	2		
	Elmer	Medren	ND (0.19)	ND (0.12)	< 0.9	< 0.9	0-2	2.6	5	0	89		
	Walt	Bokandretok	< 0.3 (0.08)	< 0.6 (0.10)	< 0.9	< 0.6	0-1	NL	NL	0	0.5		
	Fred	Enewetak	ND (0.14)	ND (0.12)	< 0.9	< 0.9	0-1	2.6	4	0	130		
	Glenn	Ikuren	0.4 (0.33)	< 0.6 (0.20)	< 0.9	< 0.7	0-1	11	3	0	17		
	Henry	Mut	< 0.3 (0.14)	< 0.6 (0.20)	< 0.9	< 0.6	0-1	13	3	0	16		
	Irwin	Boken	< 0.3 (0.08)	< 0.6 (0.46)	< 0.9	< 0.6	0-1	19	3	0	12		
	James	Ribewon	< 0.3 (0.08)	2.8	3.0	1.6	0-5	23	3	0	8		
	Keith	Kidrenen	< 0.3 (0.15)	< 0.6 (0.49)	< 0.9	< 0.6	0-2	31	3	0	10		
	Leroy*	Biken	2.8	4.8	7.6	4.7	3-8	235	13	0	5		
Northern Islands	Vera	Alembel	2.8	2	5	3.6	1-6	270	11	0	15	Yes	2 Dec 77
	Wilma	Billae	1	1	2	1.3	1-3	294	13	0	6	Yes	7 Oct 77
	Mack	Unibor	NL	NL	NL	NA	NL	452	10	0	NL		
	Ursula	Lojwa	3	1.8	5	3.6	1-7	651	12	0	16		
	Tilda	Bijire	4	2	6	4.4	2-11	774	17	0	21	Yes	29 Oct 77
	Nancy	Elle	6	5	12	8.5	1-50	1251	7	0	4	Yes	1 Mar 78
	Olive	Aej	6.5	4.5	11	7.7	1-15	1252	12	0	16	Yes	2 Feb 78
	Edna	Bokinwotme	2.8	2.4	6	4.3	5-8	9533	16	0	4	Yes	7 Oct 77

* Included in Southern Island group, though fallout levels higher than others in this group ND = non-detect NL = not listed † Table 11, NVO-140 ‡ mislabeled as Table 114 §§ Estimated

TABLE B-1. Radiological Exposure Summary Data and Access Restrictions for Islands of Enewetak Atoll for 1977 – 1980 Restoration, continued.

Group	Island Code Name	Local Name	Average Exposure Rate for Islands in Atoll (μR h^{-1} @ 1 meter) [NVO-140, Table 9‡, p. 80]					H+1 h Exposure Rate (R h^{-1}) †	Total Events Causing Fallout†	Surface Ground Zero Events	Land Area (hectares)	Restricted Island Access Controls during Restoration (Radiological)	
			^{137}Cs	^{60}Co	Total (0-3 MeV)		Range (1972)					Yes/No	Date Restricted Access Removed
					1972	1978§§							
Northern Islands	Alice	Bololuo	42	36	81	56	4-170	3383	28	0	9	Yes	25 Jul 79
	Belle	Bokombako	61	50	115	80	5-200	3382	25	0	12	Yes	21 Jul 79
	Clara	Kirunu	20	19	42	29.1	5-100	3154	24	0	3	Yes	21 Jul 79
	Daisy	Louj	6.8	14.4	21.3	12.6	5-140	3554	20	0	9	Yes	24 Jul 79
	Percy	Taiwel	2	2	5	3.7	2-11	NL	NL	0	2	Yes	7 Oct 77
	Helen§	Bokaidrikdrik	NL	NL	NL	NA	NL	NL	NL	0	NL	Yes	24 Jul 79
	Irene	Boken	14	63	80	43.9	3-560	6184	24	1	16	Yes	24 Jul 79
	Janet	Enjebi	25	13	40	29.7	2-150	3501	26	3	118	Yes	23 May 79
	Kate	Mujikadrek	11	7	19	13.8	3-22	1753	11	0	6	Yes	23 Jul 79
	Lucy	Kidrinen	6	7	14	9.4	1-20	1776	10	0	8	Yes	21 Jul 79
	Mary	Bokenelab	2	2	5	3.7	2-12	2785	18	0	5	Yes	7 Oct 77
	Pearl	Lujor	12	45	70	44	1-400	4329	13	1	22	Yes	25 Jul 79
	Ruby	Elleron	2	12	14	7.2	1-42	10643	16	2	2	Yes	21 Jul 79
	Sally	Aomon	3.5	3	7	4.9	3-110	1981	16	3	40	Yes	23 May 79
	Yvonne	Runit	5.6	22.4	33††	20.1	1-750	62849	24	8	37	Yes	Not Removed

ND = non-detect NL = not listed † Table 11, NVO-140 †† Primary additional contributions from ^{241}Am ‡ ‡ mislabeled as Table 114 § Mostly destroyed by Seminole, remainder considered part of Irene §§ Estimated

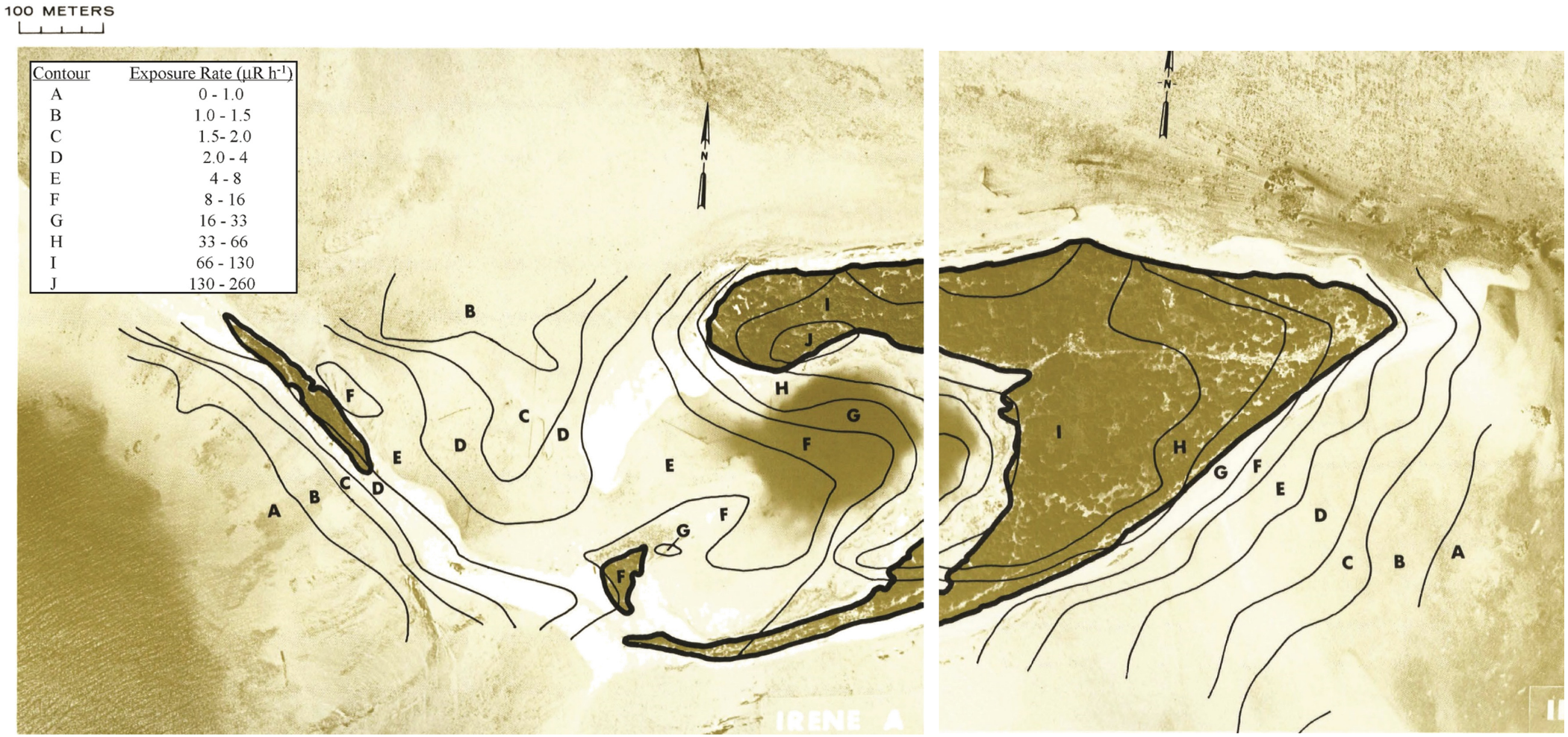


Figure B-1. Gross Count Rate Isoexposure Contours for Irene from Aerial Survey, Composited from Figures B.6.1.b and B.7.1.b NVO-140 (AEC 1973b).

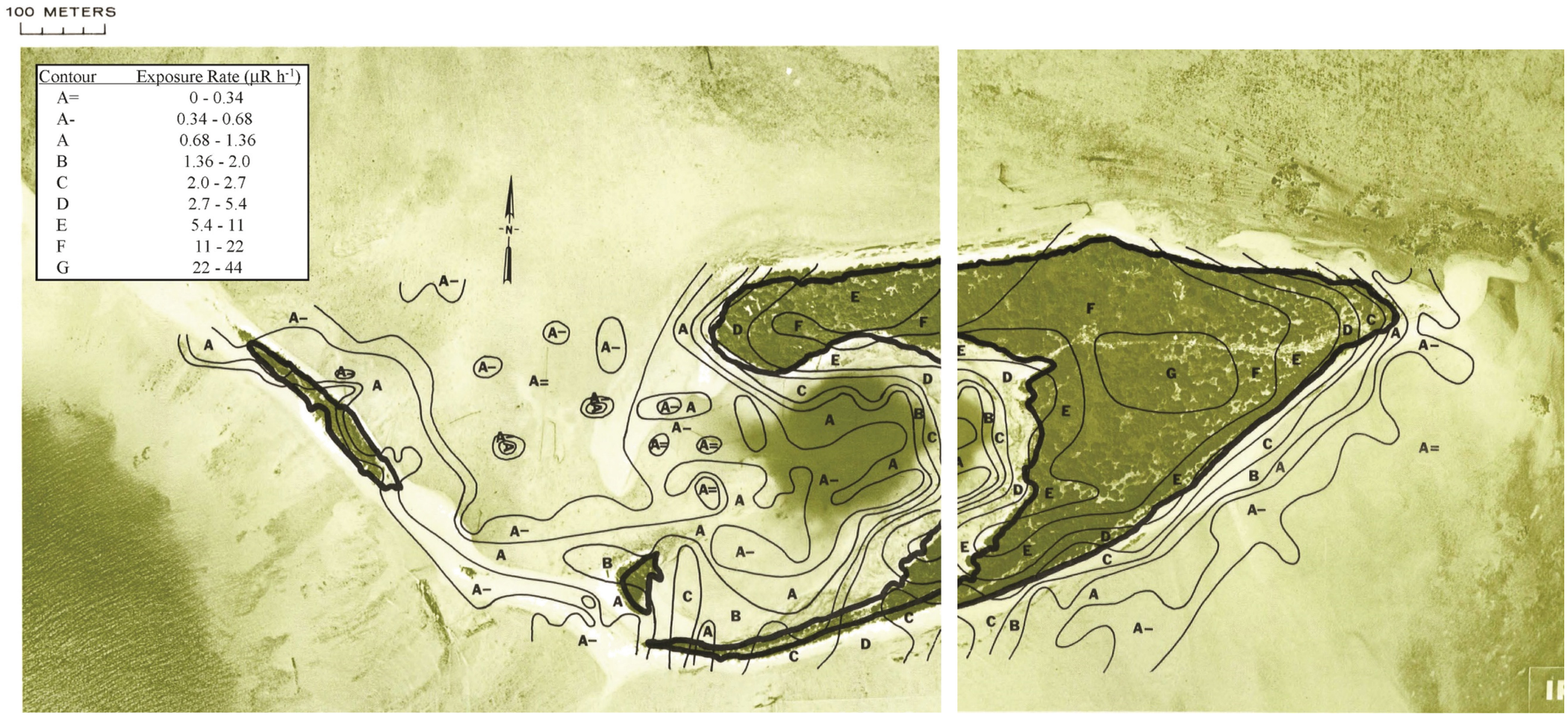


Figure B-2. ^{137}Cs Isoexposure Contours for Irene from Aerial Survey, Composited from Figures B.6.1.k and B.7.1.k NVO-140 (AEC 1973b).

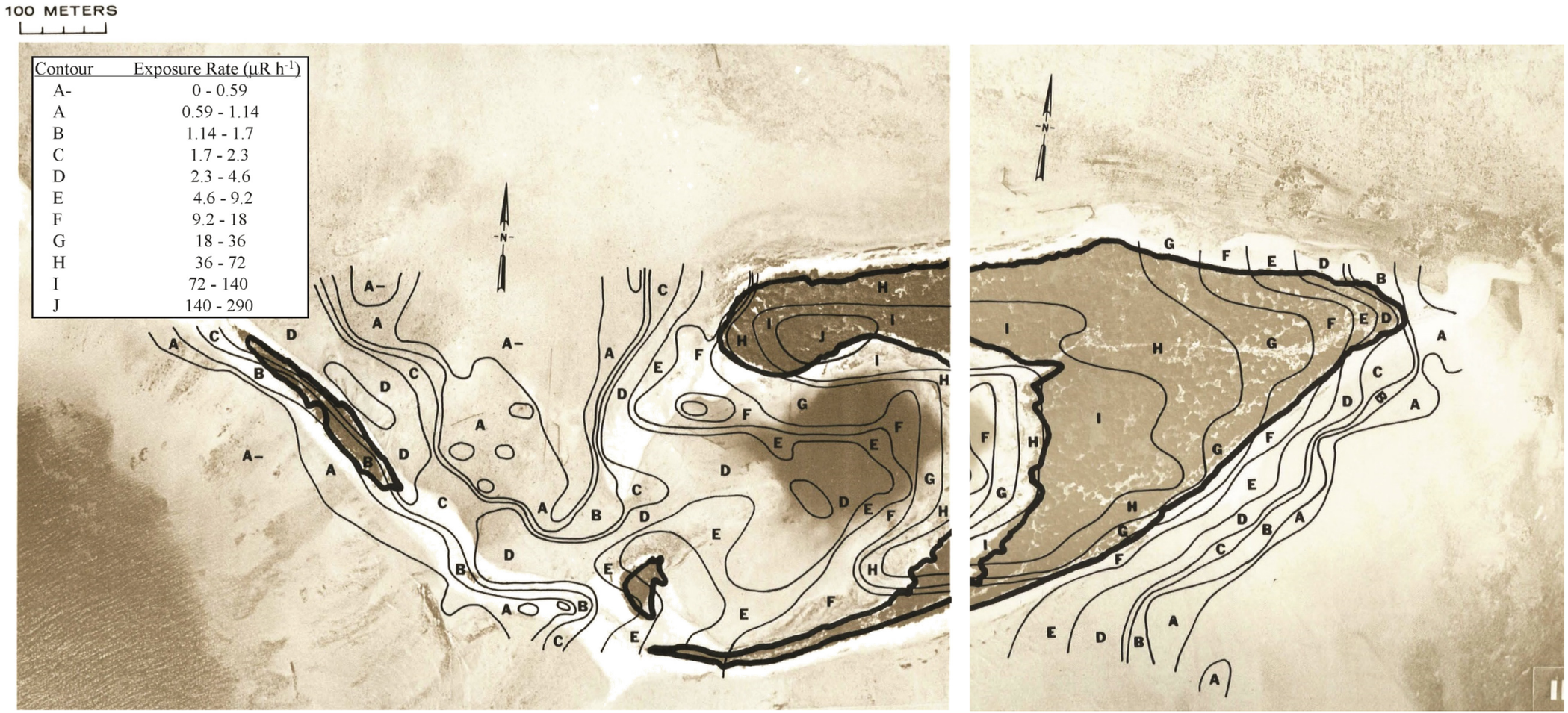


Figure B-3. ^{60}Co Isoexposure Contours for Irene from Aerial Survey, Composited from Figures B.6.1.m and B.7.1.m NVO-140 (AEC 1973b).

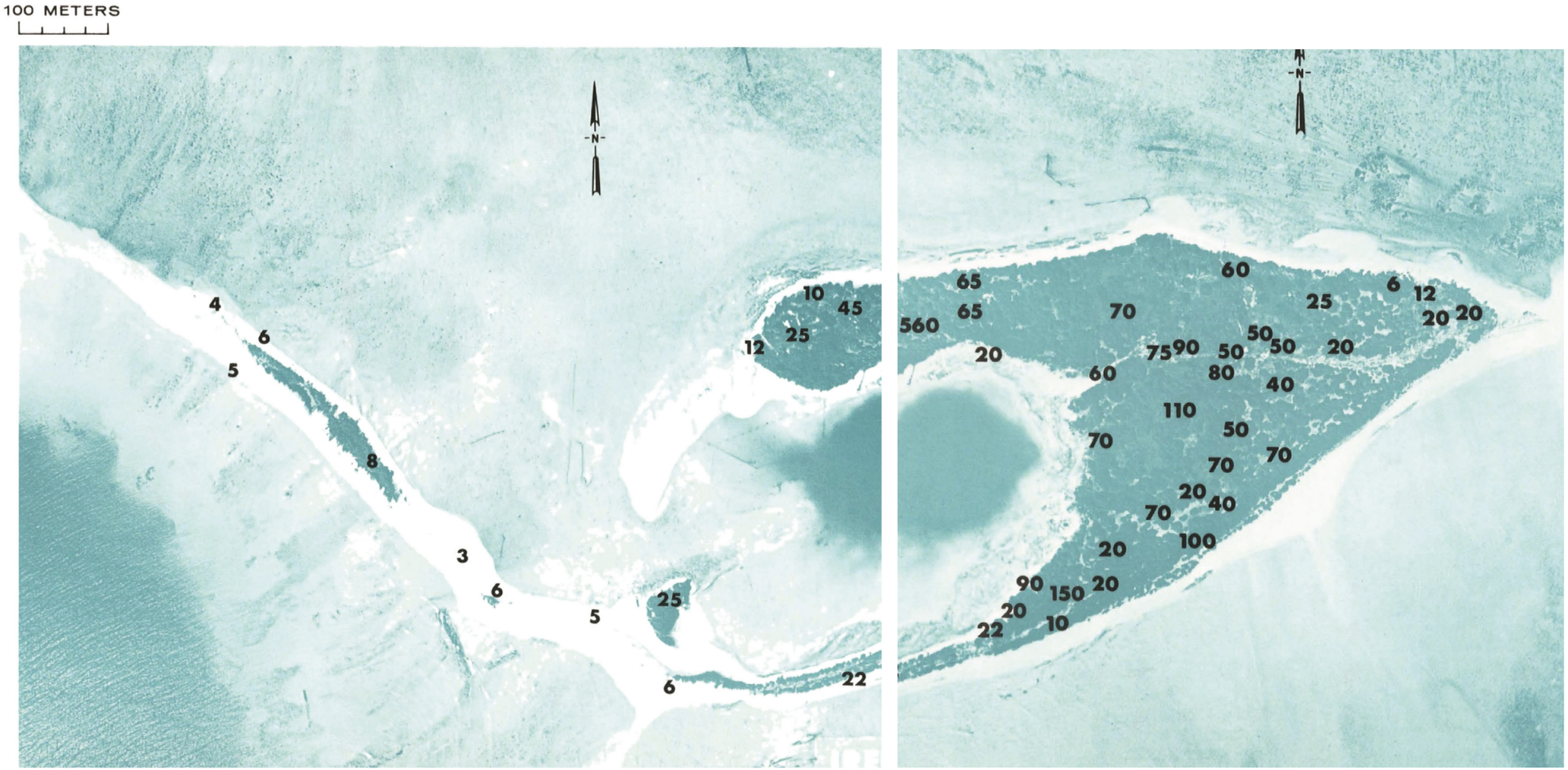


Figure B-4. Fixed Radiation Exposure Measurements at 1 m above Ground for Irene, Composited from Figures B.6.1.d and B.7.1.d NVO-140 (AEC 1973b).

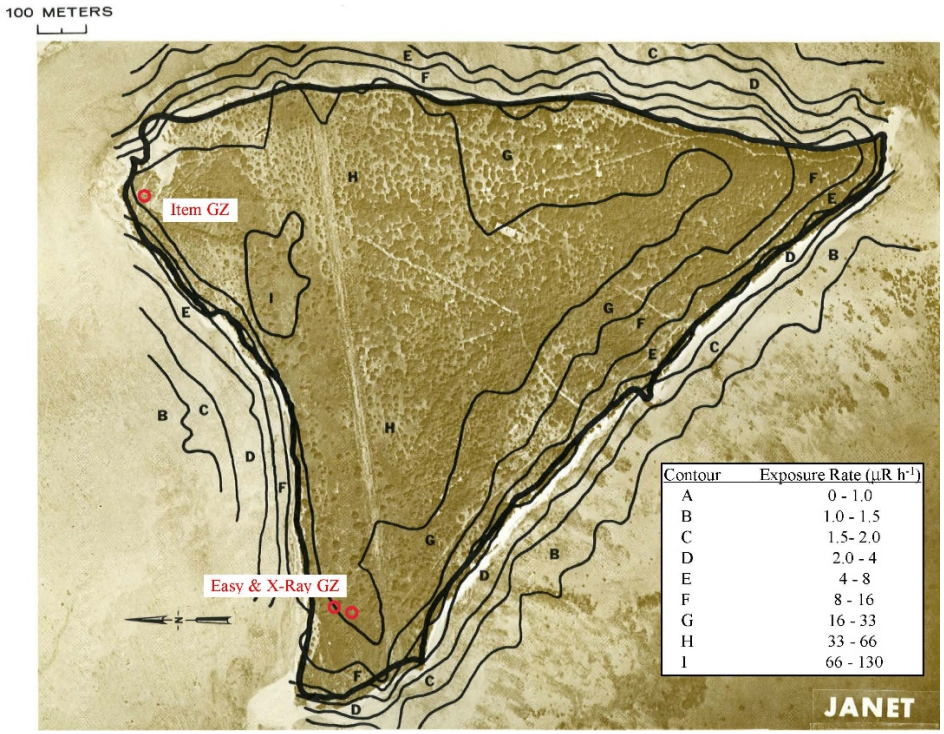


Figure B-5. Gross Count Rate Isoexposure Contours for Janet from Aerial Survey, Figure B.8.1.b NVO-140 (AEC 1973b).

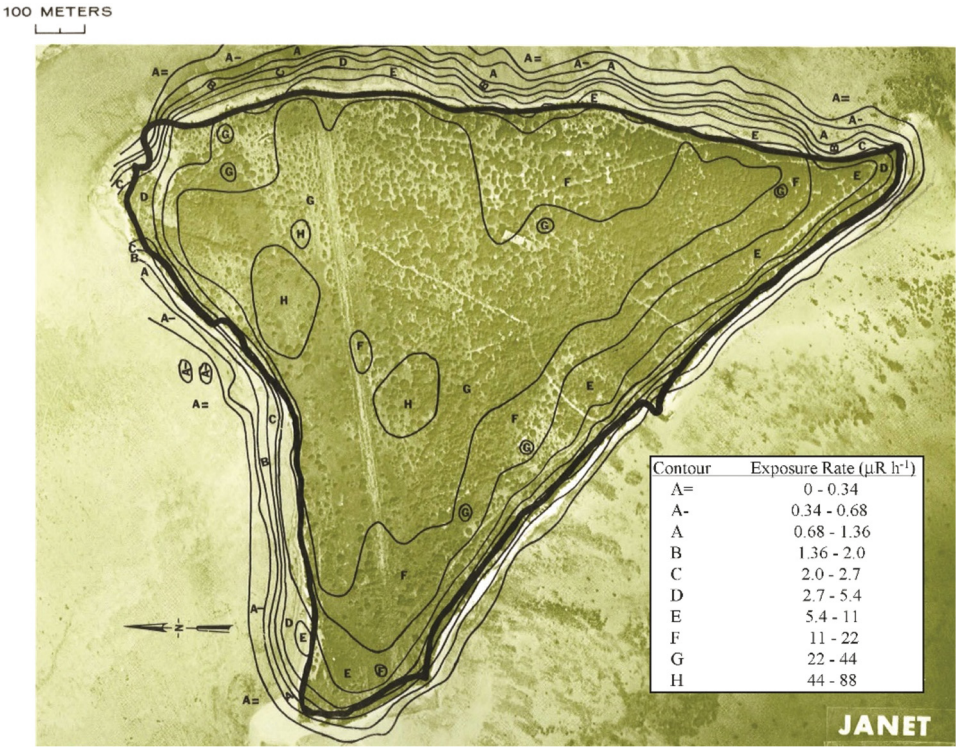


Figure B-6. ^{137}Cs Isoexposure Contours for Janet from Aerial Survey, Figure B.8.1.k NVO-140 (AEC 1973b).

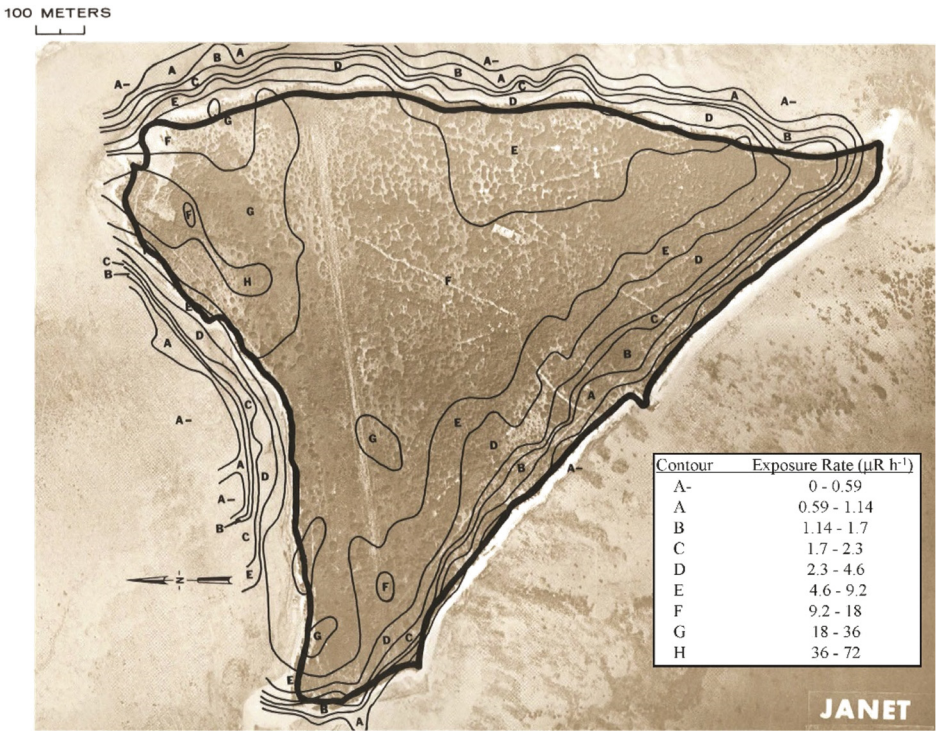


Figure B-7. ^{60}Co Isoexposure Contours for Janet from Aerial Survey, Figure B.8.1.m NVO-140 (AEC 1973b).

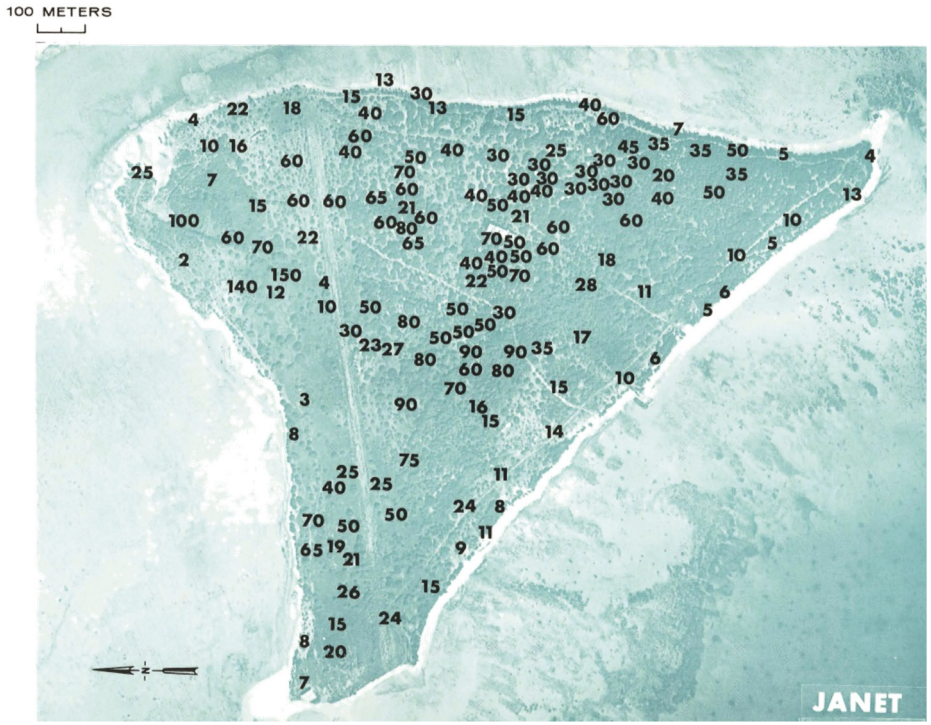


Figure B-8. Fixed Radiation Exposure Measurements at 1m above Ground for Janet, Figure B.8.1.d NVO-140 (AEC 1973b).

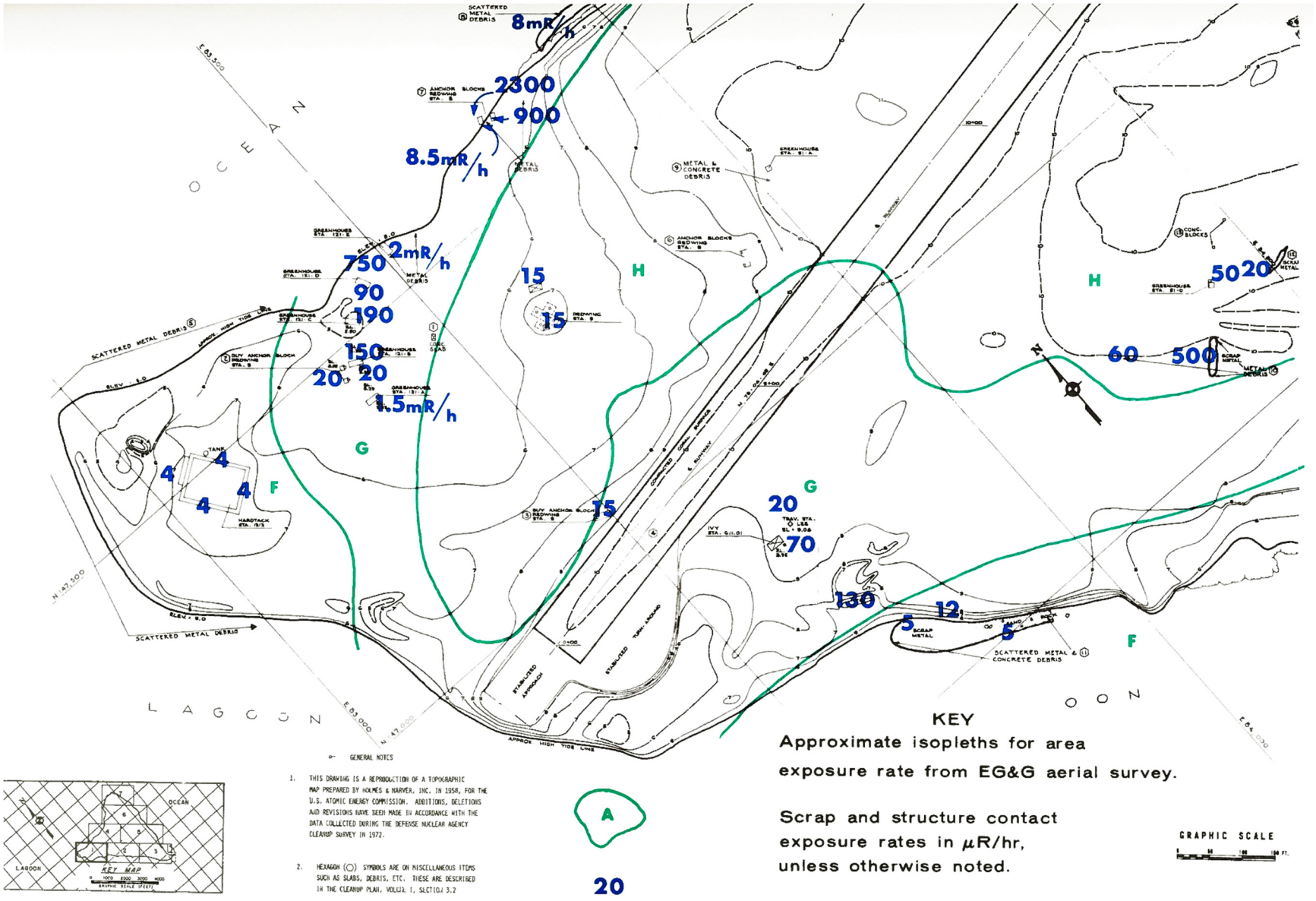


Figure B-9. Figure 97 from NVO-140, *Scrap and Structure Radiation Measurements, Janet,* NE Segment [1 of 7] (AEC 1973a).

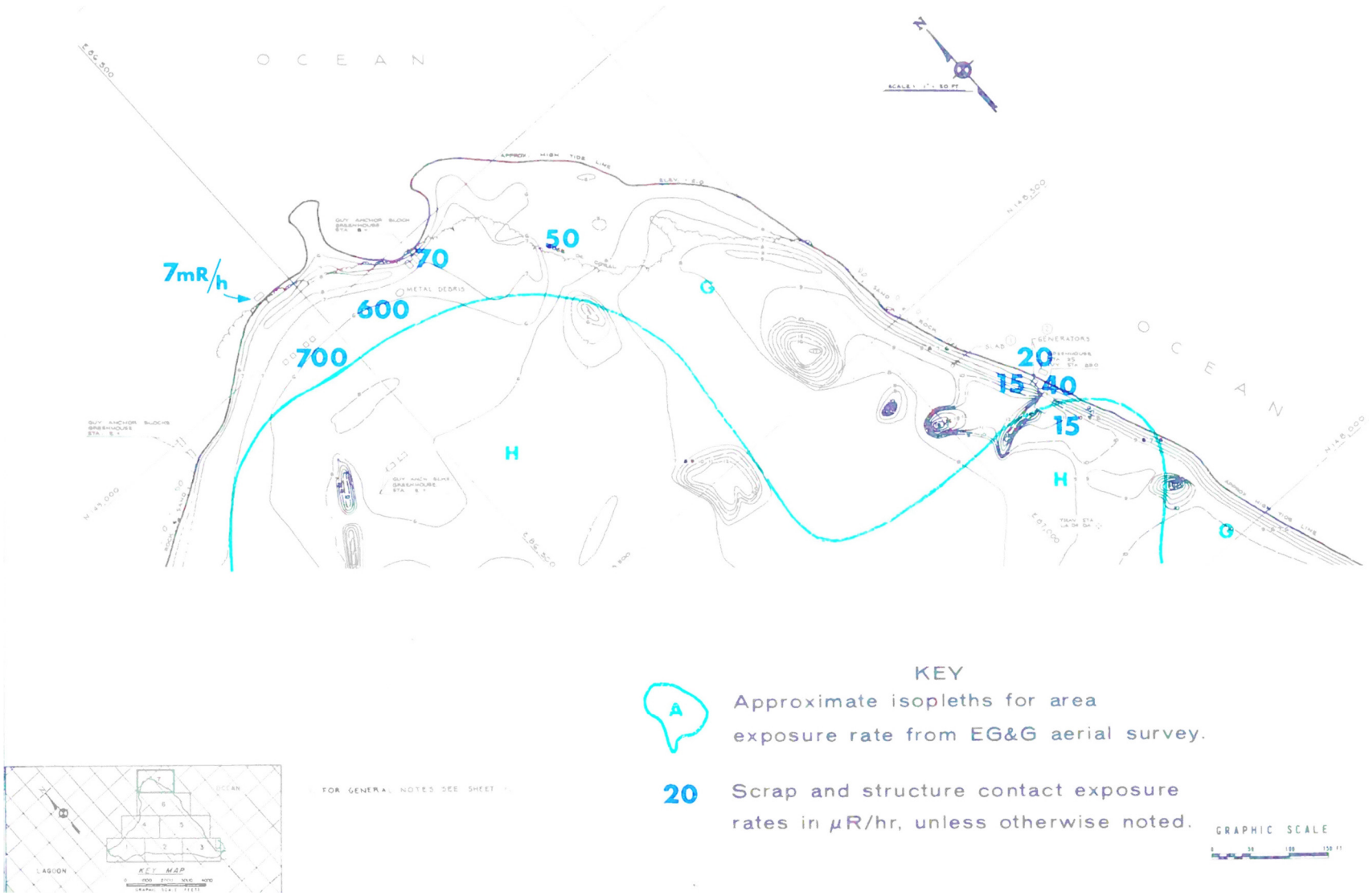


Figure B-10. Figure 103 from NVO-140, *Scrap and Structure Radiation Measurements, Janet,* NW Segment [7 of 7] (AEC 1973a).

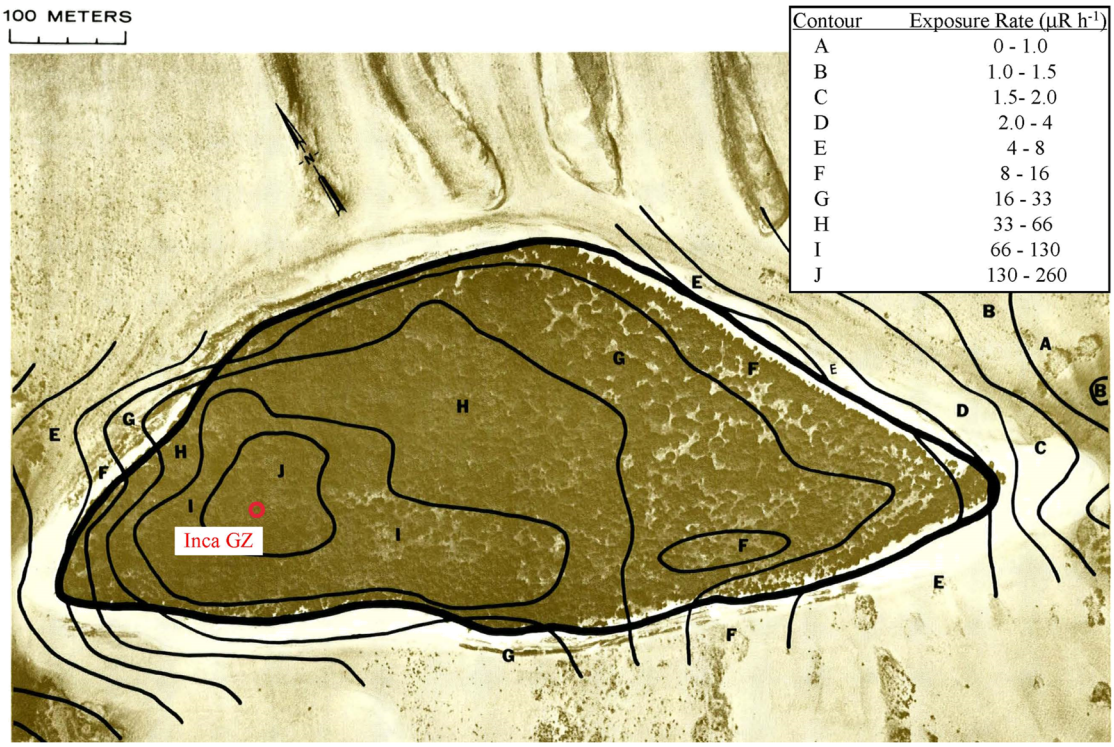


Figure B-11. Gross Count Rate Isoexposure Contours for Pearl from Aerial Survey, Figure B.15.1.b NVO-140 (AEC 1973b).

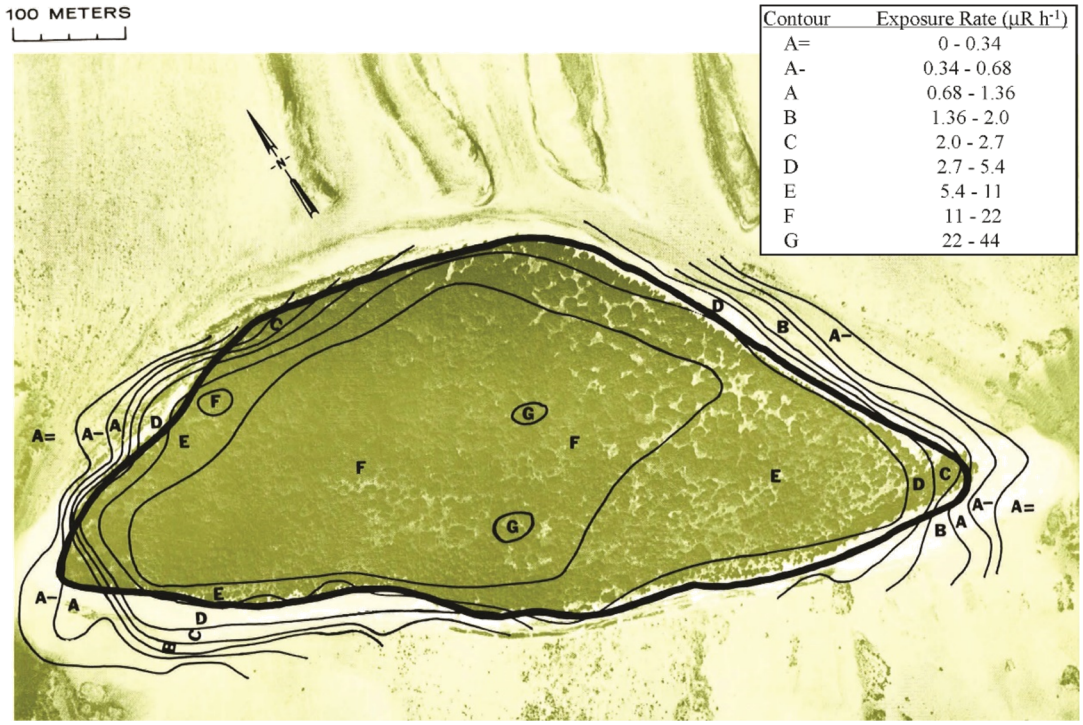


Figure B-12. ^{137}Cs Isoexposure Contours for Pearl from Aerial Survey, Figure B.15.1.k NVO-140 (AEC 1973b).

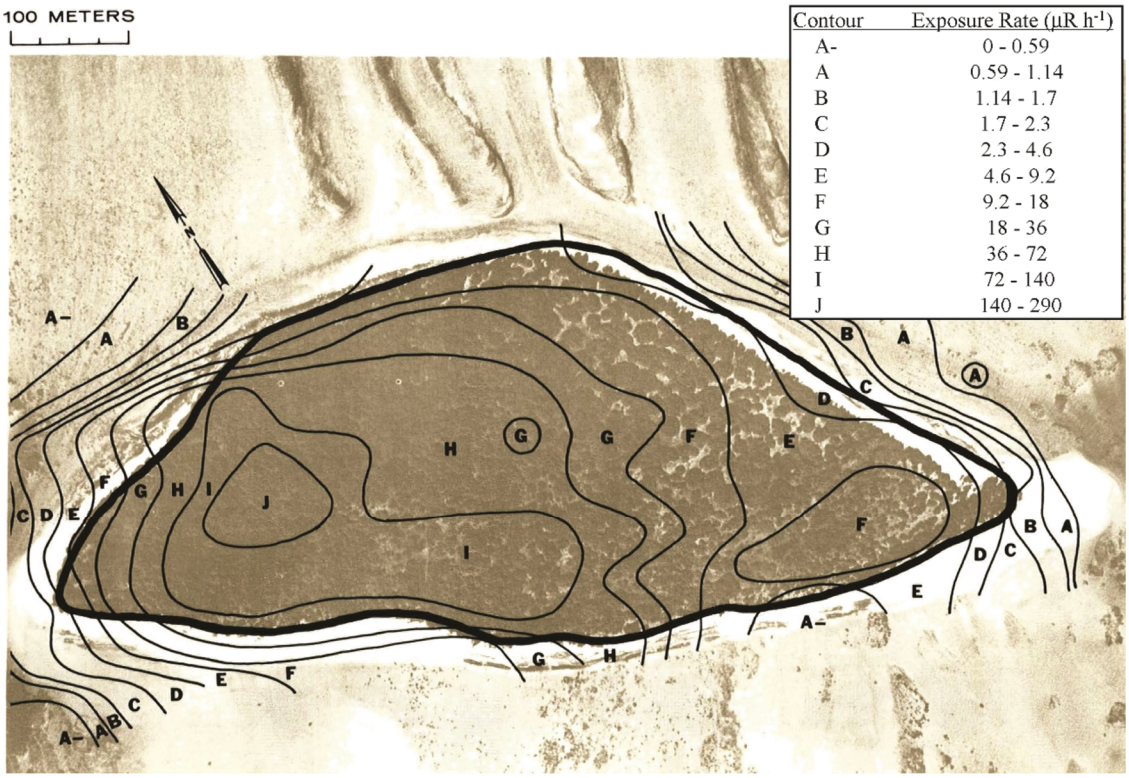


Figure B-13. ^{60}Co Isoexposure Contours for Pearl from Aerial Survey, Figure B.15.1.m NVO-140 (AEC 1973b).

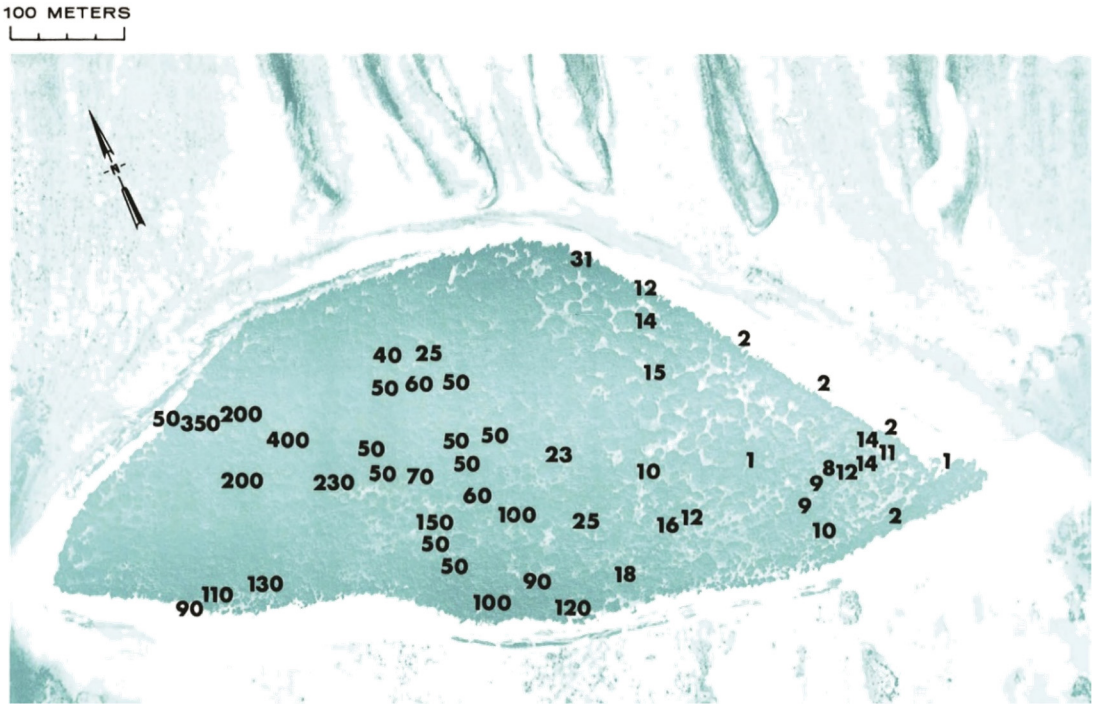


Figure B-14. Fixed Radiation Exposure Measurements at 1m above Ground for Pearl, Figure B.15.1.d NVO-140 (AEC 1973b).

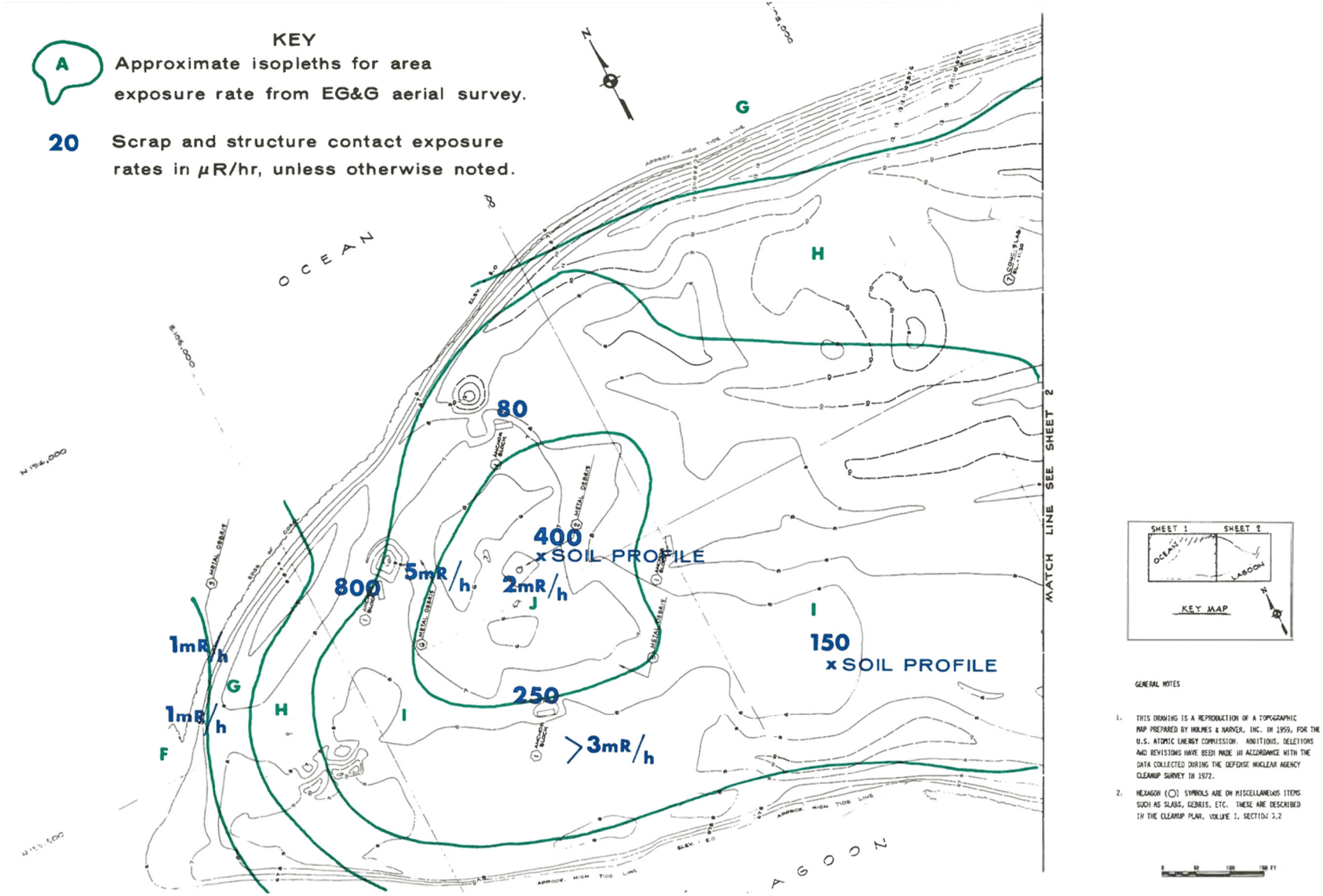


Figure B-15. Figure 104 from NVO-140, *Scrap and Structure Radiation Measurements, Pearl,* West Segment [1 of 2] (AEC 1973a).

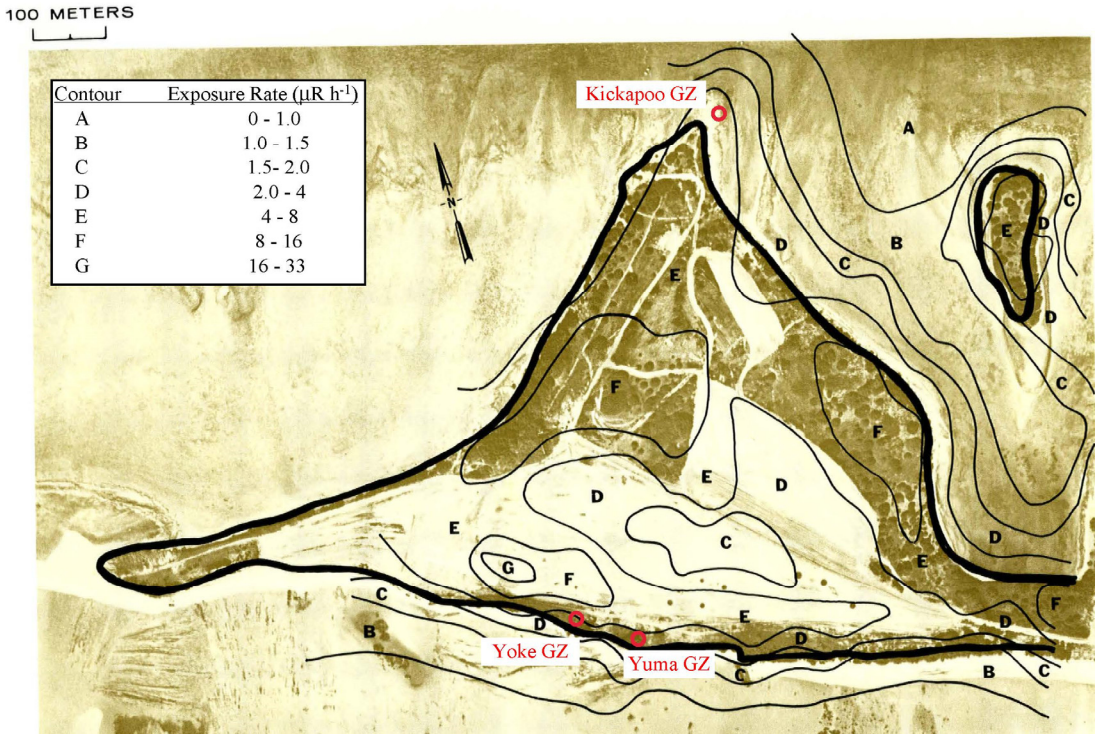


Figure B-16. Gross Count Rate Isoexposure Contours for Sally from Aerial Survey, Figure B.17.1.b NVO-140 (AEC 1973b).

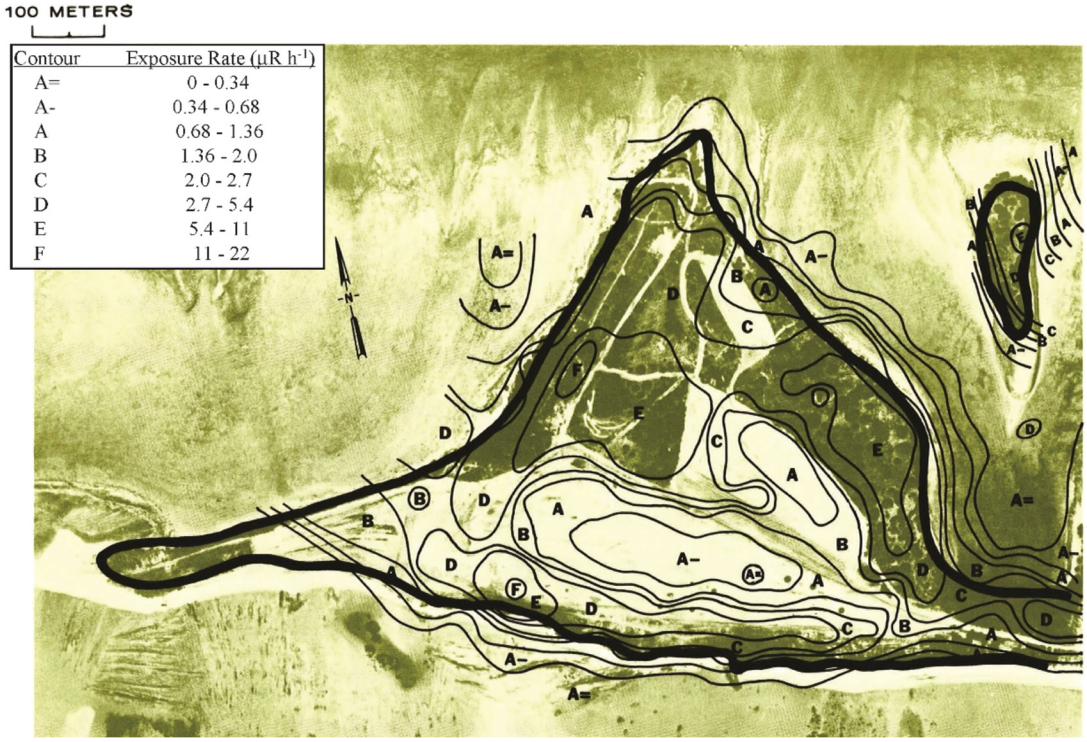


Figure B-17. ^{137}Cs Isoexposure Contours for Sally from Aerial Survey, Figure B.17.1.k NVO-140 (AEC 1973b).

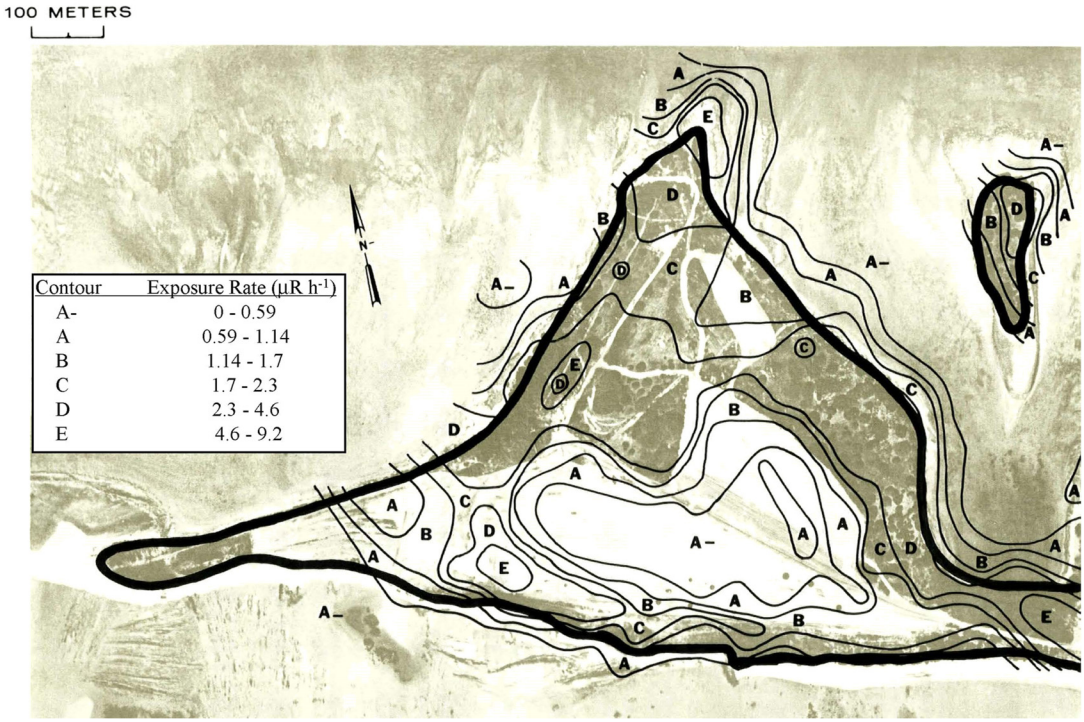


Figure B-18. ^{60}Co Isoexposure Contours for Sally from Aerial Survey, Figure B.17.1.m NVO-140 (AEC 1973b).

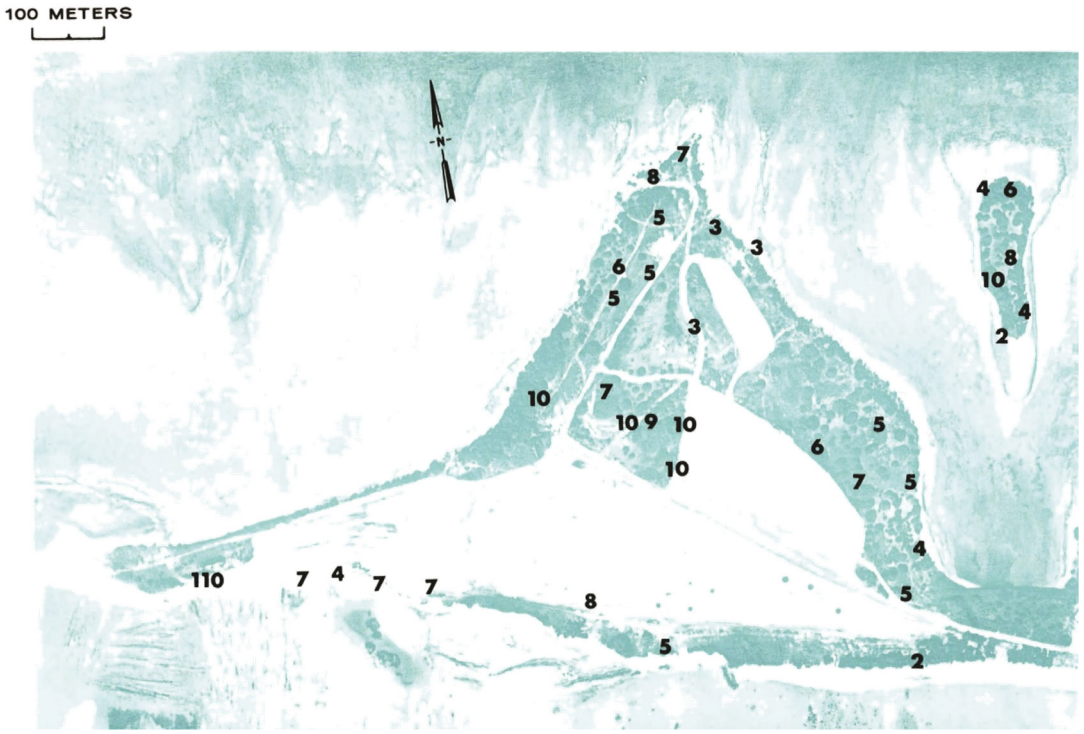


Figure B-19. Fixed Radiation Exposure Measurements at 1m above Ground for Sally, Figure B.17.1.d NVO-140 (AEC 1973b).

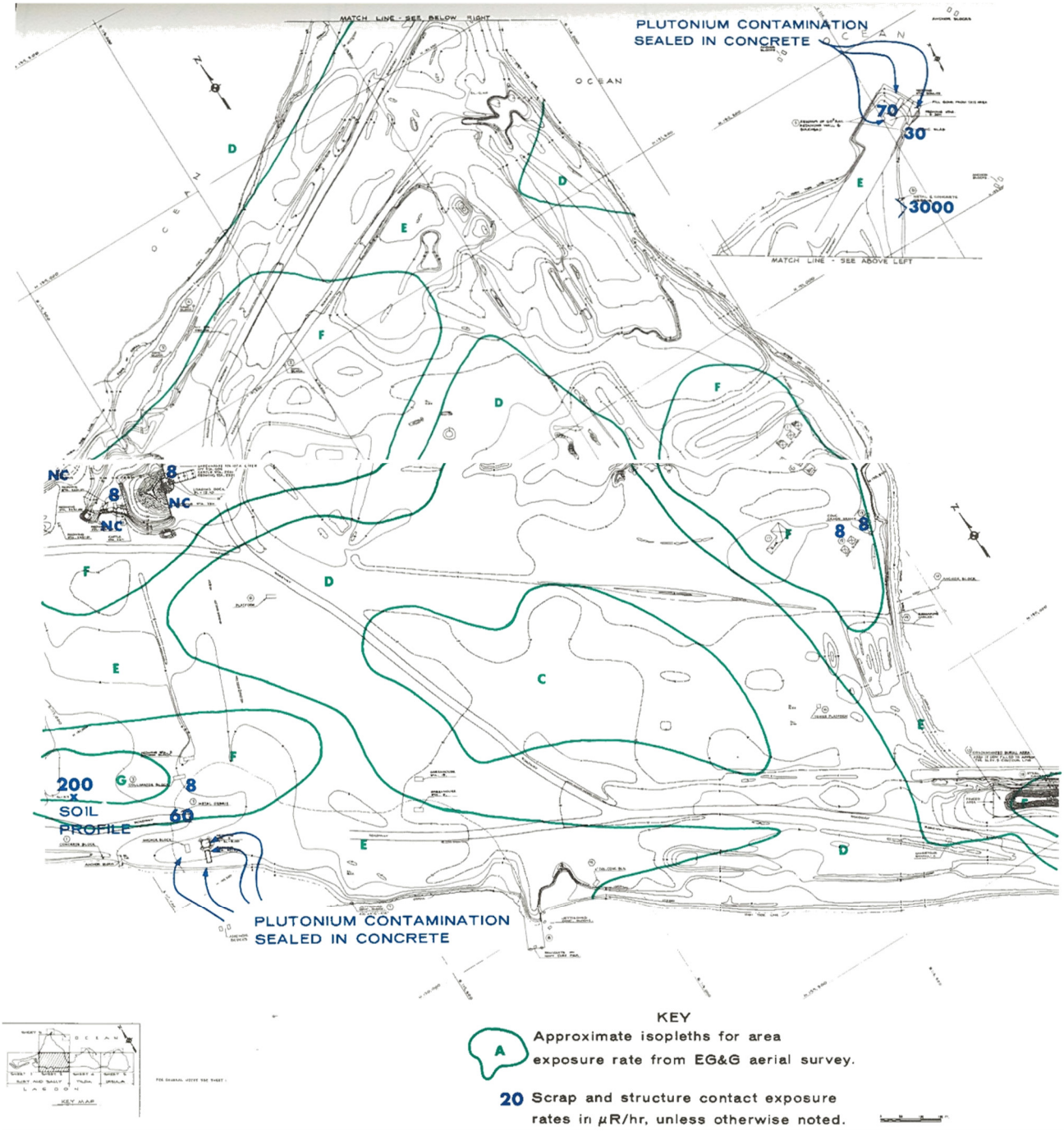


Figure B-20. Figures 107 & 108 from NVO-140, *Scrap and Structure Radiation Measurements, Sally,* North Segment [2 of 2] (AEC 1973a).

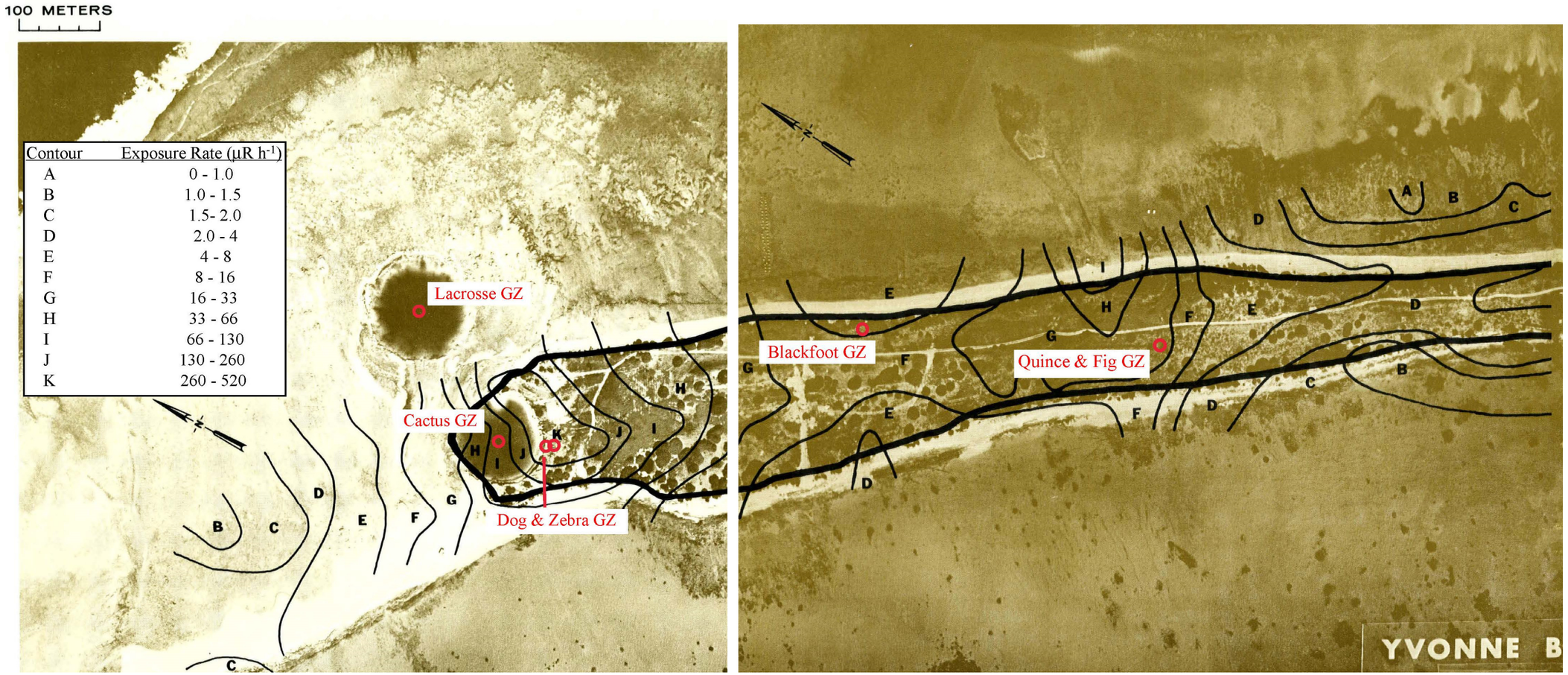


Figure B-21. Gross Count Rate Isoexposure Contours from Aerial Survey, Composited from Figures B.22.1.b and B.23.1.b NVO-140, Northern Region Yvonne (AEC 1973b/c).

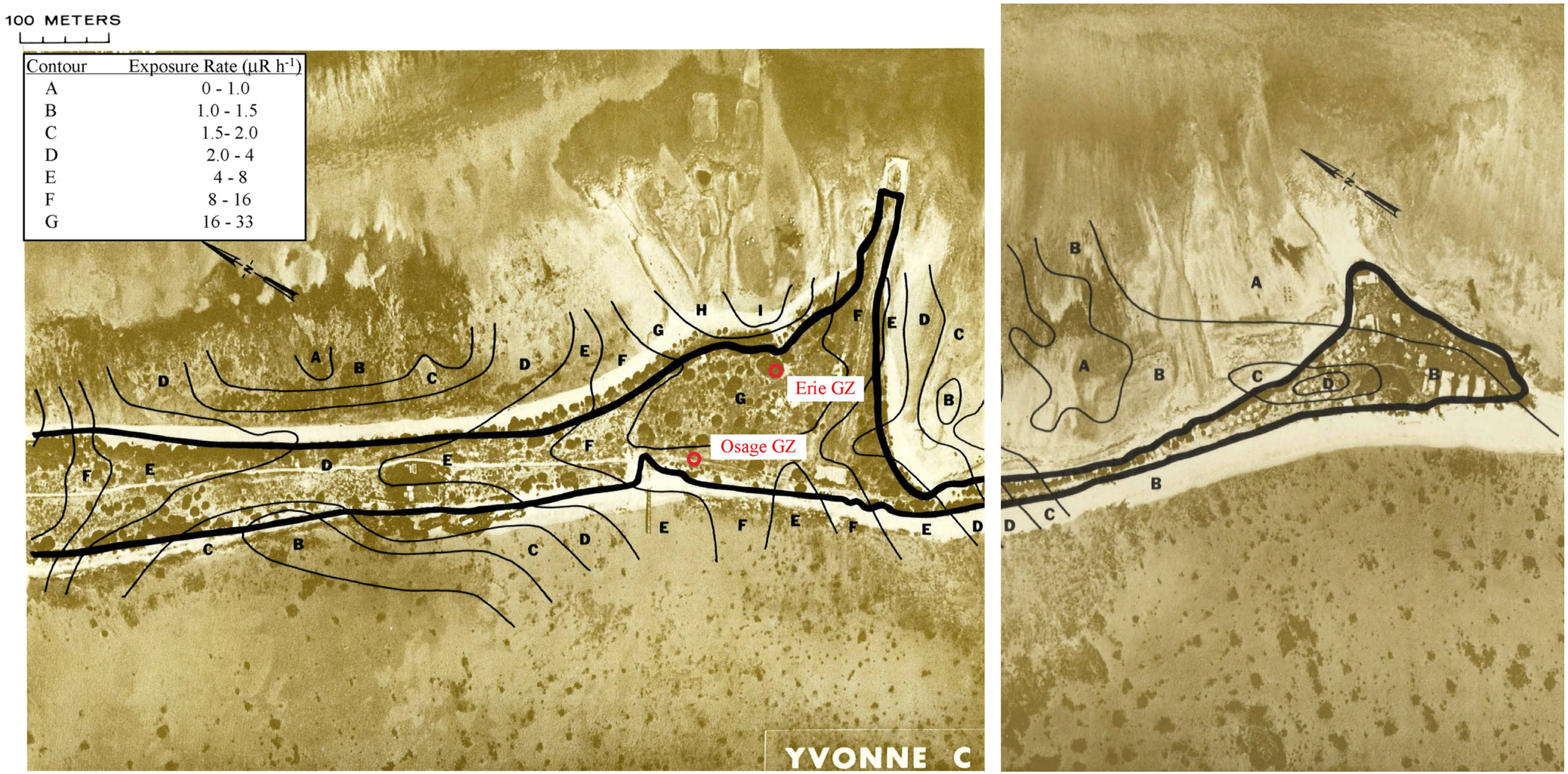


Figure B-22. Gross Count Rate Isoexposure Contours from Aerial Survey, Composited from Figures B.24.1.b and B.25.1.b NVO-140, Southern Region (AEC 1973c).

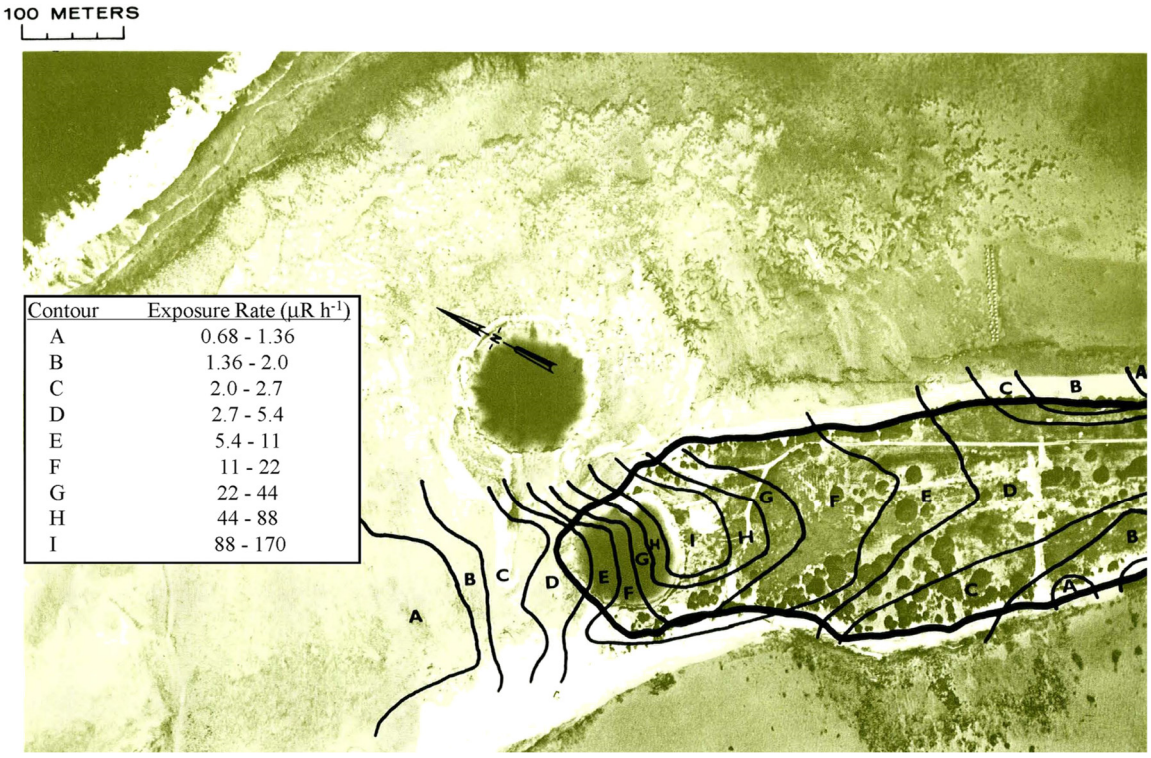


Figure B-23. ^{137}Cs Isoexposure Contours for Yvonne from Aerial Survey, Figure B.22.1.k NVO-140, Northern Region (AEC 1973b).

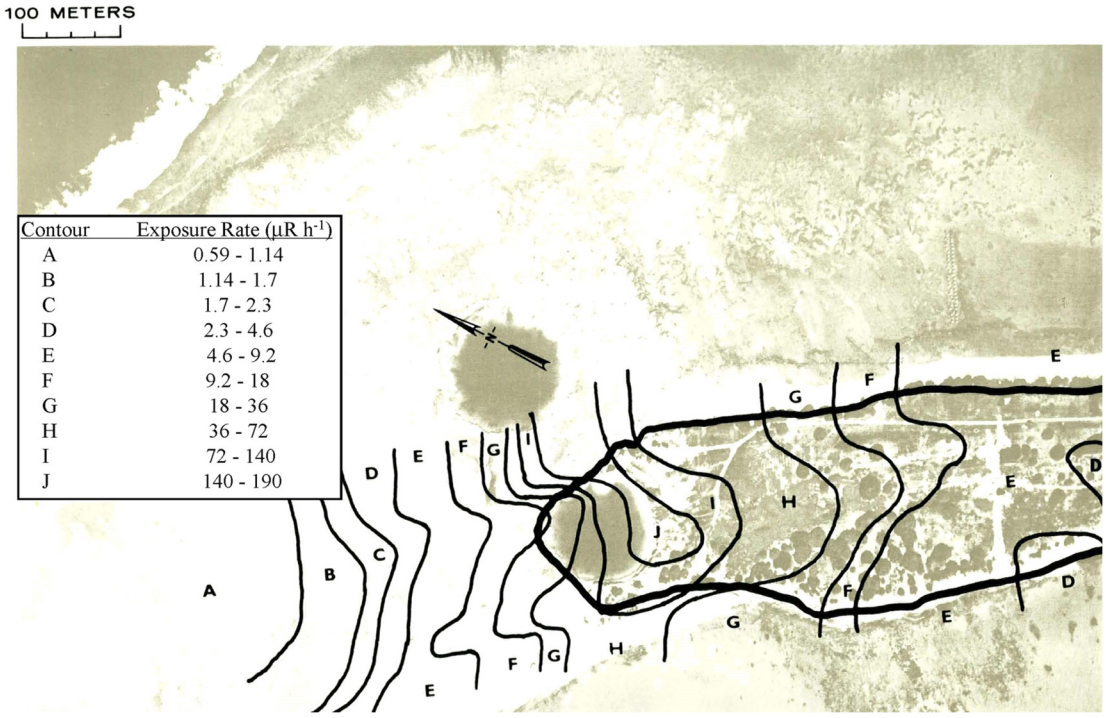


Figure B-24. ^{60}Co Isoexposure Contours for Sally from Aerial Survey, Figure B.22.1.m NVO-140, Northern Region (AEC 1973b).

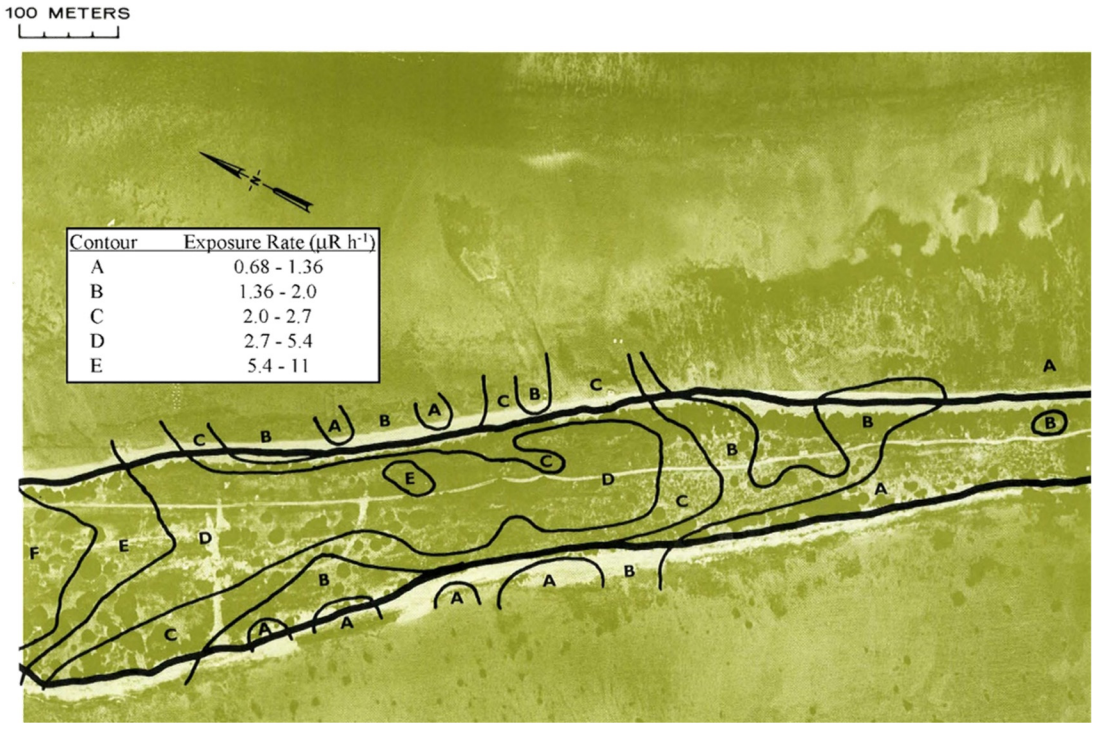


Figure B-25. ^{137}Cs Isoexposure Contours for Yvonne from Aerial Survey, Figure B.23.1.k NVO-140, North-Central Region (AEC 1973c).

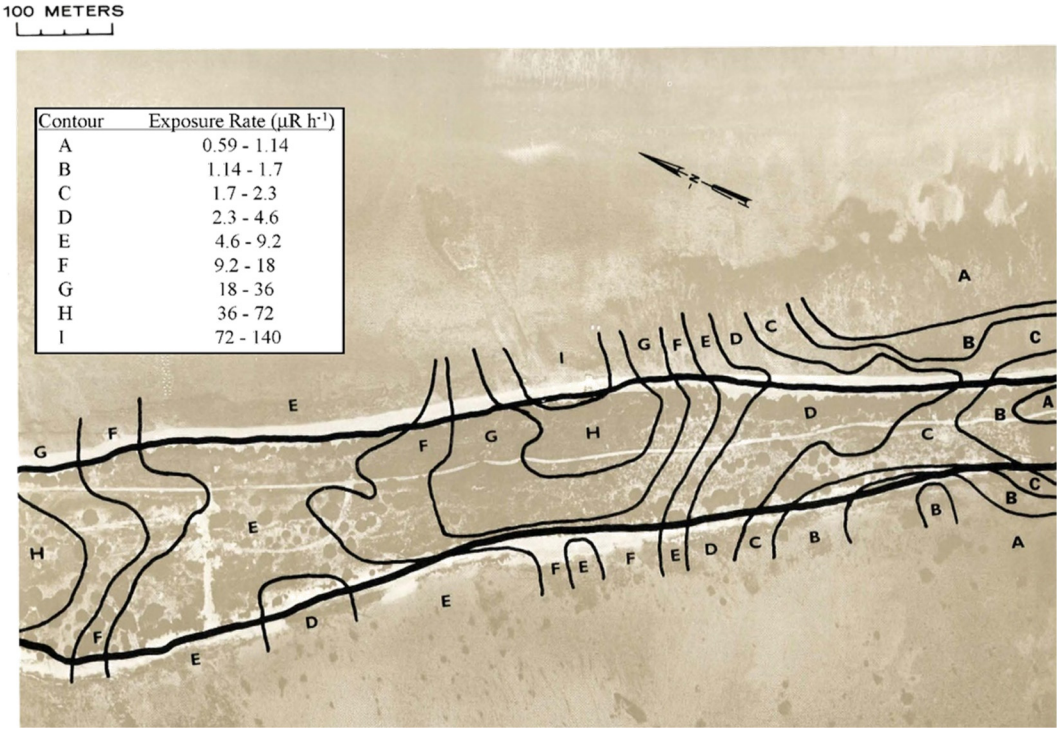


Figure B-26. ^{60}Co Isoexposure Contours for Yvonne from Aerial Survey, Figure B.23.1.m NVO-140, North-Central Region (AEC 1973c).

Figure B-27. ^{137}Cs Isoexposure Contours for Yvonne from Aerial Survey, Figure B.24.1.k NVO-140, Central-South Region (AEC 1973c).

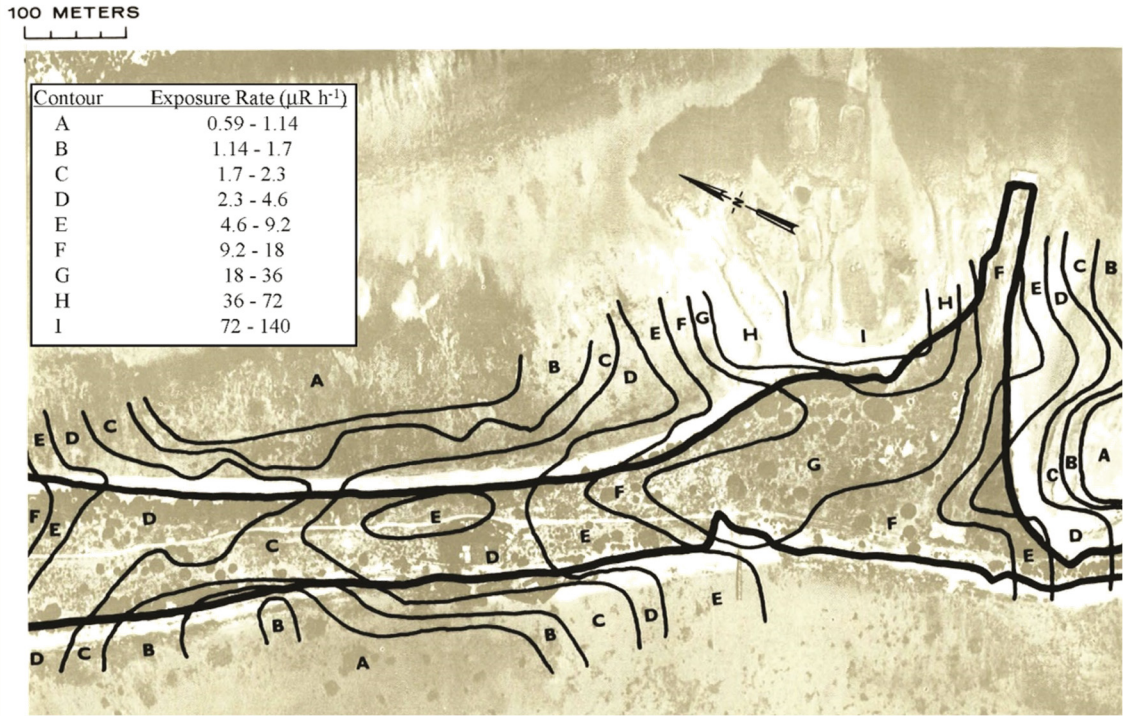


Figure B-28. ^{60}Co Isoexposure Contours for Yvonne from Aerial Survey, Figure B.24.1.m NVO-140, Central-South Region (AEC 1973c).

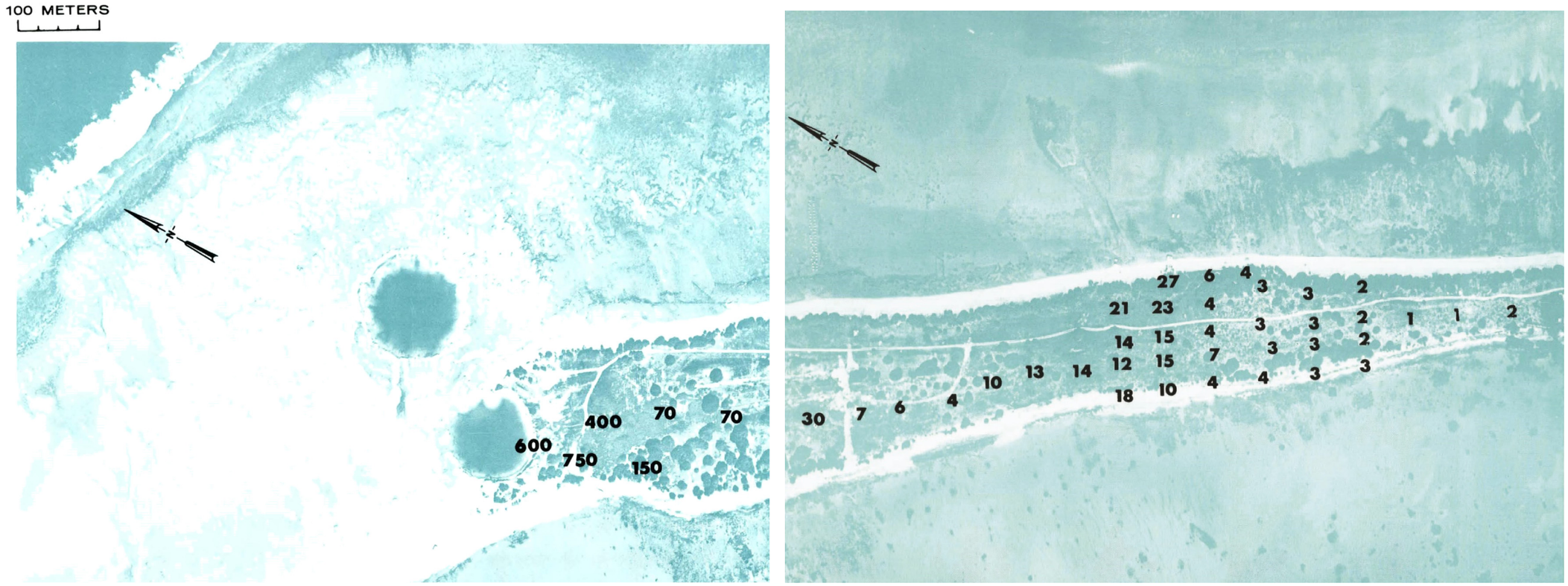


Figure B-29. Fixed Radiation Exposure Measurements at 1m above Ground, Composited from Figures B.22.1.d and B.23.1.d, Northern Region Yvonne, NVO-140 (AEC 1973b).

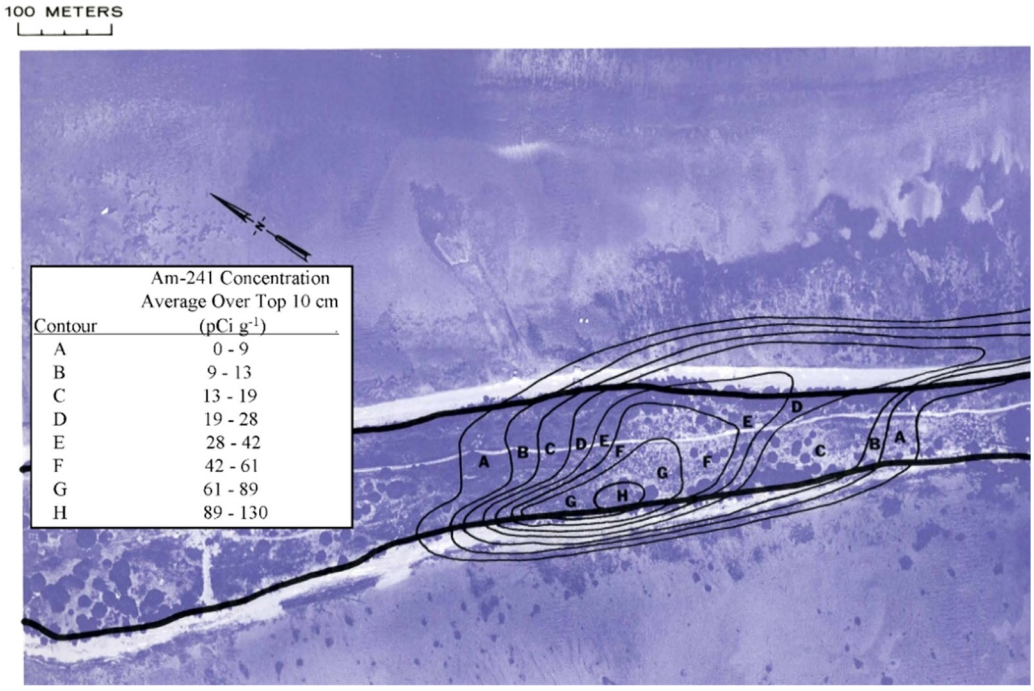


Figure B-30. ^{241}Am Isoconcentration Contours for Yvonne from Aerial Survey, Figure B.23.1.m NVO-140, North-Central Region (AEC 1973c).

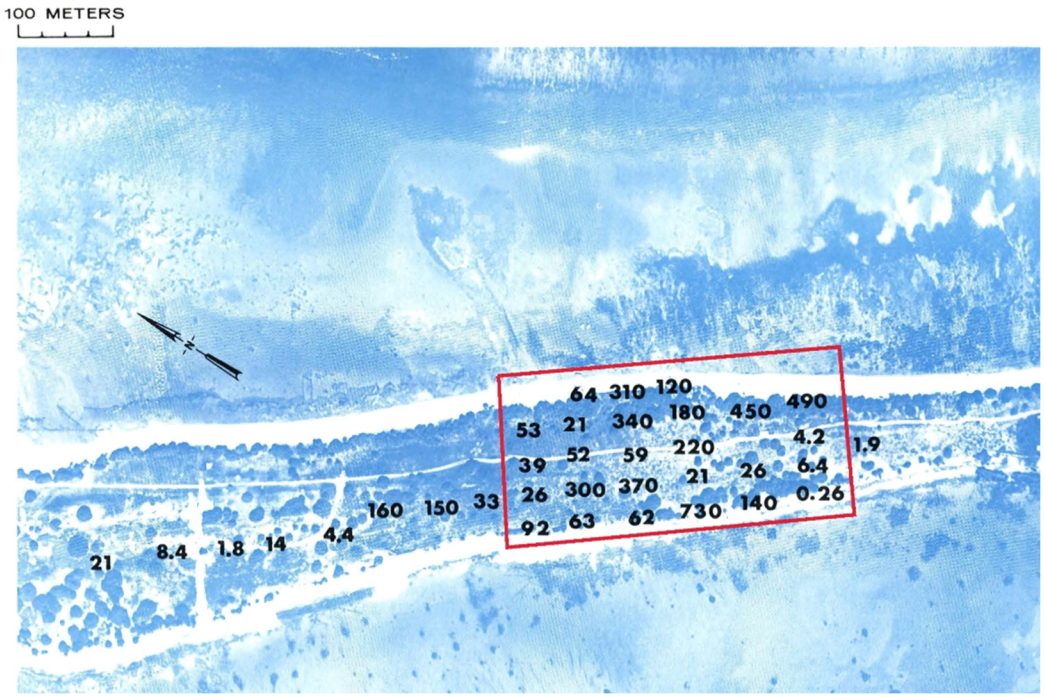


Figure B-31. The Average $^{239+240}$Pu Activity Concentration (pCi g^{-1}) in Soil Samples from Figure B.23.1.i.1 NVO-140, North-Central Region Yvonne (AEC 1973c) [Samples within Red-lined Polygon Referenced Later in this Report].

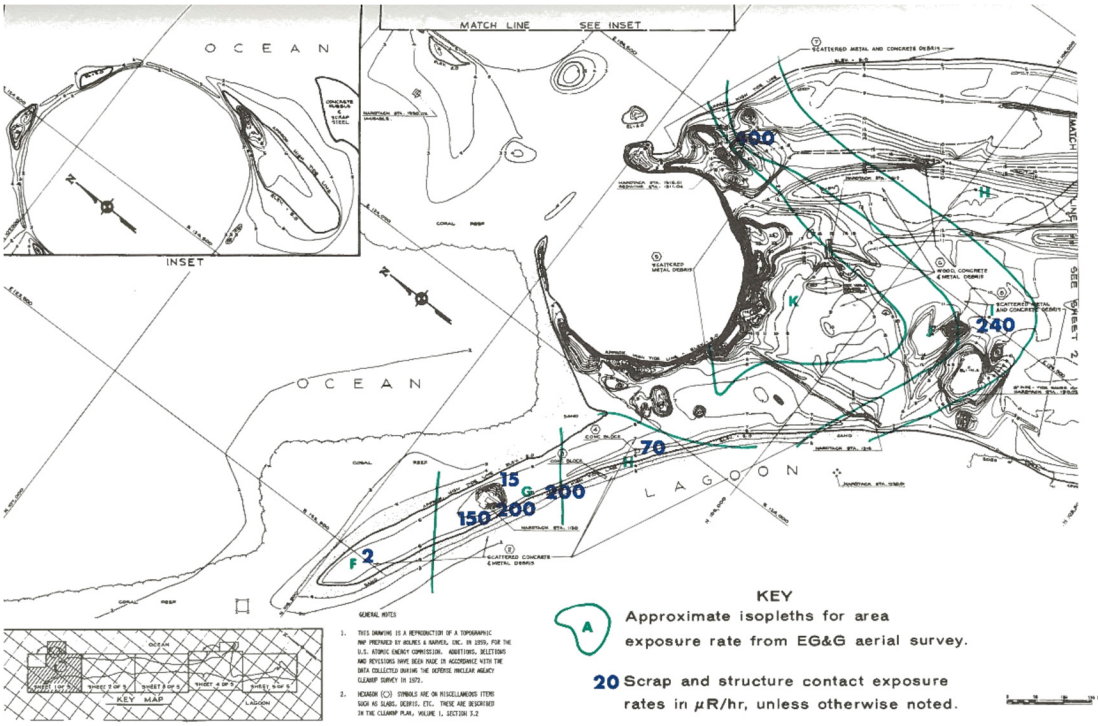


Figure B-32. Figures 109 from NVO-140, *Scrap and Structure Radiation Measurements, Yvonne,* North Segment [1 of 5] (AEC 1973a).

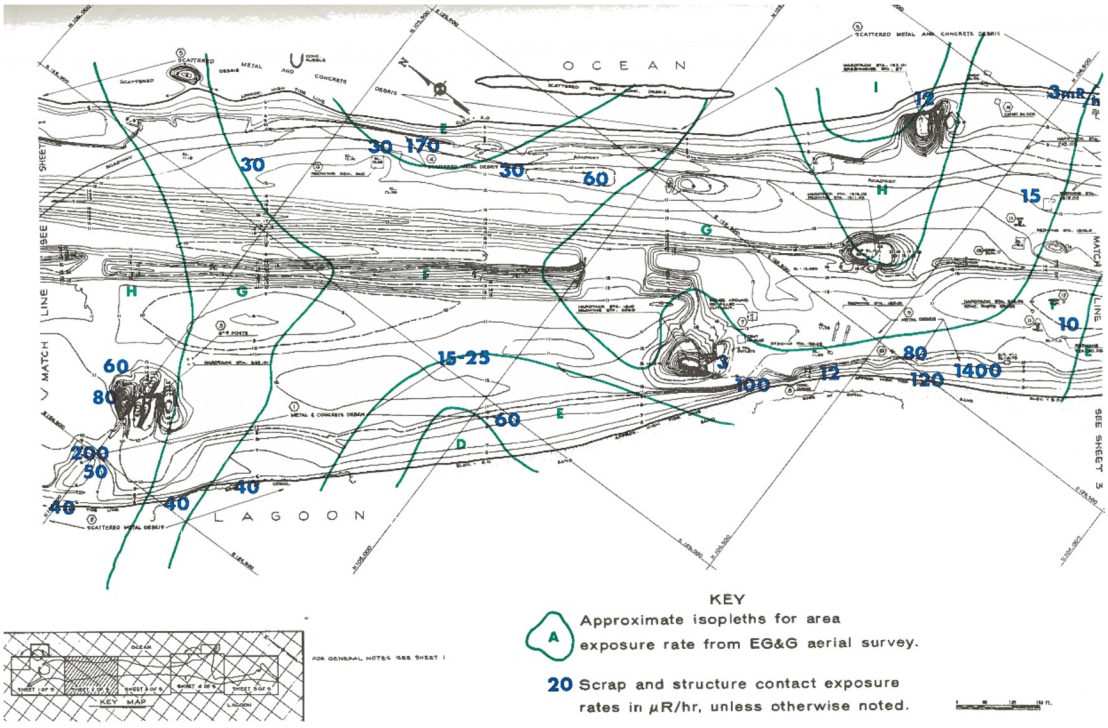


Figure B-33. Figure 110 from NVO-140, *Scrap and Structure Radiation Measurements, Yvonne,* North-Central Segment [2 of 5] (AEC 1973a).

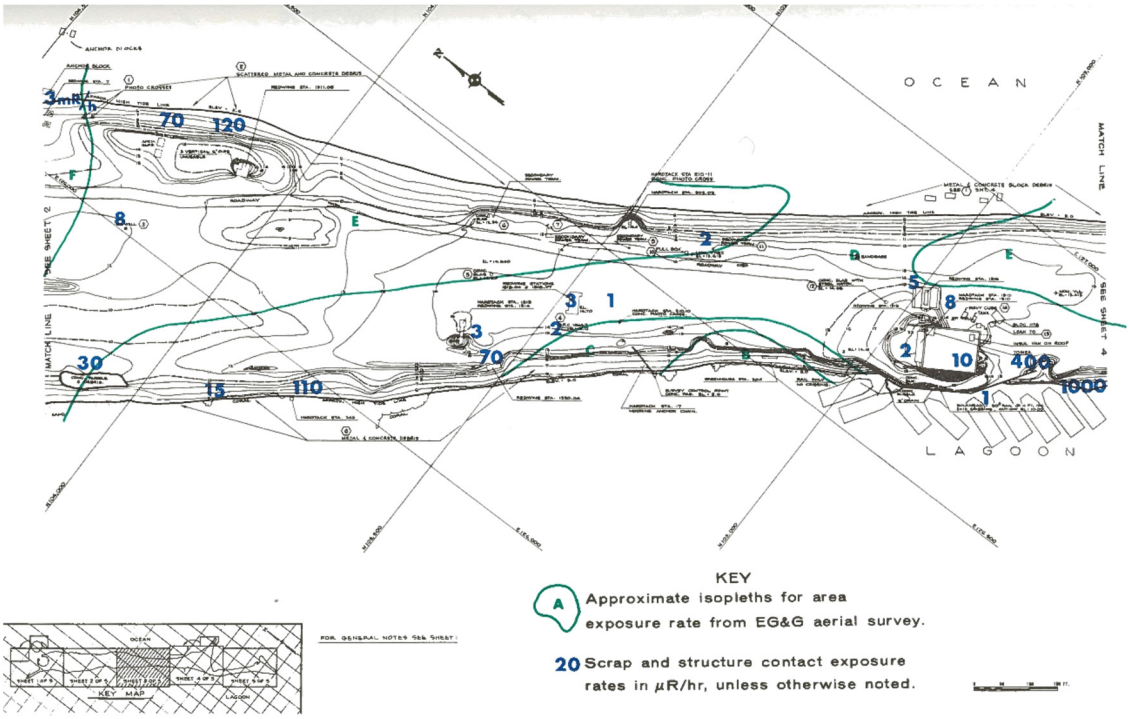


Figure B-34. Figure 111 from NVO-140, *Scrap and Structure Radiation Measurements, Yvonne,* Central Segment [3 of 5] (AEC 1973a).

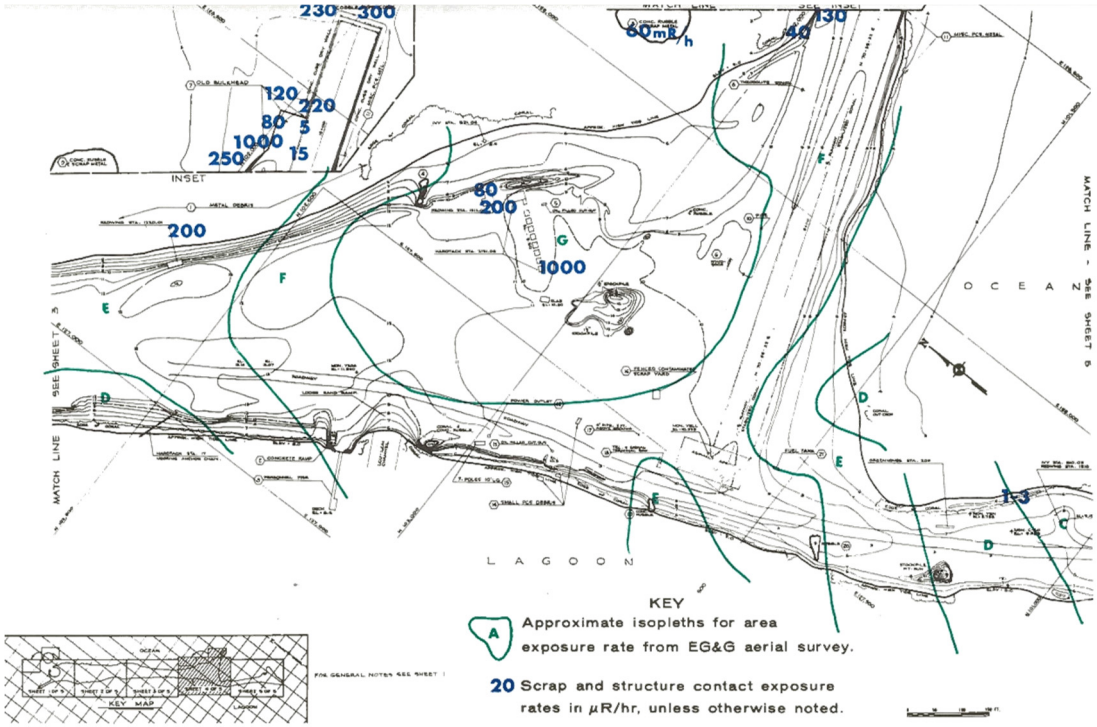


Figure B-35. Figure 112 from NVO-140, *Scrap and Structure Radiation Measurements, Yvonne,* South-Central Segment [4 of 5] (AEC 1973a).

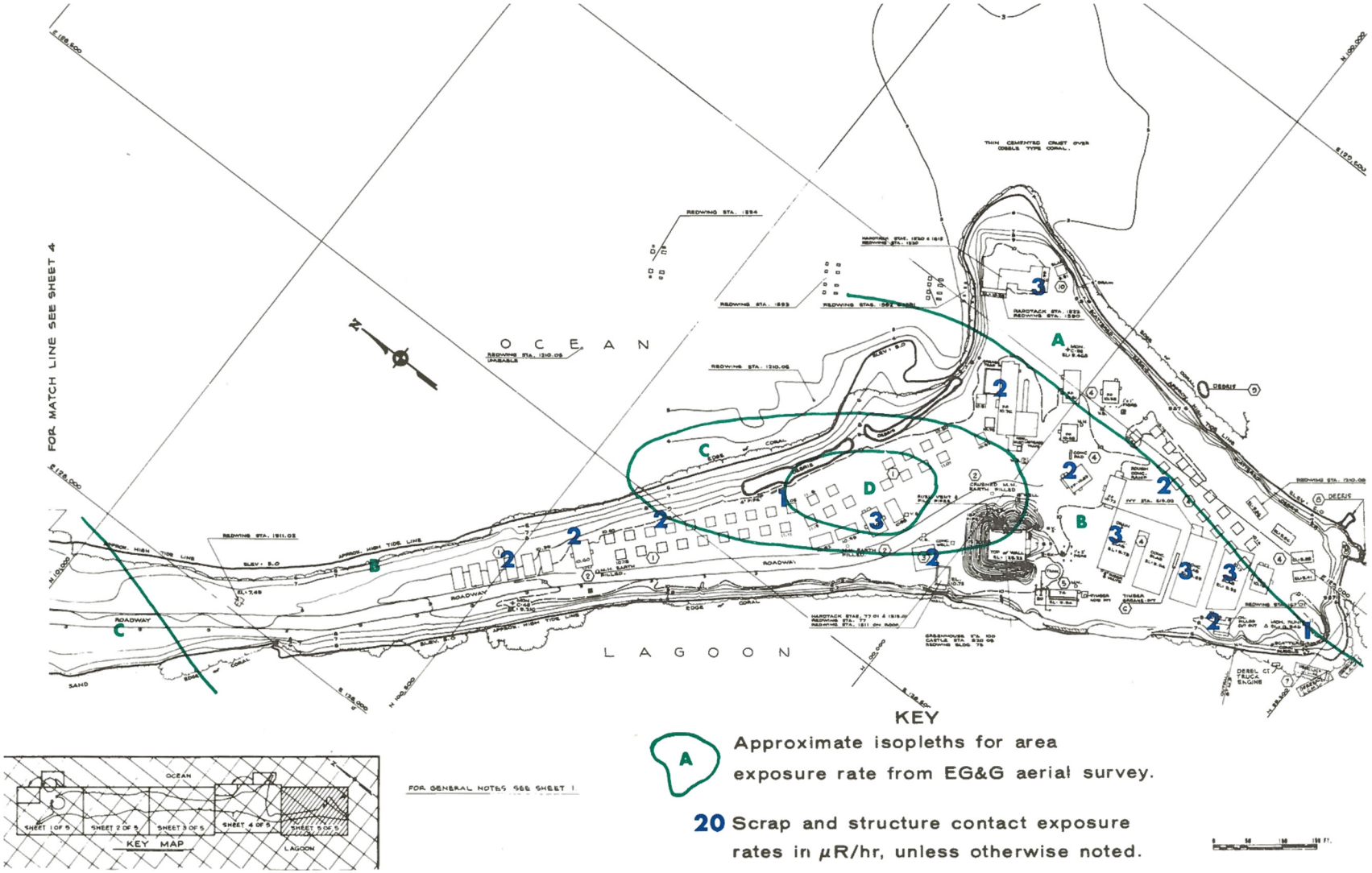


Figure B-36. Figure 113 from NVO-140, *Scrap and Structure Radiation Measurements, Yvonne,* South Segment [5 of 5] (AEC 1973a).

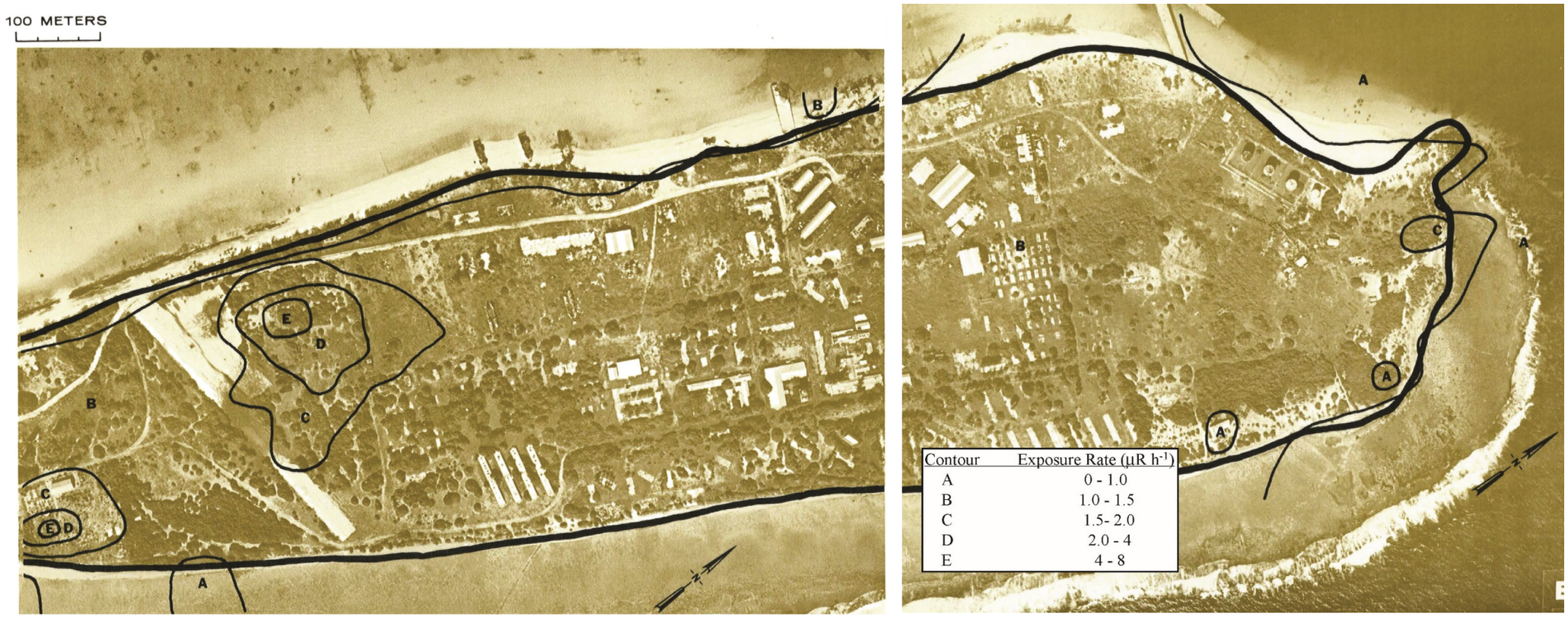


Figure B-37. Gross Count Rate Isoexposure Contours for Elmer from Aerial Survey, Composited from Figures B.37.1.b and B.38.1.b of NVO-140 (AEC 1973b). [Elevated Readings, Contours D & E Attributed to Influence of ^{60}Co Source]

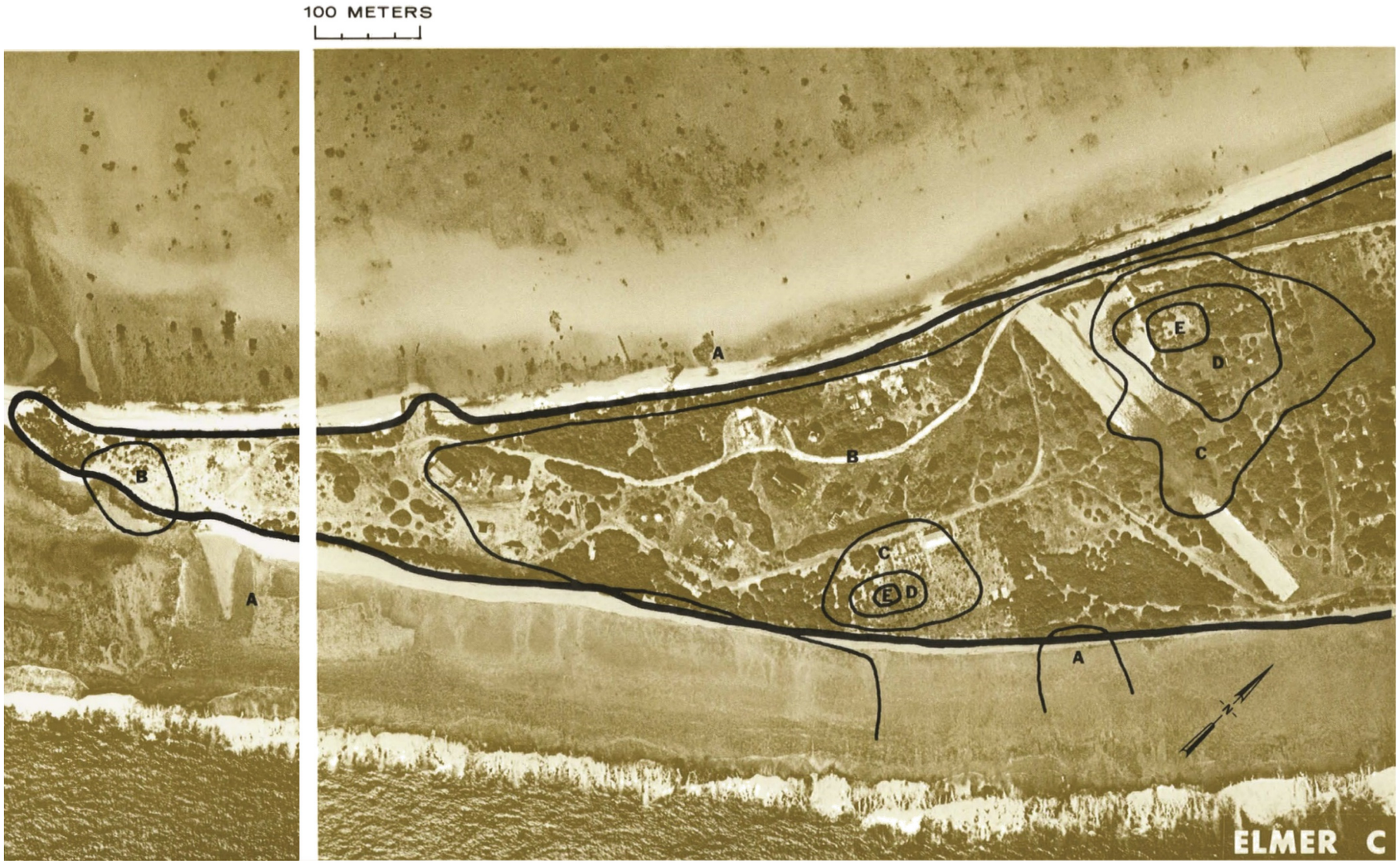


Figure B-38. Gross Count Rate Isoexposure Contours for Elmer from Aerial Survey, continued, Composited from Figures B.39.1.b and B.40.1.b of NVO-140 (AEC 1973b).

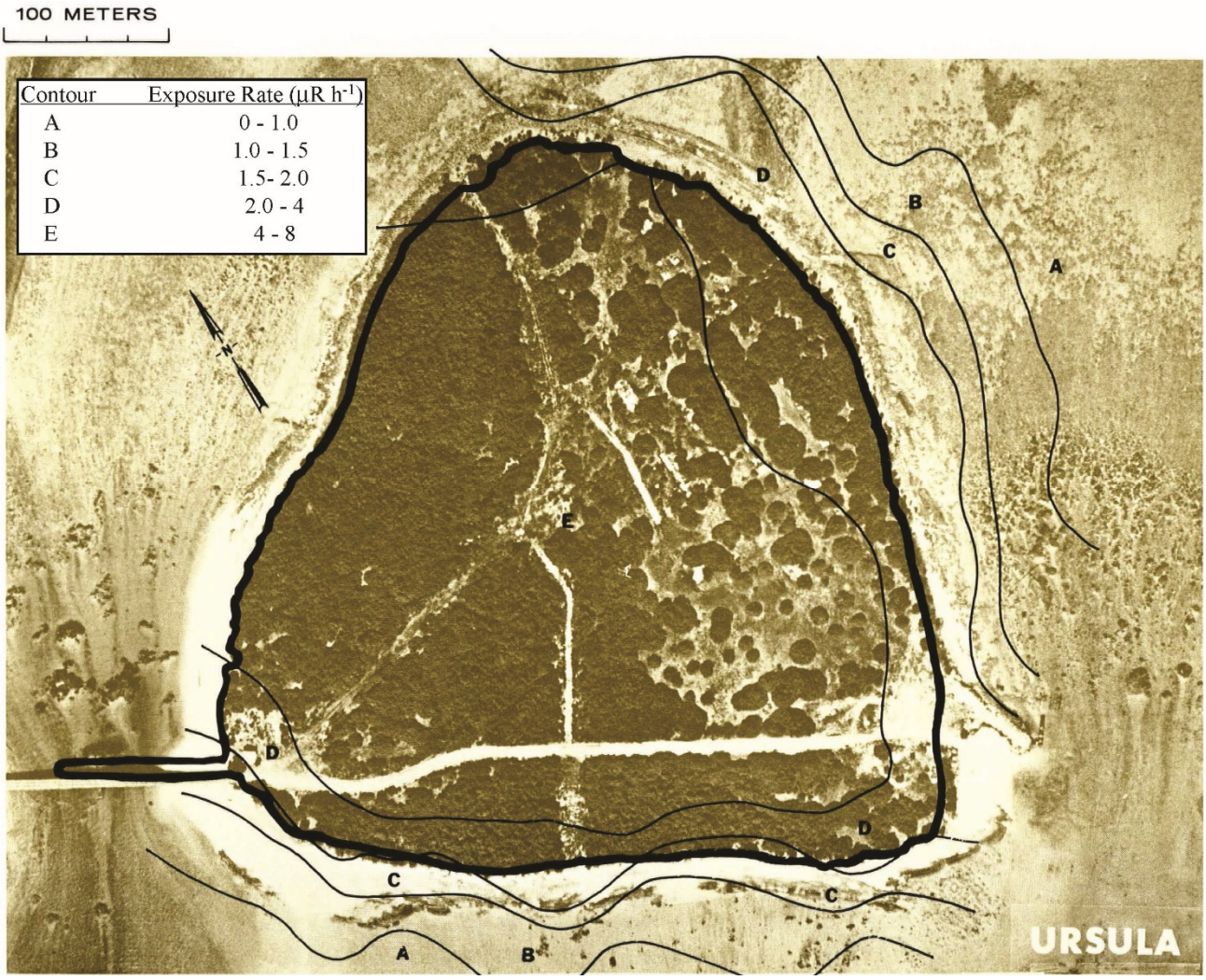


Figure B-39. Gross Count Rate Isoexposure Contours for Ursula from Aerial Survey from Figure B.19.1.b of NVO-140 (AEC 1973b).

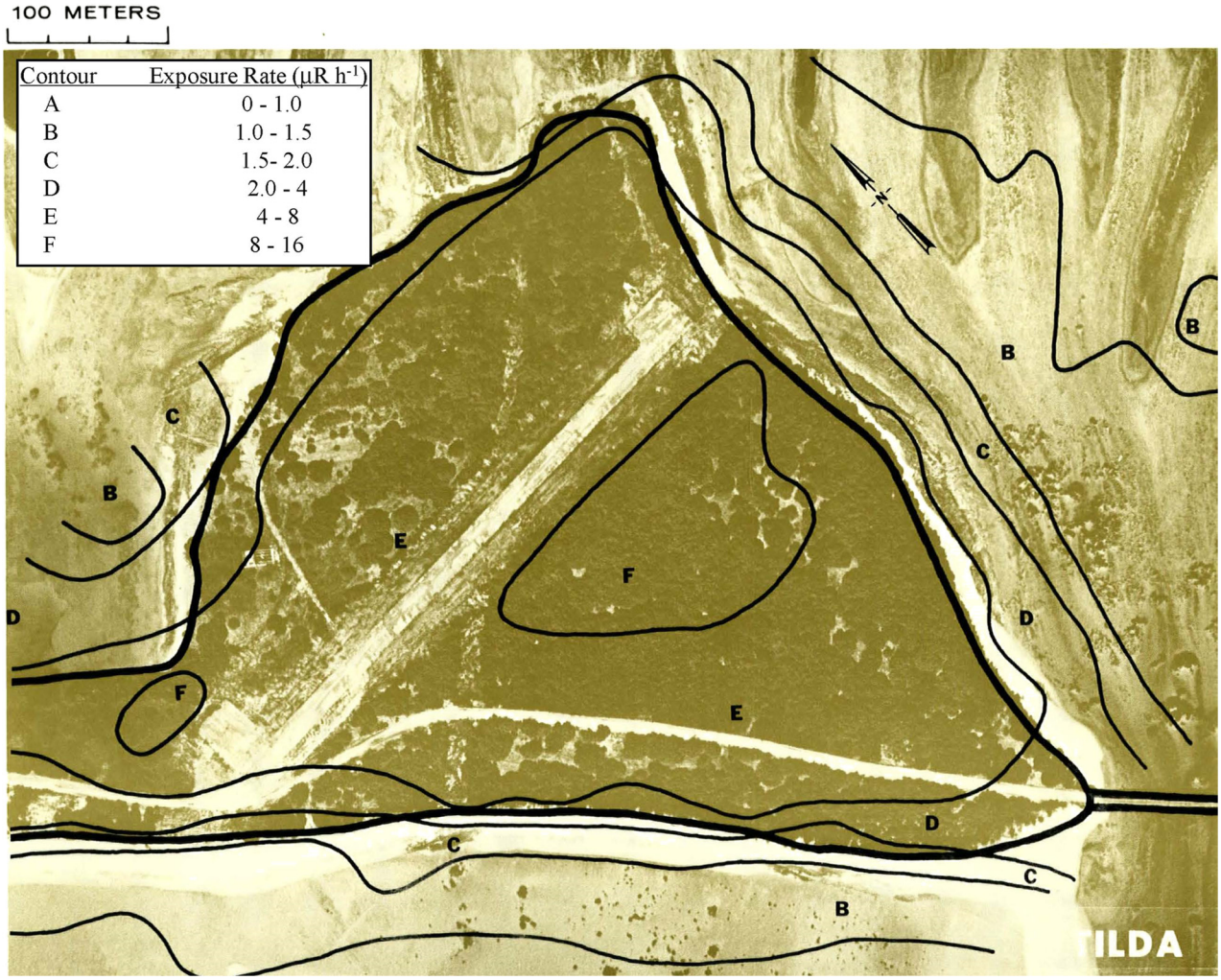


Figure B-40. Gross Count Rate Isoexposure Contours for Tilda from Aerial Survey from Figure B.18.1.b of NVO-140 (AEC 1973b).

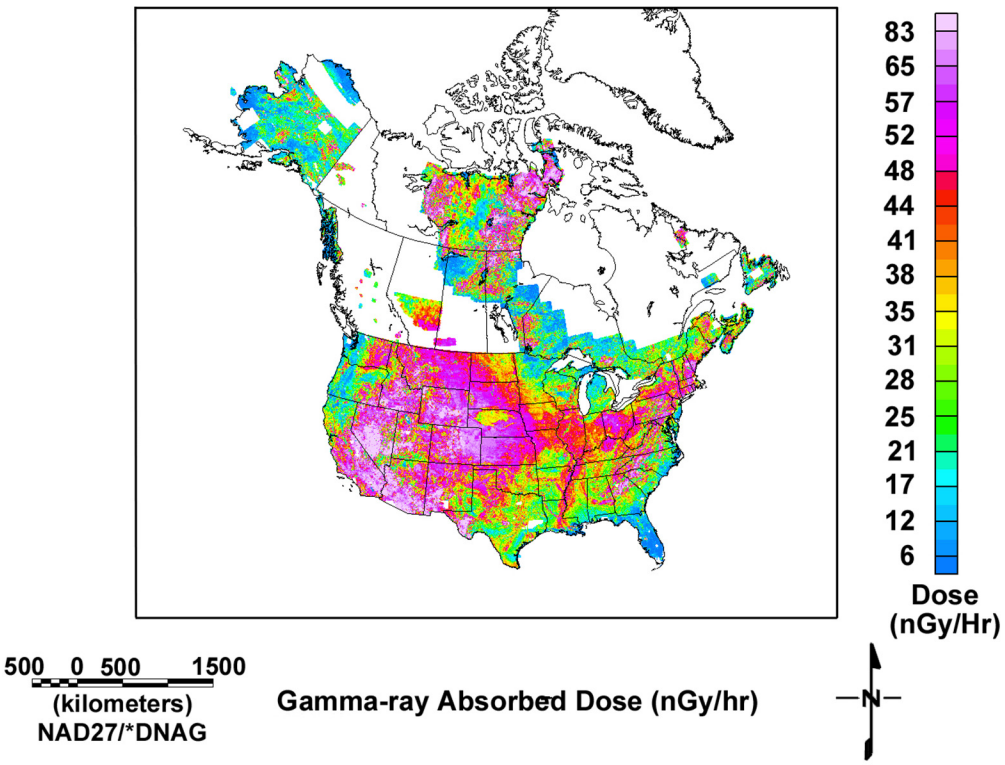


Figure B-41. Terrestrial γ-Radiation Dose Rates in Continental US, and Parts of Canada and Alaska (USGS 2003) [For Exposure Rates in μrad h^{-1}, Divide by a Factor of 10].

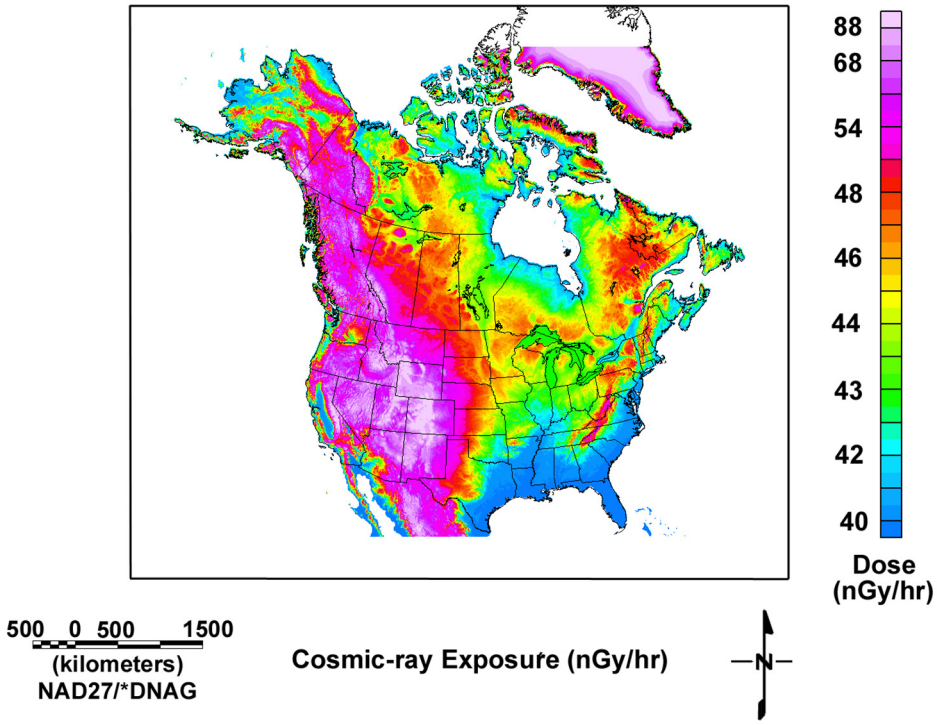


Figure B-42. Cosmic Radiation Dose Rates in Continental US, Canada, Alaska, and Parts of Greenland and Mexico (USGS 2003) [For Exposure Rates in μrad h^{-1}, Divide by a Factor of 10].

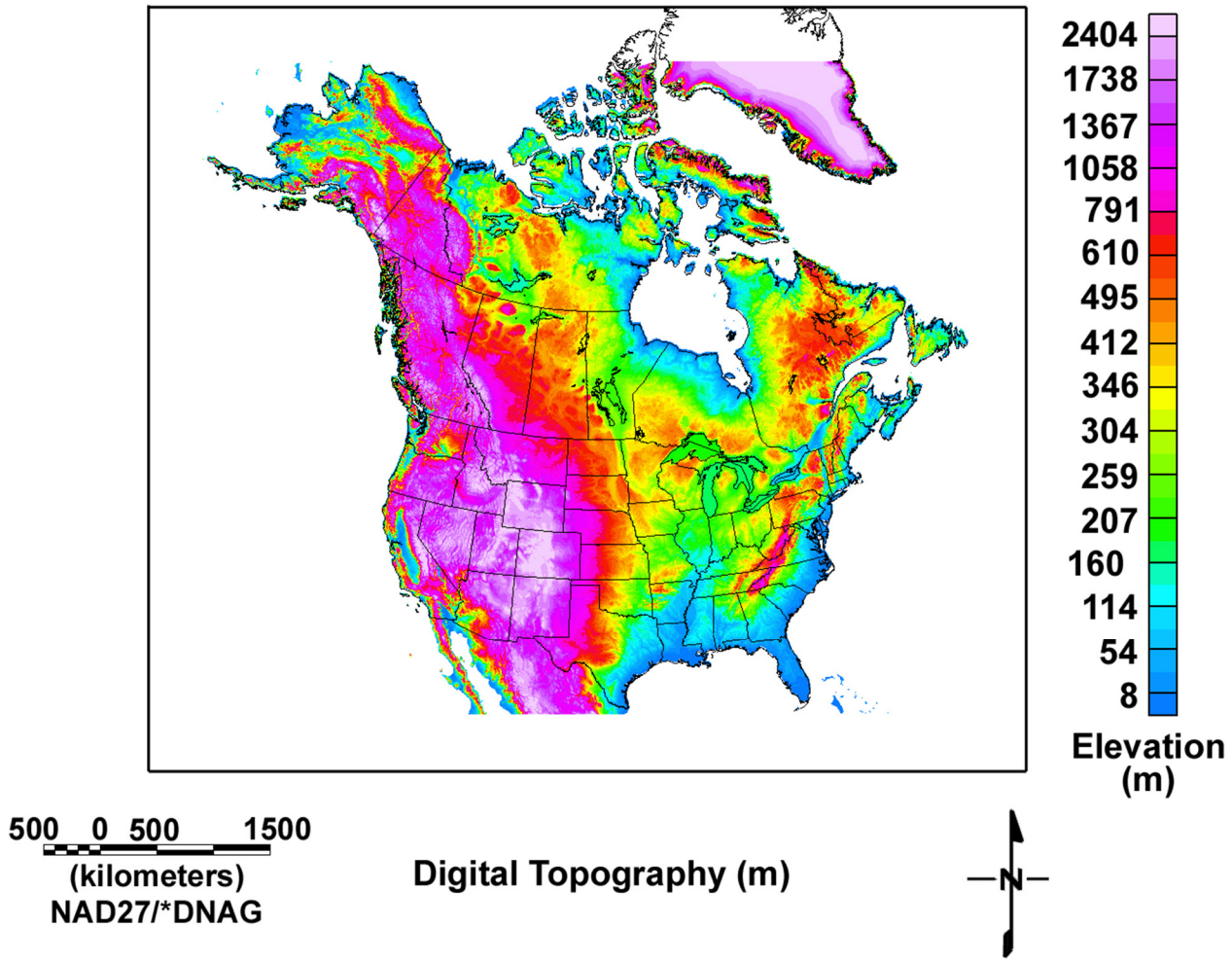


Figure B-43. Elevation Map of Continental US, Canada, Alaska, and Parts of Greenland and Mexico (USGS 2003) [For Exposure Rates in μrem h^{-1}, Divide by a Factor of 10].

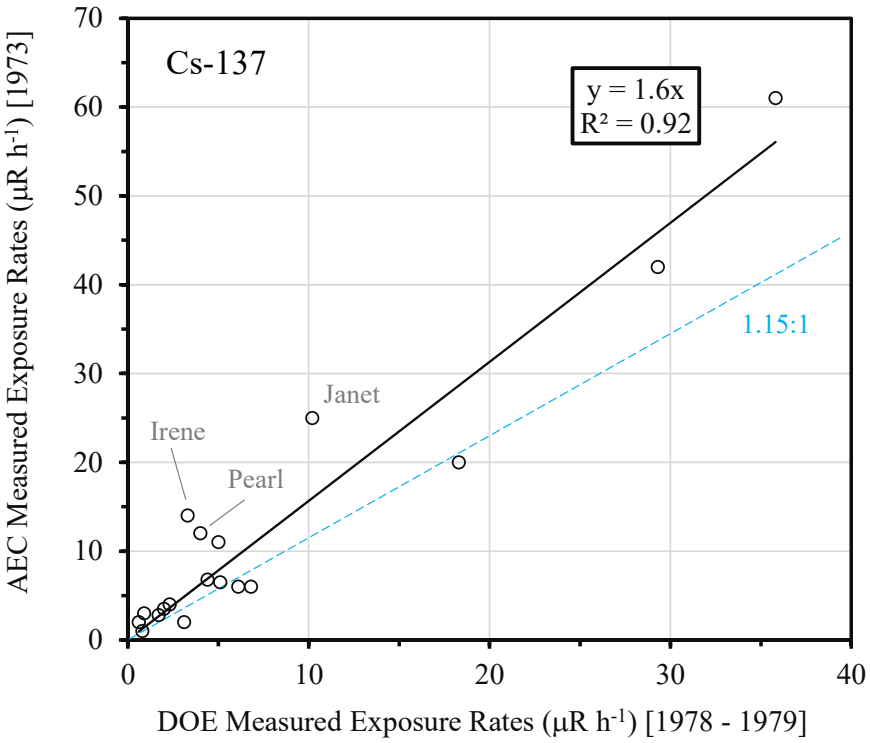


Figure B-44. Scatterplot of Mean External Exposure Rates from AEC (1973) vs. DOE (1982) for Northern Islands on Enewetak Atoll for ^{137}Cs (Light Blue Line Represents Reduction in Exposure Due to Radioactive Decay Only).

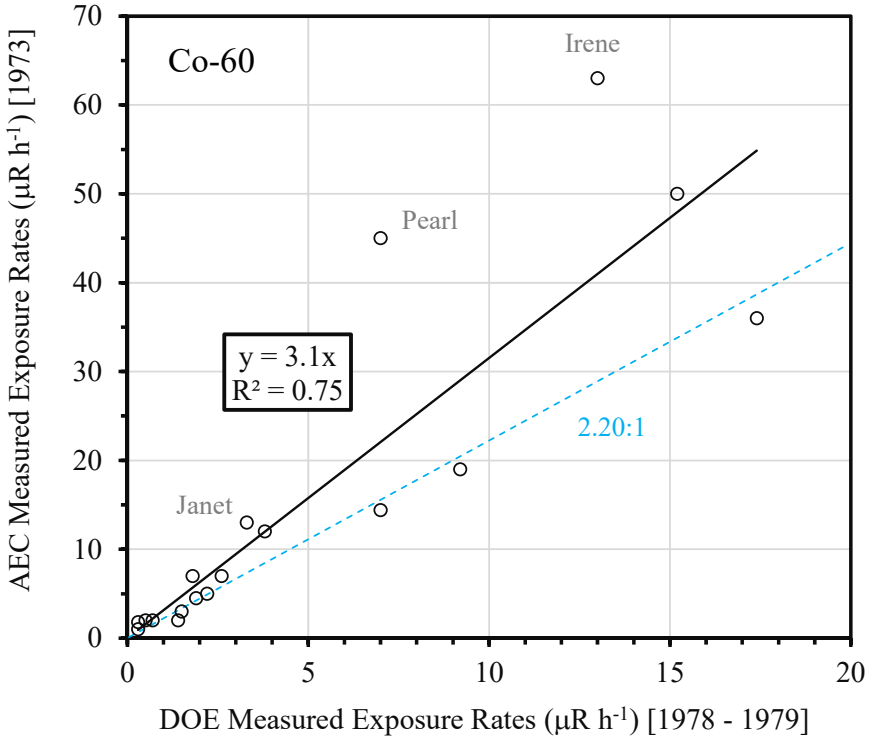


Figure B-45. Scatterplot of Mean External Exposure Rates from AEC (1973) vs. DOE (1982) for Northern Islands on Atoll for ^{60}Co (Light Blue Line Represents Reduction in Exposure Due to Radioactive Decay Only).

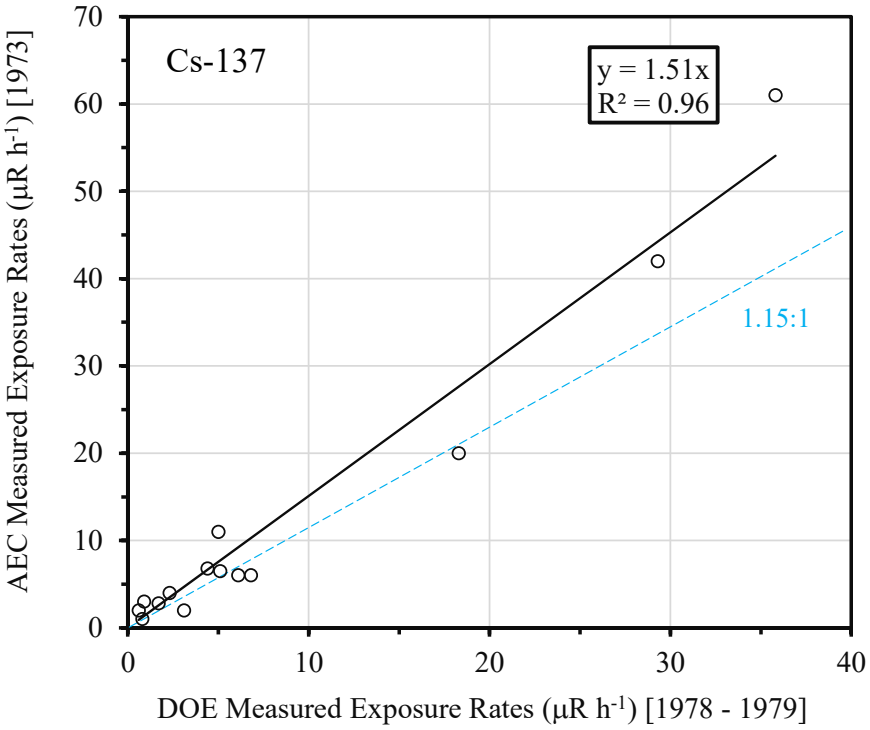


Figure B-46. Scatterplot of Mean External Exposure Rates from AEC (1973) vs. DOE (1982) for Northern Islands (wo/ Soil Excision) on Enewetak Atoll for ^{137}Cs (Light Blue Line Represents Reduction in Exposure Due to Radioactive Decay Only).

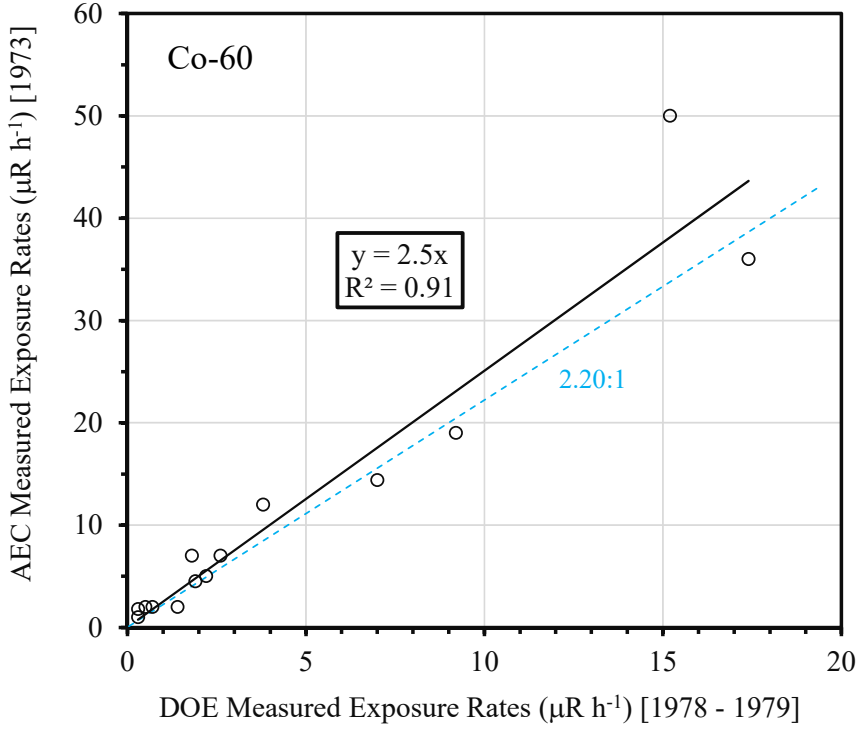


Figure B-47. Scatterplot of Mean External Exposure Rates from AEC (1973) vs. DOE (1982) for Northern Islands (wo/ Soil Excision) on Atoll for ^{60}Co (Light Blue Line Represents Reduction in Exposure Due to Radioactive Decay Only).

Appendix C.

Background Information from NVO-140 and NVO-213, Soils Data

Table C-1. Table 15, from NVO-140 (AEC 1973a).

Table 15. Enewetak soil data, "northern islands" (pCi/g in top 15 cm).

		^{90}Sr		^{137}Cs		^{239}Pu		^{60}Co	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range
ALICE		80	14-430	36	5.6-141	12	3.9-68	5.9	1.4-33
BELLE	Dense	123	14-670	48	14-170	26	7.2-130	10	3.1-30
	Sparse	44	35-130	8.6	3.3-44	11	5.8-26	4.6	2.4-9.6
CLARA		65	13-310	26	5.6-110	22	3.5-88	6.4	0.91-20
DAISY	Dense	190	100-380	11	3.4-33	41	22-98	11	6.4-26
	Sparse	32	16-120	3.8	0.86-9.0	15	3.8-33	0.85	0.37-7.4
EDNA		46	30-220	4.2	2.7-6.4	18	13-24	0.43	0.33-0.63
IRENE		30	5.9-570	3.2	0.22-41	11	2.4-280	5.4	0.12-520
JANET		44	1.6-630	16	0.57-180	8.5	0.08-170	1.9	0.02-33
KATE	Dense	67	37-200	24	18-37	17	8.6-50	2.7	1.6-5.8
	Sparse	11	1.6-49	4.8	1.8-16	2.3	0.17-14	0.46	0.03-3.5
LUCY		32	10-83	11	2.2-25	7.7	2.4-22	1.5	0.26-3.8
MARY		29	11-140	9.9	5.6-26	8.0	2.0-35	1.5	0.74-4.8
NANCY		36	16-110	12	6.0-28	9.1	2.3-28	1.6	0.56-5.3
PERCY		13	3.6-73	0.94	0.12-17	3.5	1.5-23	0.47	0.08-2.9
OLIVE	Dense	22	4.6-70	8.5	3.5-28	7.7	2.2-30	1.5	0.65-4.1
	Sparse	4.5	2.0-11	0.16	0.07-11	2.8	1.9-4.1	0.11	0.05-0.31
PEARL	Hot spot	62	35-140	19	7.4-55	51	15-530	12	3.6-70
	Remainder	17	3.2-61	7.6	1.2-34	11	0.85-100	4.1	0.49-49
RUBY		12	7.1-63	1.4	0.71-7.2	7.3	3.0-24	0.93	0.29-16
SALLY		8.4	0.87-140	3.0	0.03-30	4.3	0.21-130	0.54	0.05-69
TILDA	Dense	27	17-54	8.4	3.5-20	7.6	1.4-17	1.2	0.61-1.9
	Sparse	8.7	2.2-47	1.0	0.04-5.3	2.5	1.1-34	0.37	0.21-1.7
URSULA		6.8	2.0-19	1.7	0.13-7.8	1.3	0.26-7.3	0.31	0.05-1.7
VERA		6.3	1.1-68	2.0	0.03-12	2.5	0.60-25	0.30	0.02-2.2
WILMA		3.3	0.26-13	1.3	0.31-7.2	1.1	0.1-5.3	0.12	0.01-0.7
Southern YVONNE		1.7	0.09-20	0.40	0.02-3.6	3.2	0.02-50	0.64	0.01-20
Northern Beaches		6.4	1.2-30	0.30	0.03-9.0	2.7	0.34-18	0.13	0.03-1.6

YVONNE - Because of the complex distribution of activities on Northern YVONNE no single mean value for an isotope can be used for the island as a whole without being misleading. Readers should consult the YVONNE discussion in this section and the detailed data in Appendix II for information pertinent to their interests.

Table C-2. Table 7-1, NVO-213 (DOE 1982).

TABLE 7-1. RESULTS BY ISLAND FOR ^{137}Cs IN 0-15 cm SOIL SAMPLES FROM THE 1972 RADIOLOGICAL SURVEY AND THE 1979 FISSION PRODUCT DATA BASE PROGRAM.

	1972 Radiological Survey			1979 Fission Product Data Base Program		
Island	No. of Locations Sampled	Range of Activity, all depths, (pCi/g)	0-15 cm Mean, (pCi/g)	No. of Locations Sampled	Range of Activity, all depths, (pCi/g)	0-15cm Mean (pCi/g)
Alice	23	0.7 - 141	44.1	26	<0.4 - 114	39.9
Belle	36	0.4 - 170	47.5	40	<0.4 - 204	61.0
Clara	13	0.8 - 110	35.4	8	0.3 - 105	22.4
Daisy	20	0.9 - 33	10.5	26	<0.4 - 34	6.8
Edna	8	2.7 - 6.4	4.7	5	<0.4 - 7	2.9
Irene	58	0.2 - 41	7.3	53	<0.4 - 54	6.1
Janet	139	0.6 - 180	27.0	364	<0.4 - 142	16.4
Kate	26	0.1 - 37	13.1	18	<0.4 - 35	7.8
Lucy	28	0.1 - 25	10.3	22	<0.4 - 40	11.7
Percy	6	0.1 - 17	7.3	2	<0.4 - 2	0.6
Mary	22	0.03 - 26	8.4	12	<0.4 - 18	6.0
Mary's Dau.	*	*	*	3	<0.4 - 72	12.3
Nancy	25	0.01 - 28	11.6	11	<0.4 - 60	10.8
Olive	26	0.1 - 28	7.7	50	<0.4 - 60	7.5
Pearl	53	0.2 - 55	12.4	72	<0.4 - 43	7.2
Pearl's Dau.	*	*	*	2	<0.4 - 7	5.6
Ruby	5	0.7 - 7.2	3.2	3	1.1 - 11	2.0
Sally	27	0.1 - 30	5.7	137	<0.4 - 43	3.5
Sally's Ch.	6	0.03 - 29	8.9	4	<0.4 - 13	6.9
Tilda	32	0.04 - 20	4.2	48	<0.4 - 20	3.2
Ursula	31	0.1 - 7.8	2.6	15	<0.4 - 4	1.2
Vera	25	0.03 - 12	4.4	48	<0.4 - 20	3.0
Wilma	23	0.3 - 7.2	2.0	17	<0.4 - 5	1.3
Yvonne+	51	0.02 - 3.6	1.0	14	<0.4 - 11	1.5
Sam	5	0.02 - 0.5	0.38	**	**	**
Tom	5	0.07 - 0.56	0.32	**	**	**
Uriah	8	0.02 - 0.23	0.11	**	**	**
Van	6	0.05 - 0.20	0.14	**	**	**
Alvin	5	0.03 - 0.29	0.11	**	**	**
Bruce	13	0.02 - 1.1	0.40	**	**	**
Clyde	4	0.02 - 0.13	0.06	**	**	**
David	48	0.03 - 1.0	0.40	**	**	**
Rex	7	0.02 - 1.2	0.51	**	**	**
Elmer	51	0.02 - 1.2	0.32	**	**	**
Walt	5	0.04 - 0.3	0.15	**	**	**
Fred	24	0.02 - 0.48	0.25	**	**	**
Glenn	28	0.01 - 1.8	0.60	**	**	**
Henry	15	0.004 - 0.7	0.25	**	**	**
Irwin	8	0.008 - 0.47	0.13	**	**	**
James	8	0.02 - 0.22	0.08	**	**	**
Keith	13	0.01 - 0.81	0.28	**	**	**
Leroy	11	0.5 - 10	5.06	8	<0.4 - 28	4.2

* Not sampled in 1972 survey
**Not sampled in 1979 FPDB survey
\+ South of 1310 bunker

Table C-3. Table 7-2, NVO-213 (DOE 1982).

TABLE 7-2. RESULTS BY ISLAND FOR ^{90}Sr IN 0-15 cm SOIL SAMPLES FROM THE 1972 RADIOLOGICAL SURVEY AND THE 1979 FISSION PRODUCT DATA BASE PROGRAM.

	1972 Radiological Survey			1979 Fission Product Data Base Program		
Island	No. of Locations Sampled	Range of Activity, all depths, (pCi/g)	0-15 cm Mean, (pCi/g)	No. of Locations Sampled	Range of Activity, all depths, (pCi/g)	0-15cm Mean (pCi/g)
Alice	23	14 - 430	107.9	7	1.3 - 347	85.9
Belle	36	9.8 - 670	148.9	11	3.5 - 339	107.4
Clara	13	13 - 310	99.2	4	1.4 - 243	42.8
Daisy	20	3.4 - 380	107.7	8	1.9 - 144	34.8
Edna	8	30 - 220	68.6	3	4.3 - 48	21.7
Irene	56	8.4 - 570	52.8	15	0.6 - 136	31.0
Janet	140	1.6 - 630	72.9	99	<0.1 - 244	31.9
Kate	26	1.6 - 200	43.5	6	1.0 - 31	13.3
Lucy	28	4.4 - 83	30.1	8	1.0 - 94	21.9
Percy	6	3.6 - 73	34.6	2	2.0 - 7	5.4
Mary	22	1.2 - 140	34.8	4	1.1 - 46	14.2
Mary's Dau.	*	*	*	1	5.2 - 107	41.9
Nancy	25	3.6 - 110	39.3	6	<0.15 - 82	20.1
Olive	26	2.0 - 70	21.5	12	<0.12 - 83	16.2
Pearl	52	2.3 - 140	28.3	17	0.4 - 38	11.4
Pearl's Dau.	*	*	*	1	1.3 - 28	18.0
Ruby	5	7.1 - 63	24.3	1	5.5 - 9	5.8
Sally	27	0.9 - 140	16.0	39	<0.10 - 25	4.4
Sally's Ch.	6	3.0 - 89	25.0	4	1.0 - 60	16.7
Tilda	32	2.2 - 54	19.1	15	<0.12 - 25	5.6
Ursula	31	0.9 - 19	8.2	15	<0.08 - 70	3.0
Vera	25	1.1 - 68	12.5	13	0.2 - 29	4.8
Wilma	23	0.3 - 19	6.0	5	0.2 - 19	2.9
Yvonne+	47	0.1 - 20	3.3	5	<0.13 - 5	1.1
Sam	5	0.5 - 0.8	0.72	**	**	**
Tom	5	0.18 - 1.2	0.72	**	**	**
Uriah	8	0.05 - 1.0	0.45	**	**	**
Van	6	0.10 - 0.81	0.41	**	**	**
Alvin	5	0.21 - 0.74	0.44	**	**	**
Bruce	13	0.03 - 1.8	0.59	**	**	**
Clyde	3	0.12 - 0.36	0.23	**	**	**
David	47	0.08 - 2.6	0.55	**	**	**
Rex	6	0.03 - 1.6	0.51	**	**	**
Elmer	51	0.02 - 5.1	0.76	**	**	**
Walt	5	0.25 - 0.6	0.41	**	**	**
Fred	24	0.16 - 1.5	0.61	**	**	**
Glenn	28	0.09 - 3.9	1.37	**	**	**
Henry	14	0.13 - 2.2	0.75	**	**	**
Irwin	8	0.14 - 1.6	0.69	**	**	**
James	8	0.13 - 2.2	0.69	**	**	**
Keith	13	0.03 - 1.8	0.88	**	**	**
Leroy	11	0.42 - 34	16.8	8	0.15 - 20	5.1

* Not sampled in 1972 survey
** Not sampled in 1979 FPDB survey
+ South of 1310 bunker

Table C-4. Table 7-3, NVO-213 (DOE 1982).

TABLE 7-3. RESULTS BY ISLAND FOR $^{239,240}Pu^{\dagger}$ IN 0-15 cm SOIL SAMPLES FROM THE 1972 RADIOLOGICAL SURVEY AND THE 1979 FISSION PRODUCT DATA BASE PROGRAM.

	1972 Radiological Survey			1979 Fission Product Data Base Program		
Island	No. of Locations Sampled	Range of Activity, all depths, (pCi/g)	0-15 cm Mean, (pCi/g)	No. of Locations Sampled	Range of Activity, all depths, (pCi/g)	0-15cm Mean (pCi/g)
Alice	22	3.9 - 68	15.6	26	<2 - 226	20.5
Belle	35	4.2 - 100	27.1	40	<2 - 245	34.5
Clara	13	3.5 - 88	31.6	8	<2.5 - 54	16.0
Daisy	20	3.8 - 98	31.6	26	<2 - 121	25.4
Edna	8	13 - 24	19.4	5	9.4 - 28	17.8
Irene	56	2.4 - 280	26.2	53	<4 - 187	29.5
Janet	138	0.1 - 175++	16.2	364	<3 - 119	10.1
Kate	26	0.2 - 50	11.3	18	<1.5 - 27	5.0
Lucy	28	1.5 - 23	7.7	22	<1.5 - 74	10.1
Percy	6	1.5 - 23	9.0	2	<1.5 - 2.7	1.7
Mary	22	0.9 - 35	10.1	12	<1.5 - 27	7.2
Mary's Dau.	*	*	*	3	<1.5 - 44	8.4
Nancy	25	1.3 - 28	10.1	14	<1.5 - 48	8.0
Olive	26	1.9 - 30	8.4	50	<2 - 72	6.4
Pearl	52	0.3 - 530	38.3	72	<3.5 - 130	15.5
Pearl's Dau.	*	*	*	2	<6 - 85	44.8
Ruby	5	3.0 - 24	14.5	3	<3.5 - 7.5	5.6
Sally	27	0.2 - 130	11.0	137	<2 - 72	2.2
Sally's Ch.	6	5.6 - 78	26.9	4	<1.5 - 51	12.1
Tilda	29	1.1 - 34	6.5	48	<1.5 - 20	2.0
Ursula	31	0.2 - 4.2	1.8	15	<1.5 - 2.5	0.6
Vera	25	0.6 - 25	4.3	48	<1.5 - 22	2.2
Wilma	22	0.1 - 5.3	1.8	17	<1.5 - 10	1.1
Yvonne+	49	0.02 - 50	8.7	14	<4.5 - 93	11.6
Sam	5	0.03 - 0.2	0.09	**	**	**
Tom	5	0.01 - 0.13	0.08	**	**	**
Uriah	8	0.02 - 0.12	0.09	**	**	**
Van	6	0.04 - 0.11	0.08	**	**	**
Alvin	5	0.02 - 0.11	0.06	**	**	**
Bruce	13	0.02 - 0.22	0.09	**	**	**
Clyde	4	0.04 - 0.11	0.06	**	**	**
David	48	0.004 - 0.23	0.05	**	**	**
Rex	7	0.02 - 0.06	0.04	**	**	**
Elmer	50	0.01 - 5.5	0.21	**	**	**
Walt	5	0.02 - 0.06	0.04	**	**	**
Fred	23	0.02 - 0.4	0.08	**	**	**
Glenn	28	0.005 - 0.3	0.11	**	**	**
Henry	14	0.07 - 0.23	0.14	**	**	**
Irwin	8	0.01 - 0.22	0.13	**	**	**
James	8	0.02 - 0.16	0.08	**	**	**
Keith	13	0.01 - 0.17	0.11	**	**	**
Leroy	11	0.02 - 2.3	1.15	8	<3 - 24	1.7

† $^{239,240}Pu$ estimated from ^{241}Am data
* Not sampled in 1972 survey
**Not sampled in 1979 FPDB survey
+ South of 1310 bunker
++This value is suspect in light of other information. The next highest activity was 116 pCi/g, which appears to be a reliable value.

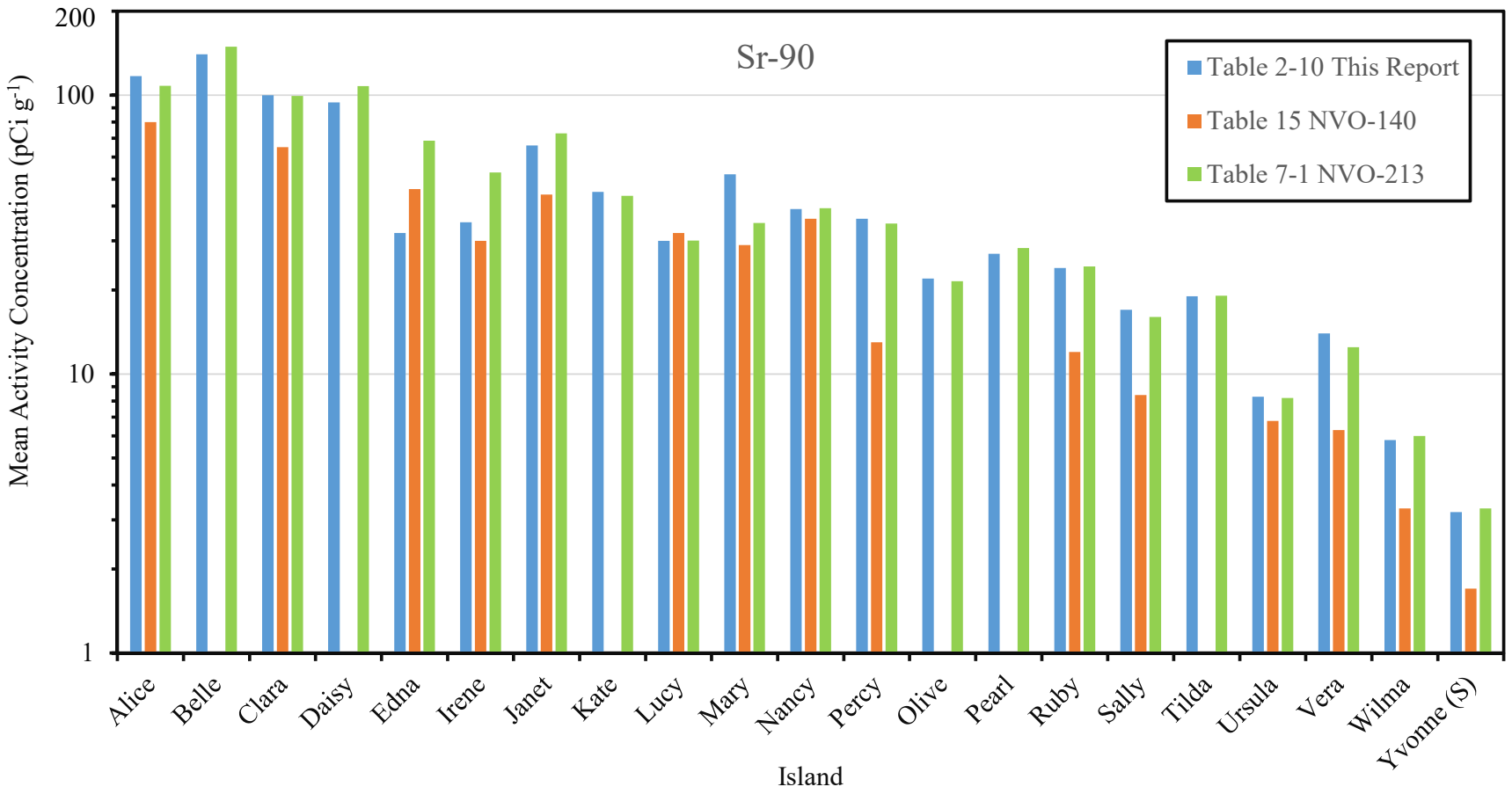


Figure C-1. Comparison of Mean ^{90}Sr in Surface Soil Samples from NVO-140 Data as Listed in Table 15 of NVO-140 (AEC 1973a) and Table 7-1 of NVO-213 (DOE 1982).

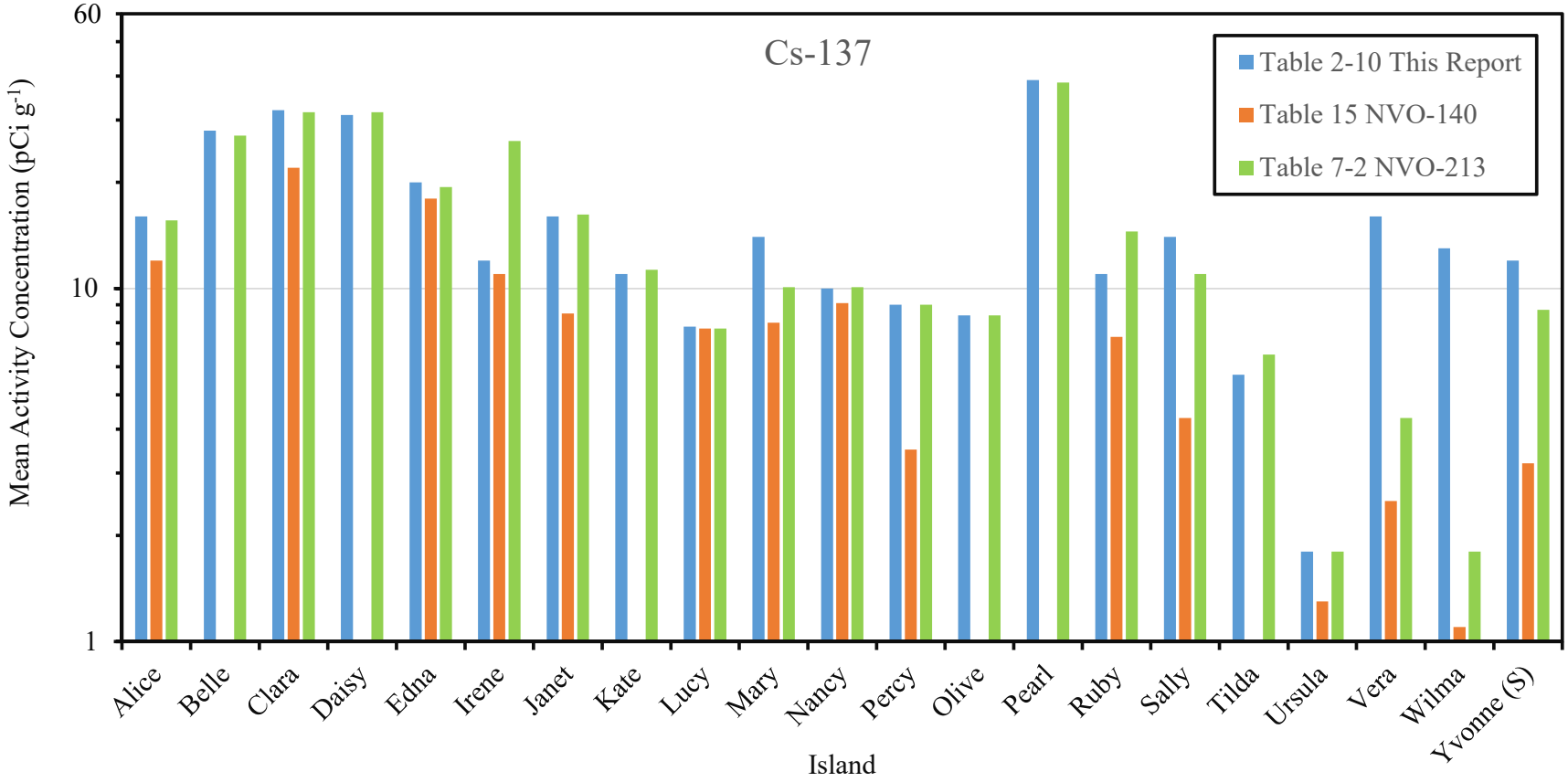


Figure C-2. Comparison of Mean ^{137}Cs in Surface Soil Samples from NVO-140 Data as Listed in Table 15 of NVO-140 (AEC 1973a) and Table 7-2 of NVO-213 (DOE 1982).

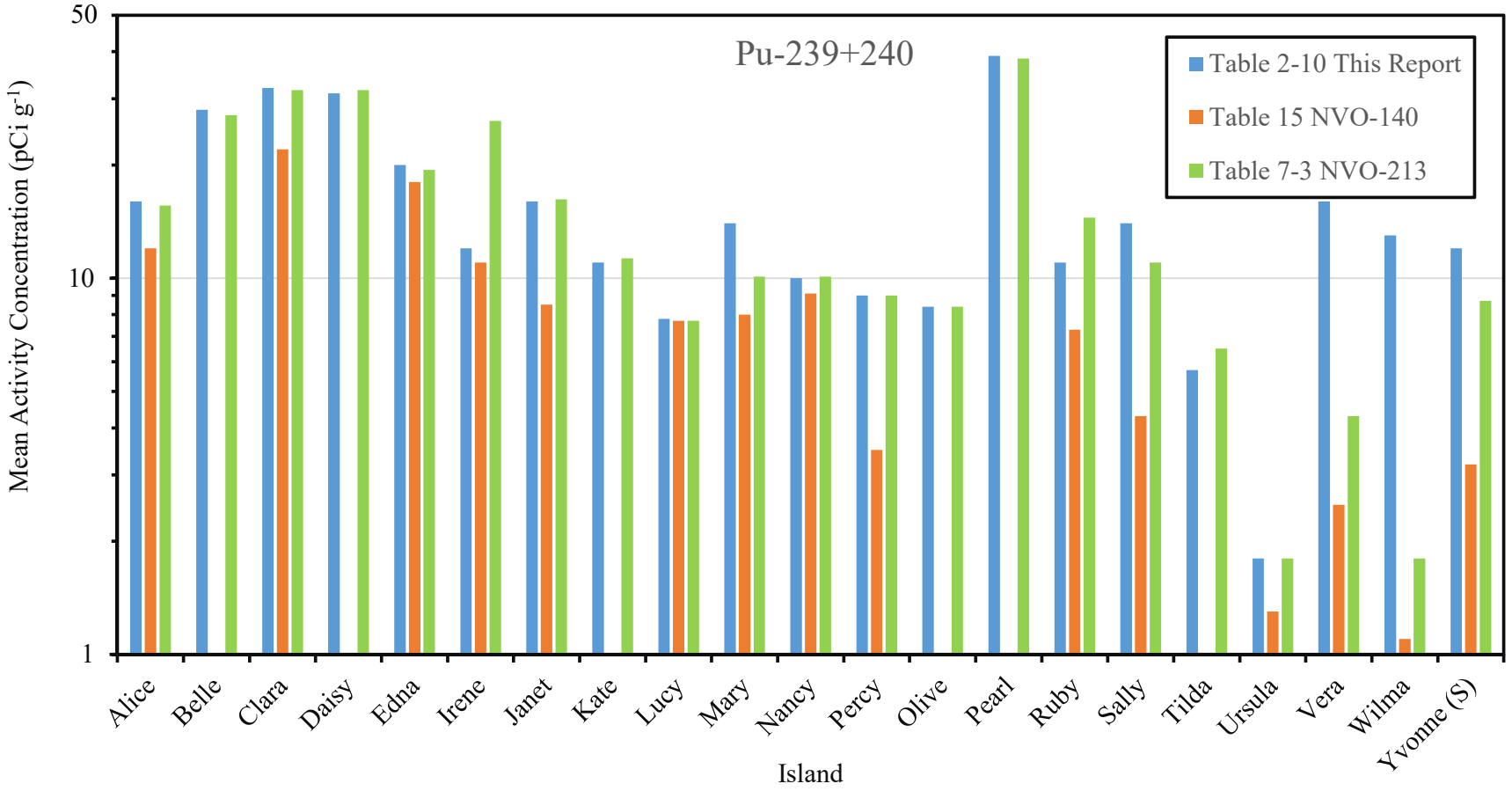


Figure C-3. Comparison of Mean $^{239+240}$Pu in Surface Soil Samples from NVO-140 Data as Listed in Table 15 of NVO-140 (AEC 1973a) and Table 7-3 of NVO-213 (DOE 1982).

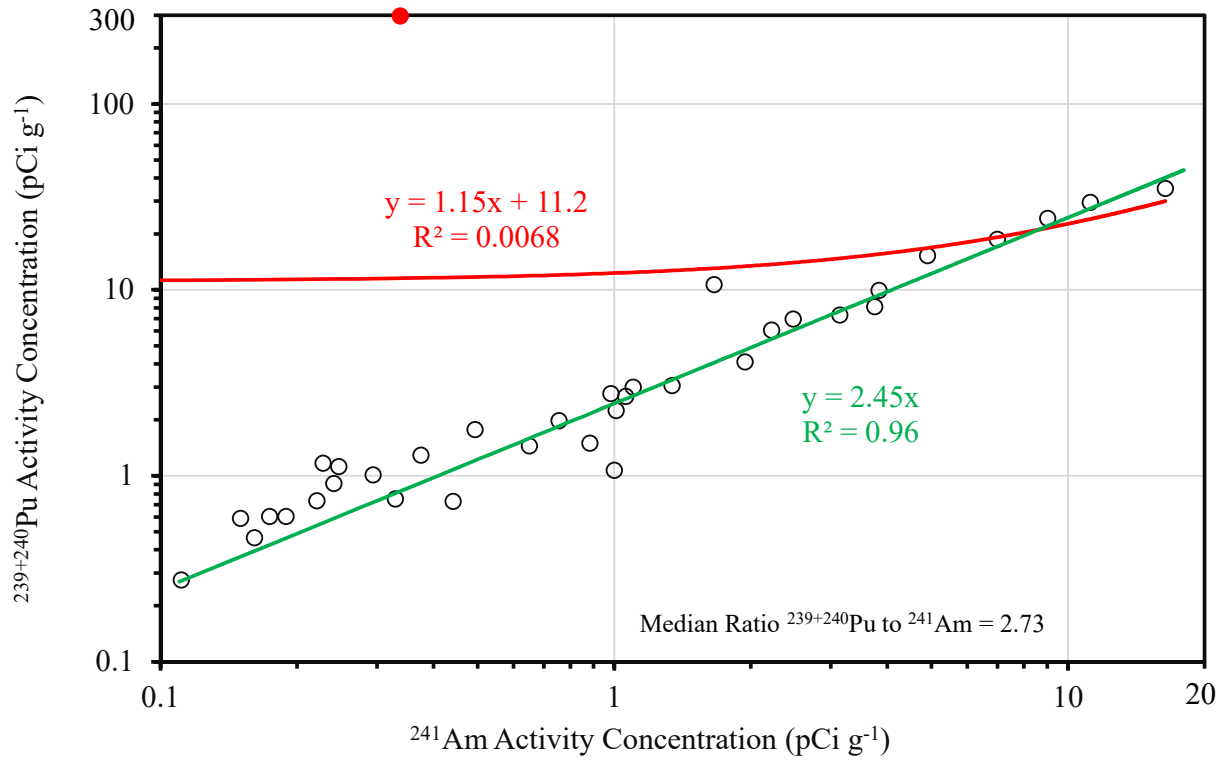


Figure C-4. Regression of $^{239+240}$Pu to ^{241}Am for Soils Data from Vera.

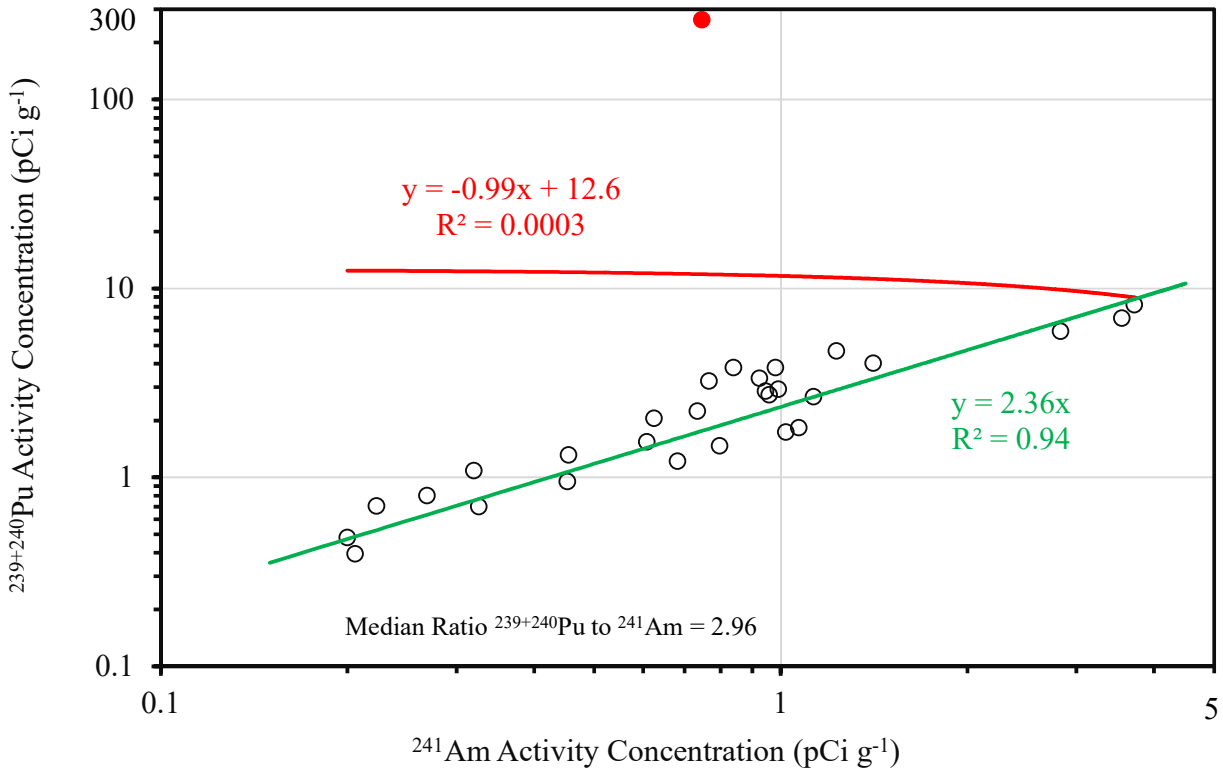


Figure C-5. Regression of $^{239+240}$Pu to ^{241}Am for Soils Data from Wilma.

Table C-5. Table 16, from NVO-140 (AEC 1973a).

Table 16. Enewetak soil data, southern islands (pCi/g in top 15 cm).

	^{90}Sr		^{137}Cs		^{239}Pu		^{60}Co	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Group A (DAVID, ELMER, FRED)	0.41	0.02-4.8	0.21	0.01-2.1	0.04	0.004-0.31	0.03	0.01-0.15
Group B (All others except LEROY)[a]	0.52	0.03-3.9	0.14	0.004-1.8	0.07	0.004-1.1	0.06	0.007-63
Group C (LEROY)	11	1.6-34	3.2	0.5-10	0.63	0.02-2.0	0.58	0.04-5.0

[a]SAM, TOM, URIAH, VAN, ALVIN, BRUCE, CLYDE, REX, WALT, GLENN, HENRY, IRWIN, JAMES and KEITH.

Table C-6. $^{239+240}$Pu Activity Concentrations (pCi g^{-1}) in Depth Profile Samples in Gridded Area Encompassing Events Quince/Fig GZ.

North	Mean Depth = 5 cm					South
	Ocean					
	63.5	314	125			
52.7	20.9	342	176	451	495	
38.6	52.3	59.5	217	1.83	4.23	
26.2	300	369	21.4	25.5	6.44	
91.9	63.1	62.2	734	136	0.259	
	Lagoon					

North	Mean Depth = 35 cm					South
	Ocean					
	109		341			
26	0.092	7.4	459	20	294	
0.34	1.9	0.33	0.62	0.12	6.7	
0.063	30	2.2	0.59	6.2	0.15	
2.5	0.096	0.15	0.15	182	0.31	
	Lagoon					

North	Mean Depth = 15 cm					South
	Ocean					
	51	121	128			
33	0.34	1.4	49	193	366	
18	0.78	0.91	139	7.3	4.1	
3.4	181	202	1.9	5.5	11	
98	2.8	1.8	0.42	532	1.8	
	Lagoon					

North	Mean Depth = 45 cm					South
	Ocean					
	3.3	11	843			
0.094		0.86	104	5.9	399	
0.087	0.14		0.68	0.026	1.1	
0.028	12	14	0.45	15	0.11	
1.4	0.20	0.088		12	0.028	
	Lagoon					

North	Mean Depth = 25 cm					South
	Ocean					
	37					
96	0.14	15	136	143	316	
2.8	0.47	0.21		0.16	3.4	
0.60	53	29	2.7	9.8	2.4	
14	0.44	0.14	16	20	0.46	
	Lagoon					

North	Mean Depth = 55 cm					South
	Ocean					
	1.34	0.946	582			
0.061		0.32	45	6.1	272	
0.044	0.017		0.44	0.061	0.072	
0.0067	17	4.1	0.89	8.9	0.036	
0.58	0.016	0.15	0.13	2.3		
	Lagoon					

Table C-6. $^{239+240}$Pu Activity Concentrations (pCi g^{-1}) in Depth Profile Samples in Gridded Area Encompassing Events Quince/Fig GZ, continued.

North	Mean Depth = 65 cm					South
	Ocean					
	0.65	1.6	840			
0.029	0.065	0.78	0.60	5.0	268	
0.038			15	0.069		
0.037	0.48	1.4	28	34	0.013	
0.26		0.035	0.0070	0.58		
	Lagoon					

North	Mean Depth = 95 cm					South
	Ocean					
	0.034	0.10	622			
0.0069		0.11	0.95	5.6	794	
0.033	0.017		1.5	0.053		
0.0034	0.033	0.80	0.96	5.3		
0.12		0.018	0.0043	2.9		
	Lagoon					

North	Mean Depth = 75 cm					South
	Ocean					
	0.33	0.61	185			
0.0020		0.83	0.52	4.6	442	
0.012	0.0069			0.12		
0.0016	1.0	0.37	74	27	0.034	
0.32	0.0009			0.29		
	Lagoon					

North	Mean Depth = 105 cm					South
	Ocean					
	0.039		65			
0.024	0.054	0.35	0.75	5.3	58	
0.0075	0.069		0.46	0.22		
0.0004		0.37	0.052	1.8		
0.081			0.0028		0.02	
	Lagoon					

North	Mean Depth = 85 cm					South
	Ocean					
	0.069	0.57	20			
0.019		2.1	3.8	4.3	441	
0.026		0.077	9.6	0.030		
0.0055	0.33	0.62	2.6	3.6		
0.032			0.015	0.32		
	Lagoon					

North	Mean Depth = 115 cm					South
	Ocean					
	0.055	0.0078	136			
0.013	0.035		0.16	4.5	36	
0.0032	0.015		2.9			
0.0008	0.12	3.8	0.0078	1.3		
0.10	0.0096		0.0015			
	Lagoon					

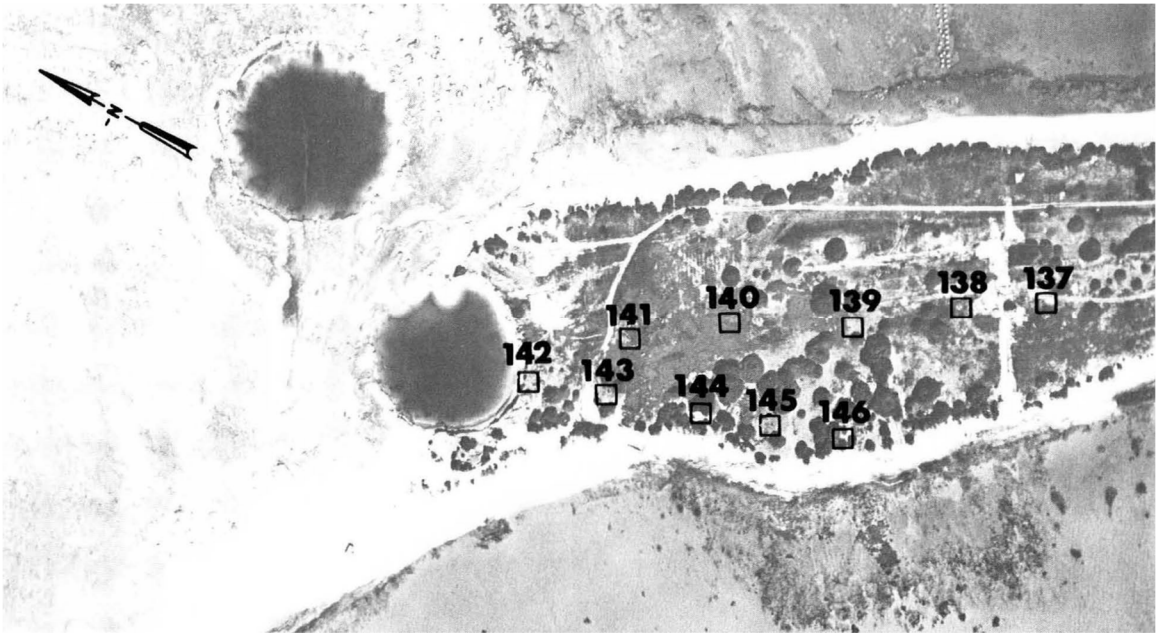


Figure C-6. Soil Sample Locations, Yvonne, Segment A, Figures B.22.1.f NVO-140 (AEC 1973b).

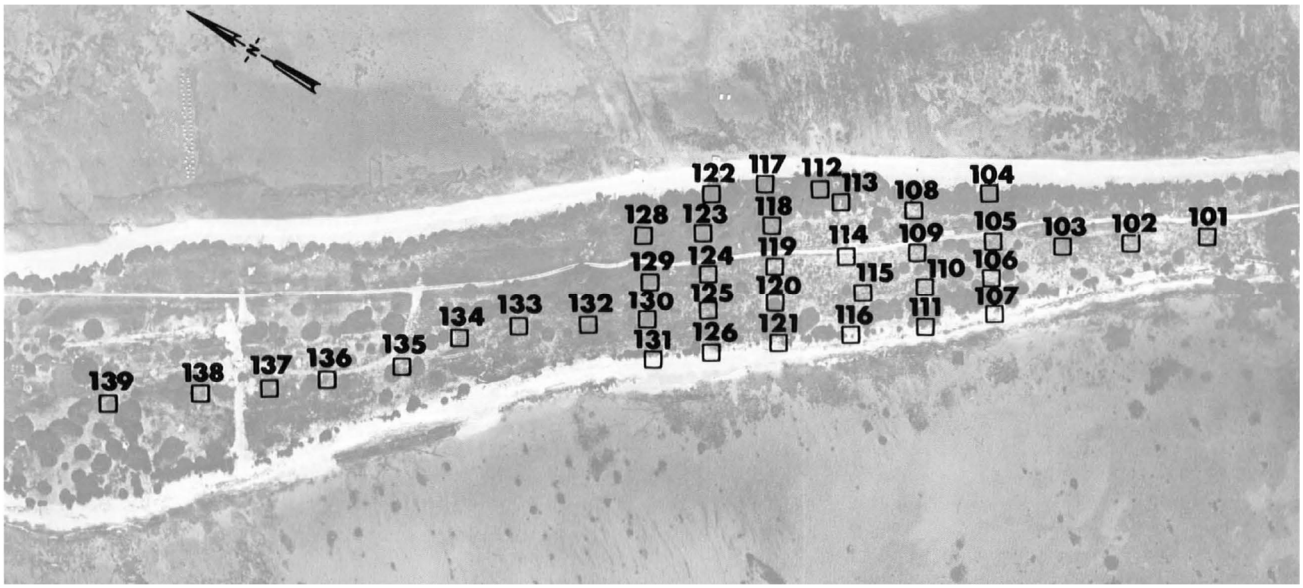


Figure C-7. Soil Sample Locations, Yvonne, Segment B, Figures B.23.1.f NVO-140 (AEC 1973c).

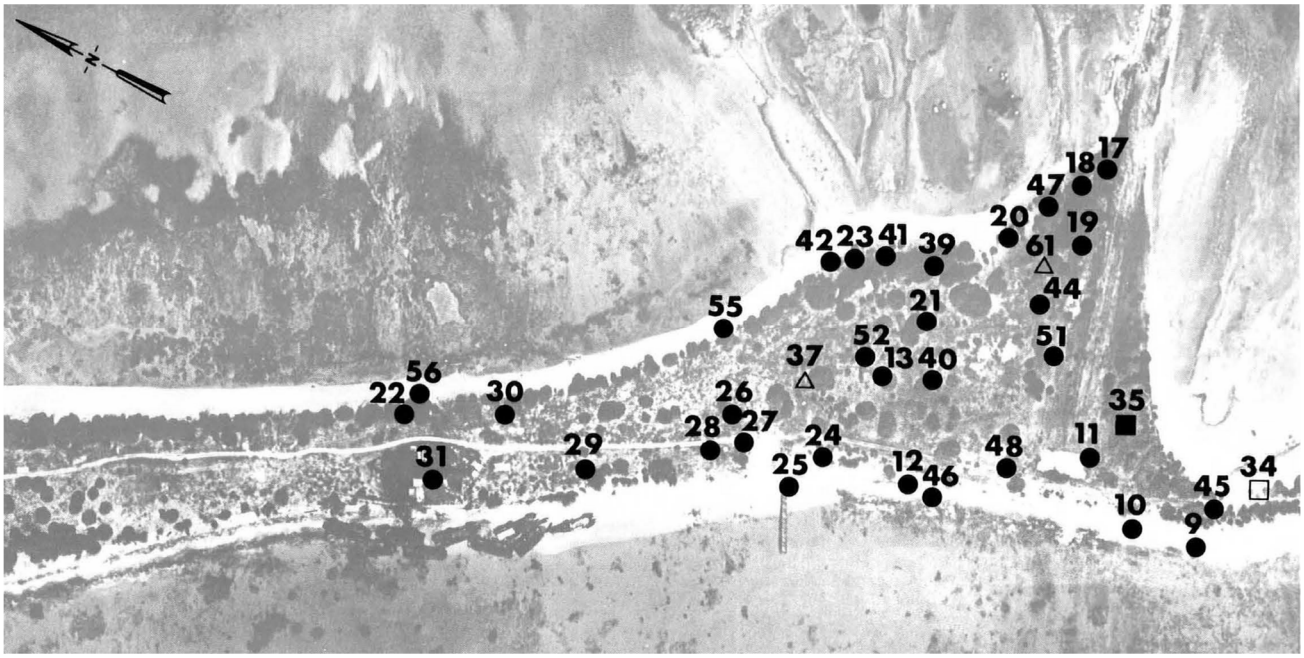


Figure C-8. Soil Sample Locations, Yvonne, Segment C, Figures B.24.1.f NVO-140 (AEC 1973c).

Figure C-9. Soil Sample Locations, Yvonne, Segment D, Figures B.24.1.f NVO-140 (AEC 1973c).

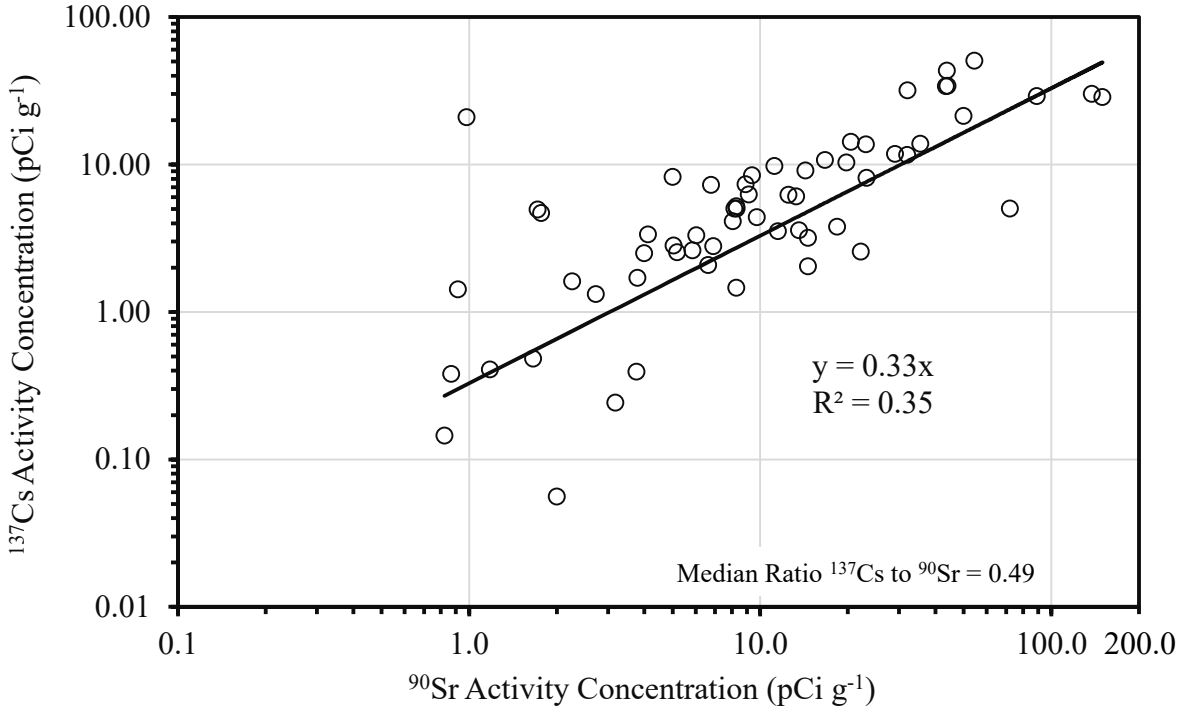


Figure C-10. Scatterplot of ^{137}Cs to ^{90}Sr for NVO-140 Soil Samples from Top 15 cm on Sally.

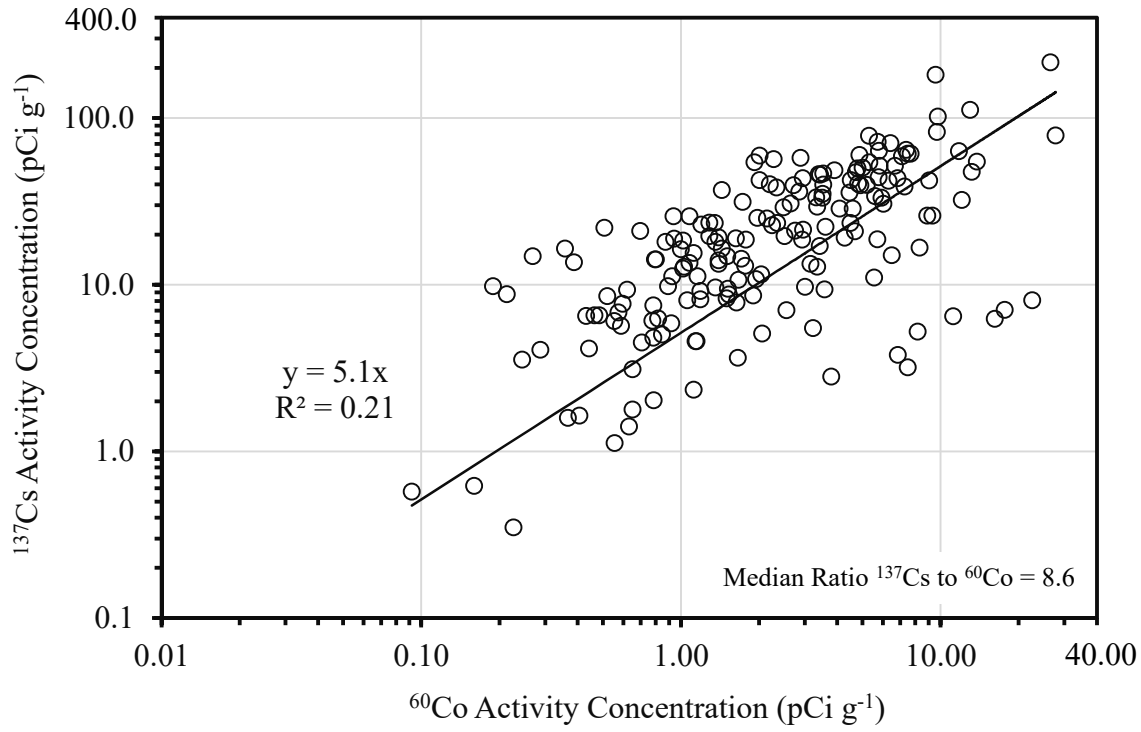


Figure C-11. Scatterplot of ^{137}Cs to ^{60}Co for NVO-140 Soil Samples from Top 15 cm on Janet.

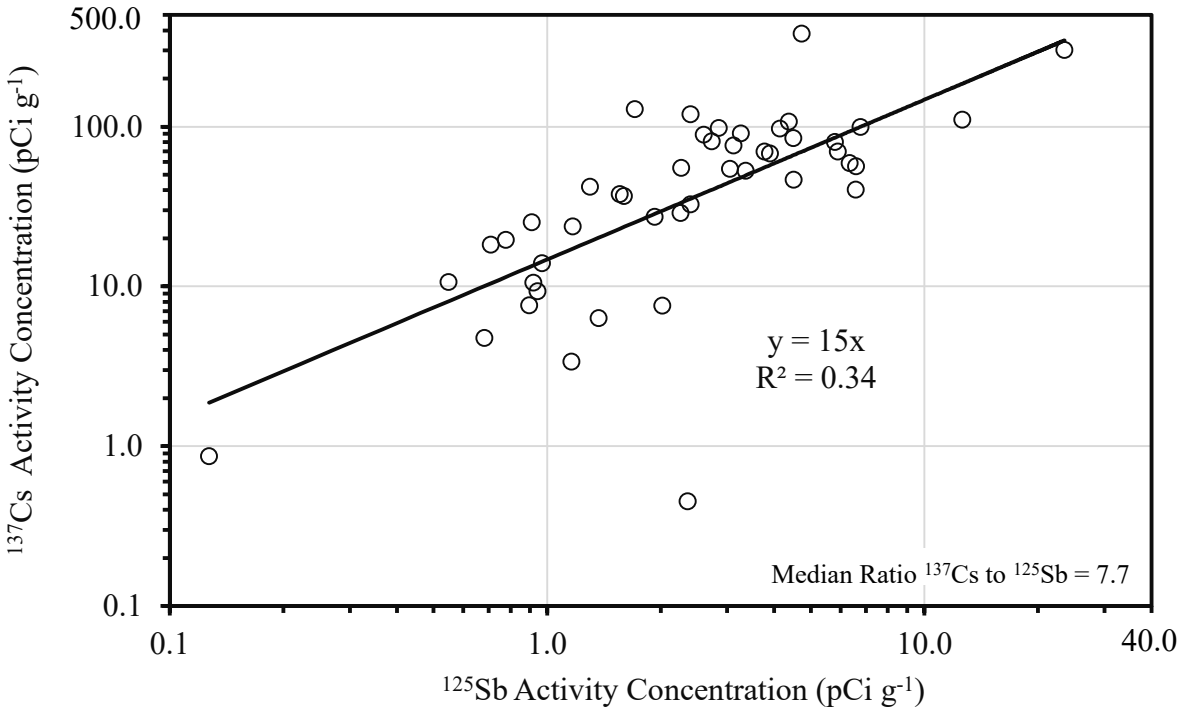


Figure C-12. Scatterplot of ^{137}Cs to ^{125}Sb for NVO-140 Soil Samples from Top 15 cm on Belle.

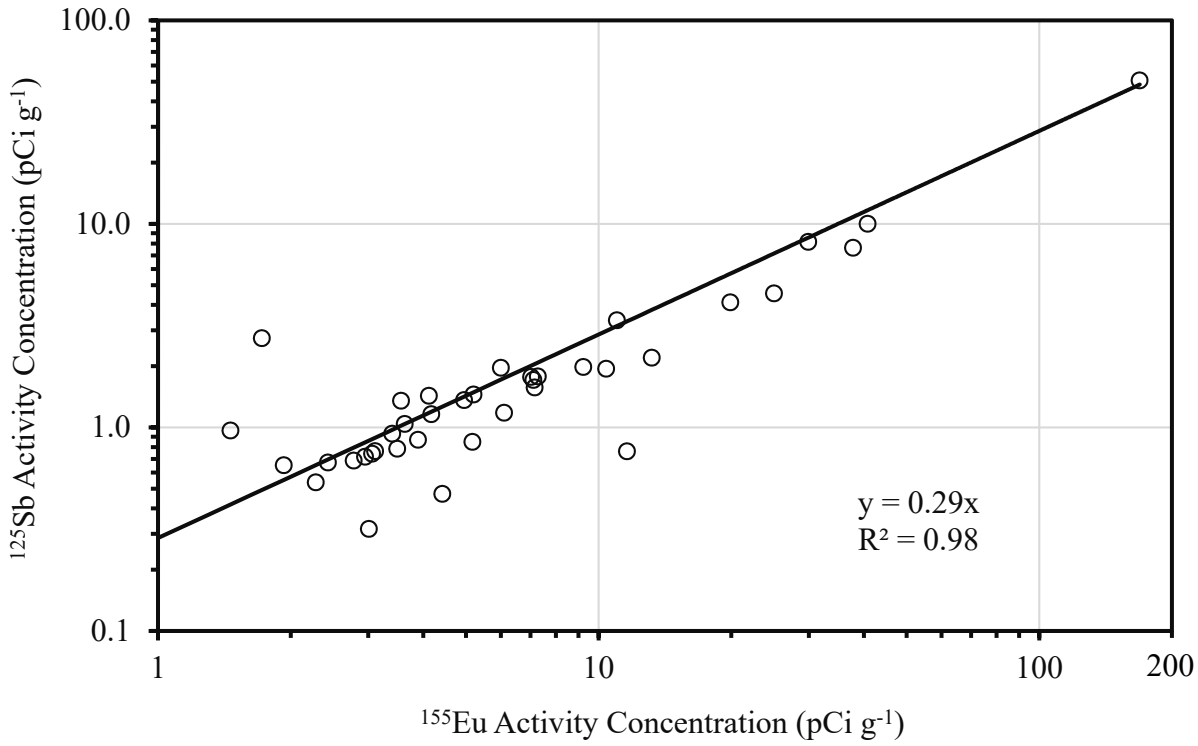


Figure C-13. Scatterplot of ^{125}Sb to ^{155}Eu for NVO-140 Soil Samples from Top 15 cm on Irene.

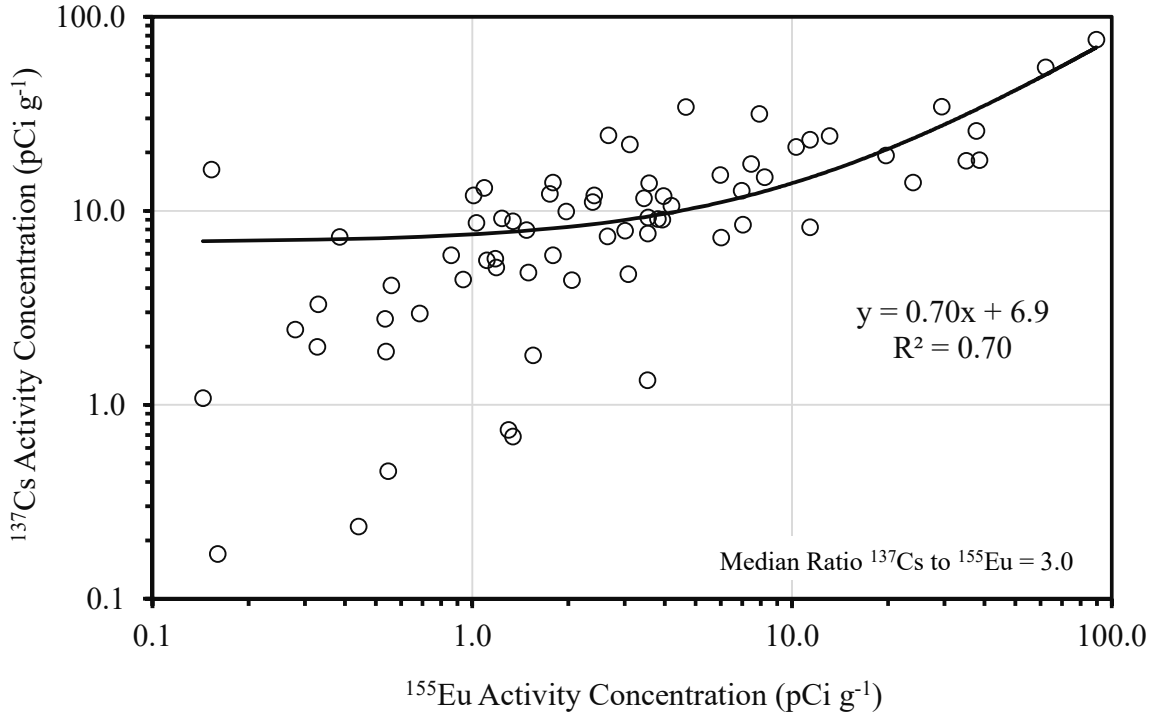


Figure C-14. Scatterplot of ^{137}Cs to ^{155}Eu for NVO-140 Soil Samples from Top 15 cm on Pearl.

Table C-7. Quantities of Material Associated with the 67 Nuclear Tests Conducted at or Near Bikini and Enewetak Atolls [Modified from Table 1 of Robison et al. (2001)].

Material	Half-Life (y)	Mass (g)	Activity	
			(Ci)	(TBq)
Sulfur	Stable	7.27×10^5	-	-
Arsenic	Stable	75.7	-	-
Yttrium	Stable	236	-	-
Rhodium	Stable	< 200	-	-
Indium	Stable	2660	-	-
Tantalum	Stable	88.3	-	-
Tungsten	Stable	3100	-	-
Gold	Stable	500	-	-
Thallium	Stable	1.55×10^5	-	-
Po-210	0.38	1.09	4900	180
Th-228	1.9	0.0023	1.8	0.068
Th-230	7.7×10^4	1494	30	1.1
Th-232	1.4×10^{10}	1.08×10^6	0.12	0.044
U-233	1.6×10^5	1094	10	0.38
U-238	4.5×10^9	6.70×10^7	22	0.83
Am-241	433	0.29	1.0	0.038
Cm-242	0.45	1.8	6200	228

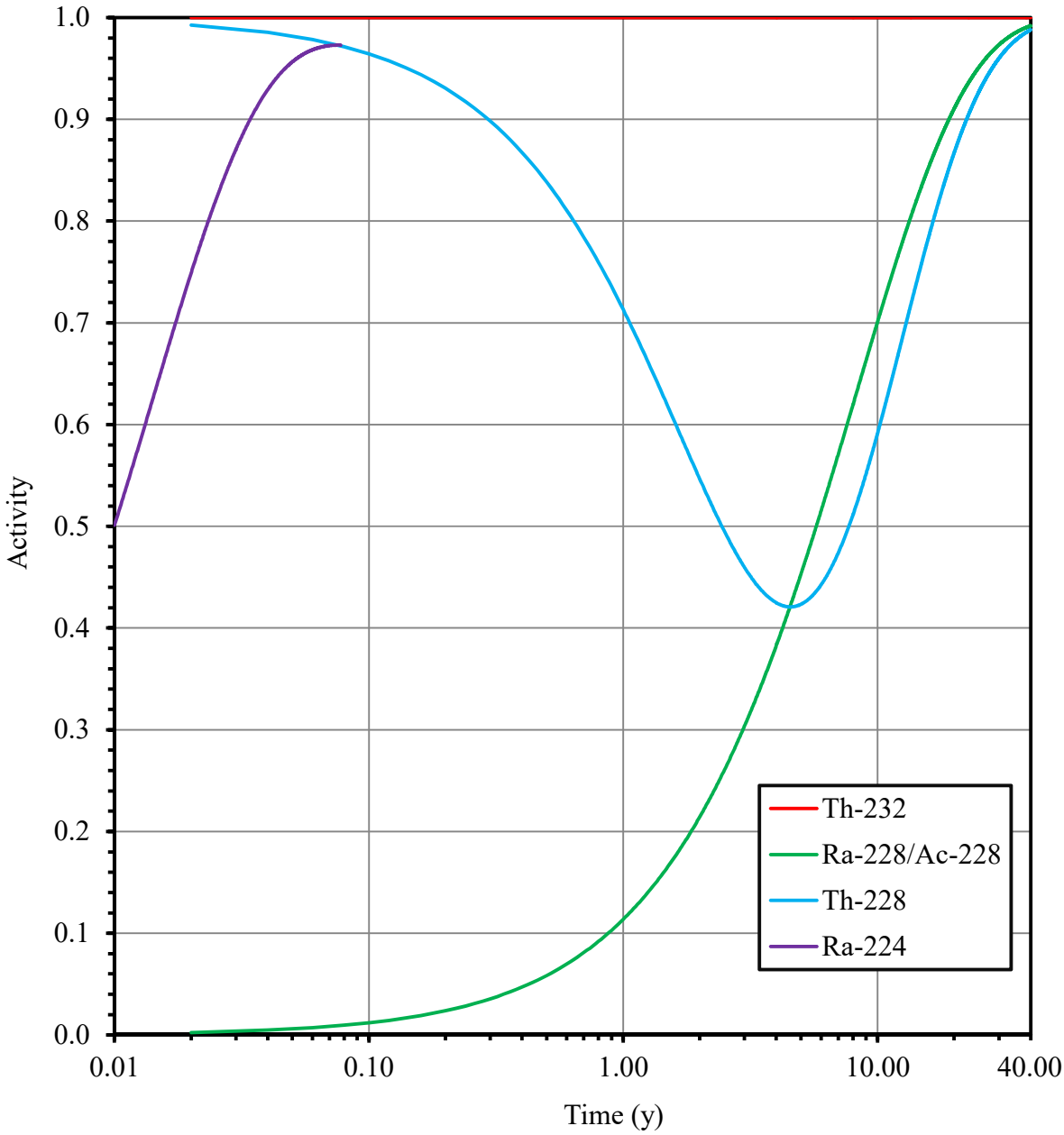


Figure C-15. Activity Concentrations of ^{232}Th Daughter Radionuclides after Chemical Purification.

Table C-8. Concentrations of ^{238}U in Corals from Global Locations [Adapted from Robison et al. (2001).

Location	Sample Number	Mean ± 1 Standard Error		Reference
		Mass ($\mu g\ g^{-1}$)	Activity ($pCi\ g^{-1}$)	
Enewetak Atoll	36	2.90 ± 0.09	0.97	Thurber at al. (1965)
Florida Keys	15	2.70 ± 0.07	0.90	Broeker and Thurber (1965)
Hawaii[a]	6	2.5 ± 0.2	0.83	Veeh and Turekian (1968)
Samoa[b]	5	2.30 ± 0.22	0.77	
Tahiti[b]	5	2.10 ± 0.11	0.70	
Tuamotu[b]	8	1.80 ± 0.12	0.60	
Enewetak[c]	18	3.90 ± 0.14	1.3	Barnes et al. (1956)
Florida Keys[c]	2	2.90 ± 0.35	0.97	Tatsumoto and Goldberg (1959)
Bikini Atoll[d]	100	2.10 ± 0.07	0.70	Robison et al. (2001)
Rongelap Island	15	1.70 ± 0.15	0.57	
Rongelap (No)	50	1.40 ± 0.08	0.47	
Rongelap (So)	176	1.70 ± 0.05	0.57	
Mejit Island	43	1.60 ± 0.08	0.53	
Ailuk Atoll[e]	16	2.20 ± 0.25	0.73	Nelson (1979)
Ailuk Atoll[f]	99	1.90 ± 0.07	0.63	Robison et al. (2001)
Utirik Atoll[g]	5	2.60 ± 0.05	0.87	Nelson (1979)
Utirik Atoll[h]	548	1.60 ± 0.04	0.53	Robison et al. (2001)
Likiep Atoll[i]	68	2.30 ± 0.19	0.77	
Bruce Island[j]	29	1.40 ± 0.11	0.47	
David Island[j]	131	2.00 ± 0.10	0.67	
Elmer Island[j]	304	1.70 ± 0.08	0.57	
Fred Island[j]	422	1.70 ± 0.09	0.57	
Olive Island[k]	15	1.80 ± 0.15	0.60	
Pearl Island[k]	45	1.40 ± 0.08	0.47	
Sally Island[k]	25	1.80 ± 0.19	0.60	
Tilda Island[k]	46	1.50 ± 0.12	0.47	
Ursula Island[k]	55	1.60 ± 0.11	0.53	
Vera Island[k]	50	1.70 ± 0.10	0.57	
Yvonne Island[k]	70	1.50 ± 0.08	0.47	
Janet Island[k]	183	1.90 ± 0.06	0.63	
Rongerik Atoll[l]	25	1.50 ± 0.12	0.50	

[a] Three samples each of two genus coral [b] Three samples of one genus of coral, and two sample of another genus
[c] Two genus coral [d] Nam (13), Iroij (4), Odrik (1), Lomilik (2), Bikini (7), Aerokojlo (36), Lele (5), Eneman (3), Enedrik (16), Lukoj (9), and Jelete (4) [e] Ailuk and Bigen Islands [f] Kapen, Enijabro, Enejelar, Bigenm and Aliet Islands
[g] Aon and Eerukku Islands [h] Utirik, Aon, Bigrak, Eerukku Islands [i] Likiep, Agohy, and Etoile Islands
[j] Enewetak Atoll (Southern) [k] Enewetak Atoll (Northern) [l] Jedibberbid,Latoback, Rongerik, Eniwetak, and Bock Islands

Table C-9. Reported Concentrations of ^{235}U in Soils Collected on Midway and Ujelang from NVO-140 (AEC 1973c).

Island	Sample	Depth (cm)	Activity Concentration (pCi g^{-1})	Island	Sample	Depth	Activity Concentration (pCi g^{-1})
Midway	1305	NS	< 0.023	Ujelang	7258	2 – 5	< 0.023
Midway	1306	NS	0.041 ± 0.008	Ujelang	7259	5 – 10	< 0.018
Midway	1307	NS	< 0.027	Ujelang	7260	10 – 15	< 0.023
Midway	1310	NS	< 0.017	Ujelang	7262	0 – 2	< 0.028
Midway	1314	NS	< 0.016	Ujelang	7263	2 – 5	0.049 ± 0.014
Midway	1315	NS	0.024 ± 0.007	Ujelang	7264	5 – 10	< 0.015
Midway	1316	NS	0.031 ± 0.007	Ujelang	7265	10 – 15	0.040 ± 0.012
Midway	1317	NS	0.028 ± 0.006	Ujelang	7267	0 – 2	< 0.053
Ujelang	7252	0 – 2	< 0.041	Ujelang	7269	2 – 5	< 0.042
Ujelang	7253	2 – 5	< 0.034	Ujelang	7251	0 – 15	< 0.035
Ujelang	7254	5 – 10	< 0.023	Ujelang	7256	0 – 15	0.046 ± 0.016
Ujelang	7255	10 – 15	< 0.036	Ujelang	7251	0 – 15	< 0.033
Ujelang	7257	0 – 2	< 0.034				

NS – not specified

Table C-10. Excerpt from Table 14, NVO-140, Median Activity Ratios* of $^{238}Pu/^{239}Pu$** in Soils Samples (AEC 1973a).

Island	Median Ratio	Island	Median Ratio	Island	Median Ratio
Alice	0.1	Kate	-	Ruby	-
Belle	0.11	Lucy	-	Sally	-
Clara	0.14	Percy	-	Tilda	-
Daisy	-	Mary	-	Ursula	-
Edna	0.06	Nancy	-	Vera	-
Irene	-	Olive	-	Wilma	-
Janet	-	Pearl	-		

* ^{238}Pu activities were measured only in a few samples (NVO-140). ** Inferred ^{239}Pu also included ^{240}Pu.

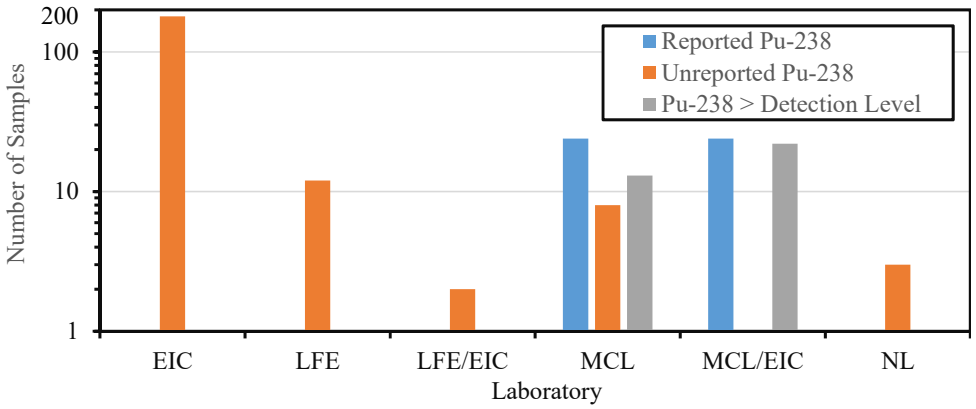


Figure C-16. ^{238}Pu Activity Concentration Reporting for Irene Island, Data from NVO-140 (1973c).

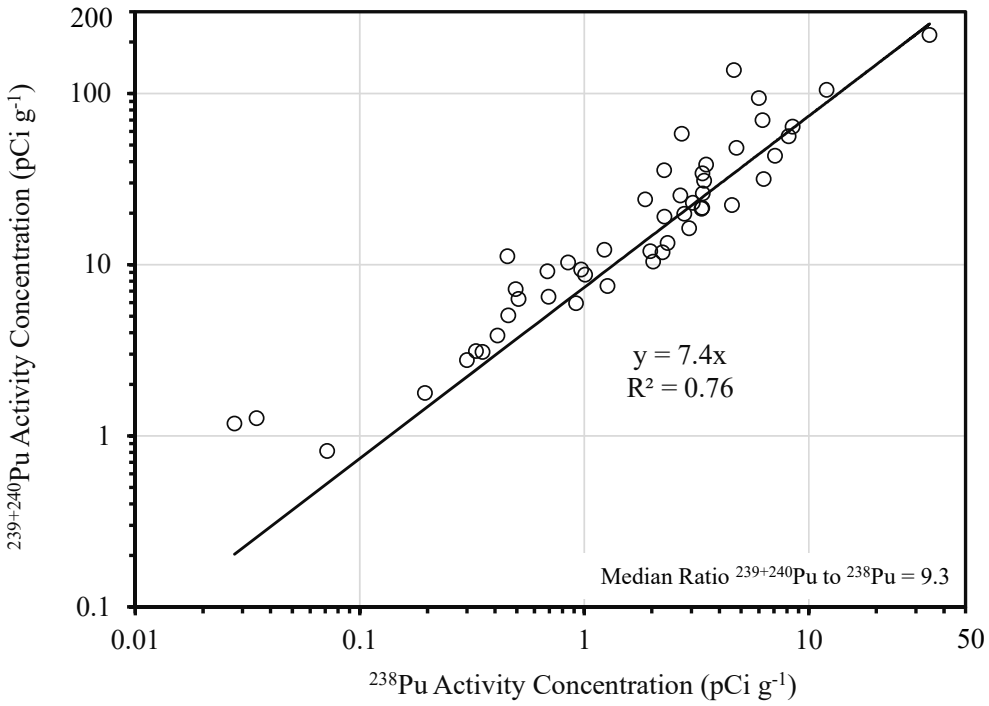


Figure C-17. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for NVO-140 Soil Samples on Belle, Data from AEC (1973c).

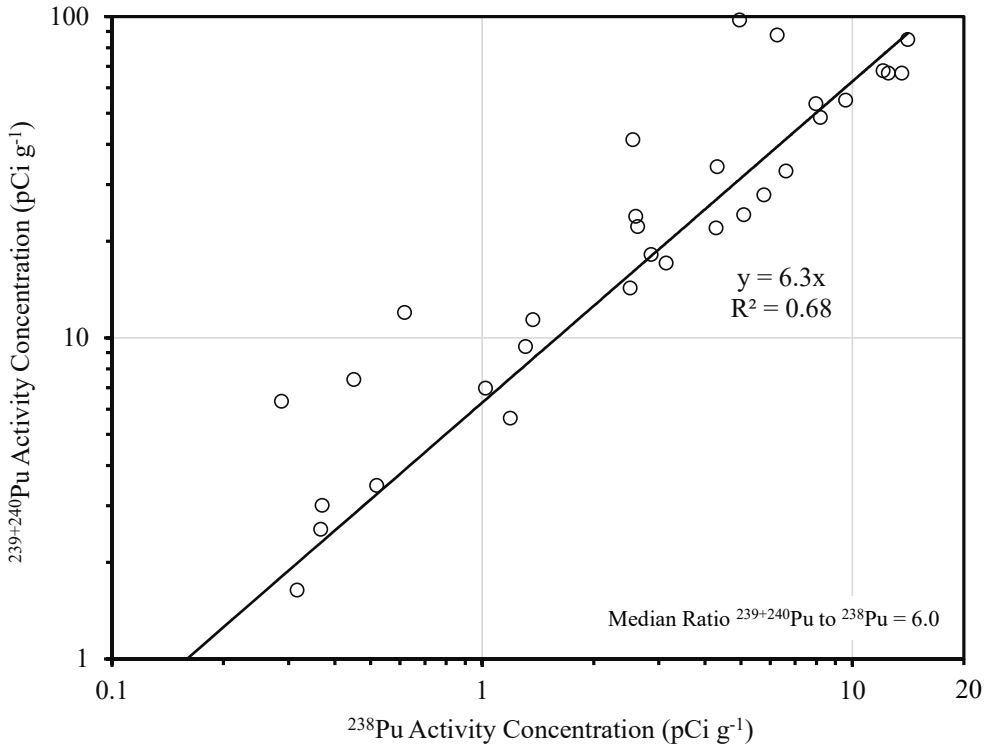


Figure C-18. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for NVO-140 Soil Samples on Clara, Data from AEC (1973c).

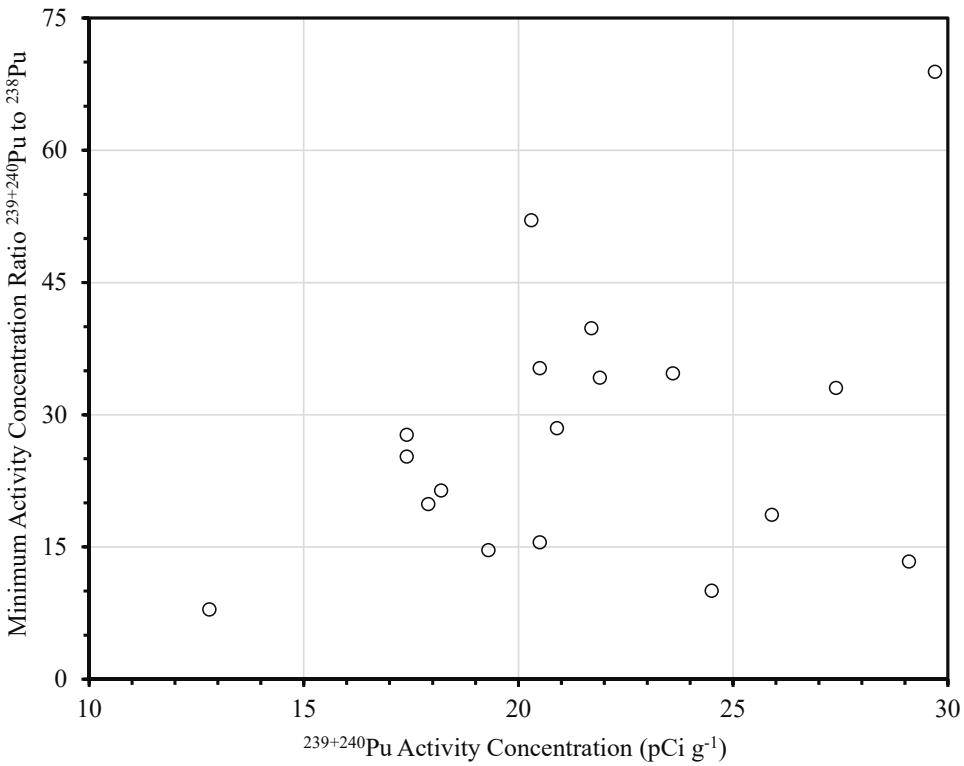


Figure C-19. Scatterplot of Minimum Activity Concentration Ratio $^{239+240}$Pu to ^{238}Pu vs. $^{239+240}$Pu for NVO-140 Soil Samples on Edna, Data from AEC (1973c).

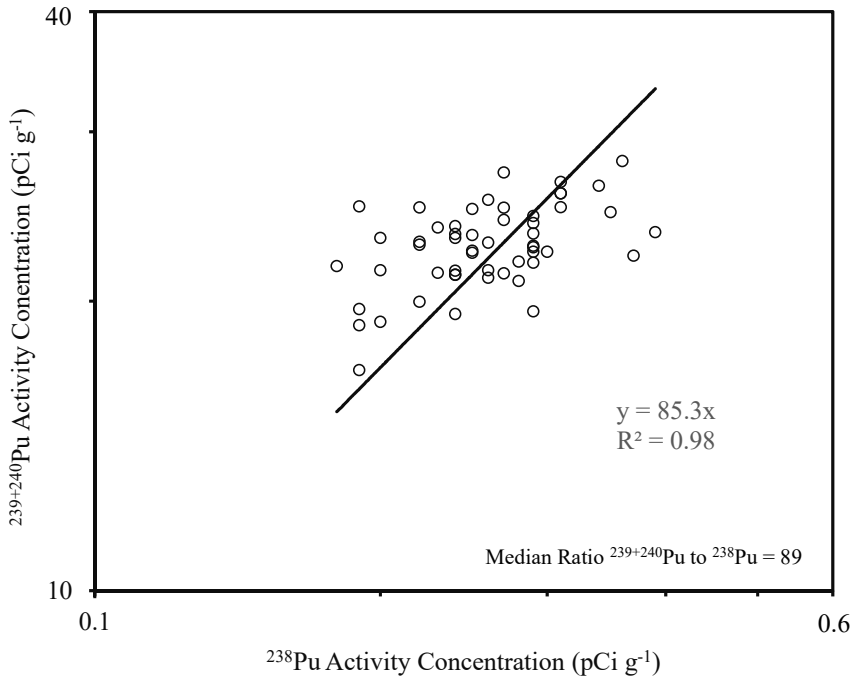


Figure C-20. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for Soil Samples on Edna, Data from DOE (1982).

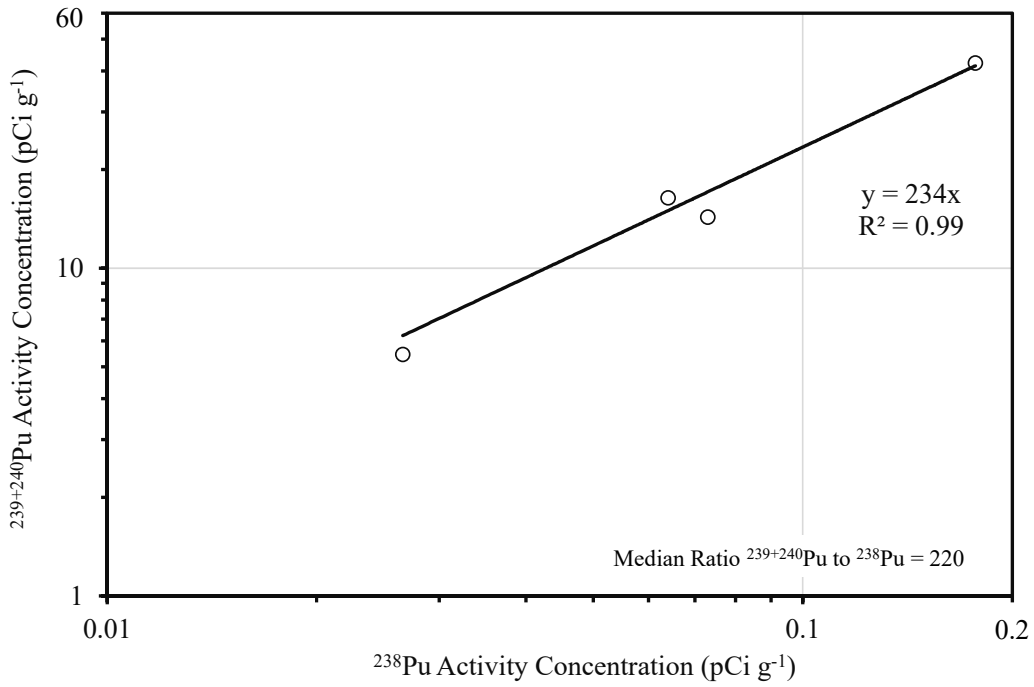


Figure C-21. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for NVO-140 Soil Samples on Percy, Data from AEC (1973c).

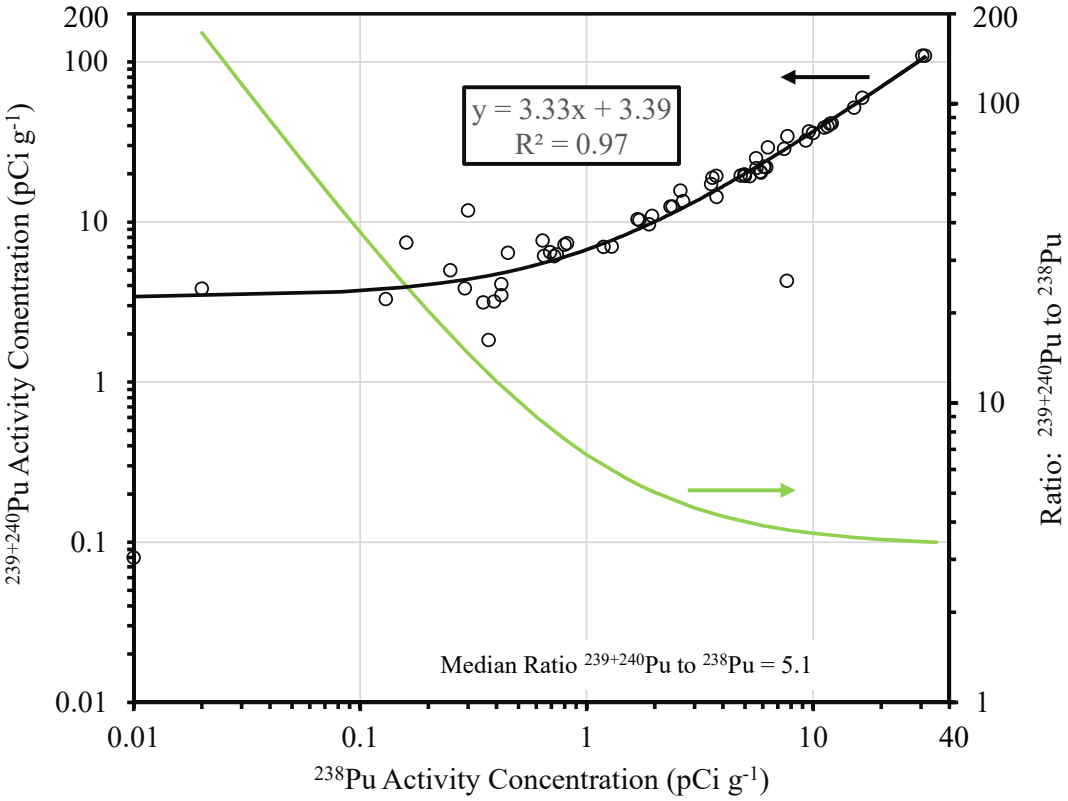


Figure C-22. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for NVO-213 Soil Samples on Irene, Data from DOE (1982).

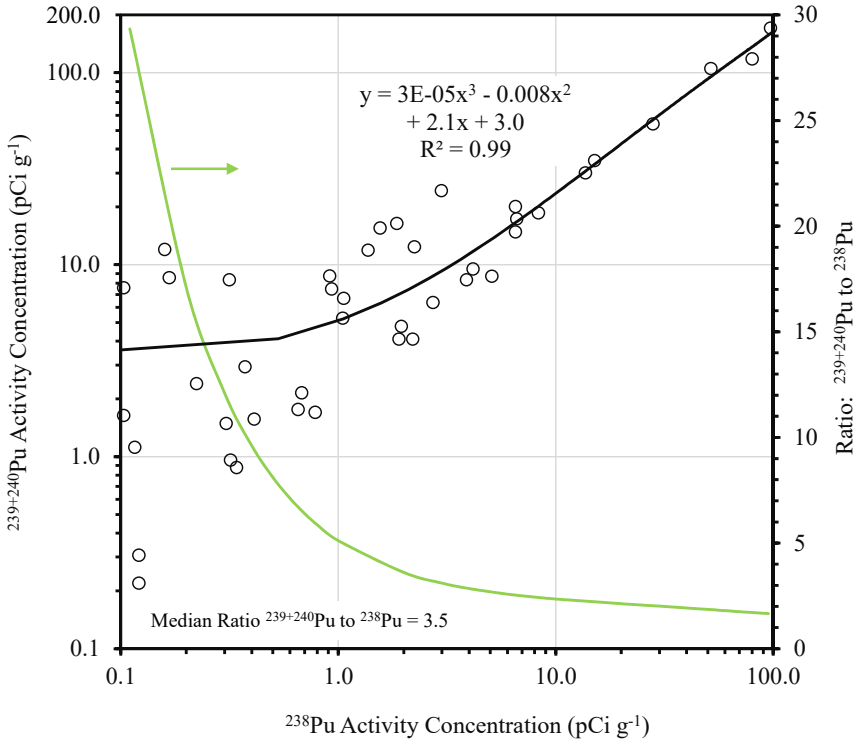


Figure C-23. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for NVO-140 Soil Samples on Pearl, Data from AEC (1973c).

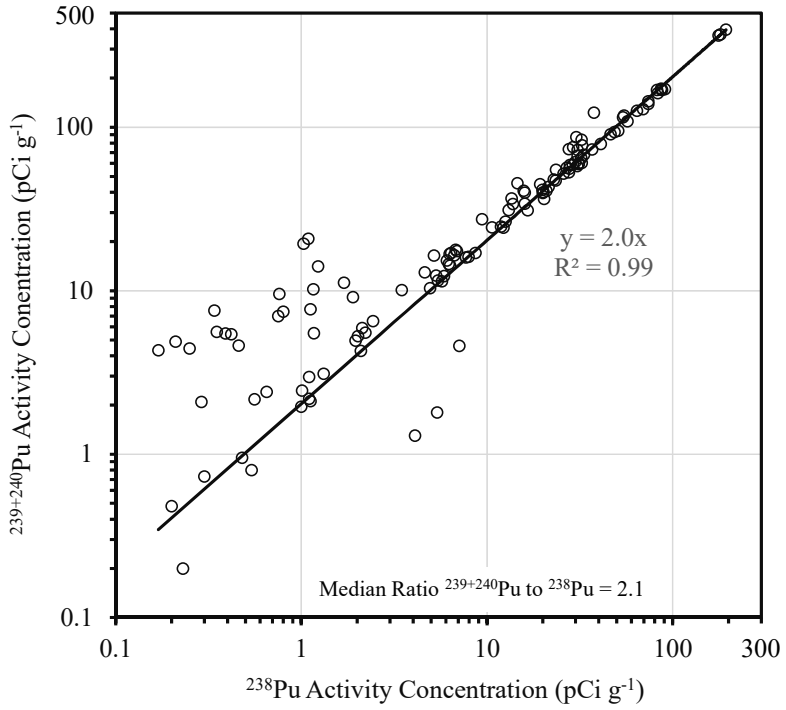


Figure C-24. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for NVO-213 Soil Samples on Pearl, Data from DOE (1982).

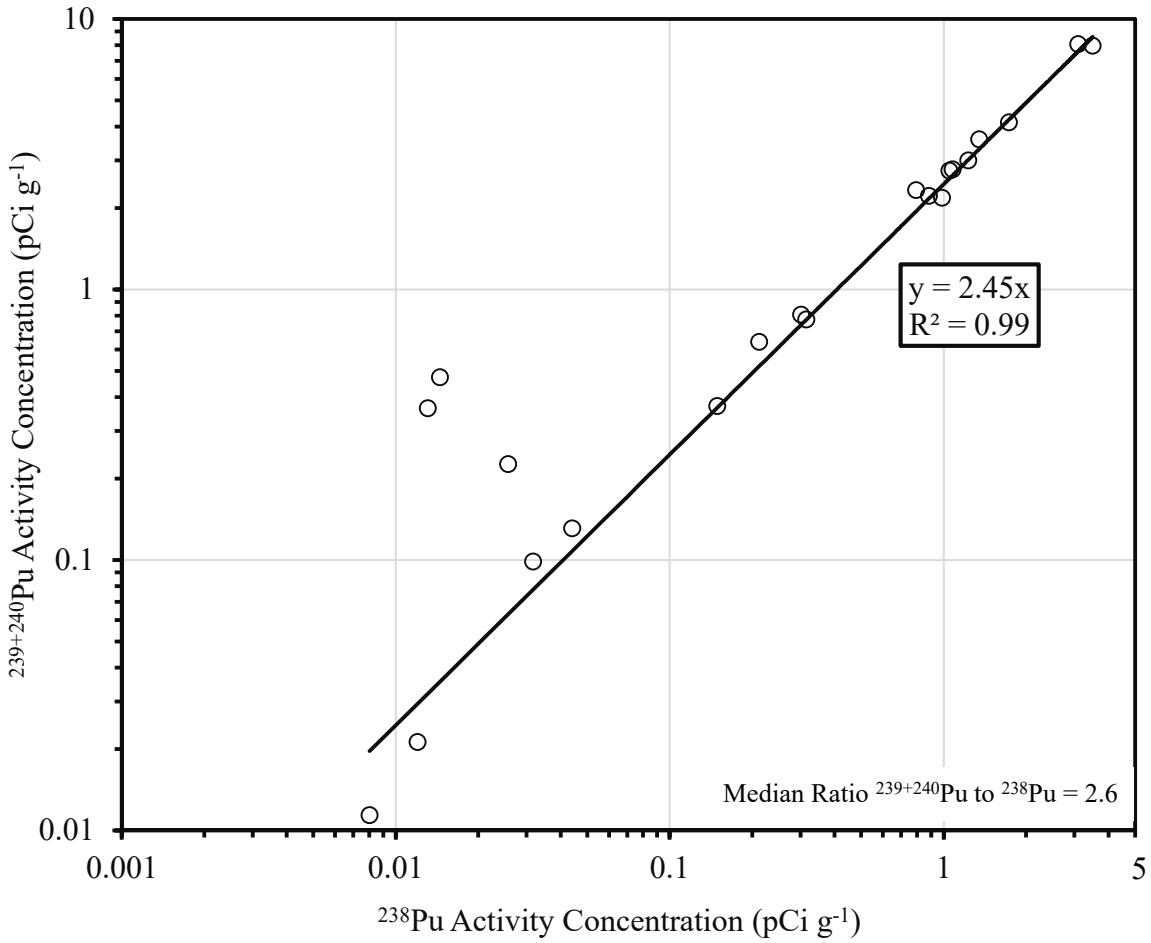


Figure C-25. Scatterplot of $^{239+240}$Pu to ^{238}Pu Activity Concentrations for NVO-140 Soil Samples on Segment C of Yvonne, Data from AEC (1973c).

TABLE C-11. Table 4, Excerpted from EPA Report SWRHL-111r (EPA 1972).

Table 4. Alpha Emitting Nuclides in Soil - Eneman (pCi/g air-dried weight)

Nuclide	100 µR/hr area	500 µR/hr area
$^{239, 240}$Pu	27	410
^{238}Pu	11	220
^{241}Am	2	40

Table C-12. Estimated Mean Transuranic Isotopic Concentrations in Surface Soils for Northern Islands.

Island	Activity Concentration (Top 10 or 15 cm) [pCi g^{-1}]				Clarifying Comments	
	$^{239+240}Pu$	^{241}Am	^{238}Pu	Total	Isotope	Text
Alice	16	5.8	1.2	24	^{238}Pu	Slope of regression analysis to $^{239+240}Pu$ (13)
Belle	28	7.8	3.7	40	^{238}Pu	Slope of regression analysis to $^{239+240}Pu$ (7.4)
Clara	32	7.4	5.3	44	^{238}Pu	Median ratio to $^{239+240}Pu$ (6.0)
Daisy	31	7.8	2.6	42	^{238}Pu	Median ratio to $^{239+240}Pu$ (12)
Edna	20	5.9	0.23	26	^{238}Pu	Slope of regression analysis to $^{239+240}Pu$ (85)†
Irene	12	2.0	5.2	19	^{238}Pu	Slope of regression analysis to $^{239+240}Pu$ (2.3)
Janet	16	5.4	1.0	22	^{241}Am	Median ratio to $^{239+240}Pu$ (3.1)
					^{238}Pu	Median ratio to $^{239+240}Pu$ (15)‡
Kate	11	4.1	Negligible	14	^{241}Am	Slope of regression analysis to $^{239+240}Pu$ (2.7)
Lucy	7.8	3.1	0.76	12	^{241}Am	Slope of regression analysis to $^{239+240}Pu$ (2.5)
Mary	14	5.4	Negligible	19		
Nancy	10	1.1	Negligible	11	^{241}Am	Median ratio to $^{239+240}Pu$ (2.5)
Percy	9.0	3.2	Negligible	12		
Olive	8.4	2.8	0.90	12	^{238}Pu	Median ratio to $^{239+240}Pu$ (9.8)
Pearl	39	5.4	21	65	^{238}Pu	Slope of regression analysis to $^{239+240}Pu$ (1.9)
Ruby	11	1.5	1.2	14	^{241}Am	Median ratio to $^{239+240}Pu$ (7.5)
					^{238}Pu	Median ratio to $^{239+240}Pu$ (9.5)
Sally	14	4.3	0.39	19	^{241}Am	Median ratio to $^{239+240}Pu$ (3.3)
					^{238}Pu	Slope of regression analysis to $^{239+240}Pu$ (36)
Tilda	5.7	2.3	0.32	8.3	^{241}Am	Median ratio to $^{239+240}Pu$ (2.5)
Ursula	1.8	0.72	Negligible	2.5		
Vera	16	1.7	Negligible	18	$^{239+240}Pu$	Biased high due to outlier sample
Wilma	13	0.6	Negligible	14	$^{239+240}Pu$	Biased high due to outlier sample
Yvonne (A)	31	3.9	13	48	^{238}Pu	Slope of regression analysis from section A/B
Yvonne (A/B)	34	2.8	14	46	^{238}Pu	Slope of regression analysis to $^{239+240}Pu$ (2.4)
Yvonne (B)	140	11	29	180	^{238}Pu	Slope of regression analysis to $^{239+240}Pu$ (4.9)
Yvonne (C)	12	1.6	4.9	18	^{238}Pu	Slope of regression analysis to $^{239+240}Pu$ (2.5)
Yvonne (D)	14	0.4	5.8	20	^{238}Pu	Slope of regression analysis from section A/B
					$^{239+240}Pu$	Biased high due to outlier sample

† NVO-213 Data ‡ NVO-213 Data Support a Higher Ratio

Table C-13. Soils Data for Northern Islands, Adapted from Tables 7-1 through 7-3, NVO-213 (DOE 1982).

Island	Sampling Date (1979)	Descriptive Statistics for Random-Selected Surface Soil Samples – Top 15 cm (pCi g^{-1})								
		^{90}Sr			^{137}Cs			$^{239+240}Pu$†		
		Number	Mean	Range	Number	Mean	Range	Number	Mean	Range
Alice	19 March	7	85.9	1.3 - 347	26	39.9	< 0.4 - 114	26	20.5	< 2 - 226
Belle	19 March	11	107.4	3.5 - 339	40	61.0	< 0.4 - 204	40	34.5	< 2 - 245
Clara	21 March	4	42.8	1.4 - 243	8	22.4	0.3 - 105	8	16.0	< 2.5 - 54
Daisy	22 March	8	34.8	1.9 - 144	26	6.8	< 0.4 - 34	26	25.4	< 2 - 121
Edna	22 March	3	21.7	4.3 - 48	5	2.9	< 0.4 - 7	5	17.8	9.4 - 28
Irene	23-24 Mar	15	31.0	0.6 - 136	53	6.1	< 0.4 - 54	53	29.5	< 4 - 187
Janet	7/15 Mar	99	31.9	< 0.1 - 244	364	16.4	< 0.4 - 142	364	10.1	< 3 - 119
Kate	30 March	6	13.3	1.0 - 31	18	7.8	< 0.4 - 35	18	5.0	< 1.5 - 27
Lucy	30 March	8	21.9	1.0 - 31	22	11.7	< 0.4 - 40	22	10.1	< 1.5 - 74
Percy	30 March	2	5.4	1.0 - 94	2	0.6	< 0.4 - 2	2	1.7	< 1.5 - 2.7
Mary	29 March	4	14.2	2.0 - 7	12	6.0	< 0.4 - 18	12	7.2	< 1.5 - 27
Mary's Daughter	29 March	1	41.9	1.1 - 46	3	12.3	< 0.4 - 72	3	8.4	< 1.5 - 44
Nancy	29 March	6	20.1	5.2 - 107	11	10.8	< 0.4 - 60	14	8.0	< 1.5 - 48
Olive	5-6 Mar	12	16.2	< 0.15 - 82	50	7.5	< 0.4 - 60	50	6.4	< 2 - 72
Pearl	27 Mar, 30 May, 13 Jun	17	11.4	< 0.12 - 83	72	7.2	< 0.4 - 43	72	15.5	< 3.5 - 130
Pearl's Daughter	31 March	1	18.0	0.4 - 38	2	5.6	< 0.4 - 7	2	44.8	< 6 - 85
Ruby	25 March	1	5.8	1.3 - 28	3	2.0	1.1 - 11	3	5.6	< 3.5 - 7.5
Sally	20/27 Mar	39	4.4	5.5 - 9	137	3.5	< 0.4 - 43	137	2.2	< 2 - 72
Sally's Child	3 April	4	16.7	< 0.10 - 25	4	6.9	< 0.4 - 13	4	12.1	< 1.5 - 51
Tilda	9/10/15 Mar	15	5.6	1.0 - 60	48	3.2	< 0.4 - 20	48	2.0	< 1.5 - 20
Ursula	14 March	15	3.0	< 0.08 - 70	15	1.2	< 0.4 - 4	15	0.6	< 1.5 - 2.5
Vera	28 Feb	13	4.8	0.2 - 29	48	3.0	< 0.4 - 20	48	2.2	< 1.5 - 22
Wilma	26 Feb	5	2.9	0.2 - 19	17	1.3	< 0.4 - 5	17	1.1	< 1.5 - 10
Yvonne (south)	2 April	5	1.1	< 0.13 - 5	14	1.5	< 0.4 - 11	14	11.6	< 4.5 - 93

† Inferred from ^{241}Am.

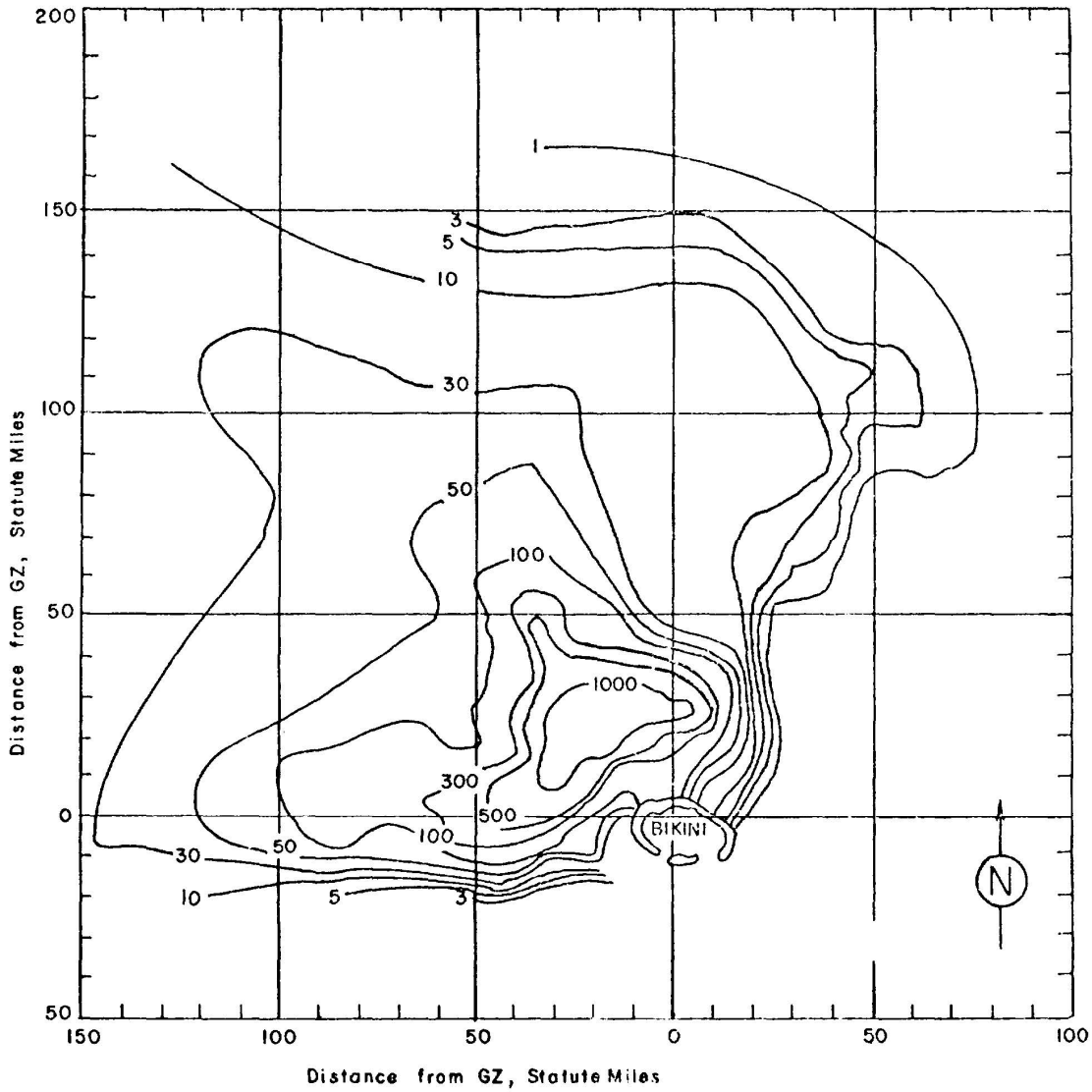


Figure C-26. Estimated Radiation Exposure Rate Contours (R h^{-1}) at One-Hour Post Detonation of Event Tewa, Bikini Atoll, 21 July 1956 [Figure 108, (DNA 1979)].

TABLE C-14. Radionuclide Concentrations for Soils in 1973 and 1959 on Elmer - Assessment Method based on 1973 AEC Data.

Isotope(s)	Activity Concentrations of Radionuclides in Soils for 1973		Activity Concentrations of Radionuclides in Soils for 1959	
	Value	Analysis Method	Value	Analysis Method
^{238}Pu	Estimated	ratio: $^{239+240}$Pu to ^{238}Pu established by regression analysis of soil data (Figure C-27)	Estimated	Relationship established to $^{239+240}$Pu for 1973 retained due to limited decay
$^{239+240}$Pu	Soil Data	mean activity of Elmer soil	Estimated	Environmental dilution extrapolated from between 1973 and 1959, $\tau_{1/2}$ = 20 y
^{241}Pu	Estimated	theoretical ratio: $^{239+240}$Pu to ^{241}Pu for 700 MWd/t (1954), decayed to 1973 (Figure C-29)	Estimated	theoretical ratio: $^{239+240}$Pu to ^{241}Pu for 700 MWd/t (1954), decayed to 1959
^{241}Am	Estimated	ratio: $^{239+240}$Pu to ^{241}Am established by regression analysis of soil data (Figure C-28)	Estimated	Ratio: $^{239+240}$Pu and ^{241}Am in 1973 decay-corrected to 1959 (1954 chemically separated)
^{137}Cs	Soil Data	mean activity of Elmer soil	Estimated	Environmental dilution and radiological decay extrapolated between 1973 and 1959. Environmental dilution half-value (y): $\tau_{1/2}$ = 12 y (Cs) $\tau_{1/2}$ = 16 y (Co, Sr, Bi, Sb, Eu, Rh)
^{90}Sr	Soil Data	mean activity of Elmer soil		
^{207}Bi	Soil Data	mean activity of Elmer soil		
^{60}Co	Estimated	regression analysis: ^{137}Cs to ^{60}Co from Alice-Belle-Clara linked to mean ^{137}Cs of Elmer soil		
^{125}Sb	Estimated	regression analysis: ^{137}Cs to ^{125}Sb from Daisy linked to mean ^{137}Cs of Elmer soil		
^{152}Eu	Estimated	regression analysis: ^{137}Cs to ^{152}Eu from Daisy linked to mean ^{137}Cs of Elmer soil		
^{154}Eu	Estimated	regression analysis: ^{152}Eu to ^{154}Eu from Belle linked to estimated ^{152}Eu in Elmer soil		
^{155}Eu	Estimated	regression analysis: ^{137}Cs to ^{155}Eu from Elmer linked to mean ^{137}Cs of Elmer soil		
^{102m}Rh	Estimated	regression analysis: ^{137}Cs to ^{102m}Rh from Alice-Belle-Clara linked to mean ^{137}Cs of Elmer soil		
^{106}Ru	Not Applicable	Infrequently observed in a few soil samples, insignificant contribution to potential internal or external doses for time of sampling	Estimated	Relationship of fission yield of each radionuclides to the same of ^{90}Sr established for 1953. Relationships decay-corrected to 1959.
^{144}Ce				
^{147}Pm				
^{151}Sm		Not analyzed		

TABLE C-15. Radionuclide Concentrations for Soils in 1973 and 1959 based on Methodology Listed in Table C-14.

Isotope(s)	Activity Concentrations of Radionuclides in Soils (pCi g^{-1}) 1973		Activity Concentrations of Radionuclides in Soils (pCi g^{-1}) 1959	
	Value	Basis	Value	Basis
^{238}Pu	0.0469	Scaling factor to $^{239+240}$Pu: 1/8.1 = 0.123	0.076	Dilution factor: 1.62, $\tau_{1/2}$ = 20 y
$^{239+240}$Pu	0.380	mean activity of Elmer soil	0.618	Dilution factor: 1.62, $\tau_{1/2}$ = 20 y
^{241}Pu	0.961	Scaling factor to $^{239+240}$Pu: 1/0.395 = 2.53	3.06	Scaling factor to $^{239+240}$Pu: 1/0.202 = 4.95
^{241}Am	0.047	Scaling factor to $^{239+240}$Pu: 1/8.1 = 0.123	0.028	Scaling factor to $^{239+240}$Pu: 1/22.3 = 0.0448
^{137}Cs	0.36	mean activity of Elmer soil	1.11	Decay & Dilution factor: 2.24, $\tau_{1/2}$ = 12 y
^{90}Sr	0.72	mean activity of Elmer soil	1.84	Decay & Dilution factor: 1.83, $\tau_{1/2}$ = 16 y
^{207}Bi	0.010	mean activity of Elmer soil	0.025	
^{60}Co	0.082	Scaling factor to ^{137}Cs: 1/4.4 = 0.227 (Fig. C-30)	0.950	
^{125}Sb	0.073	Scaling factor to ^{137}Cs: 1/4.9 = 0.204 (Fig. C-31)	4.31	
^{152}Eu	0.023	Scaling factor to ^{137}Cs: 1/16 = 0.0625 (Fig. C-32)	0.084	
^{154}Eu	0.0087	Scaling factor to ^{152}Eu: 1/2.6 = 0.385 (Fig. C-33)	0.048	
^{155}Eu	0.073	Scaling factor to ^{137}Cs: 1/4.9 = 0.204 (Fig. C-34)	0.938	
^{102m}Rh	0.0031	Scaling factor to ^{137}Cs: 1/116 = 0.009 (Fig. C-35)	0.161	
^{106}Ru	Not Estimated	Not Estimated	0.845	Ratio of ^{106}Ru to ^{90}Sr fission yield in 1953: 0.810 (atoms), 23.0 (activity). Ratio in 1959: 0.458 (activity)
^{144}Ce			0.572	Ratio of ^{144}Ce to ^{90}Sr fission yield in 1953: 1.50 (atoms), 57.0 (activity). Ratio in 1959: 0.31 (activity)
^{147}Pm			4.17	Ratio of ^{147}Nd to ^{90}Sr fission yield in 1953: 0.862 (atoms), 9.56 (activity). Ratio in 1959: 2.26 (activity). [Note: ^{147}Pm is daughter of short-lived ^{147}Nd, $\tau_{1/2}$ = 11 d].
^{151}Sm			0.172	Ratio of ^{151}Pm to ^{90}Sr fission yield in 1953: 0.260 (atoms), 0.084 (activity). Ratio in 1959: 0.093 (activity). [Note: ^{151}Sm is daughter of short-lived ^{151}Pm, $\tau_{1/2}$ = 28 h].

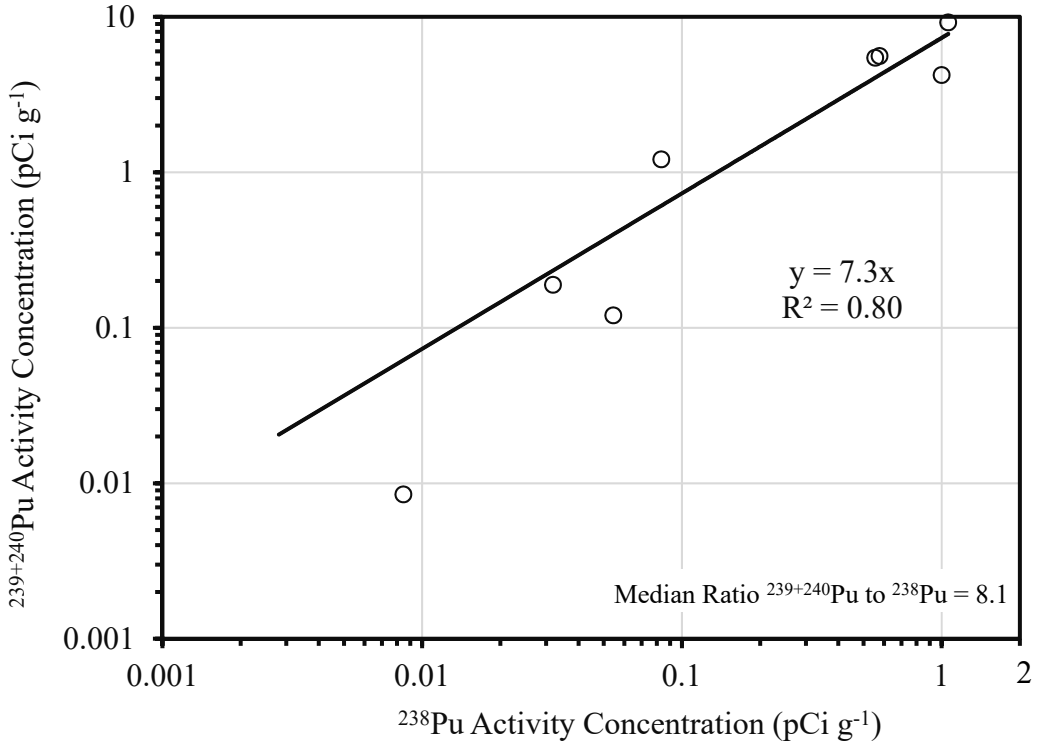


Figure C-27. Scatterplot of $^{239+240}$Pu to ^{238}Pu for NVO-140 Soil Samples from Elmer.

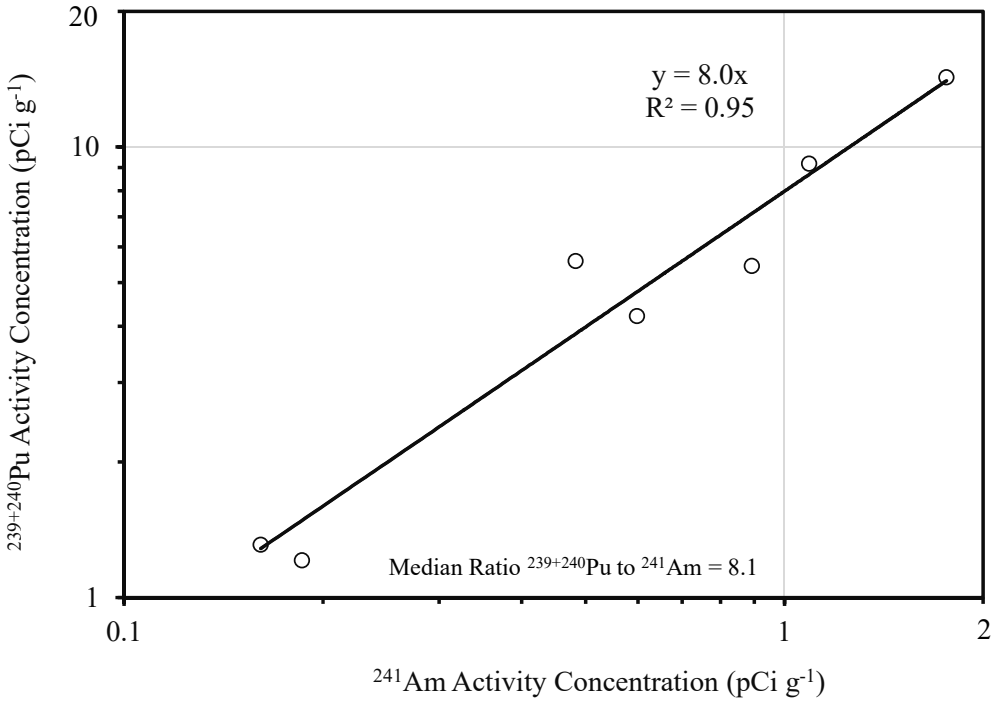


Figure C-28. Scatterplot of $^{239+240}$Pu to ^{241}Am for NVO-140 Soil Samples from Elmer.

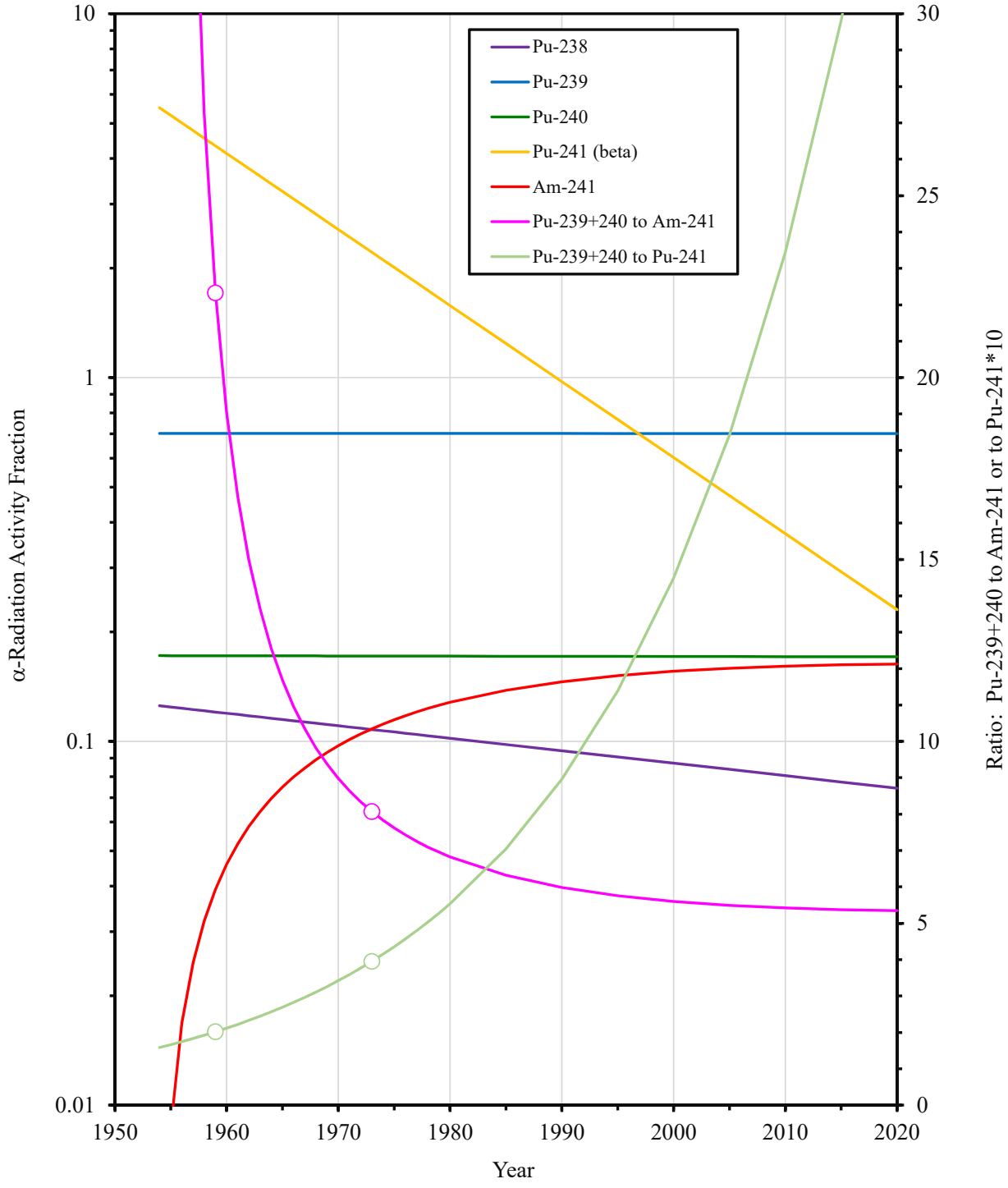


Figure C-29. Modelled Relationships between Plutonium Isotopes and ^{241}Am in Surface Soils on Island Elmer [α-Radiation Fraction Includes ^{238}Pu, ^{239}Pu, and ^{240}Pu; Circles Annotate Data Points Pertinent to Calculations in this Work].

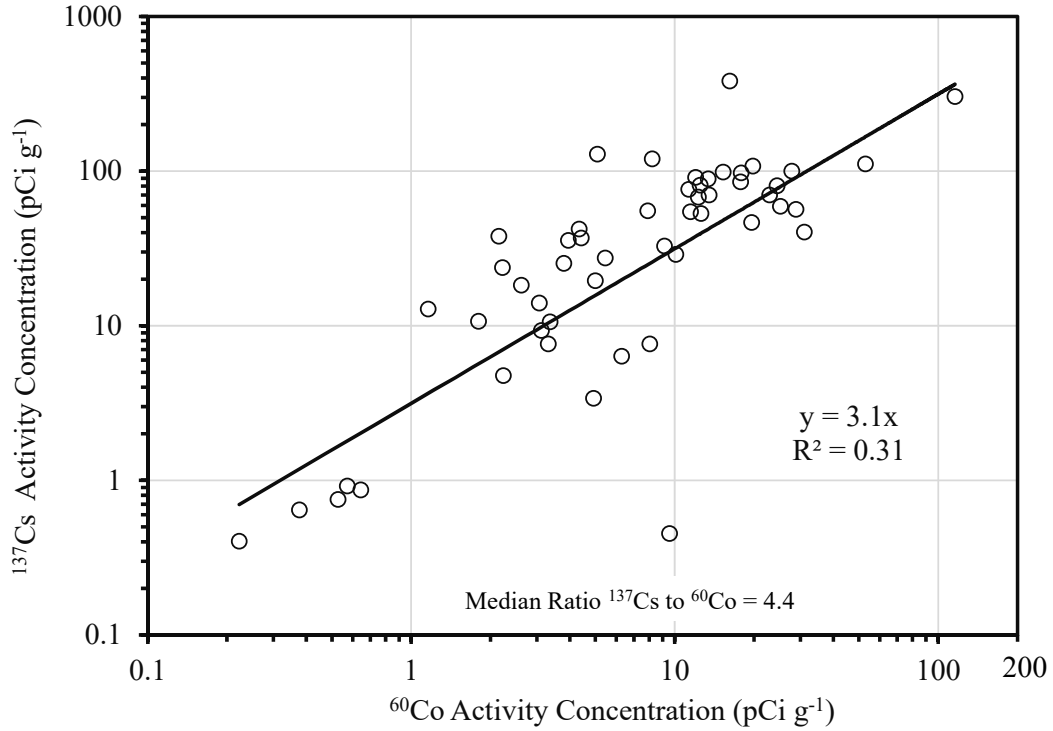


Figure C-30. Scatterplot of ^{137}Cs to ^{60}Co for NVO-140 Soil Samples from Belle.

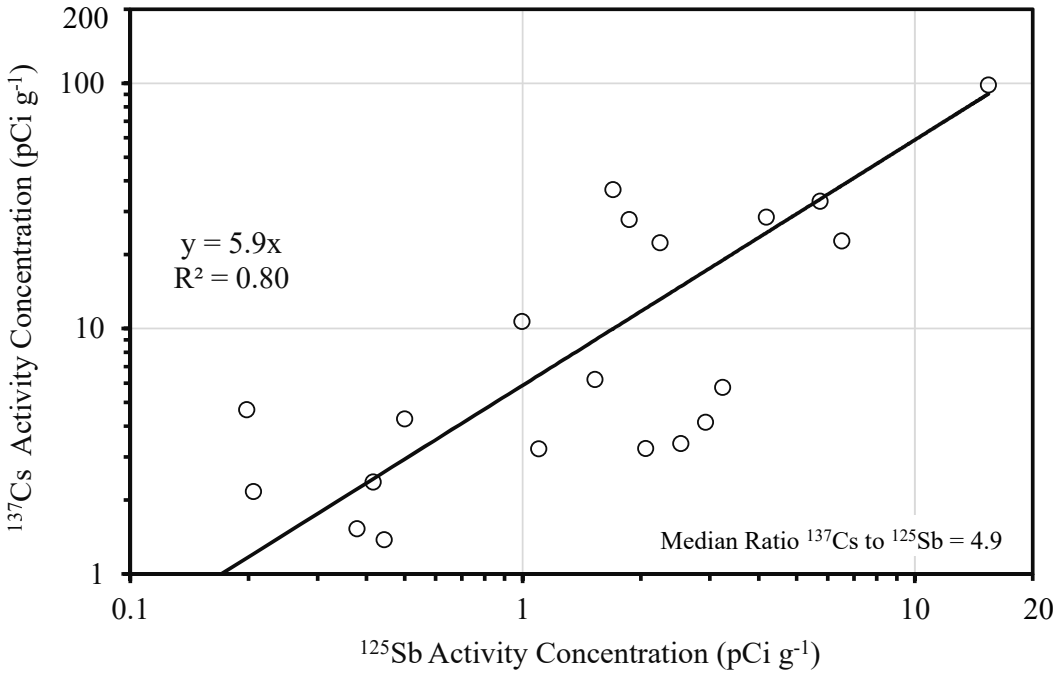


Figure C-31. Scatterplot of ^{137}Cs to ^{125}Sb for NVO-140 Soil Samples from Daisy.

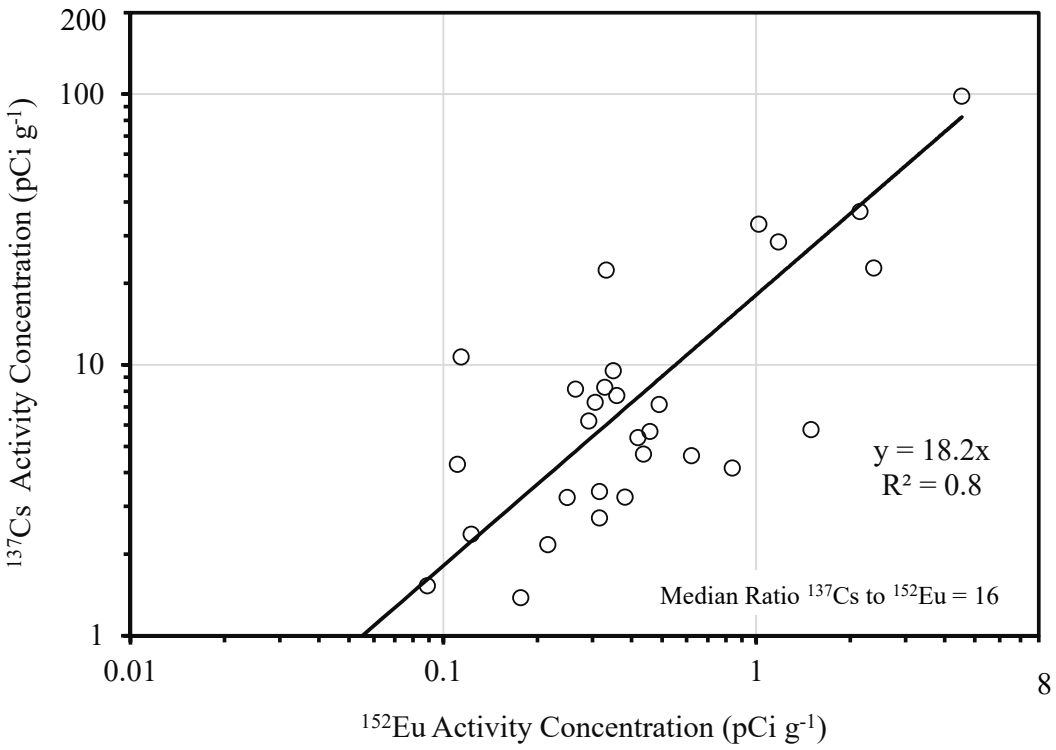


Figure C-32. Scatterplot of ^{137}Cs to ^{152}Eu for NVO-140 Soil Samples from Daisy.

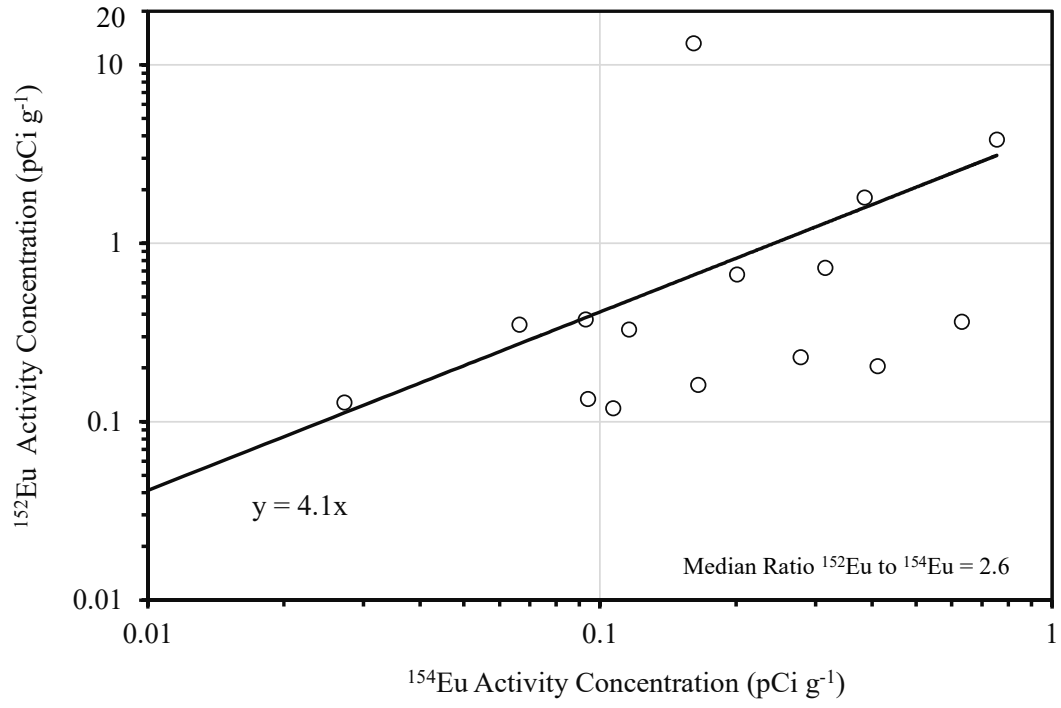


Figure C-33. Scatterplot of ^{152}Eu to ^{154}Eu for NVO-140 Soil Samples from Belle.

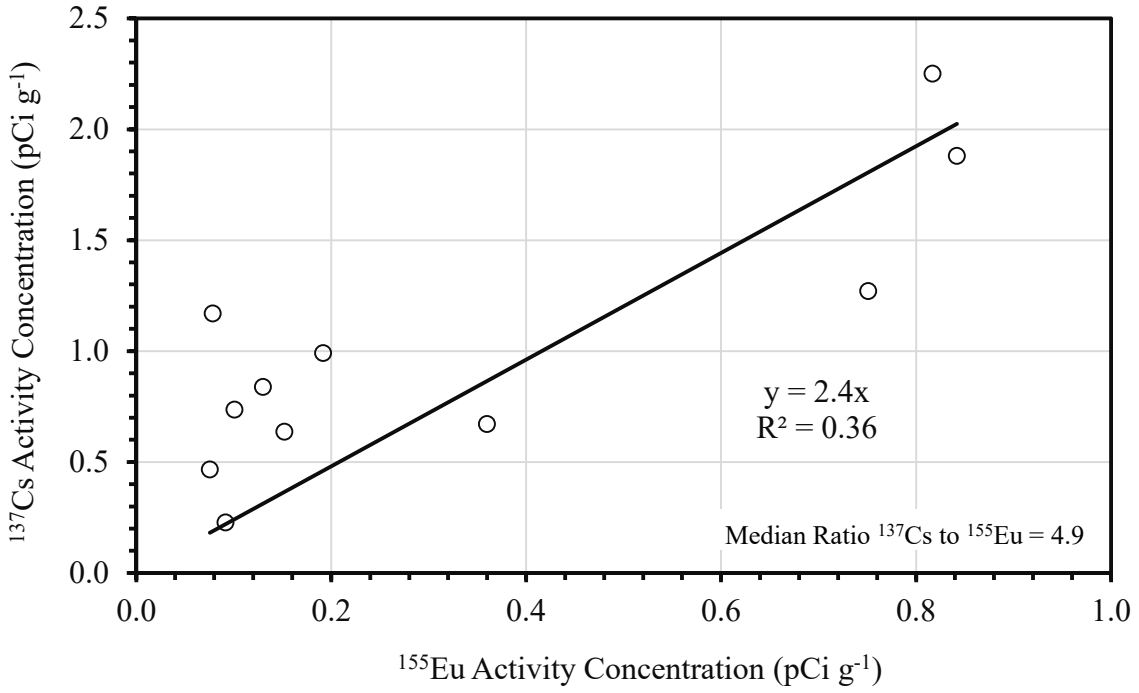


Figure C-34. Scatterplot of ^{137}Cs to ^{155}Eu for NVO-140 Soil Samples from Elmer.

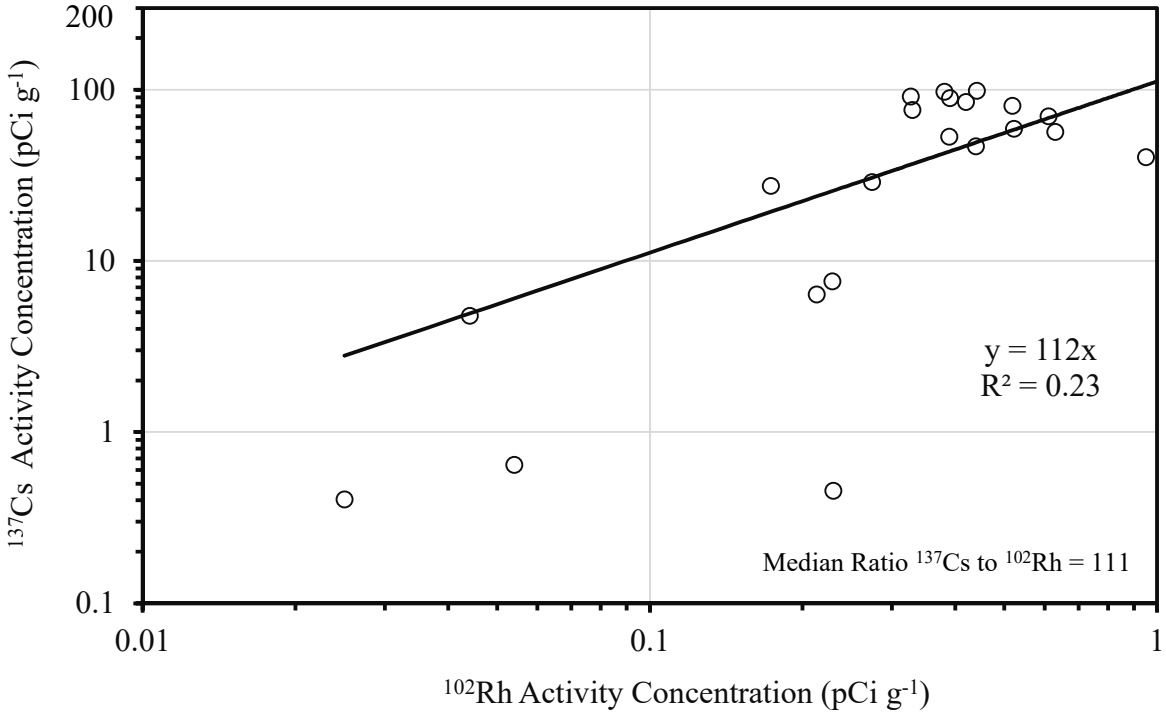


Figure C-35. Scatterplot of ^{137}Cs to ^{102}Rh for NVO-140 Soil Samples from Belle.

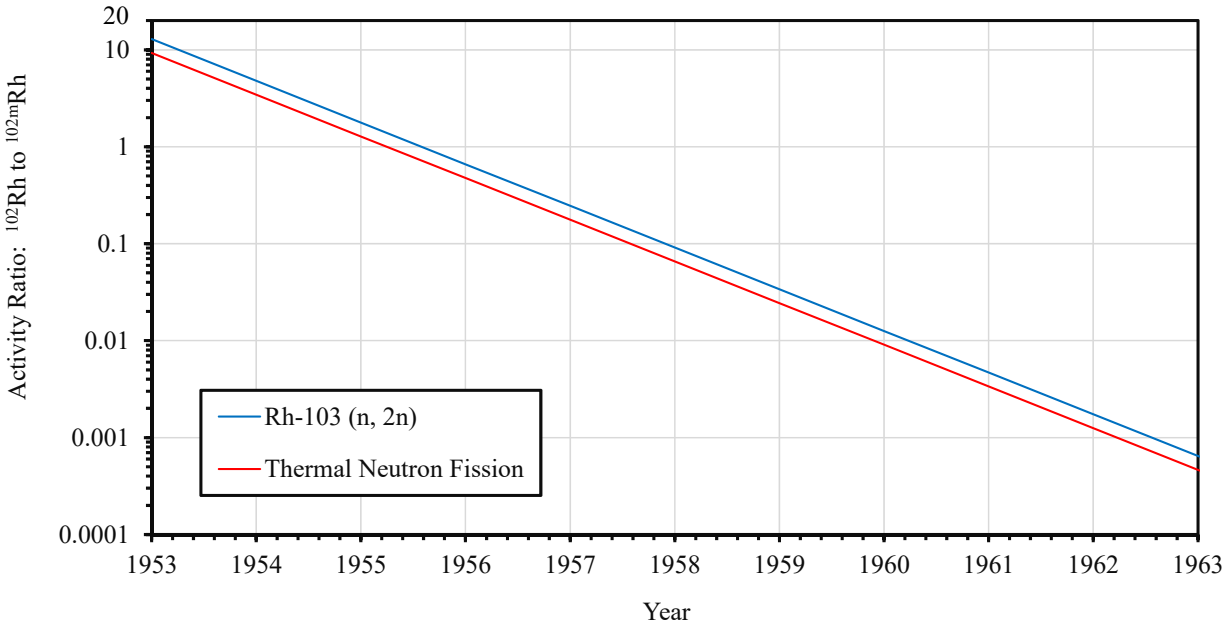


Figure C-36. Activity Ratios: ^{102}Rh to ^{102m}Rh Decayed from Production in 1953 for Fast Neutron Activation of ^{103}Rh and Thermal Neutron Fission.

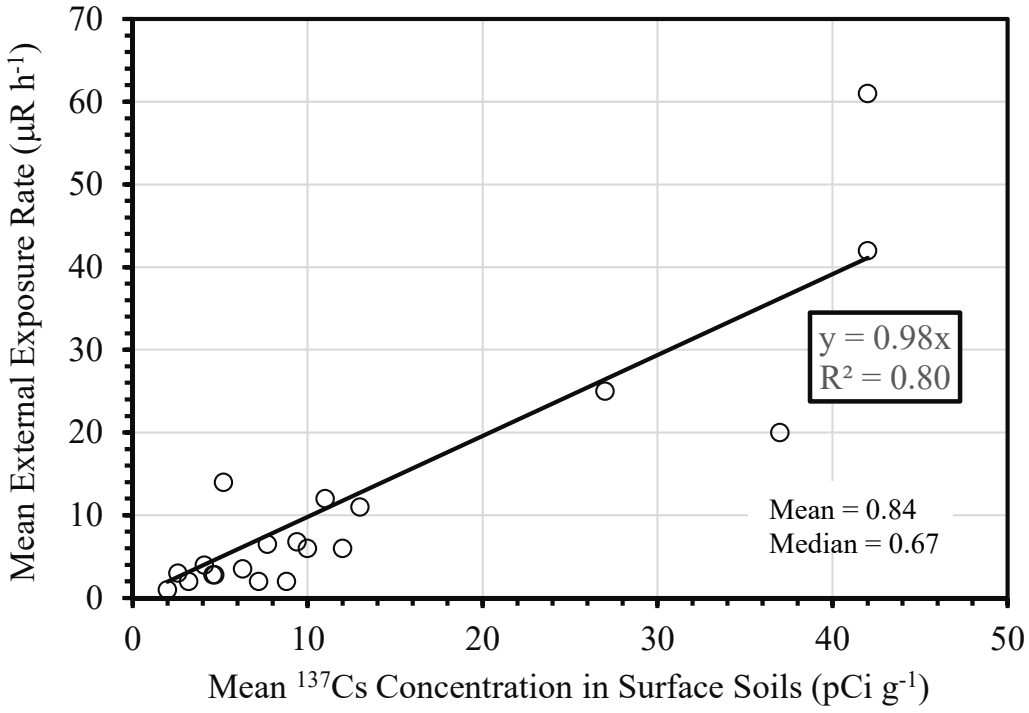


Figure C-37. Regression of Mean External Exposure from ^{137}Cs at 1 meter above Ground vs. Mean Activity Concentration of ^{137}Cs in Surface Soils.

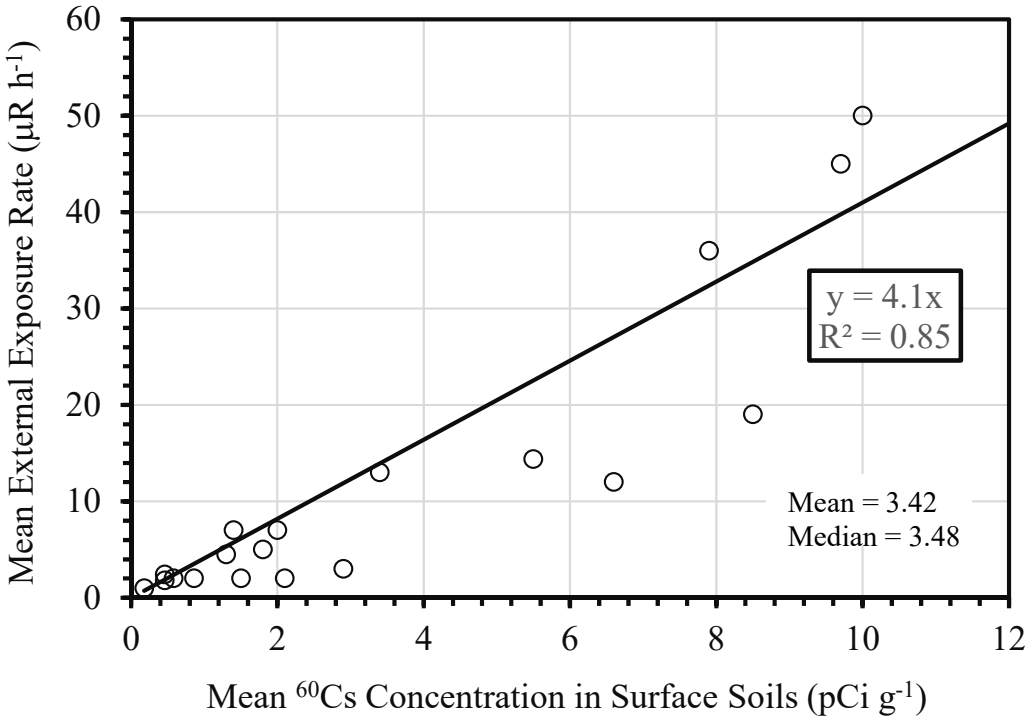


Figure C-38. Regression of Mean External Exposure from ^{60}Co at 1 meter above Ground vs. Mean Activity Concentration of ^{60}Co in Surface Soils.

Appendix D.

Information on Radiation Exposure Standards.

Table D-1. Occupational Radiation Exposures Adopted for Personnel Supporting the Enewetak Cleanup Project [Army Regulation 40-14, 20 May 1975].

Applicable Organ/Tissue	Dose Limit (rem)	
	Calendar Quarter	Calendar Year
Whole-body, head and trunk, blood-forming organs, gonads, lens of the eye*	1.25 [3]	5 [5 (N-18), N is age]
Skin of whole-body, cornea of the eye, bone	7.5	30
Hands and wrists, or feet and ankles	18.75	75
Forearms	10	30
Thyroid and other organs, tissues, and organ systems	5	15

* Acceptable dose for all adults listed first, higher limits listed in parentheses acceptable for adults 21 and older, but must required consideration of previous lifetime exposure history

Table D-2. Maximum Permissible Concentration (MPC) in Air for Radionuclides Expected in Soil Samples at Enewetak Atoll [NBS Handbook 69 (1963), 10 CFR 20 (1969), ICRP 2 (1959)].

Radionuclide	Critical Organ(s)*	Relative Solubility	MPC_{air} ($\mu Ci\ cm^{-3}$)
^{60}Co	Lower large intestine (LLI), total body (33%)	Soluble	3×10^{-7}
	Lung	Insoluble	9×10^{-9}
^{90}Sr	Bone, total body (200%)	Soluble	3×10^{-10}
	Lung	Insoluble	5×10^{-9}
^{102m}Rh†	Kidneys, spleen (100%)	Soluble	4×10^{-7}
	Lung	Insoluble	2×10^{-8}
^{106}Ru	Lower large intestine (LLI), kidney (20%)	Soluble	8×10^{-8}
	Lung	Insoluble	6×10^{-9}
^{125}Sb	Lung, total body (20%)	Soluble	5×10^{-7}
	Lung	Insoluble	3×10^{-8}
^{137}Cs	Total body, liver (33%)	Soluble	6×10^{-8}
	Lung	Insoluble	1×10^{-8}
^{144}Ce	Bone/liver, kidney (100%), total body (200%)	Soluble	6×10^{-8}
	Lung	Insoluble	6×10^{-9}
^{147}Pm	Lower large intestine (LLI)	Soluble	1×10^{-6}
	Lung	Insoluble	1×10^{-7}
^{151}Sm	Lower large intestine (LLI)	Soluble	2×10^{-6}
	Lung	Insoluble	1×10^{-7}
^{152}Eu	Kidney, total body (100%), bone (200%)	Soluble	1×10^{-8}
	Lung	Insoluble	2×10^{-8}
^{154}Eu	Kidney/bone, total body (150%)	Soluble	4×10^{-9}
	Lung	Insoluble	7×10^{-9}
^{155}Eu	Kidney, bone (11%), total body/liver (122%)	Soluble	9×10^{-8}
	Lung	Insoluble	7×10^{-8}
^{207}Bi	Kidney, LLI (100%), liver (200%)	Soluble	2×10^{-7}
	Lung	Insoluble	2×10^{-8}

Table D-2. Maximum Permissible Concentration (MPC) in Air for Radionuclides Expected in Soil Samples at Enewetak Atoll [NBS Handbook 69 (1963), 10 CFR 20 (1969), ICRP 2 (1959)], cont.

Radionuclide	Critical Organ(s)*	Relative Solubility	MPC_{air} ($\mu Ci\ cm^{-3}$)
^{238}Pu	Bone	Soluble	2×10^{-12}
	Lung	Insoluble	3×10^{-11}
^{239}Pu or ^{240}Pu	Bone	Soluble	2×10^{-12}
	Lung	Insoluble	4×10^{-11}
^{241}Am	Bone/kidney, liver (50%)	Soluble	6×10^{-12}
	Lung	Insoluble	1×10^{-10}

* Limiting critical organ(s) [LCO(s)] listed first, additional critical organs listed if MPC was $\leq$ 3-fold higher that MPC for LCO, values in parentheses list difference in MPC for additional critical organ to the MPC of LCO. † Proposed, "MPC Values for ^{102}Rh, ^{102m}Rh, and ^{107}Pd," *Health Physics*, Vol. 19, pp. 60 – 63, July 1970.

Table D-3. Federal Radiation Protection Guides (RPGs) of 1960, Federal Radiation Council (FRC), Executive Order 10831 and Public Law 86-673, and Adaptation to Enewetak Inhabitants.

Organ	Radiation Protection Guidelines (rem)		
	Individuals	Average for Population	Enewetak Individual*
Thyroid	$1.5\ y^{-1}$	$0.5\ y^{-1}$	$0.75\ y^{-1}$
Bone Marrow	$0.5\ y^{-1}$	$0.17\ y^{-1}$	$0.25\ y^{-1}$
Bone	$1.5\ y^{-1}$	$0.5\ y^{-1}$	$1.5\ y^{-1}$
Bone (alternate)	0.003 μg ^{226}Ra in skeleton	0.001 μg ^{226}Ra in skeleton	-
Whole Body	$0.5\ y^{-1}$	$0.17\ y^{-1}$	$0.25\ y^{-1}$
Gonads	5 rem in 30 y	-	4 rem in 30 y

* DNA (1981).

Table D-4. Environmental Protection Agency Proposed Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment (EPA 1977).

Criteria	Notes
1 millirad alpha radiation dose per year to pulmonary lung	Intent to limit risk of cancer to lung from inhalation route of exposure from transuranium elements in the general environment, based on the dose in the 70th year after chronic exposure
3 millirad alpha radiation dose per year to bone	Intent to limit risk of cancer to bone and liver from ingestion route of exposure from transuranium elements in the general environment, based on the dose in the 70th year after chronic exposure
$1\ fCi\ m^{-3}$ in air	Derived air concentration "screening level," based on an aerosol distribution not exceeding 0.1 μm AMAD (expected for stack release conditions), breathing rate of $2.3 \times 10^4\ L\ d^{-1}$, annual intake of 8.4 pCi.
$0.2\ \mu Ci\ m^{-2}$ in surface soil	Soil contamination "screening level," for top 1 cm of soil and for particle sizes under 2 mm. Mass loading approach for resuspension, $100\ \mu g\ m^{-3}$ and a 1 μm AMAD aerosol distribution. For a soil density of $1.5\ g\ cm^{-3}$, the soil screening level is equivalent to $13.3\ pCi\ g^{-1}$.

Table D-5. ICRP 26 Dose Equivalent Limits and Organ/Tissue Weighting Factors for Adults.

Application	Annual Limit
Total Effective Dose Equivalent (TEDE)	5 rem (50 mSv)
Deep Dose Equivalent & Committed Effective Dose Equivalent (CEDE)	50 rem to an individual organ or tissue, except lens
Lens of Eye	15 (150 mSv)
Skin	50 (500 mSv)
Extremities	50 (500 mSv)

* A value of 0.06 is applicable to each of the five remaining organs or tissues (liver, kidneys, spleen, brain, small intestine, upper large intestine, lower large intestine) receiving the highest doses.

Organ/Tissue	Weighting Factor
Gonads	0.25
Breast	0.15
Red Marrow	0.12
Lungs	0.12
Thyroid	0.03
Bone Surfaces	0.03
Remainder*	0.3

TABLE D-6. ICRP 60 Dose Equivalent Limits.

Application	Annual Limit	
	Workers	Public
Effective Dose	20 mSv (2 rem) per year averaged over defined periods of 5 yrs, but no more than 50 mSv (5 rem in any single yr)	1 mSv (0.1 rem)
Lens of Eye	150 mSv (15 rem)	15 mSv (1.5 rem)
Skin	500 mSv (50 rem)	50 mSv (5 rem)
Hands and Feet	500 mSv (50 rem)	-

TABLE D-7. ICRP 60 Organ/Tissue Weighting Factors.

Organ/Tissue Weighting Factor					
0.12	0.05	0.01	0.2	0.05 (Remainder)*	
Red Bone Marrow	Bladder	Skin	Gonads	Adrenals	Upper Lg. Intestine
Colon	Breast	Bone Surfaces		Brain	Small Intestine
Lung	Liver			Kidney	Pancreas
Stomach	Esophagus			Muscle	Thymus
	Thyroid			Spleen	Uterus

* In exceptional cases in which a single one of the remainder tissues or organs receives an equivalent dose in excess of the highest dose in any one of the twelve organs for which a weighting factor is specified, a weighting factor of 0.025 should be applied to that tissue or organ and a weighting factor of 0.025 to the average dose in the rest of the remainder as defined above.

Table D-8. Federal Guidance Report 11, Limiting Values of Radionuclide Intake and Air Concentration. [Note: Consistent with International Commission of Radiological Protection (ICRP) Reports 26 (1977), 30 (1979, 1980, 1981), 48 (1986)].

Radionuclide	Inhalation Class	Occupational Limit (source of limit)					**Effluent Concentrations (μCi cm^{-3})	
		Oral Ingestion		Inhalation				
		f_1	ALI (μCi)	f_1	ALI (μCi)	DAC (μCi cm^{-3})	Air	Water
^{238}Pu	W	*10^{-3}	0.9 (Bone Surface)	0.001	7×10^{-3} (Bone Surface)	3×10^{-12} (Bone Surface)		
			2 (CEDE)		10^{-2} (CEDE)		2×10^{-14}	2×10^{-8}
	Y	*10^{-4}	9 (CEDE)	10^{-5}	2×10^{-2} (Bone Surface)	8×10^{-12} (Bone Surface)		
		*10^{-5}	90 (CEDE)		2×10^{-2} (CEDE)		2×10^{-14}	
^{239}Pu or ^{240}Pu	W	*10^{-3}	0.8 (Bone Surface)	0.001	6×10^{-3} (Bone Surface)	3×10^{-12} (Bone Surface)		
			1.0 (CEDE)		10^{-2} (CEDE)		2×10^{-14}	2×10^{-8}
	Y	*10^{-4}	8 (CEDE)	10^{-5}	2×10^{-2} (Bone Surface)	7×10^{-12} (Bone Surface)		
		*10^{-5}	80 (CEDE)		2×10^{-2} (CEDE)		2×10^{-14}	
^{241}Am	W	10^{-4}	0.8 (Bone Surface)	0.001	6×10^{-3} (Bone Surface)	3×10^{-12} (Bone Surface)		
			1.0 (CEDE)		10^{-2} (CEDE)		2×10^{-14}	2×10^{-8}
^{207}Bi	D	0.05	1000 (CEDE)	0.05	2000 (CEDE)	7×10^{-7} (CEDE)	2×10^{-9}	1×10^{-5}
	W			0.05	400 (CEDE)	1×10^{-7} (CEDE)	5×10^{-10}	

* From Federal Guidance Report 11 (EPA 1988). ** From 10 CFR 20 (1994), Annual Individual of the Public Dose Limits: 0.1 rem CEDE
Annual Occupational Dose Limits: 5 rem for CEDE-based values, 50 rem committed effective dose (CDE) for organs/tissues

Table D-8. Federal Guidance Report 11, Limiting Values of Radionuclide Intake and Air Concentration (continued).

Radionuclide	Inhalation Class	Occupational Limit (source of limit)					**Effluent Concentrations (μCi cm^{-3})	
		Oral Ingestion		Inhalation				
		f_1	ALI (μCi)	f_1	ALI (μCi)	DAC (μCi cm^{-3})	Air	Water
^{60}Co	W	0.05	500 (CEDE)	0.05	200 (CEDE)	7×10^{-8} (CEDE)	2×10^{-10}	2×10^{-8}
	Y	0.3	200 (CEDE)	0.05	30 (CEDE)	1×10^{-8} (CEDE)	5×10^{-11}	
^{90}Sr	D	0.3	30 (BS)	0.3	20 (BS)	8×10^{-9} (BS)	3×10^{-11}	5×10^{-7}
			40 (CEDE)		20 (CEDE)			
	Y	0.01	400 (CEDE)	0.01	4 (CEDE)	2×10^{-9} (CEDE)	6×10^{-12}	
^{102m}Rh	D	0.05	3000 (LLI)	0.05	500	2×10^{-7} (CEDE)	7×10^{-10}	2×10^{-5}
	W			0.05	400	2×10^{-7} (CEDE)	5×10^{-10}	
	Y			0.05	100	5×10^{-8} (CEDE)	2×10^{-11}	
^{106}Ru	D	0.05	200 (LLI)	0.05	90	4×10^{-8} (CEDE)	1×10^{-10}	3×10^{-6}
	W			0.05	50	2×10^{-8} (CEDE)	8×10^{-10}	
	Y			0.05	10	5×10^{-9} (CEDE)	2×10^{-11}	
^{125}Sb	D	0.1	2000 (CEDE)	0.1	2000 (CEDE)	1×10^{-6} (CEDE)	3×10^{-9}	3×10^{-5}
	W	0.01	2000 (CEDE)	0.01	500 (CEDE)	2×10^{-7} (CEDE)	7×10^{-10}	
^{137}Cs	D	1	100 (CEDE)	1	200 (CEDE)	6×10^{-8} (CEDE)	2×10^{-10}	1×10^{-6}
^{144}Ce	W	3×10^{-4}	200 (LLI)	3×10^{-4}	30 (CEDE)	1×10^{-8} (CEDE)	4×10^{-11}	3×10^{-6}
			300 (CEDE)					
	Y				10 (CEDE)	6×10^{-9} (CEDE)	2×10^{-11}	
^{147}Pm	W	3×10^{-4}	4000 (LLI)	3×10^{-4}	100 (BS)	5×10^{-8} (BS)	3×10^{-10}	7×10^{-5}
			5000 (CEDE)		200 (CEDE)			
	Y				100 (CEDE)	6×10^{-8} (CEDE)	2×10^{-10}	
^{151}Sm	W	3×10^{-4}	10000 (LLI)	3×10^{-4}	100 (BS)	4×10^{-8} (BS)	2×10^{-10}	2×10^{-5}
			10000 (CEDE)		200 (CEDE)			
^{152}Eu	W	10^{-3}	800 (CEDE)	0.001	20 (CEDE)	1×10^{-8} (CEDE)	3×10^{-11}	1×10^{-5}
^{154}Eu	W	10^{-3}	500 (CEDE)	0.001	20 (CEDE)	8×10^{-9} (CEDE)	3×10^{-11}	7×10^{-6}
^{155}Eu	W	10^{-3}	4000 (CEDE)	0.001	90 (BS)	4×10^{-8} (B)	2×10^{-10}	5×10^{-5}
					100 (CEDE)			

TABLE D-9. Inhalation Dose Coefficients, ICRP Reports 68, and 71 (ICRP 1994b and ICRP 1995b).

Organ/Tissue		Committed Equivalent and Effective Doses (mrem μCi^{-1}) for 1 μm AMAD							
		Pu-238		Pu-239 or 240		Am-241	U-234		
		Type M	Type S	Type M	Type S	Type M	Type F	Type M	Type S
Adrenals		8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	5.9 E+1
Bladder Wall		8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	5.9 E+1
Bone Surface		5.2 E+6	5.9 E+3	5.6 E+6	6.7 E+5	6.3 E+6	3.5 E+4	1.4 E+4	1.9 E+3
Brain		8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	5.9 E+1
Breast		8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	5.9 E+1
GI Tract	Esophagus	8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	5.9 E+1
	St Wall	8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	6.3 E+1
	SI Wall	8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	6.3 E+1
	ULI Wall	8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	8.1 E+1
	LLI Wall	8.9 E+3	1.1 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.6 E+2	1.2 E+2
	Colon	8.9 E+3	1.1 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	9.6 E+1
Kidneys		2.2 E+4	2.7 E+3	2.4 E+4	3.0 E+3	3.2 E+4	1.3 E+4	5.2 E+3	7.0 E+2
Liver		1.2 E+6	1.3 E+5	1.2 E+6	1.4 E+5	3.7 E+5	4.8 E+3	2.0 E+3	2.6 E+2
Muscle		8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	5.9 E+1
Ovaries		6.7 E+4	7.8 E+3	7.4 E+4	8.9 E+3	2.1 E+5	1.3 E+3	5.2 E+2	5.9 E+1
Pancreas		8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	3.5 E+4	1.3 E+3	5.2 E+2	5.9 E+1
Red Bone Marrow		2.6 E+5	3.1 E+4	2.7 E+5	3.4 E+4	1.4 E+5	3.7 E+3	1.5 E+3	1.9 E+2
Respiratory Tract	Ex. Thor. Air	3.3 E+4	1.4 E+5	3.3 E+4	1.4 E+5	3.5 E+4	1.3 E+3	2.2 E+4	1.3 E+5
	Lungs	1.4 E+5	3.4 E+5	1.2 E+5	3.2 E+5	1.4 E+5	1.3 E+3	1.0 E+5	2.9 E+5
Skin		8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	5.9 E+1
Spleen		8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	5.9 E+1
Testes		7.0 E+4	8.1 E+3	7.8 E+4	9.3 E+3	1.2 E+5	1.3 E+3	5.2 E+2	5.9 E+1
Thymus		8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.0 E+4	1.3 E+3	5.2 E+2	5.9 E+1
Thyroid		8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	5.9 E+1
Uterus		8.9 E+3	1.0 E+3	1.0 E+4	1.2 E+3	1.1 E+4	1.3 E+3	5.2 E+2	5.9 E+1
Remainder		9.3 E+3	1.1 E+3	1.0 E+4	1.3 E+3	1.1 E+4	1.4 E+3	5.6 E+2	1.3 E+2
Effective Dose		1.7 E+5	5.9 E+4	1.9 E+5	6.0 E+4	1.6 E+5	2.1 E+3	1.3 E+4	3.5 E+4
Effective (5 μm AMAD)		1.2 E+5	4.3 E+4	1.3 E+5	3.1 E+4	1.1 E+5	2.4 E+3	7.8 E+3	2.5 E+4

TABLE D-9. Inhalation Dose Coefficients, ICRP Reports 68 and 71 (ICRP 1994b and ICRP 1995), continued.

Organ/Tissue		Committed Equivalent and Effective Doses (mrem μCi^{-1}) for 1 μm AMAD								
		Co-60		Sr-90		Sb-125		Th-232		Sm-151
		Type M	Type S	Type F	Type S	Type F	Type M	Type M	Type S	Type M
Adrenals		2.5E+1	8.1E+1	2.2E+0	1.3E-1	3.7E+0	4.4E+0	2.5E+4	3.1E+3	1.8E-3
Bladder Wall		9.3E+0	3.7E+0	4.8E+0	3.3E-1	2.8E+0	1.2E+0	2.5E+4	3.0E+3	1.6E-2
Bone Surface		1.4E+1	3.4E+1	1.4E+3	7.0E+1	8.5E+1	3.2E+1	8.1E+6	1.1E+6	4.1E+2
Brain		7.0E+0	7.8E+0	2.2E+0	1.3E-1	2.4E+0	1.1E+0	2.5E+4	3.0E+3	7.8E-4
Breast		2.3E+1	9.3E+0	2.2E+0	1.3E-1	1.9E+0	3.7E+0	2.5E+4	3.1E+3	6.3E-4
GI Tract	Esophagus	2.7E+1	1.0E+1	2.2E+0	1.3E-1	2.3E+0	4.4E+0	2.5E+4	3.1E+3	6.3E-4
	St Wall	1.7E+1	4.4E+0	2.3E+0	8.5E-1	2.4E+0	2.6E+0	2.5E+4	3.0E+3	2.1E-2
	SI Wall	1.2E+1	1.3E+1	2.4E+0	2.0E+0	3.2E+0	2.0E+0	2.5E+4	3.0E+3	5.2E-2
	ULI Wall	1.4E+1	1.7E+1	6.7E+0	1.3E+1	4.1E+0	3.6E+0	2.5E+4	3.2E+3	3.6E-1
	LLI Wall	1.8E+1	1.6E+1	1.9E+1	4.4E+1	6.3E+0	7.4E+0	2.6E+4	3.5E+3	1.1E+0
	Colon	1.6E+1	1.7E+1	1.2E+1	2.7E+1	4.8E+0	5.2E+0	2.6E+4	3.3E+3	6.7E-1
Kidneys		1.5E+1	3.1E+1	2.2E+0	1.3E-1	3.0E+0	2.0E+0	1.3E+5	1.8E+4	9.6E-4
Liver		3.1E+1	7.4E+1	2.2E+0	1.3E-1	7.0E+0	5.2E+0	1.3E+5	1.9E+4	1.1E+2
Muscle		1.4E+1	3.6E+1	2.2E+0	1.3E-1	2.4E+0	2.2E+0	2.5E+4	3.0E+3	8.9E-4
Ovaries		1.1E+1	8.5E+0	2.2E+0	1.3E-1	3.3E+0	1.7E+0	7.4E+4	9.6E+3	6.3E-4
Pancreas		2.1E+1	5.9E+1	2.2E+0	1.3E-1	3.1E+0	3.3E+0	2.5E+4	3.1E+3	1.0E-3
Red Bone Marrow		1.6E+1	4.4E+1	5.9E+2	3.1E+1	1.3E+1	6.3E+0	3.3E+5	4.4E+4	3.2E+1
Respiratory Tract	Ex. Thor. Air	5.9E+0	1.6E+2	6.3E+0	1.6E+2	1.1E+1	2.1E+1	4.4E+4	1.9E+5	2.0E+0
	Lungs	1.9E+2	6.7E+2	2.3E+0	4.8E+3	2.7E+0	1.2E+2	1.0E+5	5.9E+5	1.2E+1
Skin		8.9E+0	2.0E+1	2.2E+0	1.3E-1	1.8E+0	1.3E+0	2.5E+4	3.0E+3	6.7E-4
Spleen		2.0E+1	6.3E+1	2.2E+0	1.3E-1	2.5E+0	3.0E+0	2.5E+4	3.1E+3	5.9E-4
Testes		7.0E+0	1.9E+0	2.2E+0	1.3E-1	2.0E+0	7.8E-1	7.8E+4	9.6E+3	5.2E-4
Thymus		2.7E+1	1.0E+2	2.2E+0	1.3E-1	2.3E+0	4.4E+0	2.5E+4	3.1E+3	6.3E-4
Thyroid		1.4E+1	3.6E+1	2.2E+0	1.3E-1	2.4E+0	2.0E+0	2.5E+4	3.0E+3	5.6E-4
Uterus		1.0E+1	5.9E+0	2.2E+0	1.3E-1	2.8E+0	1.3E+0	2.5E+4	3.0E+3	5.2E-4
Remainder		1.4E+1	3.5E+1	2.2E+0	2.4E-1	2.5E+0	2.2E+0	2.6E+4	3.2E+3	2.9E-3
Effective Dose		3.7E+0	1.1E+2	8.9E+1	5.9E+2	5.2E+0	1.8E+1	1.7E+5	9.3E+4	1.5E+1
Effective (5 μm AMAD)		2.6E+1	6.3E+1	1.1E+2	2.8E+2	6.3E+0	1.2E+1	1.1E+5	4.4E+4	9.6E+0

TABLE D-9. Inhalation Dose Coefficients, ICRP Reports 68 and 71 (ICRP 1994b and ICRP 1995), continued.

Organ/Tissue		Committed Equivalent and Effective Doses (mrem μCi^{-1}) for 1 μm AMAD							
		Cs-137	Pm-147		Type M			Bi-207	
		Type F	Type M	Type S	Eu-152	Eu-154	Eu-155	Type F	Type M
Adrenals		1.7E+1	1.8E-3	2.6E-4	1.8E+2	1.6E+2	7.0E+0	1.0E+0	1.1E+1
Bladder Wall		1.8E+1	1.6E-2	1.0E-3	2.4E+1	2.2E+1	7.4E-1	1.1E+0	1.1E+0
Bone Surface		1.7E+1	2.8E+2	1.8E+1	7.0E+2	1.5E+3	4.4E+2	4.1E-1	4.8E+0
Brain		1.5E+1	1.5E-3	1.0E-4	3.4E+1	3.0E+1	1.0E+0	1.9E-1	8.9E-1
Breast		1.4E+1	1.6E-3	2.4E-4	4.8E+1	4.4E+1	1.6E+0	1.7E-1	1.2E+1
GI Tract	Esophagus	1.6E+1	1.6E-3	2.8E-4	4.8E+1	4.4E+1	1.9E+0	2.6E-1	1.4E+1
	St Wall	1.6E+1	6.7E-2	7.8E-1	6.3E+1	5.6E+1	2.4E+0	7.4E-1	6.3E+0
	SI Wall	1.7E+1	1.6E-1	1.9E+0	6.7E+1	5.9E+1	2.6E+0	1.5E+0	3.0E+0
	ULI Wall	1.8E+1	1.0E+0	1.2E+0	8.5E+1	7.8E+1	4.1E+0	3.6E+0	5.9E+0
	LLI Wall	1.8E+1	3.0E+0	3.4E+0	5.6E+1	5.9E+1	4.8E+0	7.8E+0	1.1E+1
	Colon	2.1E+1	1.8E+0	2.2E+0	7.4E+1	7.0E+1	4.4E+0	5.6E+0	7.8E+0
Kidneys		1.9E+1	1.7E-3	1.4E-4	1.2E+2	1.1E+2	5.2E+0	1.3E+1	9.3E+0
Liver		1.7E+1	7.4E+1	4.8E+0	1.0E+3	1.3E+3	1.4E+3	5.6E-1	9.6E+0
Muscle		1.7E+1	1.6E-3	1.6E-4	5.2E+1	4.4E+1	1.8E+0	4.4E-1	4.8E+0
Ovaries		1.6E+1	1.6E-3	1.1E-4	5.2E+1	4.4E+1	1.8E+0	1.5E+0	2.4E+0
Pancreas		1.8E+1	1.7E-3	2.2E-4	1.3E+2	1.2E+2	5.6E+0	8.5E-1	8.2E+0
Red Bone Marrow		1.8E+1	2.3E+1	1.4E+0	2.6E+2	3.4E+2	3.7E+1	5.9E-1	6.3E+0
Respiratory Tract	Ex. Thor. Air	1.6E+1	9.6E+0	3.3E+1	5.9E+1	7.0E+1	1.1E+1	2.1E+1	3.0E+1
	Lungs	2.7E+1	7.4E+1	1.4E+2	2.3E+2	3.7E+2	7.0E+1	3.0E-1	1.3E+1
Skin		1.6E+1	1.5E-3	1.2E-4	3.3E+1	2.9E+1	8.5E-1	2.3E-1	2.6E+0
Spleen		1.3E+1	1.6E-3	2.0E-4	4.8E+1	4.4E+1	1.7E+0	1.0E+0	8.2E+0
Testes		1.7E+1	1.5E-3	9.6E-5	1.4E+1	1.2E+1	3.1E-1	2.7E-1	3.3E-1
Thymus		1.6E+1	1.6E-3	2.8E-4	4.8E+1	4.4E+1	1.9E+0	2.6E-1	1.4E+1
Thyroid		1.6E+1	1.5E-3	1.4E-4	3.1E+1	2.8E+1	9.6E-1	2.2E-1	4.4E+0
Uterus		1.8E+1	1.5E-3	1.0E-4	3.7E+1	3.4E+1	1.2E+0	8.2E-1	1.3E+0
Remainder		2.1E+1	9.6E-3	2.0E-2	5.2E+1	4.4E+1	1.9E+0	1.1E+1	4.8E+0
Effective Dose		1.7E+1	1.9E+1	1.8E+1	1.6E+2	2.0E+2	2.6E+1	1.8E+0	2.1E+1
Effective (5 μm AMAD)		2.5E+1	1.3E+1	1.2E+1	1.0E+2	1.3E+2	1.7E+1	3.1E+0	1.2E+1

TABLE D-9. Inhalation Dose Coefficients, ICRP Reports 68 and 71 (ICRP 1994b and ICRP 1995b), continued.

Organ/Tissue		Committed Equivalent and Effective Doses (mrem μCi^{-1}) for 1 μm AMAD							
		Rh-102m (& Rh-102)			Ru-106 (& Rh-106)			Ce-144	
		Type F	Type M	Type S	Type F	Type M	Type S	Type M	Type S
Adrenals		6.3E+1	2.6E+1	2.9E+1	2.7E+1	1.1E+1	4.1E+0	7.4E+0	1.0E+0
Bladder Wall		4.1E+0	1.2E+1	2.7E+1	3.0E+1	1.1E+1	8.9E-1	6.3E+0	2.8E-1
Bone Surface		6.7E+0	1.7E+1	2.8E+1	2.6E+1	1.0E+1	2.0E+0	1.8E+2	7.4E+0
Brain		5.9E+0	8.9E+0	2.0E+1	2.6E+1	9.6E+0	8.5E-1	6.3E+0	3.0E-1
Breast		6.7E+1	2.2E+1	1.7E+1	2.6E+1	1.1E+1	4.1E+0	6.7E+0	1.0E+0
GI Tract	Esophagus	7.8E+1	2.7E+1	2.5E+1	2.6E+1	1.1E+1	4.8E+0	6.7E+0	1.1E+0
	St Wall	3.3E+1	1.8E+1	2.5E+1	2.7E+1	1.2E+1	4.1E+0	7.8E+0	2.0E+0
	SI Wall	1.0E+1	1.5E+1	3.0E+1	2.8E+1	1.3E+1	5.2E+0	1.0E+1	4.1E+0
	ULI Wall	1.2E+1	1.6E+1	2.8E+1	3.7E+1	3.2E+1	2.6E+1	2.7E+1	2.3E+1
	LLI Wall	1.1E+1	1.8E+1	3.2E+1	6.3E+1	7.4E+1	7.4E+1	6.7E+1	6.7E+1
	Colon	1.2E+1	1.6E+1	3.0E+1	4.8E+1	5.2E+1	4.8E+1	4.4E+1	4.1E+1
Kidneys		2.3E+1	1.6E+1	2.7E+1	2.6E+1	1.0E+1	1.7E+0	7.0E+0	4.8E-1
Liver		5.2E+1	2.3E+1	2.7E+1	2.6E+1	1.1E+1	3.4E+0	5.2E+2	2.1E+1
Muscle		2.8E+1	1.6E+1	2.3E+1	2.6E+1	1.0E+1	2.0E+0	6.7E+0	5.6E-1
Ovaries		7.8E+0	1.5E+1	3.1E+1	2.7E+1	1.0E+1	1.0E+0	6.7E+0	3.5E-1
Pancreas		4.4E+1	2.3E+1	3.0E+1	2.7E+1	1.1E+1	3.1E+0	7.4E+0	7.8E-1
Red Bone Marrow		3.5E+1	1.8E+1	2.5E+1	2.6E+1	1.0E+1	2.4E+0	1.0E+1	4.4E+0
Respiratory Tract	Ex. Thor. Air	8.2E+1	4.8E+1	5.2E+1	3.2E+1	2.8E+1	4.1E+1	3.1E+1	5.6E+1
	Lungs	3.3E+2	8.5E+1	2.3E+1	2.6E+1	7.4E+2	2.0E+3	7.0E+2	1.6E+3
Skin		1.4E+1	9.3E+0	1.6E+1	2.6E+1	9.6E+0	1.4E+0	6.3E+0	4.1E-1
Spleen		4.4E+1	2.1E+1	2.7E+1	2.6E+1	1.0E+1	3.0E+0	6.7E+0	7.8E-1
Testes		2.7E+0	9.6E+0	2.3E+1	2.6E+1	9.6E+0	7.0E-1	6.3E+0	2.6E-1
Thymus		7.8E+1	2.7E+1	2.5E+1	2.6E+1	1.1E+1	4.8E+0	6.7E+0	1.1E+0
Thyroid		2.7E+1	1.6E+1	2.5E+1	2.6E+1	1.0E+1	2.0E+0	6.7E+0	5.2E-1
Uterus		5.9E+0	1.4E+1	3.1E+1	2.7E+1	1.0E+1	8.9E-1	6.7E+0	3.0E-1
Remainder		2.6E+1	1.5E+1	3.7E+1	2.6E+1	1.0E+1	2.1E+0	6.7E+0	3.0E-1
Effective Dose		6.3E+1	2.6E+1	2.7E+1	2.9E+1	1.0E+1	2.4E+2	1.3E+2	6.7E-1
Effective (5 μm AMAD)		3.3E+1	1.9E+1	3.3E+1	3.6E+1	6.3E+1	1.3E+2	8.5E+1	1.1E+2

TABLE D-10. Ingestion Dose Coefficients, ICRP Report 56, 67, 68 and 69 (ICRP 1990a, ICRP 1992, ICRP 1994b, ICRP 1995a).

Organ/Tissue		Committed Equivalent and Effective Doses (mrem μCi^{-1})							
		Am-241	Pu-238	Pu-239/240	Co-60	Sr-90	Sb-125	Cs-137	Eu-155
Adrenals		5.6E+1	4.8E+1	5.6E+1	9.3E+0	2.4E+0	1.6E+0	5.2E+1	4.8E-2
Bladder Wall		5.6E+1	4.8E+1	5.6E+1	9.6E+0	5.6E+0	1.6E+0	5.2E+1	1.1E-1
Bone Surface		3.4E+4	2.8E+4	3.1E+4	7.8E+0	1.5E+3	3.4E+1	5.6E+1	2.4E+0
Brain		5.6E+1	4.8E+1	5.6E+1	5.2E+0	2.4E+0	9.6E-1	4.1E+1	5.6E-3
Breast		56E+1	4.8E+1	5.6E+1	5.2E+0	2.4E+0	7.8E-1	4.1E+1	7.1E-3
GI Tract	Stomach Wall	6.3E+1	5.2E+1	5.9E+1	9.6E+0	3.4E+0	1.9E+0	5.2E+1	3.7E-1
	Small Intestine Wall	7.0E+1	5.9E+1	6.7E+1	1.6E+1	4.1E+0	3.6E+0	5.2E+1	1.0E+0
	Upper Large Intestine Wall	1.3E+2	1.2E+2	1.2E+2	2.4E+1	2.2E+1	9.3E+0	5.2E+1	4.4E+0
	Lower Large Intestine Wall	2.8E+2	2.6E+2	2.5E+2	4.4E+1	8.1E+1	2.3E+1	5.2E+1	1.3E+1
Kidneys		1.7E+2	1.2E+2	1.3E+2	8.9E+0	2.4E+0	1.4E+0	4.8E+1	6.3E-2
Liver		2.0E+3	5.9E+3	6.3E+3	1.7E+1	2.4E+0	2.9E+0	4.8E+1	7.8E-1
Muscle		5.6E+1	4.8E+1	5.6E+1	7.0E+0	2.4E+0	1.1E+0	4.8E+1	4.4E-2
Ovaries		6.7E+2	3.6E+2	4.1E+2	1.6E+1	2.4E+0	3.0E+0	5.2E+1	3.5E-1
Pancreas		5.6E+1	4.8E+1	5.6E+1	9.6E+0	2.4E+0	1.4E+0	5.2E+1	6.3E-2
Red Bone Marrow		1.2E+3	1.4E+3	1.5E+3	8.1E+0	6.7E+2	5.6E+0	5.2E+1	2.6E-1
Lungs		5.6E+1	4.8E+1	5.6E+1	6.7E+0	2.4E+0	1.1E+1	4.4E+1	2.0E-2
Skin		5.6E+1	4.8E+1	5.6E+1	4.8E+0	2.4E+0	7.8E-1	4.1E+1	1.3E-2
Spleen		5.6E+1	4.8E+1	5.6E+1	7.8E+0	2.4E+0	1.1E+0	4.8E+1	3.4E-2
Testes		6.3E+2	3.7E+2	4.1E+2	6.7E+0	2.4E+0	9.6E-1	4.4E+1	2.6E-2
Thymus		5.6E+1	4.8E+1	5.6E+1	6.3E+0	2.4E+0	9.3E-1	4.8E+1	7.4E-3
Thyroid		5.6E+1	4.8E+1	5.6E+1	6.3E+0	2.4E+0	9.6E-1	4.8E+1	4.4E-3
Uterus		5.6E+1	4.8E+1	5.6E+1	1.1E+1	2.5E+0	1.9E+0	5.2E+1	1.6E-1
Effective Dose		7.8E+2	8.5E+2	9.3E+2	1.3E+1	1.0E+2	4.1E+0	4.8E+1	1.2E+0
G.I. Tract Absorption Class (f_1)		M (5×10^{-4})	M (5×10^{-4})	M (5×10^{-4})	M (0.1)	F (0.3)	F (0.1)	D (1.0)	M (5×10^{-4})
Effective Dose for Other G.I. Tract Absorption Classes (f_1)		-	1.8E+2 (1×10^{-4})	2.0E+2 (1×10^{-4})	9.3E+0 (0.05)	1.0E+1 (0.01)	-	-	-
		-	3.3E+1 (1×10^{-5})	3.3E+1 (1×10^{-5})	-	-	-	-	-

TABLE D-10. Ingestion Dose Coefficients, ICRP Report 56, 67, 68 and 69
(ICRP 1990a, ICRP 1992, ICRP 1994b, ICRP 1995a), continued.

Organ/Tissue		Committed Equivalent and Effective Doses (mrem μCi^{-1})								
		Eu-152	Eu-154	Ru-106	Ce-144	Pm-147	Sm-151	Bi-207	Th-232	U-234
Adrenals		1.2E+0	1.1E+0	5.6E+0	5.9E-2	1.1E-5	9.6E-6	5.0E-2	1.3E+2	1.0E+2
Bladder Wall		1.6E+0	1.6E+0	6.3E+0	1.1E-1	9.6E-5	8.5E-5	5.6E-1	1.3E+2	1.0E+2
Bone Surface		4.1E+0	8.5E+0	5.6E+0	1.2E+0	1.6E+0	2.1E+0	2.0E+0	4.4E+4	2.9E+3
Brain		1.8E-1	1.6E-1	5.2E+0	4.4E-2	8.5E-6	4.1E-6	5.6E-1	1.3E+2	1.0E+2
Breast		2.7E-1	2.5E-1	5.2E+0	4.4E-2	8.5E-6	3.2E-6	2.5E-2	1.3E+2	1.0E+2
GI Tract	Stomach Wall	2.2E+0	2.8E+0	1.2E+1	4.1E+0	2.6E-1	8.5E-2	2.2E+0	1.4E+2	1.1E+2
	Small Intestine Wall	5.9E+0	7.4E+0	2.1E+1	1.4E+1	6.7E-1	2.1E-1	6.3E+0	1.4E+2	1.0E+2
	Upper Large Intestine Wall	1.6E+0	2.6E+1	9.6E+1	8.5E+1	4.1E+0	1.3E+0	1.5E+1	1.9E+2	1.1E+2
	Lower Large Intestine Wall	3.7E+0	6.7E+1	2.7E+2	5.9E+1	1.2E+1	3.7E+0	3.5E+1	3.0E+2	1.6E+2
Kidneys		1.2E+0	1.2E+0	5.6E+0	7.4E-2	1.2E-5	5.6E-6	3.4E+0	6.7E+1	1.1E+2
Liver		5.9E+0	7.0E+0	5.6E+0	3.6E+0	4.4E-1	5.6E-1	6.3E-1	6.7E+1	4.1E+2
Muscle		4.8E+0	5.2E+0	5.6E+0	6.7E-2	1.1E-5	7.0E-6	5.9E+0	1.3E+2	1.0E+2
Ovaries		1.2E+0	1.2E+0	6.3E+0	2.8E-2	3.3E-5	5.9E-5	8.5E-1	3.7E+2	1.0E+2
Pancreas		2.2E+0	2.7E+0	5.6E+0	7.0E-2	1.2E-5	6.7E-6	1.2E+0	1.3E+2	1.0E+2
Red Bone Marrow		5.2E-1	4.8E-1	5.6E+0	7.0E-1	1.3E-1	1.7E-1	1.6E-1	1.7E+3	3.0E+2
Lungs		7.8E-1	7.8E-1	5.2E+0	4.8E-2	9.3E-6	7.4E-6	7.4E-1	1.3E+2	1.0E+2
Skin		3.6E-1	3.6E-1	5.2E+0	5.2E-2	9.3E-6	3.7E-6	2.9E-1	1.3E+2	1.0E+2
Spleen		6.7E-1	6.7E-1	5.6E+0	6.3E-2	1.0E-5	3.3E-6	7.4E-1	1.3E+2	1.0E+2
Testes		5.2E-1	5.2E-1	5.6E+0	6.3E-2	1.0E-5	3.0E-6	6.3E-1	3.7E+2	1.0E+2
Thymus		2.6E-1	2.4E-1	5.2E+0	4.4E-2	8.5E-6	3.2E-6	8.9E-2	1.3E+2	1.0E+2
Thyroid		1.6E-1	1.4E-1	5.2E+0	4.4E-2	8.5E-6	2.9E-6	4.4E-2	1.3E+2	1.0E+2
Uterus		2.2E+0	2.3E+0	5.9E+0	1.4E-1	1.9E-5	6.7E-6	2.7E+0	1.3E+2	1.0E+2
Effective Dose		5.2E+0	7.4E+0	2.6E+1	1.9E+1	9.6E-1	3.6E-1	4.8E+1	8.5E+2	1.9E+2
G.I. Tract Absorption Class (f_1)		M (0.0005)	M (0.0005)	M (0.05)	M (0.0005)	M (0.0005)	M (0.0005)	M (0.05)	M (0.0005)	M (0.02)
Effective Dose for Other G.I. Tract Absorption Classes (f_1)		-	-	-	-	-	-	-	340 (0.0002)	30.7 (0.002)

TABLE D-11. Generalized Internal Biokinetic Characteristics of Elements based on Group.

Group	Elements of Interest	Common Elements	Characteristics
Alkali Metals	Cs	K	Material in blood stream has similar behavior to potassium, with preferable deposition and retention in skeletal muscle. Bodily excretions primarily through the urinary tract.
Alkaline Earths	Sr	Ca	Material in blood stream has similar behavior to other alkaline earths. Similar deposition to calcium throughout mineral bone. Bodily excretions primarily through the urinary tract.
Transition Metals	Co, Ru, Rh	Fe	Material in blood stream have deposition and retention somewhat uniformly in body tissues. Bodily excretions primarily through the urinary tract.
Metalloids	Sb		Material in blood stream has deposition in the skeleton, secondarily to liver, with balance to other soft tissues. Deposition in skeleton is predominantly associated with bone surfaces. Bodily excretions through the GI and urinary tracts.
	Bi		Material in blood stream has dominant deposition and retention in the kidney, with balance to other tissues. Retention in kidney less tenacious than uranium. Bodily excretions primarily through the urinary tract.
Lanthanides (Rare Earths)	Ce, Pm, Sm, Eu	La	Material in blood stream has dominant deposition and retention in the liver and skeleton, lessor fraction to other soft tissues. Bodily excretions through the GI and urinary tracts.
Actinides	U	Ca, Hg	Material in blood stream has somewhat similar behavior to alkaline earths. Deposition in skeleton on bone surfaces, but more similar distribution over time as alkaline earth deposition throughout mineral bone. Deposition and retention in kidney similar to other heavy metals. Primary bodily excretion through urinary tract.
	Th, Pu, Am	Ac	Material in blood stream has dominant deposition and retention in the skeleton and liver, lessor fraction to other soft tissues. Deposition in skeleton is predominantly associated with bone surfaces, contrary to alkaline earth deposition throughout mineral bone. Bodily excretions through the GI and urinary tracts.

TABLE D-12. Adult f_1 Values for Inhaled Materials Passing through the GI Tract after Clearance from the Respiratory Tract (ICRP 1994b).

Element	Inhalation Type		
	F	M	S
Cobalt	-	0.1	0.05
Strontium	0.3	-	0.01
Ruthenium	0.05	0.05	0.05
Rhodium	0.05	0.05	0.05
Antimony	0.1	0.01	-
Cesium	1	-	-
Cerium	-	5×10^{-4}	5×10^{-4}
Promethium	-	5×10^{-4}	5×10^{-4}
Samarium	-	5×10^{-4}	-
Europium	-	5×10^{-4}	-
Bismuth	0.05	0.05	-
Thorium	-	5×10^{-4}	2×10^{-4}
Uranium	0.02	0.02	0.002
Plutonium	-	5×10^{-4}	1×10^{-5}
Americium	-	5×10^{-4}	-

- Values not listed for inhalation types omitted for element in ICRP 68

TABLE D-13. Dose Coefficients (Effective) for ^{232}Th and Decay Chain, and ^{230}Th from ICRP 68.

Radionuclide	Half-Life	Dose Coefficients (mrem μCi^{-1})	
		Inhalation Types	
		M	S
^{230}Th	7.7×10^4 y	1.6E+5	5.2E+4
10% M & 90% S		6.3E+4	
^{232}Th	1.4×10^{10} y	1.7E+5	9.3E+4
^{228}Ra	6.7 y	9.6E+3	5.9E+4
^{228}Ac	6.1 h	5.9E+1	5.2E+1
^{228}Th	1.9 y	1.1E+5	1.4E+5
^{224}Ra	3.64 d	1.1E+4	1.3E+4
^{220}Rn	55 s	-	-
^{216}Po	0.15 s	-	-
^{212}Pb	10.6 h	6.3E+2	7.0E+2
^{212}Bi	61 m	3.4E+1 (Type F)	1.2E+2 (Type M)
^{208}Tl	3.1 m	-	-
Sum		3.0E+5	3.1E+5
Sum (10% M & 90% S)		3.1E+5	

- Short-lived radioactive materials not provided DC by ICRP 68

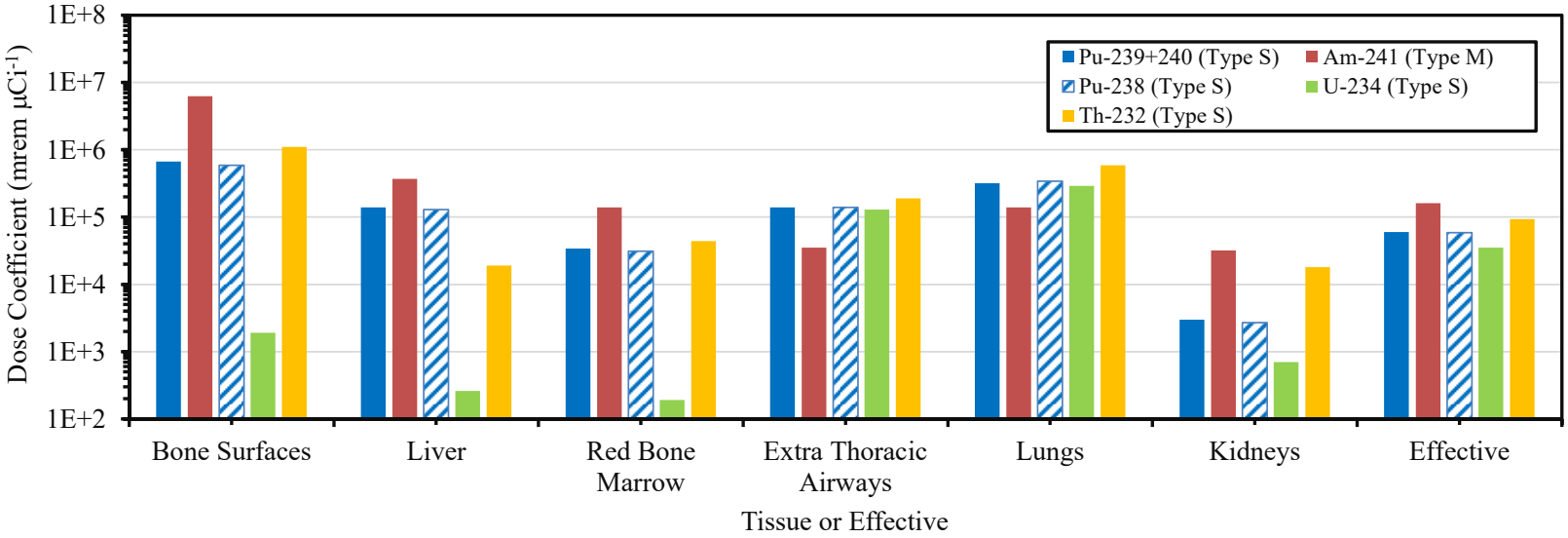


Figure D-1. Inhalation Dose Coefficients for α-Particle Emitting Radionuclides in Soil (ICRP Insoluble Types).

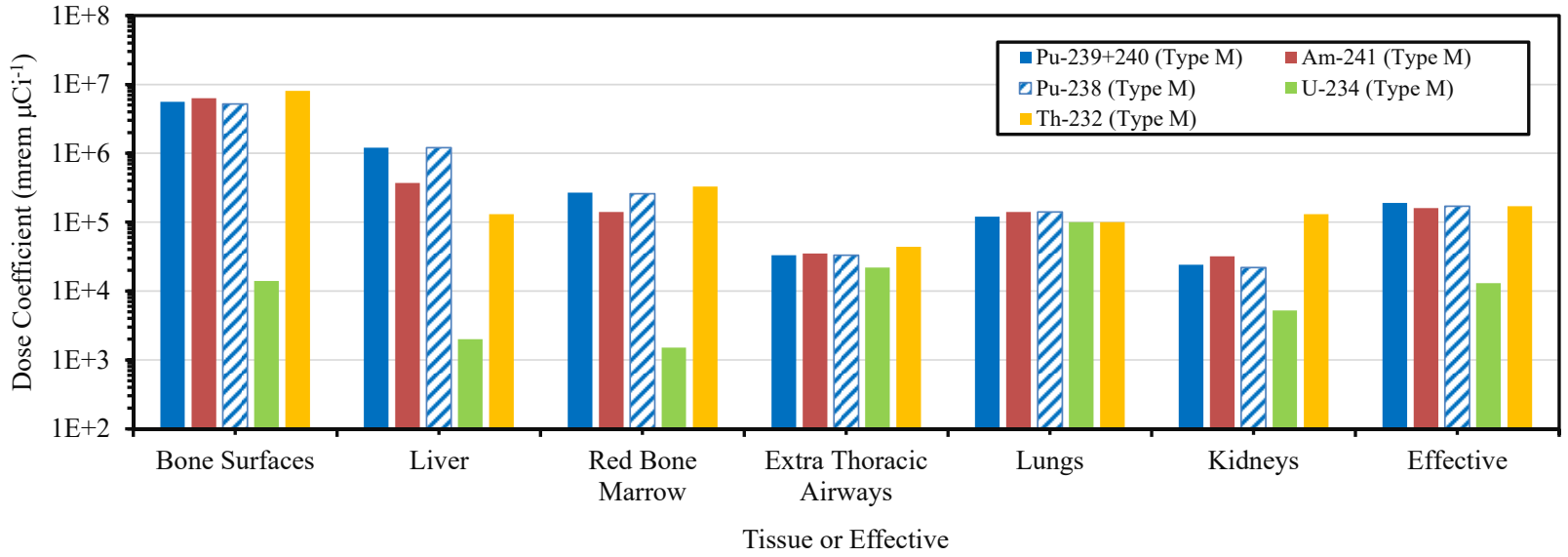


Figure D-2. Inhalation Dose Coefficients for α-Particle Emitting Radionuclides in Soil (ICRP Type M).

Appendix E.

Air Sampling Information.

Table E-1. $^{239+240}$Pu Air Sampling Data for Soil Aggregate Operations on Janet and Ursula, April & May 1977*.

Island	Sampling Date	Sampling Volume(s) (m^3)	Upwind (Quiescent)		Downwind		Concentration Ratio: Upwind to Downwind
			Concentration (pCi m^{-3})	Resuspension Factor (m^{-1})	Concentration (pCi m^{-3})	Resuspension Factor (m^{-1})	
Janet (Pile)	20 Apr	783	0.00041	1.7 E-9	0.022	9.2 E-8	0.019
Janet (Beach)	20 Apr	654/656	0.016	6.7 E-8	0.0096	4.0 E-8	1.67
Janet (Pile)	21 Apr	123	< 0.0007	< 2.9 E-9	0.002	8.3 E-9	< 0.35
Janet (Beach)	21 Apr	111/112	< 0.0004	< 1.7 E-9	0.011	4.6 E-8	< 0.036
Janet	22 Apr	1566/1548	0.00005	2.1 E-10	0.0029	1.2 E-8	0.017
	26 Apr	2376/2323	< 0.00008	< 3.3 E-10	0.0016	6.7 E-9	< 0.05
	28 Apr	864/936	0.00009	3.8 E-10	0.0023	9.6 E-9	0.039
	29 Apr	2304/2340	0.00003	1.3 E-10	0.0019	7.9 E-9	0.016
	30 Apr	2862/2376	0.00002	8.3 E-11	0.0017	7.1 E-9	0.012
Janet (Beach)	5 May	810	< 0.00011	< 4.6 E-10	0.0012	5.0 E-9	< 0.092
	6 May	1674	-	-	0.00044	1.8 E-9	NA
	7 May	2430	-	-	0.00062	2.6 E-9	NA
	8 May	2430	-	-	0.00031	1.3 E-9	NA
Ursula	22 Apr	1970	< 0.00006	< 2.2 E-9	0.00067	2.5 E-8	0.090
	26 Apr	2160	0.00011	4.1 E-9	0.0017	6.3 E-8	0.065
	28 Apr	1098	0.00005	1.9 E-9	0.00077	2.9 E-8	0.065
	29 Apr	1800	0.00011	4.1 E-9	0.00068	2.5 E-8	0.16
	30 Apr	2070	< 0.00006	< 2.2 E-9	0.00071	2.6 E-8	< 0.085
	5 May	900	< 0.0003	< 1.1 E-8	0.0012	4.4 E-8	< 0.25
	6 May	1818	< 0.00004	< 1.5 E-9	0.0024	8.9 E-8	< 0.017
	7 May	2340	0.000045	1.7 E-9	0.00096	3.6 E-8	0.047

* Resuspension factors based on mean $^{239+240}$Pu in surface soils on Ursula of 1.8 pCi g^{-1} and 16 pCi g^{-1} on Janet (see Table 2-10), soil density of 1.5 g cm^{-3}, and resuspension zone layer of top 1 cm.

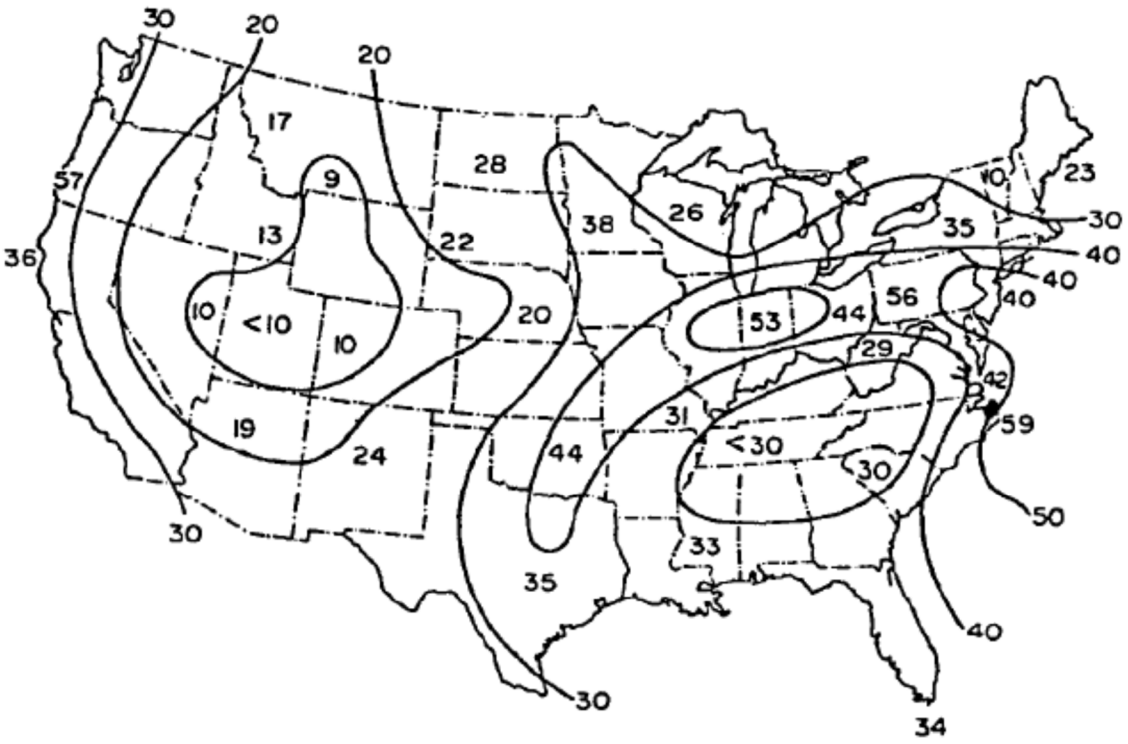


Figure E-1. Annual Mean Mass Concentrations (μg m^{-3}) of Airborne Particles from Non-Urban Stations of the U.S. National Air Sampling Network (Figure A2-2 from EPA 1977).

TABLE E-2. Plutonium Aerosol Concentrations on Bikini and Enewetak Atoll Compared (Winds 4 – 5 m s^{-1} [8.9 – 11 miles h^{-1}] from Shinn et al. (1997).

Condition	Location	Surface Description	Plutonium Activity Concentration			Estimated Enhancement Factor
			Aerosol (fCi m^{-3})	Suspended Soil (pCi g^{-1})	Surface Soil (pCi g^{-1})	
Normal Back-ground	Bikini	Coconut grove	0.059	3.2	8.1	0.41
	Bikini	Stable bare soil	0.26	12.7	15	0.82
	Janet	Vegetated field	0.24	10.8	24	0.45†
	Janet	Downwind of road	0.11	20	35	0.56†
Unusual Conditions	Bikini	Field, freshly tilled	0.065	49	15	3.10
	Janet	Garden, freshly tilled	0.076	10.8†	24	4.41†
	Janet	Garden, wk after tilled	0.030	62†	24	2.55†
	Bikini	Road with traffic	0.043	10.3	4.1	2.50

† Calculated by assuming 34 μg m^{-3} sea spray which has been verified by measurement on Bikini

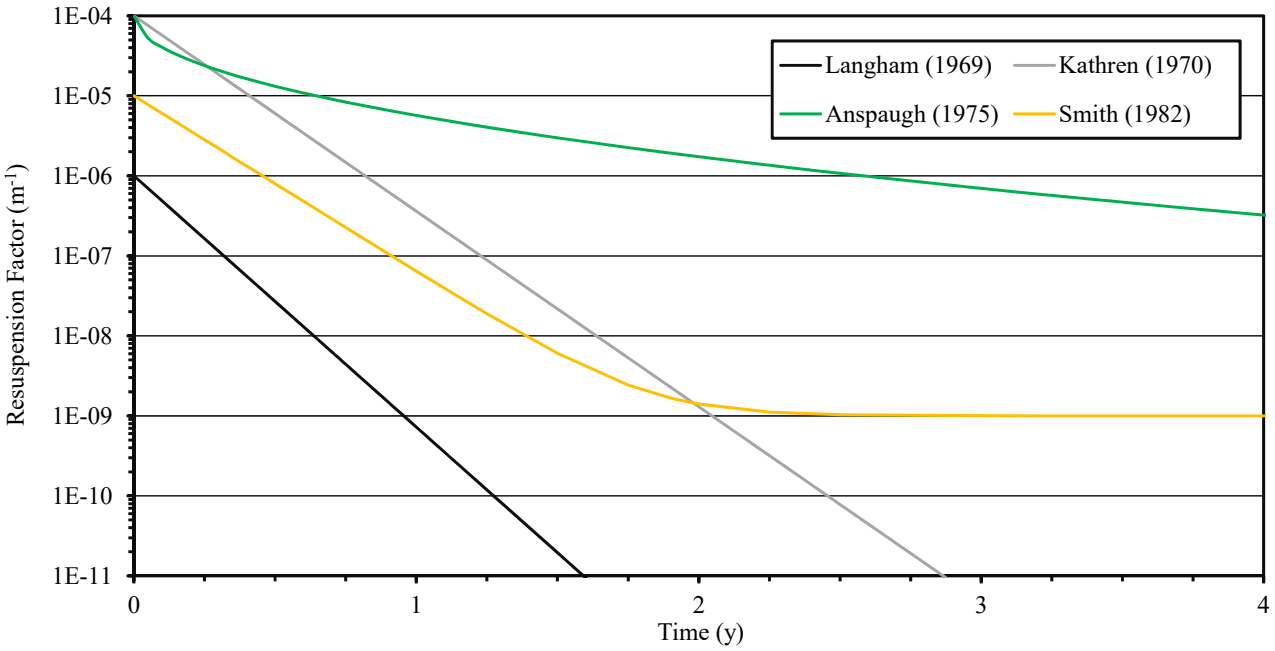


Figure E-2. Resuspension Factors of Anspaugh et al. (1975), Smith et al. (1982), and Earlier Ones.

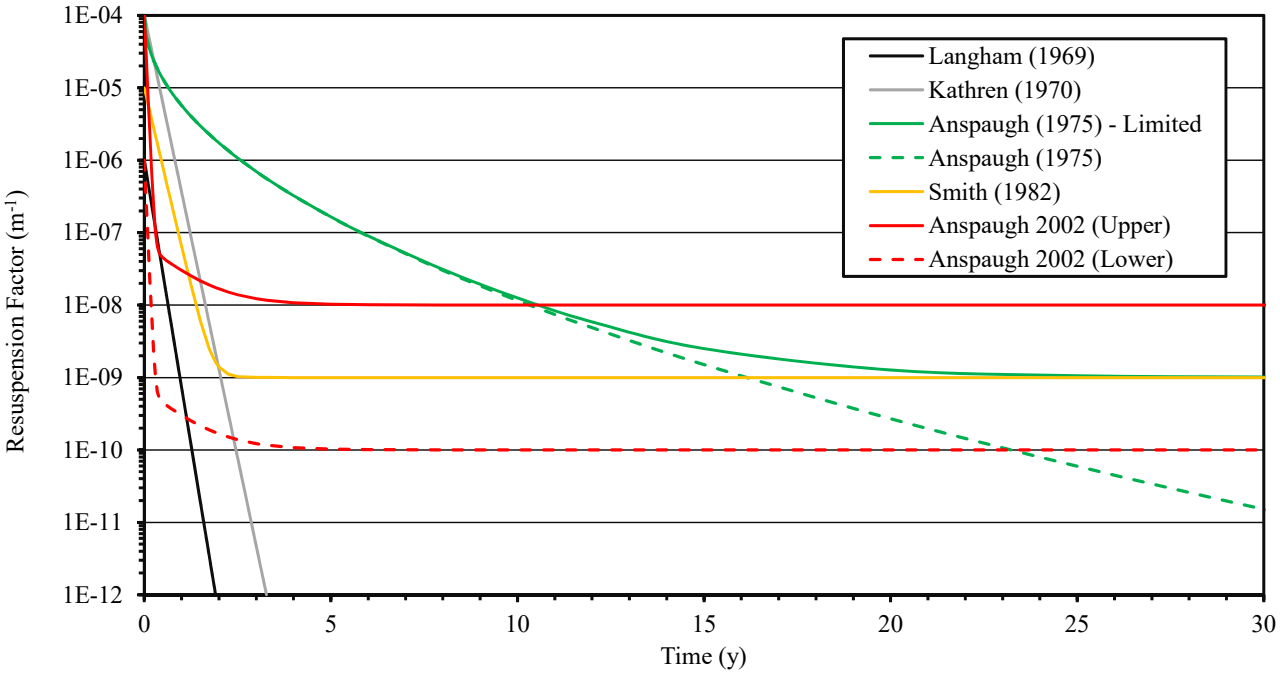


Figure E-3. Resuspension Factors based on Anspaugh et al. (2002), with Previous Models.

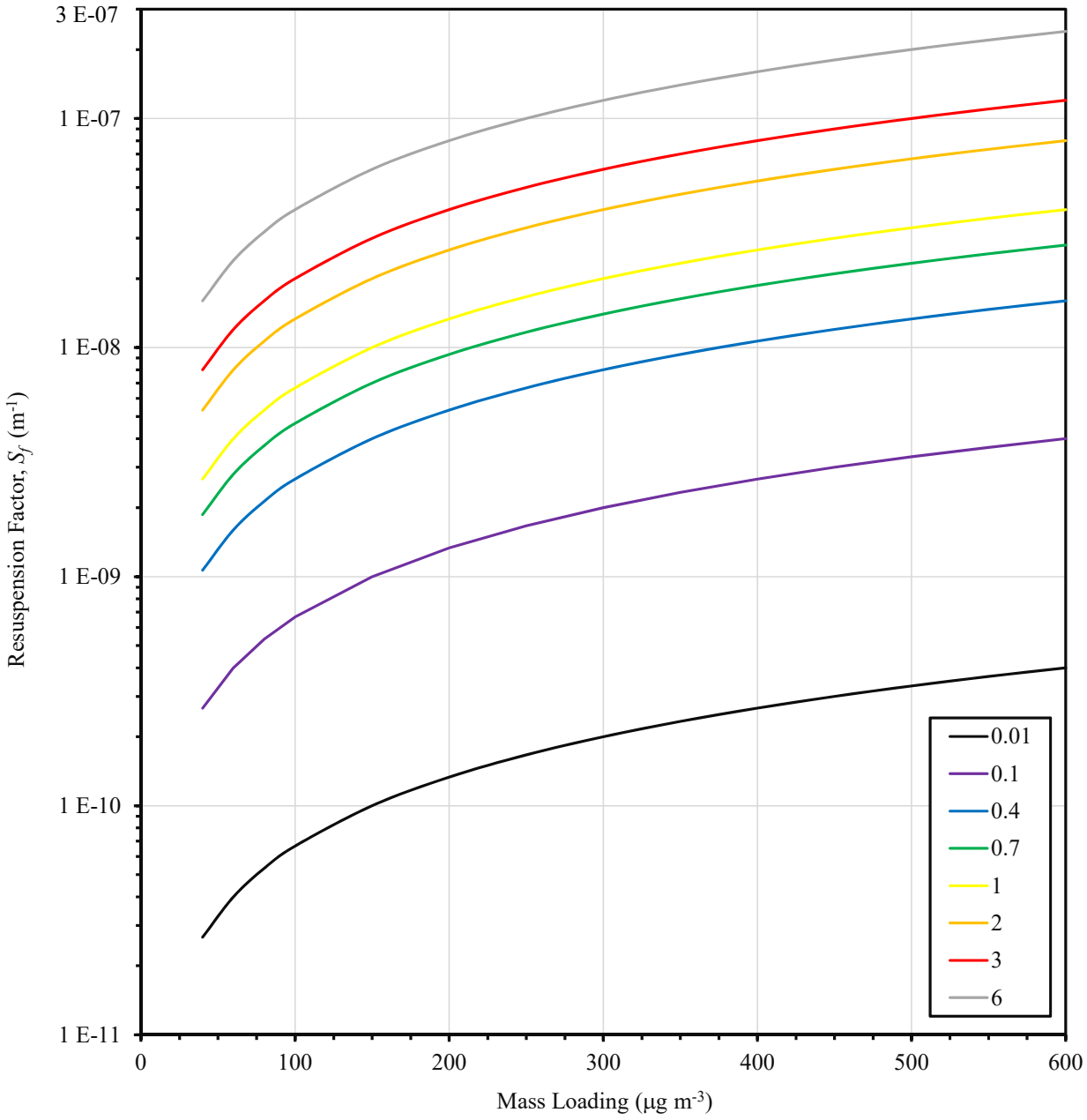


Figure E-4. Relationship of Resuspension Factor with Mass Loading for Various Enhancement Factors (ρ = 1.5 g cm^{-3} and Surface Soil Thickness Subject to Resuspension = 1 cm).

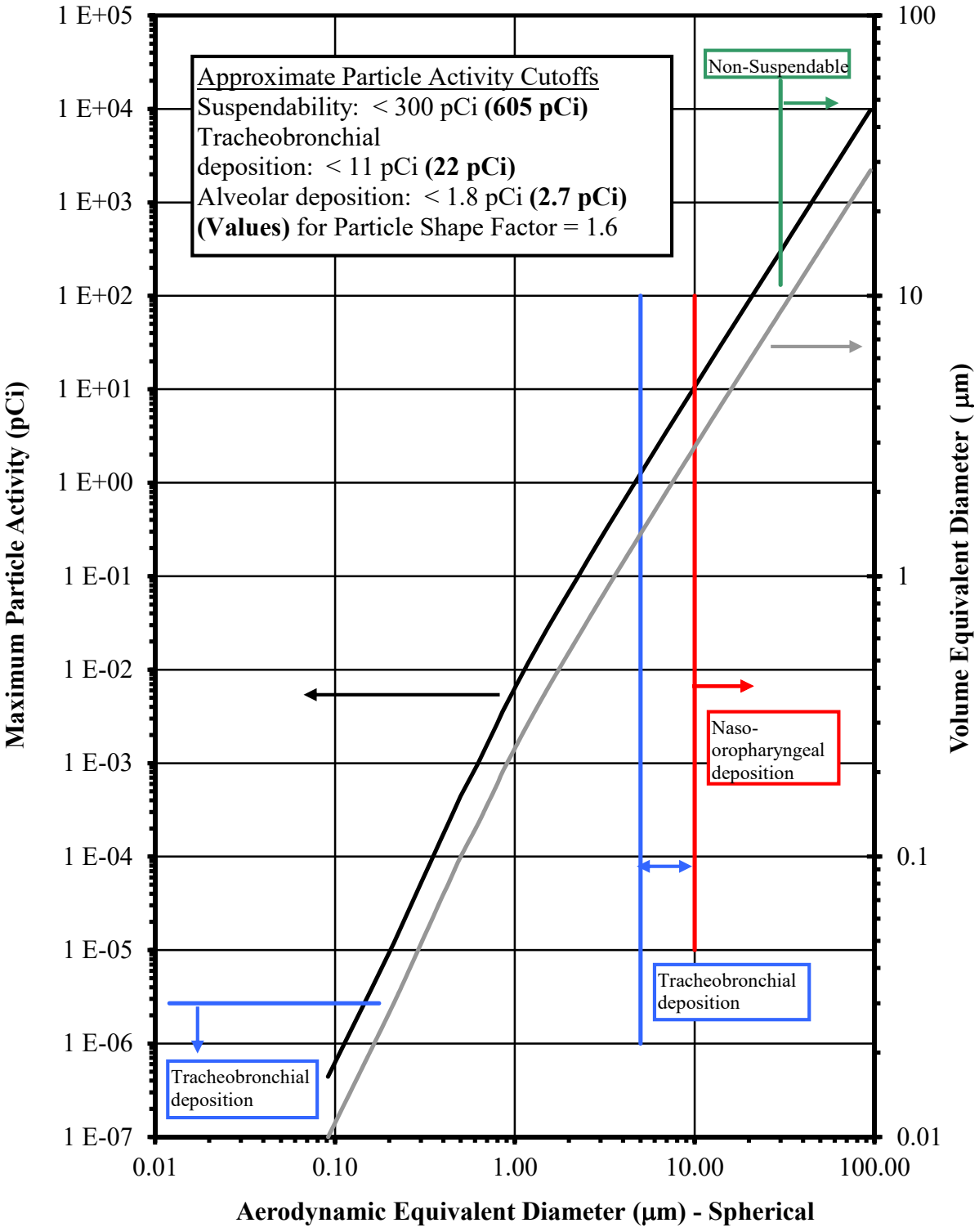


Figure E-5. Maximum Particle Activities and Volume Equivalent Diameters vs. Aerodynamic Equivalent Diameter (Spherical) $^{239+240}PuO_2$ Particles, and Respiratory Deposition Regions versus Aerodynamic Equivalent Diameter (Rademacher 2010).

TABLE E-3. Air Sample Summary for Alice, Belle, Daisy, Kate, Lucy, Nancy, Olive, Ruby, and Tilda.

Island	Date		Month	Year	Total Volume (m^3)	Number of Filters	Activity Concentration [MPC = 27 pCi m^{-3}]				Maximum Concentration [Single Filter] (pCi m^{-3})
	Start	End					Non-Detect	Detect, but < 0.01 MPC	> 0.01 MPC, but < 0.1 MPC	> 0.1 MPC	
Alice	1	31	January	1978	58	1	1	0	0	0	0.00
Alice	1	30	April	1978	231	2	2	0	0	0	0.00
Alice	14	20	May	1978	261	2	1	1	0	0	0.01
Belle	1	31	January	1978	195	2	2	0	0	0	0.00
Belle	1	28	February	1978	181	4	3	1	0	0	0.12
Belle	7	13	May	1978	226	2	2	0	0	0	0.00
Daisy	1	28	February	1978	109	2	2	0	0	0	0.00
Kate	1	31	December	1977	384	3	3	0	0	0	0.00
Kate	30	6	April/May	1978	22	1	0	1	0	0	0.01
Kate	7	13	May	1978	226	2	2	0	0	0	0.00
Kate	21	26	May	1978	173	1	1	0	0	0	0.00
Kate	28	3	May/June	1978	324	3	1	2	0	0	0.02
Kate	4	10	June	1978	253	2	0	2	0	0	0.07
Lucy	1	31	December	1977	359	5	1	4	0	0	0.04
Lucy	21	26	May	1978	349	3	1	2	0	0	0.01
Lucy	28	3	June	1978	233	2	1	1	0	0	0.01
Nancy	1	31	December	1977	302	3	2	1	0	0	0.02
Olive	1	30	November	1977	234	3	2	1	0	0	0.02
Ruby	28	3	May/June	1978	231	1	0	1	0	0	0.01
Ruby	4	10	June	1978	303	4	3	1	0	0	0.01
Tilda	1	30	September	1977	319	4	3	1	0	0	0.06
Tilda	1	31	October	1977	827	5	3	2	0	0	0.06
Tilda	1	30	November	1977	776	5	2	3	0	0	0.04

TABLE E-4. Air Sample Results during AEC 1972 Characterization, from Table 105 (AEC 1973).

Island	Sample ID	Airborne Activity Concentration (fCi m^{-3}), Standard Error in Percent								
		Be-7	K-40	Mn-54	Zr-95	Ru-106	Cs-137	Ce-144	Pu-239+240	Pu-238
Fred	UH3	ND	ND	0.38 ± 10	0.11 ± 20	< 0.25	0.21 ± 19	0.5 ± 17	< 0.003	ND
	UH5	94 ± 4	ND	0.6 ± 12	0.3 ± 20	1.3 ± 32	0.39 ± 17	1.1 ± 18	0.0067 ± 12	ND
	UH6	81 ± 10	4.5 ± 16	0.23 ± 20	0.3 ± 26	1.0 ± 35	0.41 ± 18	1.9 ± 19	0.0086 ± 6	ND
	UH7	58 ± 3	ND	0.22 ± 14	0.12 ± 18	ND	1.1 ± 5	0.36 ± 17	ND	ND
	UH8	40 ± 25	10 ± 32	0.8 ± 20	ND	< 1.5	< 0.17	ND	0.0032 ± 26	0.003 ± 22
	UH9	32 ± 10	ND	0.14 ± 25	ND	< 0.29	< 0.036	0.23 ± 36	0.0012 ± 13	ND
	UH10	95 ± 3	ND	ND	0.08 ± 14	0.42 ± 20	0.43 ± 5	0.22 ± 11	0.003 ± 21	ND
	UH11	110 ± 50	5.4 ± 24	ND	ND	1.6 ± 32	0.34 ± 30	0.83 ± 26	0.012 ± 20	ND
	UH12	6 ± 10	ND	ND	0.03 ± 22	< 0.2	0.13 ± 18	0.28 ± 16	< 0.03	ND
	VC11	ND	ND	ND	ND	ND	ND	ND	ND	ND
	VC21	116 ± 50	ND	1.9 ± 42	ND	ND	1.2 ± 41	ND	ND	ND
	VC12	81 ± 34	ND	4.0 ± 30	ND	ND	ND	ND	ND	ND
	VC22	70 ± 50	ND	1.3 ± 36	ND	ND	2.5 ± 19	ND	ND	ND
	A11A	52 ± 50	ND	ND	ND	ND	ND	ND	0.017 ± 22	ND
	A11B	ND	ND	ND	ND	ND	ND	ND	0.005 ± 25	ND
	A11C	ND	1.6 ± 18	ND	ND	ND	ND	ND	ND	ND
	A11D	ND	ND	ND	ND	ND	ND	ND	ND	ND
	A11E	ND	27 ± 10	ND	ND	ND	ND	ND	ND	ND
	A12A	43 ± 50	ND	0.4 ± 28	ND	ND	ND	ND	ND	ND
	A12B	ND	7.7 ± 32	0.4 ± 28	ND	ND	ND	ND	ND	ND
	A12C	ND	15 ± 14	0.5 ± 23	ND	ND	ND	ND	ND	ND
	A12D	ND	6.0 ± 40	0.5 ± 25	ND	ND	ND	ND	ND	ND
	A12E	ND	ND	ND	ND	ND	ND	ND	ND	ND
David	UH1	38 ± 5	ND	0.3 ± 14	ND	< 0.29	0.15 ± 23	ND	0.025 ± 6	§ 0.007 ± 9
	UH4	ND	ND	0.4 ± 12	0.2 ± 30	< 0.46	0.17 ± 32	0.4 ± 27	0.024 ± 7	0.008 ± 6
Janet	UH21	41 ± 15	ND	ND	ND	< 0.45	2.1 ± 7	ND	0.006 ± 16	0.007 ± 11
	UH22	ND	ND	ND	ND	< 1.0	0.44 ± 33	ND	< 0.006	ND
	UH23	41 ± 15	9.2 ± 24	1.3 ± 10	ND	< 0.9	0.71 ± 17	ND	< 0.008	ND

Island	Sample ID	Airborne Activity Concentration (fCi m^{-3})								
		Be-7	K-40	Mn-54	Zr-95	Ru-106	Cs-137	Ce-144	Pu-239+240	Pu-238
Sally	UH24	41 ± 15	ND	ND	ND	< 0.65	0.66 ± 19	ND	0.005 ± 21	ND
	UH25	41 ± 15	ND	ND	0.2 ± 18	< 0.34	0.34 ± 13	1.5 ± 12	0.0011 ± 19	ND
Yvonne	UH26	167 ± 9	ND	ND	ND	< 0.86	0.49 ± 24	2.5 ± 23	1.8 ± 5	0.04 ± 9
	UH27†	193 ± 2	ND	ND	0.4 ± 6	1.6 ± 22	0.82 ± 5	3.7 ± 7	2.6 ± 13	< 0.14
	UH28	143 ± 22	22 ± 25	ND	ND	< 3.3	< 0.58	ND	1.1 ± 12	0.13 ± 13
	VC31	ND	25 ± 37	1.1 ± 43	ND	ND	ND	ND	0.49 ± 9	ND
	VC41	ND	ND	1.5 ± 34	ND	ND	ND	ND	ND	ND
	VC32	ND	4.2 ± 23	ND	ND	ND	ND	ND	0.033 ± 14	ND
	VC42	190 ± 50	ND	2.1 ± 23	ND	ND	ND	ND	ND	ND
	A21A	152 ± 50	ND	0.6 ± 34	ND	2.6 ± 66	ND	ND	0.18 ± 25	ND
	A21B	ND	32 ± 11	ND	ND	ND	ND	ND	ND	ND
	A21C	ND	16 ± 24	ND	ND	ND	ND	ND	ND	ND
	A21D	ND	ND	ND	ND	ND	ND	ND	ND	ND
	A21E	ND	17 ± 19	ND	ND	ND	ND	ND	ND	ND
	A22A	41 ± 15	21 ±12	0.5 ± 30	ND	ND	ND	ND	0.011 ± 22	ND
	A22B	7.5 ± 60	15 ± 17	0.5 ± 35	ND	ND	ND	ND	0.01 ± 18	ND
	A22C	ND	15 ± 25	0.5 ± 43	ND	ND	ND	ND	ND	ND
	A22D	ND	ND	ND	ND	ND	ND	ND	0.074 ± 9	ND
	A22E	ND	ND	ND	ND	ND	ND	ND	0.022 ± 12	ND

ND = Not Detected, limit of sensitivity not established [sensitivity values can be derived from data archived on microfische]

† ^{241}Am detected: 0.30 fCi m^{-3} (± 32%), ^{103}Ru detected: 5.5 fCi m^{-3} (± 17%), & ^{125}Sb detected: 0.27 fCi m^{-3} (± 24%)

§ Value established from data archived on microfische

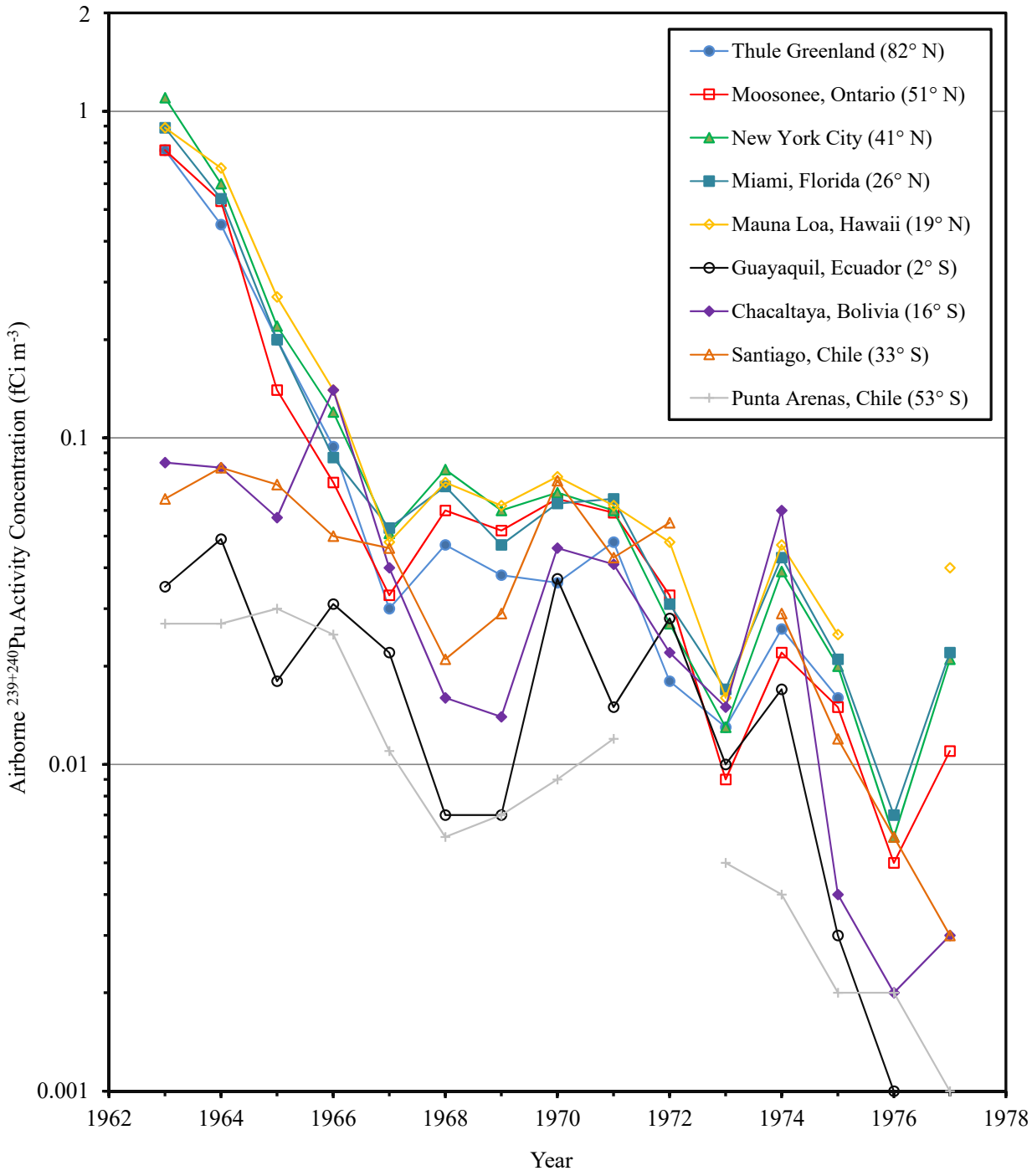


Figure E-6. Worldwide Concentrations of Plutonium (Harley 1980).

Appendix F.

Information on Soil Excision Areas.

TABLE F-1. Volume and Transuranic Activity of Soil Excised during the Radiological Clean-up of Enewetak Atoll, from DOE (1982).

Island	Soil Volume (m^3)*	Transuranics ($^{238+239+240}Pu$ & ^{241}Am)		Total Area with Soil Excision	
		Activity (Ci)	Mean Concentration (pCi g^{-1})	Area (ha)	% of Island
Janet	40,525	2.6	43	15.5	13.1
Pearl	11,415	1.7	99	9.7	44.1
Sally	8,100	1.3	107	1.8	4.5
Sally (Crypt)	7,475	0.9	80	0.2	1.0
Irene	3,775	1.0	180	0.6	3.3
Yvonne	8,210	7.2	585	5.0	13.5
Total	79,500	14.7	123	32.8	

* For cubic yards, multiply by 1.31

TABLE F-2. Soil Plowing and Excision Details for Janet, from DNA (1981).

Period	Volume Removed		Notes
	m^3	yd^3	
Mid-June 1978	None	None	Surface soil plowing activity to evaluate effectiveness of dilution method, Oak Ridge National Lab
Early-July 1978	1,973	2,580	Removal of soils with TRU > 60 pCi g^{-1}
Mid-July to Mid-August 1978	12,609	16,492	Removal of soils with TRU > 50 pCi g^{-1}
End-August to End-October 1978	9,649	12,621	Removal of soils with TRU > 45 pCi g^{-1}
November 1978 to End-April 1979	15,516	20,294	Reduced surface soils TRU from 45 to 40 pCi g^{-1}, (2,600 yd^3 sub-surface soils)
Early-May 1979	627	820	Plow experimental areas excavated
Total	40,374*	52,807	

* Small difference with value reported by DOE (1982) and listed in Table F-1.

TABLE F-3. Soil Excision Details for Pearl, from DNA (1981).

Period	Volume Removed		Notes
	m^3	yd^3	
7 April – 8 June 1979	11,096	14,513	Removal of surface soils with TRU > 80 pCi g^{-1}
7 – 8 July 1979	318	416	Removal of sub-surface soils with TRU > 160 pCi g^{-1}
Total	11,414	14,929	

TABLE F-4. Soil Excision Details for Sally (Aamon), from DNA (1981).

Period	Volume Removed		Notes
	m^3	yd^3	
8 March – August 1978	4,207	5,503	Soil removal from Kickapoo area, TRU > 40 pCi g^{-1}
	2,523	3,300	Soil removal from Yuma area, TRU > 40 pCi g^{-1}
	1,376	1,800	Soil removal from Hustead area, TRU > 40 pCi g^{-1}
16 January – 30 April 1979	6,881	9,000	Contaminated soil in Aamon (Sally) Crypt surveyed and removed, with TRU > 400 pCi g^{-1}
	256	335	Contaminated debris in Aamon (Sally) Crypt survey and removed, with TRU > 400 pCi g^{-1}
Total	15,244	19,938	

TABLE F-5. Soil Excision Details for Irene, from DNA (1981).

Period	Volume Removed		Notes
	m^3	yd^3	
December 1978 – 23 April 1979	2,597	3,397	Removal of surface soils with TRU > 80 pCi g^{-1} and sub-surface soils with TRU > 160 pCi g^{-1}
11 June – 7 July 1979	1,177	1,540	Removal of additional sub-surface soils with TRU > 160 pCi g^{-1}
Total	3,775	4,937	

TABLE F-6. Soil and Debris Excision Details for Yvonne, from DNA (1981).

Period	Volume Removed		Notes
	m^3	yd^3	
28 November – 23 December 1977	NA	NA	AF FRST members excised local hot-spots with aid of FIDLER instruments. Soil added to Spring 1979 disposal action.
Fall 1978	1,318	1,724	Primarily contaminated debris from Southern Yvonne
13 March – 26 July 1979	8,207	10,735	Removal of surface soils with TRU > 160 pCi g^{-1} in one-quarter hectare areas from Fig-Quince Test Area
September 1979	92	120	Additional contaminated debris (emplaced in 1st Cactus Crater extension)
November 1979 – March 1980	4	5	Additional contaminated debris (emplaced in 2nd Cactus Crater extension)
Total	9,617	12,579	

TABLE F-7. Debris Survey and Excision Details for Other Northern Islands, from DNA (1981).

Island	Period	Volume Removed		Notes
		m^3	yd^3	
Percy	25 November – 5 December 1977	NL	NL	Limited debris removed; no known radioactive burial; all debris uncontaminated based on Sept 1977 survey
Mary	13 Decem 1977 – 8 February 1978	121	158	No known radioactive burial; all debris uncontaminated based on Sept 1977 survey
Pearl	15 Novem 1977 – 22 February 1978	207	271	No known radioactive burial; majority of debris removed radioactive
Olive	20 February 1978 – 21 March 1978	0.76	1	No known radioactive burial
Wilma	5 January 1978 – 26 February 1978	49	64	No known radioactive burial; all debris uncontaminated based on August 1977 survey
Vera	19 January 1978 – 3 March 1978	0.76	1	No known radioactive burial; all debris uncontaminated
Nancy	6 March 1978 – 19 March 1978	0.76	1	No known radioactive burial; all debris uncontaminated
Irene & Helen	4 January 1978 – 12 July 1978	1,457	1,905	No known radioactive burial; all debris uncontaminated
Alice	10 February – 14 June 1978	1,205	1,575	No known radioactive burial; all debris uncontaminated
Belle	5 March – 9 June 1978	24	28	No known radioactive burial; all debris uncontaminated
Kate	5 April – 16 June 1978	821	1,073	No known radioactive burial; all debris uncontaminated
Lucy	5 April – 16 June 1978	197	257	No known radioactive burial; all debris uncontaminated
Daisy	26 April – 15 May 1978	3.8	5	No known radioactive burial; all debris uncontaminated
Edna	15 May 1978	NA	NA	No known radioactive burial; no debris
Clara	26 April – 9 June 1978	386	505	No known radioactive burial; all debris uncontaminated
Ruby	1 Jun – 10 Jul 1978	191	250	Majority of debris contaminated
Sally	16 January – 29 July 1978	2,229	2,914	Debris survey initiated 8 December 1977; about three fourths of debris uncontaminated
Tilda	8 June – 23 July 1978	551	720	No known radioactive burial; all debris uncontaminated
Janet	26 January 1978 – 15 May 1979	12,603	16,477	Debris survey initiated July 1977; about 3% contaminated debris

Table F-8. Summary of Work Performed on Southern Islands, NVO-213 (DOE 1982).

Island	History	Restoration Actions	Post Restoration Survey
David (Japtan)	Coconut plantation in 19th Century. Housing area for research animals, recreation area, and radio receiver site during atmospheric testing.	Rehabilitation of some buildings for use by driEnewetak. Debris cleanup between 8 Jun and 13 Oct 78, on 1,290 yd^3 of uncontaminated debris.	Soil samples at eight locations, but no IMP in-situ, due to low residual contamination levels.
Elmer (Medren)	One of main support islands during atmospheric testing.	Soil removed summer 1978, as related to lab or tech operations during testing period. Some buildings left for driEnewetak. Debris cleanup: Feb 78 and Feb 80. Majority of 27k yd^3 concrete debris used to extend north point of island. Another 32.5k yd^3 salvaged as scrap metal and 14k yd^3 disposed in lagoon.	Soil samples at six locations. IMP measurements at 91 locations in the vicinity of former laboratory and decontamination facilities.
Fred (Enewtak)	One of main support islands during atmospheric testing, and primary support for various activities after testing and during restoration.	Airfield runway kept in place. Numerous building rehabilitated for driEnewetak.	Soil samples at 24 locations. IMP in-situ measurements at 14 locations.
Leroy (Biken)	Isolated island in Atoll. Remnants of scientific stations from three tests	No rehabilitation.	Soil samples at four locations, but no IMP in-situ, due to low residual contamination levels.
Sam, Tom, Uriah, Van, Alvin, Bruce, Clyde, Rex, Walt, Glenn, Henry, Irwin, James, Keith	Few scientific stations to support test and little debris.	Minor debris removal.	Soil samples at four locations/island, except Glenn (5). No IMP in-situ, due to low residual contamination levels.

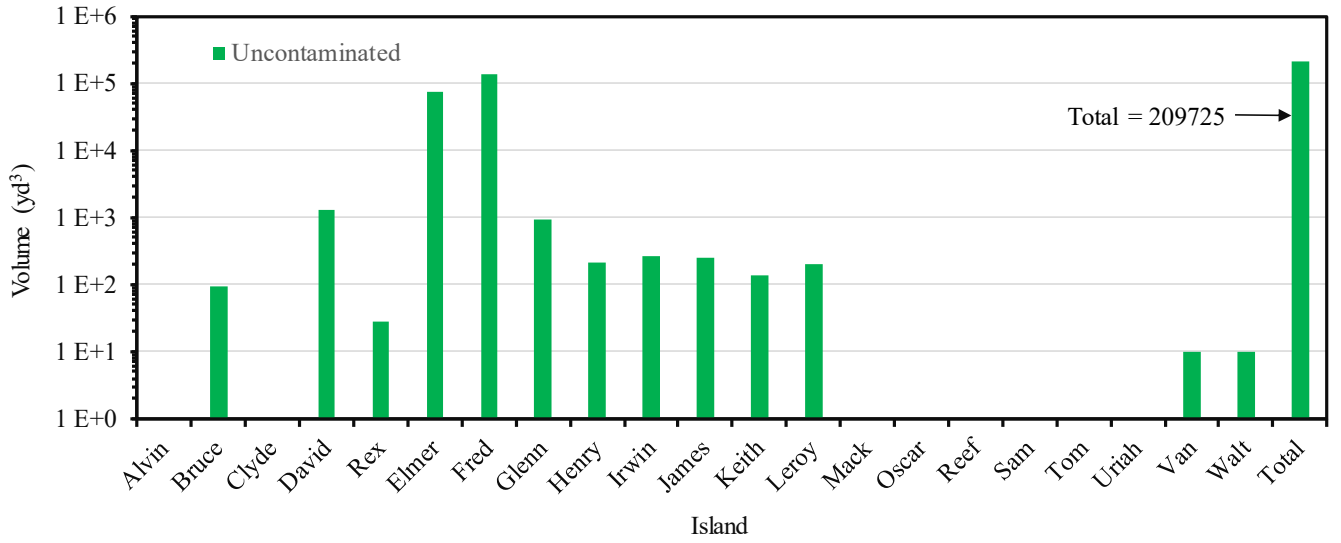


Figure F-1. Histogram of Debris Volume Removals on Southern Islands of Atoll.

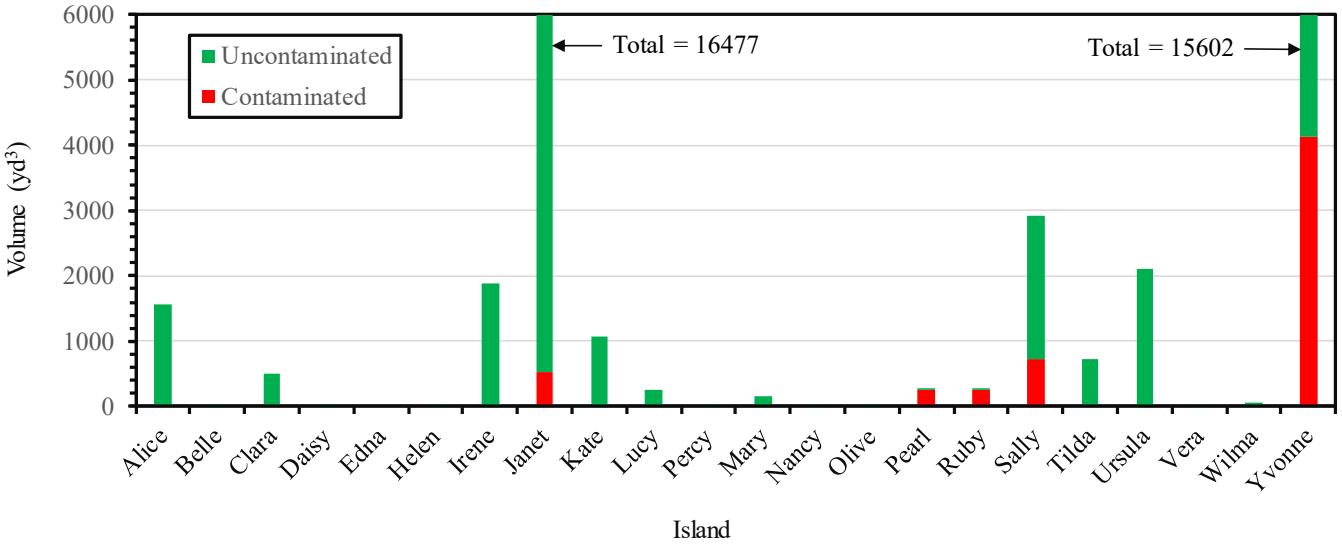


Figure F-2. Histogram of Debris Volume Removals on Northern Islands of Atoll.

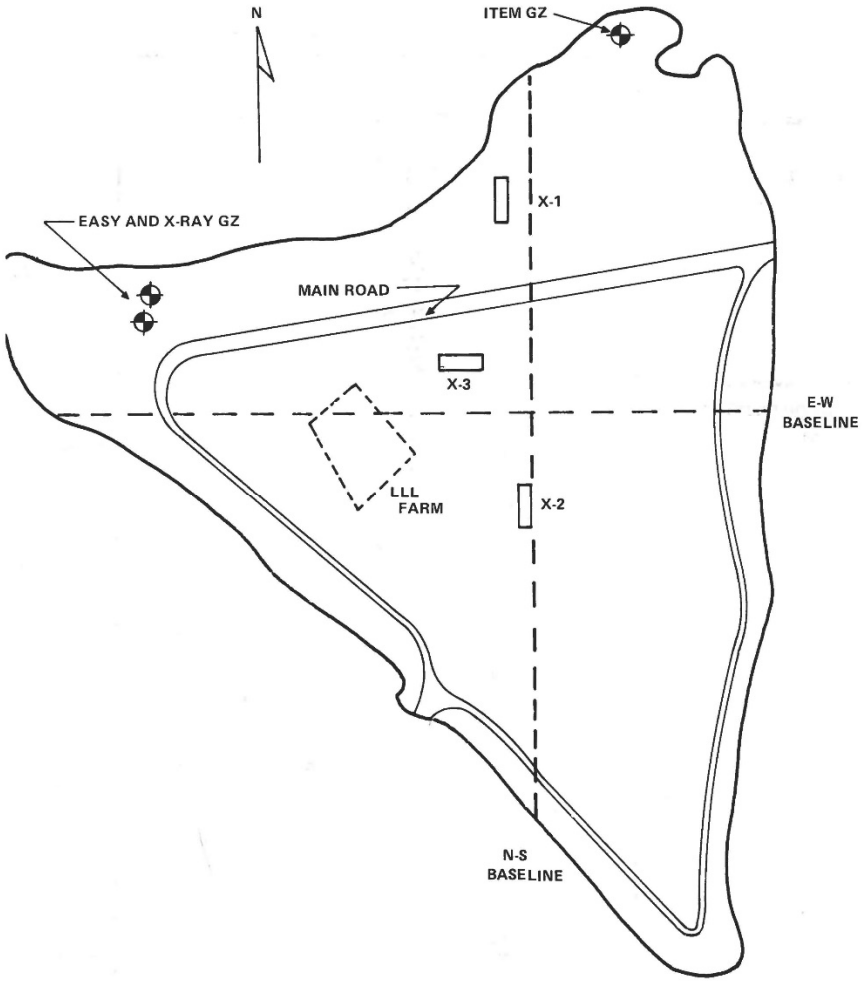


Figure F-3. Plowing Experimental Testing Sites on Janet [Figure 7-8, (DNA 1981)].

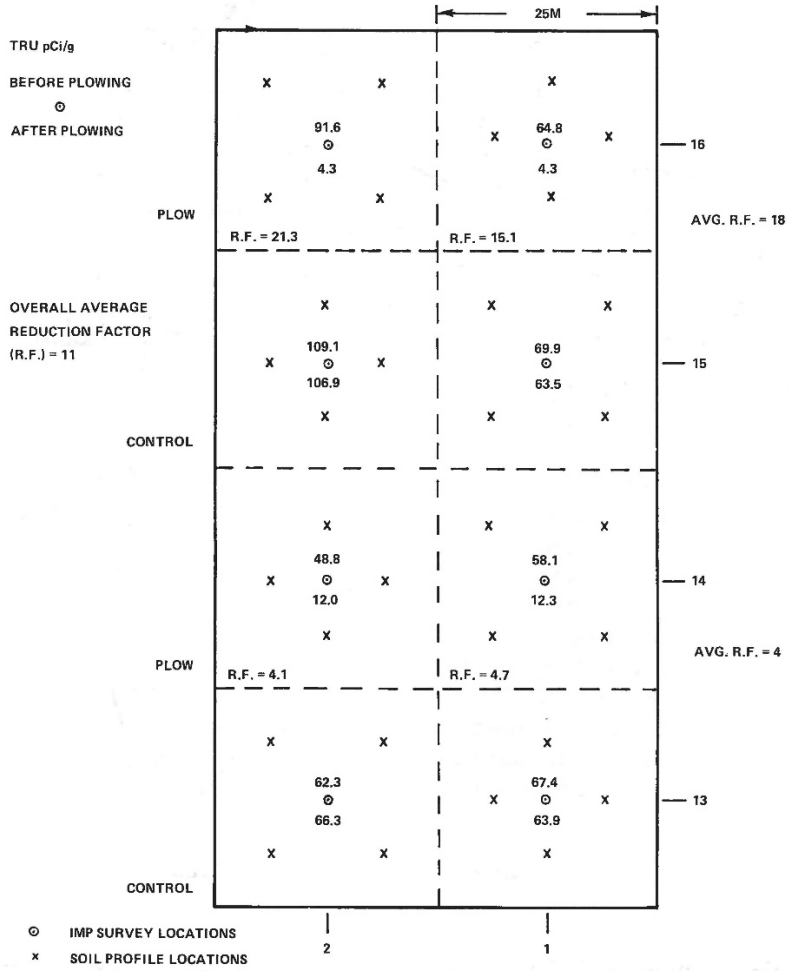


Figure F-4. Plow Test X-1 Area on Janet [Figure 7-9, (DNA 1981)].

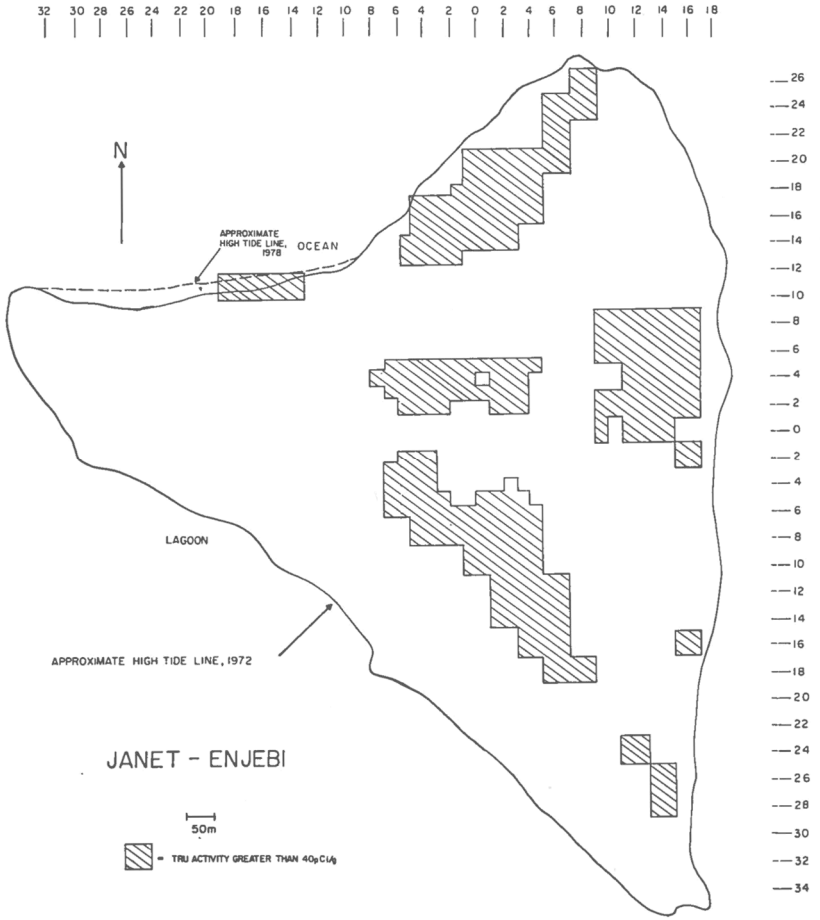


Figure F-5. Initial Characterization of Surface Transuranic Activity on Island Janet [Figure 7-66, (DOE 1982)].

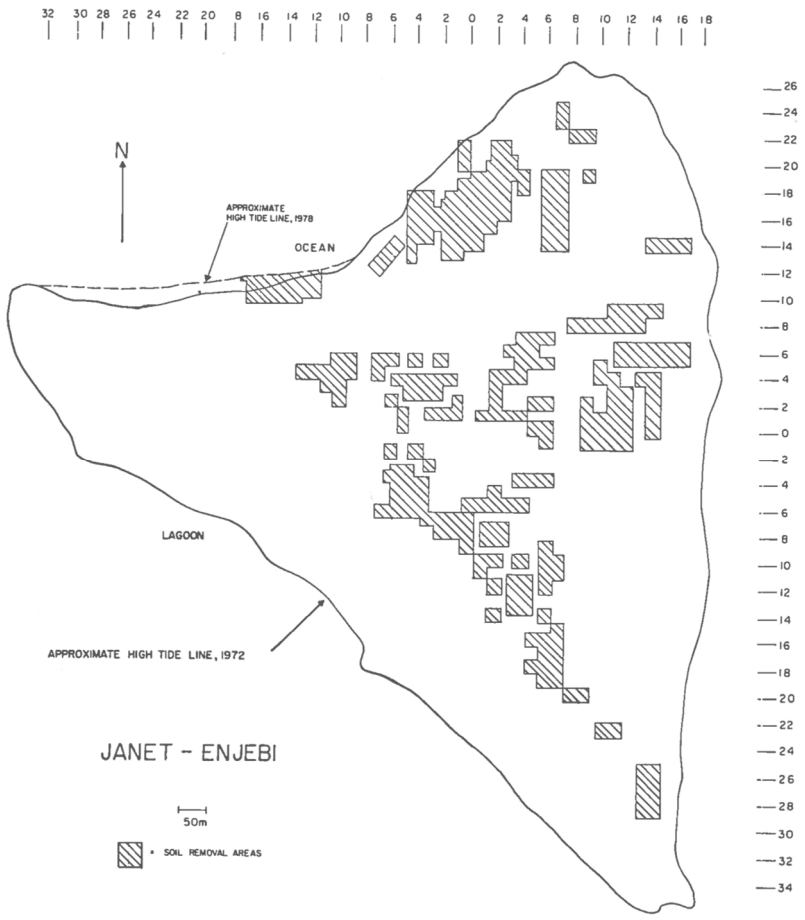


Figure F-6. Areas of Soil Removal for Surface Cleanup on Island Janet [Figure 7-67, (DOE 1982)].

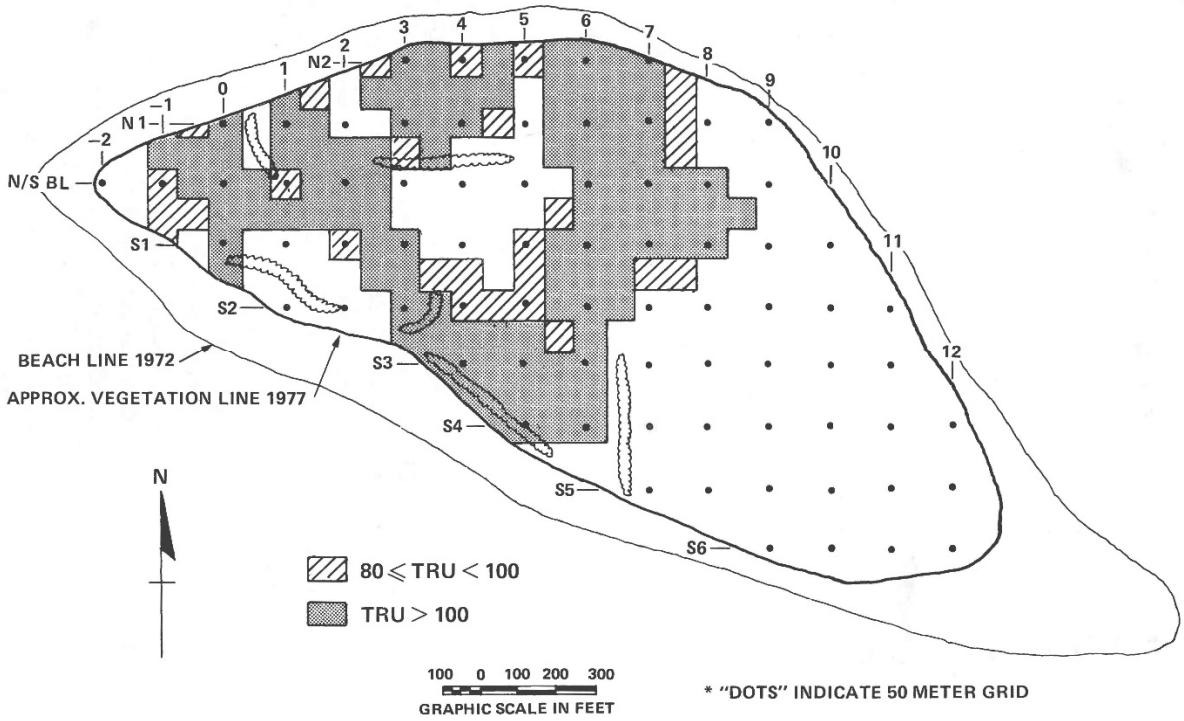


Figure F-7. Island Pearl Cleanup Areas [Figure 7-50, (DNA 1981)].

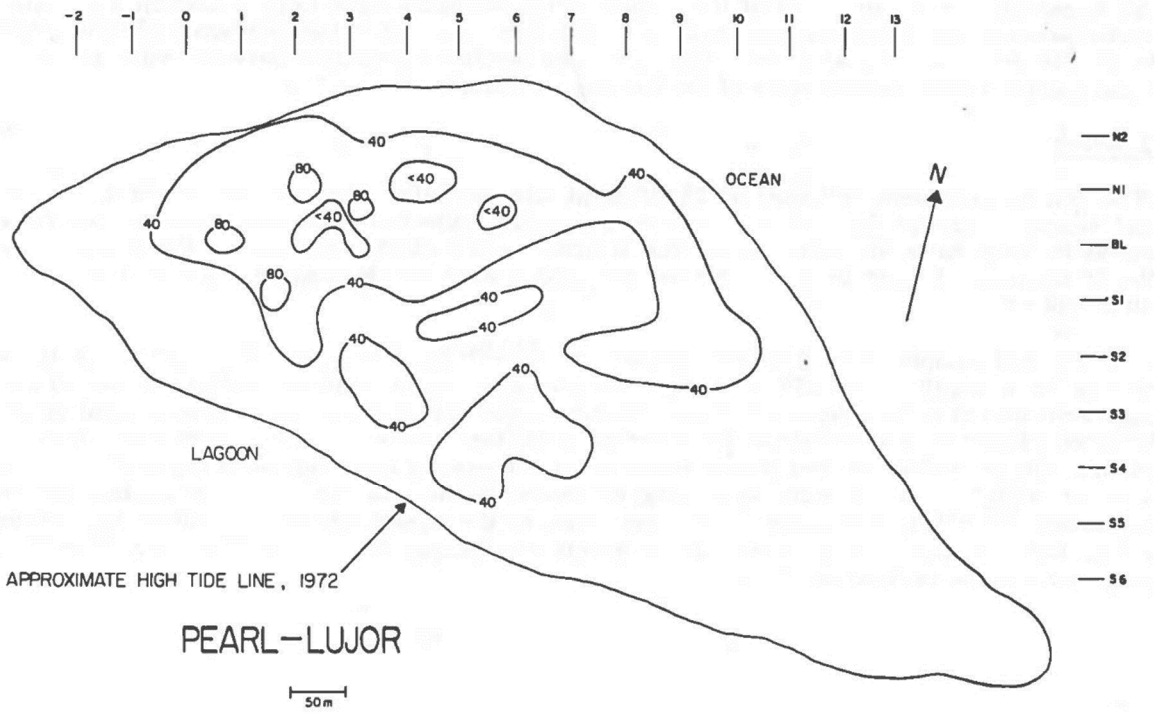


Figure F-8. Final Estimated Transuranic Activity Isopleths (pCi g^{-1}) for Island Pearl [Figure 7-96, (DOE 1982)].

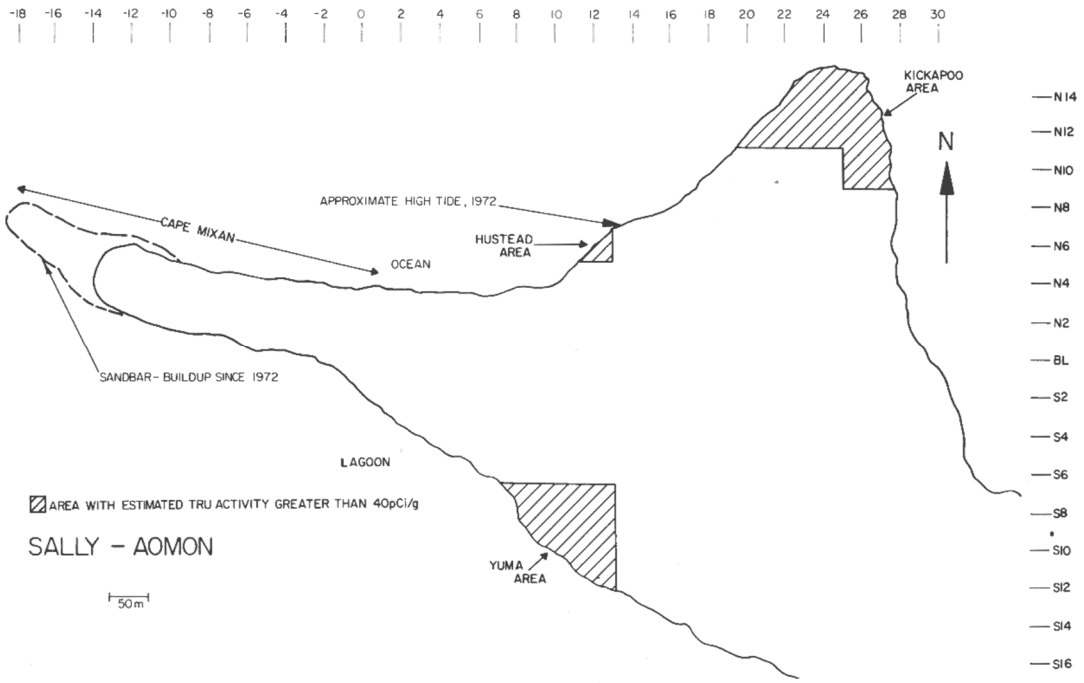


Figure F-9. Areas of Island Sally Designated for Soil Excision [Figure 7-98, DOE (1982)].

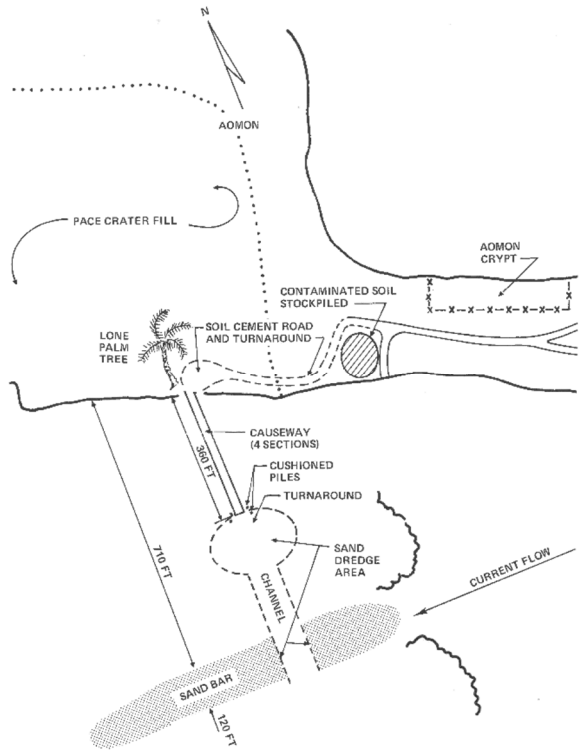


Figure F-10. Area Cleared by Sand Dredging on Island Sally and Details of Soil Stockpiles and Aomon Crypt Excavation Area [Figure 7-42, DNA (1981)].

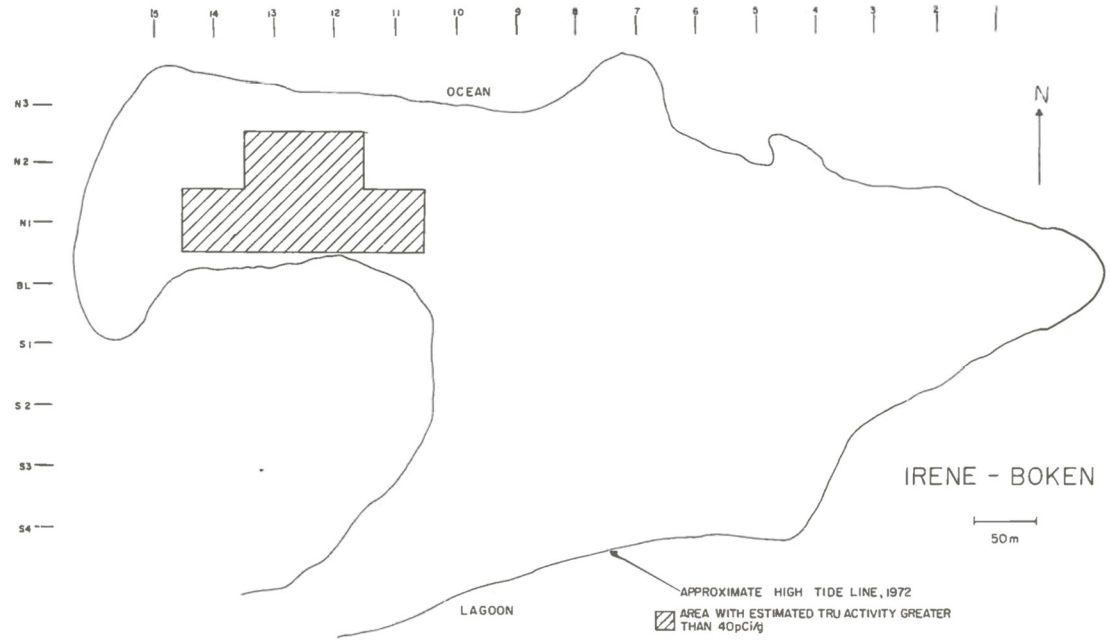


Figure F-11. Surface Soil Areas of Island Irene with Estimated Transuranic Activity Greater than 40 pCi g^{-1} [Figure 7-51, (DOE 1982)].

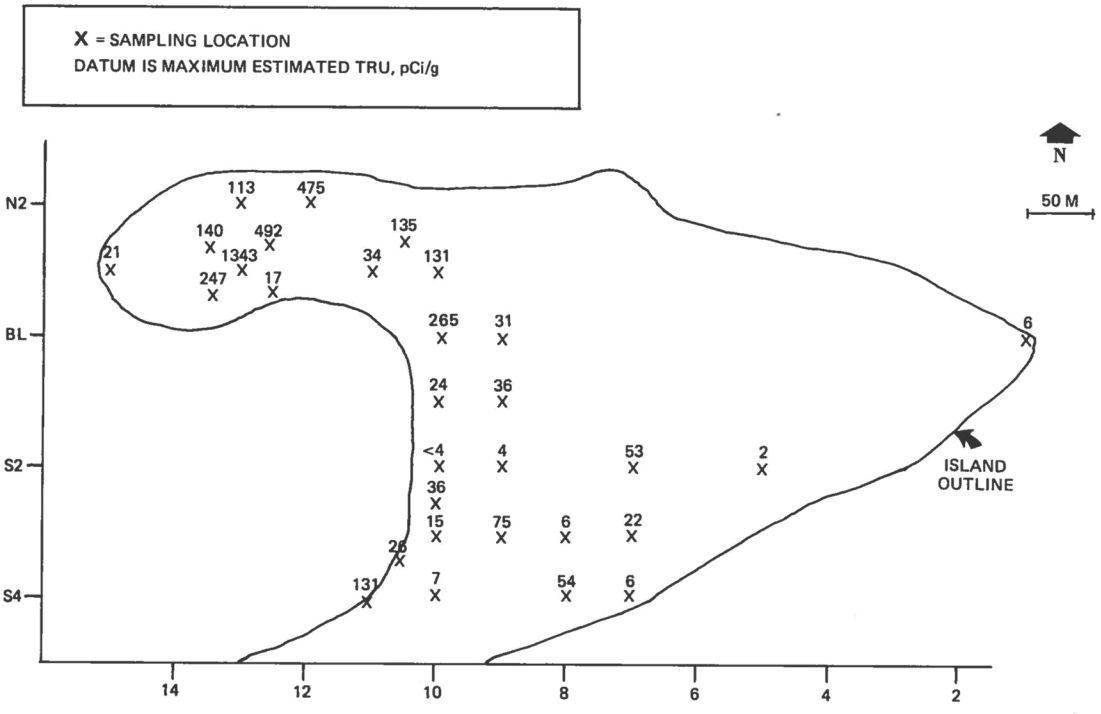


Figure F-12. Sub-Surface Sampling Locations on Island Irene with Notation of Transuranic Activity Concentrations [Figure 7-52, (DOE 1982)].

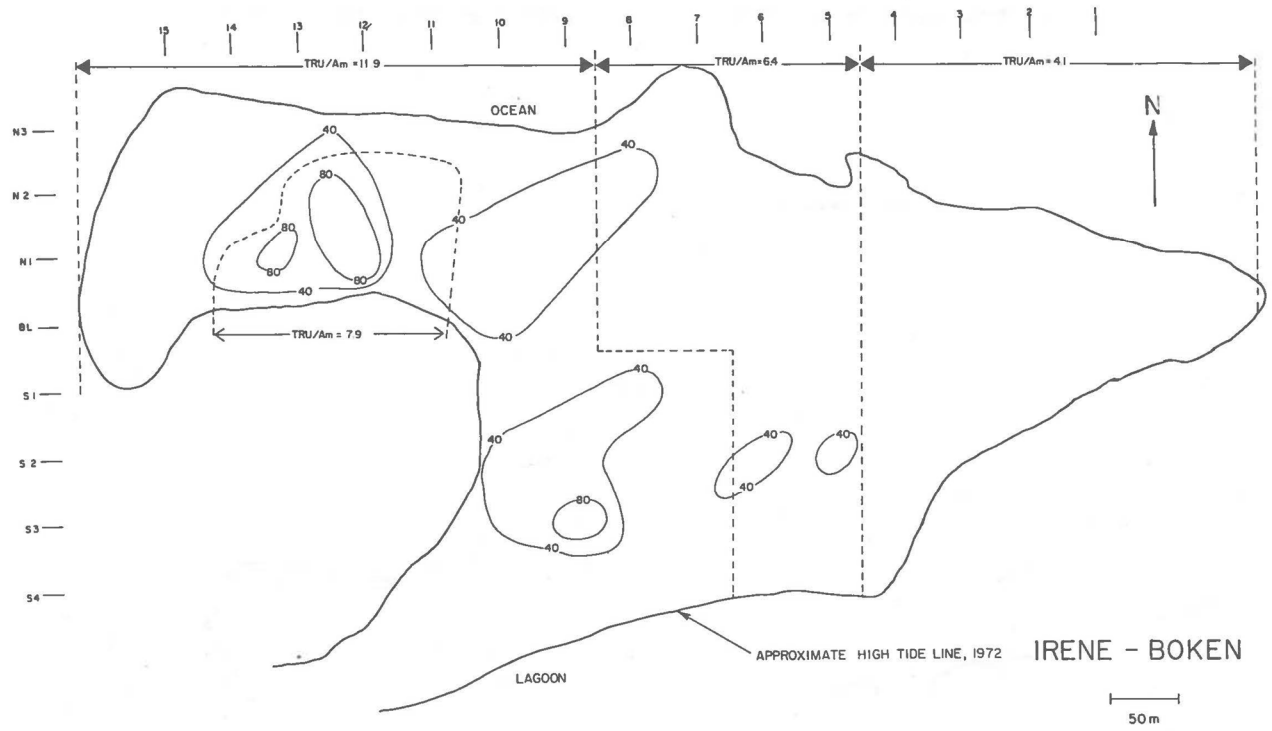


Figure F-13. Final Estimated Transuranic Activity Isopleths (pCi g^{-1}) for Island Irene, with Annotation of Total Transuranic to ^{241}Am Ratios [Figure 7-64, (DOE 1982)].

Appendix G.

Controlled Island Access Log Data and Personnel Protection Equipment (PPE) Specifications.

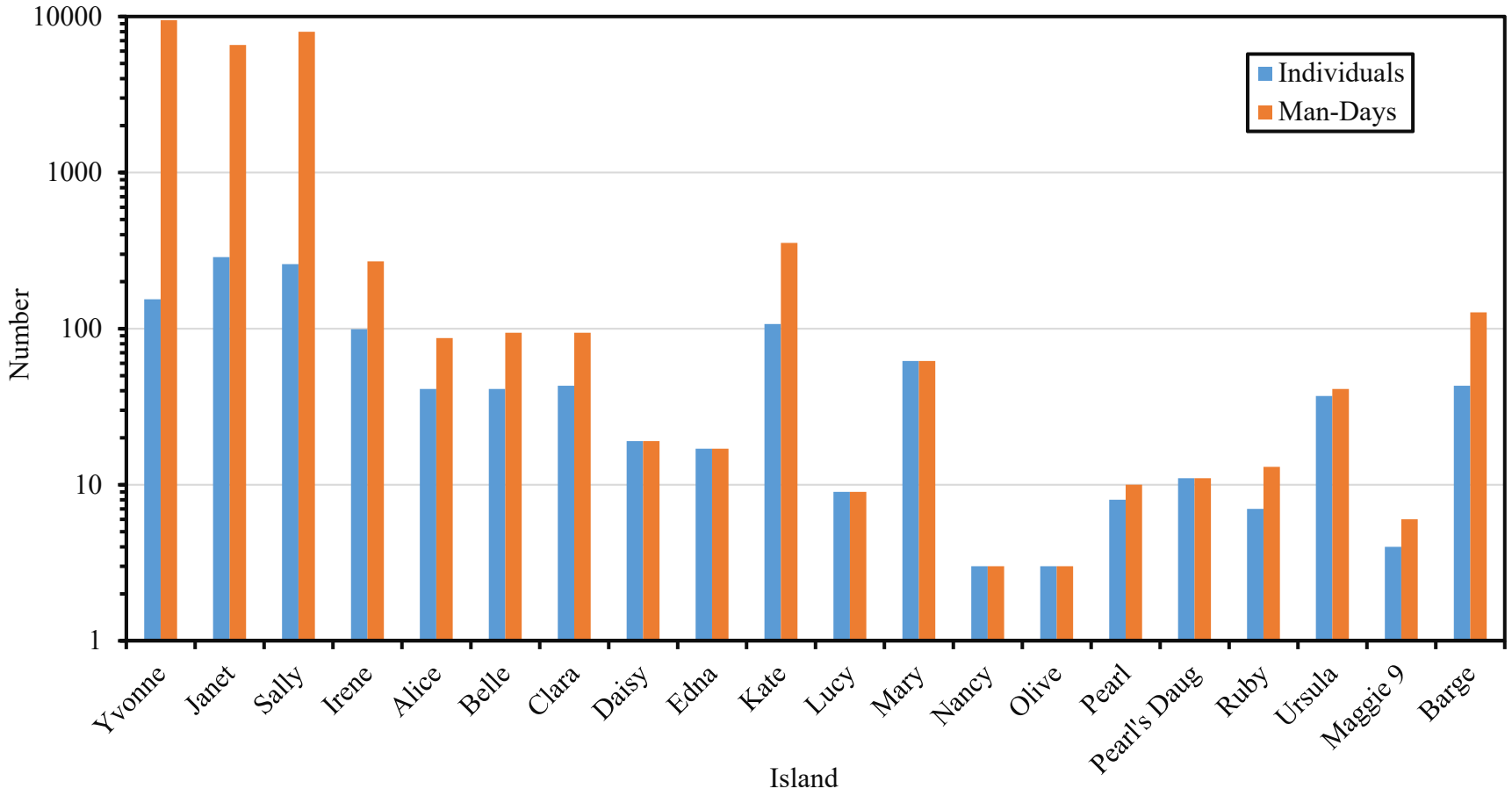


Figure G-1. Controlled Access Island Manning Data for April 1978.

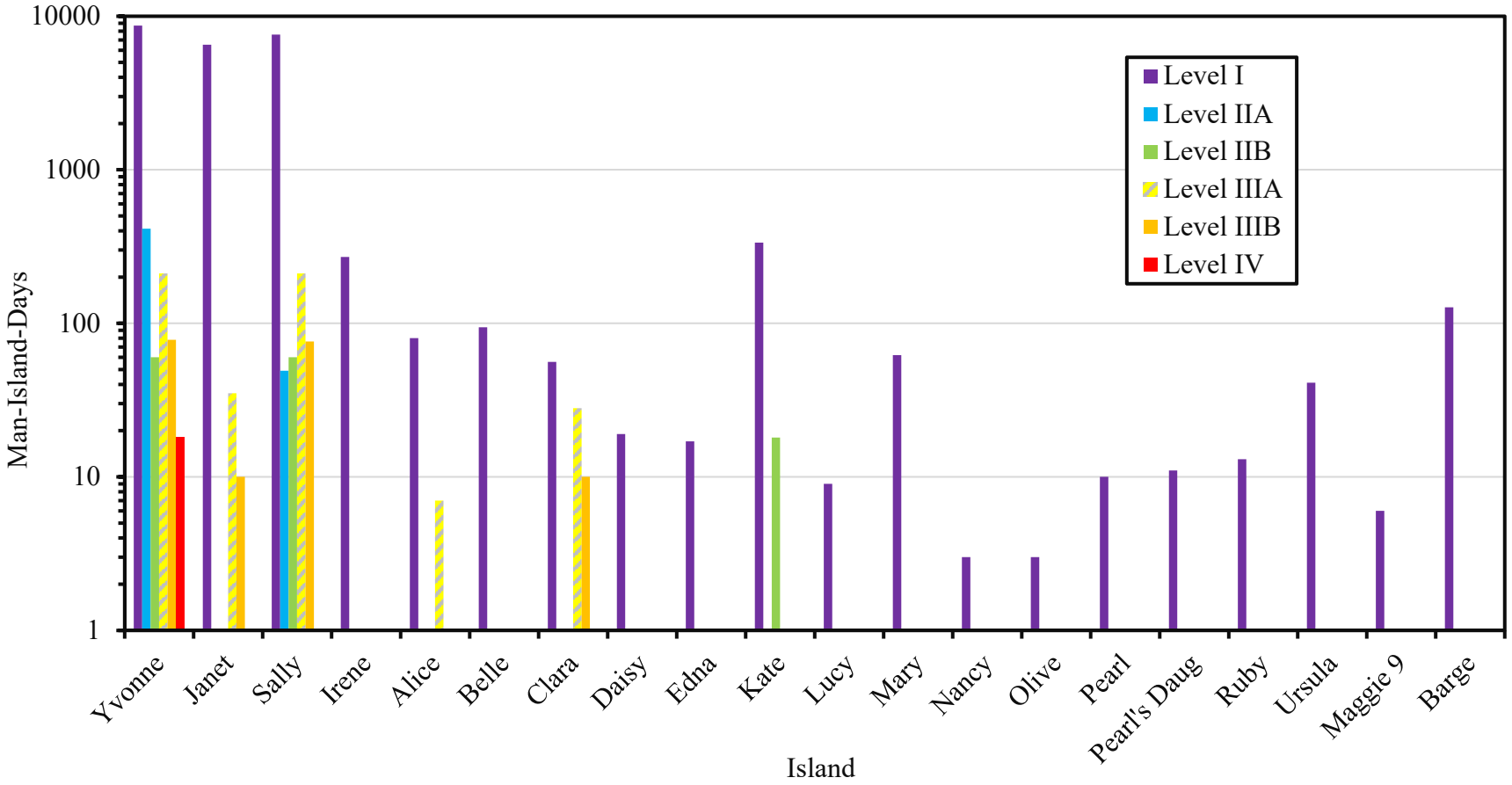


Figure G-2. PPE Levels for Work Conducted on Controlled Islands in April 1978.

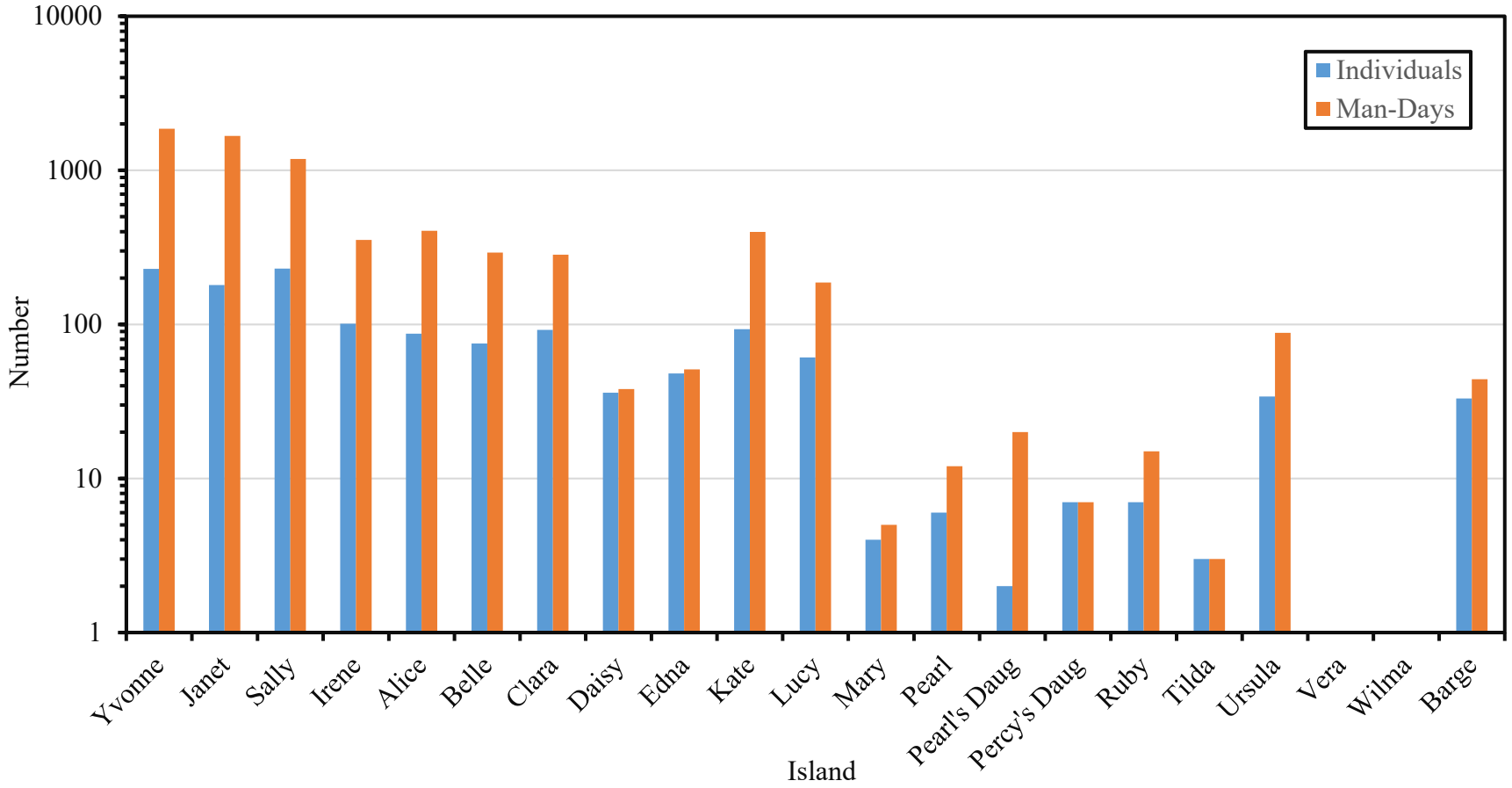


Figure G-3. Controlled Access Island Manning Data for May 1978.

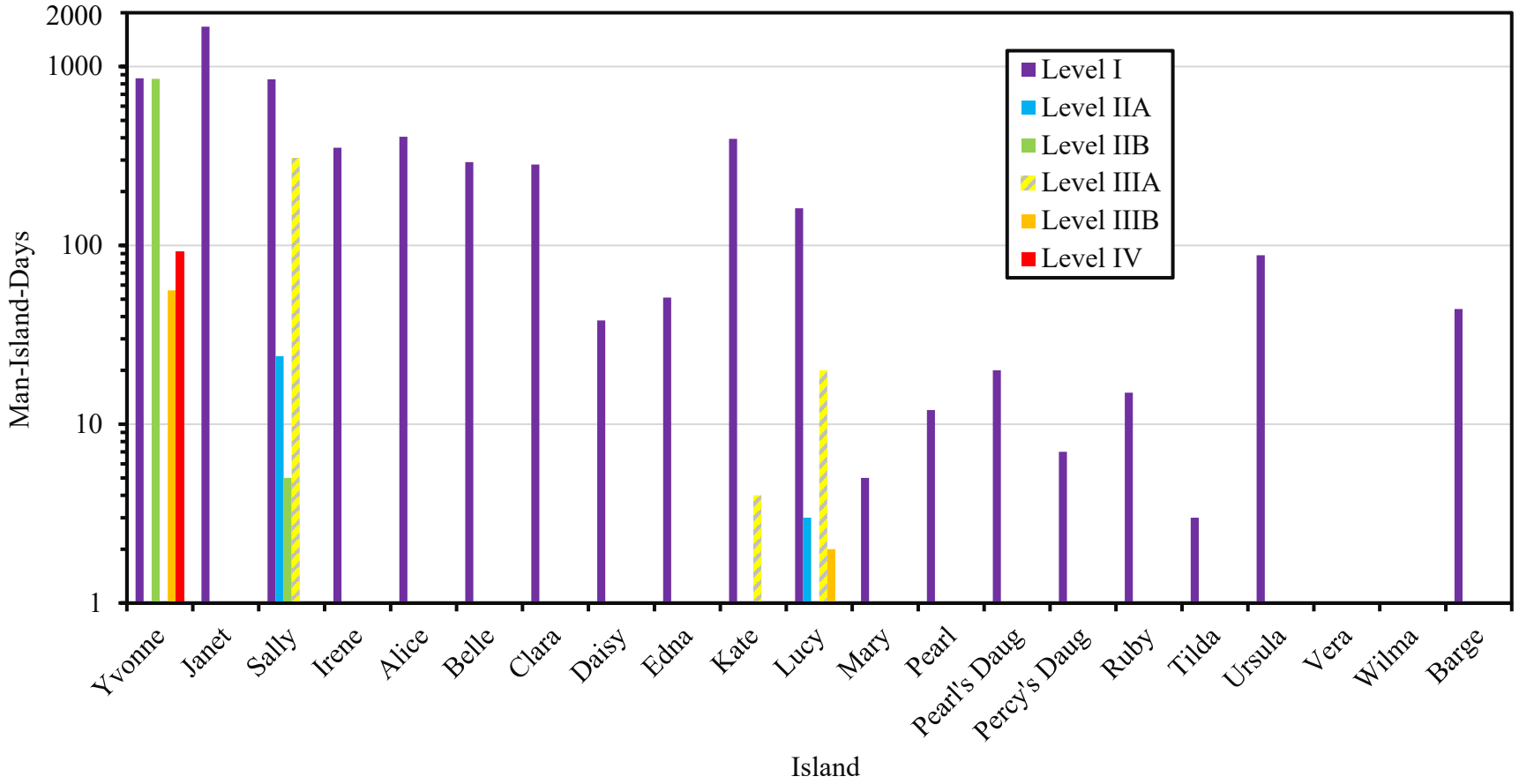


Figure G-4. PPE Levels for Work Conducted on Controlled Islands in May 1978.

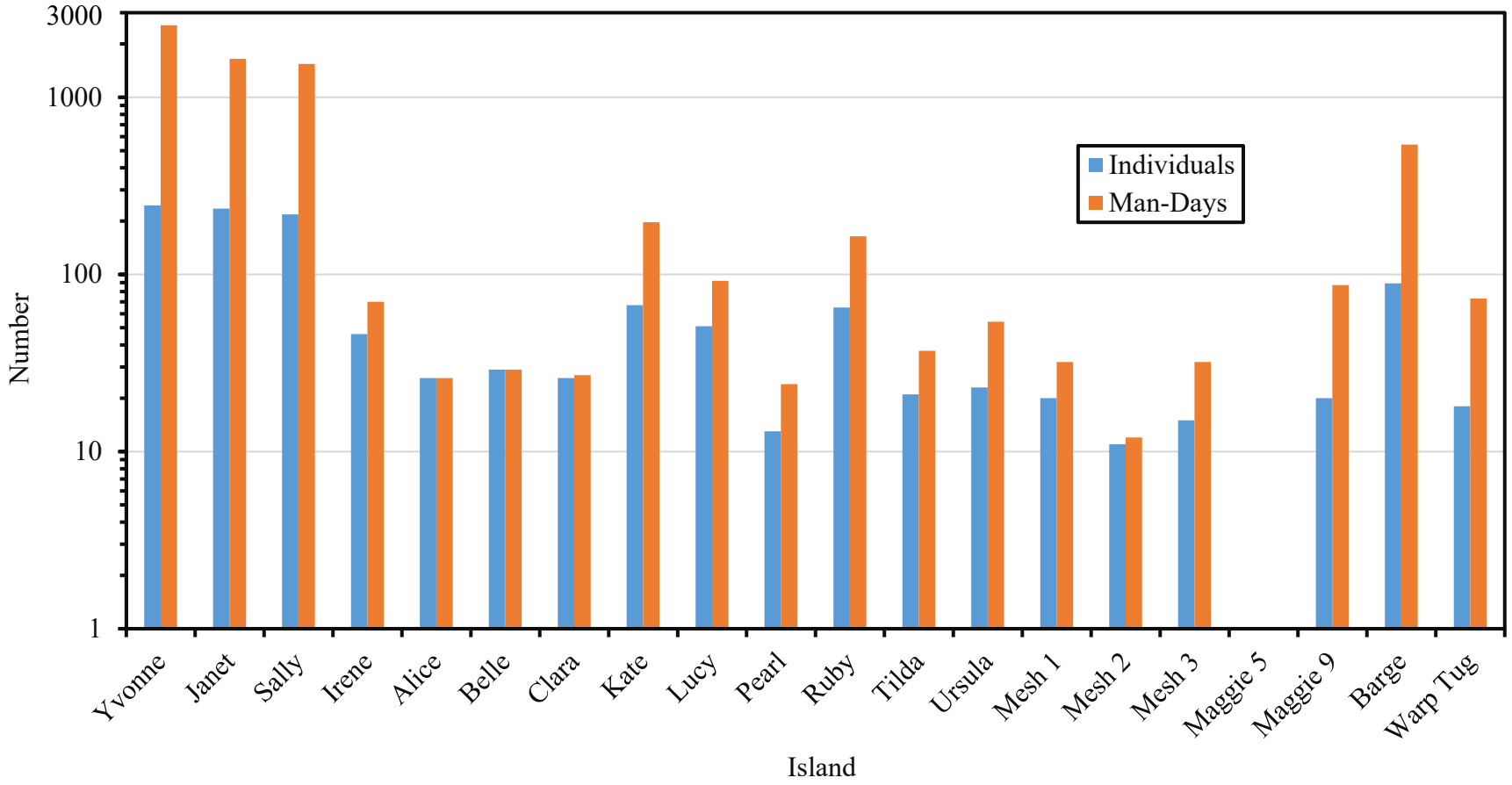


Figure G-5. Controlled Access Island Manning Data for June 1978.

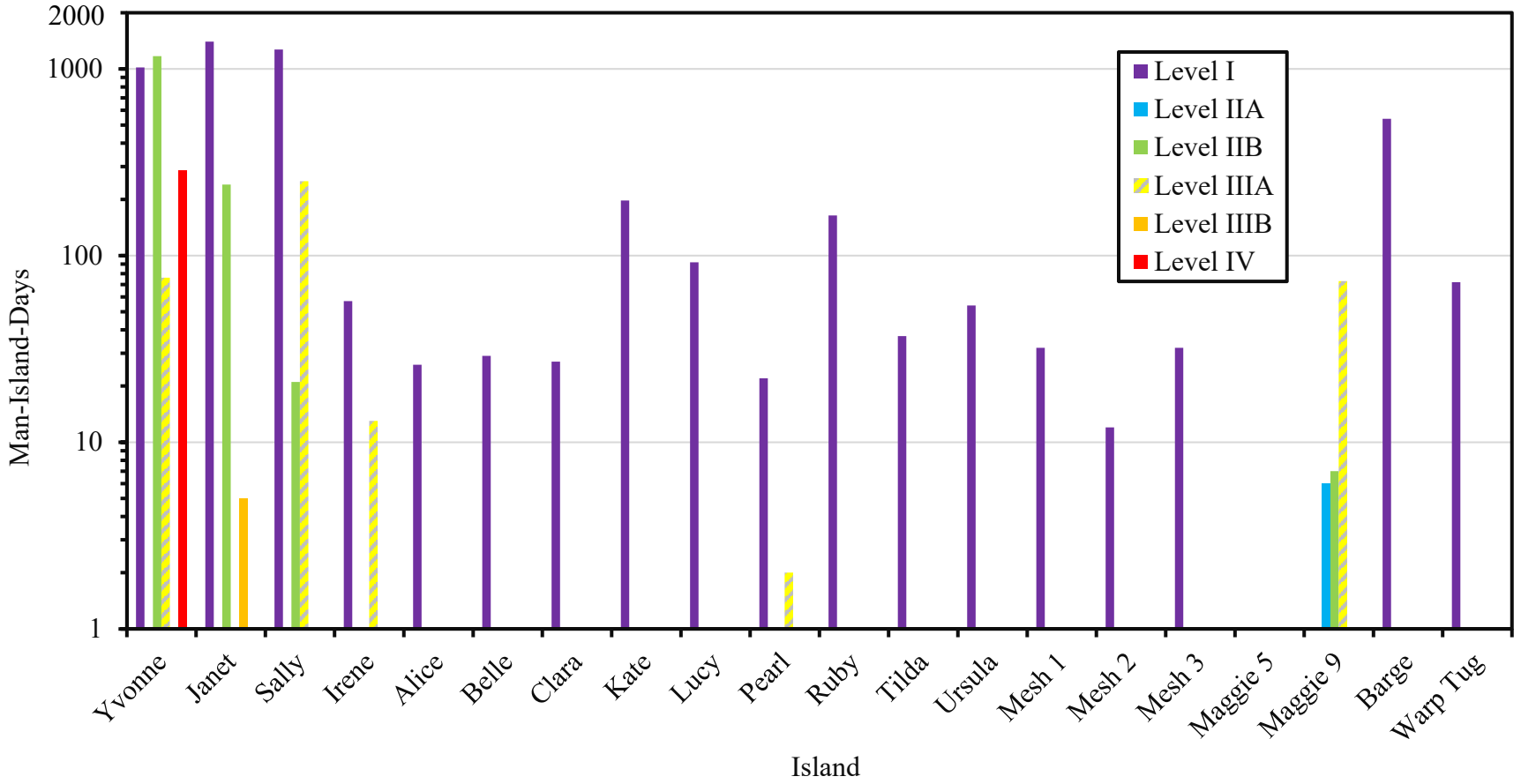


Figure G-6. PPE Levels for Work Conducted on Controlled Islands in June 1978.

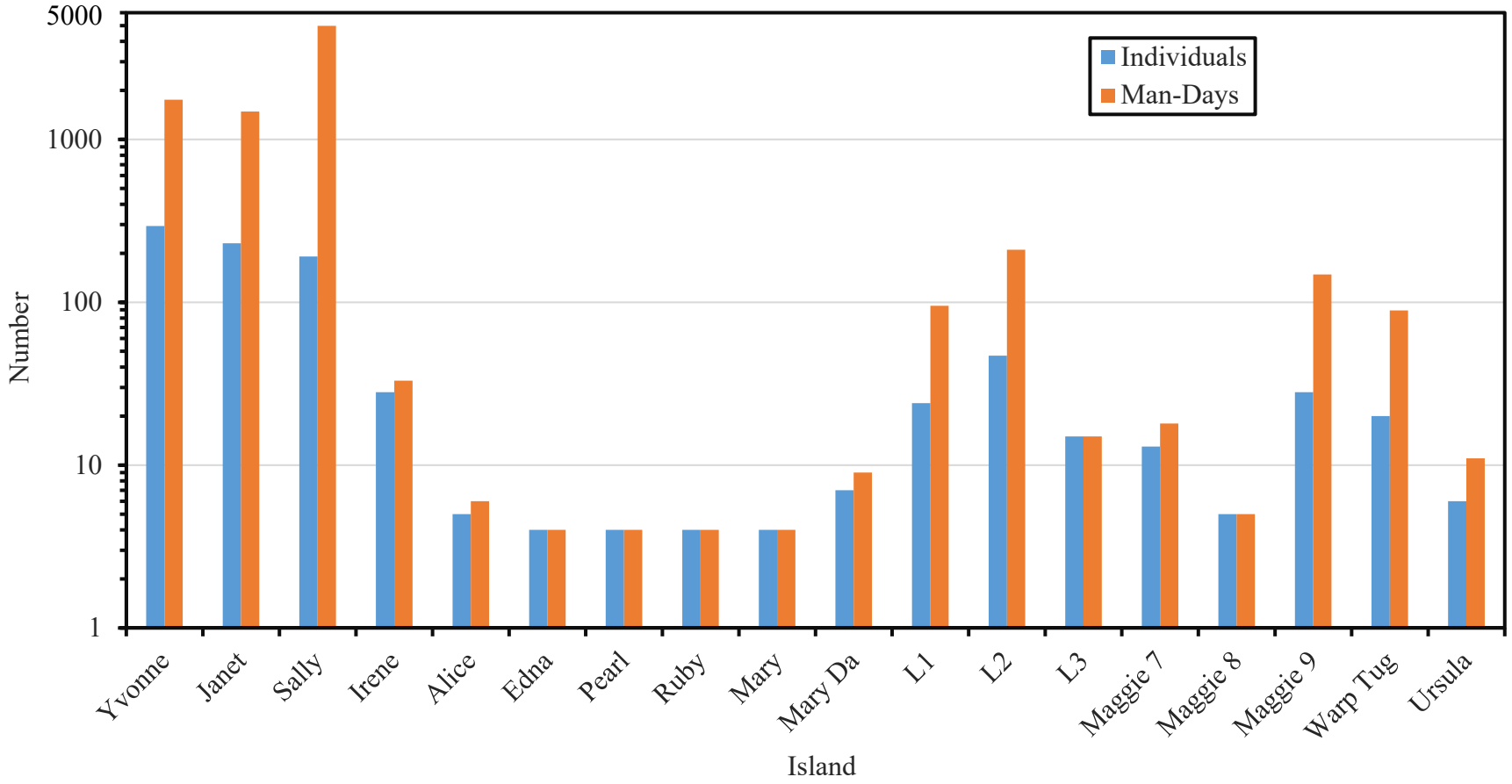


Figure G-7. Controlled Access Island Manning Data for August 1978.

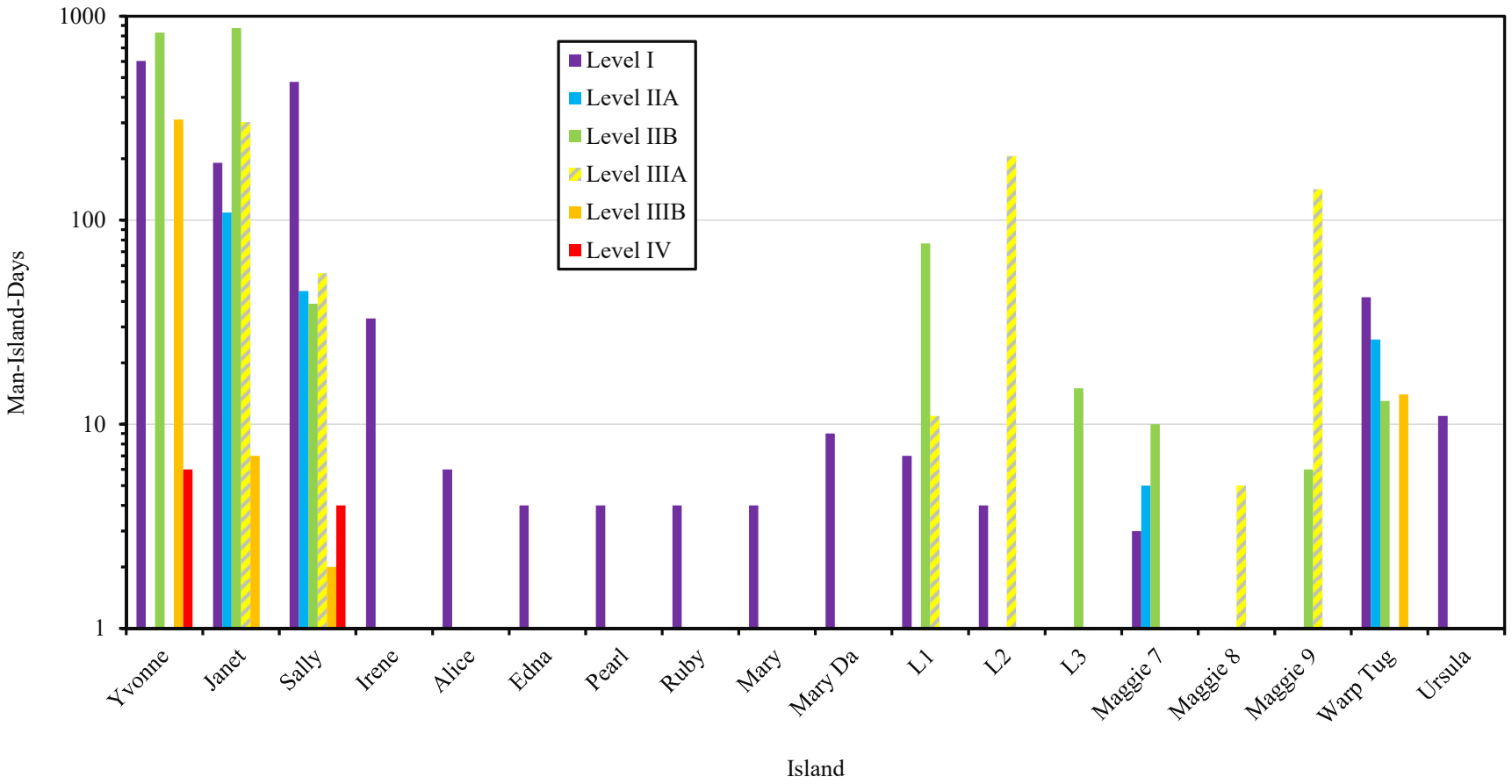


Figure G-8. PPE Levels for Work Conducted on Controlled Islands in August 1978.

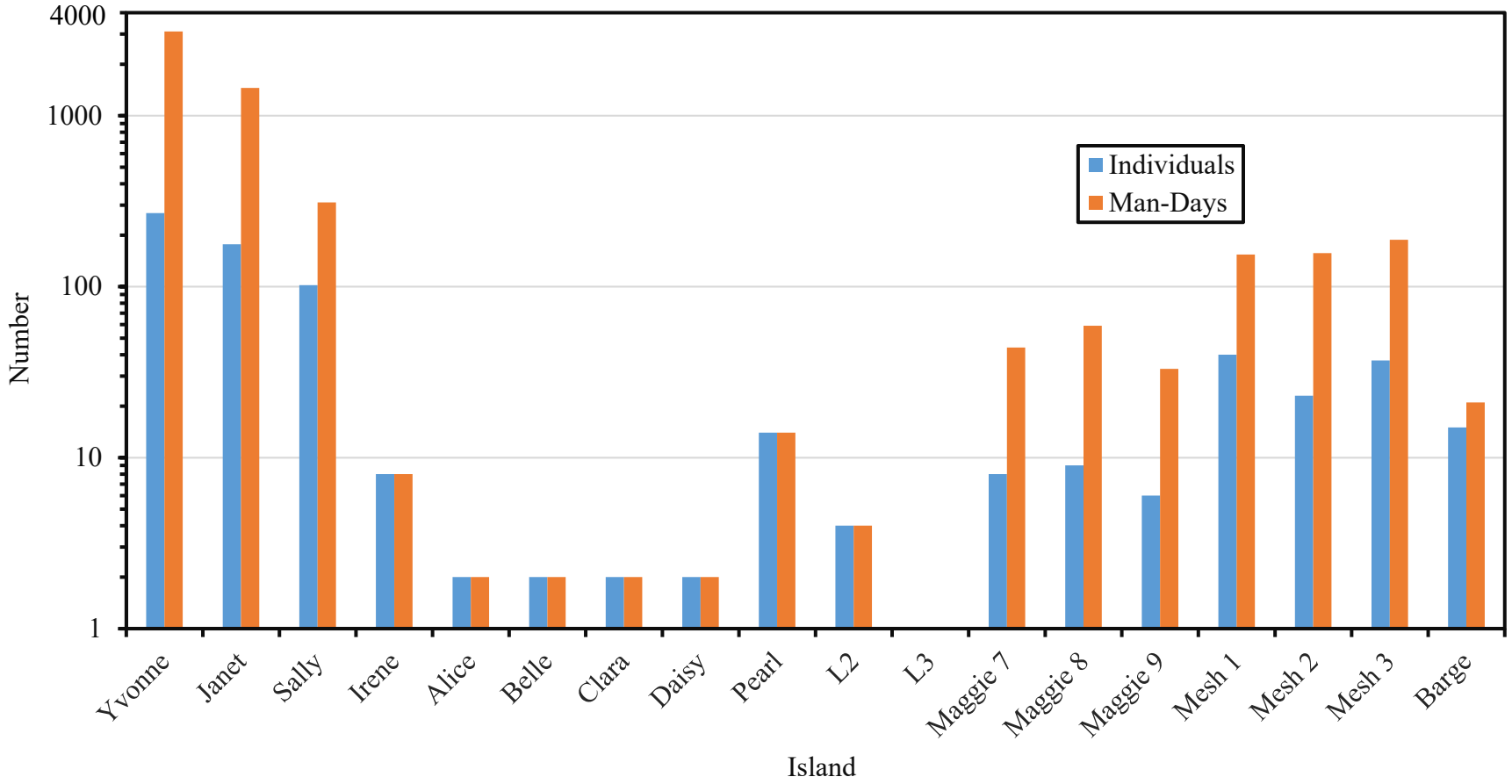


Figure G-9. Controlled Access Island Manning Data for October 1978.

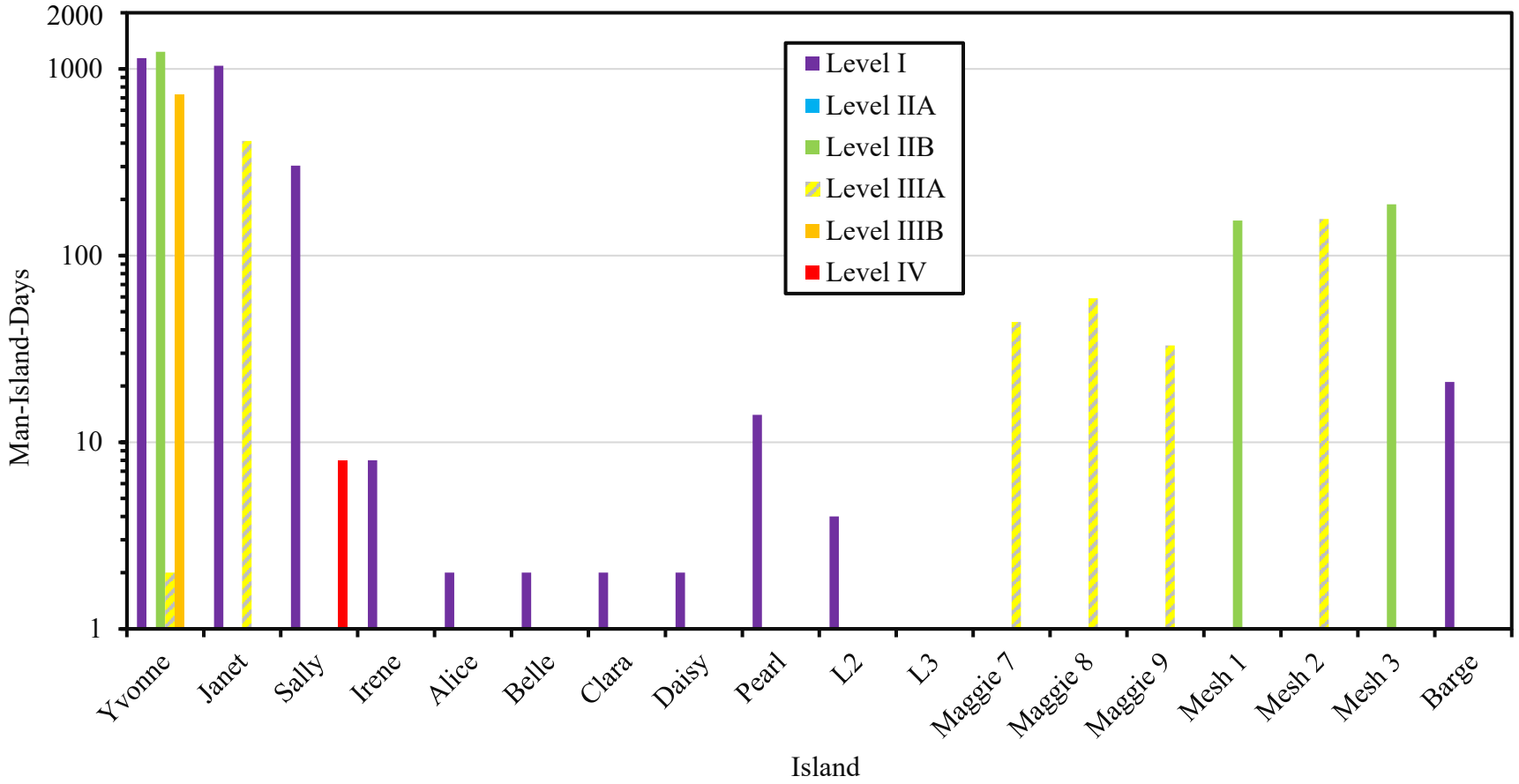


Figure G-10. PPE Levels for Work Conducted on Controlled Islands in October 1978.

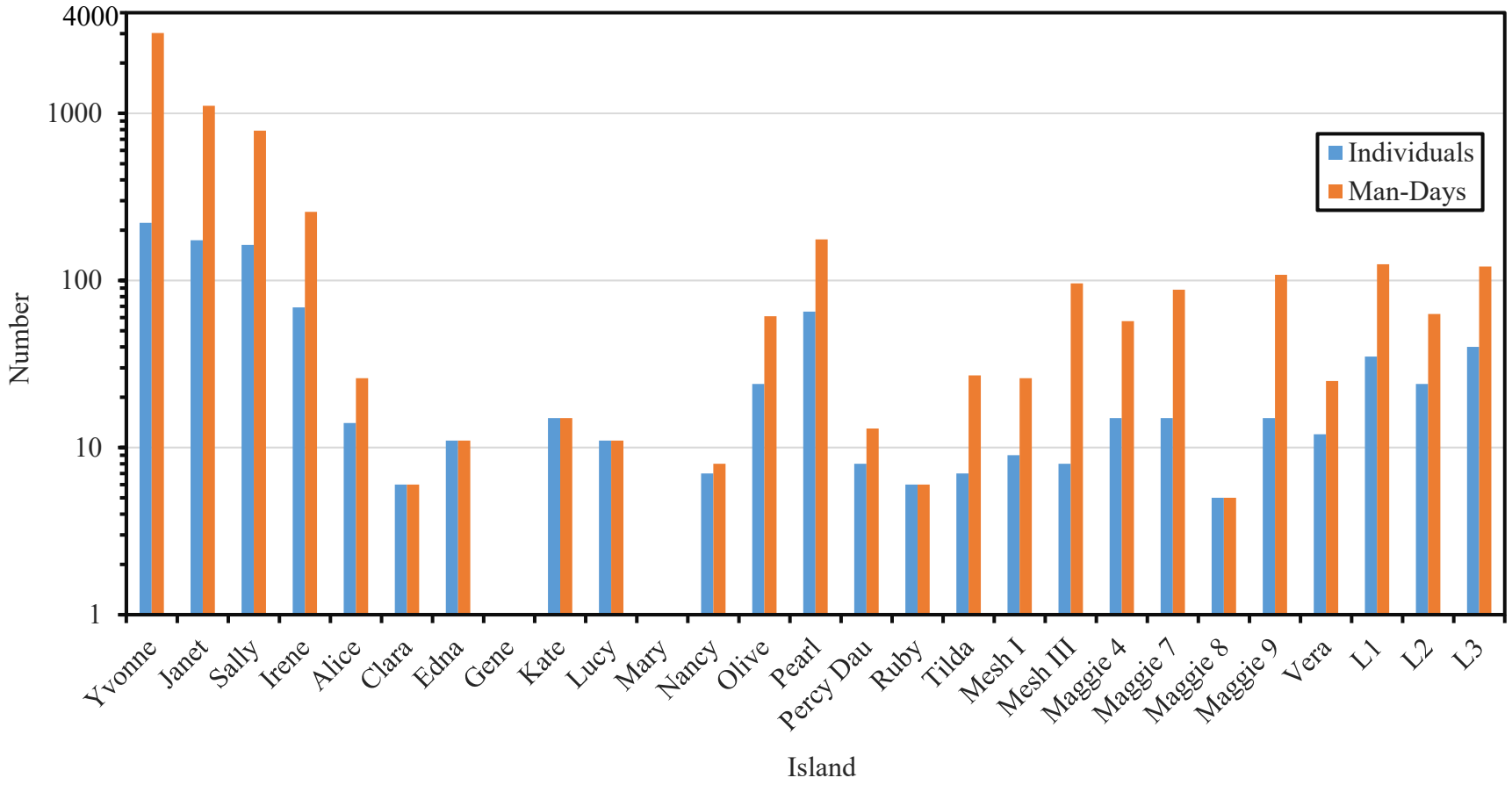


Figure G-11. Controlled Access Island Manning Data for December 1978.

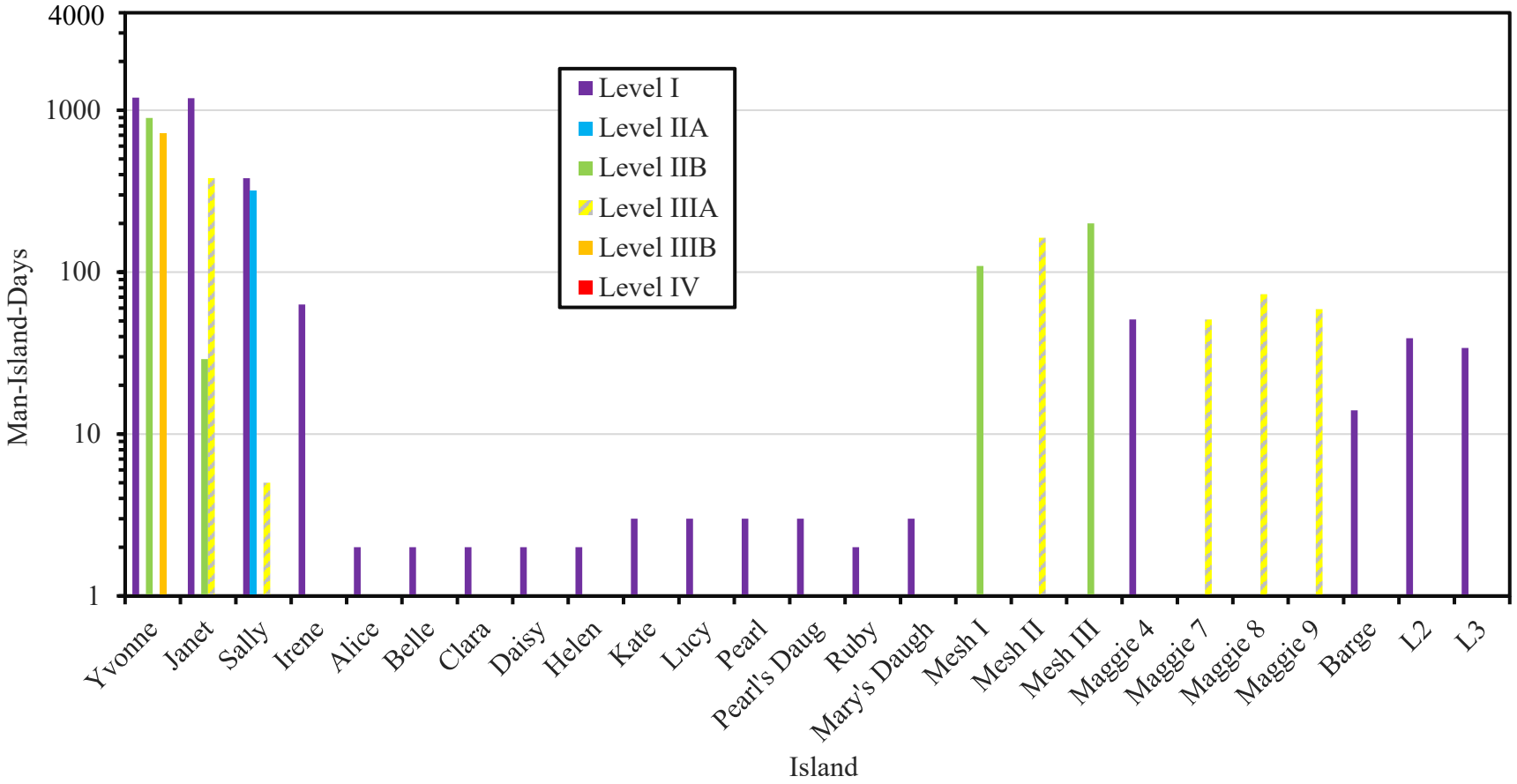


Figure G-12. PPE Levels for Work Conducted on Controlled Islands in December 1978.

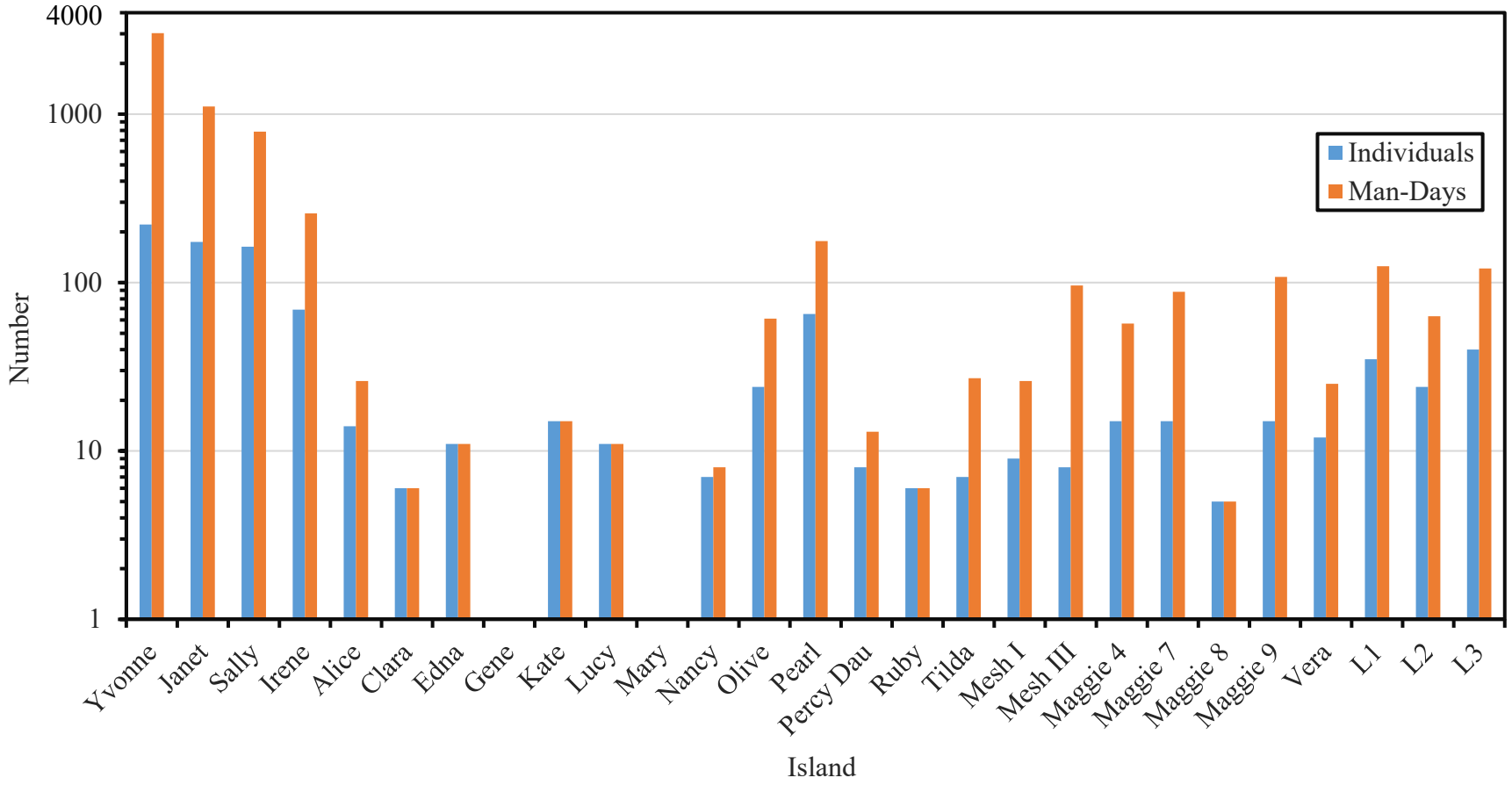


Figure G-13. Controlled Access Island Manning Data for March 1979.

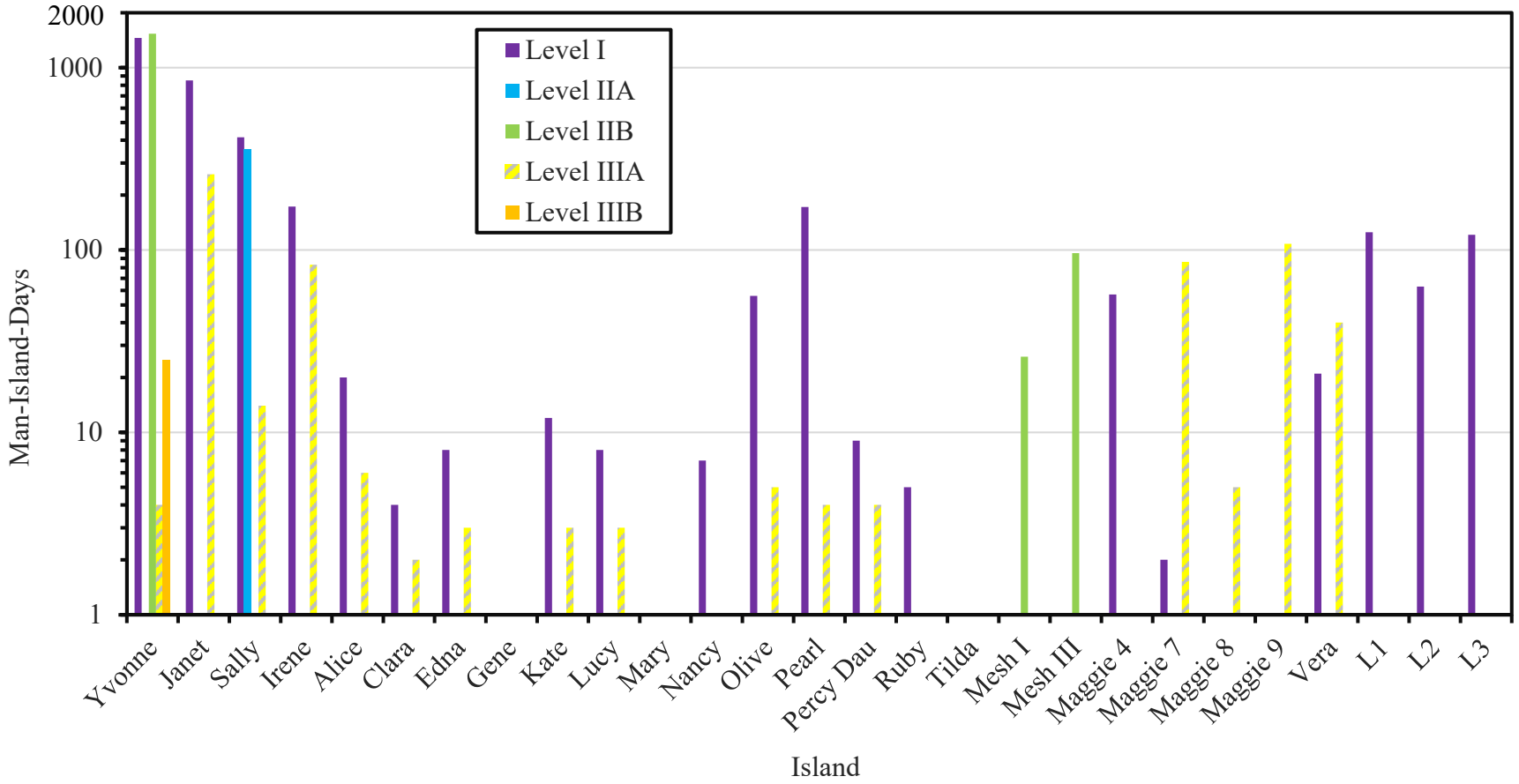


Figure G-14. PPE Levels for Work Conducted on Controlled Islands in March 1979.

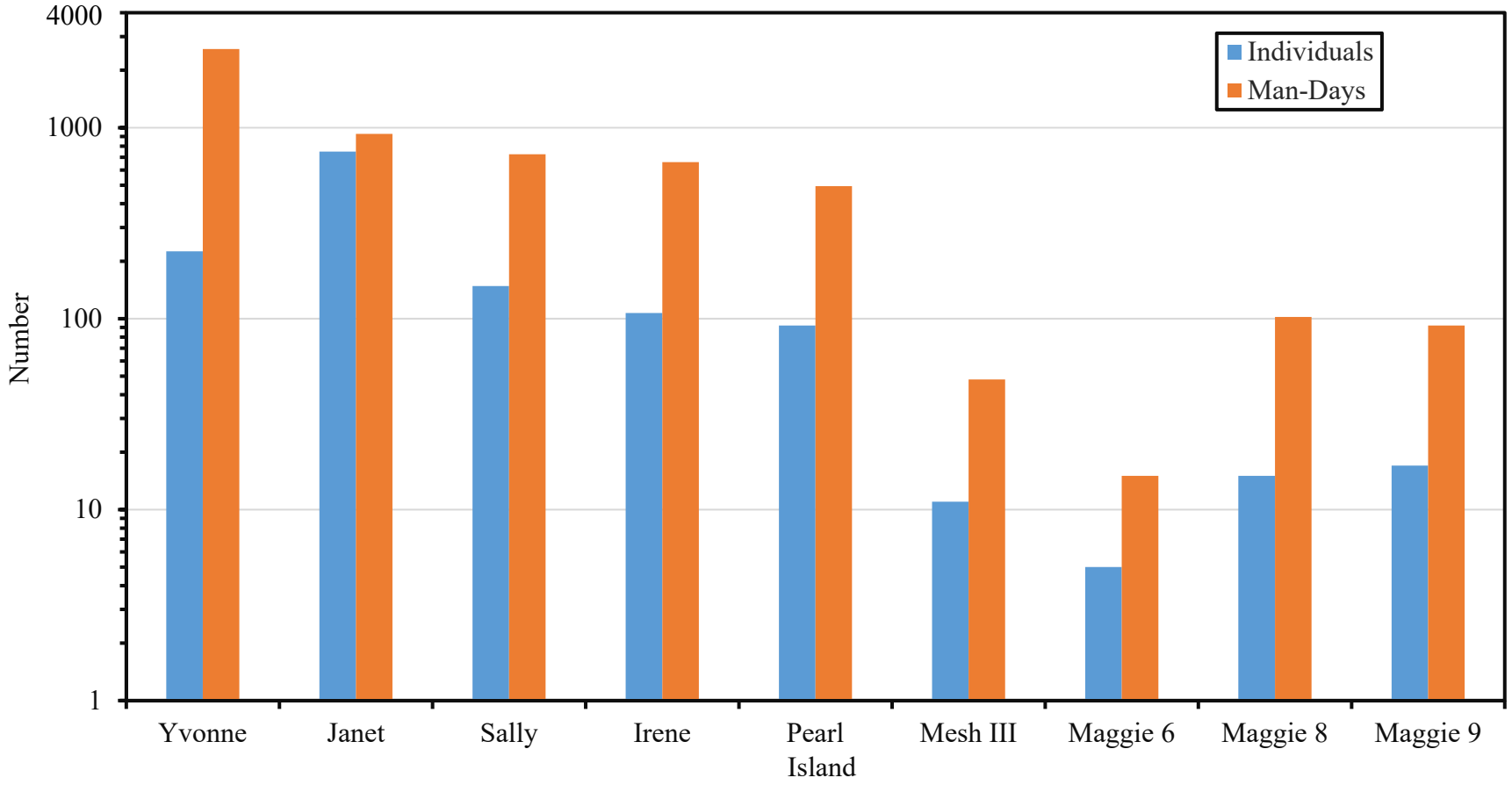


Figure G-15. Controlled Access Island Manning Data for April 1979.

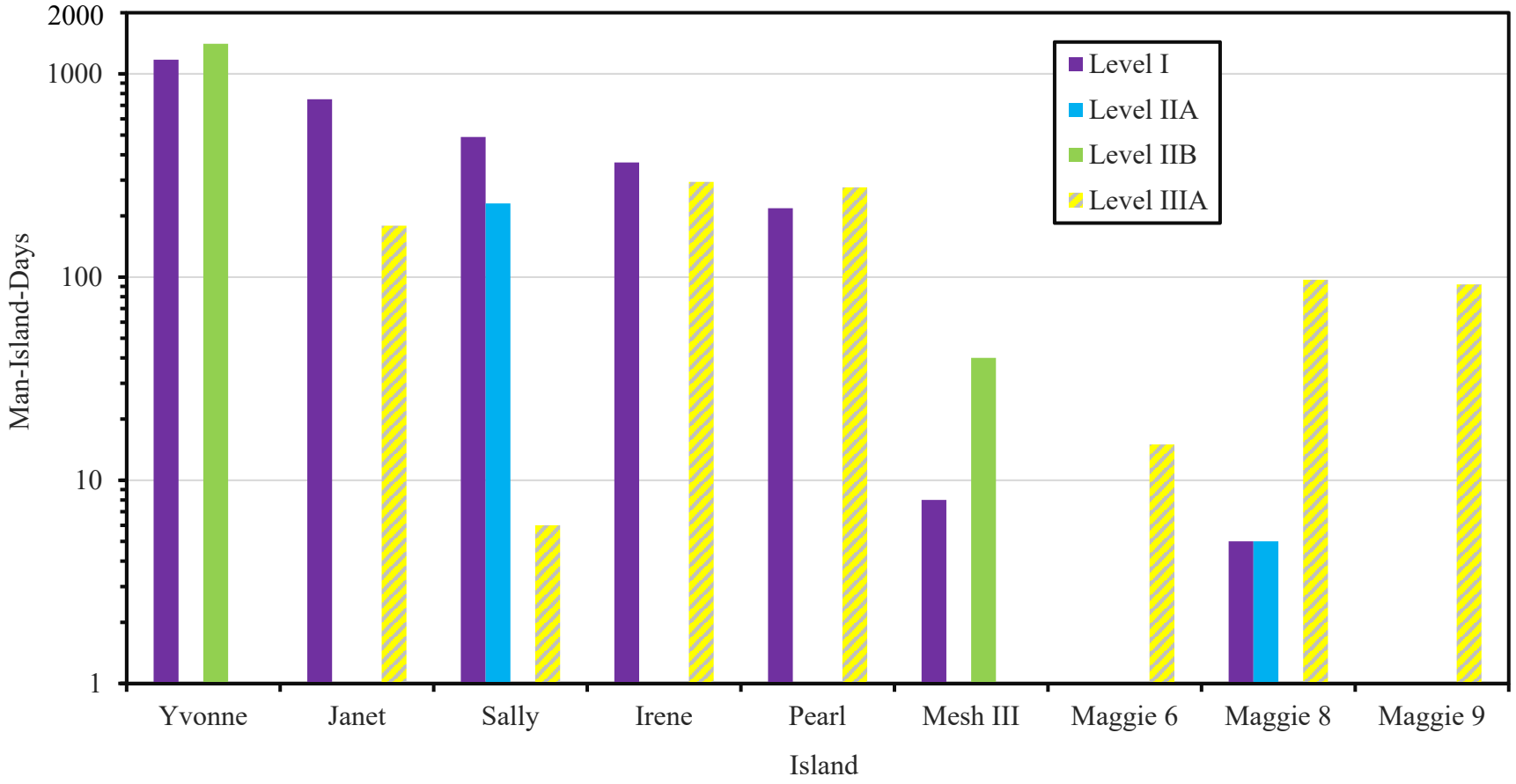


Figure G-16. PPE Levels for Work Conducted on Controlled Islands in April 1979.

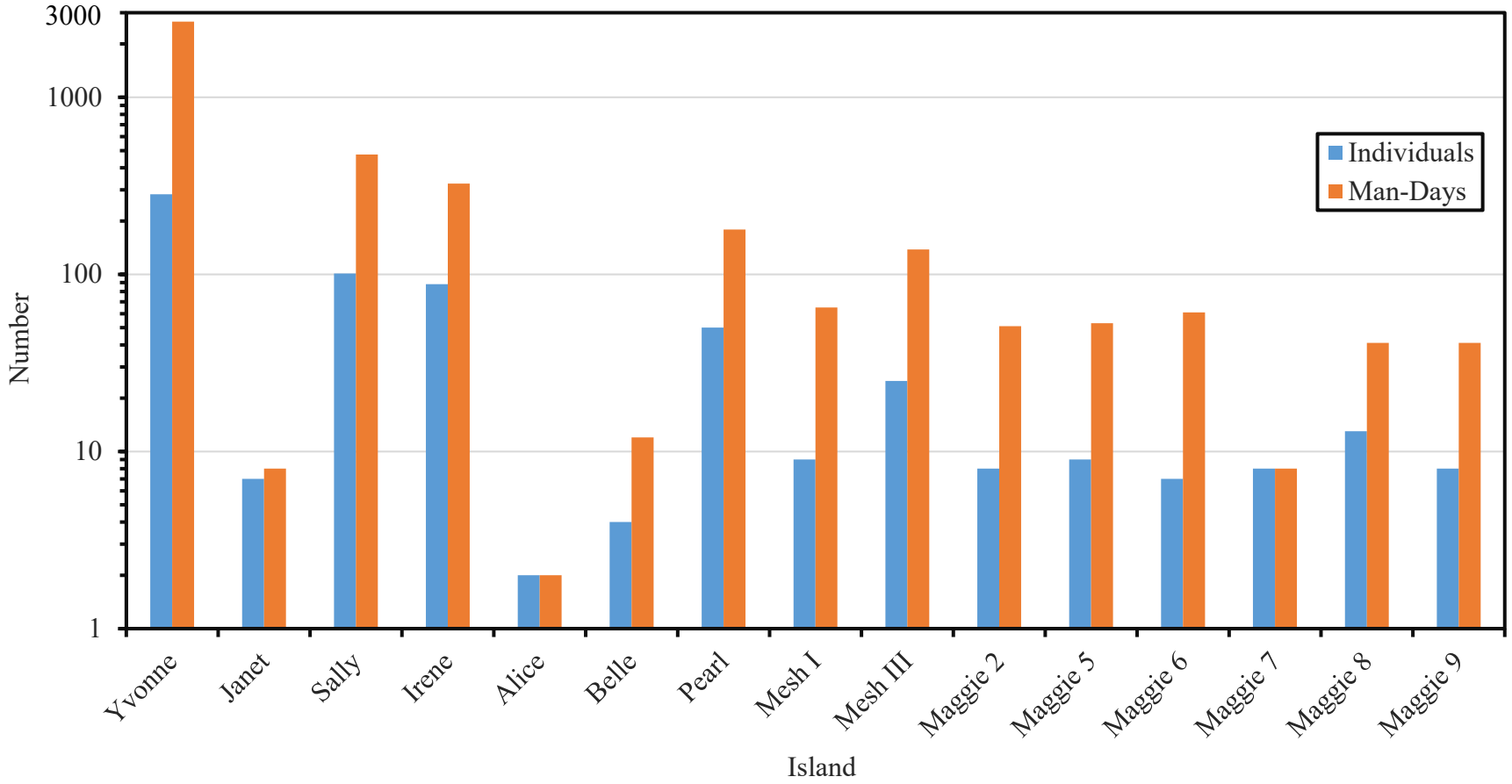


Figure G-17. Controlled Access Island Manning Data for June 1979.

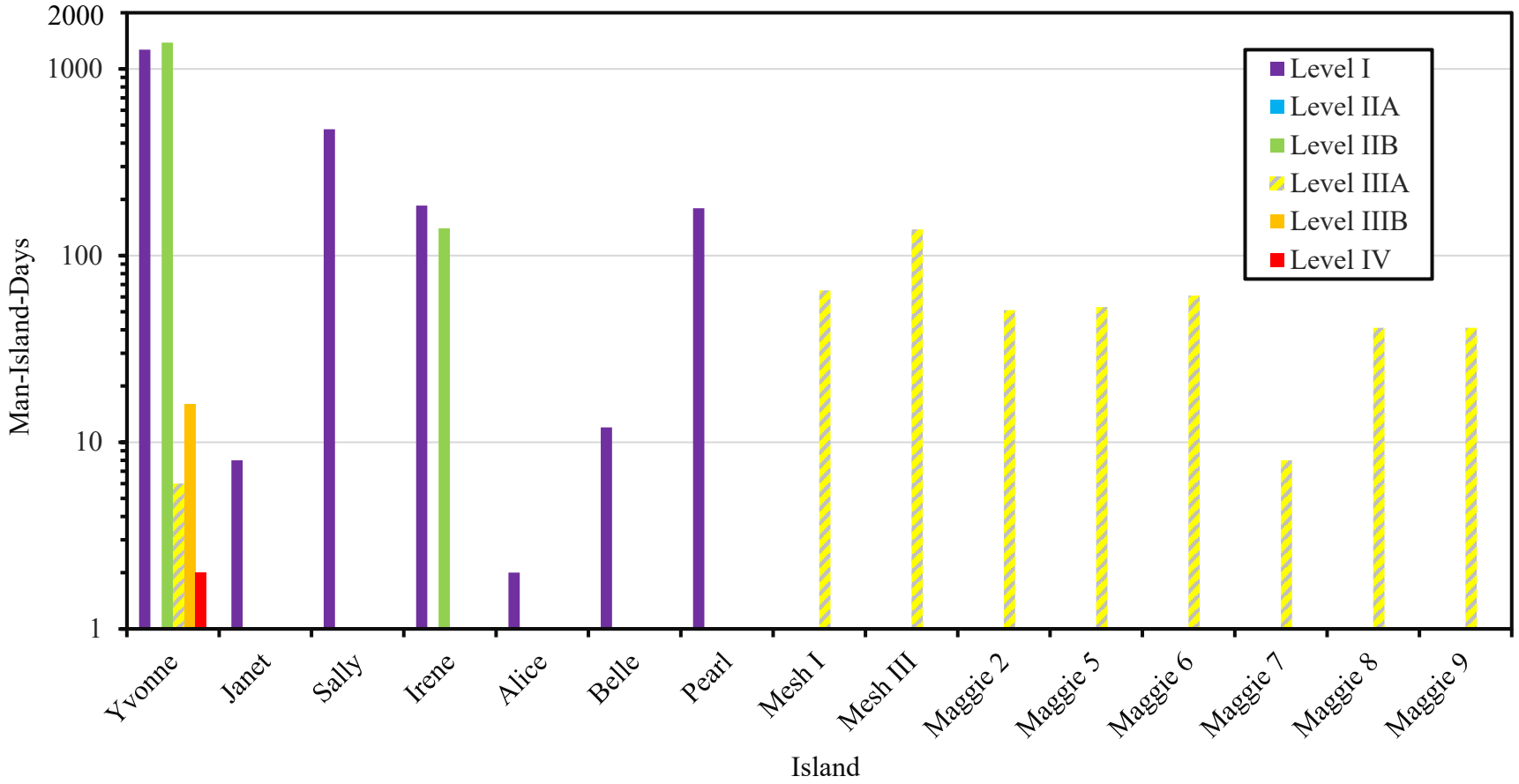


Figure G-18. PPE Levels for Work Conducted on Controlled Islands in June 1979.

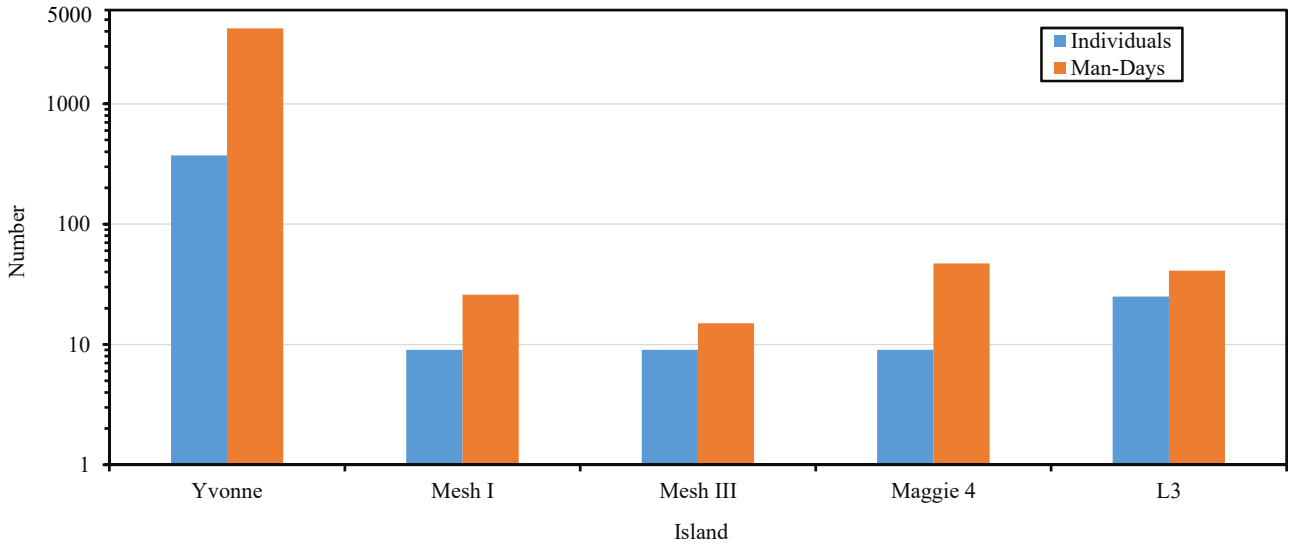


Figure G-19. Controlled Access Island Manning Data for August 1979.

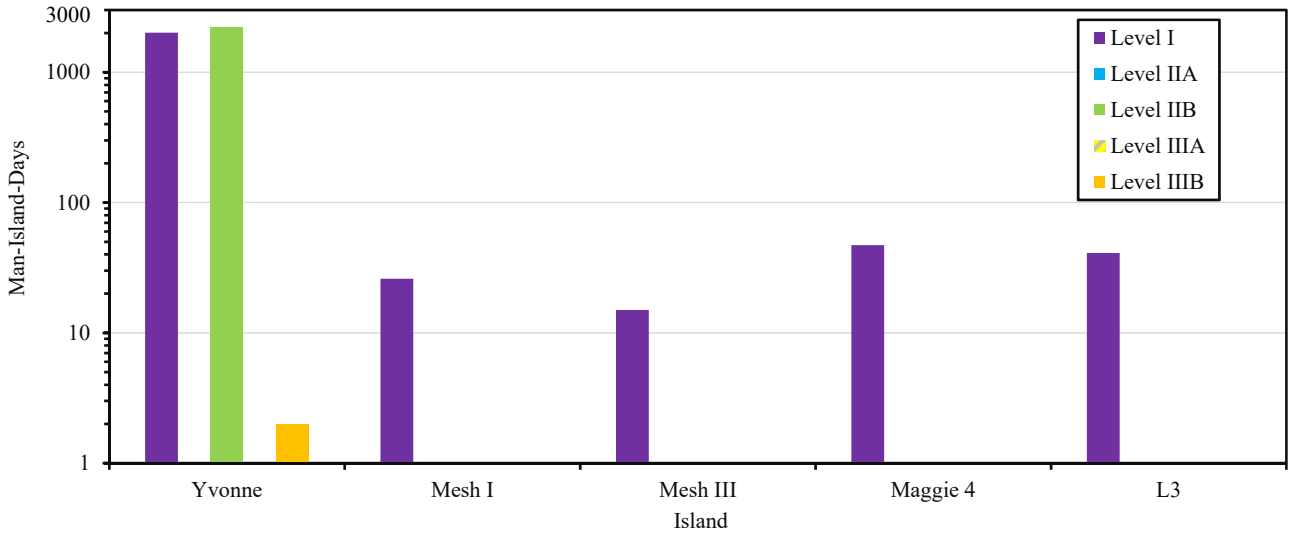


Figure G-20. PPE Levels for Work Conducted on Controlled Islands in August 1979.

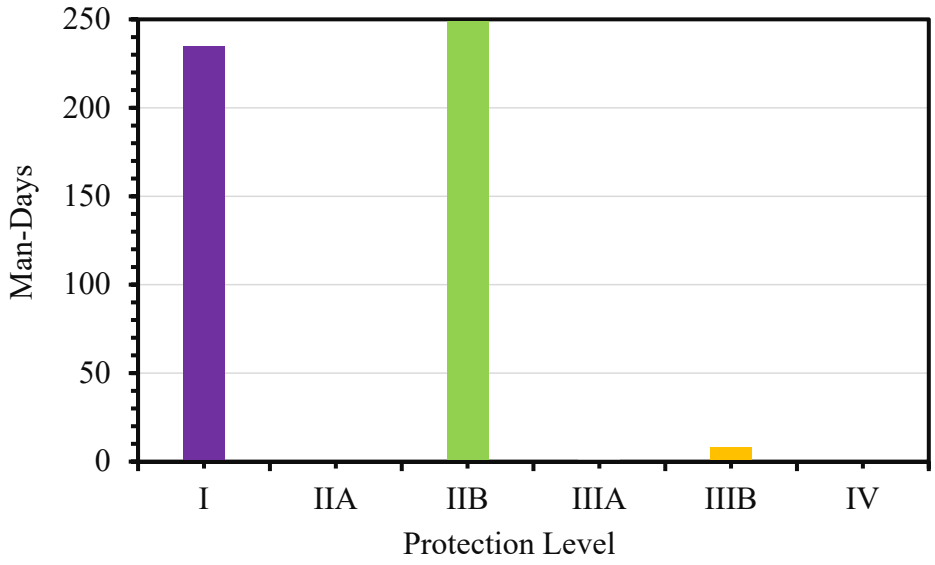


Figure G-21. PPE Levels for Work Conducted on Yvonne Island in January to April 1980, 143 Individuals.

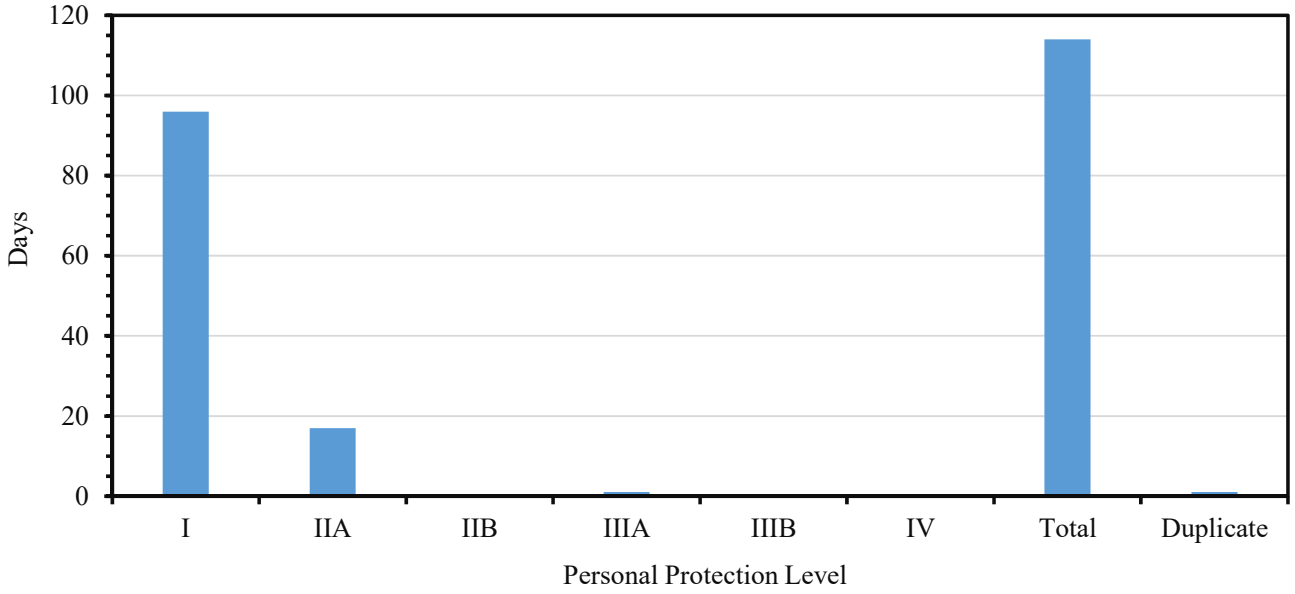


Figure G-22. PPE Levels for Work Conducted by an AF FRST Member on Sally and L3 in February to June 1979.

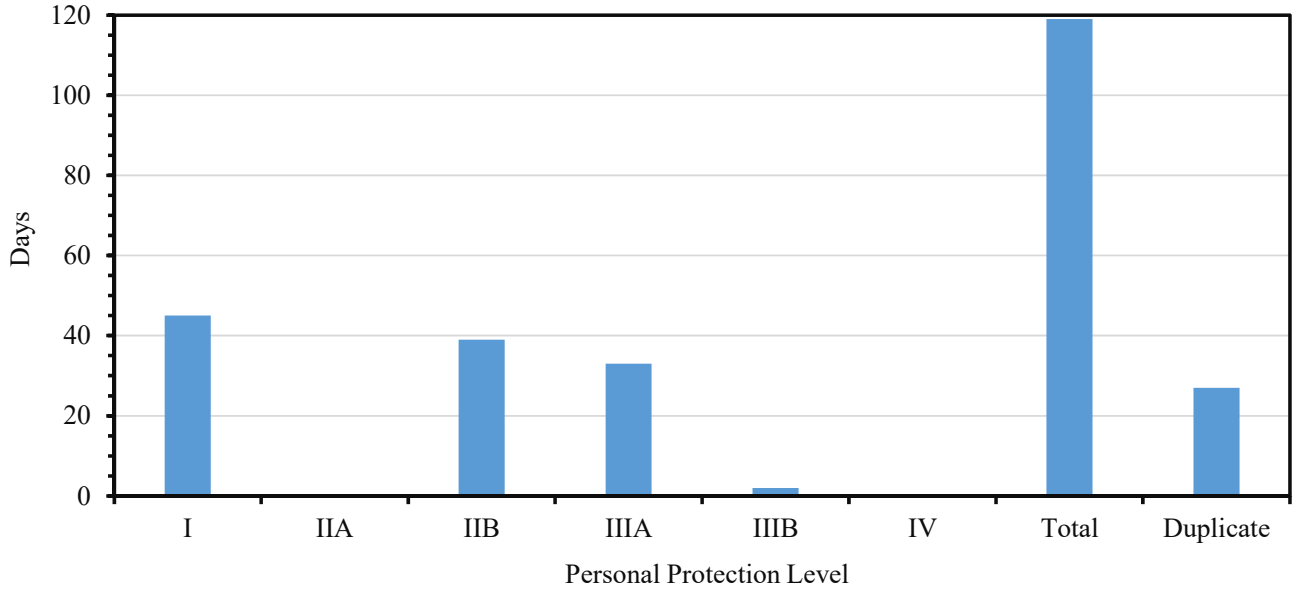


Figure G-23. PPE Levels for Work Conducted by an AF FRST Member on Irene, Janet, Pearl, Sally, Yvonne, Mesh 1, and L2 in January to June 1979.

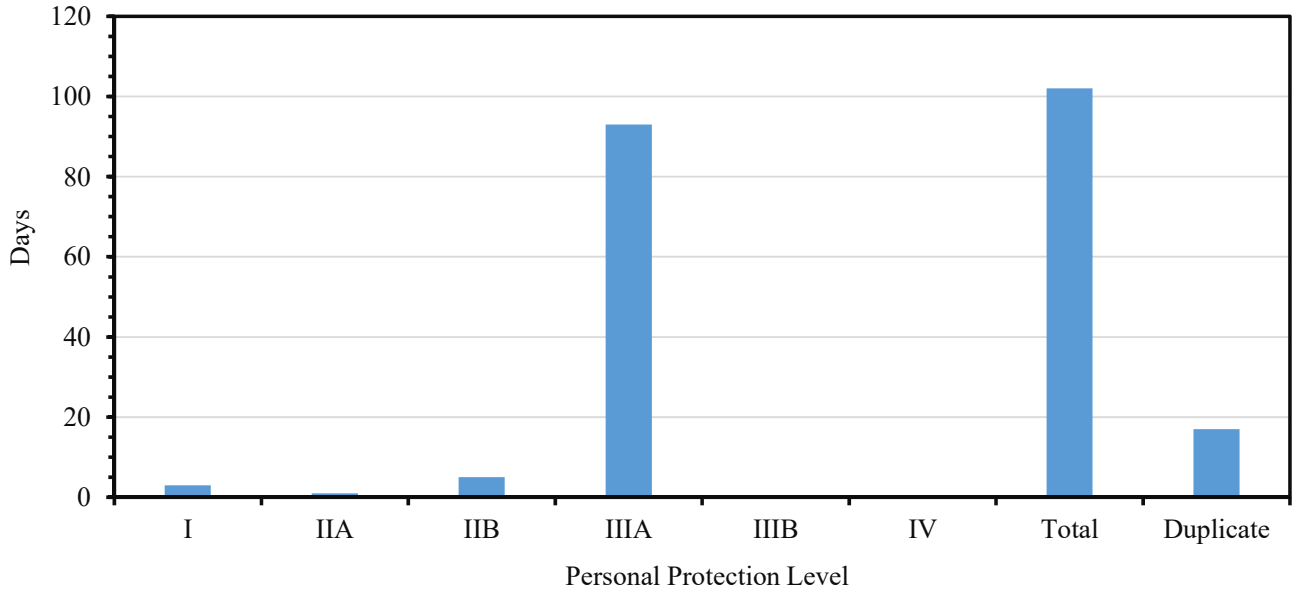


Figure G-24. PPE Levels for Work Conducted by an AF FRST Member on Pearl, Sally, Yvonne, Mesh 3, Maggie 8, and Maggie 9 in January to June 1979.

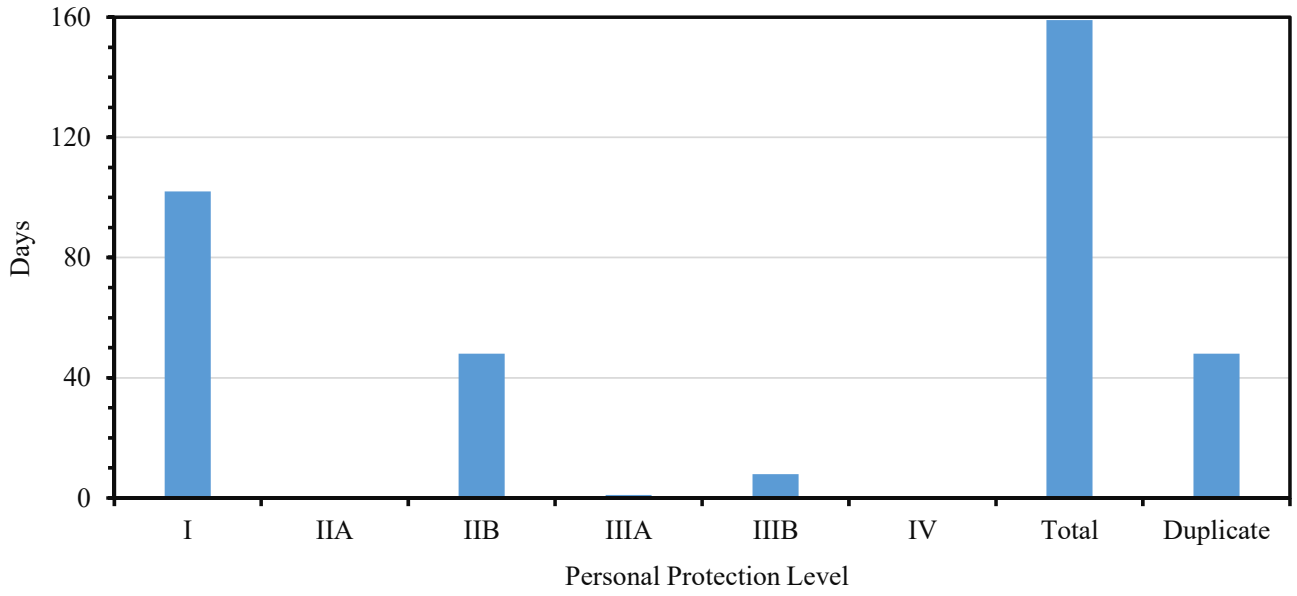


Figure G-25. PPE Levels for Work Conducted by an AF FRST Member on Alice, Belle, Clara, Daisy, Edna, Janet, Lucy, Olive, Pearl, Ruby, Sally, Yvonne, L1, L2, L3, and Mesh I in April to September 1978.

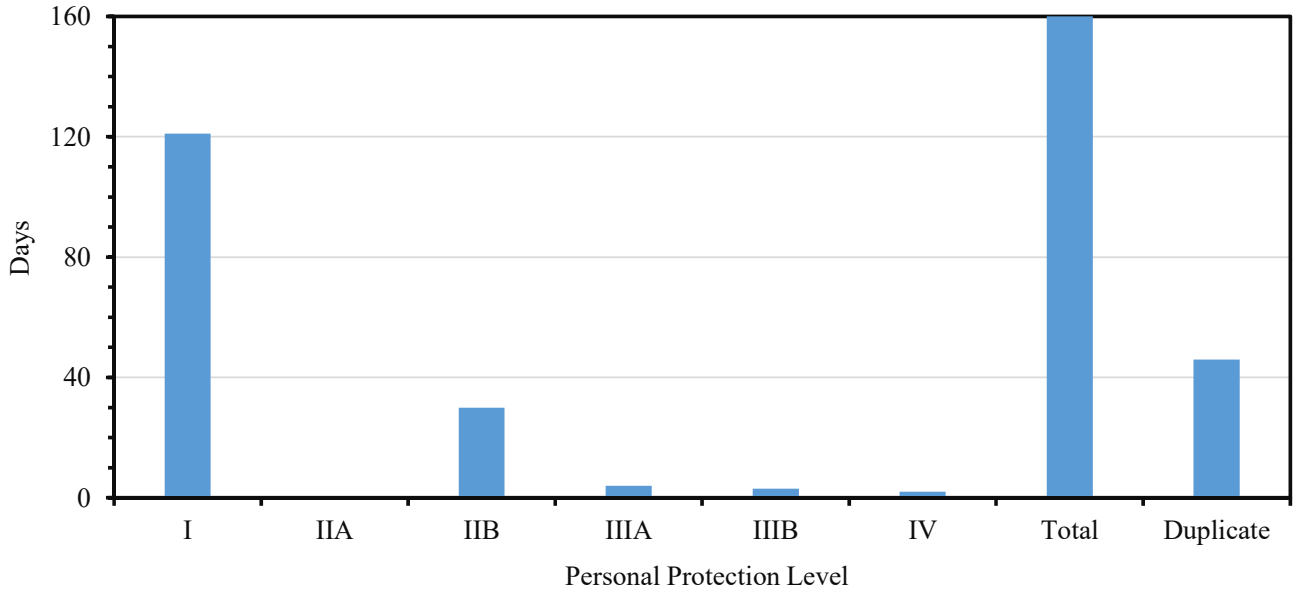


Figure G-26. PPE Levels for Work Conducted by an AF FRST Member on Alice, Belle, Clara, Daisy, Edna, Irene, Janet, Kate, Sally, Yvonne, L2, L3, and Mesh II in April to August 1978.

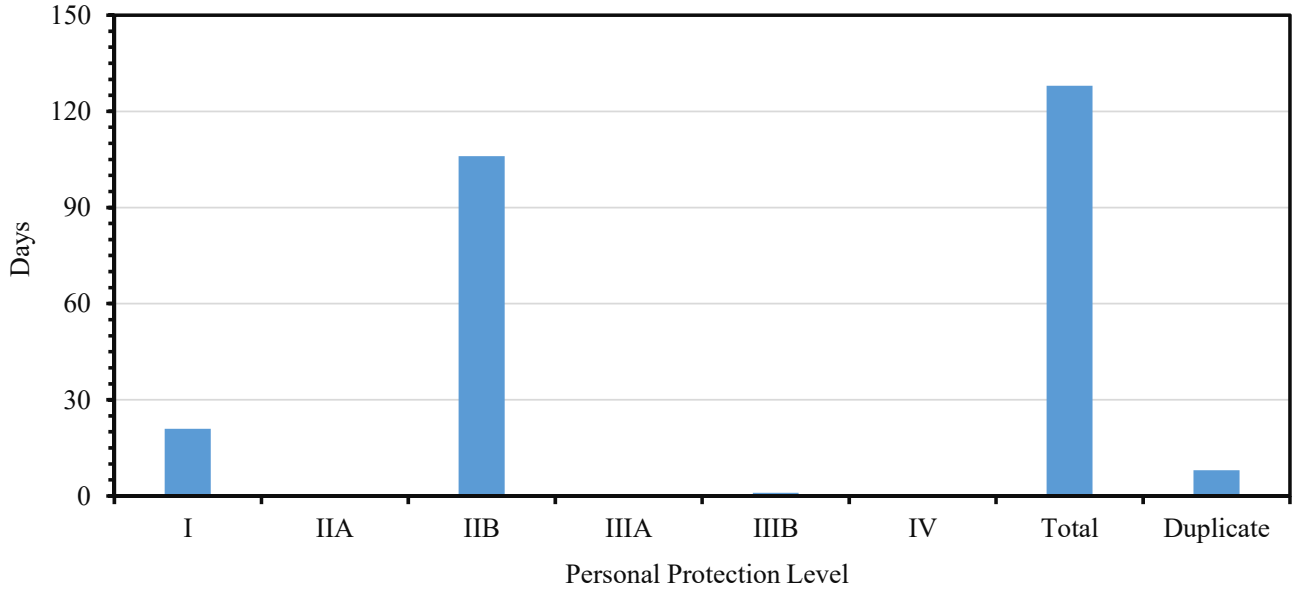


Figure G-27. PPE Levels for Work Conducted by an AF FRST Member on Yvonne, L1, L2, and L3, in January to June 1979.

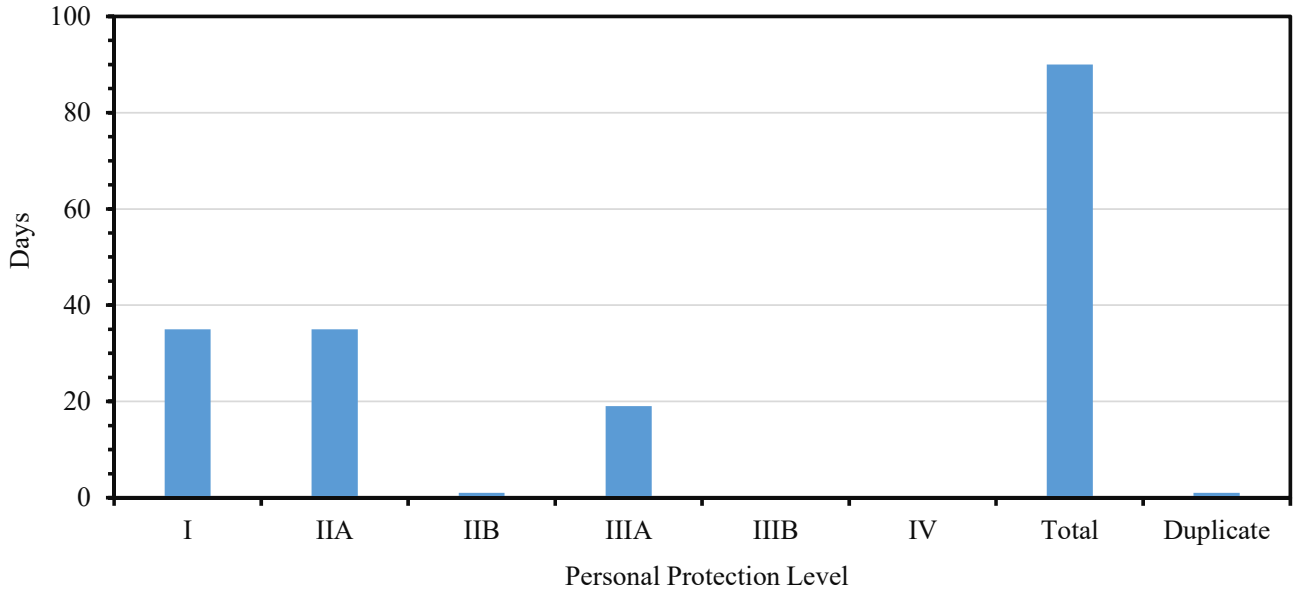


Figure G-28. PPE Levels for Work Conducted by an Army Veteran on Irene, Janet, Pearl, Sally, Yvonne, and Maggie 9, in January to June 1979.

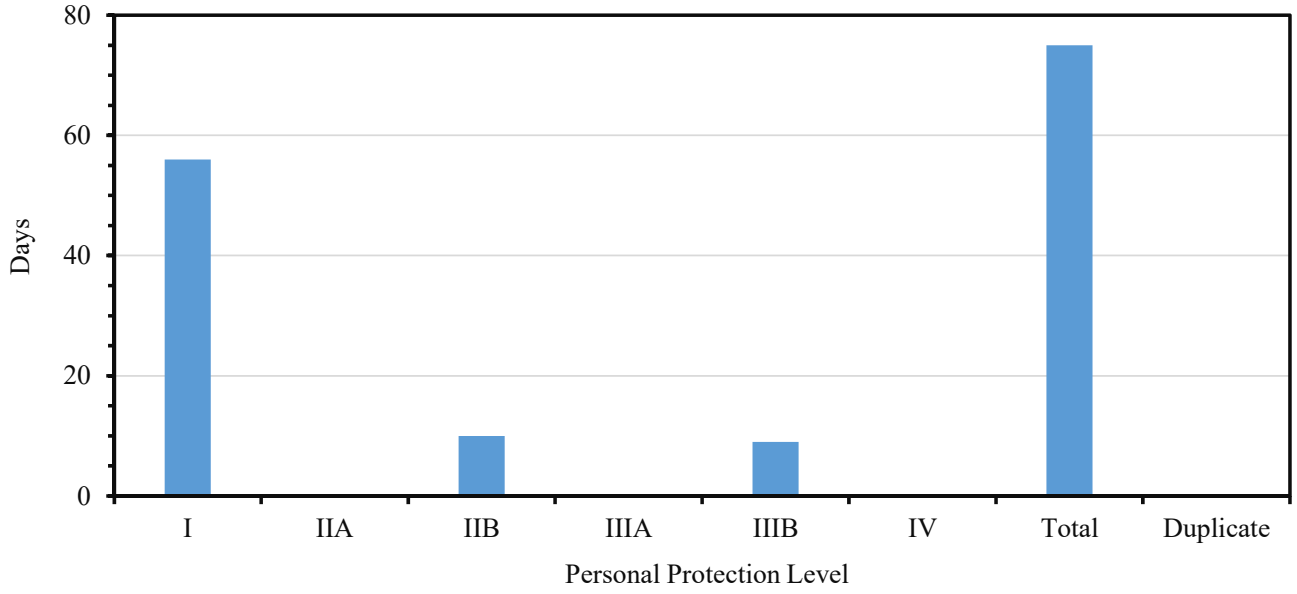


Figure G-29. PPE Levels for Work Conducted by an Army Veteran on Yvonne in January to June 1979.

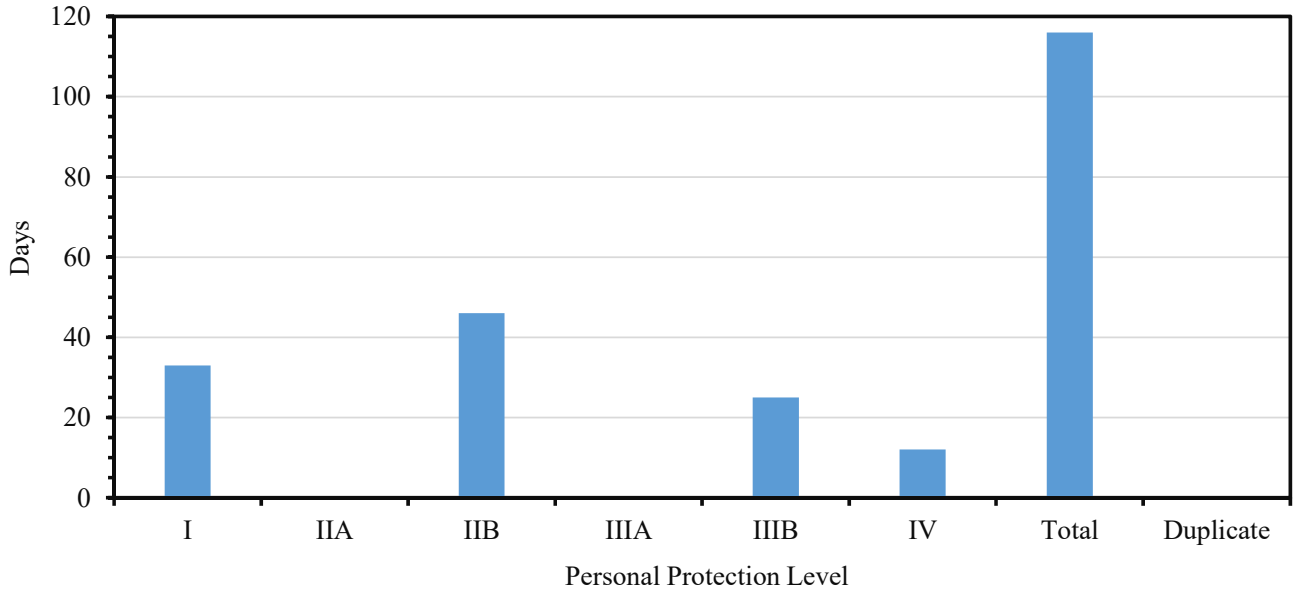


Figure G-30. PPE Levels for Work Conducted by an Army Veteran on Yvonne in April to September 1978.

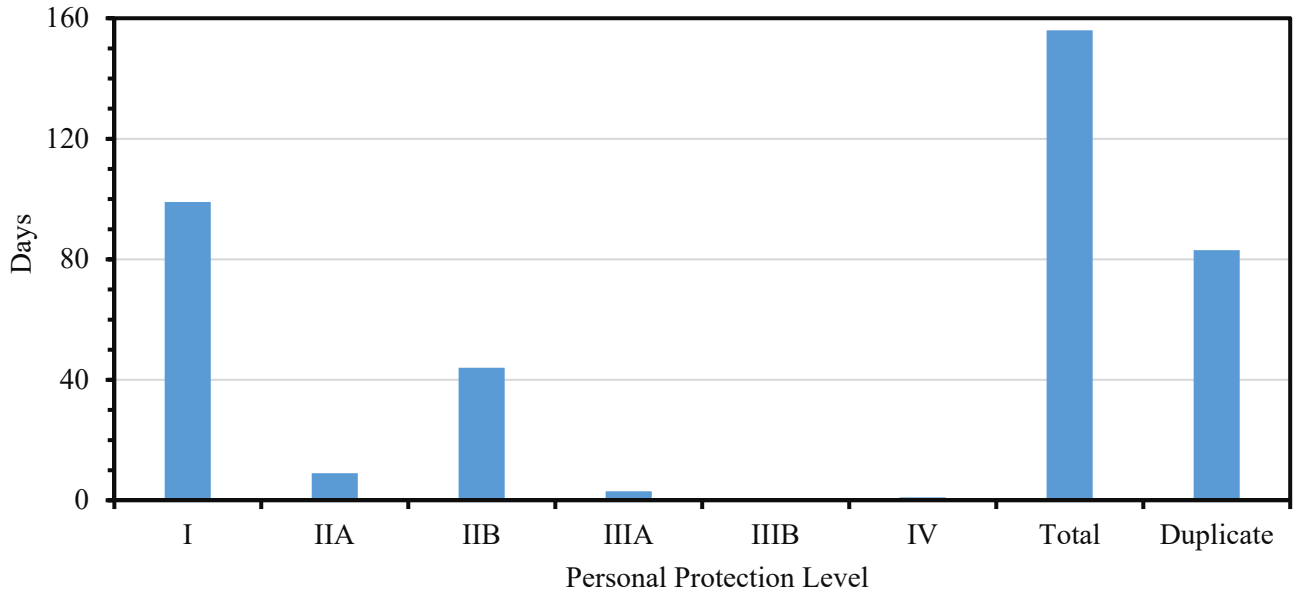


Figure G-31. PPE Levels for Work Conducted by an Army Veteran between April 1978 to May 1979.

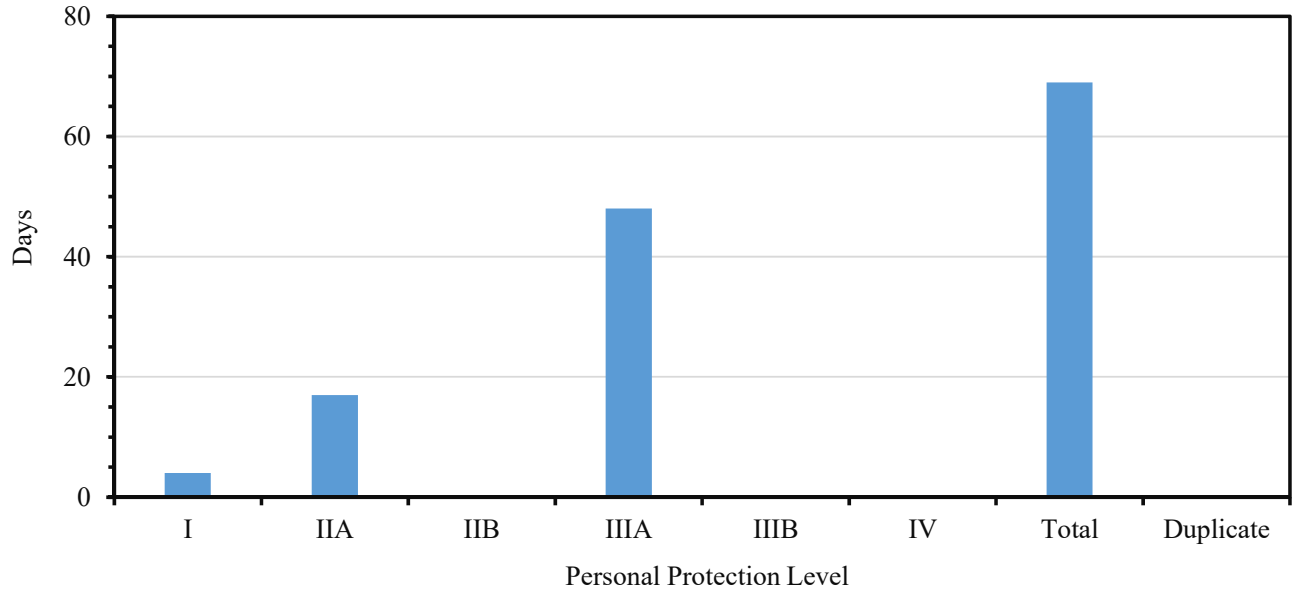


Figure G-32. PPE Levels for Work Conducted by a Navy Veteran on Sally, Maggie 7 and Maggie 9 between November 1978 and April 1979.

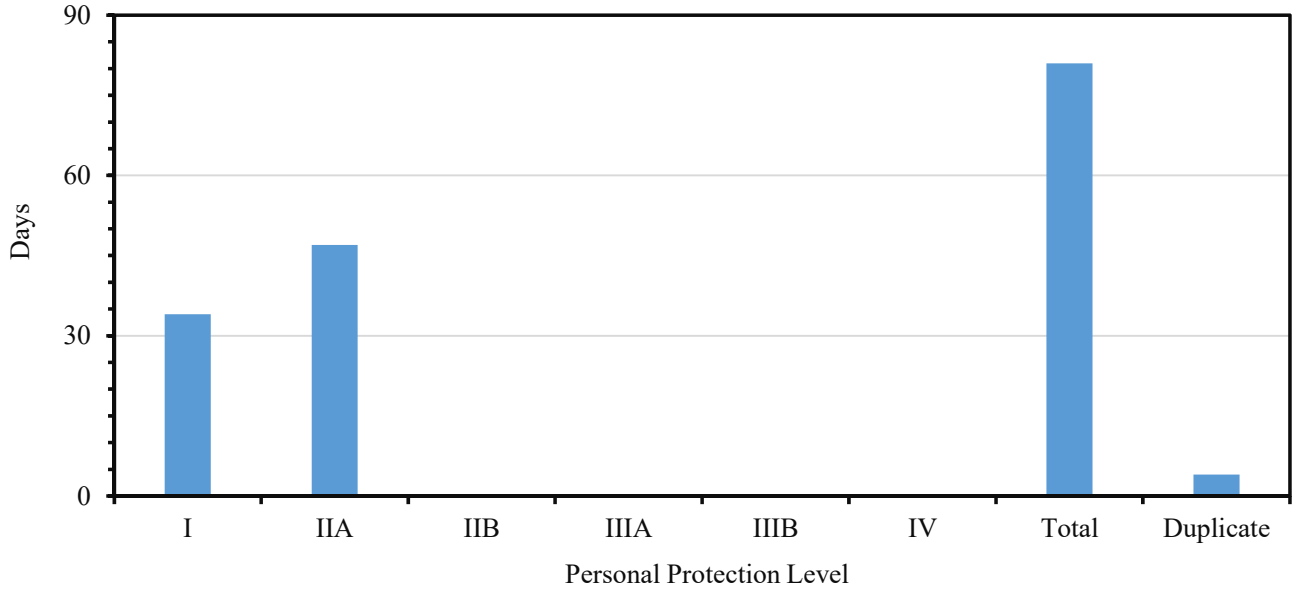


Figure G-33. PPE Levels for Work Conducted by a Navy Veteran on Alice, Belle, Edna, Irene, Janet, Kate, Lucy, Nancy, Olive, Pearl, Percy, Sally, Vera, Wilma, and Yvonne between November 1978 to April 1979.

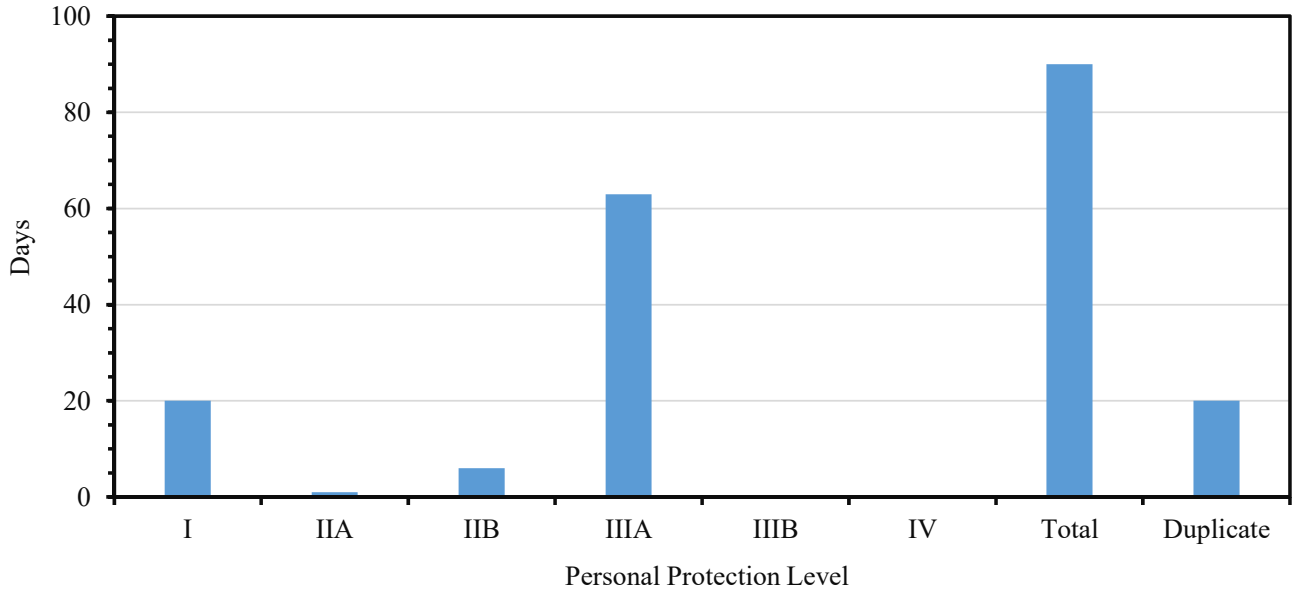


Figure G-34. PPE Levels for Work Conducted by a Navy Veteran on Irene, Janet, Kate, Maggie 7, Maggie 9, and Yvonne between April to August 1978.

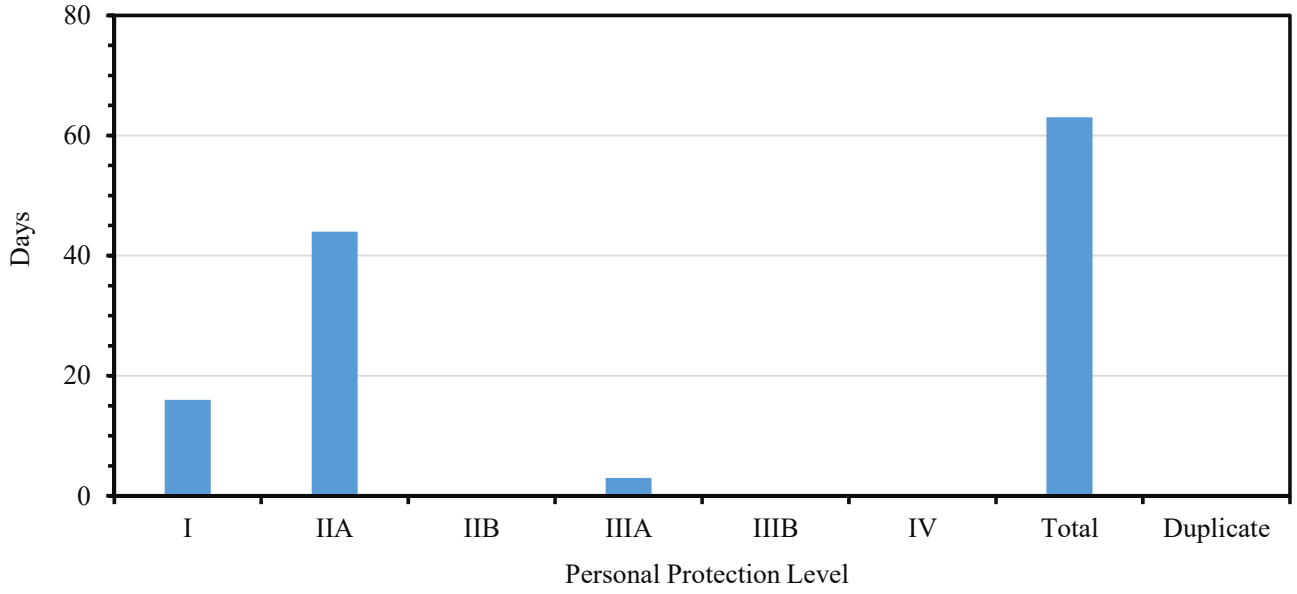


Figure G-35. PPE Levels for Work Conducted by a Civilian Contract Employee on Sally between November 1978 and May 1979.

Appendix H.

Dosimetry and Bioassay Information

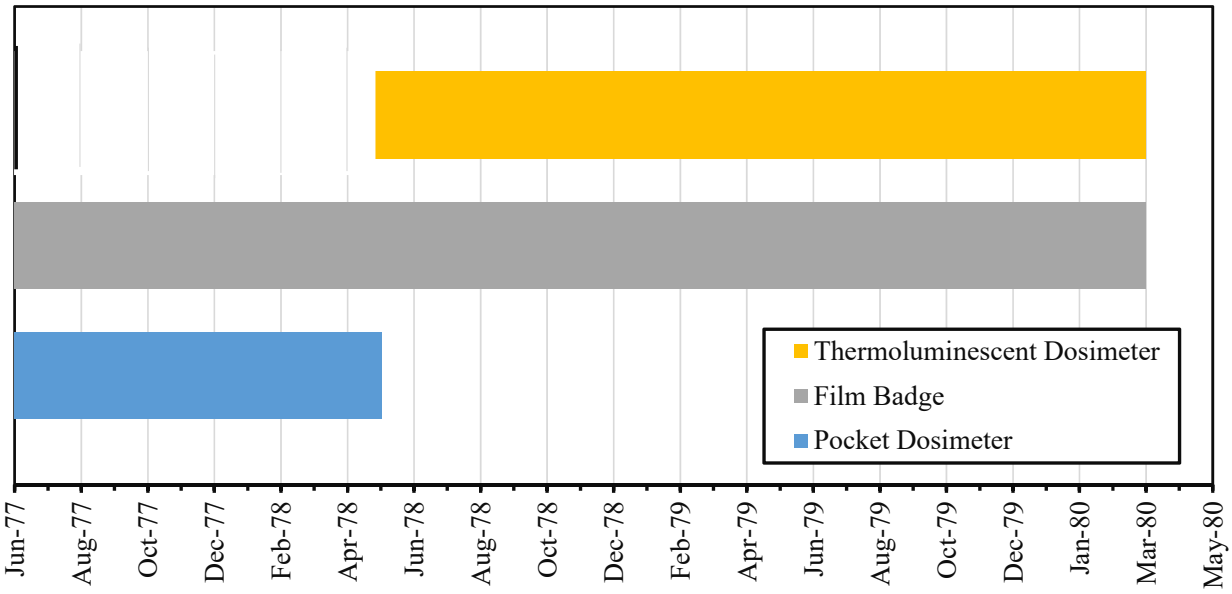
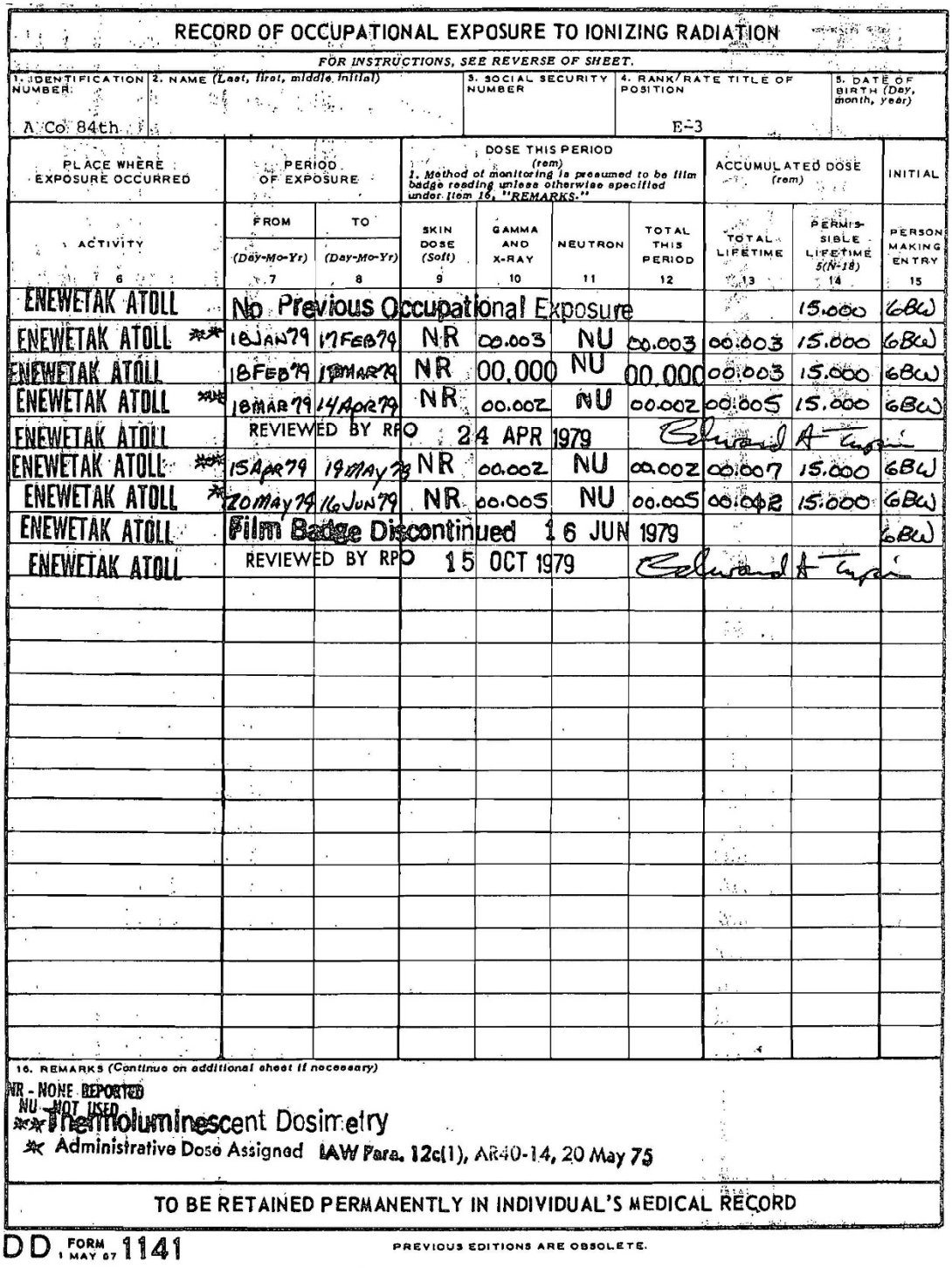


Figure H-1. Dosimetry Use Timeline on Enewetak.



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)
A Co 84th			E-3	

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	FROM (Day-Mo-Yr)	TO (Day-Mo-Yr)	SKIN DOSE (Soft)	GAMMA AND X-RAY	NEUTRON	TOTAL THIS PERIOD	TOTAL LIFETIME	PERMISSIBLE LIFETIME 5(N-18)	PERSON MAKING ENTRY
6	7	8	9	10	11	12	13	14	15
ENEWETAK ATOLL	No Previous Occupational Exposure							15.000	GBW
ENEWETAK ATOLL ***	18JAN79	17FEB79	NR	00.003	NU	00.003	00.003	15.000	GBW
ENEWETAK ATOLL	18FEB79	18MAR79	NR	00.000	NU	00.000	00.003	15.000	GBW
ENEWETAK ATOLL ***	18MAR79	14APR79	NR	00.002	NU	00.002	00.005	15.000	GBW
ENEWETAK ATOLL	REVIEWED BY RPO 24 APR 1979								
ENEWETAK ATOLL ***	15APR79	19MAY79	NR	00.002	NU	00.002	00.007	15.000	GBW
ENEWETAK ATOLL *	20MAY79	16JUN79	NR	00.005	NU	00.005	00.012	15.000	GBW
ENEWETAK ATOLL	Film Badge Discontinued 16 JUN 1979								GBW
ENEWETAK ATOLL	REVIEWED BY RPO 15 OCT 1979								

16. REMARKS (Continue on additional sheet if necessary)

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

TO BE RETAINED PERMANENTLY IN INDIVIDUAL'S MEDICAL RECORD

DD FORM 1 MAY 67 1141 PREVIOUS EDITIONS ARE OBSOLETE.

Figure H-2. Example DD Form 1141 for 84th Engineering Company Enewetak Veteran [Name and SSN Masked from Form].

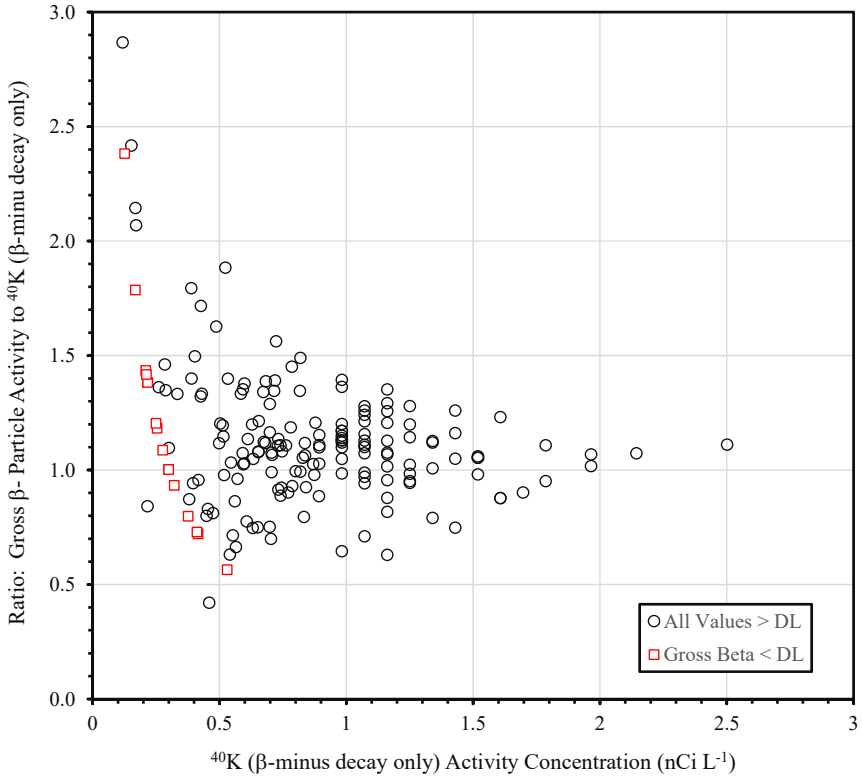


Figure H-3. Regression: Ratio Gross β-Particle to ^{40}K Activity Concentrations vs. ^{40}K Activity Concentration for AF Member Urine Samples (^{40}K β-Emission Fraction Only).

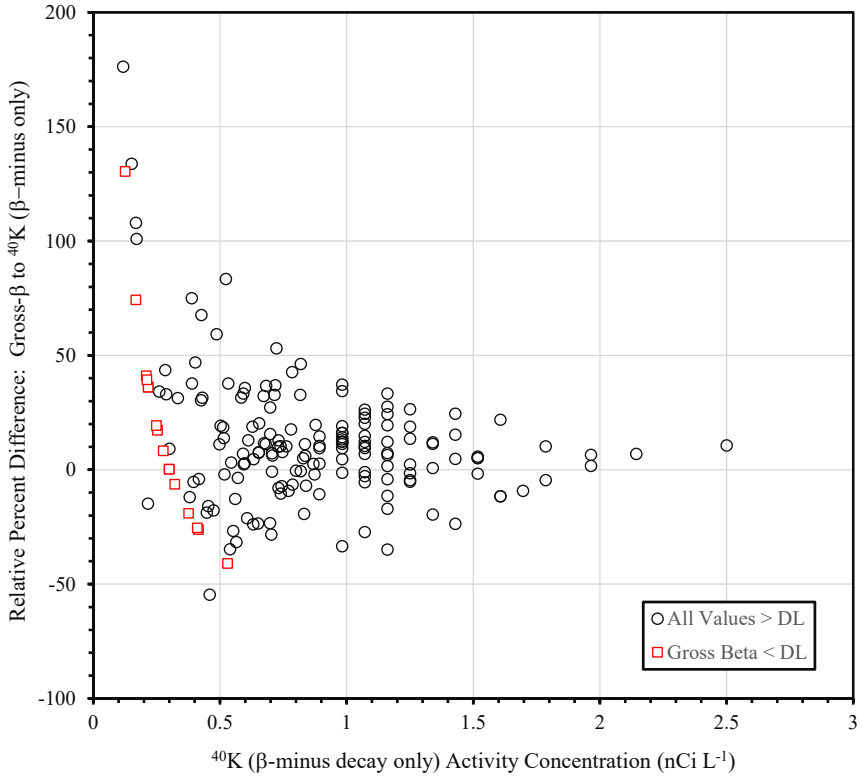


Figure H-4. Regression of Relative Percent Difference in Gross β-Particle Activity Concentration to ^{40}K Activity Concentration (β-Emission Fraction Only) for AF Member Urine Samples.

Table H-1. Nose Swipe Summaries.

Period			Total	Reason for Swipe						
Month	Dates	Year		Random	No Mask or Improper Wear	Defective Mask or Filters	Procedure Violation	Air Sample Action Level	Unknown	Requested by Individual
June		1977	27	27						
July		1977	57	57						
August		1977	25	25						
September		1977	2	2						
October		1977	0	0						
November		1977	0	0						
December		1977	12	3	4	1	4			
January		1978	8	1	5		2			
February		1978	14	3	2		2	3	4	
March		1978	25			4	2	19		
April		1978	68	47	3	2	16			
May		1978	24	21	3					
June		1978	37	15	3	8		10	1	
July		1978	31	1	30					
August		1978	6		6					
September		1978	31		21		8	2		
October		1978	38		31	6		4		
November	1 - 24	1978	16		16					
November	25 – 28	1978	62		33	4	4	20		1
December	2 – 7	1978	47		3	1	1	42		
December	8 – 18	1978	170		11	5		142		1

Table H-1. Nasal Swipe Summaries (continued).

Period			Total	Reason for Swipe						
Start Date	End Date	Year(s)		Random	No Mask or Improper Wear	Defective Mask or Filters	Procedure Violation	Air Sample Action Level	Unknown	Requested by Individual
18 Dec	8 Jan	1978/1979	64		51	8		4		1
15 Jan	17 Jan	1979	78		11	2		62		2
18 Jan	12 Feb	1979	84		52	3		12		2
13 Feb	13 Mar	1979	47		41	5				
14 Mar	26 Mar	1979	38		33	2	2			1
30 Mar	4 Apr	1979	13		13					
5 Apr	11 Apr	1979	16		15		1			
12 Apr	14 Apr	1979	8		8					
18 Apr	20 Apr	1979	16		7		9			
2 May	8 May	1979	18		16	1	1			
9 May	14 May	1979	6		6					
17 May	23 May	1979	7		7					
26 May	1 Jun	1979	10		10					
6 Jun	13 Jun	1979	12		12					
18 Jun	28 Jun	1979	16		16					
2 Jul	23 Jul	1979	10		10					
24 Jul	1 Aug	1979	12		7					5
2 Aug	24 Aug	1979	6		4					2
25 Aug	7 Sep	1979	12		12					
15 Nov	21 Nov	1979	12		12					
2 Dec	7 Dec	1979	42					42		
		Totals	1227	202	514	52	52	362	5	15

Appendix I.

1972-1973 AEC (AEC 1973) Water Sampling Information

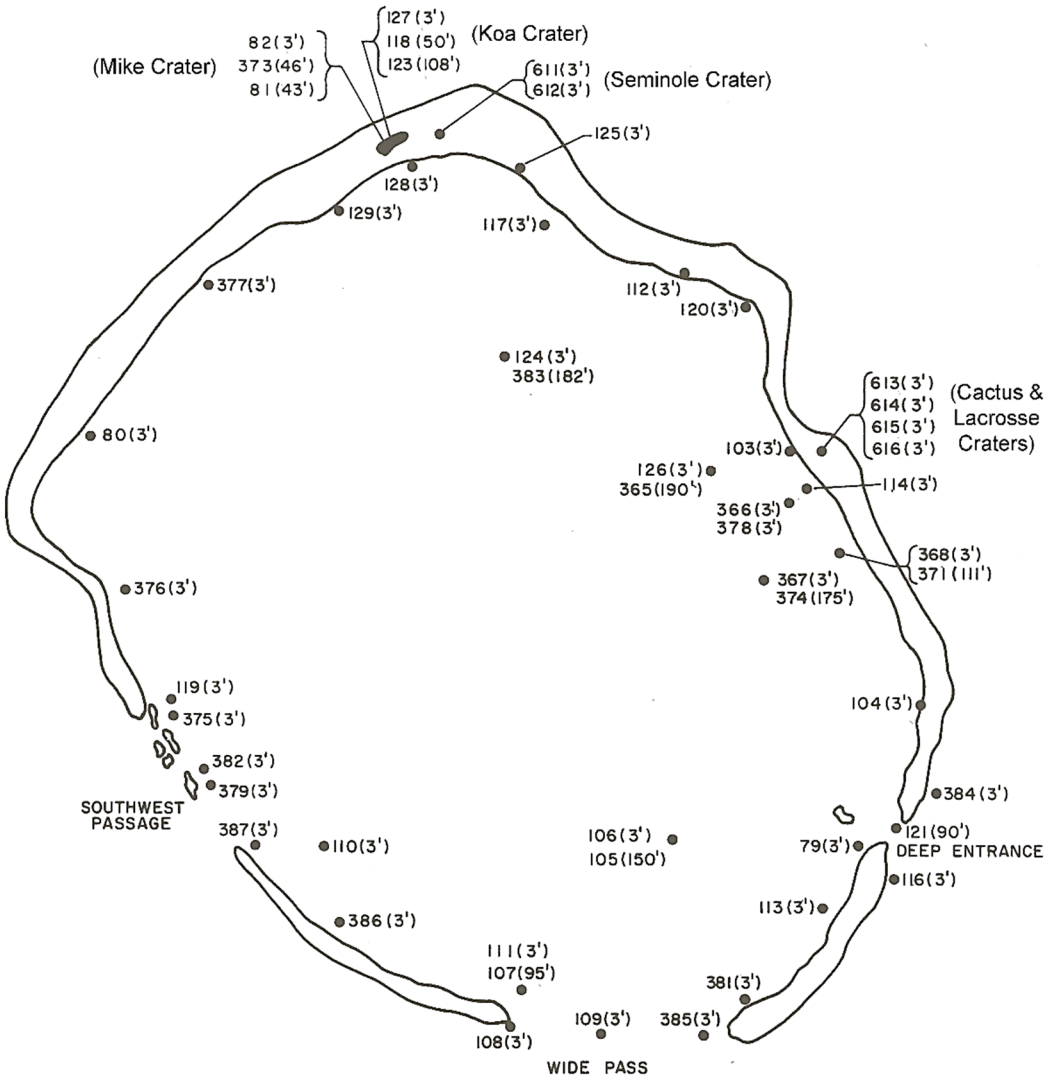


Figure I-1. Location and Identification of 55-liter Water Samples Collected by AEC in 1972 and 1973, Water Sampling Depth Annotated in Feet, Crater Sampling Locations Annotated [Adapted from Figure 79, (AEC 1973)].

TABLE I-1. AEC 1972 and 1973 Water Sampling Results [Adapted from Tables 54, 55 and 56, (AEC 1973)].

Sample Number	γ-Spectrometry Results from Hydroxide Fraction (fCi L^{-1})				Element Extraction (Cs-137) (fCi kg^{-1})	Isotopic Plutonium by α-Particle Spectrometry (fCi kg^{-1}) §		Depth (feet)	
	Co-60	Eu-155	Bi-207	Am-241		Pu-239+240	Pu-238	Bottom	Sample
79					296	6	1.1		3
80					471	32.5	2.7	36	3
81*					3200	54.6	1.9	95	93
82*					730	23.4	2	95	3
103	116		< 224		486	43.6	6.8	60	3
104					241	13.1	1.9		3
105					300	17.4	2.5		150
106					342	22.4	2.2		3
107					190	9.6	0.9	100	95
108					229	10.2	1.1	20	3
109					228	9.6	1	70	3
110					377	28.9	3.8	> 100	3
111					258	11.6	1.4		3
112	146		< 53		163	15.4	1.9	22	3
113					170	4.8	0.6	80	3
114	518				462	51.9	7.1	100	3
116					32	0.43	0.01		3
117					107	11.8	1.7	34	3
118*					1100	26.4	3.2	110	50
119					290	18	2.3	48	3
120‡					228	7.4	1.1		3
121					251	2.8	0.14	93	90
123*	354	1433	420	346	8910	1510	236	110	108
124	< 68		734		579	71.2	10	190	3
125					59	6.8	1.6	40	3
126	< 67		261		322	30.4	3.9	197	3
127*					1170	19	1.7	110	3
128					532	33.1	3	35	3

TABLE I-1. AEC 1972 and 1973 Water Sampling Results [Adapted from Tables 54, 55 and 56, (AEC 1973)], continued.

Sample Number	γ-Spectrometry Results from Hydroxide Fraction (fCi L^{-1})				Isotopic Cesium (Cs-137) (fCi kg^{-1})	Isotopic Plutonium by α-Particle Spectrometry (fCi kg^{-1}) §		Depth (feet)	
	Co-60	Eu-155	Bi-207	Am-241		Pu-239+240	Pu-238	Bottom	Sample
129	< 40		570		538	44.4	4.4	175	3
365	842	940	1266	314	427	3780	1280	197	195
366	121		258		499	77	13.3	171	3
367					482	66.2	7.9	175	3
368	138		204		410	96.1	14.9	114	3
371					305	75.2	11.2	114	111
373*	136		< 88		4220	71.9	7	95	46
374	118		< 242		462	63.2	9	175	175
375					305	29	3.7	90	3
376					250	18.6	2.6	54	3
377	< 51		413		364	62.9	9.7	6	3
378					497	43.1	7.1	171	167
379					246	14.5	2.1	100	3
381					176	6.8	0.7	70	3
382					766	54.3	4	30	3
383	< 50	67	683	36	295	53.3	4.6	190	182
384					146	0.21	0		3
385					130	1.6	0.5	65	3
386	< 61		154		291	13.9	2	40	3
387					109	0.38	0.03	30	3
611*					970	1330	411		3
612*					212	302	65		3
613*					118	57	26		3
614*					935	185	98		3
615*					108	46	24		3
616*					302	105	52		3
Bkgd†						0.32	89		3

* Crater sampling location (see Figure I-1) † Collected East of Enewetak Atoll in open Ocean ‡ Collected near Ursula § Units of kg and L used in sources

Table I-2. Descriptive Statistics for Water Samples Collected at Depth of 3 feet, from Table I-2.

Parameter	Concentration (fCi kg^{-1})			
	Cs-137	Pu-239+240	Pu-238	Transuranics*
Minimum	32	0.2	0	0.2
Maximum	1170	1330	411	1741
Median	294	23	2.5	25
Mean	360	71	19	90

* ^{238}Pu, $^{239+240}Pu$, plus ^{241}Am

Table I-3. Radionuclides in Coconut Meat [Table 164, AEC (1973)].

Island No.	Island	Concentration, pCi/g dry wt					
		^{3}H	^{55}Fe	^{60}Co	^{90}Sr	^{137}Cs	$^{239,240}Pu$
4	DAISY[a]	0.415		<0.059	0.200	7.17	
9	IRENE			<0.067	0.067	1.77	0.0362
			86.5	<1.70	1.61	5.11	<0.034
10	JANET	0.343		<0.069	0.207	84.7	
14	MARY		1.18	<0.055	0.136	14.3	<0.0005
			76.6	<0.017	14.1	5.58	<0.43
15	NANCY	0.333	1.95	<0.054	0.167	18.8	<0.0006
22	VERA			<0.053	0.134	9.30	0.00013
24	YVONNE	0.664		0.077	0.011	3.96	
			<0.19	<0.066	<0.054	1.99	<0.0020
31	BRUCE			<0.014		0.582	
33	DAVID	0.313		<0.060	0.014	2.59	0.0027
				<0.012	0.026	0.399	0.0034
35	ELMER	0.305	<0.63	<0.028	<0.075	3.45	<0.0052
				<0.068	0.032	2.14	0.00044
37	FRED	0.390		<0.020	0.030	2.39	
		0.302	<0.35	<0.021	0.367	0.530	<0.0058
38	GLENN		<0.27	<0.053	<0.049	1.30	<0.0013
				<0.029	0.020	1.01	<0.0025
39	HENRY[b]		<0.11	<0.007	<0.028	0.565	<0.0010
40	IRWIN		<0.64	0.074	<0.086	0.2~9	<0.0027
42	KEITH		<0.29	<0.064	<0.056	0.952	<0.0009
43	LEROY			<0.015	0.189	3.90	0.00073

[a] A concentration of 0.065 pCi ^{207}Bi/g was measured in the sample from DAISY.

[b] A concentration of 0.098 pCi ^{155}Eu/g was measured in the sample from HENRY.

Table I-4. Radionuclides in Meat and Milk Coconut [Table 165, AEC (1973)].

Island No.	Island	Plant part	Concentration, pCi/g wet					$\left(\frac{\text{Dry wt}}{\text{Wet wt}}\right)$[a]
			^{55}Fe	^{60}Co	^{90}Sr	^{137}Cs	^{239,240}Pu	
4	DAISY	Meat		<0.029	0.100	3.58		0.50
		Milk	<0.30	<0.051	0.068	0.084	<0.0016	0.048
9	IRENE	Meat		<0.034	0.033	0.885	0.0181	0.50
		Meat	5.60	<0.11	0.104	0.331	<0.0022	0.065[b]
		Milk	<2.7	<0.15	<0.077		<0.0086	0.046
10	JANET	Meat		0.035	0.103	42.3		0.50
		Milk	<0.12	<0.030	0.084	11.2	<0.0005	0.053
14	MARY	Meat	0.590	<0.027	0.068	7.14	<0.0003	0.50
		Meat	42.2	<0.009	7.79	3.07	<0.24	0.55
		Milk	<0.35	<0.016	0.042	4.52	<0.0046	0.067
15	NANCY	Meat	0.975	<0.027	0.084	9.42	<0.0003	0.50
		Milk	0.266	<0.060	0.051	6.65	<0.0010	0.045
33	DAVID	Meat		<0.030	0.0069	1.30	0.0014	0.50
		Meat		<0.0059	0.013	0.199	0.0017	0.50
		Milk	<0.13	<0.012	<0.023	1.09	<0.0015	0.047

[a]Where wet and dry weights were not determined, the dry-wt/wet-wt ratio of coconut meat was assumed to be 0.50[4,6].
[b]This coconut sample was green and hence yielded little meat.

Table I-5. Radionuclides in Meat and Milk Coconut [Table 169, AEC (1973)].

Island No.	Island	Tissue	Concentration, pCi/g dry					
			^{3}H	^{60}Co	^{90}Sr	^{137}Cs	^{152}Eu	^{239,240}Pu
31	BRUCE	Muscle	0.424	0.198	0.185	1.98		0.0012
		Hepatopancreas	0.157	0.402	0.133	0.420		0.0023
38	GLENN	Muscle	0.685	0.247		1.88		0.0013
		Hepatopancreas	0.266	0.276	0.269	0.545		<0.0066
41	JAMES	Muscle		1.05	0.079	1.25		0.00076
		Hepatopancreas		1.56	0.0014	0.317		0.0019
42	KEITH	Muscle		0.420	1.19	1.92		0.0014
		Hepatopancreas		1.03	0.401	0.496	0.066	0.0098
43	LEROY	Muscle	0.867	1.23	1.58	12.6		0.0031
		Hepatopancreas	0.207	1.46	2.58	3.29		0.0038

Table I-6. Radionuclides in Pandanus and Tacca [Table 166, AEC (1973)].

Island No.	Island	Plant type	Concentration, pCi/g dry[a]					
			^{3}H	^{55}Fe	^{60}Co	^{90}Sr	^{137}Cs	$^{239,240}Pu$
2	BELLE	Pandanus fruit	0.859		0.140	206	923	0.00343
		Pandanus leaves		0.438	<0.14	391	679	<0.24
10	JANET	Pandanus leaves		2.32	<0.12	4.41	0.620	0.00204
19	SALLY	Pandanus leaves		0.703	<0.11	1.97	15.0	0.0149
20	TILDA	Pandanus leaves		2.94	<0.12	15.5	152	0.00698
22	VERA	Pandanus leaves			<0.069	4.64	17.6	0.00757
33	DAVID	Pandanus leaves		0.127	<0.11	3.56	15.9	0.00132
		Tacca corm	0.516	<1.31	<0.09	0.096	8.96	0.00114
35	ELMER	Pandanus leaves		0.416	<0.034	25.1	3.09	0.00195
37	FRED	Pandanus leaves		0.851	<0.066	0.422	4.29	0.00770
42	KEITH	Pandanus fruit	1.99	12.2	<0.10	13.1	0.860	
		Pandanus leaves		0.356	<0.027	(lost)	0.569	0.00447
43	LEROY	Pandanus leaves		0.210	<0.074	1.69	9.14	0.00222

[a]Additional nuclides measured at levels above detection limits: (1) ^{125}Sb, 3.01 pCi/g in pandanus fruit from BELLE; (2) ^{102}Rh, 0.114 pCi/g in tacca corm (DAVID); (3) ^{144}Ce, 0.724 pCi/g in pandanus leaves from KEITH and 0.469 pCi/g in pandanus leaves from LEROY; (4) ^{207}Bi, 0.043 pCi/g in pandanus leaves from KEITH and 0.108 pCi/g in pandanus leaves from JANET.

Appendix J.

Inhalation Exposure Pathway Information

TABLE J-1. Assigned Respiratory Protection Factors (RPF), Excerpted from Table 1 of OSHA (2009).

Type of Respirator		Half Mask	Full Facepiece	Helmet/ Hood	Loose-fitting Facepiece
Air-purifying respirator		10	50	-	-
Powered Air Purifying Respirator		50	1,000	25/1,000	25
Supplied-Air Respirator	Demand mode	10	50	-	-
	Continuous flow mode	50	1,000	25/1,000	25
	Positive-pressure mode	50	1,000	-	-
Self-Contained Breathing Apparatus	Demand mode	10	50	50	-
	Positive-pressure mode	-	10,000	10,000	-

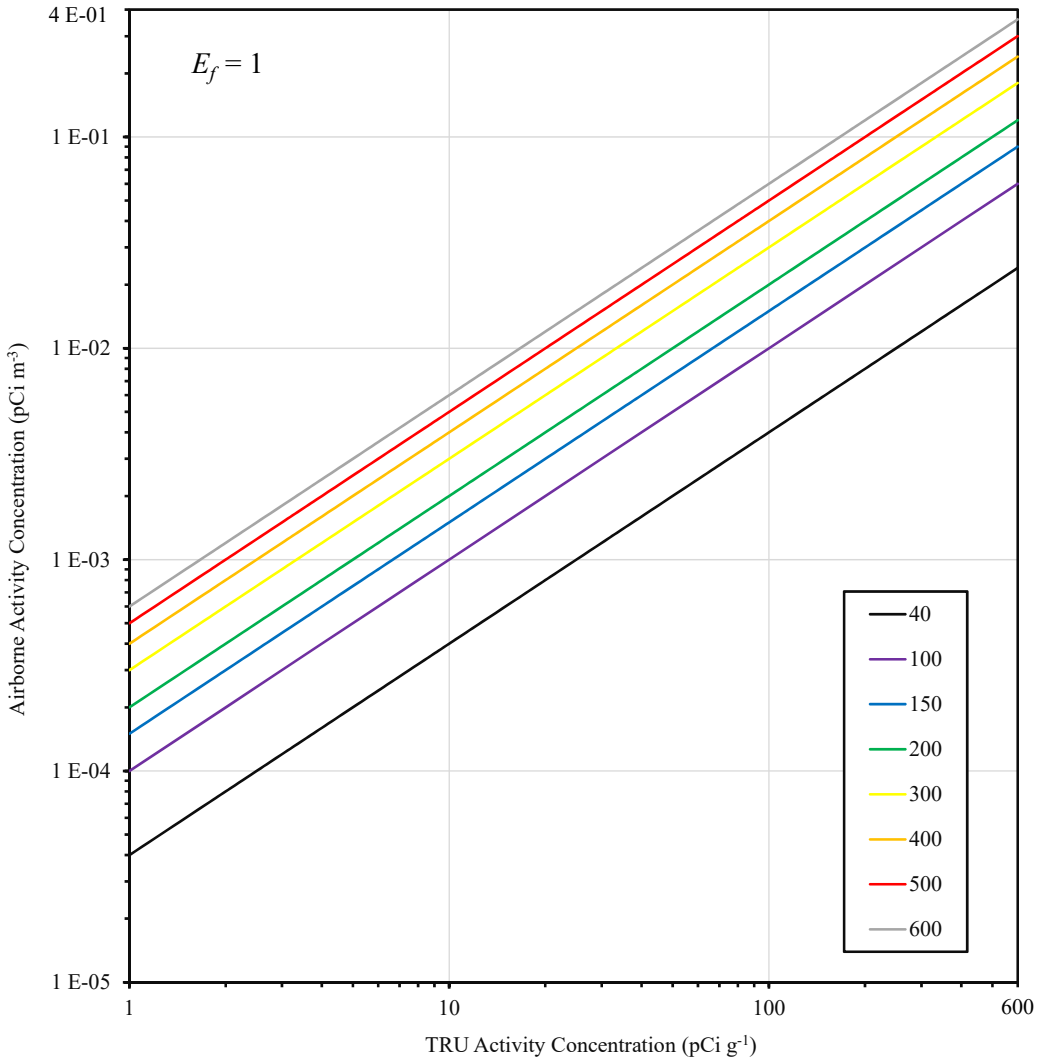


Figure J-1. Airborne vs. Soil Activity Concentrations for Various Mass Loading Values, Enhancement Factor, E_f = 1.

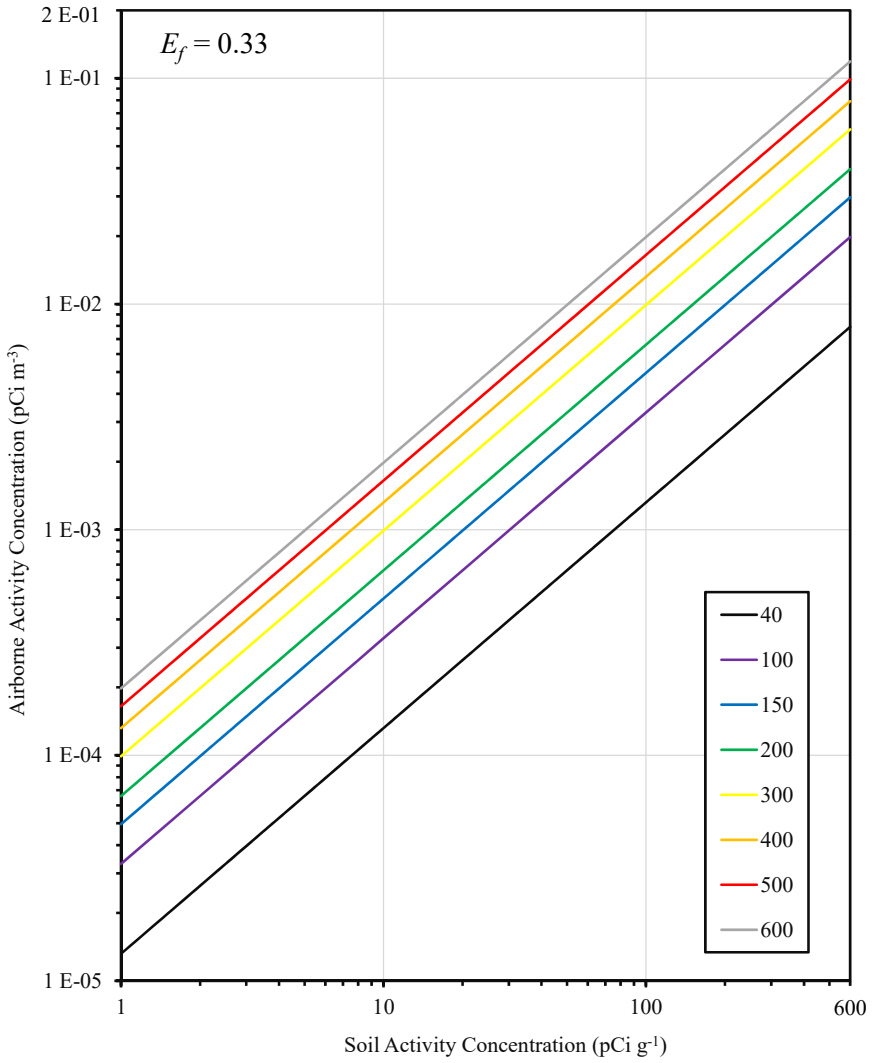


Figure J-2. Airborne vs. Soil Activity Concentrations for Various Mass Loading Values, Enhancement Factor, E_f = 0.33.

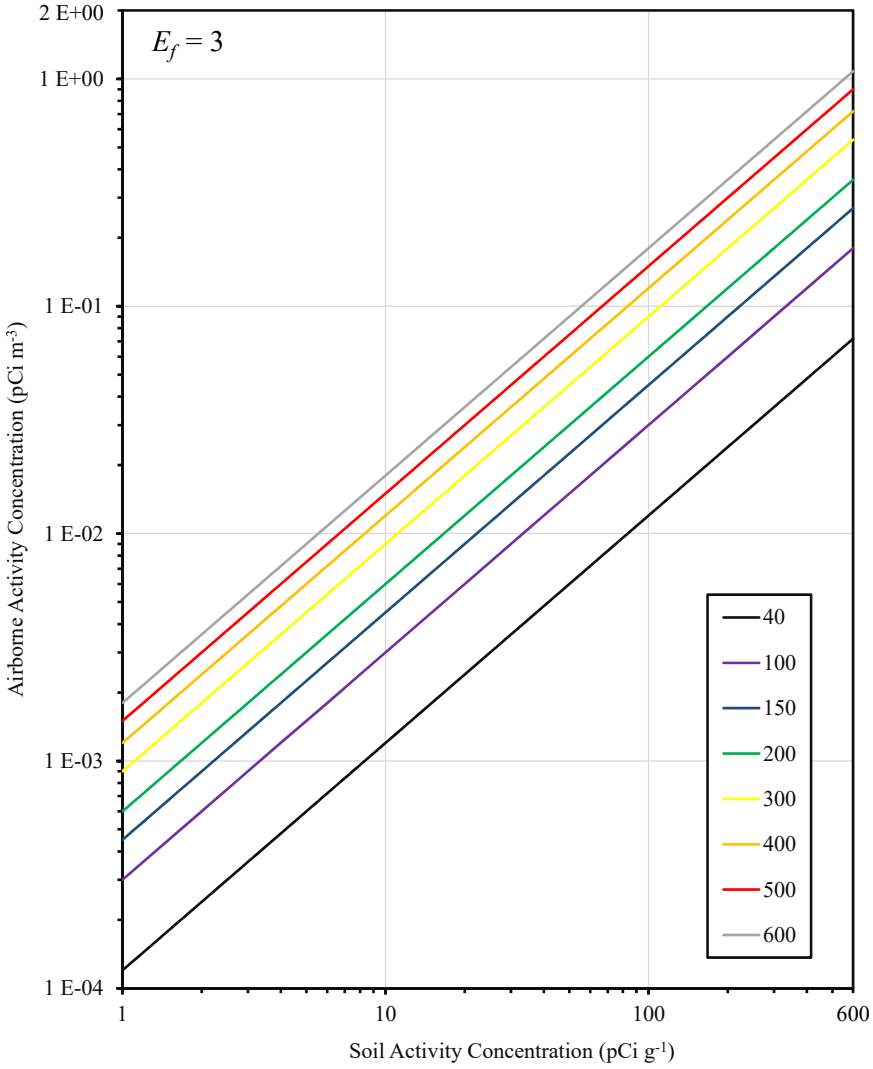


Figure J-3. Airborne vs. Soil Activity Concentrations for Various Mass Loading Values, Enhancement Factor, E_f = 3.

Table J-2. Soils Data for Northern Islands, from Archived Data Soils Data of NVO-140 (AEC 1973), Supplemented by Data From NVO-213 and Analysis in Table C-11, Radiological Decay Considerations Only for Extrapolation from 1973 Data.

Island	$^{239+240}$Pu Activity Concentrations in Soils (pCi g^{-1}) – 15 cm Depth							Estimated Fractional Relationship to $^{239+240}$Pu Activity Concentration for 1978			
	All Samples		Sample Percentile								
	Mean	Range	25th	40th	70th	75th	80th	^{241}Am	^{238}Pu	^{90}Sr	^{137}Cs
Alice	16	0.08 - 71	5.0	6.4	19.8	21.3	23.0	0.313	0.072	4.81	2.29
Belle	28	4.2 - 105	10.0	16.3	28.5	34.5	38.4	0.278	0.108	4.56	1.31
Clara	32	3.5 – 88	16.0	22.8	39.7	44.4	44.5	0.204	0.167	2.79	1.01
Daisy	31	3.8 - 98	16.0	21.7	30.0	31.8	42.1	0.300	0.110	3.33	0.264
Edna	20	13 - 25	19.5	19.8	20.5	20.7	20.8	0.295	0.011[1]	2.17	0.205
Irene	12	2 - 95	4.2	5.6	11.4	11.9	15.1	0.175	0.428	2.79	0.378
Janet	16	0.08 - 180	4.0	6.6	16.0	18.6	22.9	0.323	0.050	4.33	1.47
Kate	11	0.2 - 50	2.35	4.7	14.7	15.1	17.7	0.363	0.098[2]	3.77	1.03
Lucy	7.8	1.5 - 23	2.73	5.0	8.8	9.5	10.3	0.382	0.098	3.61	1.12
Mary	14	0.92 - 53	2.16	4.8	12.9	14.7	22.7	0.352	0.098[2]	2.89	0.548
Nancy	10	0.12 - 42	4.2	6.5	11.7	13.0	14.0	0.400	0.010	3.61	1.05
Percy	9.0	1.5 – 23	2.04	4.8	10.6	13.1	15.5	0.347	0.005	3.77	0.697
Olive	8.4	1.9 - 30	3.11	4.1	9.2	14.3	16.1	0.332	0.102	2.28	0.799
Pearl	39	0.34 - 530	7.00	10.1	18.5	52.9	55.0	0.138	0.538	2.22	0.246
Ruby	11	1.8 - 24	3.04	9.6	21.5	24.0	24.0	0.133	0.105	2.01	0.253
Sally	14	0.21 - 130	2.05	4.3	8.7	11.9	14.8	0.305	0.028	2.79	0.392
Tilda	5.7	0.64 - 34	1.26	1.7	6.1	7.9	9.3	0.395	0.056	3.94	0.627
Ursula	1.8	0.23 - 7.3	0.64	1.03	1.91	2.87	3.0	0.333	0.056[4]	4.13	1.26
Vera	16	0.6 - 300	1.17	2.1	6.8	7.3	8.5	0.366	0.005	2.79	0.847
Wilma	13	0.1 - 260	0.61	0.86	2.88	2.95	2.96	0.338	0.005[5]	3.09	0.979
Yvonne (A)	31	3.8 - 120	6.9	9.0	24.0	30.9	37.6	0.114	0.417[6]	1.58	0.534
Yvonne (A/B)	34	1.8 - 160	5.4	8.5	17.8	19.6	21.4	0.072	0.417	0.760	0.090
Yvonne (B)	140	0.26 – 730	21.3	44.1	145	186	283	0.093	0.204	0.084	0.014
Yvonne (C)	12	0.71 – 50	3.0	6.5	12.2	14.0	16.3	0.123	0.400	0.301	0.094
Yvonne (D)	14	0.083 – 210	0.18	0.28	1.13	1.55	2.33	0.139	0.417[6]	2.71	0.026

[1] All samples non-detect for Pu-238, value based on NVO-213, Figure C-21 [1] All samples non-detect for Pu-238; values based on mean ratio from Lucy
[3] Estimated ratio for mean concentrations, Table C-11 [4] Only few samples with Pu-238 detects, value based on Tilda [5] Only few samples with detect for Pu-238, about one-half apparently did not have Pu-238 content assessment by isotopic Pu method, value based on Vera [6] No Pu-238 analysis, value based on Segment A/B

Table J-2. Soils Data for Northern Islands, from Archived Data Soils Data of NVO-140 (AEC 1973a), Supplemented by Data from NVO-213 and Analysis in Table C-11, Radiological Decay Considerations Only for Extrapolation from AEC (1973) Data, continued.

Island	$^{239+240}$Pu Activity Concentrations in Soils (pCi g^{-1}) – 15 cm Depth				Estimated Fractional Relationship to $^{239+240}$Pu Activity Concentration for 1978						
	All Samples		Sample Percentile								
	Mean	Range	40th	80th	^{60}Co	^{125}Sb	^{152}Eu	^{154}Eu	^{155}Eu	^{207}Bi	^{151}Sm[2]
Alice	16	0.08 - 71	6.4	23.0	0.231	0.0225	0.0067	-	0.147	0.744	1.20
Belle	28	4.2 - 105	16.3	38.4	0.135	0.0384	0.0092	-	0.0848	0.0131	1.14
Clara	32	3.5 – 88	22.8	44.5	0.104	0.0120	0.0075	-	0.0709	0.0109	0.699
Daisy	31	3.8 - 98	21.7	42.1	0.048	0.0122	0.0083	-	0.0943	0.0242	0.833
Edna	20	13 - 25	19.8	20.8	0.008	0.0019	0.0054	-	0.0731	0.0413	0.542
Irene	12	2 - 95	5.6	15.1	0.220	0.0276	0.0349	-	0.145	0.0732	0.699
Janet	16	0.08 - 180	6.6	22.9	0.078	0.0151	0.0319	-	0.0773	0.0285	1.08
Kate	11	0.2 - 50	4.7	17.7	0.067	0.0111	-	-	0.0757	0.0168	0.942
Lucy	7.8	1.5 - 23	5.0	10.3	0.054	0.0181	-	-	0.0846	0.0133	0.903
Mary	14	0.92 - 53	4.8	22.7	0.052	0.0083	-	-	0.0667	0.0184	0.722
Nancy	10	0.12 - 42	6.5	14.0	0.054	0.0158	-	-	0.0816	-	0.903
Percy	9.0	1.5 – 23	4.8	15.5	0.085	0.0113	-	-	0.0941	0.0391	0.942
Olive	8.4	1.9 - 30	4.1	16.1	0.082	0.0139	-	-	0.102	0.164	0.570
Pearl	39	0.34 - 530	10.1	55.0	0.056	0.0065	0.614	0.042	0.0409	-	0.555
Ruby	11	1.8 - 24	9.6	24.0	0.061	0.0185	0.0905	-	0.275	-	0.504
Sally	14	0.21 - 130	4.3	14.8	0.025	0.0056	0.0265	0.00152	0.0265	-	0.699
Tilda	5.7	0.64 - 34	1.7	9.3	0.069	0.0346	-	-	0.0783	-	0.985
Ursula	1.8	0.23 - 7.3	1.03	3.0	0.098	0.0219	-	-	0.137	-	1.03
Vera	16	0.6 - 300	2.1	8.5	0.045	0.0148	-	-	0.0683	-	0.699
Wilma	13	0.1 - 260	0.86	2.96	0.072	0.0317	-	-	0.104	-	0.774
Yvonne (A)	31	3.8 - 120	9.0	37.6	0.331	0.0378[1]	2.67[1]	0.271[1]	0.184	-	0.394
Yvonne (A/B)	34	1.8 - 160	8.5	21.4	0.0218	0.0063[1]	0.448[1]	0.0455[1]	0.0285	-	0.190
Yvonne (B)	140	0.26 – 730	44.1	283	0.0055	0.0010[1]	0.0715[1]	0.0073[1]	0.0074	-	0.021
Yvonne (C)	12	0.71 – 50	6.5	16.3	0.107	0.0067[1]	0.472[1]	0.048[1]	0.0786	-	0.075
Yvonne (D)	14	0.083 – 210	0.28	2.33	0.0087	0.0019[1]	0.131[1]	0.0133[1]	0.0142	-	0.677

[1] Relationship of given radionuclide to ^{137}Cs for all Yvonne segments based on analysis of all samples combined. [2] ^{151}Sm based on fixed fraction of 0.25 to ^{90}Sr, based on § 2.3.5.4.18.

Table J-3. ^{232}Th and Decay Chain, and ^{230}Th Soils Data for Segments A and A/B on Yvonne from Archived Data Soils Data of NVO-140 (AEC 1973) and Analysis in Sections 2.3.5.4.14 and 3.8.

Parameter	Reference	Units	Island Segment	
			A	A/B
Mean $^{239+240}$Pu in Surface Soils	Tables C-11, 2-12 & J-2	pCi g^{-1}	31	34
Mean TRU in Surface Soils	Table J-2	pCi g^{-1}	47	51
Mean ^{228}Th in Surface Soils	§ 2.3.5.4.14	pCi g^{-1}	3.3	0.9
Assumed ^{232}Th in Surface Soils		pCi g^{-1}	3.3	0.9
Assumed ^{230}Th in Surface Soils		pCi g^{-1}	33	9.0
Effective dose (inhalation) DC $^{239+240}$Pu (20% Type M & 80% Type S)	Table 3-2 & Figure 3-11	$\frac{\text{mrem}}{\mu\text{Ci}}$	8.6×10^4	
Effective dose (inhalation) DC ^{232}Th & Decay Chain (10% Type M & 90% Type S)	Table 3-2 & Table D-13	$\frac{\text{mrem}}{\mu\text{Ci}}$	3.1×10^5	
Effective Dose (inhalation) DC ^{230}Th (10% Type M & 90% Type S)		$\frac{\text{mrem}}{\mu\text{Ci}}$	6.3×10^4	
$^{239+240}$Pu Equivalent for ^{232}Th & Decay Chain	Table 3-2, Figure 3-11, and Table D-13	pCi g^{-1}	12	3.2
$^{239+240}$Pu Equivalent for ^{230}Th		pCi g^{-1}	24	6.6

Table J-4. Transuranic Activity of Soils Excised during Radiological Clean-up off Enewetak Atoll with Estimated Airborne α-Particle Activity for Various Mass Loading and Enhancement Factors.

Island	Mean TRU Concentration in Soil (pCi g^{-1})*	Airborne α-Particle Activity Concentration (pCi g^{-1}) for Mass Loading of 600 μg m^{-3}			Recommended Parameters		
					E_f	Soil TRU Concentration (pCi g^{-1})	
		$E_f = 0.33$	$E_f = 1$	$E_f = 3$			
Janet	43	0.0085	0.026	0.077	3	129	3 - 9 Sep 1978
					3	43	Other times
Pearl	99	0.020	0.059	0.18	3	396	7 Apr - 19 May 79
					2	99	20 May - 8 Jul 79
Sally	107	0.021	0.064	0.19	3	214	Mar-Apr 1978
					2	107	May-Aug 1978
Sally (Crypt)	80	0.016	0.048	0.14	2	80	
Irene	180	0.036	0.108	0.32	1	180	
Yvonne	585	0.12	0.35	1.05	1	585	

* Listed in Table F-1, from DOE (1982)

Table J-5. Transuranic Activity of Soils during Non-Soil Excision Activities during Radiological Clean-up off Enewetak Atoll with Estimated Airborne α-Particle Activity for Various Mass Loading and Enhancement Factors.

Island	TRU Activity Concentration in Soil (pCi g^{-1})		Airborne α-Particle Activity Concentration (pCi m^3) [40th Percentile]			Airborne α-Particle Activity Concentration (pCi m^3) [80th Percentile]		
	Sample Percentile		Mass Loading = 100 μg/m^3, E_f = 1	Mass Loading = 100 μg/m^3, E_f = 3	Mass Loading = 300 μg/m^3, E_f = 3	Mass Loading = 100 μg/m^3, E_f = 1	Mass Loading = 100 μg/m^3, E_f = 3	Mass Loading = 300 μg/m^3, E_f = 3
	40th	80th						
Alice	8.86	31.9	0.00089	0.00266	0.00798	0.00319	0.00956	0.0287
Belle	22.6	53.2	0.00226	0.00678	0.0203	0.00532	0.0160	0.0479
Clara	31.3	61.0	0.00313	0.00938	0.0281	0.00610	0.0183	0.0549
Daisy	30.6	59.4	0.00306	0.00918	0.0275	0.00594	0.0178	0.0534
Edna	25.9	27.2	0.00259	0.00776	0.0233	0.00272	0.00815	0.0244
Irene	8.98	24.2	0.00090	0.00269	0.00808	0.00242	0.00726	0.0218
Janet	9.06	31.4	0.00091	0.00272	0.00816	0.00314	0.00943	0.0283
Kate	6.87	25.9	0.00069	0.00206	0.00618	0.00259	0.00776	0.0233
Lucy	7.40	15.2	0.00074	0.00222	0.00666	0.00152	0.00457	0.0137
Mary	6.96	32.9	0.00070	0.00209	0.00626	0.00329	0.00987	0.0296
Nancy	9.17	19.7	0.00092	0.00275	0.00825	0.00197	0.00592	0.0178
Percy	6.49	21.0	0.00065	0.00195	0.00584	0.00210	0.00629	0.0189
Olive	5.88	23.1	0.00059	0.00176	0.00529	0.00231	0.00693	0.0208
Pearl	16.9	92.2	0.00169	0.00508	0.01523	0.00922	0.0277	0.0830
Ruby	11.9	29.7	0.00119	0.00357	0.01070	0.00297	0.00891	0.0267
Sally	5.73	19.7	0.00057	0.00172	0.00516	0.00197	0.00592	0.0178
Tilda	2.47	13.5	0.00025	0.00074	0.00222	0.00135	0.00405	0.0121
Ursula	1.43	4.17	0.00014	0.00043	0.00129	0.00042	0.00125	0.00375
Vera	2.88	11.7	0.00029	0.00086	0.00259	0.00117	0.00350	0.0105
Wilma	1.15	3.98	0.00012	0.00035	0.00104	0.00040	0.00119	0.00358
Yvonne (A)	24.2	101	0.00242	0.00727	0.0218	0.0101	0.0304	0.0911
Yvonne (A/B)	15.1	38.0	0.00151	0.00453	0.0136	0.00380	0.0114	0.0342
Yvonne (B)	57.2	367	0.00572	0.01716	0.0515	0.0367	0.110	0.330
Yvonne (C)	9.90	24.8	0.00099	0.00297	0.00891	0.00248	0.00745	0.0223
Yvonne (D)	0.436	3.63	0.000044	0.00013	0.00039	0.000363	0.00109	0.00326

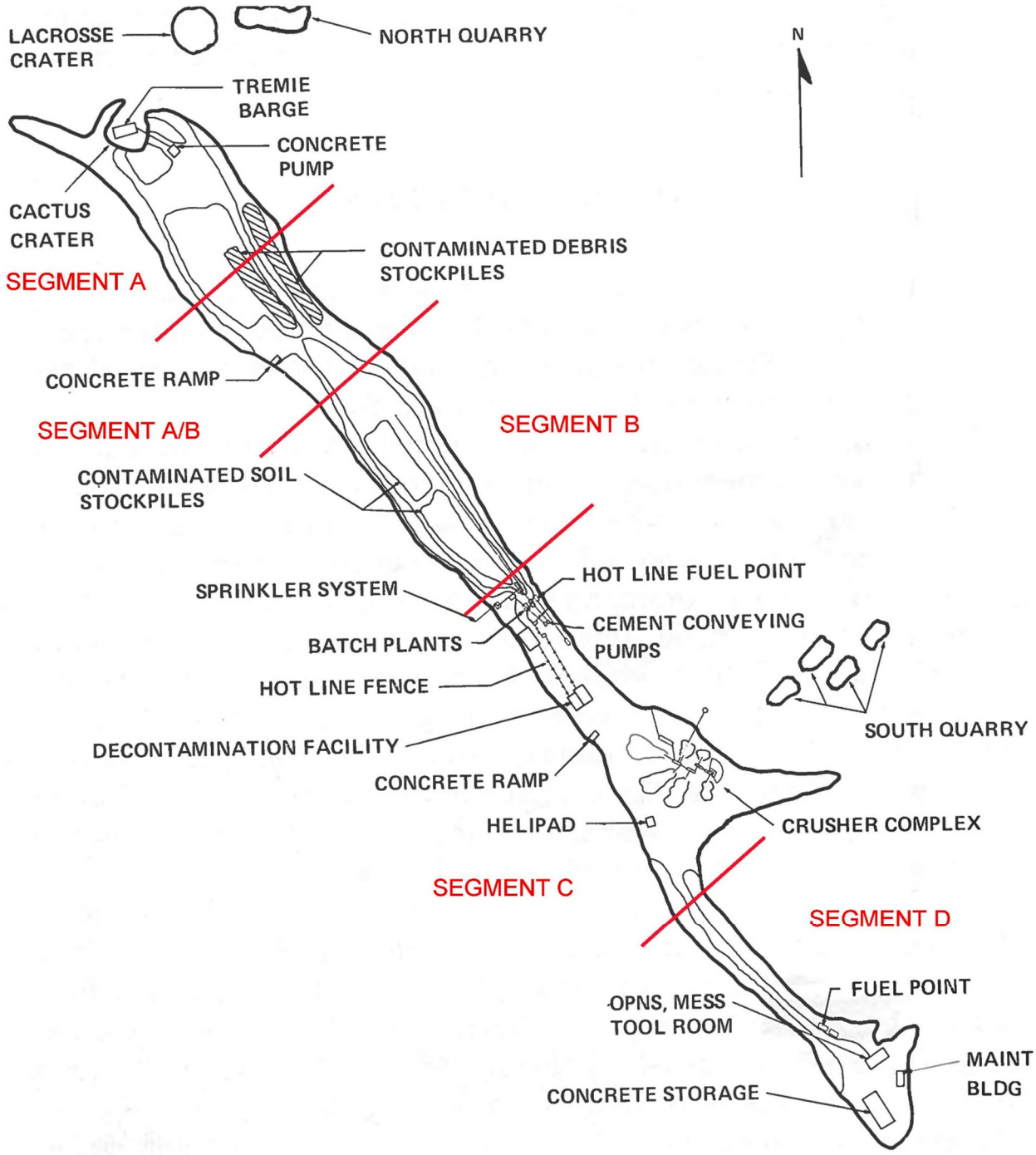


Figure J-4. Facilities Operated on Yvonne During Cleanup
[Adapted from Figure D-12, DNA (1981)].

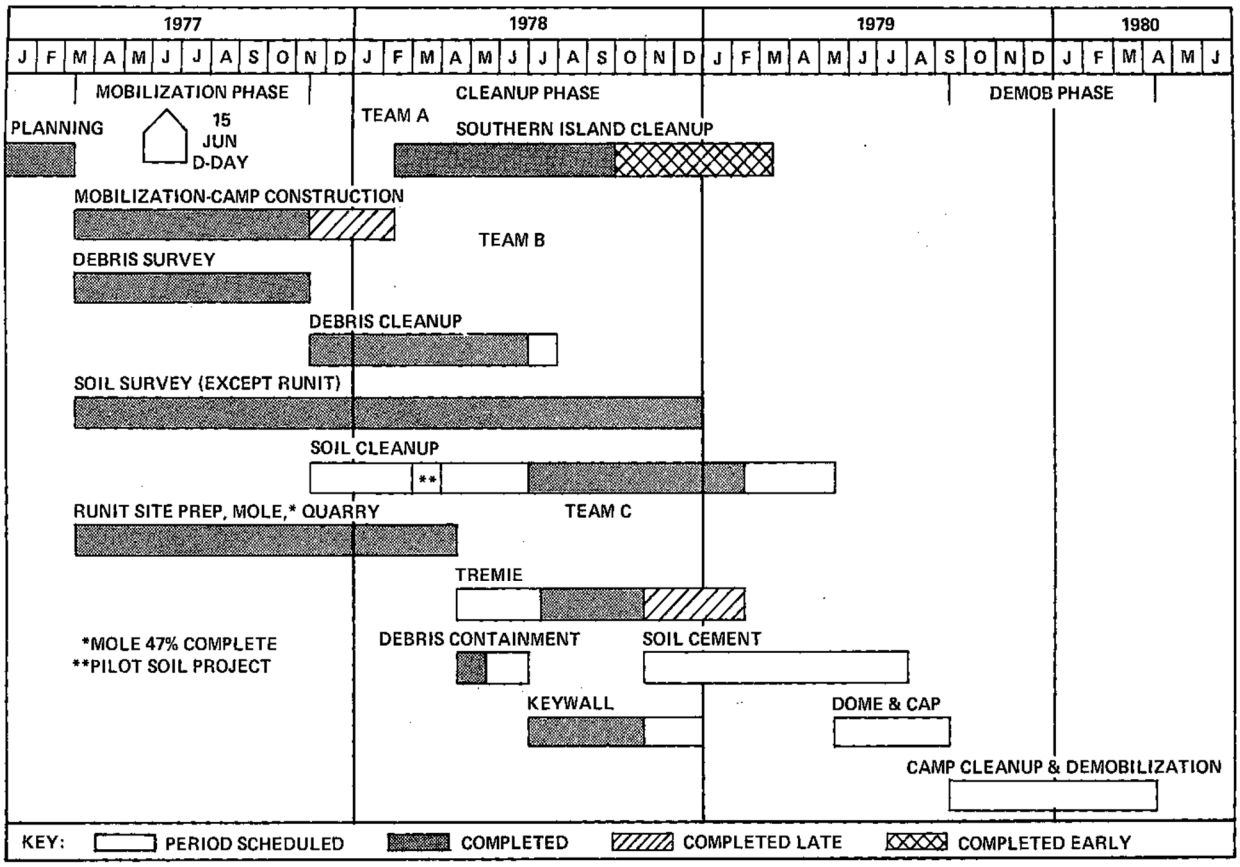


Figure J-5. Enewetak Cleanup Project Status, 12 Feb 79 [Figure D-28, DNA (1981)].

TABLE J-6. Estimated Airborne Concentrations of TRU During Navy Vessel Transport of Contaminated Soil from Sally, Janet, Irene, and Pearl to Yvonne for Entombment.

Naval Vessel	Period of Operation	Recommended TRU Airborne Activity Concentration (pCi m^{-3})
YC Barge	June – December 1978	0.04
LARC 22	February – March 1979	0.04
MESH 1 (LCU)	October 1978 – July 1979	0.02
MESH 2 (LCU)	July 1978 – May 1979	0.04
MESH 3 (LCU)	October 1978 – July 1979	0.04
Maggie 2 (LCM 8)	27 May – 9 June 1979	0.20
	10 – 23 June 1979	0.02
Maggie 5 (LCM 8)	May – June 1978 17 June – 7 July 1979	0.02
	6 May 1979 – 9 June 1979	0.20
Maggie 6 (LCM 8)	22 April – 2 June 1979	0.06
	3 June – 7 July 1979	0.02
Maggie 7 (LCM 8)	October 1978 – 20 January 1979 10 – 16 June 1979	0.02
	28 January - 14 April 1979	0.06
	15 - 28 April 1979	0.60
Maggie 8 (LCM 8)	17 December 1978 – 14 April 1979 17 June – 7 July 1979	0.04
	15 April – 9 June 1979	0.20
Maggie 9 (LCM 8)	7 October 1978 – 7 April 1979 10 June – 7 July 1979	0.02
	8 April – 9 June 1979	0.60

TABLE J-7. Estimated Airborne Concentrations of TRU During Key Operations on Yvonne.

Activity	Island Segment	Mass Loading ($\mu g\ m^3$)	TRU Activity Concentration in Soil ($pCi\ g^{-1}$)	E_f	Estimated TRU Airborne Activity Concentration ($pCi\ m^3$)
Work in southern part of island, mess hall, operations building, maintenance building, fuel operations, including construction	D	100	2.33	3	0.0011
Quarrying and crushing rock from southern Yvonne and Janet	C	300	6.5	3	0.0089
Quarrying and emplacing rock from northern Yvonne in Cactus Crate revetment	A/B	300	15.1	3	0.014
General presence near Cactus Crater in quiescent conditions (e.g., debris/soil survey, debris removal)	A	100	101	3	0.030
General presence in area south of hotline, quiescent conditions (e.g., debris/soil survey, debris removal, logistic transports)	C	100	16.3	3	0.0075
General presence in Fig/Quince GZ segment, quiescent conditions, prior to restoration [13 Mar 79] (e.g., debris/soil survey, debris removal, logistic transports)	B	100	283	1	0.028
General presence in Fig/Quince GZ segment, quiescent conditions, after excision [26 Jul 79] (e.g., debris/soil survey, debris removal, logistic transports)	B	100	124*	1	0.012
General presence in Fig/Quince GZ segment, quiescent conditions, after excision and clean soil added to excision	B	100	53*	1	0.0053
Work in contaminated debris loading area	A + A/B	100	70	3	0.021
Trenching foundation for Cactus Crater keywall	A	300	101	3	0.091
Soil/concrete emplacement, mixing, wetting, and compacting in Cactus Crater entombment	A	600	198	3	0.36
Excision of soil from Fig/Quince GZ	B	600	585	1	0.35
Concrete dome and cap emplacement	A	100	101	3	0.030
Erie Site investigation	C	300	16.3	3	0.015

* DNA reported that a 75% reduction in surface soil concentrations in the Fig/Quince GZ had been achieved; pre- and post-grid in-situ measurements contained in Figures 8-36 and 8-41 show a relative reduction to 44% for segment B as a whole. Post excision survey, excision areas were filled with clean soil; post- and pre-clean soil fill grid measurements showed a reduction to 19% for segment B as a whole. Clean soil fill in-situ grid measurements in Figure 8-42 (DNA 1981).

Appendix K.

Internal Exposure Dose Examples

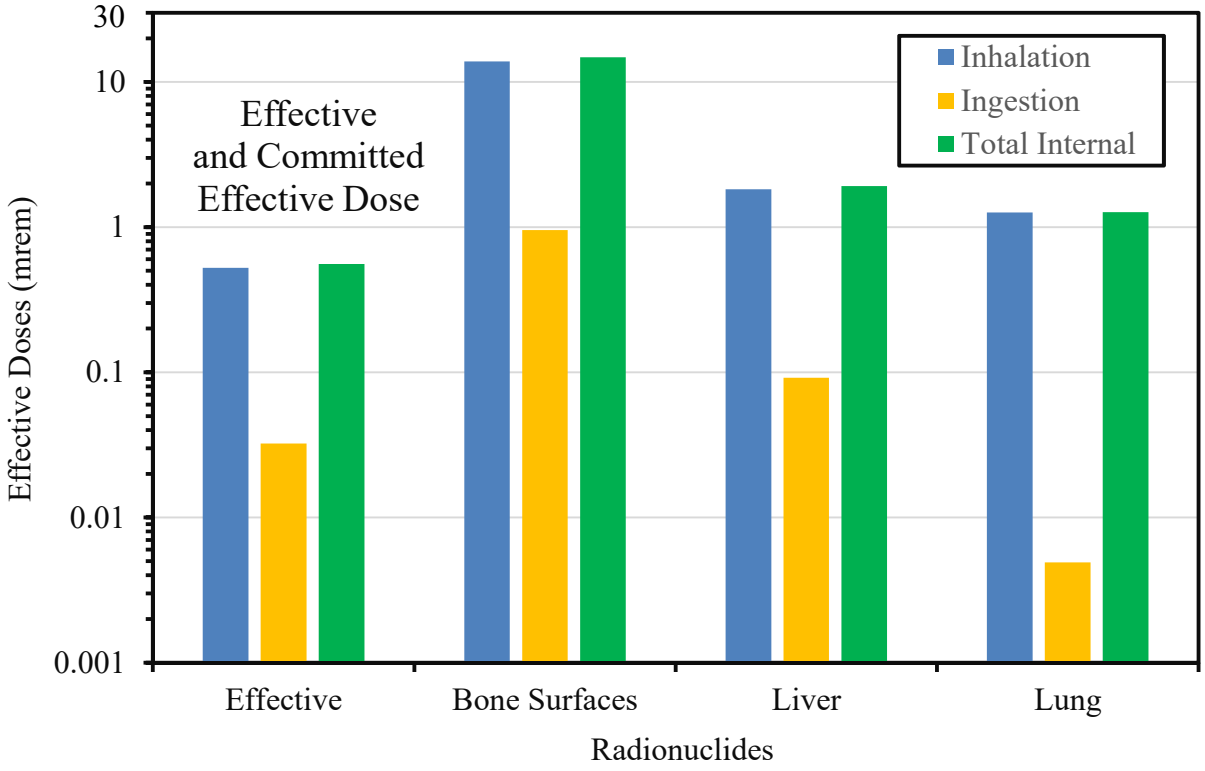


Figure K-1. Histogram of Effective and Committed Effective Dose to Bone Surfaces, Liver, and Lung for Worker Assigned to Duties on Ursula for Six-Months from Inhalation and Ingestion.

Table K-1. ICRP Inhalation Type Combinations for Inhalation and Ingestion Exposures Summarized in Figure K-1.

Radionuclide(s)	Inhalation Intakes Fractions			Ingestion Intake Fractions		
	F	M	S	F	M	S
Pu-238+239+240	0	0.2	0.8	0.1	0.1	0.8
Pu-241	0	0.2	0.8	0.1	0.1	0.8
Am-241	0	1	0	0	1	0
Co-60	0	1	0	0	1	0
Sr-90	0.2	0	0.8	0.2	0	0.8
Sb-125	0	1	0	1	0	0
Cs-137	1	0	0	1	0	0
Eu-152	0	1	0	0	1	0
Eu-154	0	1	0	0	1	0
Eu-155	0	1	0	0	1	0
Bi-207	0	1	0	1	0	0
Rh-102m	0	1	0	0	1	0
Ru-106	1	0	0	1	0	0
Ce-144	0	0.2	0.8	0	1	0
Pm-147	0	0.2	0.8	0	1	0
Sm-151	0	1	0	0	1	0

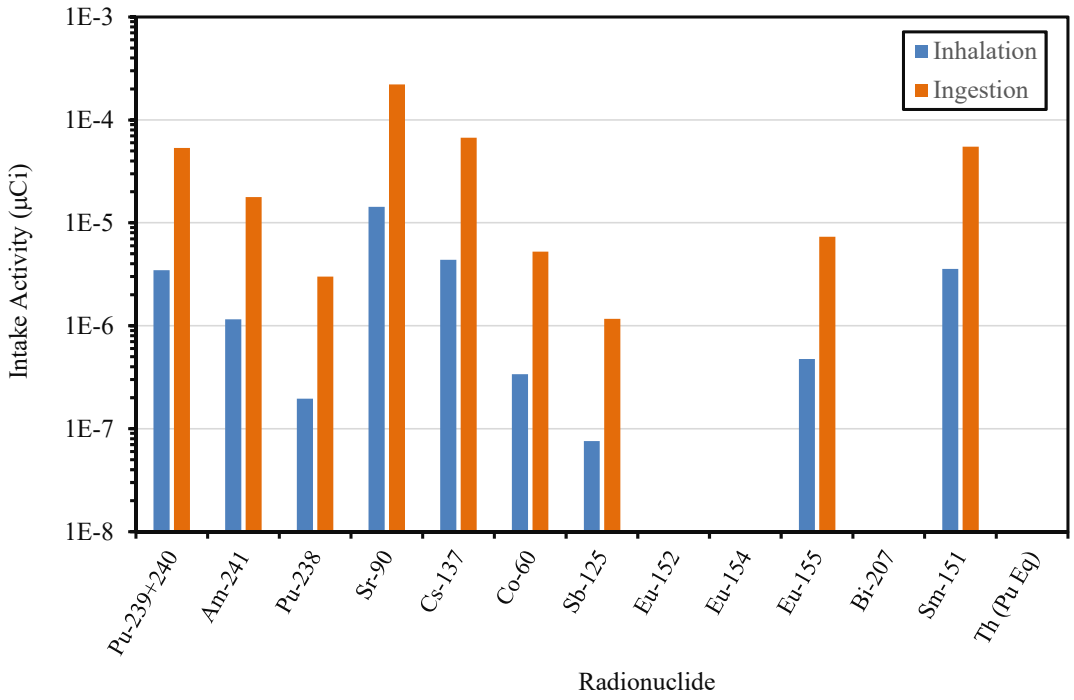


Figure K-2. Histogram of Individual Radionuclide Contributions to Effective Dose for Worker Assigned to Duties on Ursula for Six-Months from Inhalation and Ingestion.

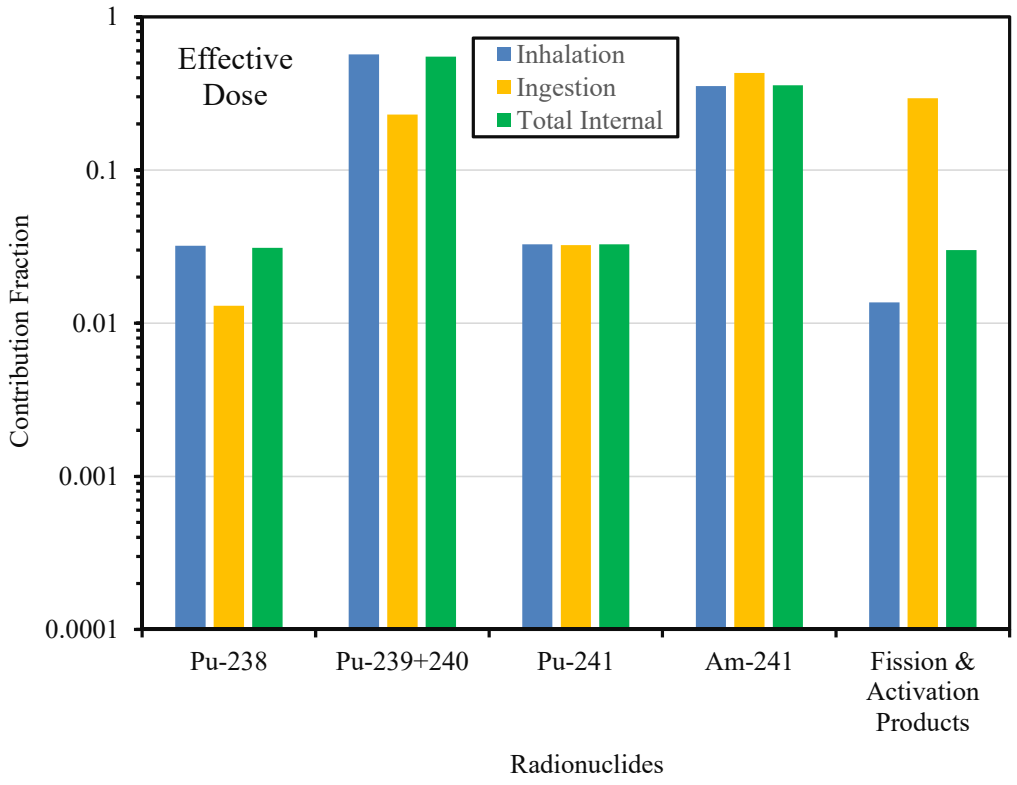


Figure K-3. Histogram of Transuranic, and Fission & Activation Product Contributions to Effective Dose for Worker Assigned to Duties on Ursula for Six-Months from Inhalation and Ingestion.

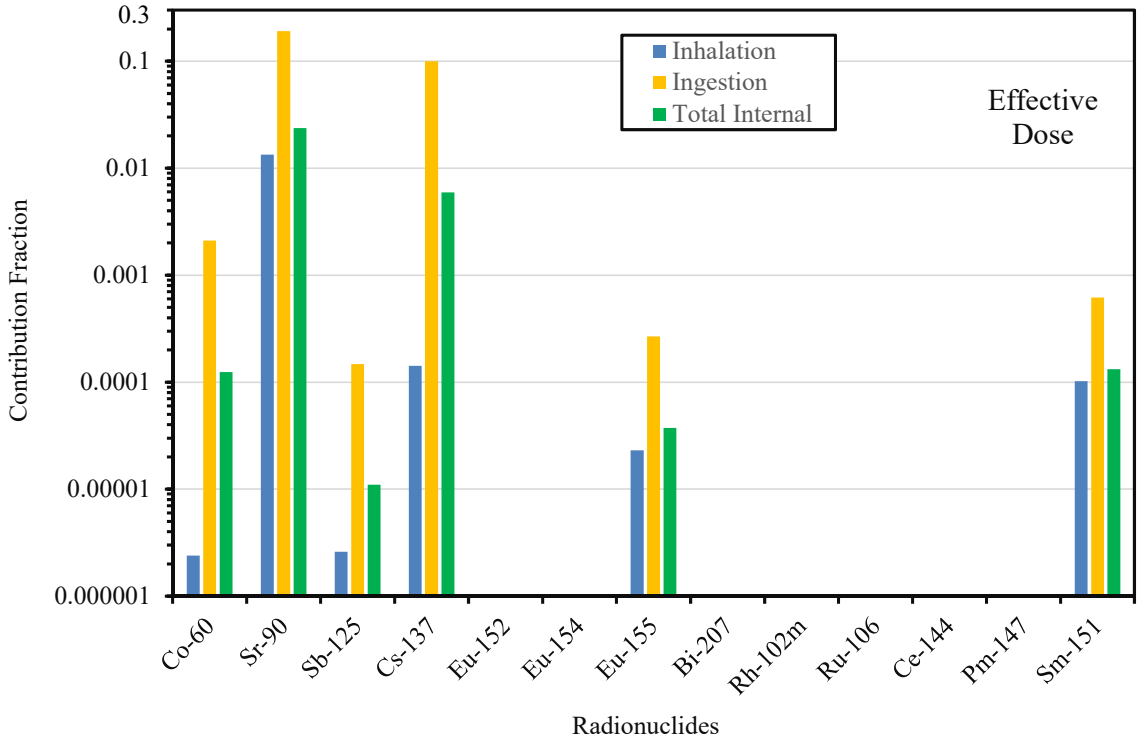


Figure K-4. Histogram of Fission & Activation Product Contributions to Effective Dose for Worker Assigned to Duties on Ursula for Six-Months from Inhalation and Ingestion.

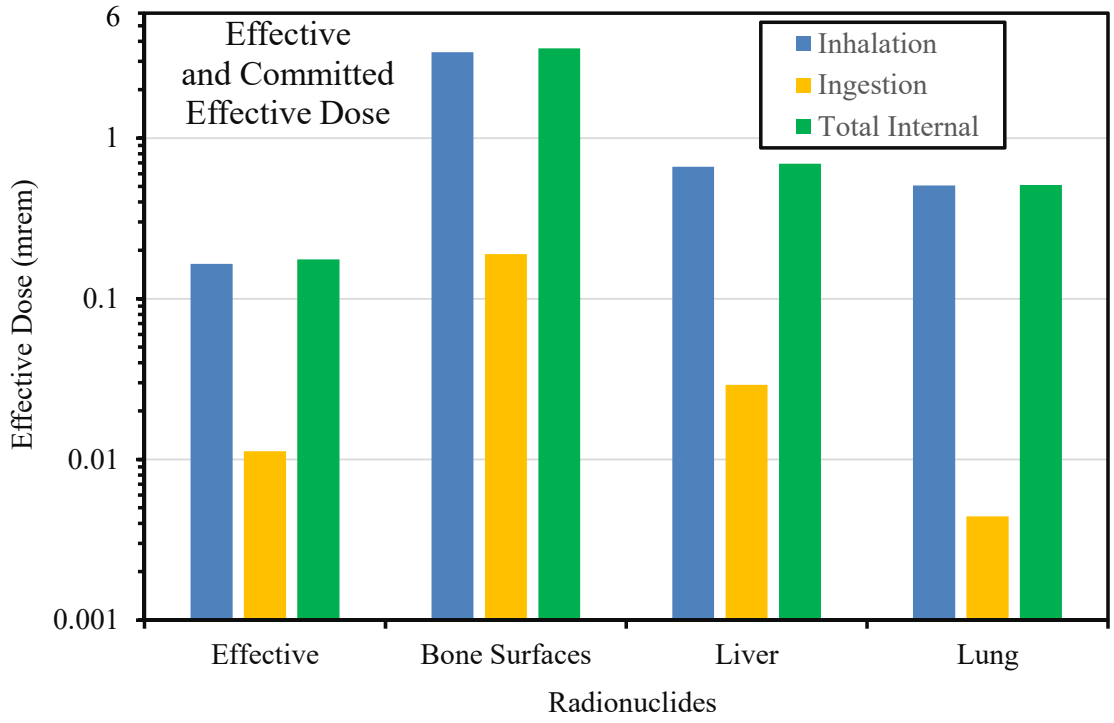


Figure K-5. Histogram of Effective and Committed Effective Dose to Bone Surfaces, Liver, and Lung for Worker Assigned to Duties on Elmer for One Year in 1959 from Inhalation and Ingestion.

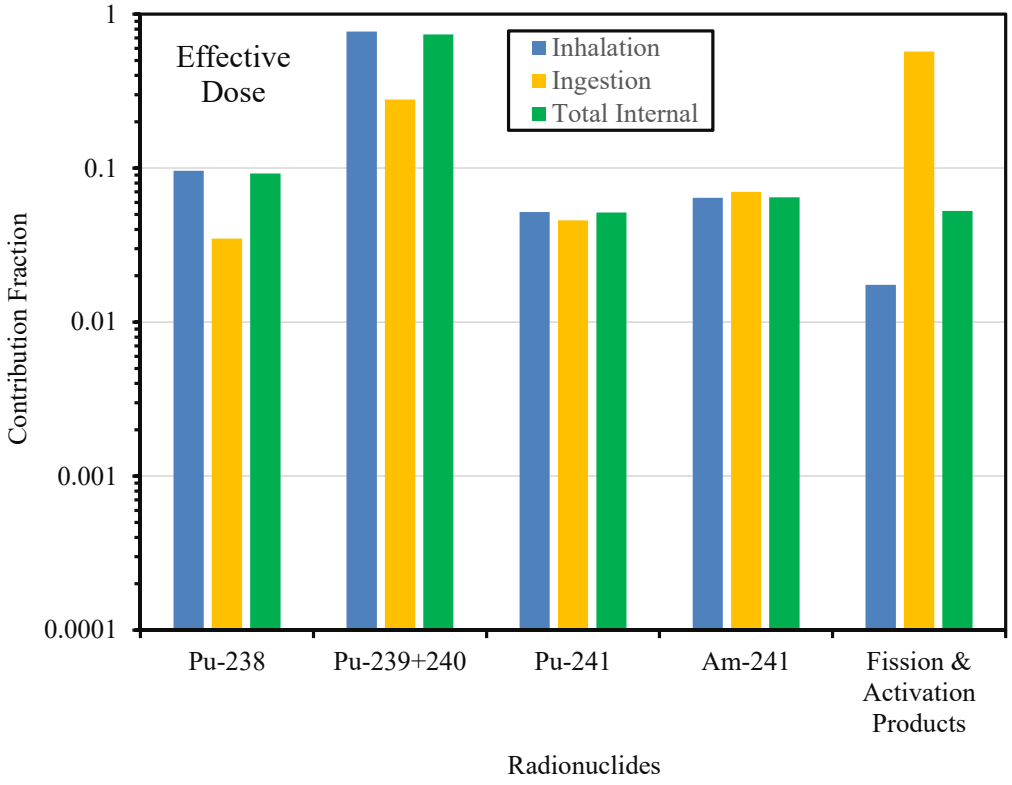


Figure K-6. Histogram of Transuranic, and Fission & Activation Product Contributions to Effective Dose for Worker Assigned to Duties on Elmer for One Year in 1959 from Inhalation and Ingestion.

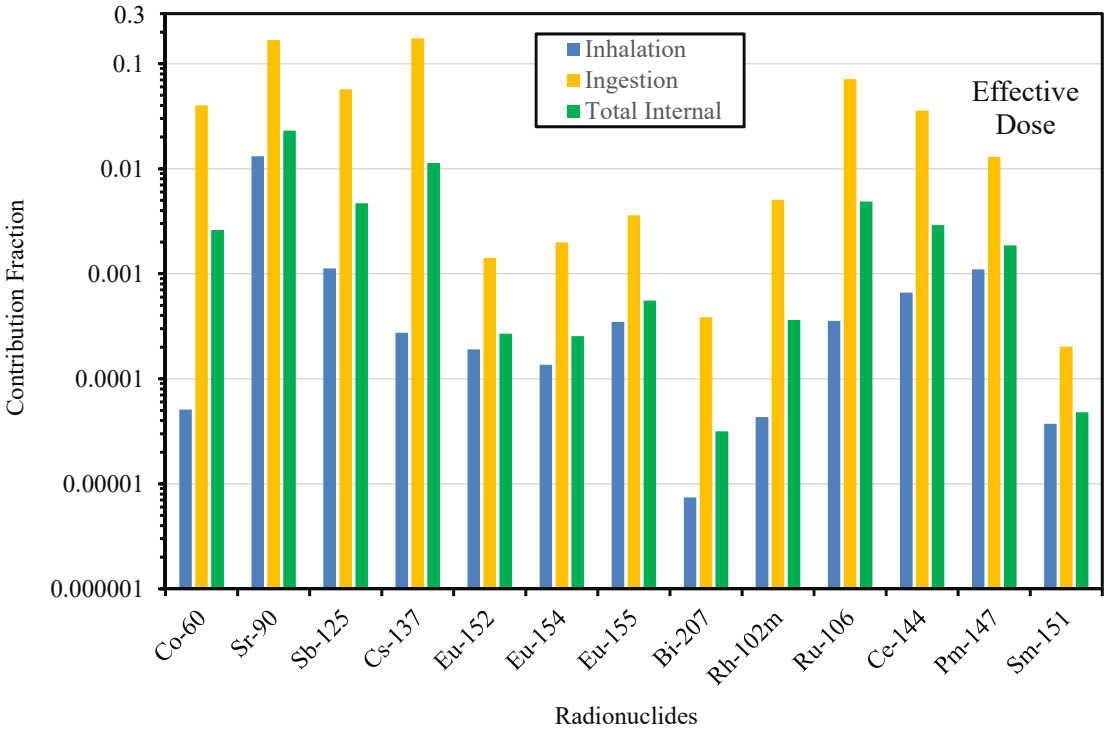


Figure K-7. Histogram of Fission & Activation Product Contributions to Effective Dose for Worker Assigned to Duties on Elmer for One Year in 1959 from Inhalation and Ingestion.

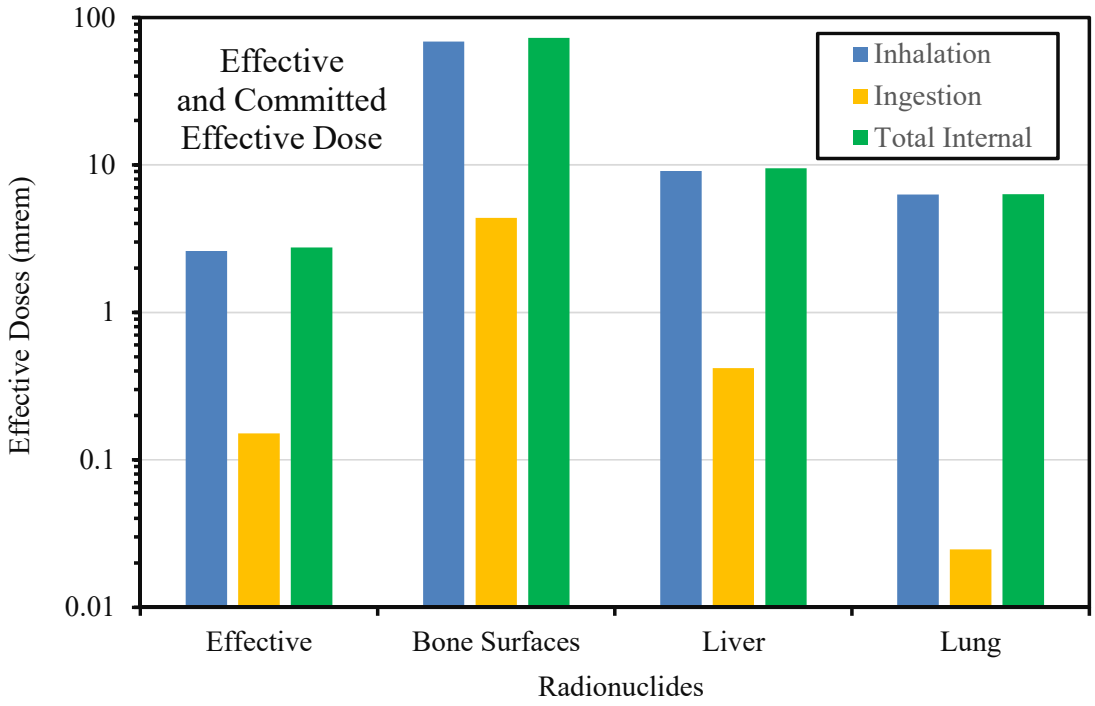


Figure K-8. Histogram of Effective and Committed Effective Dose to Bone Surfaces, Liver, and Lung for Worker Assigned to Duties on Janet for Six Months from Inhalation and Ingestion [General Work in Interior, RPF = 1].

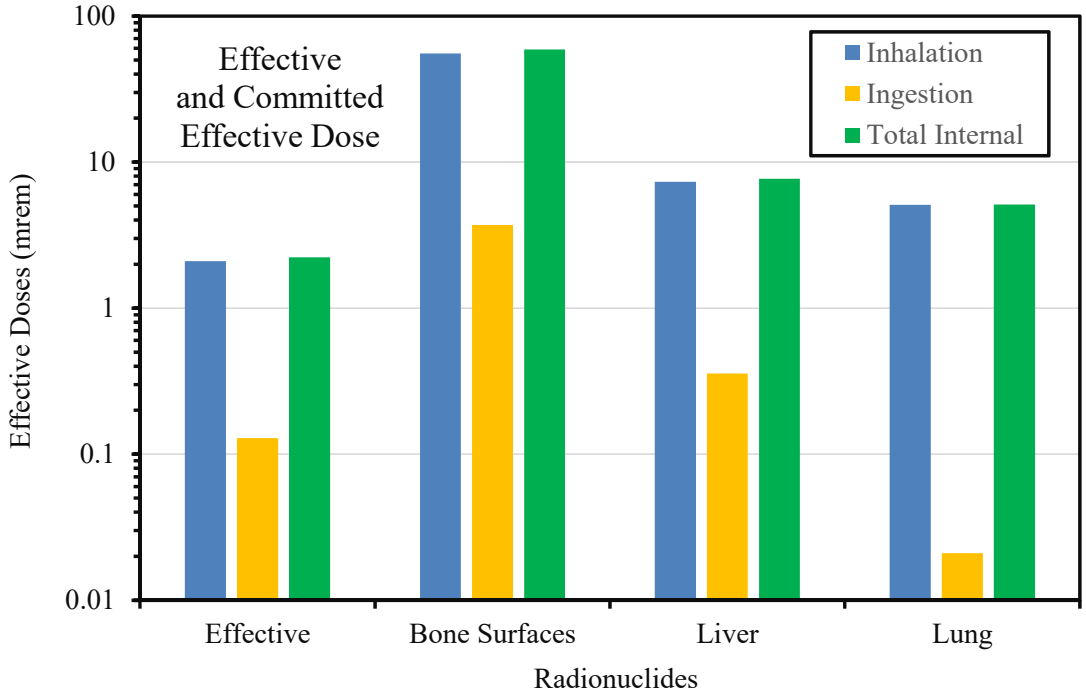


Figure K-9. Histogram of Effective and Committed Effective Dose to Bone Surfaces, Liver, and Lung for Worker Assigned to Duties on Janet for Six Months from Inhalation and Ingestion [General Work in Interior, RPF = 1 (75%), RPF = 50 (25%)].

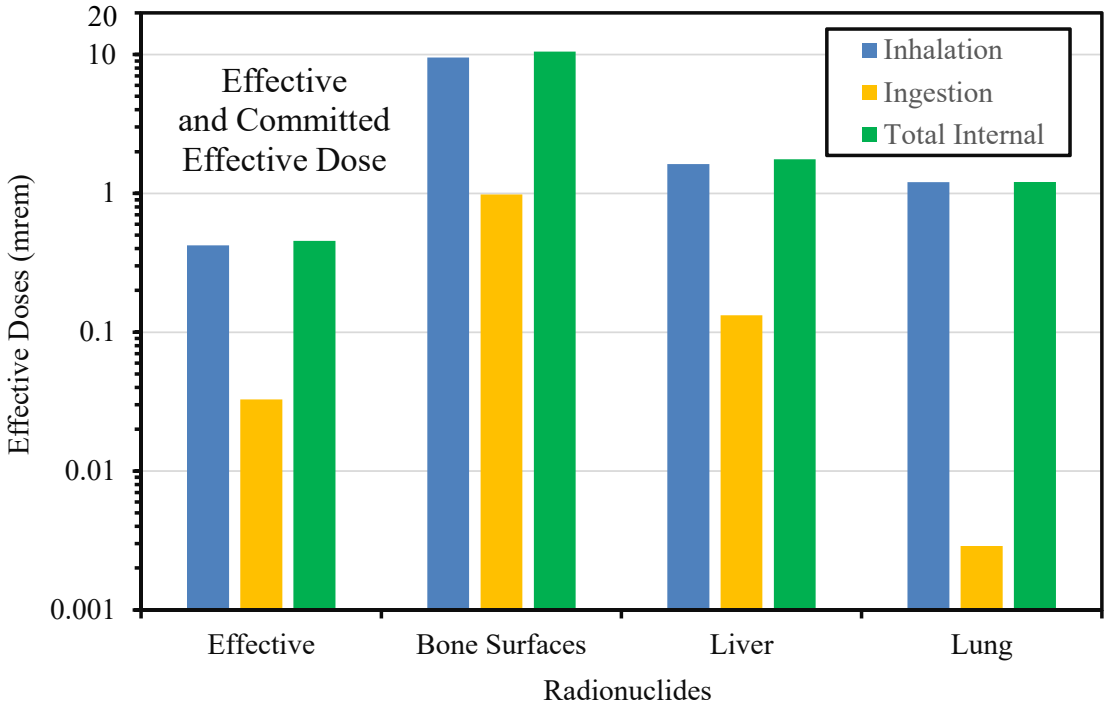


Figure K-10. Histogram of Effective and Committed Effective Dose to Bone Surfaces, Liver, and Lung for Worker Assigned to Duties on Pearl for One Month in May 1979 from Inhalation and Ingestion [Soil Excision, RPF = 50 (100%)].

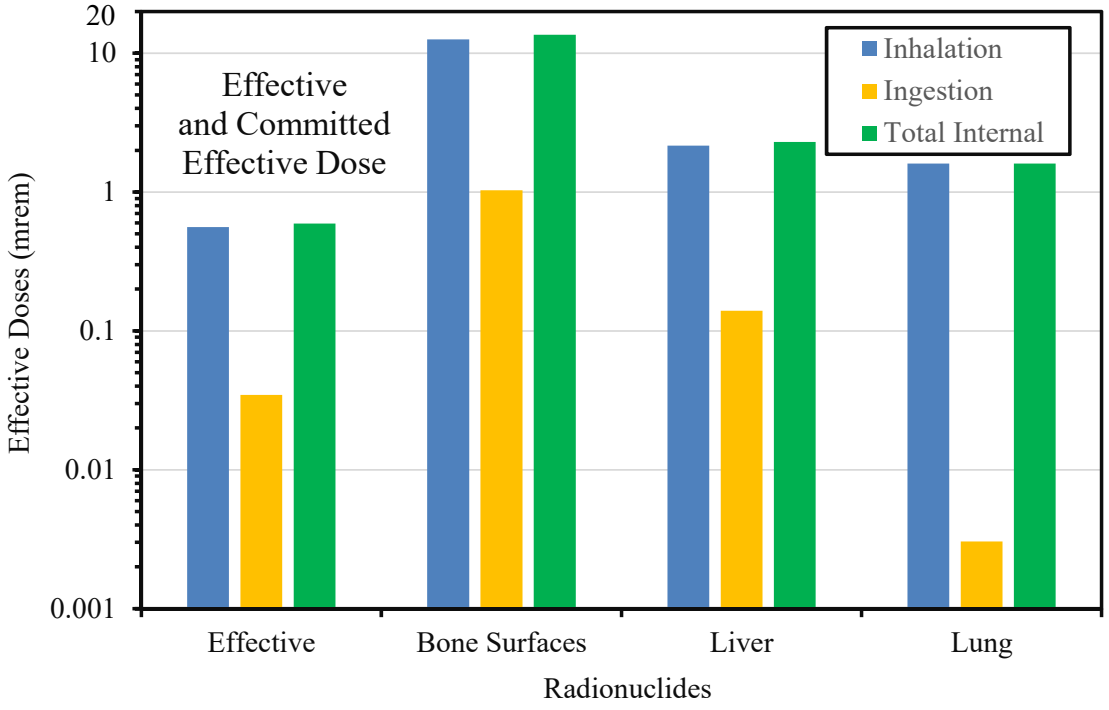


Figure K-11. Histogram of Effective and Committed Effective Dose to Bone Surfaces, Liver, and Lung for Worker Assigned to Duties on Pearl for One Month in May 1979 from Inhalation and Ingestion [Soil Excision, RPF = 50 (80%); General Work in Interior, RPF = 1 (20%)].

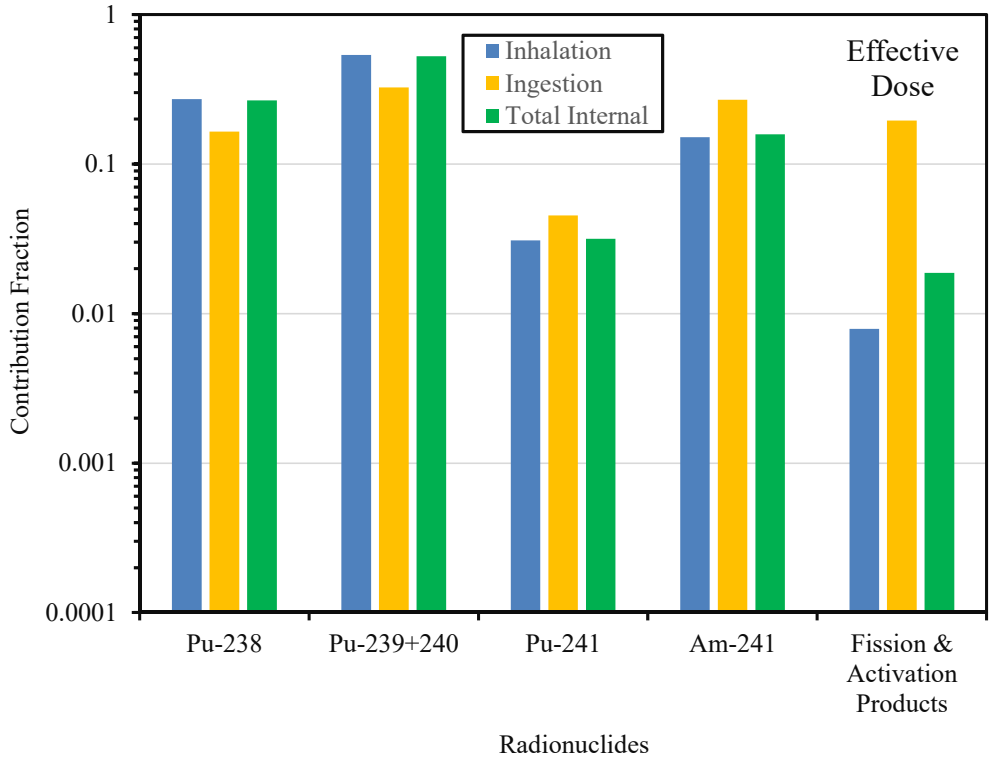


Figure K-12. Histogram of Transuranic, and Fission & Activation Product Contributions to Effective Dose for Worker Assigned to Duties on Pearl for One Month in May 1979 from Inhalation and Ingestion [Soil Excision, RPF = 50 (80%); General Work in Interior, RPF = 1 (20%)].

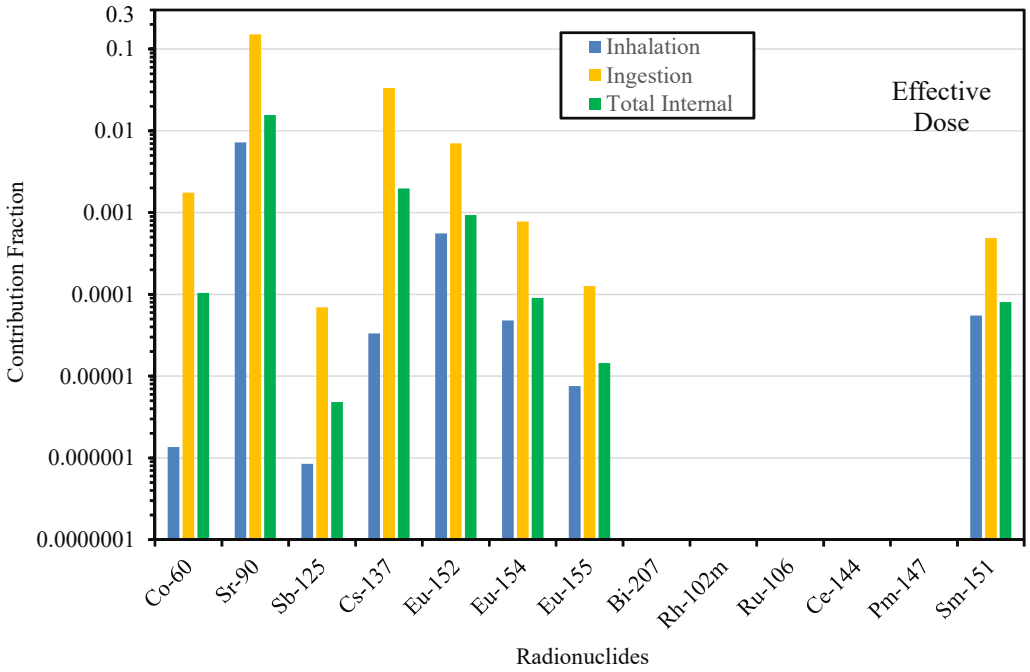


Figure K-13. Histogram of Fission & Activation Product Contributions to Effective Dose for Worker Assigned to Duties on Pearl for One Month in May 1979 from Inhalation and Ingestion [Soil Excision, RPF = 50 (80%); General Work in Interior, RPF = 1 (20%)].

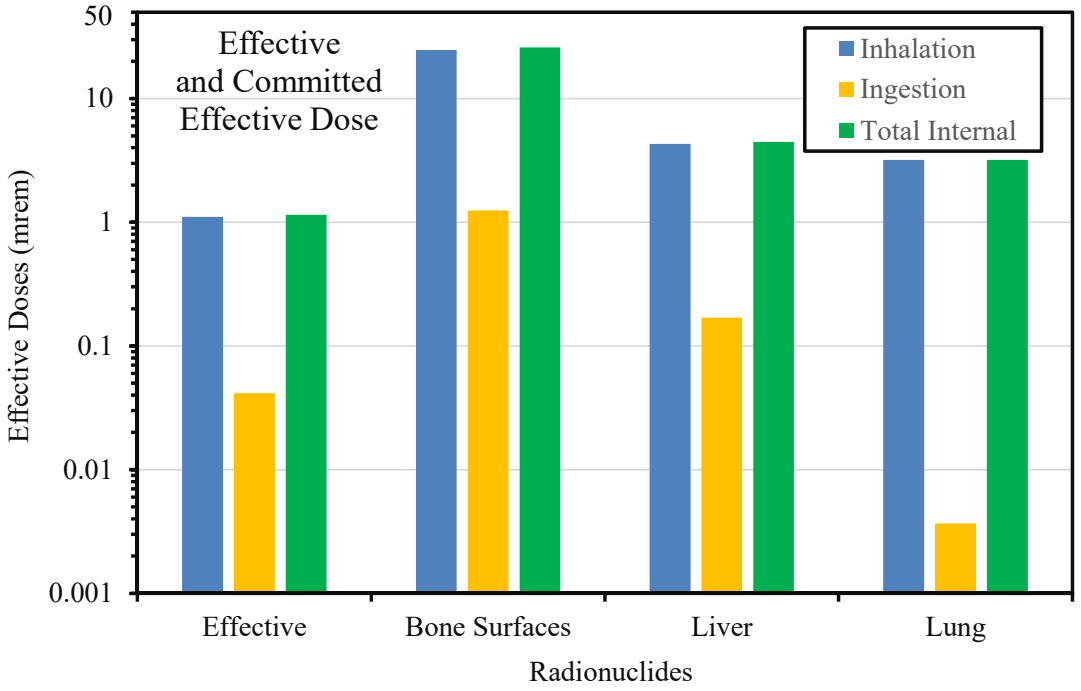


Figure K-14. Histogram of Effective and Committed Effective Dose to Bone Surfaces, Liver, and Lung for Worker Assigned to Duties on Pearl for One Month from Inhalation and Ingestion [Soil General Work in Interior, RPF = 1].

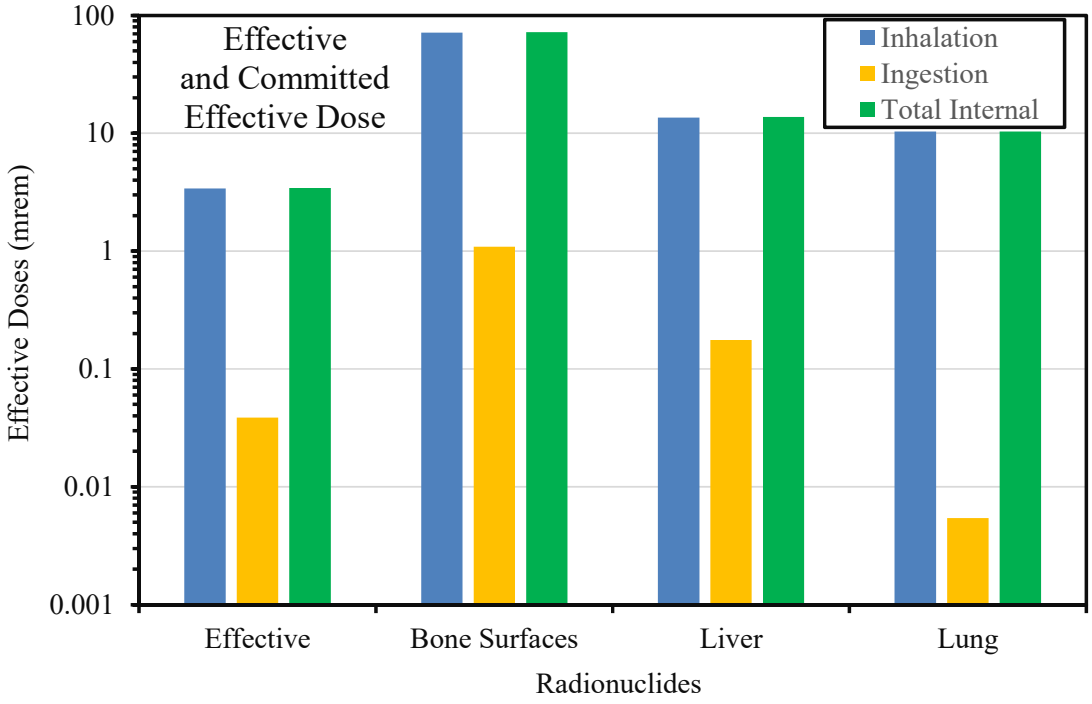


Figure K-15. Histogram of Effective and Committed Effective Dose to Bone Surfaces, Liver, and Lung for Worker Assigned to Duties on Yvonne, Segment A, for One Month from Inhalation and Ingestion [Soil Trenching in Interior, RPF = 1].

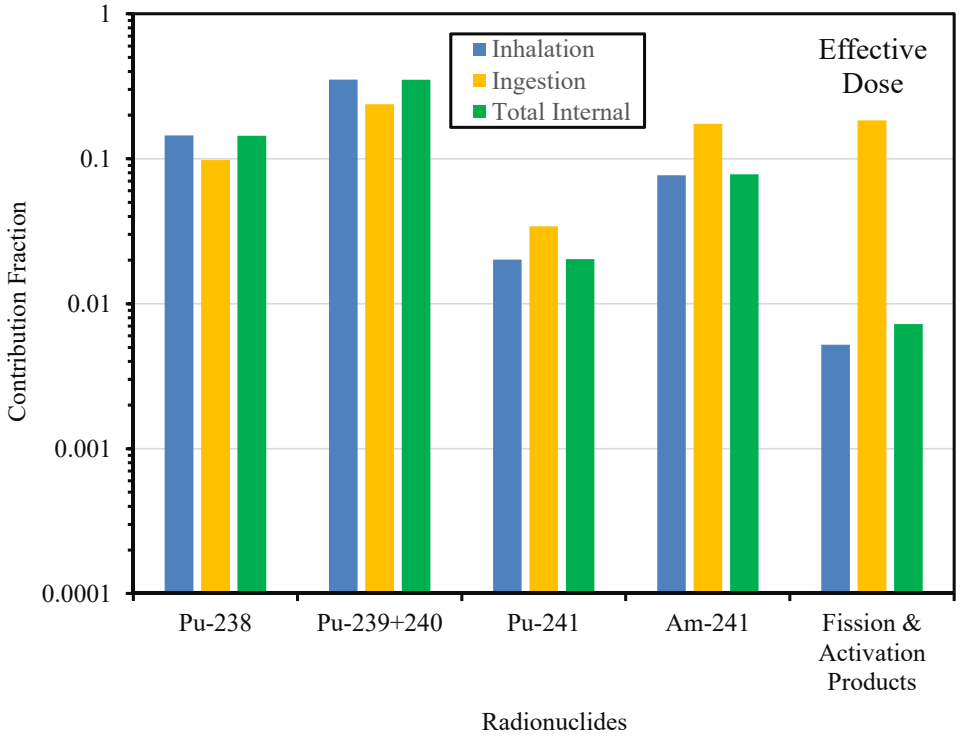


Figure K-16. Histogram of Transuranic, and Fission & Activation Product Contributions to Effective Dose for Worker Assigned to Duties on Yvonne, Segment A, for One Month from Inhalation and Ingestion [Soil Trenching in Interior, RPF = 1].

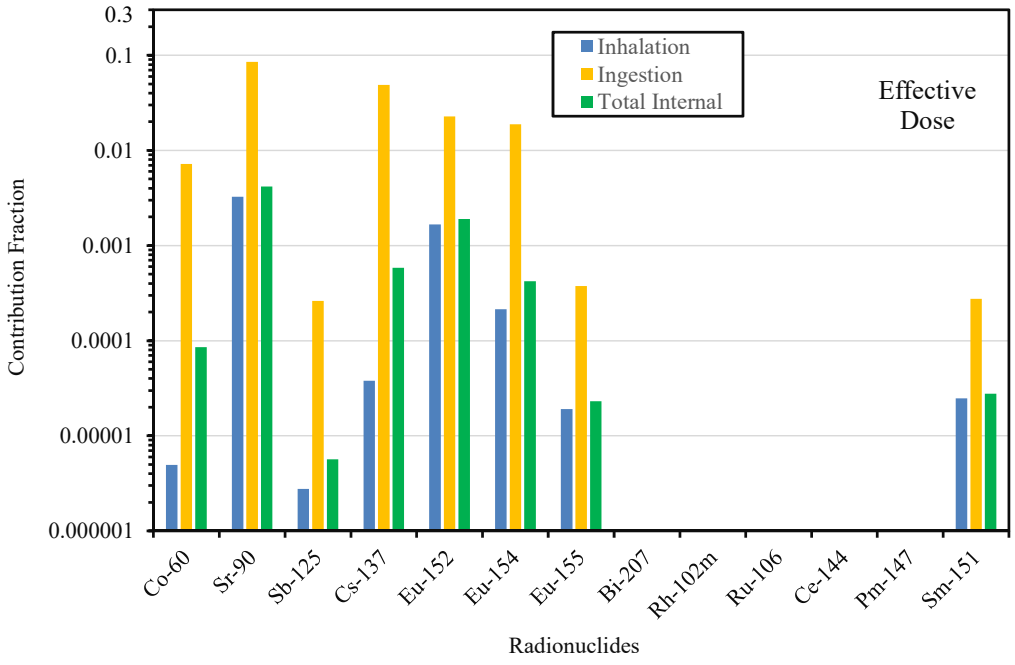


Figure K-17. Histogram of Fission & Activation Product Contributions to Effective Dose for Worker Assigned to Duties on Yvonne, Segment A, for One Month from Inhalation and Ingestion [Soil Trenching in Interior, RPF = 1].

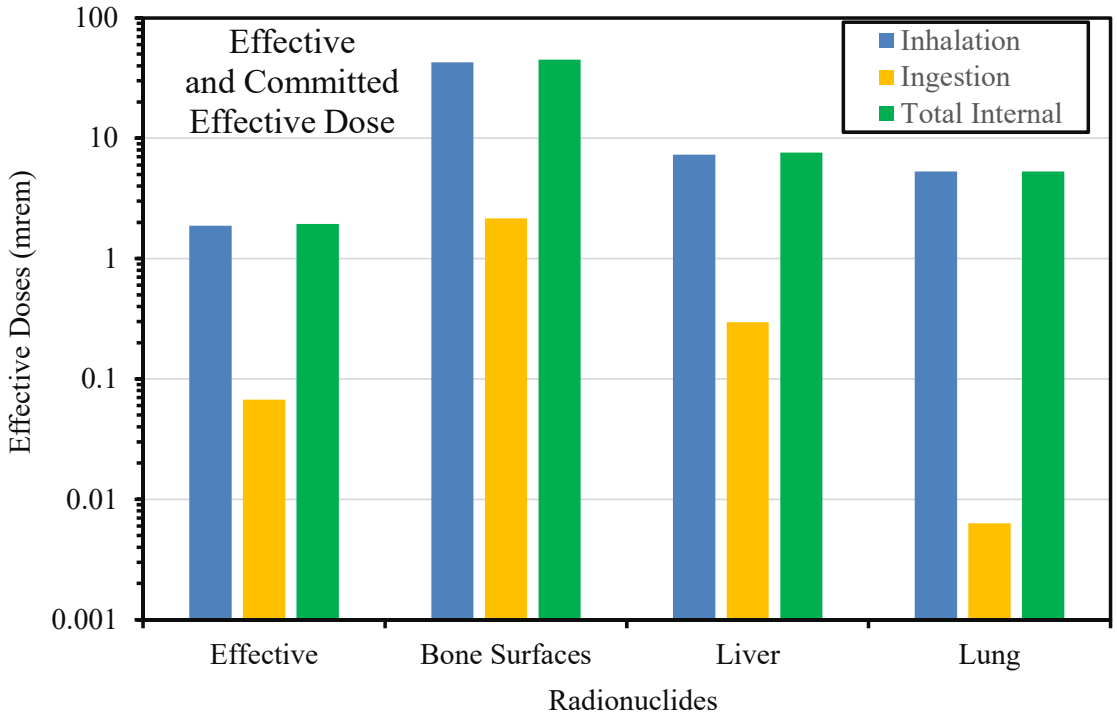


Figure K-18. Histogram of Effective and Committed Effective Dose to Bone Surfaces, Liver, and Lung for Worker Assigned to Duties on Yvonne, Segment C, for Six Months from Inhalation and Ingestion [General Work in Interior, RPF = 1].

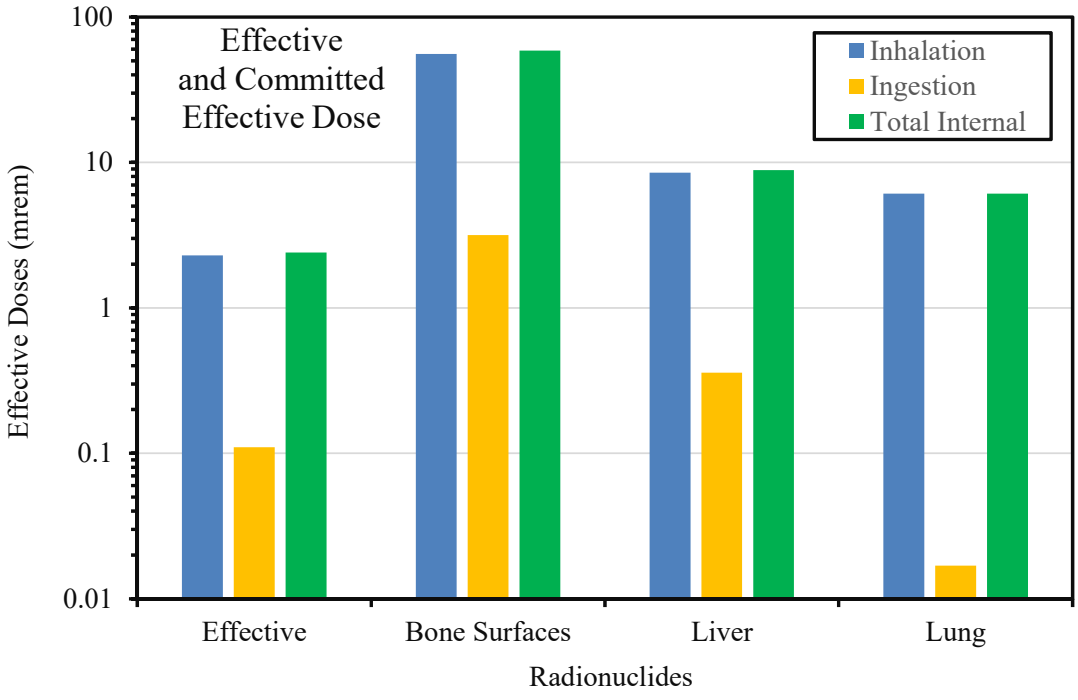


Figure K-19. Histogram of Effective and Committed Effective Dose to Bone Surfaces, Liver, and Lung for Worker Assigned to Duties on Clara for Three Months from Inhalation and Ingestion [General Work in Interior, RPF = 1].

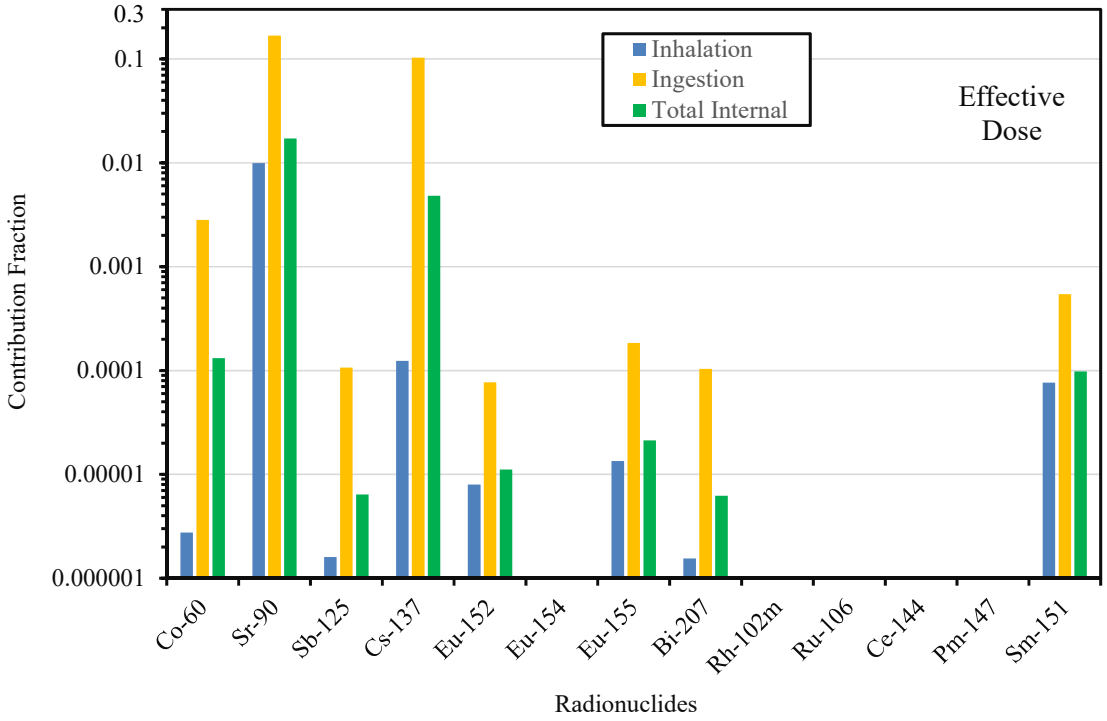


Figure K-20. Histogram of Fission & Activation Product Contributions to Effective Dose for Worker Assigned to Duties on Clara for Three Months from Inhalation and Ingestion [General Work in Interior, RPF = 1].

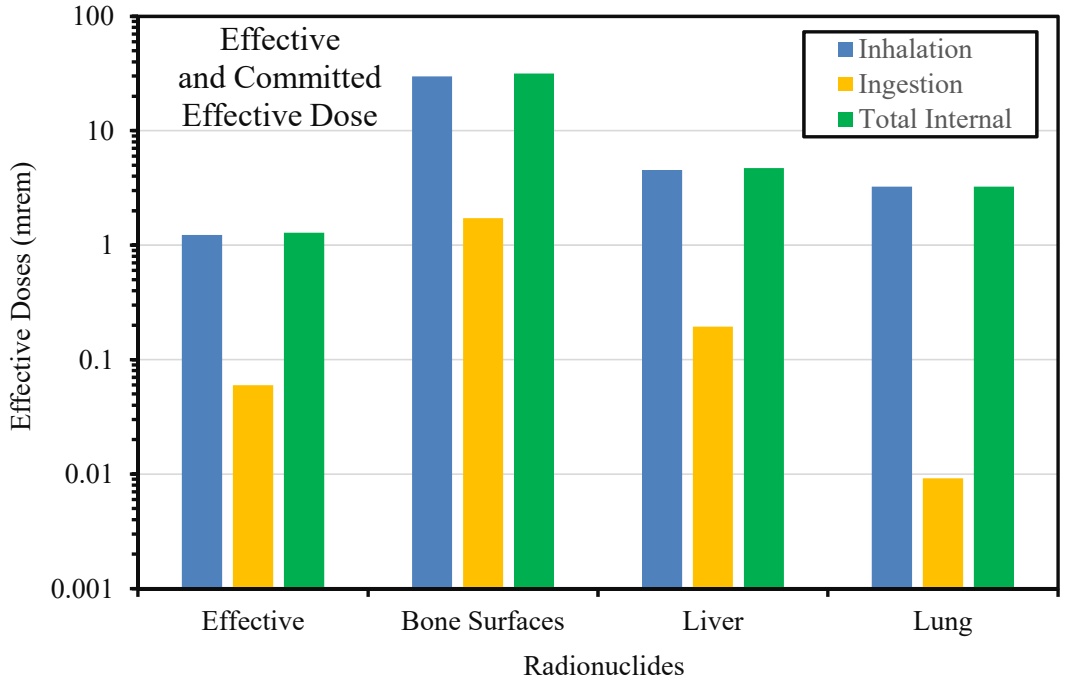


Figure K-21. Histogram of Effective and Committed Effective Dose to Bone Surfaces, Liver, and Lung for Worker Assigned to Duties on Clara for Three Months from Inhalation and Ingestion [General Work in Beach Areas, RPF = 1].

Appendix L.

In-Situ Skin Dose Data

Table L-1. In-Situ Skin Exposure Parameters.

Parameter	Value	Comment
β-particle dermal contamination dose coefficient (rem cm^2 μCi^{-1} h^{-1}), consistent with DTRA (2017), Table 26	3.83	Co-60
	12.0	Sr-90
	5.69	Cs-137
Skin-dose modification factor (SDMF) for β-particle dermal contamination, consistent with DTRA (2017), Table 28, from Apostoaei and Kocher (2010)	1.3	Face, forehead, neck, shoulders, torso, and upper legs
	0.9	Forearms and lower legs
	0.3	Palms of the hands and soles of feet
Interception and retention fraction, *I/R*, consistent with DTRA (2017), Table 29, from Apostoaei and Kocher (2010)	0.015	Face, forehead, shoulders, back/sides torso, palms of the hands
	0.03	Chest
	0.06	Forearms, upper and lower legs
	0.23	Scalp
	1.5	Back of neck (under collar), under belt, under boot edge, and behind ears
Exposure duration	12 h	10 h d^{-1}, assumed work day, 8 h d^{-1} work period more practical for incorporating transit time from Ursula to northern island work sites, 4 h exposure period post work prior to showering
	6 d w^{-1}	
Deposition velocity, V_d, (m h^{-1})	3600	Consistent with DTRA (2017), Table 25, from Apostoaei and Kocher (2010)
Mass loading, *ML*, (μg m^{-3})	100	Quiescent
	300	Trenching, brush removal, rock crushing
	600	Soil excision

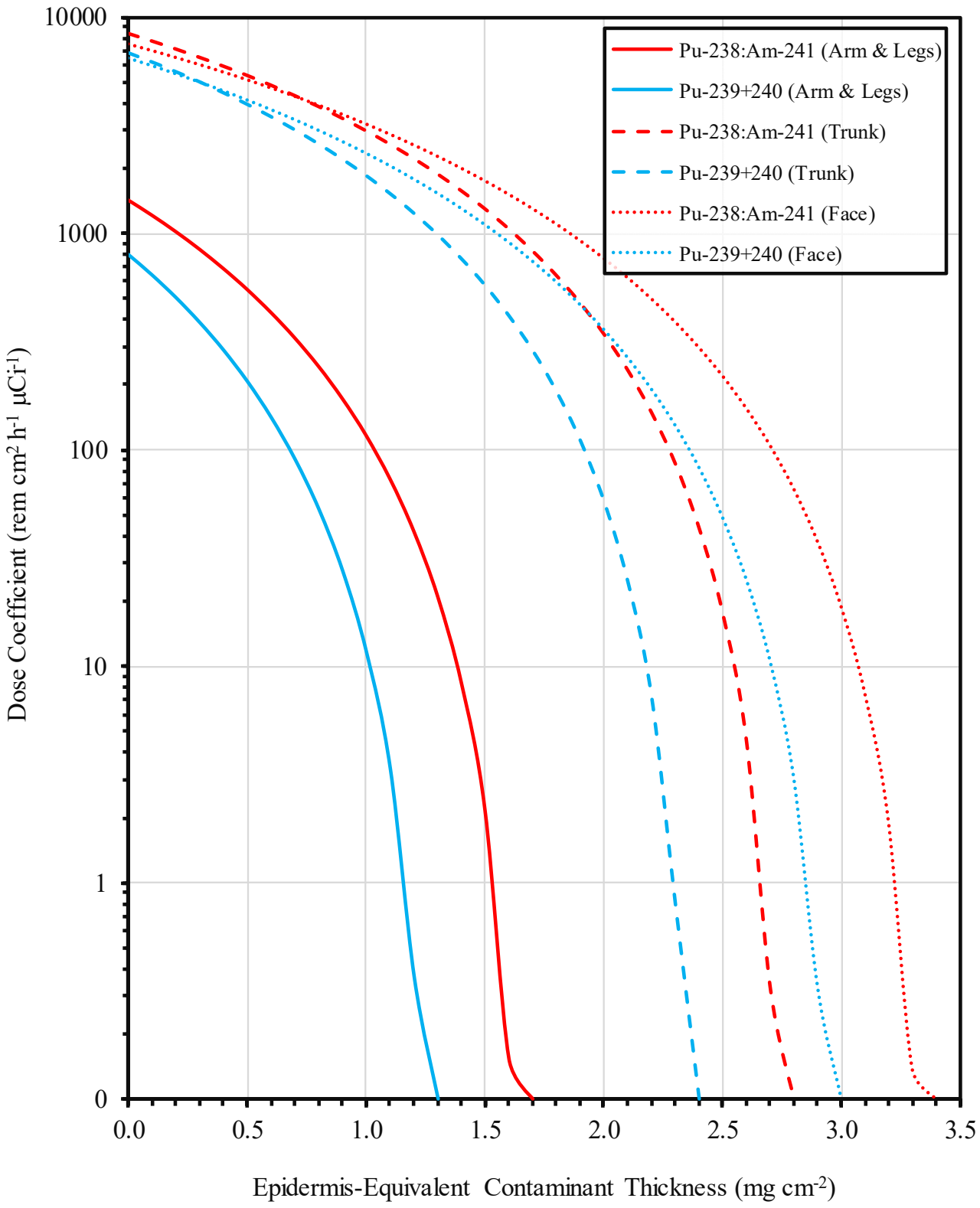


Figure L-1. Dose Coefficient Curves for Varied Density Thicknesses of α-Particle Emitting Contamination Deposited and Retained on Skin Surfaces, Modified from Method of Eatough (1997).

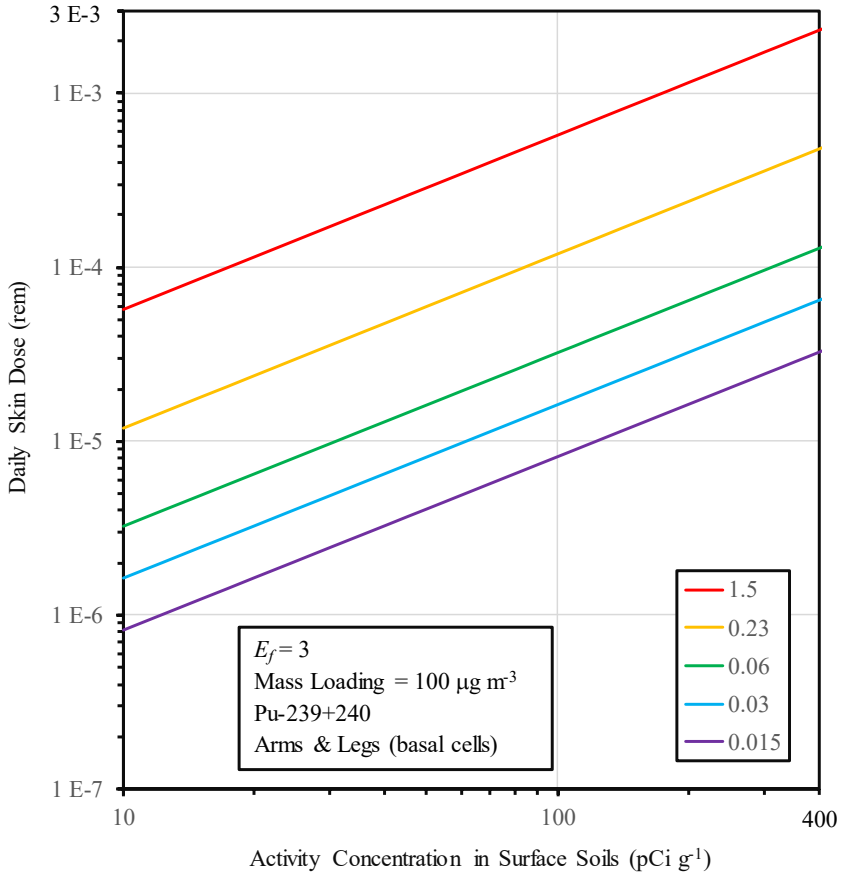


Figure L-2. Single-Day Skin Dose from $^{239+240}$Pu α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors [Basal Cells of Arms and Legs, E_f= 3, Mass Loading 100 µg m^{-3}].

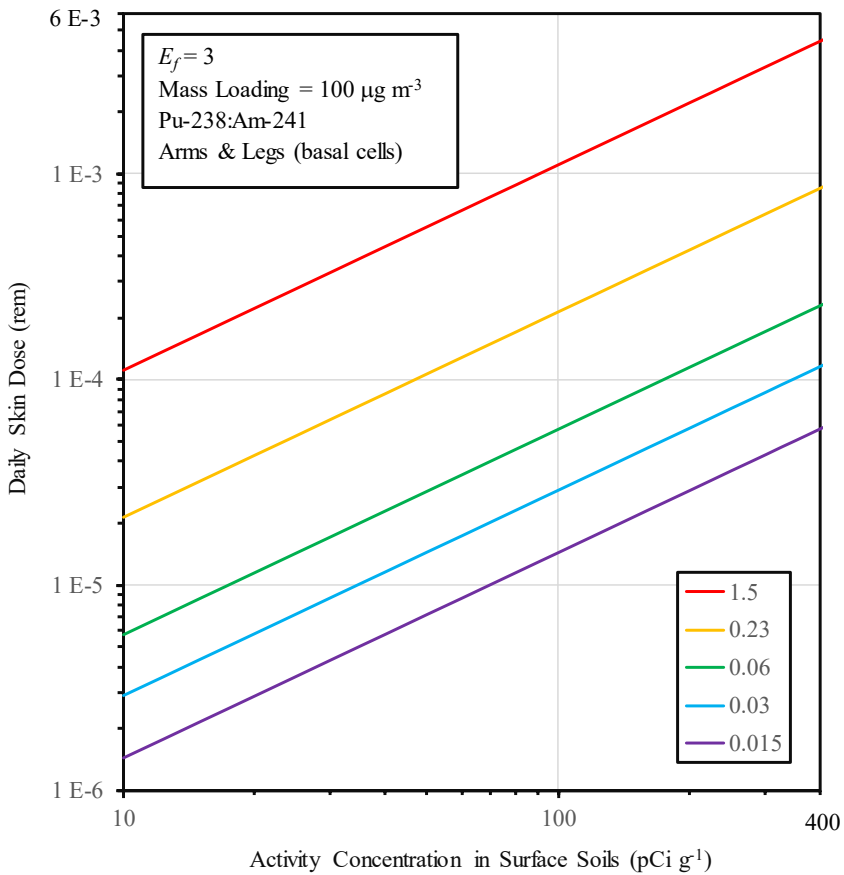


Figure L-3. Single-Day Skin Dose from ^{238}Pu:^{241}Am α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Arms and Legs, E_f= 3, Mass Loading 100 µg m^{-3}].

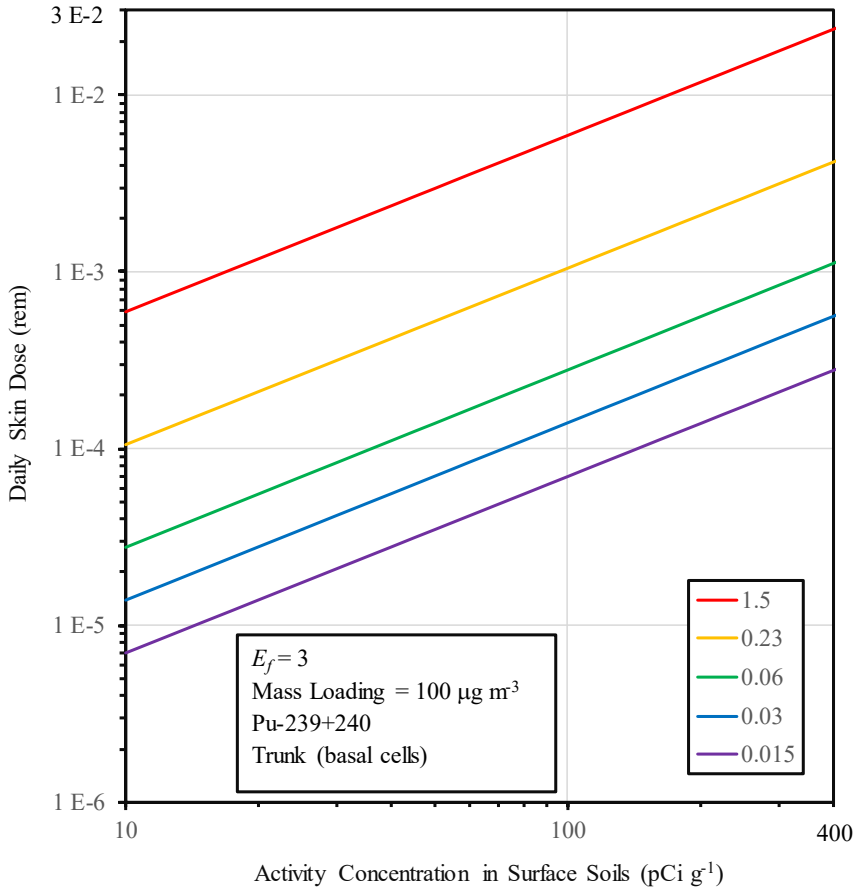


Figure L-4. Single-Day Skin Dose from $^{239+240}$Pu α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors [Basal Cells of Body Trunk, E_f = 3, Mass Loading 100 µg m^{-3}].

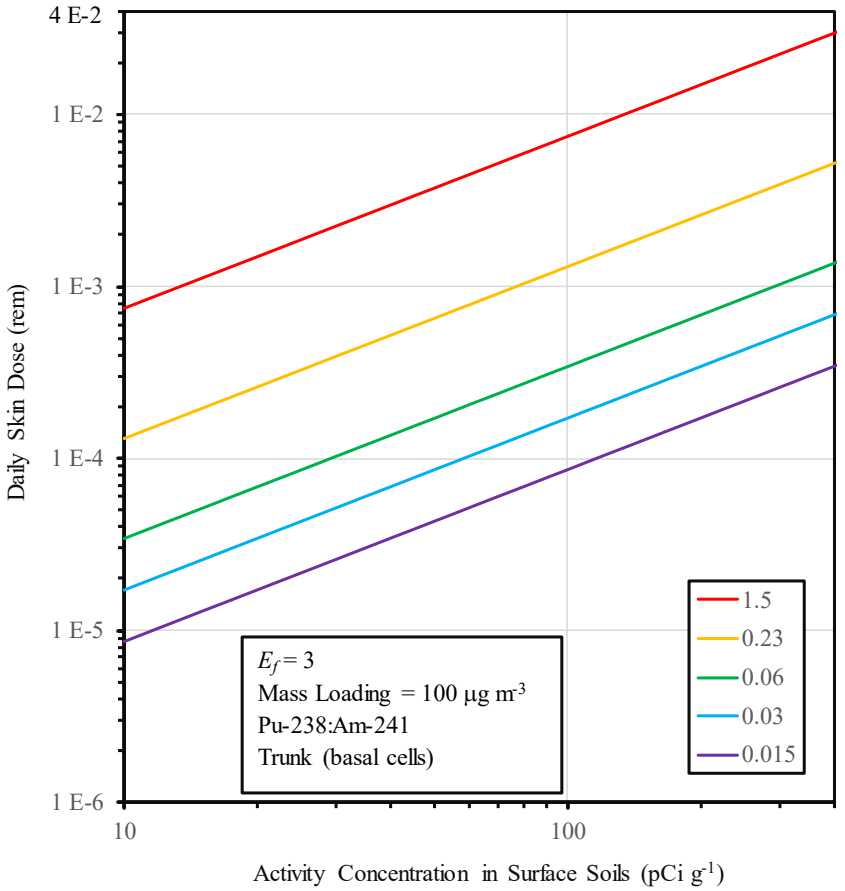


Figure L-5. Single-Day Skin Dose from ^{238}Pu:^{241}Am α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Body Trunk, E_f = 3, Mass Loading 100 µg m^{-3}].

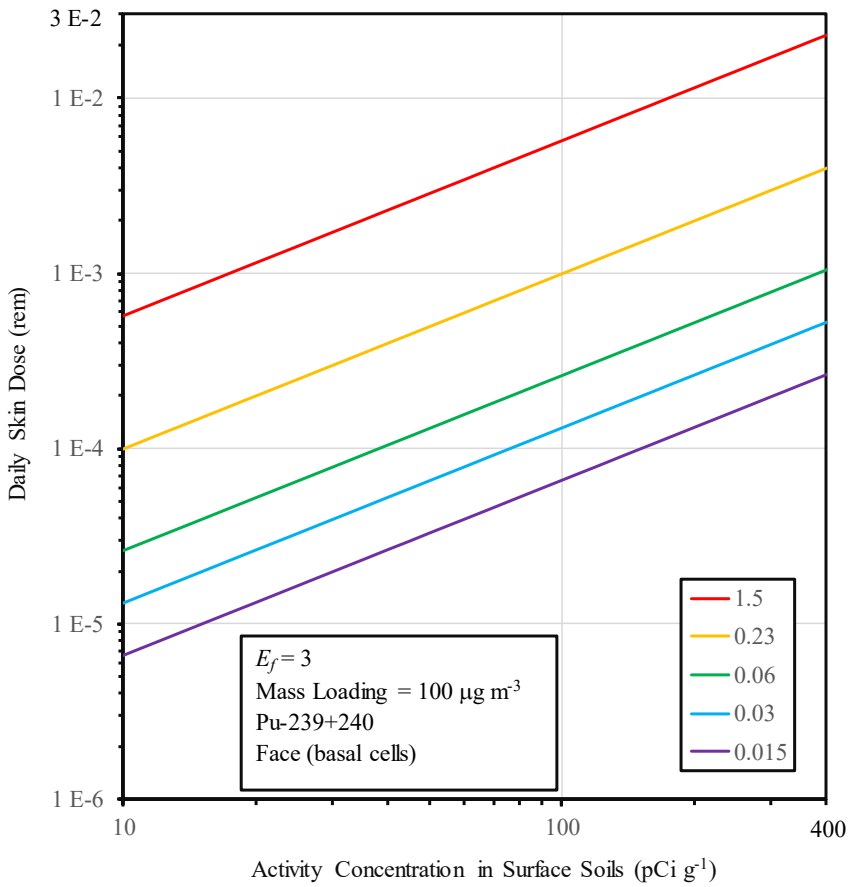


Figure L-6. Single-Day Skin Dose from $^{239+240}$Pu α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors [Basal Cells of Face, E_f = 3, Mass Loading 100 µg m^{-3}].

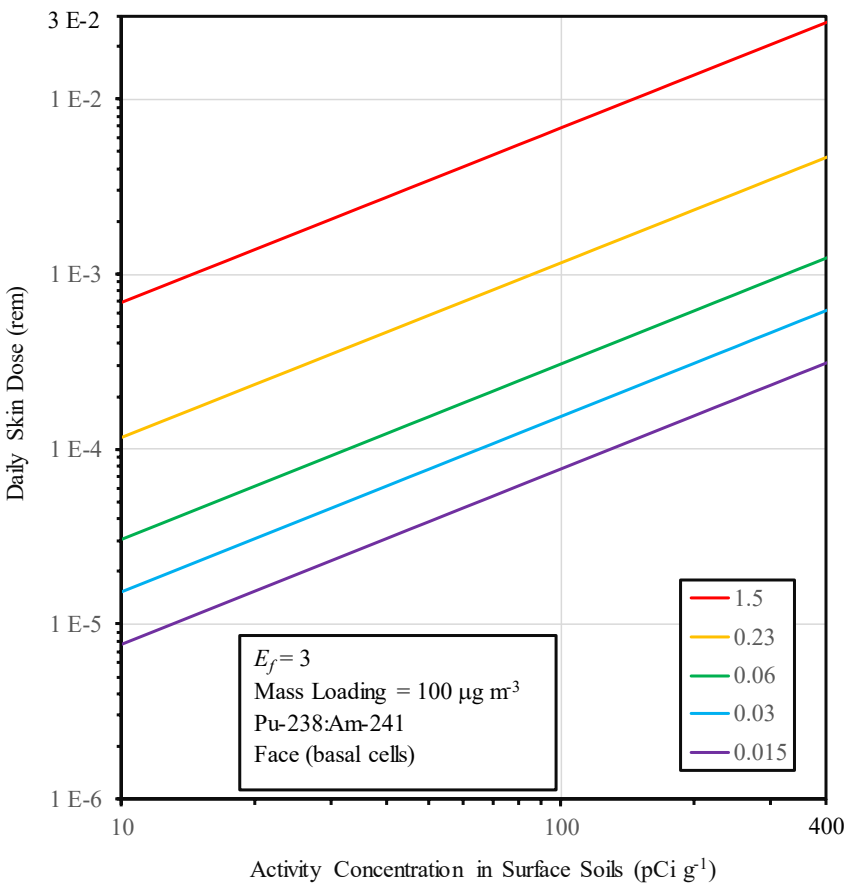


Figure L-7. Single-Day Skin Dose from ^{238}Pu:^{241}Am α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Face, E_f = 3, Mass Loading 100 µg m^{-3}].

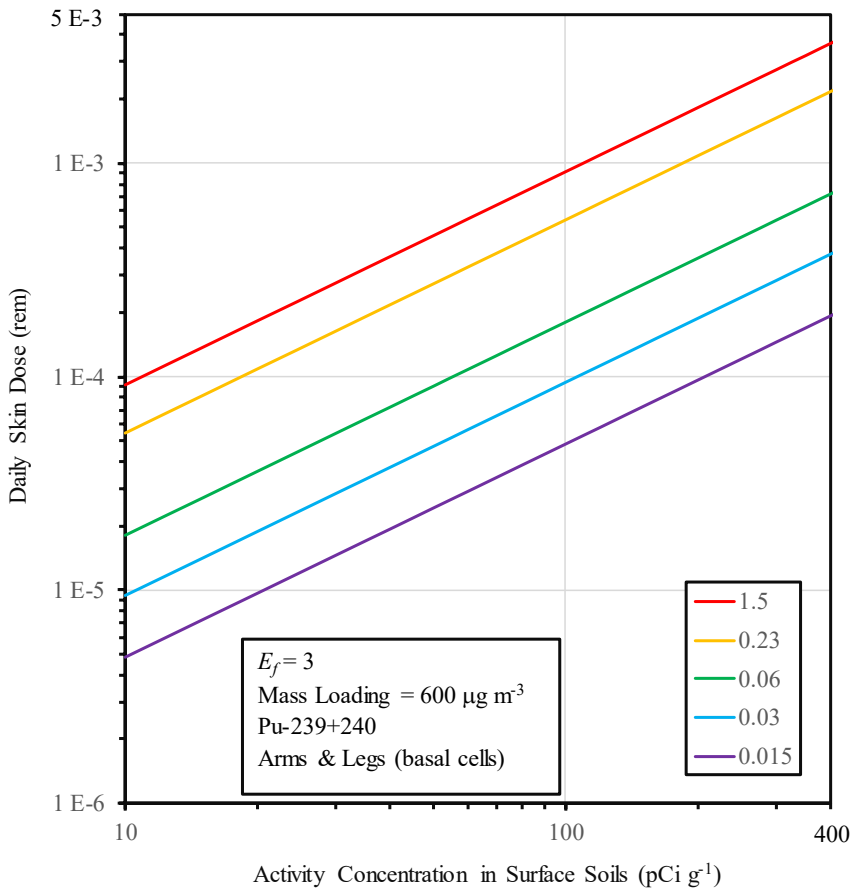


Figure L-8. Single-Day Skin Dose from $^{239+240}$Pu α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors [Basal Cells of Arms and Legs, E_f= 3, Mass Loading 600 µg m^{-3}].

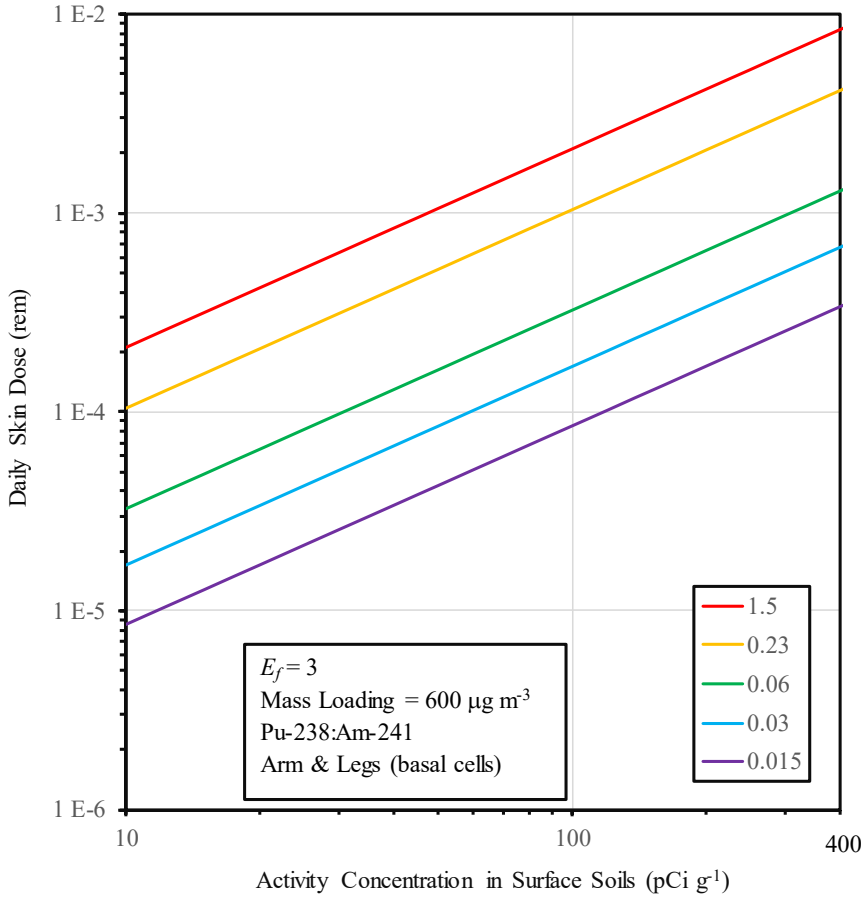


Figure L-9. Single-Day Skin Dose from ^{238}Pu:^{241}Am α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Arms and Legs, E_f= 3, Mass Loading 600 µg m^{-3}].

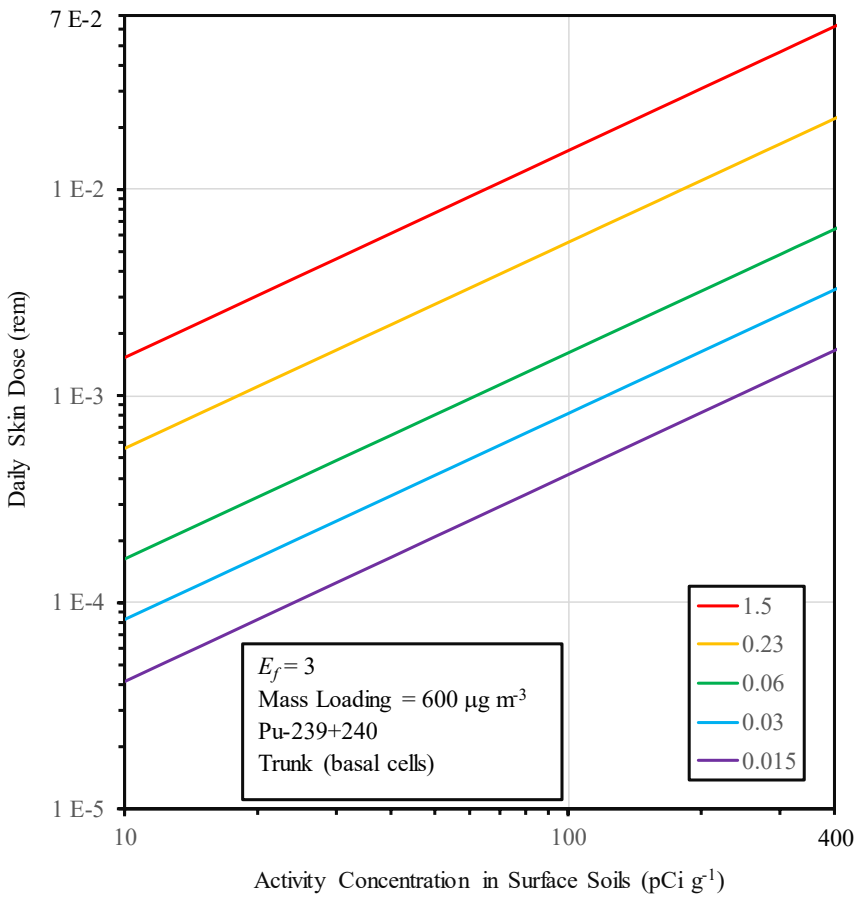


Figure L-10. Single-Day Skin Dose from $^{239+240}$Pu α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors [Basal Cells of Trunk of Body, E_f= 3, Mass Loading 600 µg m^{-3}].

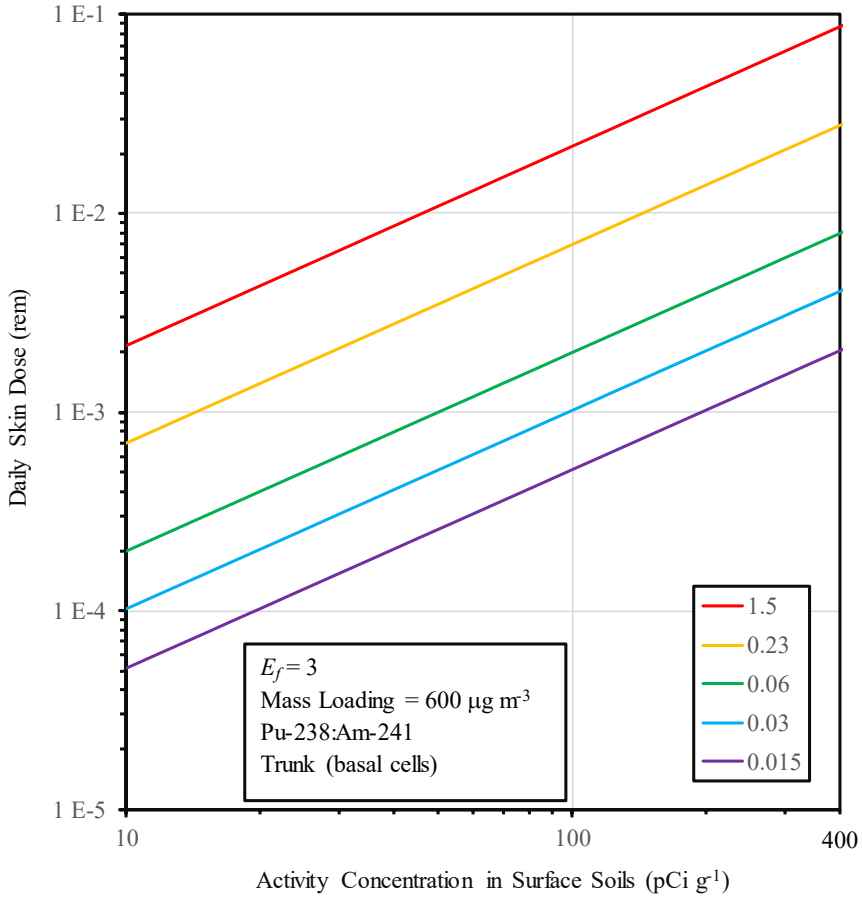


Figure L-11. Single-Day Skin Dose from ^{238}Pu:^{241}Am α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Trunk of Body, E_f= 3, Mass Loading 600 µg m^{-3}].

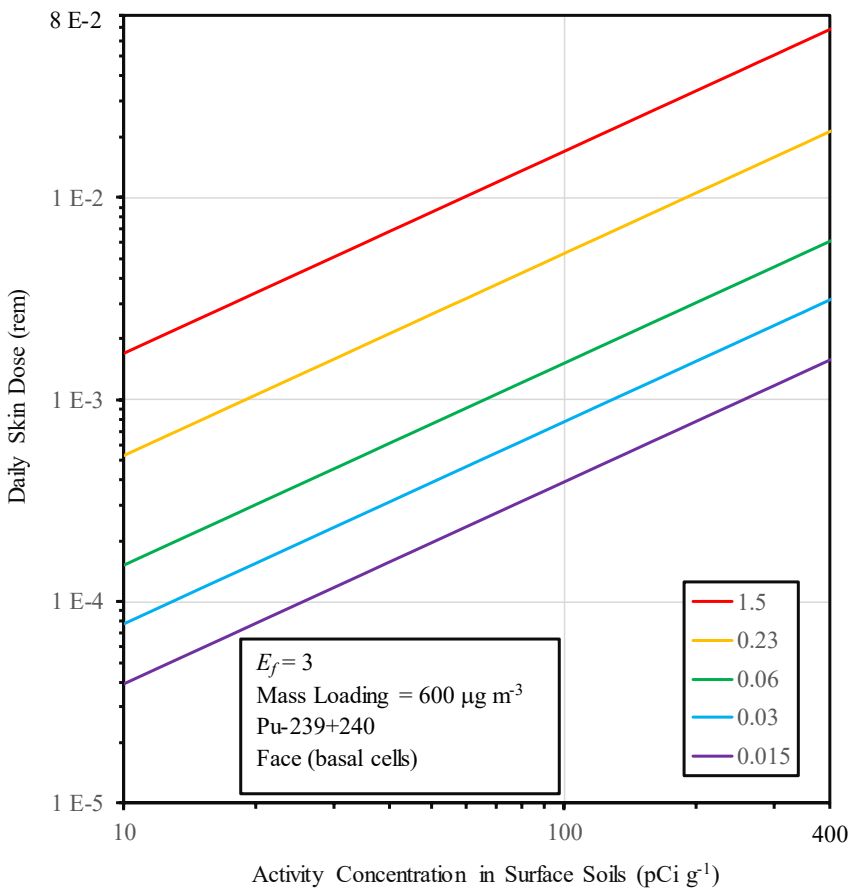


Figure L-12. Single-Day Skin Dose from $^{239+240}$Pu α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors [Basal Cells of Face, E_f= 3, Mass Loading 600 µg m^{-3}].

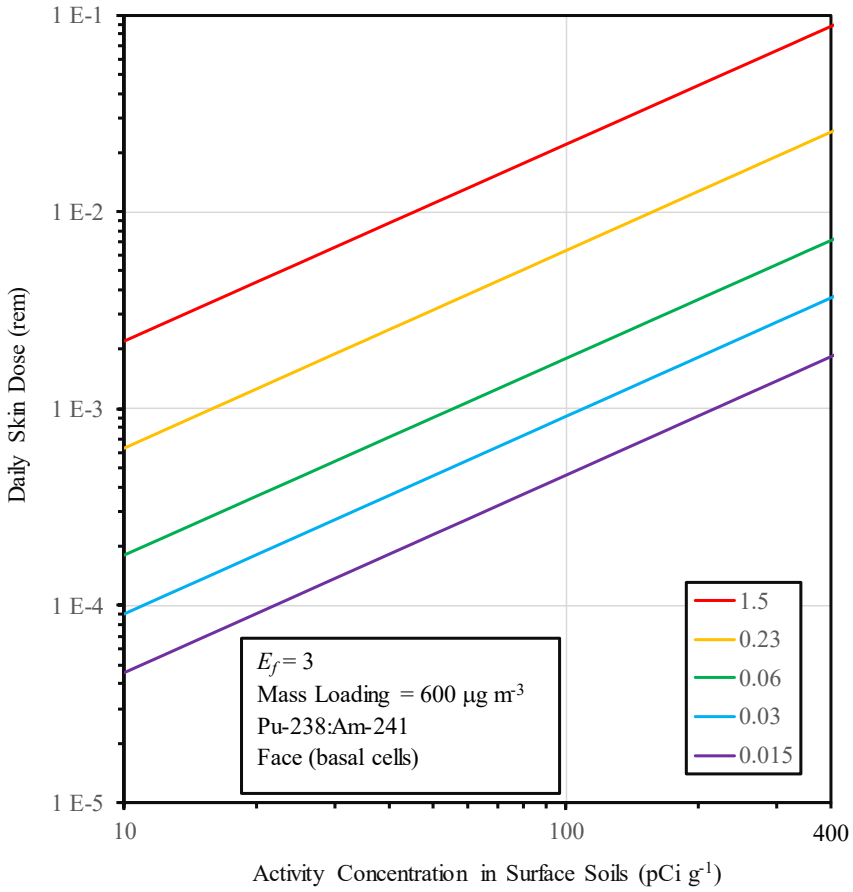


Figure L-13. Single-Day Skin Dose from ^{238}Pu:^{241}Am α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Face, E_f= 3, Mass Loading 600 µg m^{-3}].

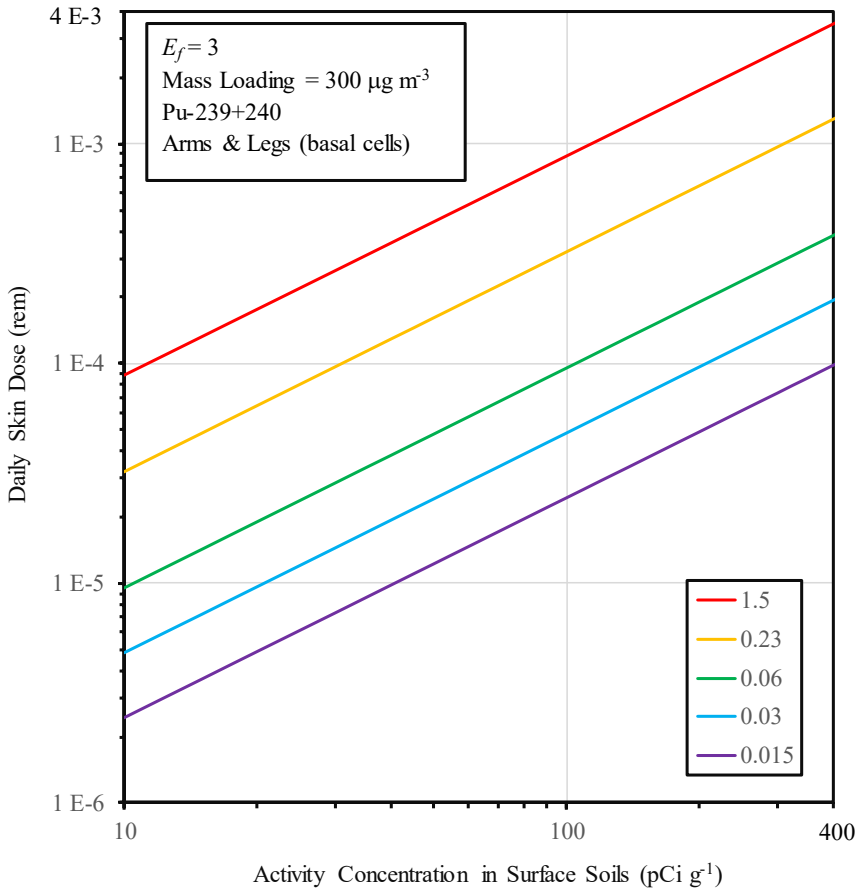


Figure L-14. Single-Day Skin Dose from $^{239+240}$Pu α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors [Basal Cells of Arms and Legs, E_f = 3, Mass Loading 300 µg m^{-3}].

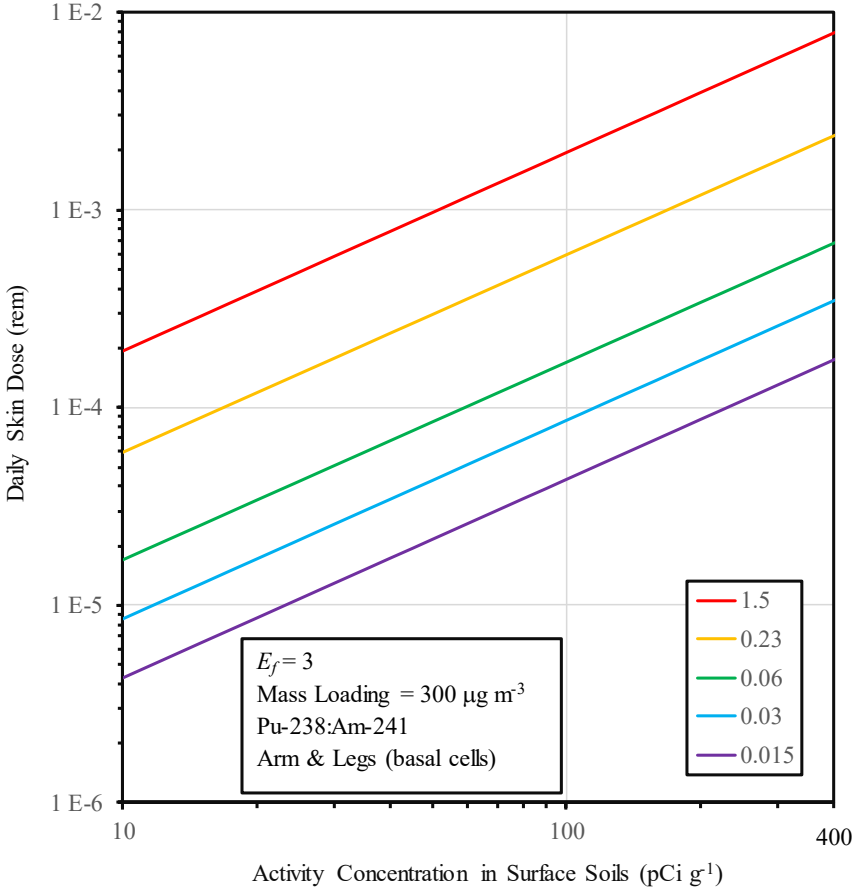


Figure L-15. Single-Day Skin Dose from ^{238}Pu:^{241}Am α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Arms and Legs, E_f = 3, Mass Loading 300 µg m^{-3}].

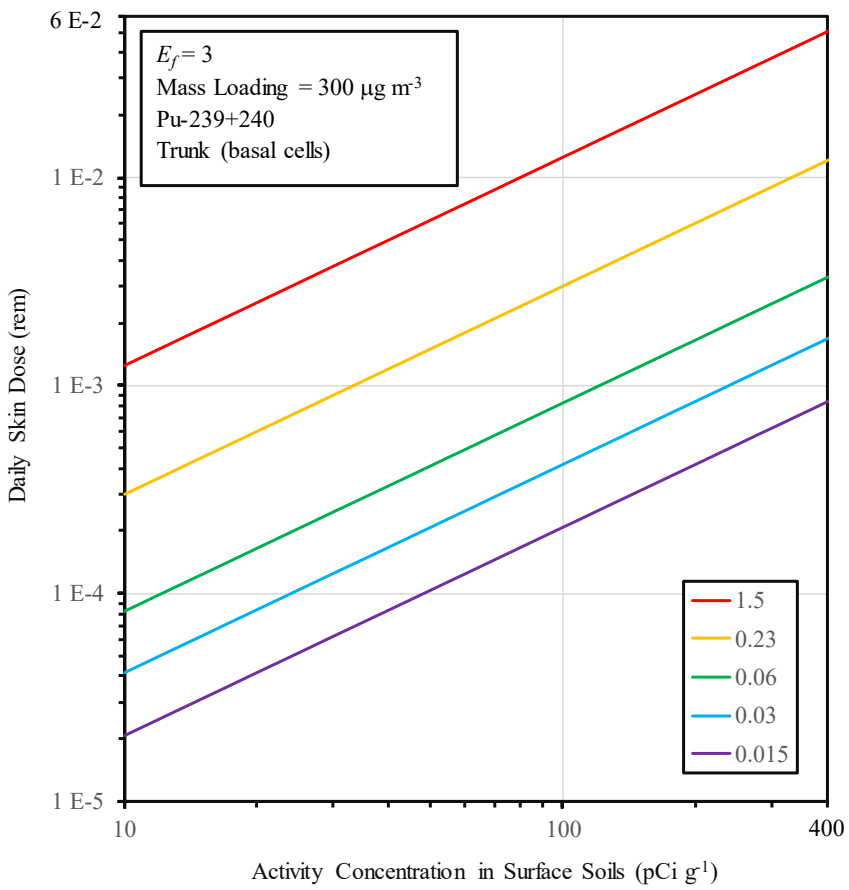


Figure L-16. Single-Day Skin Dose from $^{239+240}$Pu α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors [Basal Cells of Trunk of Body, E_f = 3, Mass Loading 300 µg m^{-3}].

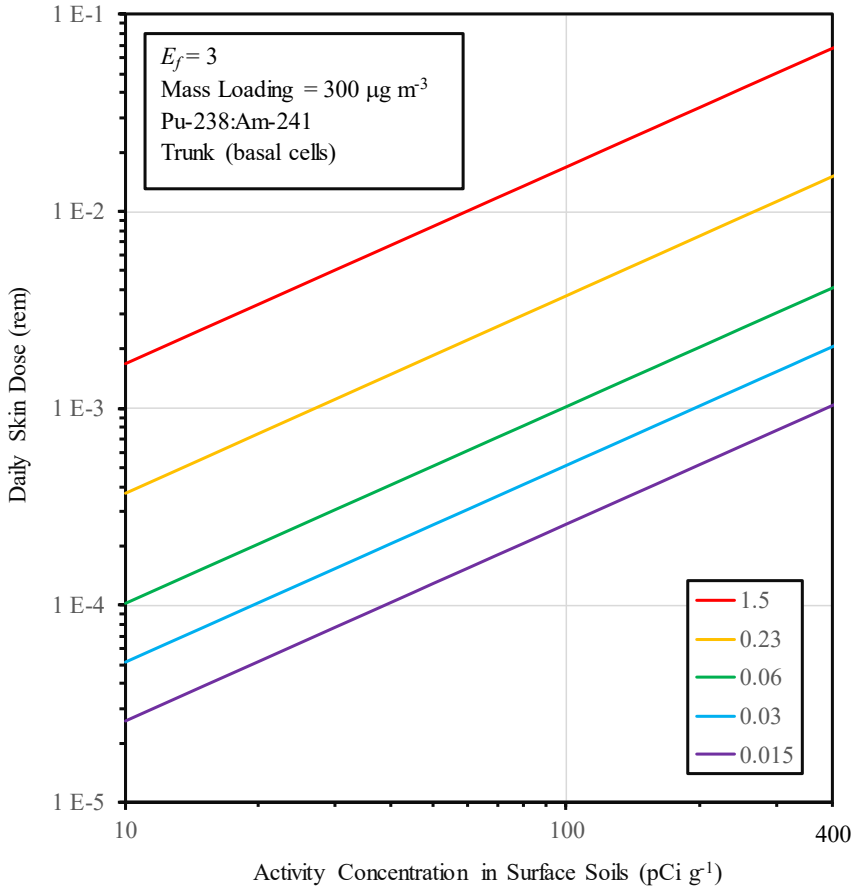


Figure L-17. Single-Day Skin Dose from ^{238}Pu:^{241}Am α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Trunk of Body, E_f = 3, Mass Loading 300 µg m^{-3}].

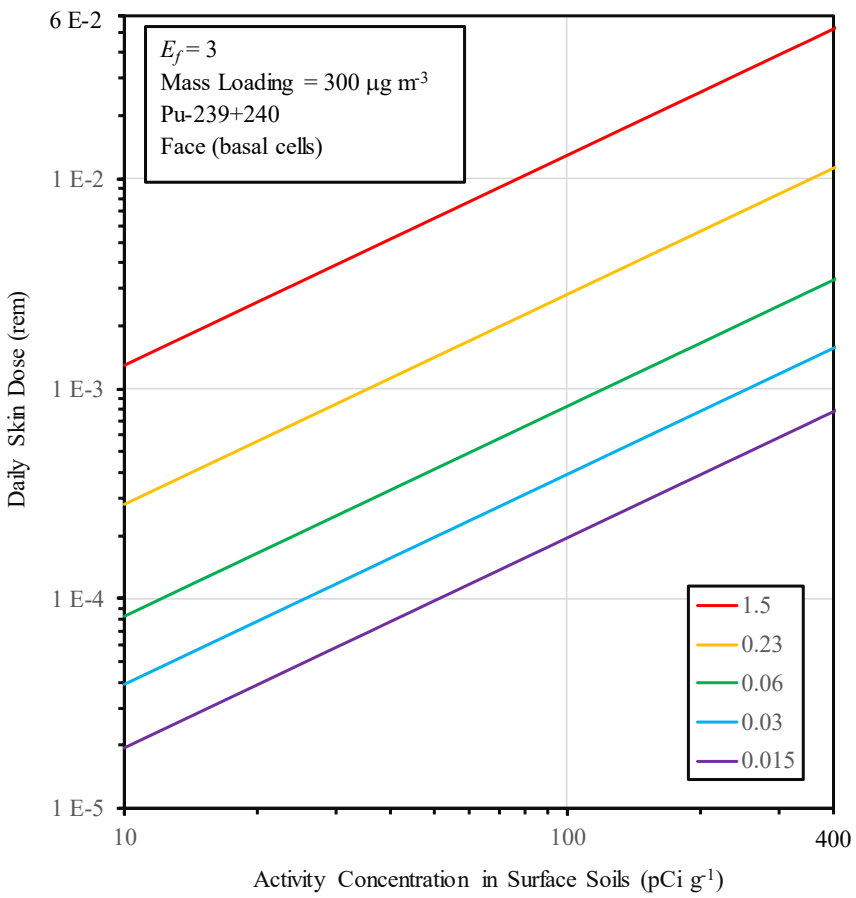


Figure L-18. Single-Day Skin Dose from $^{239+240}$Pu α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors [Basal Cells of Face, E_f = 3, Mass Loading 300 µg m^{-3}].

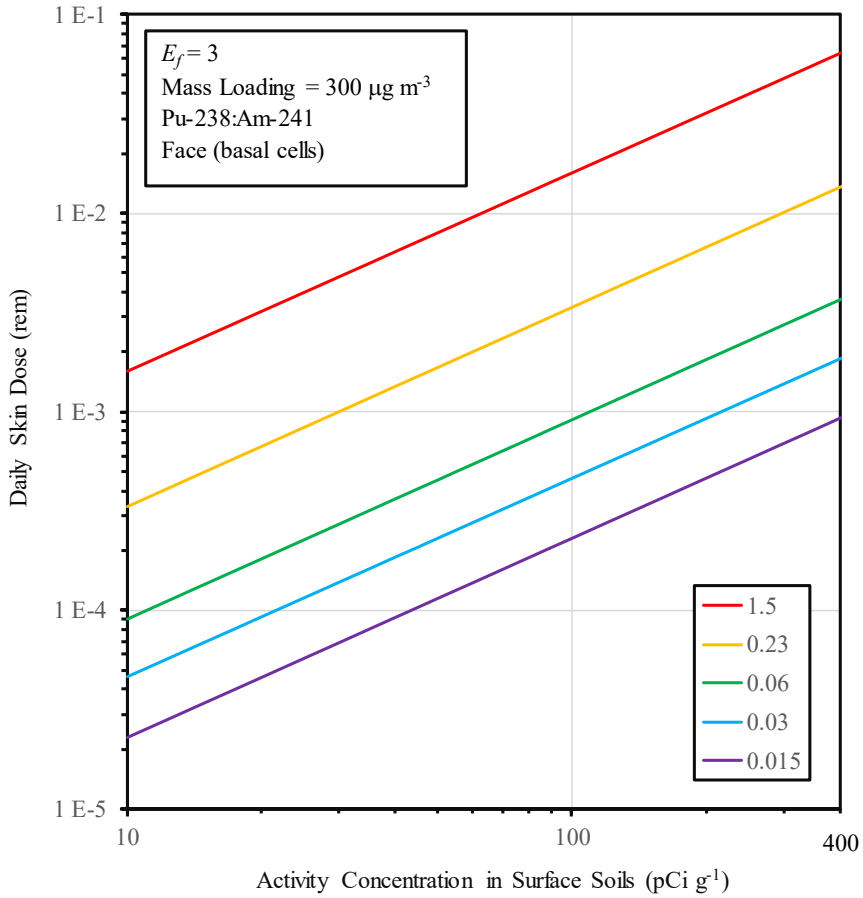


Figure L-19. Single-Day Skin Dose from ^{238}Pu:^{241}Am α-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Face, E_f = 3, Mass Loading 300 µg m^{-3}].

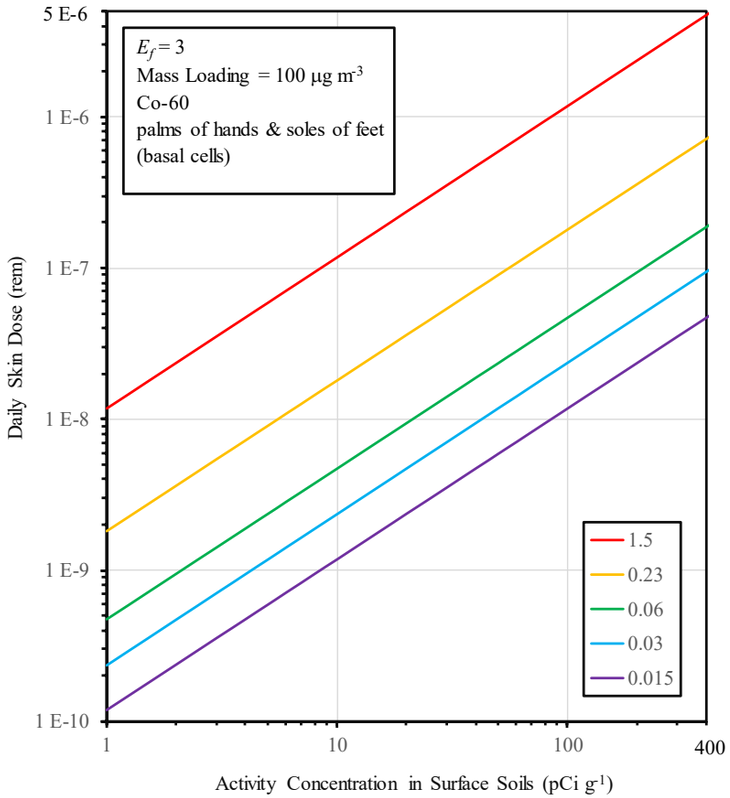


Figure L-20. Single-Day Skin Dose from ^{60}Co β-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors [Basal Cells of Palms of Hands & Soles of Feet, E_f = 3, Mass Loading 100 µg m^{-3}].

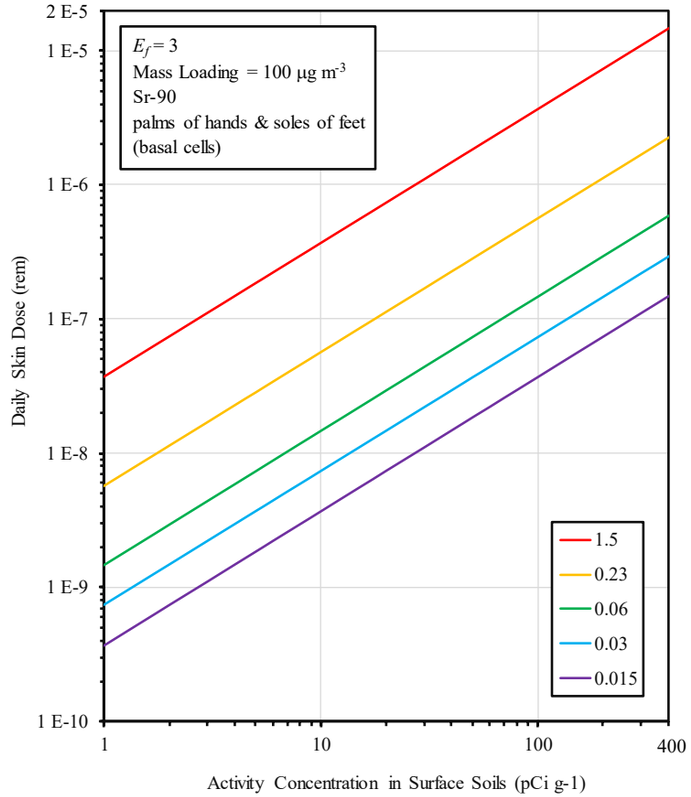


Figure L-21. Single-Day Skin Dose from ^{90}Sr β-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Palms of Hands & Soles of Feet, E_f = 3, Mass Loading 100 µg m^{-3}].

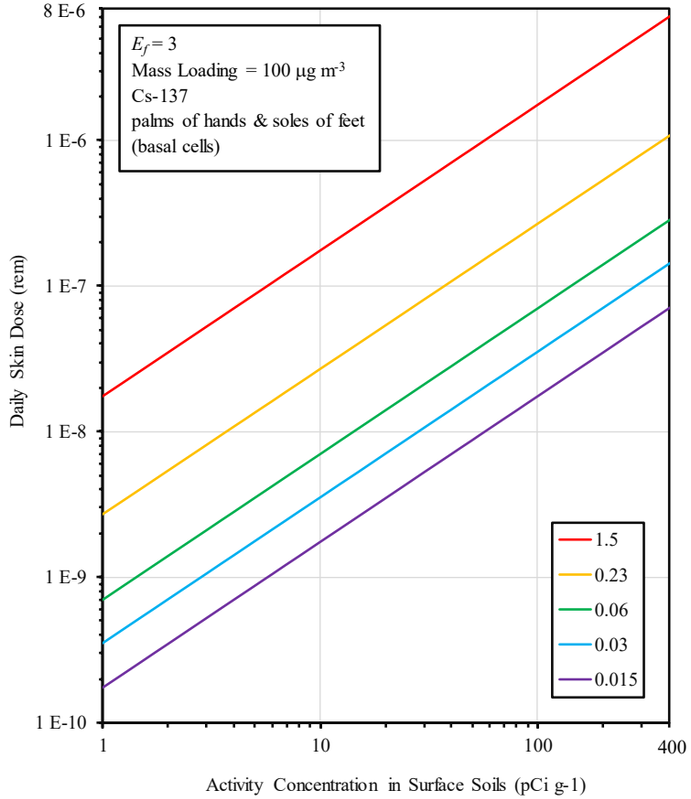


Figure L-22. Single-Day Skin Dose from ^{137}Cs β-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Palms of Hands & Soles of Feet, E_f = 3, Mass Loading 100 µg m^{-3}].

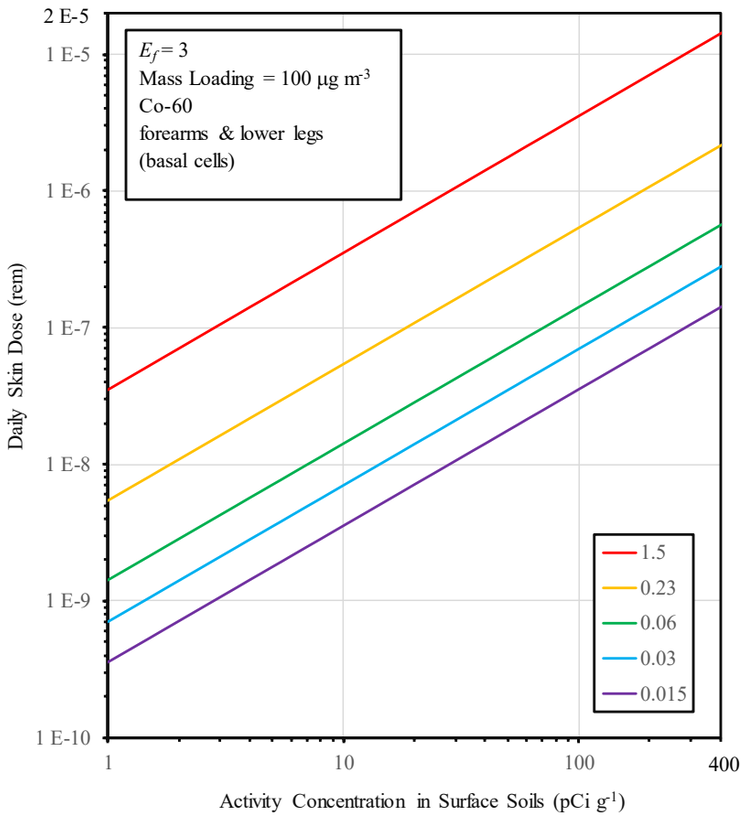


Figure L-23. Single-Day Skin Dose from ^{60}Co β-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors [Basal Cells of Forearms & Lower Legs, E_f = 3, Mass Loading 100 µg m^{-3}].

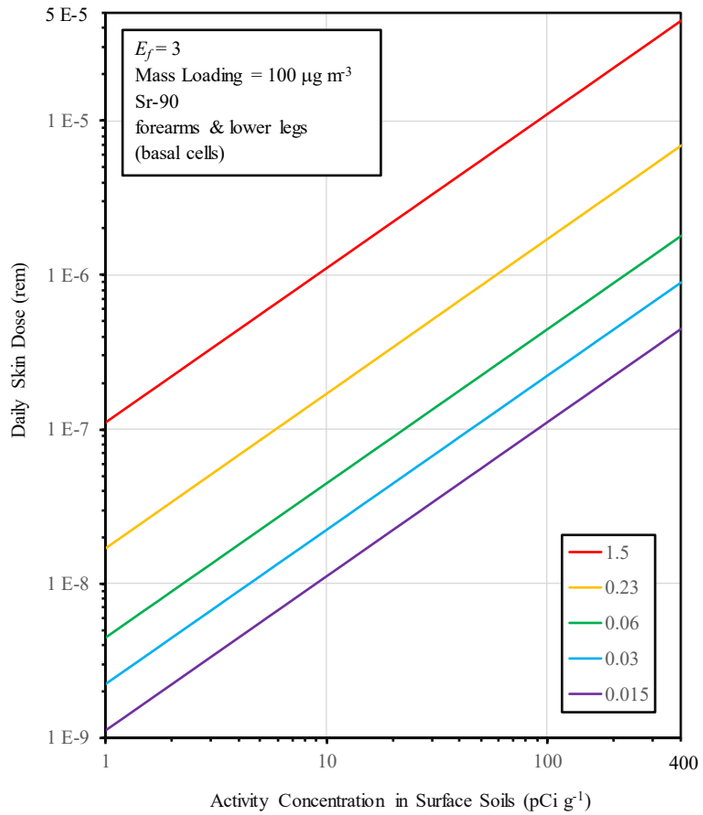


Figure L-24. Single-Day Skin Dose from ^{90}Sr β-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Forearms & Lower Legs, E_f = 3, Mass Loading 100 µg m^{-3}].

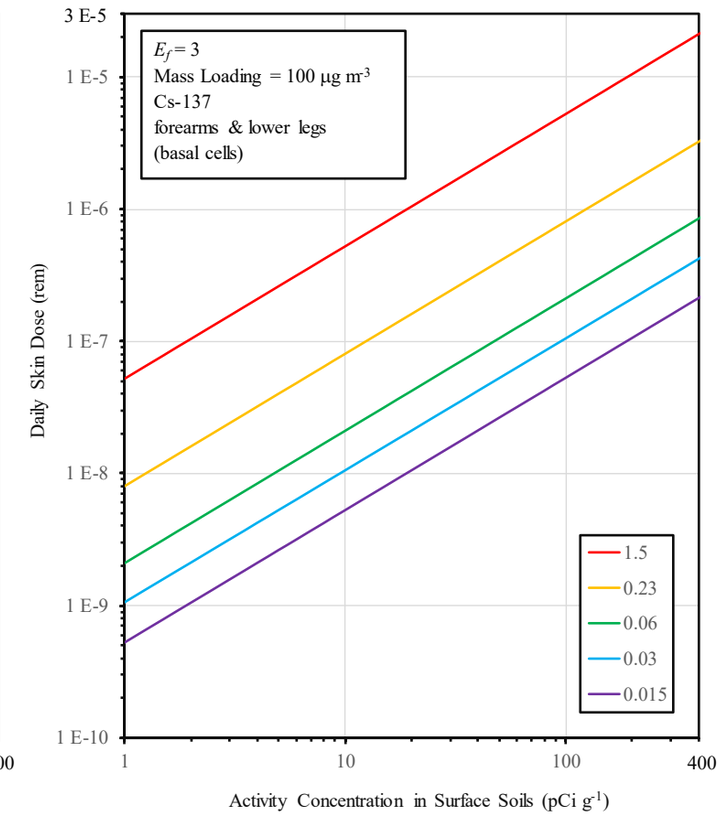


Figure L-25. Single-Day Skin Dose from ^{137}Cs β-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Forearms & Lower Legs, E_f = 3, Mass Loading 100 µg m^{-3}].

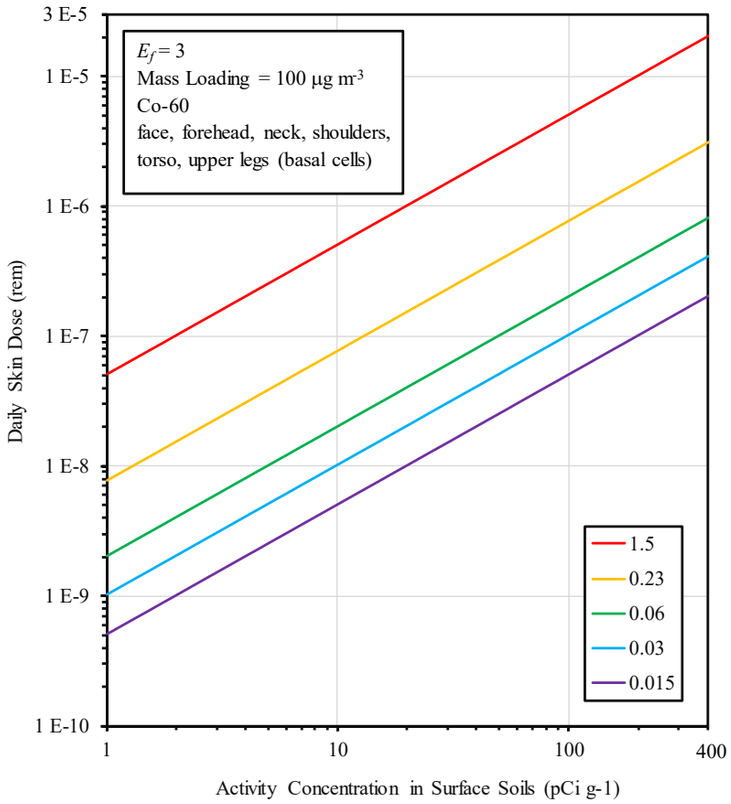


Figure L-26. Single-Day Skin Dose from ^{60}Co β-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors [Basal Cells of Face, Forehead, Neck, Shoulders, Torso, Upper Legs, E_f = 3, Mass Loading 100 µg m^{-3}].

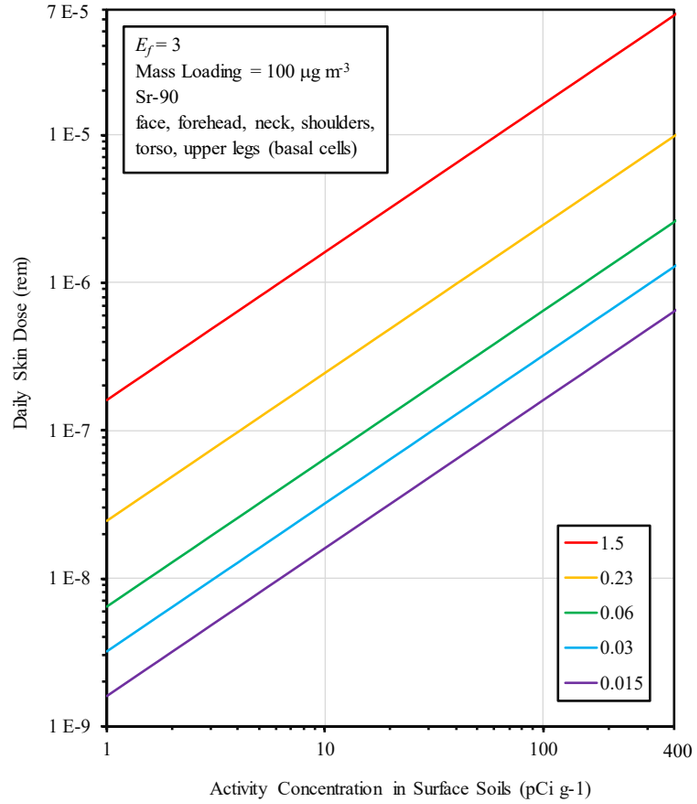


Figure L-27. Single-Day Skin Dose from ^{90}Sr β-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Face, Forehead, Neck, Shoulders, Torso, Upper Legs, E_f = 3, Mass Loading 100 µg m^{-3}].

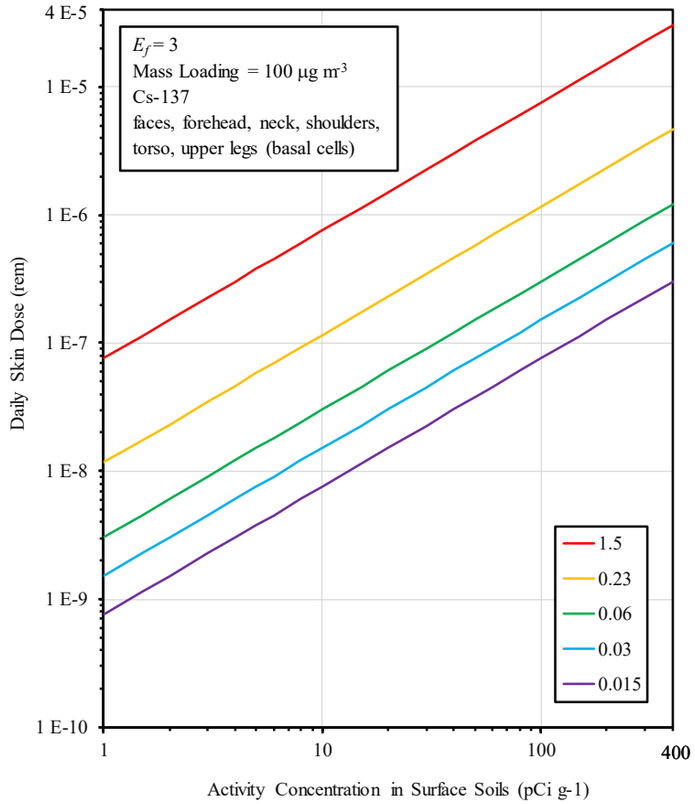


Figure L-28. Single-Day Skin Dose from ^{137}Cs β-Particles, Dermal Contaminant Build-up Over 8-h Work Period, 4-h Delay to Removal for Various Interception and Retention Factors, [Basal Cells of Face, Forehead, Neck, Shoulders, Torso, Upper Legs, E_f = 3, Mass Loading 100 µg m^{-3}].

Table L-2. Example Daily Skin Doses for Various Exposure Scenarios [8-h Contamination Accumulation Period, 4-h Delay Period Prior to Removal].

Island	Skin Tissue	Parameters			Radionuclide Concentration, S_o (pCi g^{-1})					Dose (rem)*					
		E_f	I/R	M (μg m^3)	$^{239+240}$Pu	^{238}Pu+^{241}Am	^{60}Co	^{90}Sr	^{137}Cs	$^{239+240}$Pu	^{238}Pu+^{241}Am	^{60}Co	^{90}Sr	^{137}Cs	Total
Pearl	Chest	3	0.03	600	236.3	159.7	13.2	525	58.1	1.95E-3	1.62E-3	8.1E-8	1.0E-5	5.3E-7	3.6E-3
Pearl	Behind Ear	3	1.5	600	236.3	159.7	13.2	525	58.1	3.98E-2	3.50E-2	4.0E-6	5.0E-4	2.6E-5	7.6E-2
Pearl	Forearm	3	0.06	600	236.3	159.7	13.2	525	58.1	4.29E-4	5.21E-4	1.1E-7	1.4E-5	7.3E-7	9.6E-4
Pearl	Back of Hand	3	0.06	600	236.3	159.7	13.2	525	58.1	0	0	1.1E-7	1.4E-5	7.3E-7	1.5E-5
Yvonne (A)	Scalp	3	0.23	300	37.4	20.0	12.4	59.4	20.1	1.07E-3	6.71E-4	2.9E-7	4.4E-6	7.0E-7	1.8E-3
Yvonne (A)	Scalp	3	0.23	100	37.4	20.0	12.4	59.4	20.1	3.69E-4	2.32E-4	9.7E-8	1.5E-6	2.3E-7	6.0E-4
Yvonne (A)	Face	3	0.015	100	37.4	20.0	12.4	59.4	20.1	2.45E-5	1.54E-5	6.3E-9	9.5E-8	1.5E-8	1.6E-5
Yvonne (A)	Chest	3	0.03	100	37.4	20.0	12.4	59.4	20.1	5.22E-5	3.44E-5	1.3E-8	1.9E-7	3.0E-8	8.7E-5
Yvonne (C)	Chest	3	0.03	300	16.3	8.5	2.7	4.9	1.5	6.79E-5	4.36E-5	8.3E-9	4.7E-8	6.8E-9	1.1E-4
Yvonne (B)	Chest	1	0.03	600	451	134	24.8	37.9	6.3	1.24E-3	4.54E-4	5.1E-8	2.4E-7	1.9E-8	1.7E-3
Yvonne (B)	Chest	3	0.03	100	283	84.1	1.6	23.8	4.0	3.96E-4	1.44E-4	1.6E-9	7.6E-8	6.1E-9	5.4E-4
Belle	Chest (Belt)	3	1.5	100	38.4	14.7	5.2	175	50.3	2.28E-3	1.10E-3	2.7E-7	2.8E-5	3.8E-6	3.4E-3
Belle	Forearm	3	0.06	100	38.4	14.7	5.2	175	50.3	2.20E-5	8.42E-6	7.3E-9	7.7E-7	1.1E-7	3.1E-5
Janet	Face	3	0.015	100	22.9	8.55	1.8	99	33.7	1.50E-5	6.58E-6	9.2E-10	1.6E-7	2.5E-8	2.2E-5
Janet	Chest	3	0.03	100	22.9	8.55	1.8	99	33.7	3.20E-5	1.47E-5	1.8E-9	3.2E-7	5.1E-8	4.7E-5
Janet	Forearm	3	0.06	100	22.9	8.55	1.8	99	33.7	7.44E-6	4.91E-6	2.5E-9	4.4E-7	7.1E-8	1.3E-5
Janet	Chest	3	0.03	600	22.9	8.55	1.8	99	33.7	1.89E-4	8.70E-5	1.1E-8	1.9E-6	3.1E-7	2.8E-4
Vera	Forearm	3	0.06	100	22.9	8.55	1.8	99	33.7	7.44E-6	4.91E-6	2.5E-9	4.4E-7	7.1E-8	1.3E-5
Sally	Face	3	0.015	100	14.8	4.9	0.37	41.3	5.8	9.70E-6	3.77E-6	1.9E-10	6.6E-8	4.4E-9	1.4E-5
Sally	Chest	3	0.03	100	14.8	4.9	0.37	41.3	5.8	2.07E-5	8.42E-6	3.7E-10	1.3E-7	8.8E-9	2.9E-5
Sally	Face	3	0.015	600	161	53	4.0	449	62.9	6.29E-4	2.43E-4	1.2E-8	4.3E-6	2.9E-7	8.8E-4

* Skin doses for individuals working in Segment A of Yvonne had additional contributions from thorium isotopes

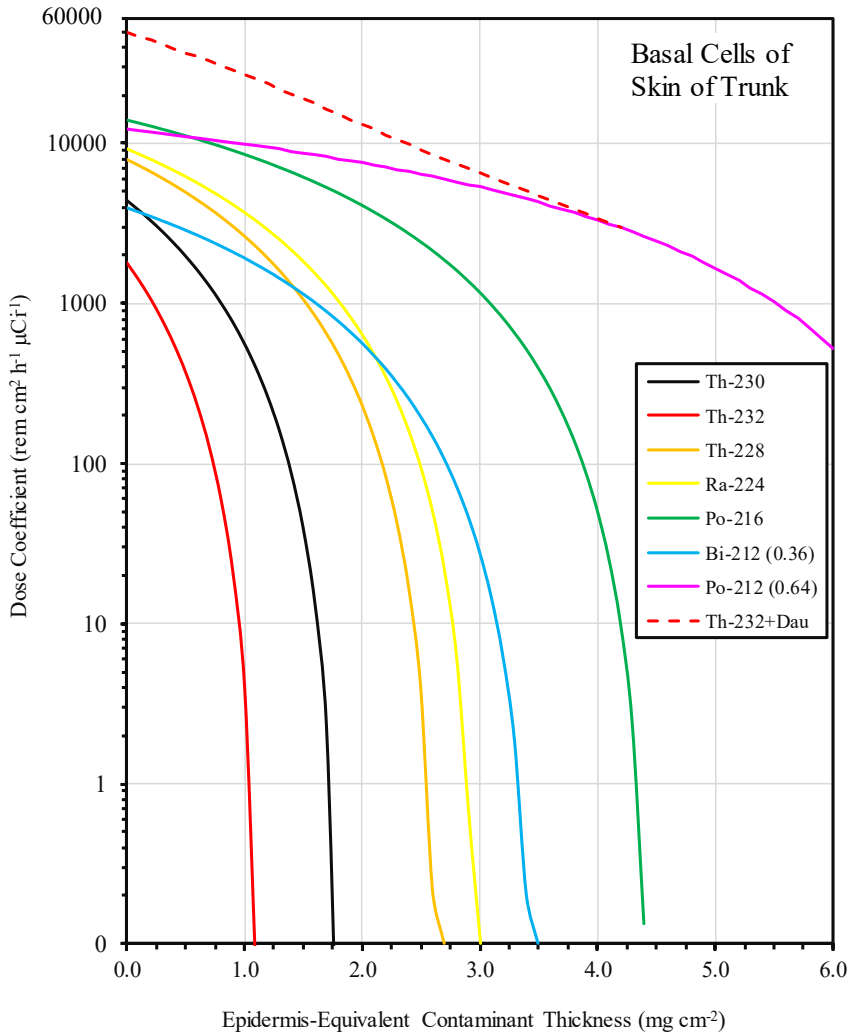


Figure L-29. Dose Coefficient Curves for Varied Density Thicknesses of α-Particle Emitting Contamination Deposited and Retained on Skin Surfaces, Modified from Method of Eatough (1997) for ^{230}Th and ^{232}Th and Decay Chain Daughters for Basal Cells of Skin of Trunk.

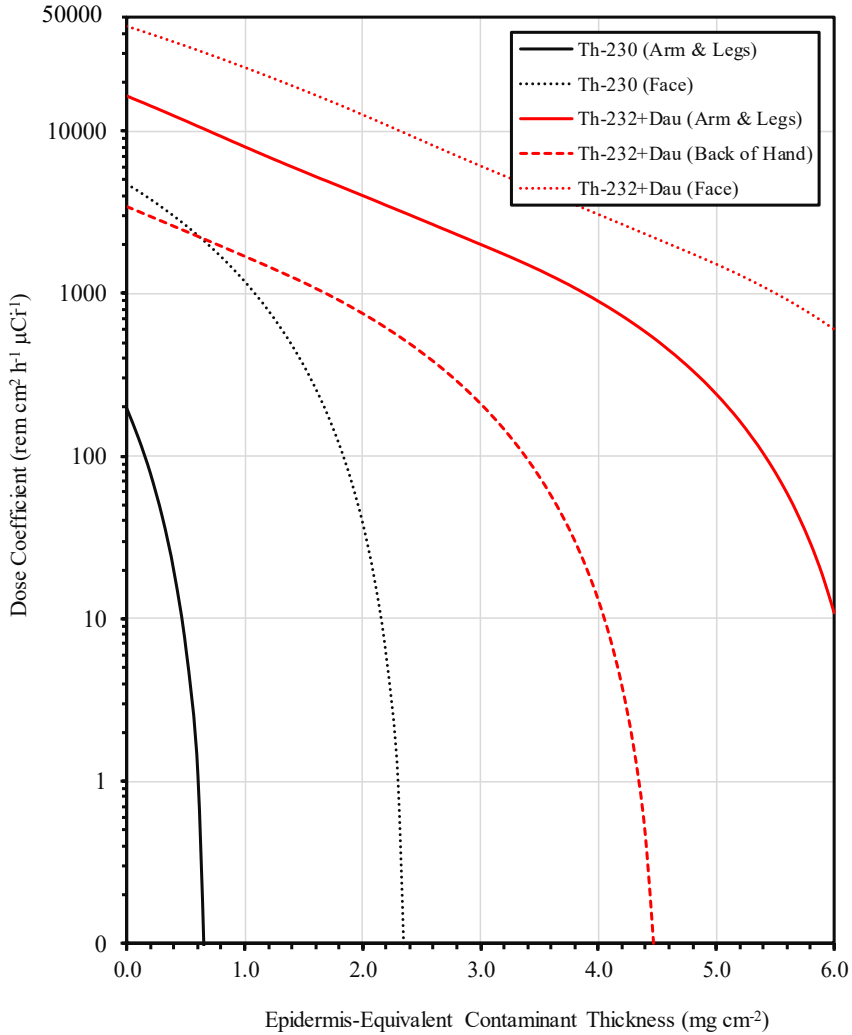


Figure L-30. Dose Coefficient Curves for Varied Density Thicknesses of α-Particle Emitting Contamination Deposited and Retained on Skin Surfaces, Modified from Method of Eatough (1997) for ^{230}Th and ^{232}Th and Decay Chain Daughters for Basal Cells of Skin of Arm & Leg, Back of Hand, and Face.

Table L-3. Single Day Skin Dose Values (rem) from Deposition and Retention of ^{230}Th and ^{232}Th and Decay Chain Daughters on Skin for Segments A and A/B of Yvonne (Scaled to 80% and 40% Percentiles $^{239+240}$Pu from Tables J-2 and J-3), E_f = 3, M = 300 μg m^{-3}).

		Segment A (80%)		Segment A/B (80%)		Segment A (40%)		Segment A/B (40%)	
		Activity Concentration (pCi/g)		Activity Concentration (pCi/g)		Activity Concentration (pCi/g)		Activity Concentration (pCi/g)	
	I/R	40	4.0	5.7	0.57	9.58	0.958	2.25	0.225
		Th-230	Th-232+Dau	Th-230	Th-232+Dau	Th-230	Th-232+Dau	Th-230	Th-232+Dau
Face	1.5	3.37E-03	4.11E-03	4.81E-04	5.82E-04	8.08E-04	9.85E-04	1.90E-04	2.31E-04
	0.23	8.20E-04	7.93E-04	1.17E-04	1.12E-04	1.96E-04	1.90E-04	4.61E-05	4.46E-05
	0.06	2.28E-04	2.14E-04	3.24E-05	3.02E-05	5.45E-05	5.12E-05	1.28E-05	1.20E-05
	0.03	1.15E-04	1.07E-04	1.64E-05	1.52E-05	2.75E-05	2.57E-05	6.46E-06	6.04E-06
	0.015	5.76E-05	5.38E-05	8.21E-06	7.61E-06	1.38E-05	1.29E-05	3.24E-06	3.03E-06
Trunk	1.5	2.70E-03	4.58E-03	3.85E-04	6.48E-04	6.48E-04	1.10E-03	1.52E-04	2.58E-04
	0.23	7.56E-04	8.92E-04	1.08E-04	1.26E-04	1.81E-04	2.14E-04	4.25E-05	5.02E-05
	0.06	2.14E-03	2.41E-04	3.04E-04	3.40E-05	5.12E-04	5.76E-05	1.20E-04	1.35E-05
	0.03	1.08E-04	1.21E-04	1.54E-05	1.71E-05	2.60E-05	2.90E-05	6.10E-06	6.80E-06
	0.015	5.44E-05	6.06E-05	7.75E-06	8.58E-06	1.30E-05	1.45E-05	3.06E-06	3.41E-06
Arm & Legs	1.5	4.36E-05	1.45E-03	6.21E-06	2.05E-04	1.04E-05	3.47E-04	2.45E-06	8.14E-05
	0.23	2.74E-05	2.94E-04	3.90E-06	4.16E-05	6.56E-06	7.04E-05	1.54E-06	1.65E-05
	0.06	9.00E-06	7.97E-05	1.28E-06	1.13E-05	2.16E-06	1.91E-05	5.06E-07	4.48E-06
	0.03	4.68E-06	4.01E-05	6.67E-07	5.68E-06	1.12E-06	9.61E-06	2.63E-07	2.26E-06
	0.015	2.38E-06	2.01E-05	3.40E-07	2.85E-06	5.71E-07	4.82E-06	1.34E-07	1.13E-06
Back of Hand	1.5	0.00E+00	3.02E-04	0.00E+00	4.28E-05	0.00E+00	7.24E-05	0.00E+00	1.70E-05
	0.23	0.00E+00	6.09E-05	0.00E+00	8.62E-06	0.00E+00	1.46E-05	0.00E+00	3.43E-06
	0.06	0.00E+00	1.66E-05	0.00E+00	2.35E-06	0.00E+00	3.97E-06	0.00E+00	9.32E-07
	0.03	0.00E+00	8.35E-06	0.00E+00	1.18E-06	0.00E+00	2.00E-06	0.00E+00	4.70E-07
	0.015	0.00E+00	4.18E-06	0.00E+00	5.92E-07	0.00E+00	1.00E-06	0.00E+00	2.35E-07

Table L-4. Single Day Skin Dose Values (rem) from Deposition and Retention of ^{230}Th and ^{232}Th and Decay Chain Daughters on Skin for Segments A and A/B of Yvonne (Scaled to 80% and 40% Percentiles $^{239+240}$Pu from Tables J-2 and J-3), E_f = 3, M = 100 μg m^{-3})

		Segment A (80%)		Segment A/B (80%)		Segment A (40%)		Segment A/B (40%)	
		Activity Concentration (pCi/g)		Activity Concentration (pCi/g)		Activity Concentration (pCi/g)		Activity Concentration (pCi/g)	
	I/R	40	4.0	5.7	0.57	9.58	0.958	2.25	0.225
		Th-230	Th-232+Dau	Th-230	Th-232+Dau	Th-230	Th-232+Dau	Th-230	Th-232+Dau
Face	1.5	1.62E-03	1.65E-03	2.31E-04	2.33E-04	3.88E-04	3.94E-04	9.11E-05	9.25E-05
	0.23	3.09E-04	2.72E-04	4.40E-05	3.85E-05	7.40E-05	6.51E-05	1.74E-05	1.53E-05
	0.06	7.68E-05	7.17E-05	1.09E-05	1.01E-05	1.84E-05	1.72E-05	4.32E-06	4.03E-06
	0.03	3.86E-05	3.59E-05	5.50E-06	5.08E-06	9.24E-06	8.60E-06	2.17E-06	2.02E-06
	0.015	1.93E-05	1.80E-05	2.75E-06	2.55E-06	4.63E-06	4.31E-06	1.09E-06	1.01E-06
Trunk	1.5	1.45E-03	1.84E-03	2.07E-04	2.61E-04	3.48E-04	4.41E-04	8.17E-05	1.04E-04
	0.23	2.71E-04	3.06E-04	3.86E-05	4.33E-05	6.49E-05	7.34E-05	1.52E-05	1.72E-05
	0.06	7.24E-05	8.08E-05	1.03E-05	1.14E-05	1.73E-05	1.94E-05	4.07E-06	4.55E-06
	0.03	3.64E-05	4.05E-05	5.19E-06	5.73E-06	8.72E-06	9.69E-06	2.05E-06	2.28E-06
	0.015	1.82E-05	2.02E-05	2.60E-06	2.87E-06	4.37E-06	4.85E-06	1.03E-06	1.14E-06
Arm & Legs	1.5	4.16E-05	6.00E-04	5.93E-06	8.49E-05	9.96E-06	1.44E-04	2.34E-06	3.38E-05
	0.23	1.12E-05	1.01E-04	1.60E-06	1.44E-05	2.69E-06	2.43E-05	6.32E-07	5.71E-06
	0.06	3.16E-06	2.68E-05	4.50E-07	3.79E-06	7.57E-07	6.42E-06	1.78E-07	1.51E-06
	0.03	1.60E-06	1.34E-05	2.28E-07	1.90E-06	3.83E-07	3.21E-06	9.00E-08	7.55E-07
	0.015	8.04E-07	6.72E-06	1.15E-07	9.51E-07	1.93E-07	1.61E-06	4.52E-08	3.78E-07
Back of Hand	1.5	0.00E+00	1.23E-04	0.00E+00	1.74E-05	0.00E+00	2.94E-05	0.00E+00	6.91E-06
	0.23	0.00E+00	2.11E-05	0.00E+00	2.98E-06	0.00E+00	5.05E-06	0.00E+00	1.19E-06
	0.06	0.00E+00	5.57E-06	0.00E+00	7.88E-07	0.00E+00	1.33E-06	0.00E+00	3.13E-07
	0.03	0.00E+00	2.79E-06	0.00E+00	3.95E-07	0.00E+00	6.69E-07	0.00E+00	1.57E-07
	0.015	0.00E+00	1.40E-06	0.00E+00	1.98E-07	0.00E+00	3.35E-07	0.00E+00	7.87E-08