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Plutonium Exposures to Personnel Assigned to Johnston Atoll

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14. ABSTRACT
Johnston Atoll supported U.S. atmospheric nuclear weapons testing under Operations Hardtack I and Dominic I. The most significant incident occurring during these Operations impacting the Atoll was Thor missile launch mishap of Bluegill Prime (25 July 1962) under Dominic I. The mishap involved the dispersal of weapons grade plutonium, which was largely mitigated shortly after the accident. The persistence of low-level residuals created exposure potential for individuals working in the Thor missile launch emplacement and other areas on the Island. The purpose of this report is to document potential dose from these exposures. Estimated doses were low and not expected to be a health hazard to individuals.

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Executive Summary

Johnston Atoll supported U.S. atmospheric nuclear weapons testing under Operations Hardtack I and Dominic I. The most significant incidents occurring during these Operations impacting the Atoll were three Thor missile launch mishaps under Dominic I: Starfish (19 June 1962), Bluegill Prime (25 July 1962), and Bluegill Double Prime (15 Oct 62). The most important of these mishaps was Bluegill Prime, responsible for dispersal of weapons grade plutonium (WGP), highly-enriched uranium (HEU), and depleted uranium (DU) on the Thor LE-1 pad and vicinity, due to a low-order detonation and fire to the nuclear warhead on the pad. The Starfish mishap, while involving a high-altitude conventional detonation of the nuclear warhead, did have impact of the same radiological contaminants to the Atoll, but to a significantly lesser degree. The vast majority of the plutonium deposited on land within the vicinity of the LE-1 pad was remediated shortly after the Bluegill Prime mishap during the Dominic I. There is neither environmental evidence nor an expectation that the Atoll would have been impacted by local fission and activation product impacts from the nuclear weapon detonations that were supported by missile launches from the Atoll or bomb drops in the vicinity of the Atoll.

Ionizing radiation exposures related to atmospheric testing had the potential for health effects on military veterans and other personnel supporting the atmospheric nuclear weapon testing program. While some acute radiogenic effects may have occurred, i.e., skin burns, from fallout, the most significant concern for individuals supporting the tests is the risk for delayed induction of cancer. The VA has a number of radiogenic cancers that are presumptively compensated if the veteran has one of these cancer types and was an on-site participant. While many individuals supporting atmospheric testing were primarily exposed to external radiation sources, the most important exposure potential to individuals on Johnston Atoll during Dominic I was due to resuspended WGP within the Thor launch area. Key cancers attributed to high-level, internal plutonium exposure are to the lung, bone, and liver, based on extensive animal exposure studies and human epidemiological studies. All three of these organs are on the VA list of presumptive radiogenic cancers (38 CFR §3.309d).

While the vast majority of the WGP deposited in the vicinity of LE-1 was remediated during Operation Dominic I, some low-level residuals remained. Significant radiological monitoring was accomplished during the initial remedial action and continued for decades until the Atoll no longer supported military operations in 2004. As well, a number of significant remedial actions were accomplished on WGP contamination after Operation Dominic I until 2002, when the pile of higher-levels of WGP was buried on Johnston Island. This report documents radiological sampling and surveys accomplished on Johnston Atoll from the Bluegill Prime mishap through the mid-1990s. The data generated demonstrated that potential radiological exposures to individuals from residual contamination were very low compared to U.S. and internationally-accepted standards that existed at the time of the mishaps and current ones. Though standards for internal plutonium exposures have evolved over many decades, current standards are very similar in acceptable plutonium exposure levels that existed at the time of the 1962 mishaps.

Veterans present on the Atoll after Operation Dominic I, 30 June 1963, are not covered under 38 CFR §3.309d for presumptive radiogenic cancers. These exposures are evaluated under the provisions of 38 CFR §3.311b, where the VA calculates a probability of causation (PC) for individual cancer types and a radiation exposure estimate. For example exposure scenarios evaluated in this report, favorable PC values for key plutonium-related cancers are not apparent based on the magnitude of screening level doses listed in this report. The exposure scenarios were

evaluated under highly conservative assumptions. Exposures to individuals assigned to Johnston Atoll would have been much lower. The screening levels were provided in this report for informational purposes. The adjudication of health claims and calculation of PC values for individual claims are within the scope of the VA. The DoD's primary role is the assessment of veteran radiation exposure potential, following the approach in 32 CFR 218. Part 218 is specific to the determination and reporting of nuclear radiation dose for DoD participants in the atmospheric nuclear test program (1945 – 1962), though the concepts and approaches are reasonably applied to radiogenic health effects claims that are covered under 38 CFR §3.311b and also not part of the Nuclear Test Personnel Review (NTPR).

While this report is primarily focused on veteran exposures, the activities during Operations Hardtack I and Dominic I, and post-testing missions accomplished on the Atoll had the support of civilian employees. Some of the employees were Government, while others contract employees. Data provided in the report would be useful in assessments of possible claims among these groups of employees.

Due to the unique deposition and retention of plutonium in the body from internal exposures, this report contains a detailed summary of health effects, based on animal exposure studies and epidemiological studies of workers exposed to plutonium.

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List of Acronyms and Abbreviations

α	alpha
AB	Air Base
ADC	Aerospace Defense Command
ADS	Aerospace Defense Squadron
AEC	Atomic Energy Commission
AF	Air Force
AFB	Air Force Base
AFIERA	AF Institute for Environment, Safety and Occupational Health Risk Analysis
ALARA	as low as is reasonably achievable
ALI	annual limit of intake
ALL	acute lymphocytic leukemia
AMAD	activity median aerodynamic diameter
AML	acute myelocytic leukemia
AO	Agent Orange
ASAT	anti-satellite
β	beta
BOMARC	Boeing Michigan Aeronautical Research Center
Bq	Becquerel, Système International unit of radioactivity, one disintegration per second
^{o}C	degrees Celsius
CED	committed equivalent dose
CEDE	committed effective dose equivalent
CFR	Code of Federal Regulation
Ci	Curie, Traditional unit or radioactivity, 3.7×10^{10} disintegrations per second

CLL	chronic lymphocytic leukemia
d	day
DAC	derived air concentration
DASA	Defense Atomic Support Agency
DC	dose coefficient
DCT	disaster control team
DNA	Defense Nuclear Agency
DoD	Department of Defense
DOE	Department of Energy
DOL	Department of Labor
DRMIA	Dosimetry Registry of the Mayak Industrial Association
DTRA	Defense Threat Reduction Agency
DTRIAC	Defense Threat Reduction Information Analysis Center
DU	depleted uranium
EG&G	Edgerton, Germeshausen & Grier
E	effective dose
ECP	entry control point
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
EPA	Environmental Protection Agency
ERDA	Energy Research Development Administration
ET	extra-thoracic
f_1	gastro-intestinal tract uptake factor
fCi	femptoCurie, one-quadrillionth of a Curie, 3.7×10^{-5} disintegrations per second
FIDLER	field instrument for the detection of low energy radiation
γ	gamma

GI	gastro-intestinal
H	hour
ha	hectare, unit of area, 10,000 m^2
HE	high explosives
HEU	highly-enriched uranium
kcpm	kilo counts per minute
kg	kilogram
kt	kiloton
IARC	International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiological Units
IRBM	intermediate range ballistic missile
JACADS	Johnston Island Chemical Agent Disposal System
JTF	Joint Task Force
keV	kiloelectron Volts
km	kilometer, 1,000 meters
LALN	lung-associated lymph nodes
LANL	Los Alamos National Laboratory
LE	launch emplacement
LE-1	first Thor launch emplacement
LE-2	second Thor launch emplacement
LLNL	Lawrence Livermore National Laboratory
LN(ET)	Extrathoracic lymph nodes
LN(TH)	Thoracic lymph nodes
MATS	Military Air Transport Service

mCi	milliCurie, 1/100th of a Curie, 3.7 x 10^{7} disintegrations per second
μCi	microCurie, one-millionth of a Curie, 3.7 x 10^{4} disintegrations per second
μμCi	micro-microCurie, historical term used in AEC, equivalent to a pCi
MDC	minimal detectable concentration
MED	Manhattan Engineering District
MeV	megaelectron Volts
mg	milligram, 1,000th of a gram
MMAD	mass median aerodynamic activity
MPBB	maximum permissible body burden
MPC	maximum permissible concentration
MPOB	maximum permissible organ burden
Mt	megaton
NCI	National Cancer Institute
NAS	National Academy of Sciences
NaI(Tl)	thallium-activated sodium iodide
NBS	National Bureau of Standards
nCi	nanoCurie, one-billionth of a Curie, 37 disintegrations per second
NCRP	National Committee on Radiation Protection and Measurements
NIH	National Institute of Health
nmi	nautical miles
NRDC	National Research Defense Council
NPG	Nevada Proving Grounds
NRC	Nuclear Regulatory Commission
NTPR	Nuclear Test Personnel Review
OEHL	Occupational, Environmental Health Laboratory

PAC	portable alpha counter
PC	Probability of Causation
pCi	picoCurie, one-trillionth of a Curie, 0.037 disintegrations per second
PHS	Public Health Service
PPE	personal protective equipment
PPG	Pacific Proving Grounds
PPE	personal protective equipment
RCA	radiation control area
RECA	Radiation Exposure Compensation Act
REF	radiation effectiveness factor
ResRad	Residual Radiation
RHL	Radiological Health Laboratory
RBE	relative biological effectiveness
RTGs	radioisotopic thermal generators
S&I	storage and inspection
SEE	specific effective energy
SEI	secondary electron imaging
SGS	segmented gate system
TDY	temporary duty
TLD	thermo-luminescent dosimetry
UK	United Kingdom
UNLV	University of Nevada, Las Vegas
US	United States
USAF	US Air Force
USTUR	U.S. Transuranium and Uranium Registries

USN	US Navy
USSR	Union of Soviet Socialist Republic
VA	Department of Veterans Affairs
WGP	weapons grade plutonium
WWII	World War II
y	year

Plutonium Exposures to Personnel Assigned to Johnston Atoll

1.0 Introduction

1.1 Disability Compensation for US Veterans.

The United States, beginning with a Continental Congress resolution on August 26, 1776, provided payments for veterans with disabilities associated with their military service (CRS 2010). Benefits to veterans and surviving family members have changed over time based on legislation created by Congress. Historically, these claims have been largely based on physical trauma from combat, including loss of life. Within the last few decades, a larger proportion of claims are based on diseases or illnesses incurred by a veteran. In general, the burden of proof was placed on the veteran, which commonly could be met by documentation contained in their service records that would have a record of diagnosis and treatment for specific injuries or diseases. For some diseases, the condition may not become manifest within the time of the veteran's service, where a causal link between the veteran's service and a condition may not be readily apparent, and the burden of establishing a connection is challenging (CRS 2010). This is especially pertinent to ionizing radiation exposure, where the primary concern is risk of delayed induction cancer. In 1921, Congress for the first time established a presumption of service connection of tuberculosis and neuropsychiatric disease occurring within two years of separation from active duty (CRS 2010). Since that time, presumptive disease and condition connections to service expanded considerably to include tropical diseases and others. In the 1980's, expansion included presumptive compensation for exposures to Agent Orange and ionizing radiation.

1.2 Disability Compensation for Veteran's Exposed to Ionizing Radiation.

The seminal event in radiogenic disease compensation occurred in 1977 when the Veterans Administration (VA) Office in Boise, ID, denied a claim by retired Army Sergeant Paul R. Cooper for service connection of his condition of acute myelocytic leukemia (AML) to radiation exposures he may have received in 1957. Sergeant Cooper participated in Shot Smoky of Operation Plumbbob, an atmospheric nuclear weapon test conducted at the Nevada Test Site (DTRA 2014). The VA decision led to a series of events that ultimately involved the DoD, Department of Energy (DOE), the National Academy of Sciences (NAS), the Department of Health and Human Services, and the White House (DTRA 2014). DoD established the Nuclear Test Personnel Review (NTPR) program in 1978 with an initial task of evaluating exposures from veterans participating in atmospheric testing of nuclear weapons, the majority of which was conducted at the Nevada Proving Grounds (NPG), and the Pacific Proving Grounds (PPG) in the vicinity of Bikini and Eniwetok Atolls.

In 1981, the VA began offering medical care to atmospheric nuclear test participants and veterans that were part of the occupation forces in Hiroshima and Nagasaki (Public Law 1981). In 1982, the Public Health Service (PHS) was tasked with developing radioepidemiological tables for probability of causation (PC) for cancer from radiation exposure (Public Law 1983). In 1984, Congress enacted the Veterans' Dioxin and Radiation Exposure Compensation Act that established standards for compensation of veterans exposed to ionizing radiation from atmospheric nuclear testing and the occupation of Hiroshima and Nagasaki (Public Law 1984). The law also established an advisory committee on environmental matters, and for the NTPR program, it established guidelines for dose reporting. In 1988, Congress provided veteran's with presumptive service connection for a number of

cancers to on-site participation in atmospheric nuclear weapon testing and the occupation of Hiroshima and Nagasaki (Public Law 1988). This alleviated dose assessment burdens and subsequent PC assessments for specific cancers. Over the years, the listing of presumptively covered medical conditions has been expanded, as listed in the Table A-1. In addition, presumptively-compensated exposure conditions have been expanded. Prisoners of war in Japan that received exposures similar to those for Hiroshima and Nagasaki occupation forces are included. Veterans assigned for duties at gaseous diffusion plants under the management of the Atomic Energy Commission (AEC), Energy Research and Development Administration (ERDA), or the DOE are included under specific conditions. Veterans that participated in underground nuclear tests at Amchitka Island, AK, prior to 1 January 1974 are covered under the presumptively connected group of medical conditions. In addition to on-site participation during testing, individuals that were present at a test site up to a six month period of time after the completion of a test series were covered. Unique coverage was also included for personnel garrisoned on Eniwetok Atoll specified periods of time, and Naval shipyard workers that decontaminated ships which had been part of Operation Crossroads tests. Operations Hardtack I and Dominic I involved Johnston Island. The period of testing for Hardtack I was between 28 April and 31 October 1958 (CFR 2013), with the six month period after the test extending to 30 April 1959. The period of testing for Dominic I was between 25 April and 31 December 1962 (CFR 2013), with the six month period after the test extending to 30 June 1963.

1.3 Disability Compensation for Veteran's Exposed to Ionizing Radiation on Johnston Island.

The atmospheric nuclear weapon tests conducted from Johnston Island were somewhat unique compared to tests conducted by the US in other parts of the Pacific in that a number of the nuclear detonations occurred at high altitude, as launched by missiles from Johnston Island. Two nuclear warhead launch tests were aborted and resulted in radioactive material contamination to Johnston Island. The launch of a third was aborted, but did not appear to contaminate the Island to a measureable degree. The most important radioactive material released was weapons grade plutonium (WGP). While the Bikini and Eniwetok Atolls were contaminated with fission products from nuclear tests, Johnston Island was not contaminated with fission products, as all nuclear tests based from the Atoll occurred at considerable distances. As a consequence, radiation exposure potential for individuals that were assigned to Johnston Atoll during and after atmospheric testing was based predominantly on intakes of radioactive materials through inhalation and ingestion, with a negligible external radiation component. In contrast, the exposure to individuals on Bikini and Eniwetok Atolls had internal and external radiation exposure components. Expedited doses may include external exposure for claims managed under the NTPR.

Veterans with on-site participation at Johnston Atoll during either the Hardtack I tests conducted in 1958 and Dominic I tests conducted in 1962 are eligible for presumptive compensation for diseases listed in 38 Code of Federal Regulations (CFR), Part 3.309(d), and listed in Appendix A. As noted above, on-site presence of a veteran up to six months after the operational period of each test series is also included in presumptive compensation. Almost exclusively, veteran claims for ionizing radiation exposure under 38 CFR 3.309 are evaluated by Defense Threat Reduction Agency/NTPR to establish participation. Civilian onsite participants are eligible for compensation under the Radiation Exposure Compensation Act (RECA) passed by Congress in 1990, though this act also covers other exposure categories.

Johnston Island supported many other DoD missions after the completion of Operation Dominic I, which provided some potential for exposure to residual radiological contamination from the failed

launches on Johnston Island. Importantly, the greatest exposure potential would have been incurred by individuals that worked in Launch Emplacement 1 (LE-1) that suffered a launch pad fire and explosion which included a nuclear warhead. This unsuccessful test was codenamed Bluegill Prime and occurred on 25 July 1962. For individuals that worked on Johnston Island outside the timeframe of presumptive compensation specified in 38 CFR 3.309, adjudication of health claims is accomplished under Part 3.311, "Claims Based on Exposure to Ionizing Radiation." Whereas exposure scenarios under Part 3.309 are narrowly-defined, Part 3.311 covers any radiation exposure a veteran may receive during the course of his duties. Common exposure scenarios across the DoD are sailors with assigned duties on nuclear-propelled vessels, medical providers that use radionuclides and machine-generated radiation for treatment and diagnosis of disease, nuclear weapon maintenance personnel, nuclear reactor operators, and non-destructive inspection operators. Within this program, the list of diseases is much larger than those covered under Part 3.309 for ionizing radiation exposures, and are listed in Appendix A. Under Part 3.311, the VA considers the following factors in adjudication of claims (VA 2004):

- the probable* dose, in terms of type, rate, and duration as a factor in inducing the disease, taking into account any known limitations in the dosimetry devices employed in its measurement or the methodologies employed in its estimation or the methodologies employed in its estimation [*Note: in practice VA typically uses upper-bound dose estimates];
- the relative sensitivity of the involved tissue to induction, by ionizing radiation, of the specific pathology;
- the veteran's gender and pertinent family history;
- the veteran's age at the time of exposure;
- the time-lapse between exposure and the on-set of disease; and
- the extent to which exposure to radiation, or other carcinogens, outside service may have contributed to development of the disease.

In some cases, veterans may meet the requirement as a participant in the radiation risk activities defined in Part 3.309, but may not have a disease that is presumptively-connected to the activity. In these cases, a claim would be adjudicated under the provisions of Part 3.311, with a dose assessment by DTRA.

1.4 Use of This Report. This report provides a comprehensive tabulation and summary of radiological data collected as a result of the mishaps responsible for plutonium contamination to the Atoll. With this data, this report provides some estimates of dose to individuals assigned to Johnston Atoll. As well, the data may be useful for independent evaluations of exposure potential by another organization, e.g., US Army, DTRA. Exposures to participants in Operations Hardtack I and Dominic I are thoroughly described in previously published NTPR Program Reports: Gladeck et al. (1982) and Berkhouse et al. (1983), respectively, with the exception of air sampling data that was collected after the Bluegill Prime launch failure, and provided in this report. All DoD components have been assigned personnel to duties on Johnston Island in support of atmospheric nuclear testing and post-testing missions. Also, Government civilian employees and their contractors have also been assigned to duties at Johnston Island. Nevertheless, the greatest exposure potential existed for individuals with duties in LE-1. Post-testing, this area supported an Air Force anti-satellite (ASAT) missile program and periodic remedial actions on radiologically-contaminated soil and materials. In other areas on Johnston Island, much lower exposure potential existed, as documented under a robust radiation safety program. Due to the unique deposition and retention of plutonium in the body, this report provides a detailed summary of health effects from internal plutonium exposure, and a historical summary of safety standards applicable to WGP.

2.0 Background Information on Johnston Island

2.1 Early History of Johnston Island.

Johnston Atoll is an uninhabited atoll in the North Pacific Ocean located about 715 nautical miles (nmi) [823 statute miles] southwest of Honolulu, Oahu Island, Hawaii. The Atoll is about one-third of the distance separating Oahu and the capital of the Marshall Islands chain, Majuro, as shown in Figure 1-1. The atoll is comprised of four islands: Johnston, Sand, North, and East, as shown in Figure 1-2. North and East Islands were artificially created fully by dredging in 1963-1964, while Johnston and Sand Islands were expanded in their natural area by dredging. American claim to the Atoll was made in 1858, under the auspices of the Guano Islands Act of 1856 (34th Congress, Session I, August 18, 1856). Guano was commercially mined from the Atoll for a number of decades. In 1923, by Executive Order, President Calvin Coolidge established the Atoll as a Federal bird refuge, though later in 1934 President Roosevelt placed the Atoll under the Department of the Navy, due to its strategic potential. The Department of the Interior remained involved with maintenance of a wildlife refuge during the Navy's period of control and jurisdiction.

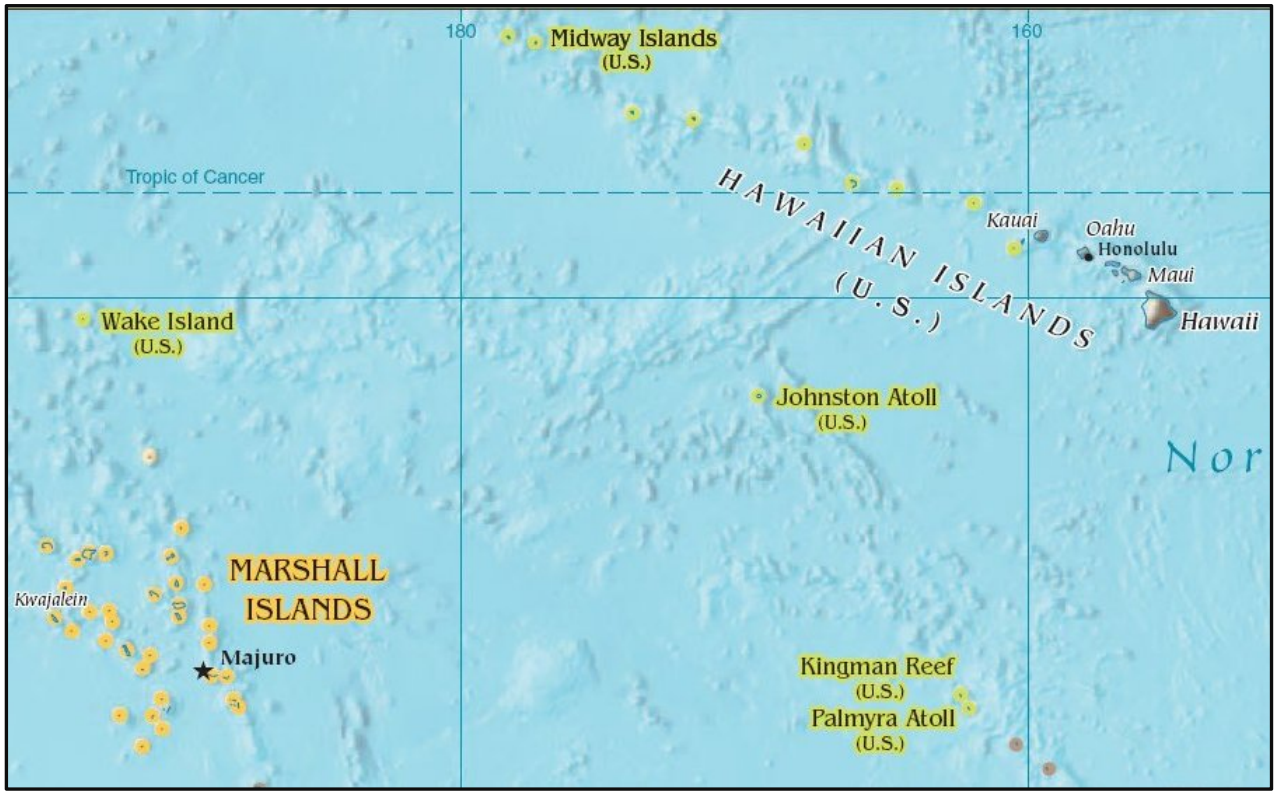


Figure 2-1. Location of Johnston Atoll with Respect to the Hawaiian and Marshall Islands.

Figure 2-2. Satellite Image of Johnston Atoll.

2.2 Early Military Uses.

The Navy, in 1936, developed infrastructure at the Atoll to support seaplane operations. Buildings and a boat landing were constructed on Sand Island. In 1939, sections of the lagoon were dredged to provide greater depth for seaplane landings, with the excavated coral used to expand Sand Island with a causeway and a connecting parking area for aircraft. In 1943, a further expansion of the parking area was conducted with material dredged from the lagoon. By this time, Sand Island encompassed approximately 9 hectares (ha) [22 acres].

During 1941 and 1942, construction of a 4,000 x 500 foot runway was completed on Johnston Island, along with barracks, mess halls, a hospital, and other support facilities. A ship channel was dredged, with the material used to expand the islands area. The diagram in Figure 2-3 shows the relative area of Johnston Island at the various stages of its expansion. After completion of construction between 1941 and 1942, the island had an area of about 24 ha [60 acres]. In the latter part of World War II (WWII), Johnston Island had become an important refueling stop for military flights. The island also supported a communications station. In latter parts of WWII, additional expansion of the island's area occurred through coral dredging of the lagoon, as well as an extension of the length of the runway to 6,000 feet. The Navy continued use of the Atoll facilities at the end of WWII, but at a significantly reduced activity.

On 1 July 1948, the Atoll was transferred to the newly created Air Force and supported the Military Air Transport Service (MATS). During the Korean War, strategic significance of the Atoll increased, as did the size of Johnston Island, the length of the runway, and infrastructure on Johnston Island. After the war, activity levels at the Atoll decreased. In 1957, only about 100 personnel were assigned to the Atoll.

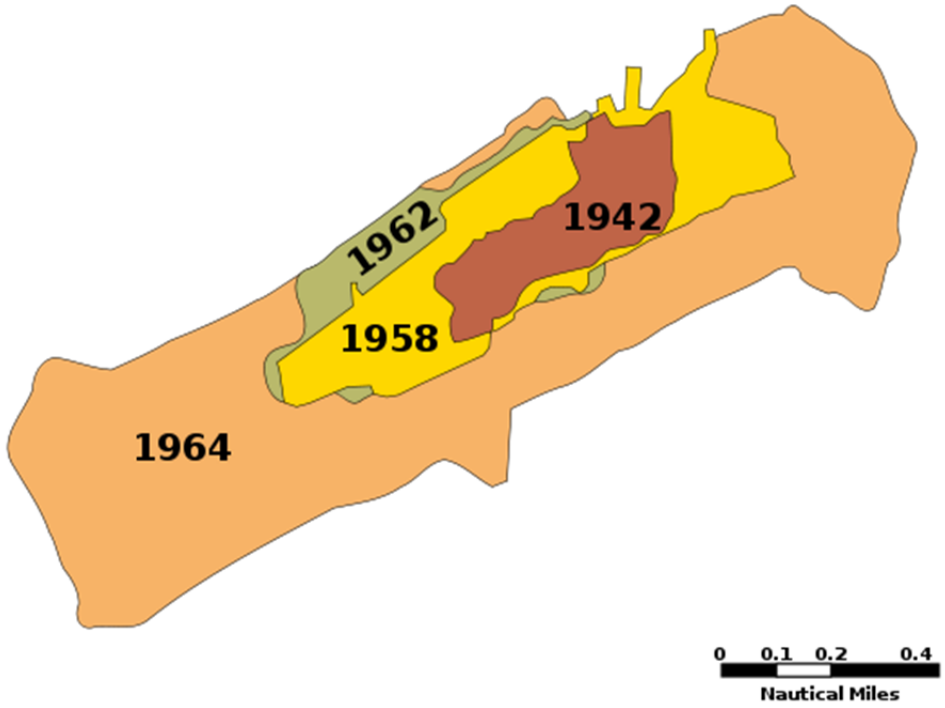


Figure 2-3. Johnston Island Expansion at Various Stages.

2.3 Nuclear Weapons Testing in the Pacific Proving Grounds.

The resumption of nuclear weapon testing at the PPG in 1958 increased use of the Atoll. In addition to use of the airfield for transportation between Hawaii and other islands supporting testing, some tests were staged from Johnston Island during Operations Hardtack I and Dominic I. These operations were respectively conducted under Joint Task Force (JTF) Seven and JTF Eight. Operation Hardtack I comprised 35 nuclear tests, of which 33 were conducted at Enewetok and Bikini Atolls in the Marshall Islands and two from missile launch emplacements at Johnston Island (Gladeck et al. 1982). Operation Dominic I comprised 36 nuclear tests. Twenty-four were airdrop tests conducted over the ocean south of Christmas Island. Five other airdrop tests were conducted over the ocean in the vicinity of Johnston Island. Five high-altitude detonation tests were conducted with missiles launched from Johnston Island. Two open ocean shots were conducted by the Navy at substantial distances from any land masses. During 1958, in conjunction with Operation Hardtack I, Johnston Island was expanded in area from 60 to 185 acres. In 1962, another 35 acres were added in conjunction with Operation Dominic I. In both expansions, coral dredged from the lagoon was used for the fill material. In 1964, again substantial expansion in the Johnston Island area was accomplished through coral dredging operations. This brought the total area of Johnston Island to 625 acres.

2.4 Hardtack I Tests. During the series, two nuclear warheads launched from Johnston Island on Redstone liquid-fueled (alcohol and liquid-oxygen) rockets. The launches were from different launch pads, within the launch complex constructed on a section of the 1958 land expansion on the eastern portion of Johnston Island. The two nuclear-tipped missile launches were conducted on 1 and 12 August 1958, and were the beginning of 145 missile launches from the Island, ending in 1975. A list of missile launches from the Island is contained in Table B-1. Both warheads successfully detonated and had estimated yields of 3.8 megaton (Mt), with respective burst altitudes of 76.8 and 43 kilometers (km) for shots Teak (1 August) and Orange (12 August). In support of the two nuclear tests, 43 low, throw-weight missiles were also launched from the Island. Manned aircraft were not used for air sampling during either of the high-altitude missile launch tests conducted from Johnston Atoll in this test series (Gladeck et al. 1982).

2.5 Dominic I Tests. During this series of tests, nine notable missile launches were attempted from Johnston Island, as listed in Table 2-1. Eight were using the Thor intermediate range ballistic missile (IRBM) and one with the solid-fueled, Nike Hercules designed to carry smaller warheads. The first Thor launch during the Dominic series was with a non-nuclear payload and was a success. Three Thor launches with nuclear warheads were successful during Dominic: Starfish Prime, Bluegill Triple Prime, and Kingfish. Four Thor launches with nuclear warheads, however, encountered a failure of some type. The Bluegill launch was aborted shortly after launch due to a tracking radar problem, while Starfish had a booster rocket malfunction shortly after launch, invoking a range safety officer self-destruct action. For the latter test, missile debris, including radioactive materials from the nuclear warhead were scattered on Johnston Island and surrounding waters. The warhead on the Bluegill launch did not have air-dispersed radioactive materials as a result of the aborted launch. Bluegill Double Prime was also aborted shortly after take-off due to a missile malfunction, with a similar self-destruction action to the Starfish failure, however, in this case, missile debris and radioactive contamination did not impact Johnston Island to the same degree as was the case of the Starfish failure. The failure of the Bluegill Prime launch occurred on the launch pad and resulted in explosions and fire that engulfed the missile and nuclear warhead. Extensive radioactive contamination to the launch pad occurred as a result of this launch failure. The radiological impacts of the Bluegill Prime launch failure invoked significant clean-up activities during Dominic I and for nearly four decades after the failures. The focus of this report is on the radiological impacts of these failures.

2.6 Johnston Island after Dominic I, Short-term. JTF Eight use of the Island was completed in December 1962, though the JTF was directed to maintain control of the Island through 1964, the year additional testing was planned. Improvements in facilities and an increase in the area of Johnston Island was initiated in 1963 and completed in 1964, as shown in Figure 2-3. As well, the completely man-made islands: North (24 acres) and East (17 acres) were constructed from coral dredged from the lagoon. Though not intentional, some of the dredged coral was contaminated with radioactive materials that deposited in the lagoon from the failed Thor launches during Operation Dominic I. During this period of JTF control, other DoD missions were also initiated, most notably use of the Island for missile launch testing and strategic nuclear defense. With the Limited Test Ban Treaty being signed in late 1963, plans for testing in 1964 were cancelled. Nevertheless, control was maintained by JTF Eight through the Director, Defense Atomic Support Agency (DASA). DASA is a predecessor organization to Defense Nuclear Agency (DNA) and later DTRA.

2.7 AF Anti-Satellite Missile Mission. The AF, based on results of high-altitude nuclear detonations conducted during Dominic I explored the potential for fielding an anti-satellite capability with nuclear-tipped Thor missiles in late 1962 (Chun 2000). Johnston Island was designated as the operational base which would maintain alert posture of two Thor missiles, with Vandenberg AFB as a support and training facility. Additional facilities and infrastructure for this program were developed on Johnston Island in 1963. Four Thor test launches were conducted in 1964 to evaluate the ability of the missiles to intercept targets. The first three launches were a success, with the fourth having a failure shortly after launch (Chun 2000). The 10th Aerospace Defense Squadron (ADS) became operational on 10 June 1964. Aerospace Defense Command (ADC) rotated launch crews to Johnston Island from Vandenberg AFB for 90 day temporary duty (TDY) assignments. Thors were launched and remained on alert on Launch Emplacements 1 and 2, the same emplacements used for the Thor launches during Dominic I. The ASAT mission at Johnston Island was terminated in 1970, though additional Thor test launches were conducted until 1975.

2.8 Other Missions. Johnston Island continued to support several communication systems, including cabling between Johnston Island and Sand, North, and East Islands. The island remained a refueling stop for military flights supporting the conflict in Vietnam, as well as commercial flights to a number of Pacific islands. Operational control of the island reverted back to the AF in 1970. In 1971, Johnston Island was chosen for the storage of chemical munitions, which were placed in the southwest quadrant of the Island. In 1972, the DoD added the storage of 1.37 million gallons of Agent Orange (AO) to an area north of the chemical munitions storage area. In 1973, host manager responsibilities for the Atoll were reassigned to DNA. The AO stored on Johnston Island, along with additional 15,000 55-gallon drums from Gulfport, MS, were burned on the vessel Vulcanus, about 120 miles west of the Island. Three separate burn missions were completed between 17 July and August 17, 1977.

2.9 Radiological Cleanup Program.

Post Dominic I tests, there were a number of separate radiological cleanup efforts conducted on the Island. In 1964, the PHS conducted a portable, α-particle radiation survey resulting in the collection and removal of additional contaminated debris from Johnston Island (Jaffe and Tipton 1982). A survey using a low-energy, photon detection system yielded an additional 50 drums of contaminated debris (Jaffe and Tipton 1982). In 1973, the Nevada Operations Office of the AEC conducted a survey using a field instrument for the detection of low energy radiation (FIDLER). Contaminated locations in Launch Emplacement 1 (LE-1) and up to Launch Emplacement 2 (LE-2) were identified, as were locations outside the Thor launch complex and on Sand Island (Jaffe and Tipton 1982). Contaminated coral from locations identified outside the Thor launch complex were removed (Jaffe and Tipton 1982).

In 1974, DNA launched a program to remove isolated areas of contamination through use of FIDLER detector systems. The program started in 1974 with a radiological survey of Johnston and Sand Islands by a team from the AF Special Weapons Center (USAF 1974), and physical removals beginning in 1975. Additional survey work was accomplished after this period of time, but will be detailed later in this report.

TABLE 2-1. Notable Missile Launches from Johnston Island during Dominic I (1962).

Test Name	Date	Missile	Results
Tigerfish	2 May	Thor DSV-2E	Successful launch, missile achieves 481 km altitude, non-nuclear payload test
Bluegill	3 Jun	Thor DSV-2E	Missile aborted shortly after launch due to radar tracking failure, no nuclear detonation or contamination from nuclear payload
Starfish	19 Jun	Thor DSV-2E	Stage 1 missile failure, range safety officer initiated self-destruct 59 s after launch, single-point detonation of warhead conventional high explosives at 10.6 km altitude, radioactive material in warhead dispersed, some on Johnston and Sand Islands
Starfish Prime	8 Jul	Thor DSV-2E	Successful launch, missile achieves 400 km altitude, 1.4 MT nuclear detonation
Bluegill Prime	25 Jul	Thor DSV-2E	Stage 1 missile failure prior to lift-off, range safety officer initiated self-destruct on launch pad, explosions and fire engulfed the missile, radioactive material in warhead dispersed
Bluegill Double Prime	15 Oct	Thor DSV-2E	Booster stage missile failure at 86 s after launch, range safety officer initiated self-destruct 95 s after launch, but prior to nuclear detonation, single-point detonation of warhead conventional high explosives at 33.1 km altitude, radioactive material in warhead dispersed
Bluegill Triple Prime	25 Oct	Thor DSV-2E	Successful launch, high altitude, sub-megaton nuclear detonation
Kingfish	1 Nov	Thor DSV-2E	Successful launch, high altitude, sub-megaton nuclear detonation
Tightrope	3 Nov	Nike Hercules	Successful launch, high altitude, 18 km NW of Johnston Island, low nuclear yield
	Key radiological contaminating events to Johnston Island.		

2.10 Johnston Island Chemical Agent Disposal System (JACADS). With the US in 1975 signing the Geneva Protocol banning the first use of chemical weapons, destruction of the US stockpile appeared more certain. In 1985, Congress enacted the Chemical Demilitarization Program. The JACADS achieved full-scale operational status in May 1993 with production beginning in January 1994. In 2000, the last remaining chemical weapons stockpiled were destroyed. The Army initiated actions to dismantle the JACADS facility, with completion in 2003.

3.0 Radiological Contaminants of Concern

3.1 Radioactive Materials used in Nuclear Weapons. A number of radioactive materials are used in the construction of a nuclear weapon. The types and amounts of materials used are highly varied depending on the specific weapon. All US systems will contain a nuclear trigger that contains fissile radioactive material. US weapons commonly contained uranium, highly-enriched in its ^{235}U mass content (i.e., HEU), WGP, which contains a high mass content of ^{239}Pu, or possibly a combination of the two materials. It is common to surround the fissile materials with a suitable material to reflect neutrons, effectively reducing the amount of fissile material required to create a critical mass (Glasstone and Dolan 1977). Dense reflective materials act as a tamper, affording more efficient use of the fissile material (Glasstone and Dolan 1977). Some nuclear weapons use boosting gases comprised of tritium, deuterium, or a mixture of the two to enhance the yield of the trigger stage of a nuclear weapon.

3.2 Radioactive Materials used in Weapons on Johnston Island Thor Missile Launch Failures. The types and amounts of radioactive materials used in the nuclear weapons on the Starfish, Bluegill Prime, and Bluegill Double Prime launch failure events remain classified. The terms plutonium and alpha-radiation contaminations have been used in conjunction with the launch failures, although it appears to have been implicitly accepted that uranium also contributed to the radiological contaminant mixture. Jaffe and Tipton (1982) reported uranium analysis results of coral soil samples, along with isotopes of plutonium, americium, and other radionuclides of potential interest. The isotopic relationship among the isotopes of uranium in samples were within expectation for nuclear weapon components and were similar to results obtained from similar sample types collected in a 1973 study performed by the Nevada Operations Office of the AEC (Jaffe and Tipton 1982). The activity concentration of uranium isotopes, however, was substantially lower than that of the $^{239+240}$Pu and ^{241}Am, which have consistently been the emphasized radiological contaminants of concern from the failed launch events on Johnston Island. This condition is typical for nuclear weapons accidents involving both WGP and uranium, and is due to the large disparity in the specific activity of WGP and the various potential isotopic forms of uranium as shown in Figure 3-1. The WGP in the example is assumed to be 6% ^{240}Pu, by mass, based on mass spectrometry completed for Jaffe and Tipton (1982) on samples from the site. For residual radiological contaminants at the Boeing Michigan Aeronautical Research Center (BOMARC) outside of McGuire AFB in 1960, the activity ratio between the $^{239+240}$Pu to $^{234+235+238}$U was about 500:1 for the weapon involved in the accident that contained WGP, HEU, and DU. Due to this fact, the isotopes of uranium had negligible impact on health risk analyses. This condition was also important to other DoD accidents involving the release of plutonium, i.e., Palomares, Spain (1966) and Thule, Greenland (1968). WGP will be variously described in terms of its $^{239+240}$Pu or $^{238+239+240}$Pu activity content throughout this report. In the context of discussions in this report, there is only a minor difference between the two entities. For each case, the author has maintained accuracy for the specific application. More discussion of radiological data, including WGP specific to Johnston Island will be discussed later in this report.

3.3 Other Radionuclides of Potential Concern.

The fact that Johnston Island supported nuclear weapons testing bore interest in the potential for fission and neutron activation product impacts to the Island. Nevertheless, from a planning perspective, the Island was never expected to be impacted in this manner during the Hardtack I and Dominic I tests. Table A-2 contains a listing of nuclear detonations in the vicinity of Johnston Island. Among the tests, eight were high altitude tests. The two highest yield tests, Teak and Orange, at 3.8 Mt yield were

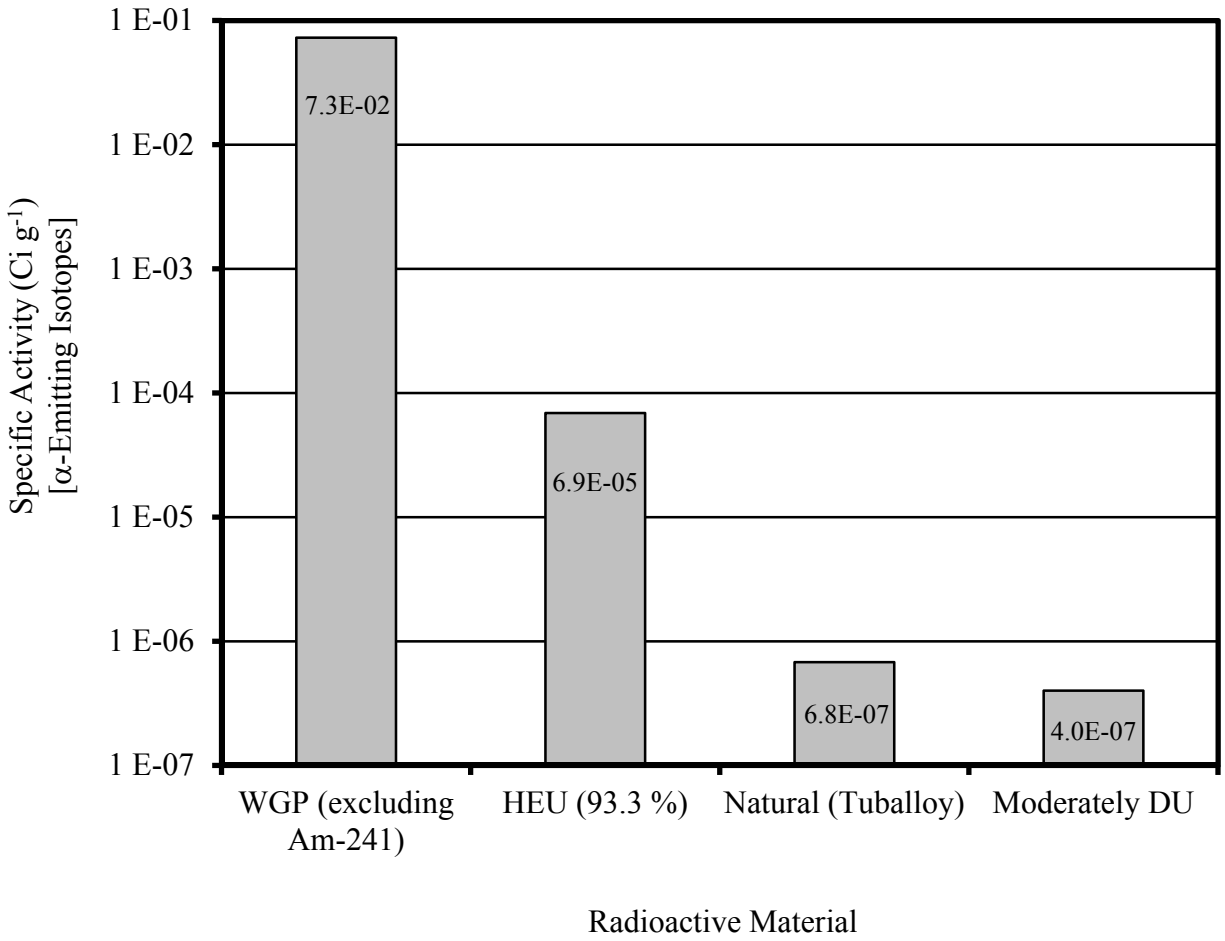


Figure 3-1. Comparison of Specific Activity of α-Emitting Radionuclides In Radioactive Material Potentially Used in Nuclear Weapons.

detonated at respective altitudes of 76.8 and 43 km. Starfish Prime, 1.4 Mt yield detonation, and two sub-Mt detonations, Bluegill Triple Prime and Kingfish, were detonated at high altitude. For these types of detonations, the intensely hot core of the detonation, sometimes called the "fireball," does not touch the surface. The fission products, activation products, and un-consumed nuclear fuel are vaporized by the intense heat. When the fireball rises and cools, these materials condense as fine particles in the upper atmosphere. In the upper atmosphere, they are subject to the weather distribution patterns, with very little local deposition. Though non-essential personnel were evacuated from Johnston Island for mission launch of nuclear test payloads, it was primarily over concern for a mishap on the launch pad, or shortly after a launch. No increase in external radiation exposure levels or evidence of local fallout was observed on Johnston Island during Hardtack I (Gadeck et al. 1982) and Dominic I (CJTF 1964 and Berkhouse et al. 1983). Two low-yield nuclear weapon tests were launched by missile systems, as well. The yields of these tests were substantially lower than the other high altitude tests. In the case of the Checkmate test, the detonation was at high altitude, laterally 80 km from Johnston Island. Due to the extreme altitude of the detonation, radioactive debris would have been carried in the upper atmosphere with negligible local deposition. Similarly for the Tightrope Test, radioactive debris for this test would

have been carried in the stratosphere, with negligible local deposition. This test was sufficiently close to Johnston Island to provide measureable prompt external radiation had the test been of a high-yield device.

Prompt external radiation and fallout deposition impacts to Johnston Island from the five airdrop tests were negligible. Among the five, the minimum separation distance between ground zero and Johnston Island was 290 km. The altitude of the detonations ranged from 3.1 to 3.7 km, a sufficient altitude to preclude the fireball from impacting the ocean surface. In these cases, similar to the high-altitude detonations associated with the missile launched test weapons, radioactive debris would have been in a fine particle form. In the case of the high-yield detonations, the debris would have been largely carried to high altitudes, with negligible local fallout. The two low-yield detonations, Androscoggin – 75 kt and Bumping – 11.3 kt, radioactive materials associated with the detonations would not have been carried to the same altitude as the high-yield devices due to substantially lower updraft. Nevertheless, due to the detonations occurring at substantial distances to the southeast of Johnston Island, the Island would not have experienced any local fallout.

Johnston Island supported aircraft and surface ship activities before, during, and after the detonation tests. This support offered only a minor potential for impacts of radioactive materials associated with testing to areas on the Island, excluding the two launch failures that were known to have impacted the Atoll with plutonium and uranium. A number of the missiles that contained the nuclear warhead planned for detonation also contained test pods that were explosively separated from the missile prior to the planned detonation time. These pods provided telemetry data back to Johnston Island, and in some cases were planned to be retrieved after the test by surface ships or helicopters. This was also the case for a number of smaller rockets that were launched in planned time sequence(s) with the detonation of the test device. Some of the pods were retrievable, while others were not. Devices retrieved were typically handled on Johnston Island. Figure 3-2 is an image of a pod being handled on Johnston Island after a nuclear test. The primary radiological hazard to personnel was from external radiation emission from neutron activation products, but not from fission product contamination (Gladeck et al. 1982). During the two high altitude tests conducted during Hardtack I at Johnston Island, aircraft participated in tests for various projects, however, no debris sampling was performed (Gladeck et al. 1982). During Dominic I tests conducted in the vicinity of Johnston Island, a number of the nuclear test shots incorporated airborne sampling of debris clouds with manned aircraft; however, in spite of the construction of a decontamination pad near the runway, it was never used (Berkhouse et al. 1983). Aircraft used for airborne sampling were left overnight at Johnston Island to allow radioactive decay without decontamination and flown to Barbers Point Naval Air Station, Oahu, where decontamination took place (Berkhouse et al. 1983). Hence, fission and activation products from nuclear tests conducted in the vicinity of Johnston Island are not expected to be observable in surface soil on the Atoll, with the exception of that from world-wide fallout. Soil sampling conducted in 1980 by EG&G (Jaffe and Tipton 1982) made note of ^{137}Cs detected in soil samples, but at levels typical of world-wide fallout (Jaffe and Tipton 1982). More discussion of the 1980 EG&G survey will be made later in this report.

Figure 3-2. Test Pod from Shot Teak being Handled on Johnston Island, from Gladeck et al. (1982).

4.0 Radiation Exposure Potential and Consequences

4.1 Characteristics and Toxicity of Plutonium.

Plutonium is a silvery-white metal. Only trace amounts of the element are from natural sources. The most significant source of plutonium in surface soils is from atmospheric testing of nuclear weapons, which released world-wide about 10,000 kg (ATSDR 2010). Substantial amounts are contained subterranean at underground test sites as well. All isotopes of the metal are radioactive. The isotope ^{239}Pu, as used in nuclear weapons, is produced in nuclear reactors by bombardment of ^{238}U by neutrons and subsequent radioactive decay of the ^{239}Np product, as illustrated in the equations below:

$$^{238}_{92}U + n \rightarrow {}^{239}_{92}U \rightarrow {}^{239}_{93}Np + \beta^{-1} \qquad {}^{238}_{93}Np \rightarrow {}^{239}_{94}Pu + \beta^{-1}$$

Plutonium isotopes of higher mass number are produced from subsequent neutron capture interactions that occur while in the nuclear reactor, e.g., ^{240}Pu, ^{241}Pu, and ^{242}Pu. Among these, ^{241}Pu, has a 14 y half-life and undergoes β-particle decay to form ^{241}Am, an α-particle emitter with a 432 y half-life. The amount of ^{241}Am, in relation to the α-particle emitting isotopes of plutonium in WGP is dependent on the original ^{241}Pu mass fraction and the time since chemical separation from the reactor fuel. Plutonium-238 is used as a heat source in radioisotopic thermal generators (RTGs), with one production method involving the bombardment of ^{238}U by deuterons and subsequent β-particle decay of the ^{238}Np product, as shown in the equations below.

$$^{238}_{92}U + ^{2}_{1}H \rightarrow ^{238}_{93}Np + 2n \qquad ^{238}_{93}Np \rightarrow ^{238}_{94}Pu + \beta^{-1}$$

The toxicity of plutonium to living organisms derives from the biological effects to tissue from radioactive decay of plutonium atoms (ATSDR 2010). The key isotopes of plutonium: ^{238}Pu, ^{239}Pu, and ^{240}Pu, all undergo radioactive decay through the emission of an α-particle and accompanying low-energy photons of low frequency. As such, with the exception of a consolidated mass of WGP in a nuclear weapon or ^{238}Pu in RTGs, external radiation dose rates are negligible when the materials are a dispersed contaminant in the environment. Table 4-1 contains primary radiation emissions from key plutonium isotopes and ^{241}Am. Figure 4-1 contains a measured γ-radiation spectra from a WGP particle collected at the BOMARC missile accident site near McGuire AFB, NJ. The prominent emission is the 60 keV γ-ray from ^{241}Am, which is commonly used to quantify WGP in the environment. Nevertheless, due to the low-energies of the photon emissions from WGP, they are subject to attenuation in soil matrices which further reduces exposure potential.

TABLE 4-1. Primary Radiation Emissions from Key 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	
^{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

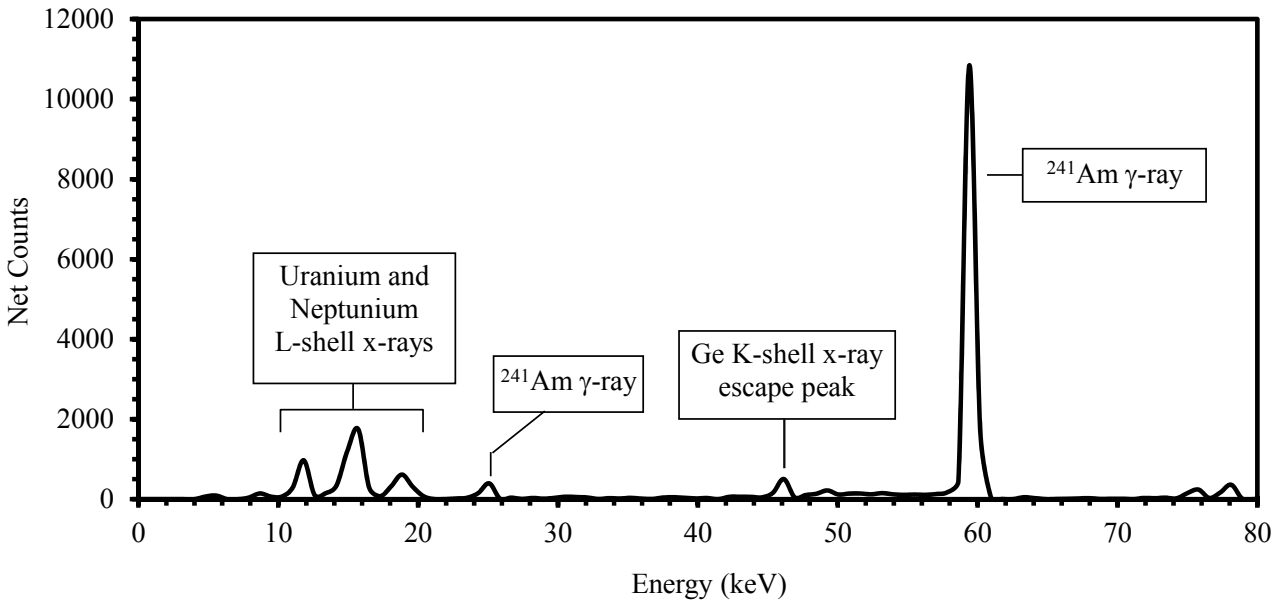


Figure 4-1. Photon Emission Spectrum of WGP Particle from BOMARC Missile Accident Site with Low-Energy Germanium Detector (Rademacher 2010).

As a contaminant dispersed to the environment, the most significant health risk from WGP is from inhalation or ingestion exposures. In workplaces where plutonium was machined, exposures were also possible from uptakes in open wounds, especially when a puncture or abrasion wound was directly related to a piece of plutonium. This exposure pathway, however, is not reasonably applicable to exposures from WGP dispersed to the environment.

The inhalation exposure pathway is commonly the most important for environmental exposures, as well as observed in workplaces that processed plutonium. Inhaled plutonium particles that deposit in the respiratory tract are evaluated for exposure potential based on the region of deposition in the respiratory tract and the chemical form of the plutonium. Deposition potential for inhaled particles is strongly influenced by the aerodynamic behavior of an aerosol. Suspended particles of higher aerodynamic equivalent diameters tend to deposit in the upper regions of the respiratory tract – the naso-oropharynx, and larynx, while particles of lower aerodynamic equivalent diameters are more apt to penetrate to greater depth in the respiratory tract with deposition potential in bronchi, bronchioles, and alveoli. The fate of deposited particles in the respiratory tract is varied. Some material will be transported to the blood stream where it has the potential for deposition in other parts of the body. Mucociliary transport can redistribute material within the respiratory tract and provides transport to the pharynx where the material can enter the gastro-intestinal (GI) tract. Some material initially deposited in the respiratory tract can be transported to the lymphatic system. Particles deposited in the thoracic region are transported to the lung-associated lymph nodes (LALN) and those from the naso-oropharynx region to the extra thoracic lymph nodes [LN(ET)]. For insoluble chemical forms there is long-term retention of particles deposited in the bronchial and alveolar regions. The same is true for insoluble chemical forms of plutonium transported to the lymph nodes. Subsequently, the insoluble forms provide greater dose to tissues in the lung and lymph nodes as compared to the soluble forms that are more readily cleared.

Plutonium ingested, or plutonium inhaled and deposited in the respiratory tract but cleared by mucociliary action to the esophagus has the potential for uptake into the blood stream during transit through the GI tract. The fraction of material transiting the GI tract and taken into the blood stream is highly dependent on the chemical forms, with the more insoluble forms of plutonium having extremely low uptake fractions. Material not taken up into the blood stream is assumed to be excreted in the feces. Material brought into the blood stream is circulated with potential deposition in other tissues, as well as excretion in urine. Among the internal organs, plutonium is preferably transferred from the bloodstream to the liver, bone surfaces, and the bone volume, where it is retained for long periods of time. Small fractions of deposition from the blood to soft tissue and the gonads occur, but significantly lower than the fraction deposited in the bone and liver.

Plutonium dioxide is the most stable of the oxides of plutonium found in the environment and is formed under most conditions, especially when plutonium is ignited in air (Burley 1990). PuO_2 has a high melting point (2,240 ^{o}C), has a high chemical stability, and is highly insoluble in water. The behavior of plutonium in soils can vary depending on the local soil characteristics and the form the plutonium is in at the time of introduction. The Bluegill Prime launch pad accident would have provided a high-temperature, oxidizing environment, favoring the formation of PuO_2.

The US has experienced a number of environmental releases of plutonium that have resulted from high-temperature, oxidizing circumstances. The BOMARC missile accident that occurred near McGuire AFB in 1960 involved the dispersal of WGP when a warhead and missile were engulfed in a liquid rocket fuel fire. The majority of the plutonium was left as a residual in the missile shelter and removed by the AEC, while a small fraction was dispersed to the environment. The predominant mechanism responsible for dispersal to the environment was the gravitational flow of fire-fighting water. Over the many decades since the accident, but prior to completion of all restoration activities in 2008, numerous environmental sampling and monitoring efforts were conducted. Historical records noted radiological monitoring difficulties introduced by the heterogeneously-distributed WGP contaminant, which was observed while accomplishing field survey work and through laboratory analysis of samples. In 1999 the AF Safety Center [Rademacher(a) 1999] and the AF Institute for Environment, Safety and Occupational Health Risk Analysis (AFIERA) began studying the effects of heterogeneity on γ-spectrometry analyses of soils. A study on soil samples was conducted by examining the degree of variability that existed in γ-spectrometry analysis of samples split into multiple sub-aliquots, and counted on a high-resolution γ-spectrometry. The sub-aliquots were firmly packed into plastic petri dishes and assessed on both sides of the sample. The results for one sample are shown in Figure C-1. The mean $^{239+240}$Pu activity concentration for the sample as a whole was 2,792 pCi g^{-1}, though about 92% of the total activity was in aliquot 2. The other aliquots had 6.7 and 1.1%. Clear this shows evidence of the discrete nature of the plutonium contaminant in soils. For aliquot 2, the ratio of estimated activity between the conjugate counts was 4.3, which was near the theoretical maximum, based on a particle being on the outermost edge of the petri dish sample container. If the activity in aliquot 2 was dominated by a single particle, the activity would be about 1.5 μCi. Other samples did not have as significant variability among the aliquots, as illustrated in Figure C-2, where there was good agreement among the seven aliquots, and conjugate counts. The activity concentration of the whole sample was only 2.9 pCi g^{-1}, substantially lower than that of the sample described by data in Figure C-1. Secondary electron imaging (SEI) photographs of a discrete radioactive particle are in Figure C-3, as accomplished by the Radiochemistry Research Group, Harry Reid Center and Department of Chemistry, University of Nevada, Las Vegas (UNLV), NV [Figure 13, Appendix E, (Cabrera 2006)]. The estimated

$^{239+240}$Pu activity of the particle was 0.8 μCi. UNLV concluded that the majority of the activity in the samples analyzed from the BOMARC site reside in discrete particles, and exhibit a degree of pores and fractures that likely resulted during particle formation due to rapid cooling. And further stated, "the particles are chemically and physically stable and will likely remain in this form under normal environmental weathering" (Cabrera 2006). It is clear that a significant fraction of activity in discrete particle form is aerodynamically too large for suspension in air as an aerosol, greatly limiting respiratory intake potential. Figure C-4 contains additional SEI photographs of discrete radioactive particles from the BOMARC site from Gostic (2010). Figure C-5 is a scatter plot of the ratios of estimated activities of final status soil samples assessed by conjugate counting using a similar method as the AFIERA study. Clear from the distribution of data, the effect of heterogeneity was apparent throughout the range of mean sample activity concentration. The 67 and 95 percentile lines are the predicted variability in the ratio expected from counting statistics alone, and under the assumption of homogeneous samples.

Soil contaminated with WGP from the 1966 nuclear weapons accident in Palomares, Spain is also characterized by a heterogeneous distribution of the contaminant. Researchers have studied the contaminated soils with similar techniques that have been performed on BOMARC soils. Jiménez-Ramos et al. (2001) concluded that a considerable fraction of the remaining contamination in the area was present in discrete particles. The work by Jiménez-Ramos et al. (2001) confirmed previous studies of contaminants on the site and that the inhalation exposure pathway would have diminished contribution to dose to individuals living in the area due to the relatively large contaminant particle sizes. Iranzo et al. (1998) reported the results of a long-term air sampling study, 1966 – 1996, from the WGP contamination at Palomares, Spain, and concluded that with the exception of some air samples collected in 1967 and 1969, average annual air samples were below one-tenth of the derived concentration deemed acceptable for the general public (Figure C-6). Iranzo at al. (1994) estimated WGP resuspension factors, S_f, on the order of 10^{-9} m^{-1} within a few months after the accident and on the order of 10^{-9} to 10^{-10} m^{-1} several years later. Shinn (1998) noted that the time-dependent empirical model for resuspension described in Anspaugh et al. (1975) was too conservative and over predicts Pu resuspension shortly after releases. This is supported by the Iranzo et al. (1994) work.

4.2 Exposure Circumstances and Pathways.

4.2.1 Exposure Groups.

The radiological exposure potential for individuals assigned to duties on Johnston Atoll is highly varied, dependent primarily on the period of time assigned to Johnston Island, the types of duties performed, and access and occupancy in the Thor missile launch emplacement area. Table 4-2 contains a summary of exposure circumstances. Individuals present on Johnston Island during the Starfish and Bluegill Prime launch failures had the potential for inhalation of radiological contaminants dispersed to the atmosphere. For both accidents, airborne radiological contaminants would have been the highest during the release. In the Starfish launch failure, concentrations of airborne radiological contaminants would have significantly decreased after the debris cloud was carried by winds away from Johnston Island. For the Bluegill Prime failure, concentrations of airborne radiological contaminants would have decreased after the fire that encompassed the Thor launch pad was finished. Radiological contaminants deposited on the ground would have been subjected to re-suspension by surface winds and presented inhalation exposure potential for the area, though of significantly lower airborne concentrations than those that existed during the period of time the releases occurred. For all high altitude missile launch tests

conducted from Johnston Atoll during Dominic 1, non-essential personnel were evacuated from the Island prior to the test, due to the small size of the Island (Berkhouse et al. 1983). Non-essential personnel returned to the Island the day after the shot. For the Starfish and Bluegill Prime launch failures, the delay in re-entries to the Island would have allowed radioactive materials (initially released to the atmosphere by the failures) to be deposited on the ground or been carried away from the Island by winds. During the tests, essential crew remained on the Island and consisted of launch control members, experiment personnel, and disaster control team (DCT) members which consisted of fire-fighters, medical personnel, and radiation detection personnel. Berkhouse et al. (1983) noted that the exact number of personnel remaining on the Island during the missile launches was not documented in test records. DTRA/NTPR currently believes some non-essential personal remained on the Island during the Bluegill Prime launch (Murray 2015). Because the Thor launch pad was located on a northwest portion of the Island and the prevailing winds travelled from east to west, with the exception of personnel supporting the Thor launch pad rehabilitation, inhalation hazards from re-suspended radiological materials would have been very low. Figure 4-2 shows key areas on Johnston Island during the Dominic I test period.

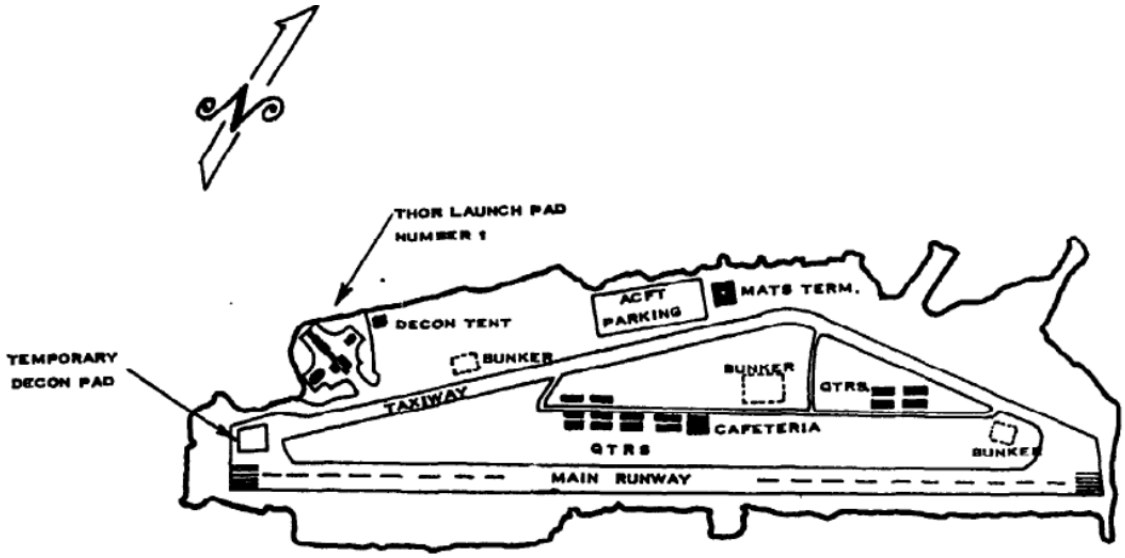


Figure 4-2. Map Showing Key Areas on Johnston Island during Dominic I Tests, from Berkhouse et al. (1983).

After the Bluegill Prime launch failure, an operation pause of 82 days was incurred that allowed rehabilitation of the Thor launch pad. In connection with this action, most personnel supporting the task force returned to their home stations. The population of personnel on Johnston Island was 520 in July, but dropped to 311 in August. In October when test operations were resumed, the population increased to 793 (Berkhouse et al. 1983). Exposure potential during the pause in test operations was greatest for personnel supporting the remedial action. However, during the critical early period of remedial action, personal protective equipment, e.g., anti-contamination clothing and air-purifying respirators were used by personnel performing the work, and contamination control monitoring and air sampling support were provided. Prior to the next launch, another Thor launch pad (LE-2) was constructed to the northeast of the existing Thor launch pad (LE-1).

TABLE 4-2. Exposure Potential by Groups and Time Period.

Time Period	Personnel Group	Exposure Potential	Comments
19 June 1962 (Starfish Launch Failure)	Nuclear Test Support	Inhalation	The majority of personnel were evacuated for the launch. Remaining personnel had potential for exposure from radiological material dispersed from high altitude detonation of test item. Inhalation potential from re-suspension of ground-deposited material much lower than during passage of contaminated plume.
	Debris Recovery Personnel	Inhalation, Contamination	Personnel recovering debris had potential for contamination from the handling of contaminated debris. Inhalation potential is dependent on whether present on Johnston Island during failed launch.
25 July 1962 (Bluegill Launch Failure)	Nuclear Test Support	Inhalation	The majority of personnel were evacuated for the launch. Explosions and fire occurred at down-wind location on Johnston Island which limited inhalation potential from initial air dispersal of contamination.
25 July – 15 October 1962 (Operations Pause)	Launch Emplacement Remediation Action Support Personnel	Inhalation, Contamination	Personnel supporting remedial actions wore personal protective equipment during field activities, mitigating inhalation and contamination exposures. Active radiological monitoring.
	Others	Inhalation	Contaminated Thor launch emplacement at downwind location on Johnston Island. Limited inhalation potential for other personnel. Active airborne radiological monitoring at site boundary until 2 September.
15 October - 1 November 1962	Thor Launch Support (Dominic)	Inhalation, Contamination	Residual contamination in launch emplacement posed inhalation and contamination potential to personnel in area.
	Others	Inhalation	Limited inhalation potential.
1 November 1962 - 1970	USAF ASAT Program Support (Thor Emplacement)	Inhalation, Contamination	Residual contamination in launch emplacement posed inhalation and contamination potential to personnel in area. Radiological monitoring performed in launch emplacement area.
1975	USAF Thor Missile Launches	Inhalation, Contamination	Residual contamination in launch emplacement posed inhalation and contamination potential to personnel in area. Air sampling conducted as part of Island-wide monitoring program.
1 November 1962 to Island Closure	Intermittent Work in Thor Launch Emplacement Area	Inhalation, Contamination	Intermittent activities involving small-scale remedial actions, radiological monitoring, and large-scale site restoration activities. Varied exposure potential dependent on activity. Some activities involved specific monitoring.
	Others	Inhalation	Limited inhalation potential. Air sampling conducted as part of Island-wide monitoring.

Three additional Thor missile launches were conducted when testing was resumed on 15 October until their completion on 1 November. Two were launched from the new Thor launch pad and one from the previously damaged one. Some inhalation and contamination potential existed to personnel with duties in the Thor launch areas due to the existence of residual radiological contaminants. However, the contamination source term was significantly degraded by the remedial actions conducted, and was primarily limited to the areas surrounding the first Thor launch pad (LE-1) constructed.

After the 1 November 1962 Thor missile launch from launch emplacement 2 (LE-2) - the newest of the two launch pads, the next Thor missile was not launched from Johnston Island until 14 February 1964 under AF Program 437, an ASAT ballistic missile mission. During 1963, the Air Force began to develop the capability, including plans for modifications to Johnston Island to support two alert missiles from the Thor launch emplacements. In late 1969, due to funding shortfalls, the AF removed nuclear warheads from missiles and stored them on-site (Chun 2000). AF Program 437 on Johnston Island was terminated on 2 October 1970 (Chun 2000). Between 1963 and 1970, potential inhalation and contamination exposures from radiological contaminants existed for personnel supporting this program and requiring access to the Thor launch pads. After Dominic I and until the completion of plutonium remediation on Johnston Island in the latter 1990's, other personnel periodically accessed the Thor launch emplacement area. Some of the access was required to accomplish small scale radiologically-contaminated coral and property removals, radiological survey work, facilities maintenance, air sampling, etc. Some of the activities involved air sampling and contamination monitoring specific to the activity, while routine air sampling and radiological contamination monitoring was completed in the Thor launch area and other locations on the Island. The most extensive air sampling program for areas outside of the Thor launch pads was conducted from 1975 until the early 1990s.

4.3 Animal and Human Studies on Plutonium Exposure, and Epidemiological Studies of Human Workers Occupationally Exposed to Plutonium.

4.3.1. Early Studies.

In the earliest days of plutonium production in the Manhattan Project, concerns for the health hazards of plutonium were recognized. On 5 January 1944, Glenn Seaborg wrote the following to the Medical Director of the Manhattan Engineering District (MED) [Stannard 1988]:

> "It has occurred to me that the physiological hazards of working with plutonium and its compounds may be very great. Due to its alpha radiation and long life it may be that the permanent location in the body of even very small amounts, say one milligram or less, may be very harmful. The ingestion of such extraordinarily small amounts as some tens of micrograms might be unpleasant, if it locates itself in a permanent position. In the handling of the relatively large amounts soon to begin here and at Site Y, there are many conceivable methods by which amounts of this order might be taken in unless the greatest care is exercised. In addition to helping set up safety measures in handling so as to prevent the occurrence of such accidents, I would like to suggest that a program to trace the course of plutonium in the body be initiated as soon as possible. In my opinion such a program should be given the very highest priority."

Some of the first animal studies involved oral and varied injection site administrations of plutonium to rats (Stannard 1988). These early studies found preferable deposition and retention of plutonium in the skeleton and liver and relatively poor uptakes in the gut from oral intakes. Mice and dogs were also the subject of early animal injection and oral intake studies, with principal investigations being conducted by the Berkeley group (University of California Radiation Laboratory and later Lawrence Berkeley

National Laboratory), the Metallurgical Laboratory (later Argonne National Laboratory), and Los Alamos Scientific Laboratory. Initial concerns regarding plutonium and its toxicity were related to the knowledge that already existed for radium ingestion. In the early animal studies, they determined that plutonium had a propensity to deposit on the endosteal and peritoneal surfaces of bone, as compared to radium (also strontium) which was found in the mineral crystals by exchange with calcium (Stannard 1988). In a study of plutonium retention in bovine bone, Chipperfield and Taylor (1970) found bone glycoproteins largely responsible for uptake and retention of plutonium on endosteal surfaces.

Between April 1945 and July 1947, eighteen human patients received injections of soluble plutonium at the University of Chicago, Oak Ridge, TN, University of Rochester, University of California, San Francisco and formed the initial basis for understanding the metabolism of plutonium in man (Stannard 1988). Early results from follow-up on some of these patients, along with results from animal studies, were reported by Langham (1959). A longer term follow-up was provided in 1980 by Langham et al. (1980). Important information gained from these studies was the retention and excretion rates of plutonium from the patients. Due to the fact that only small amounts were injected in the patients, acute effects were not observed (Langham et al. 1980). Autopsies on some of the patients after natural death found the bone (mineral and marrow) and liver sites of dominant retention (Langham et al. 1980), with general similarity to results found from animal injection and oral ingestion studies.

The much larger doses of plutonium given to laboratory animal subjects demonstrated a number of acute and delayed health effects. High doses in rodents showed extensive GI-tract hemorrhage, liver damage, anemia, bone and soft tissue tumors, and retarded healing of skeleton fracture (Stannard 1988). High doses in dogs produced anemia and liver damage from injection studies performed in the mid-1940's (Stannard 1988).

Limited plutonium inhalation studies on animals were conducted during the war, and as noted by Stannard (1988) the quality of the work was hampered by problems producing aerosols and delivery systems. Stannard noted that important early work was conducted by investigators at Berkeley group and in Chicago, associated with the Metallurgical Laboratory. Stannard noted important findings from the Berkeley work on rats were identification of significant differences in lung absorption between plutonium as a nitrate versus oxide chemical forms, and that 75% of the PuO_2 inhaled was initially retained in the lung. Stannard noted similar results from the Chicago work on differences in retention in the lungs of rats dependent on the valence state of plutonium compounds. Plutonium compounds of valence states III and VI were removed more quickly by biological processes than IV valence state compounds. Stannard also noted that animals exhibited extensive damage to the lung – inflammation, necrosis, and abscess formation, and preferable retention of plutonium in the skeleton once transferred from the lung to other parts of the body via the bloodstream. Lesser amounts were found in the liver.

4.3.2 Post-War Studies on Animals.

After the war, there was a considerable expansion in animal studies on the effects plutonium, especially inhalation exposure studies which were deemed important in establishing safety criteria for workers handling plutonium where inhalation exposure potential existed. Many of these studies were aimed at the long-term effects of low-level exposures which would be more appropriate to expected exposure levels in occupational settings involving plutonium. Inherent with studies of this nature is the long-term follow-up required. Dogs have over a decade of life expectancy and were often the animal of choice for

these studies. Table 4-3 summarizes information from some of the key animal studies conducted after the war. Because the WGP released by the accidents on Johnston Island and AF nuclear weapon accidents is expected to be in an oxide form, the summary notes primarily findings for $^{239}PuO_2$ administered to animals. These studies and other US research involved other chemical forms of WGP: ^{238}Pu that is used as a heat source in RTGs, and many other actinides. Among the actinides, ^{241}Am, is important, due to its ingrowth in WGP from the decay of ^{241}Pu.

The studies summarized in Table 4-3 had many objectives: assessment of acute and chronic toxicity, comparisons of toxicity among many radionuclides and varied chemical forms of the same radionuclide, evaluation of the metabolism of radionuclides after intake, retention and excretion. The injection and intravenously-administered exposures demonstrated similar metabolism characteristics as studies completed during the war: plutonium was preferably deposited and retained in the skeleton and liver. The plutonium deposited preferably on the endosteal and peritoneal surfaces of bone, as compared to ^{226}Ra, which is a calcium analogue and deposits predominantly in the mineral bone. As a result of this difference, ^{239}Pu was much more effective in producing osteosarcomas than ^{226}Ra. Animals receiving the higher doses had acute effects related to deposition in the liver and bone surfaces. Acute effects observed in these animal studies are highly unlikely to be observed in occupational exposures to humans due to the substantially lower exposure levels. The delayed induction of neoplasms in bone and liver were identified as important chronic toxic effects, though non-neoplastic effects were also identified. Liver necrosis and bone atrophy were among the most common effects identified in animals.

Among the inhalation studies summarized in Table 4-3, those conducted at Hanford and the Lovelace Foundation involving beagle dogs were the most extensive. Although in inhalation exposures to plutonium, the lung and other portions of the respiratory tract are the sites of initial deposition, translocation to other tissues and organs in the body occurs. Plutonium trans-located to the bloodstream will have a preferable deposition and retention in the skeleton and liver, similar to that for human and animal participant injection studies. The rate and amount of plutonium deposited in the respiratory tract and trans-located to other tissues and organs in the body is highly dependent on the chemical form of the material and the site of initial deposition in the lung based on the animal studies summarized in Table 4-3. The relatively insoluble and biologically-immobile $^{239}PuO_2$ was found in these animal studies to have long-term retention for depositions in the pulmonary regions. Material deposited in the upper portions of the respiratory tract was cleared more readily due to the action of ciliated epithelium and phagocytosis (Stannard 1988). Plutonium deposited in the upper respiratory tract that is not absorbed into the blood stream or lymphatic system is swallowed, and enters the gastrointestinal (GI) tract unless it is expectorated or released by nose blowing. Materials transferred to the GI tract from the respiratory tract are expected to have uptake and retention in a similar manner to normal ingestion. Relatively insoluble PuO_2 and $Pu(OH)_2$ have very low uptakes from the GI tract, with the vast majority being excreted in the feces. In both the Hanford and Lovelace studies on inhalation of $^{239}PuO_2$ with beagle dogs, the majority of plutonium was trans-located to the thoracic lymph nodes. Smaller fractions were trans-located to the liver and skeleton.

Beagle dogs subjected to inhalation of $^{239}PuO_2$ exhibited many non-neoplastic effects on the lungs and the thoracic lymph nodes. In the dogs with highest exposures, a majority died of radiation pneumonitis. Most animals exhibited lymphopenia, atrophy and fibrosis of the lymph nodes, and pulmonary fibrosis.

Table 4-3. Key Animal Studies on Plutonium Exposures (Summarized from Stannard [1988]).

Study Group	Animals Studied	Exposure Routes	Notes
Argonne National Laboratory	Mice	Intravenous	- ^{239}Pu & ^{210}Po more effective inducing mortality than ^{226}Ra; similar for carcinogenesis - Acute and chronic toxicity endpoints studied - Lymphoid tumor induction rate low for bone-seeking radionuclides (i.e., ^{239}Pu) compared to those depositing primarily in soft tissue - ^{239}Pu the most potent bone tissue carcinogen at low doses among radionuclides studied; ^{45}Ca and ^{90}Sr the most effective at high doses - Low dose effects of fatty and parechymatous degeneration of liver, degradation of white blood cell count, osteosarcomas, but no liver carcinogenesis - Degraded hemoglobin levels at high doses
Hanford	Dogs	Injection	- Highly varied distribution and excretion of injected ^{238}Pu and ^{239}Pu in nitrate, 30-days post injection. ^{239}Pu higher overall retention, 99%, compared to 79% for ^{238}Pu. Highest ^{239}Pu retention in liver, though highest for ^{238}Pu in the skeleton.
		Inhalation (1960's)	- Exposures of < 1 to 50 μCi $^{239}PuO_2$, 3 μm MMD - Highest exposed dogs exhibited acute effects: lung hemorrhage and edema & respiratory insufficiency - Low to moderate dose produced lung fibrosis and lymphocytopenia, and lung cancer - Slow translocation of pulmonary-deposited material to liver, skeleton, and thoracic lymph nodes; notably high deposition and retention in ovaries
		Inhalation (1970's)	Added from Park et al. (2012), Thompson (1989) - Exposures of 0.0035 to 5.8 μCi $^{239}PuO_2$, with six exposure groupings - Seven of eight dogs in highest exposure group died of radiation pneumonitis, the other of a lung tumor - Dogs living >10 y had 70% of residual Pu in lymph nodes (thoracic), 15% lung, 10% liver, and 2% bone - Neoplasms: 47% developed lung tumors, (3) bone tumors (low dose), no leukemia or liver tumors - Primary non-neoplastic effects: lymphopenia, atrophy and fibrosis of thoracic lymph nodes, radiation pneumonitis and pulmonary fibrosis - Thoracic lymph node lesions in 98 of 108 dogs, but none primary lesions of lymph nodes
	Mice	Inhalation	- Squamous cell carcinomas from intratracheal injection of PuO_2 and $Pu(OH)_2$

Table 4-3. Key Animal Studies on Plutonium Exposures (Summarized from Stannard [1988]), continued.

Study Group	Animals Studied	Exposure Routes	Notes
Colorado State University	Dogs	Wound Intake Simulation	- Studied metabolism of plutonium from wound sites for air-oxidized, high-fire oxidized, and nitrated chemical forms. Nitrated form had 14-fold greater transport to the blood than air-oxidized form, led to greater plutonium content in femurs than for animals given subcutaneous air-oxidized plutonium. - Rapid movement of air-oxidized plutonium from sub-cutaneous injection sites to proximal lymph nodes.
University of Utah	Dogs	Injection	- ^{239}Pu more effective inducing osteosarcomas than ^{226}Ra - Preferable deposition of plutonium in the liver, bile duct tumors but no tumors in liver, liver necrosis - Some early depression of white cell counts and early transient anemia, but recovery over time for dogs with lower exposure levels - Progressive and serious anemia in only dogs with the highest exposures
University of Rochester	Dogs	Inhalation	- $^{239}PuO_2$ deposited in the lung had preferable translocation to thoracic lymph nodes, though low translocation to bone and liver, but notably higher deposition in the gonads - progressive lymphopenia and focal pulmonary fibrosis noted shortly after exposures
Lovelace Foundation, Albuquerque	Dogs	Inhalation	Notes augmented from Muggenburg et al. (2008) - Varied monodisperse $^{239}PuO_2$ particle exposures - lymphopenia, atrophy and fibrosis of the thoracic lymph nodes, radiation pneumonitis, and pulmonary fibrosis - Neoplasms almost exclusively limited to the lung, no primary tumors in thoracic lymph nodes, and no leukemias, bone & liver cancers similar to controls - No clear dependence of effect on particle size of toxic effects
Los Alamos National Laboratory	Hampster	Inhalation	- Pu-ZrO_2 produced respiratory tract tumors

Lung tumors were the most prominent neoplastic effect attributed to $^{239}PuO_2$ inhalation in the Lovelace and Hanford studies. However, in these studies, no primary tumors were identified in the lymph nodes

and none of the animals developed leukemia, which would be considered connected to deposition and retention of plutonium on bone surfaces, enabling dose to the bone marrow. Liver cancer was not observed in beagle dogs in the Hanford study (Park et al. 2012), however, a small number were observed in controls and dogs receiving $^{239}PuO_2$ in the Lovelace work (Muggenburg et al. 2008). In the latter study, control dogs had a greater frequency of occurrence of liver cancer than the dogs receiving $^{239}PuO_2$. Primary bone tumors were identified in three of the Hanford study dogs receiving $^{239}PuO_2$, with only one in the Lovelace study dogs receiving $^{239}PuO_2$ and one control dog (Muggenburg et al. 2008). Muggenburg et al. (2008), however, found no increase in occurrence of malignant or benign tumors in organ systems outside the respiratory tracts in animals receiving $^{239}PuO_2$ over control dog groups.

Inhalation studies with $^{239}Pu(NO_3)_4$ and $^{238}PuO_2$ were also performed on dogs and other study animals involved with the $^{239}PuO_2$ exposures. In comparison to $^{239}PuO_2$, these compounds were much more readily trans-located from the lungs to the bloodstream, that allowed substantially higher deposition in the liver and bone (Stannard 1988), and subsequently increased occurrence of liver and bone cancers in inhalation exposures with dogs (ATSDR 2010). Nevertheless, these compounds were not related to accidents involving WGP releases at Johnston Island and AF nuclear weapons accidents, though ^{238}Pu exists in trace activity fractions in WGP, including WGP released during the Johnston Island mishaps.

Deposition and retention of plutonium in testes and ovaries is of interest out of concern for possible irradiation of germ cells and possible genetic effects. As noted in Table 4-3 for inhalation studies with dogs at Hanford and in animal other studies described by ATSDR (2010), some concerns were raised for this potential. ATSDR (2010), however, noted that the results from various internal radiation studies with plutonium did not raise particular concern for reproductive toxicity.

In summary, animal studies on the inhalation of $^{239}PuO_2$ demonstrated non-neoplastic effects primarily in the lungs and thoracic lymph nodes, with the most significant risk for neoplasms in the respiratory tract.

4.3.3 Studies of Human Workers Exposed to Plutonium.

4.3.3.1 General.

The United States was the first country to handle large quantities of plutonium. The processing and fabrication of plutonium used for the first atomic detonation was accomplished at Los Alamos under "extraordinarily crude" working conditions (Hempelmann et al. 1973). A medical follow-up report on 25 men who performed this work and were deemed "heavily exposed to plutonium" was provided by Hempelmann et al. (1973). Subsequent follow-ups at 32-years (Voelz et al. 1979), 37-years (Voelz et al. 1985), 42-years (Voelz et al. 1991), and 50-years (Voelz et al. 1997) were reported in the literature. This study was later combined with Los Alamos National Laboratory (LANL) workers that handled plutonium after the war (Wiggs et al. 1994). Studies were also performed for Rocky Flats and Hanford workers.

The United States established the National Plutonium Registry in 1968, with subsequent name changes in 1970 (US Transuranium Registry) and 1992 to the US Transuranium and Uranium Registries (USTUR) when the US Uranium Registry was joined administratively (James and Brooks

2007). The USTUR is a human tissue research program where voluntary tissue donors allow access to their employment and occupational exposure histories, and medical records (James and Brooks 2007). The registry has provided invaluable contributions to modeling the transport, deposition, and retention of radionuclides in tissues and excreta that are used to refine International Commission on Radiological Protection (ICRP) models. The USTUR has followed up to old age 875 volunteer registrants that worked in DOE facilities (USTUR 2012). A number of the early Los Alamos plutonium workers volunteered for participation in the Registry. The largest groups of donors are from the Hanford Site and Rocky Flats (James and Brooks 2007).

Other countries that have produced WGP for nuclear weapons programs have conducted follow-up health studies on their workers. Because workers handling plutonium at the Mayak nuclear facility in the former Union of Soviet Socialist Republic (USSR) had substantially higher intakes of plutonium than US or British workers (Bouville et al. 2015), based on published data, the epidemiological studies on these workers provides better insight into the health effects related to plutonium exposure. Also, these studies are unique in that a substantial portion of the workforce was comprised of females, in contrast to US or British plutonium workers that were predominantly men (Shilnikova et al. 2003). Reports on these workers did not start until after the fall of the USSR and included US support by grants from US National Cancer Institute (NCI) and the DOE.

4.3.3.2 Summary of Epidemiological Studies.

Table 4-4 provides a summary of epidemiological studies on human workers exposed to plutonium as summarized by the Agency for Toxic Substances and Disease Registry (ATSDR 2010). Similar reviews, but in less detail, are also provided by the International Agency for Research on Cancer (IARC) in Volume D, *Radiation*, IARC (2012). Epidemiology studies have been accomplished for workers at three DOE sites with plutonium exposure potential: Hanford, WA, Rocky Flats, CO, and LANL, NM.

Neither the Hanford or LANL study found statistically significant excess cancer mortality trends for the plutonium workers compared to control workers for all cancers combined, lung, bone, lymphatic system, hemopoietic system, digestive tract (includes liver). The LANL study found a rate ratio of 1.78 for lung cancers between plutonium workers and controls, however, the observation was not statistically significant, having a 95% confidence interval: 0.79-3.99. The authors noted that the finding may have been spurious, as it was based on only eight reported lung cancer deaths among the plutonium exposed workers, and interpretation of the lung cancer results was difficult due to the absence of data on smoking habits (Wiggs et al. 1994).

The LANL plutonium exposed worker cohort had one death associated with an osteosarcoma, but no primary bone cancers associated with the control group (Wiggs et al. 1994), a finding that was previously reported by Voelz and Lawrence (1991), as this individual was one of the 26 individuals that was exposed to plutonium at Los Alamos during the war. This worker had inhalation exposures to plutonium in 1945-1946, and the excision of thumb wound contaminated with a plutonium solution, and had an estimated cumulative dose to the surfaces of bone of 44 rad (880 rem, with a radiation weighting factor of 20) two years prior to the appearance of the tumor (Voelz et al. 1991). Primary bone cancers of any type are rare compared to other types of cancer, with an incidence of about only one new case in a year among a population of 100,000 (NCI 2014), with only about 10%

TABLE 4-4. Summary of Human Epidemiological Studies on Human Workers Exposed to Plutonium. [Compiled from ATSDR (2010)].

Group	Exposures	Findings and Notes
Hanford	Inhalation of Plutonium, External	- Total cohort of 31,500 reviewed, subset of 457 with plutonium bioassay analysis results - 136 individuals had estimated body burdens (5 – 99% of the MPBB, 40 nCi), 6 had estimated body burdens ≥ 100 % of the MPBB - No evidence for statistically significant excess cancer mortality or trends in cancer mortality with external radiation or internally-deposited plutonium (all cancer types, digestive tract, lung, lymphatic and hemopoietic tissues, or prostate)
Los Alamos	Inhalation of Plutonium, External	- Cohort of 15,427 males employed in plutonium production facility from 1943 to 1973, subset of 3,775 monitored for plutonium exposures - Compared mortality between workers with internal deposition of plutonium above (n=303) 2 nCi (5% of MPBB under ICRP 2) and below (n=3,472) - No statistically significant difference in cancer rates for all types, bone, lung, lympho- and hemo- poietic systems - Rate ratio for lung cancer 1.78 (95% CI: 0.79-3.99) based on 8 cases of lung cancer, but not significant
Rocky Flats	Inhalation of Plutonium, External	- Preliminary database of 22,883 workers reviewed for study - Odds ratio (1.05) for lung cancer mortality significant for estimated internal lung doses between 40 & 64.4 rem, but not for doses > 64.4 rem - No associations between lung cancer mortality and cumulative penetrating radiation or cumulative exposures to asbestos, beryllium, hexavalent chromium, or nickel
U.K. Nuclear Facilities	Inhalation of Plutonium, External	- Mortality rate ratios not elevated for cancers in tissues receiving the highest plutonium doses (bone, liver, lung)
Mayak, U.K.	Inhalation of Plutonium, External	- Increased risk of cancer mortality (bone, liver, and lung) due to internal body-burden of plutonium after adjustment for confounding risks from external radiation - Cancer mortality risks higher for woman than men - Risks of leukemia mortality not associated with internal plutonium exposure - Mean body burden of plutonium among cohort of 11k Mayak workers: 102 nCi (male) and 164 nCi (females) - Lung cancer risk reasonably derived by a linear function; liver cancer risk better described by quadratic function - Uncertainty in analysis due to varied reliability of monitoring data across individuals in the cohort

of osteosarcoma cases developing in individuals in their 60's and 70's (ACS 2014). Voelz et al. (1991) estimated the probability of observing a case among the 26 LANL workers that were part of their study about 1% for the 40+ years of medical follow-up. As such, this study and the larger group of LANL workers studied by Wiggs et al. (1994) had insufficient power to find a causal link of plutonium exposures and bone cancers due to the small number in the cohort and relatively low plutonium doses received by the workers. This was not unexpected, as the beagle dog studies that involved inhalation exposures to $^{239}PuO_2$ had significantly higher incidence of lung cancer compared to bone cancers.

The Rocky Flats study referenced in Table 4-4 conducted by Brown et al. (2004) was limited in scope to lung mortality and internal dose from plutonium, americium, and uranium, external dose, asbestos, beryllium, hexavalent chromium, and nickel. A weak association, odds ratio 1.05, was found between age at first internal lung dose and lung cancer mortality for lung doses between 40 and 64.4 rem. No association with exposures to asbestos, the metals considered, and external radiation were identified. Interestingly, no statistically significant association with lung cancer incidence at lung doses greater than 64.4 rem was found. The authors of the study noted that it was likely that misclassification of lung dose by plutonium systemic deposition was responsible for the weak association between system deposition and lung cancer in the group of individuals with the lower lung doses from internal exposure.

Wilkinson et al. (1987) found an elevated rate ratios for lymphopoietic and other cancers in comparison of workers with plutonium body burdens $\geq$ 2 nCi and less than 2 nCi in a population of Rocky Flats plutonium workers. However, overall fewer than expected lung cancer and all cancers deaths were observed for the population studied. An excess brain cancer finding existed for the entire cohort of workers studied, though this finding was not specific to internal burdens of plutonium, as the cohort had external exposures as well.

More recently, Fallahian et al. (2012) completed an exploratory epidemiological study on 319 deceased nuclear workers that had intakes of transuranics, histories of employment between 1943 and 1995, and had been a voluntarily participated in the USTUR. The workers had been employed primarily at Rocky Flats, LANL, Hanford, and the Savannah River site. The analysis was conducted in two separate analyses: one considering the cause of death due to cancer of any site (primary cause or a contributing cause) and the cumulative external dose, and the other reviewing cause of death due to cancer of the lung or liver and the estimated cumulative dose to that organ. Lymphomas were excluded because none of the deaths in the study group were associated with cancer in the thoracic lymph nodes. Bone cancer deaths were excluded because of the difficulties estimating doses to various tissues in the skeleton, and only two of the 130 cancer deaths were cases of osteosarcoma. The practice of assigning incidence rates based on such a small number of cases is considered unreliable and not scientifically valid (Rothman et al. 2008). The study found no relationship between external penetrating radiation and any type of cancer, as well as lung and liver cancer related to organ doses from internally-deposited plutonium and americium. However, not surprisingly, a statistically significant association was found between a mere history of smoking behavior (and the rate of smoking, i.e., packs a day) and death due to any cancer.

A number of studies were performed on British plutonium workers with the strongest study being conducted on a cohort of workers at the Sellafield Plant, UK (ATSDR 2010). Similar to the US worker studies, no association was found between plutonium exposures and cancers in tissues receiving the greatest radiation doses from plutonium deposition and retention.

The Mayak production facility was constructed in the former Soviet Union in 1945 for the production, separation, and machining of plutonium. As noted above, plutonium exposures to workers in the former USSR were substantially higher than the US and UK workers. The Russian Federation also maintains an active registry of autopsy results on former workers, "Russian Federation's Dosimetry Registry of the Mayak Industrial Association" (DRMIA). A recent comparison was made of $^{239+240}$Pu concentrations in the liver of body and organ donors of USTUR and DRMIA (USTUR 2012) and are displayed in Figure 4-3. The median concentration of $^{239+240}$Pu among livers studied in Mayak workers was about 400-fold higher than among the livers studied in USTUR cases (USTUR 2012), though there is some overlap in the data. The histogram is based on 260 USTUR cases and 74 DRMIA donors.

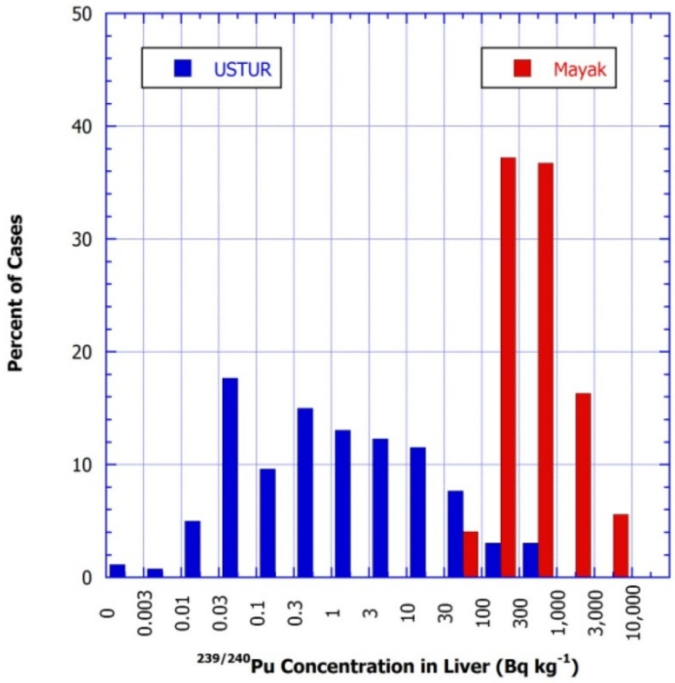


Figure 4-3. $^{239+240}$Pu Concentration in Liver Compared for USTUR and Mayak Workers [Figure 14, USTUR (2012)].

Epidemiology studies of the Mayak workers demonstrated statistically significant increases in lung, liver, and bone cancer based on plutonium exposure, as noted in Table 4-4 after adjustments were made for confounding risk of external radiation exposure. No increased risk of leukemia was noted among the cohort of workers exposed to plutonium (IARC 2010). The risk for lung cancer was best related by a linear correlation with dose, while liver cancers were more appropriately described by a quadratic dose-response function. IARC (2010) noted some uncertainty existed in the shape of the dose-response curve for bone and liver cancers among Mayak workers, reflective of the small number of cases of these cancers. Mayak workers were exposed to airborne ^{239}Pu in oxide and nitrate chemical forms. Suslova et al. (2006) noted, however, much lower retention of plutonium in the liver, compared to that predicted by ICRP models in workers with liver diseases, including cirrhosis. Cirrhosis of the liver, along with hepatitis B infection, are risk factors for liver cancer. The Russian Federation is among the highest countries in per-capita alcohol consumption.

Wilson et al. (2010) performed a comparative study of lung, liver, and bone cancer mortality among beagle dogs exposed to ^{239}Pu and Mayak workers. The authors noted that human data is always preferable over animal data for establishing risk factors for human exposures. However, the augmentation of data from animal studies aids in establishing time-dependent functions of organ-specific plutonium dose, more detailed information on health effects, and a greater range of exposures. In this study, the authors determined that the primary predictor variable of cancer to the organs of interest was cumulative dose from plutonium. In this study, the authors used a life-span adjustment factor of approximately eight between dogs and humans. The study found good correlation in lung cancer mortality rates in Mayak workers and beagle dogs, based on estimated cumulative dose to the lung. The liver and bone cancer risk models developed for Mayak workers did not correlate as well to the beagle dog data, however (Wilson et al. 2010). The authors noted that some uncertainties in modeling bone cancer risk among Mayak workers was due to the small number of cases of bone cancer in the control group (5 cases) and exposed group (6 cases). In addition, some plutonium workers were not monitored during their working years at Mayak, though histories indicated that they had exposure potential and were included in the cohort study (Sokolnikov 2008). This factor could also contribute to uncertainties on dosimetry, and overall risk modeling.

4.3.3.3 Example Autopsy Cases in Workers Exposed to Plutonium.

Table 4-5 contains relative quantities of plutonium in tissues for four USTUR registry tissue donors. These example cases are listed here to illustrate the distribution of plutonium in workers at the time of death. Among these cases, there is a considerable amount of variability in the content among the primary organs of deposition. While there is expected to be variability among individuals in the deposition and retention of plutonium from occupational exposures, there is the expectation for variations introduced by difference in the chemical form of plutonium and the exposure route. For the three latter cases listed in the table, the exposure was limited to ^{239}Pu, which inherently also contains ^{240}Pu, while the worker in the first case was also exposed to ^{238}Pu. In inhalation exposures of $^{238}PuO_2$ to beagles, the material was more readily transferred to the bloodstream and more systemic deposition to the liver and bone surfaces than similar exposure conditions to ^{239}Pu. In addition, each worker had varied exposure potential to plutonium metal, oxides, and nitrates, each of which are expected to have different transferability to the bloodstream and systemic deposition following inhalation exposures. The separation time between exposure and death is varied, with for many cases multiple intakes over long periods of time. Some individual workers may also have received intakes via wounds, which further complicate assessment. Regardless of the variability, the cases demonstrate primary retention of plutonium in the thoracic lymph nodes, lung, liver, and bones. This is one limitation of using groups of workplace human plutonium exposure cases to evaluate the deposition, retention, and transport of plutonium – the varied intake and chemical forms of plutonium. In animal studies, these variables are controlled and with fairly consistent exposures among animals in the same exposure group. Table A-3 and Figure A-1 provide nasal swab and urinalysis bioassay data from USTR Case #193 for informational purposes. Urinalyses were accomplished for this worker through 1982.

Gold and Kathren (1998) summarized cause of death for a cohort of 260 US plutonium workers. No unusual findings for deaths among the cohort were reported. The authors reported that essentially all of the deaths associated with lung carcinoma were associated with individuals that smoked. One osteosarcoma and four cases of liver cancer were among the causes of death.

TABLE 4-5. Relative Quantities of Pu in Tissues
(Norwood and Newton 1974) and (McInroy et al. 1991).

Organ/Tissue	Case			
	05TM Case #0005 $^{238}Pu/^{239}Pu$ metal/oxide Body Content 42.8 nCi	01TM Case #0004 ^{239}Pu metal/oxide/nitrate Body Content 0.27 nCi	01TM Case #0006 ^{239}Pu metal/oxide/nitrate Body Content 42.24 nCi	USTR Case #193 ^{239}Pu metal/oxide/nitrate Body Content 6.6 nCi
Thor. lymph nodes	1.0 *	1.8×10^{-1}	1.2×10^{-1}	5.0×10^{-1}
Abdm. lymph nodes	3.6×10^{-4}			
Lungs	6.4×10^{-2}	7.9×10^{-3}	3.6×10^{-2}	1.0 ****
Bones	2.1×10^{-3}	5.0×10^{-2}	2.3×10^{-1}	5.9×10^{-1}
Liver	1.1×10^{-2}	1.0 **	1.0 ***	5.6×10^{-1}
Thyroid	9.6×10^{-4}			
Kidneys	6.3×10^{-5}	1×10^{-2}	2.5×10^{-2}	8.5×10^{-4}
Spleen		8×10^{-2}	3.8×10^{-2}	1.7×10^{-2}
Testes	2.1×10^{-4}		2.8×10^{-2}	1.3×10^{-4}
Muscle	1.2×10^{-4}		2.1×10^{-3}	
Fat	8.5×10^{-5}		7.1×10^{-4}	
Pancreas	2.0×10^{-4}			2.5×10^{-3}
Skin			6.6×10^{-3}	2.8×10^{-2}
Prostate	1.5×10^{-4}			1.1×10^{-3}
Bladder	6.8×10^{-4}			
Trachea/larynx	1.0×10^{-4}			8.5×10^{-4}
Adrenal	2.9×10^{-4}	2.1×10^{-2}	1.6×10^{-1}	2.6×10^{-4}
Aorta	1.2×10^{-3}			
Stomach	3.4×10^{-4}			5.3×10^{-3}
Large intestine	7.4×10^{-5}			
Small intestine	5.7×10^{-5}			
Heart	2.0×10^{-4}	1.3×10^{-2}	1.5×10^{-2}	8.8×10^{-4}
Brain		5.3×10^{-4}		2.0×10^{-3}
Brain stem		1.8×10^{-3}		
Primary cause of death	Lung Carcinoma	Gunshot wound	Myocardial infarction	Pneumonia

Specified organ activity concentrations: *34 pCi g^{-1}, ** 0.17 pCi g^{-1}, *** 6.3 pCi g^{-1}, **** 1.8 pCi g^{-1}

4.4 Exposure Standards for External Radiation and Plutonium.

4.4.1 Background.

The earliest occupational exposure standards for plutonium were developed within the MED out of concern for worker safety for the newly discovered element that was planned for large scale production. Some concern by MED health professionals was likely reinforced by the recent publication of the tolerance levels for occupational exposures to ^{226}Ra (Moss and Eckhard 1995a) by the National Bureau of Standards (NBS) Handbook 27 (NBS 1941). The total acceptable body burden for ^{226}Ra was set at

0.1 μg (0.1 μCi) and was based on eliminating potential for a number of acute health effects (e.g., anemia, leukopenia, necrosis of the jaw) and chronic health effects (e.g., demineralization of the bone, bone fractures, bone deformities, and osteosarcomas) (Moss and Eckhard 1995a). Radium is a calcium analogue and deposits almost exclusively in mineral bone, which is also the case for strontium. Having some similarities in chemical and nuclear properties to radium, plutonium was thought possibly to be as dangerous as radium (Moss and Eckhard 1995a). Prior to laboratory study data on plutonium metabolism, the MED Plutonium Project adopted a tolerance level of 5 μg retained in the body[1] in January 1944 (Moss and Eckhard 1995a). In July 1945, at the insistence of Wright Langham, whom was a biochemist involved with early animal experiments at Los Alamos (MED, Site Y), the limit was lowered to 1 μg (62 nCi)[1] based primarily on recent findings of lower excretion fractions of plutonium than for radium, and the preferable deposition of plutonium on bone surfaces as compared to radium which deposits throughout the volume of mineral bone (Moss and Eckhard 1995b). The Hanford Site at the time had established an even lower limit of 0.03 μCi (Inkret et al. 1995).

4.4.2 Early US National and International Standards.

The NBS published Handbook 52 in 1953 with permissible amounts of radioisotopes in the human body and maximum permissible concentration(s) (MPC) in air and water for a multitude of radioisotopes studied to that point. Table D-1 contains a listing of quantities for ^{226}Ra, ^{239}Pu, U-natural, and ^{210}Pu, all representative α-particle emitters that were used in the U.S. weapons program at that time. For soluble forms of ^{239}Pu, a maximum permissible body burden (MPBB) of 40 nCi was established (NBS 1953). This level was based on an activity level, as compared to the previous Plutonium Project limits that were based on mass. Using a 0.062 Ci g^{-1} specific activity, this is equivalent to 0.65 μg, about two-thirds the latest level established in the Plutonium Project. The MPBB, however, for insoluble forms was lower, 8 nCi. The criteria for soluble forms of plutonium remained unchanged with an NBS update in 1959, Handbook 69, and its addendum 1963 (NBS 1963). Handbook 69 was also published under the designation of National Committee on Radiation Protection and Measurements (NCRP) Report 22. Similar criteria were also released in ICRP Publication 2 for internal emitters (ICRPa 1959). This was a companion document to ICRP Publication 1 which provided basic recommendations (ICRPb 1959). Note: ICRP prior to 1950 was known as the International X-Ray and Radium Protection Commission (ICRP 1959a). This Commission was founded in 1928, with a parallel U.S. entity, "Advisory Committee on X-Ray and Radium Protection." The International Commission did not develop standards for internal emitters until ICRP Publication 2, while the U.S. had developed an internal exposure standard for radium in NBS Handbook 27 and expanded recommendations to a number of other isotopes in Handbook 52.

During WWII, the external radiation protection standard in place in the U.S. was 0.1 Roentgen per day, as established by the U.S. Advisory Committee on X-Ray and Radium Protection in 1934 (Inkret et al. 1995). After WWII, with the concerns over expanded use of radioactive materials and fallout from nuclear weapons testing, and the potential for health effects, there was significant work by both the ICRP and NCRP to re-address exposure standards. In 1948, NCRP proposed a number of new standards (NBS 1958). A key proposal was establishing a permissible exposure limit of 0.3 Roentgen per week (R wk^{-1}) to the blood-forming organs, a factor of two drop from the previous standard. Also, separate standards were set for the skin (0.6 R wk^{-1}), depth of 7 mg cm^{-2}, hands and feet (1.5 R wk^{-1}), and relative

[1] 310 nCi, with the assumption of a 0.062 Ci g^{-1} α-particle emission rate

biological effectiveness (RBE) factors for various forms of ionizing radiation. This standard was not published until 1954 in NBS Handbook 59 and retained consistency with the ICRP and the International Commission on Radiological Units (ICRU) recommendations in 1950 that were published in NBS Handbook 47 (NBS 1951). In addition, the NCRP defined limits in terms of "permissible dose – the dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime." The NCRP felt that the "tolerance dose" term led to ambiguity (NBS 1954). A 1958 addendum to the Handbook lowered the annual limit to whole-body, head and trunk, active blood-forming organs, or gonads accumulated at any age not to exceed 5 rem times *(N-18)*, where *N* is the age, but limited to 12 rem in a year. The Handbook also established quarterly limits, and applied the new limits to internal emitters, with the exception of bone-seekers that retained the MPBB equivalence with ^{226}Ra. For inhalation of insoluble forms of plutonium, however, limits were tied to critical organ dose limits. The critical organ concept was almost simultaneously developed by the ICRP and NCRP. After WWII and the formation of the AEC under the Atomic Energy Act of 1946, AEC facilities followed the NCRP guideline published in NBS Handbooks and eventually promulgated them as AEC regulation, effective in 1957 (NRCa 2014).

4.4.3 NCRP Report 22 (NBS Handbook 69), ICRP 2, 10 CFR 20.

The work between NCRP and ICRP subcommittees on internal dose in the later 1950's produced the most comprehensive standards for assessment of internal exposures to radionuclides for that time. Although the subcommittees built on many existing principles developed for radium, other radionuclides, and revised external radiation exposure standards developed in the later 1940's and early 1950's, the number of radioisotopes was substantially greater due to the extensive amount of animal research. The principle of the critical organ or tissue for limiting dose was carried over revisions made to the external dose standards in the early 1950's by the ICRP and NCRP. However, critical organs and tissues of concern in the external radiation standard of ICRP (NBS Handbook 47) and NCRP (NBS Handbook 59) emphasized the whole-body, blood-forming organs, skin, gonads, and the lens of the eyes, while the new standard for internal dose recognized a much larger list of critical organs that were radioisotope dependent. Critical organs were determined by four criteria: 1) the organ that accumulates the greatest concentration of the radioactive material, 2) the essentialness of indispensability of the organ to the well-being of the body, 3) organ damaged by entry of the radioactive material into the body, and 4) the radiosensitivity of the organ. Handbook 52 listed permissible exposure concentration based on continuous exposure, a 168-h week. The new standard contained concentrations for the standard 40-h work week in addition to those for continuous exposure.

ICRP 2 provided complete information on the recommendations (ICRPa 1959), while NBS Handbook 69 (also called NCRP Report 22) was an abridged version of the same primary recommendations. The AEC also incorporated the new standard into 10 Code of Federal Regulation (CFR), Part 20, for AEC licensees; Appendix B contained MPC values. Internal exposures were "consistent as far as possible" by the principles governing external dose and age-proration (NBS 1963) as summarized in Table 4-6. Some practical problems existed to implement this approach for workplaces due to the varied ages of workers that would have allowed separate controlling exposure levels. As such, the calculated MPC values listed in the respective report and the CFR's would have listed the most limiting values for a 40-h work week and continuous exposure conditions. MPC's are the respective concentration of a radioisotope in air or water that result in a dose to the critical organ equal to the annual limit on dose to that organ at equilibrium to an exposed worker, with a limit of 50 y for radioisotopes that do not achieve

equilibrium. For bone seekers, the MPBB is the limiting criteria vice a dose limit. For long-lived bone seekers, i.e., ^{239}Pu, ^{90}Sr, ^{226}Ra, equilibrium is not established in 50 y due to the long-term retention in tissues. For short-lived radioisotopes and/or those with short biological retention in the body, exposures at the MPC would incur the maximum dose in the first working year of an employee. For long-lived radionuclides with long-term biological retention, if an employee was exposed to concentrations at the MPC for a prolonged career, doses in the early part of a career could be much lower than those at the latter part of their career. Table D-2 contains MPC values and MPBB for key weapons-related

TABLE 4-6. ICRP 2, NCRP 22 (NBS Handbook 69) Permissible Occupational Exposure Levels.

Category	Organs	Maximum Permissible Dose (rem)		
		Accumulated at any age	Annual	Any 13-consecutive weeks
External exposure to critical organs	whole-body, head & trunk, active blood-forming organs, eyes, gonads	*5 (N – 18), where N is age in years*		3
External dose to other organs	skin		30	10 (NCRP), 8 (ICRP)
	hand/forearm, feet/ankle		75	25
Internal doses (special limits for bone-seekers)	skin		30	
	whole-body, gonads		5	
	other organs		15	
	thyroid		30	8 (ICRP)

radioactive materials under ICRP 2. For soluble compounds of ^{239}Pu, the MPC (air) for continuous exposures was lowered by a factor of about 3, while for insoluble ^{239}Pu compounds the MPC (air) was raised by a factor of five between NBS Handbooks 52 and 69. The MPBB, applicable to inhalation of soluble forms of ^{239}Pu, remained the same between the two handbooks, attributing the difference to varied assumptions of deposition, retention, and translocation in the body between the two handbooks. The MPC (air) for insoluble ^{239}Pu, under NBS Handbook 52 was set equivalent to the MPC (air) for soluble forms under the "possibility of transference of some of the insoluble material from the lungs to the skeleton," (NBS 1951) and not based on a dose calculation to the lungs, as was the case under NBS Handbook 69. Per the methodology in NBS Handbook 52 and ICRP 2, material initially deposited in the lung was not considered part of the body burden – only that material trans-located to the bloodstream with eventual deposition in other organs, i.e., liver and bone in the case of plutonium. The 40-h week MPC's for air and water are not directly scaled by time duration to those for the 168-h period. Rather, for both air and water, it is assumed that total volume inhaled or ingested in an eight hour work period is one half that of a full 24-h day. Effectively, the difference is a factor of 2.8 between the 40-h work week and 168-h continuous exposure period. NBS Report 69 contains MPC values for ^{241}Am and ^{238}Pu, while values for these radioisotopes were not available when NBS Handbook 52 was published. The primary chemical forms of plutonium handled in the weapons production complex were metals, oxides, and nitrates. The metallic and oxide forms were considered insoluble under the ICRP and NCRP internal dosimetry schemes, while the nitrate forms were soluble. Though NBS Handbook 69 did not limit inhalation exposure of insoluble forms of plutonium by the MPBB or MPOB concept, the annual dose limit of 15 rem to the lung equated to a permissible lung burden of 16 nCi (Stannard 1975) and was

commonly referenced as the benchmark for *in situ* assessments of individuals occupationally exposed to insoluble forms of plutonium.

In the example autopsies of workers exposed to plutonium discussed previously in this report, it is clear that the thoracic lymph nodes retain a significant fraction of inhaled insoluble chemical forms of plutonium. Stannard (1975) discussed this issue in detail, with the notable dilemma regarding assignment of tissue mass. He noted that if a 15 g mass is assumed for the thoracic lymph nodes, this organ would be a more appropriate selection for the critical organ, with a 440-fold reduction in acceptable air concentrations over use of the lung as a critical organ under the ICRP 2 methodology. An assumption of a 1,000 g mass for lymph tissue, in contrast, would retain a similar MPC to that for the lung. Stannard (1975) noted that ultimately the lack of damage, except fibrosis, to the lymphatic tissue, has been the primary reason the thoracic lymph tissue was not chosen as the critical organ – a conclusion based on the extensive animal exposure studies. Stannard (1975) noted that the practice represented the largest extant modification of standards for plutonium due to a tissues' relative radiosensivity.

Air samples collected after the plutonium mishaps during Operation Dominic I were compared to an MPC value of 2 pCi m^{-3}, consistent with ICRP 2, NCRP 22, and NBS Handbook 69 for soluble chemical forms of plutonium to meet a MPBB of 0.04 μCi. Use of this criterion for the exposure circumstances that existed on Johnston Island was conservative for two primary reasons. First, plutonium released from the accidents would be expected to be a dioxide, an insoluble chemical form that had an MPC 20-fold higher. Second, exposure durations were limited compared to the assumptions used in derivation of MPC values, which assumed possible exposure 2,000 hours in a year and a 50-y employment duration for an individual.

4.4.4 ICRP 26 and 30.

ICRP 2 was replaced in 1977 by a new set of recommendations in ICRP Publication 26 (ICRP 1977), although implementation by the Nuclear Regulatory Commission (NRC) of the new recommendations did not occur until 1991. Occupational limits for internal dosimetry were made in a multi-volume ICRP Publication 30 (ICRPa/b 1979, ICRP 1980, ICRPa/b 1982). ICRP no longer used the critical organ approach, but rather provided protection from stochastic effects (cancer and genetic) based on a weighted sum of dose equivalent values to irradiated tissues/organs. The weighted sum of dose equivalents, the effective dose equivalent (EDE), was limited to 5 rem in a year. Quarterly limits were removed. The ICRP assumed that the risk to radiation workers would be acceptable if an annual mortality risk at this dose level did not exceed 10^{-4}, which in the U.S. was equivalent to annual workplace fatalities among more hazardous occupations. Genetic risks were assumed to represent only 25% of the total stochastic risk (Jones 2005). Protection from non-stochastic effects was based on annual limits to individual organs. Non-stochastic effects are those where an apparent threshold below which clinically observable effects do not occur. As well, the severity of the damage commonly depends on the magnitude of the dose, provided it meets the exposure threshold. Non-stochastic effects are generally related to a sufficient degree of radiation induced cell death in affected organs or tissues to produce clinically observable effects. In contrast, stochastic effects are based on cells that are modified, yet not killed. Doses were also limited by the as low as is reasonably achievable (ALARA) principle and the expectation of an overall benefit from the activity causing the exposure. The bone seeking radionuclides, e.g., ^{226}Ra, ^{239}Pu, ^{232}Th, and others that were traditionally limited to equivalence with ^{226}Ra were limited on a dose basis.

Dose modeling under the ICRP 26/30 system incorporated substantially updated lung and bone models compared to those used under ICRP 2. The new lung model assigned aerosols into one of three classes, compared to the two contained under ICRP 2. Though dose limitation to the critical organ was not retained, some bases for development of the critical organ was retained in the varied organ weighting factors listed in Table 4-7 along with the basic dose limits. The new bone model increased the specific effective energy (SEE) to endosteal tissue for ^{226}Ra by a factor of 1.6 over that used in ICRP 2. For ^{239}Pu, the SEE was raised by a factor of 12 in the ICRP 30, compared to ICRP 2.

TABLE 4-7. ICRP 26 Dose Limits and Organ/Tissue Weighting Factors for Adults.

Application	Annual Limit	Organ/Tissue	Weighting Factor
Total Effective Dose Equivalent (TEDE)	5 rem	Gonads	0.25
Deep Dose Equivalent & Committed Dose Equivalent	50 rem to an individual organ or tissue, except lens	Breast	0.15
Lens of Eye	15	Red Marrow	0.12
Skin	50	Lungs	0.12
Extremities	50	Thyroid	0.03
		Bone Surfaces	0.03
		Remainder*	0.3

* 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.

Doses from internally-deposited radionuclides were handled differently than under ICRP 2. Intakes occurring during an annual monitoring period had 50-y of the committed dose calculated from the intake applied to the year of exposure. Due to this methodology, the period of time varied between time of intakes and the realization of dose to tissues/organs, dependent of the chemical form of the radioactive material, half-life of the radioactive material, and biological retention in the body. Some radioactive material, e.g. tritium (^{3}H) and ^{131}I, have relatively short effective retention in the body. Tritium has an effective biological half-life 10 d, though the radiological half-life is 12.4 y. In contrast, iodine has a biological retention in the adult thyroid of 80 d, though the effective retention of ^{131}I in the thyroid is only about 7 d due to its short, 8 d radiological half-life. For ^{239}Pu, due to its relatively long biological retention in tissues, it may take decades for a large fraction of the 50-y committed dose to be realized. For individuals receiving an intake later in life, only a fraction of the 50-y committed dose may be realized, reducing probability for cancer induction. Many non-stochastic effects are based on large doses received in an acute manner. For ^{239}Pu, a possible effect is cytopenia, due to deposition of plutonium on bone surfaces. From an inhalation exposure, committed dose to the bone surfaces would be assigned to an annual monitoring period, however, due to the slow removal from the lung and subsequent transport to the bone surfaces via the blood stream, an acute dose of 50 rem to the bone surface would never be realized with common inhalation intake scenarios at the annual limit of intake (ALI). Most occupational intakes to plutonium for US workers were acquired from 1) accidental releases in controlled workplaces that were deftly mitigated, 2) exposures over short periods of time associated with responses to successful atmospheric tests, 3) over a short period clearing up residuals from nuclear weapons accidents, or 4) from an accident experienced during atmospheric testing of nuclear weapons, i.e., Johnston Island. Additionally, the quality factors used to modify absorbed dose

are developed for stochastic effects. Modifying factors more appropriate for non-stochastic effects from high, linear energy transfer radiations, like α-particles, would be lower than the assigned quality factors.

Table D-3 contains a summary of ALIs and derived air concentration (DAC) limits for a 2,000 h work year for ^{238}Pu, $^{239/240}$Pu, and ^{241}Am based on Federal Guidance Report (FGR) 11, and consistent with ICRP 26, 30 and 48. ICRP 48 modified the metabolism assumptions from ICRP 30 for plutonium and some other related compounds. ICRP 30 proportioned deposition from the bloodstream equally at 45% for the bone and liver, with about 7% to soft tissue and 3% to urinary and fecal excreta. In ICRP 48, the bone was assumed to receive 50% from the bloodstream and the liver 30%. As well, for inhalation Class W compounds, the f_1 value was increased from 10^{-4} to 10^{-3} from ICRP 30 to ICRP 48. Inhalation Class Y compounds, hydroxides and oxides, have a DAC of 7×10^{-12} μCi cm^{-3}, based on the non-stochastic limit of 50 rem to the bone surfaces, though the committed effective dose equivalent (CEDE) is very close to 5 rem at the ALI. Inhalation Class W compounds have a DAC of 3×10^{-12} μCi cm^{-3}, based on the non-stochastic dose limit to the bone surfaces, though inhalation intakes at the ALI only produce a CEDE of 2.76 rem. Figure 4-4 contains a bar graph of the dose equivalent values to organs/tissues and the CEDE for inhalation intakes at the ALI for Class W and Y ^{239}Pu. Clear for the Class Y plutonium is the strong modeled retention in the lung vs. Class W forms that are assumed to be more readily cleared. For both inhalation classes, dose to the liver dominates the sum of remainder organ/tissue dose equivalent. For PuO_2, the ICRP 26/30/48 DAC is a factor of 5.7 lower than the MPC for air (40-h week) under ICRP 2. For plutonium nitrates, the ICRP 26/30/48 DAC is only a factor of 1.5 lower than the MPC for air (40-h week) under ICRP 2. Table D-4 contains dose conversion factors to individual organs from Federal Guidance Report 11, which is consistent with ICRP 26/30/48. 10 CFR 20, promulgated in 1991, is consistent with ICRP 26/30, but has some differences with FGR 11 for plutonium and americium, as it did not incorporate ICRP 48.

Sutcliffe et al. (1995) noted that an acutely lethal dose from plutonium would require the ingestion of 0.5 g, while death from pulmonary fibrosis or edema would require an inhalation intake of 20 mg of a properly sized aerosol. With a specific activity of 0.072 Ci g^{-1}, this would be equivalent to inhalation and ingestion intakes of 36 and 1.44 mCi, respectively. Condit (1993) noted a lethal (within 30 d) lung burden from an acute intake at 0.26 mCi. For either intake pathway, there is an inherent assumption of the most favorable chemical form:

1) a soluble form for ingestion, allowing for the greatest gastrointestinal tract uptake and

2) an insoluble form for inhalation that allows for the greatest retention in the lung.

Table 4-8 contains a comparison of acute lethal intake activities to the ICRP 26/30/48 ALIs. The Class Y compound inhalation ALI is 72,000-fold lower than the acute lethal intake level. For the most soluble chemical, $f_1 = 10^{-3}$, the ALI is 45-fold lower than the acute intake level.

4.4.5 ICRP 60/61/66/68.

In 1990, ICRP replaced the 1977 recommendations contained in ICRP 26 with ICRP Report 60 (ICRPb 1991). The recommendations were prompted by new biological information on radiation and trends in safety standards. These recommendations used new terminology. Radiation weighting factors were used to modify dose for the various types of radiation and energy for stochastic effects, compared to the

TABLE 4-8. Comparison of Acute Lethal Intakes to ICRP 26, 30, and 48 ALI's for $^{239+240}$Pu.

Exposure Route	Acute Lethal Intake (mCi)	ALI (mCi)	Inhalation Class (Limiting Organ)	f_l
Inhalation	1.44	6×10^{-6}	W (Bone Surface)	NA
		2×10^{-5}	Y (Bone Surface/CEDE)	
Ingestion	36	0.8	NA	10^{-3}
		8		10^{-4}
		80		10^{-5}

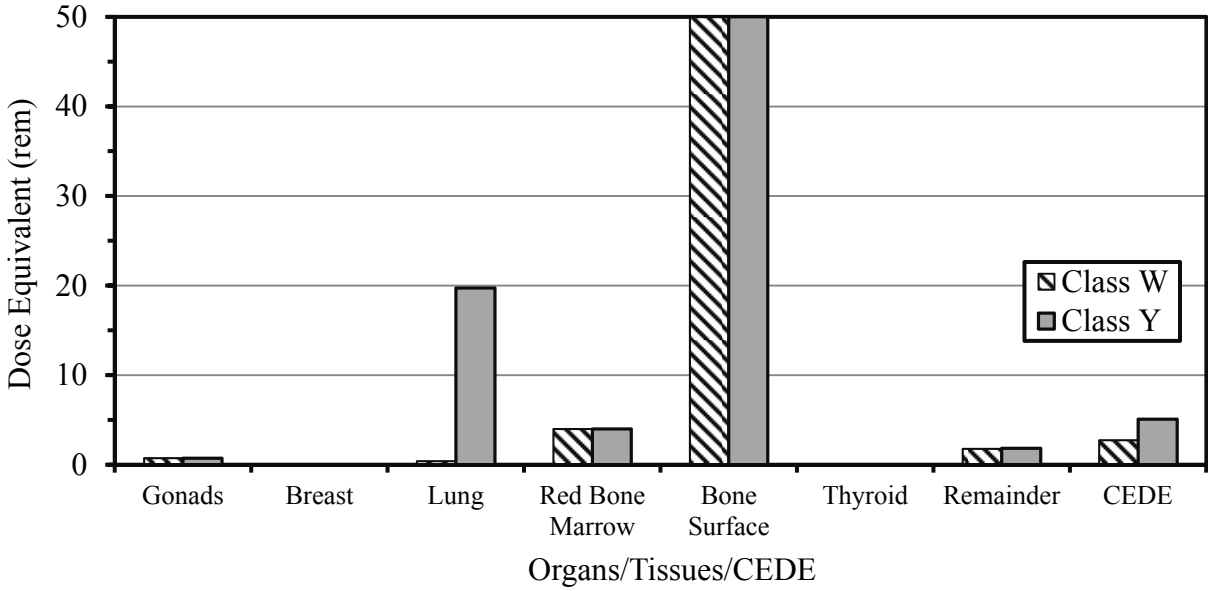


Figure 4-4. Bar Graph of 5-Year Committed Dose Equivalent Values to Organs, Tissues, and the CEDE from Inhalation Intakes at the Class W and Y ALIs, ICRP 26/30.

quality factors used in the previous ICRP recommendation. The dose modified by this factor for an organ or tissue was termed equivalent dose in the new recommendations. The radiation weighting factor, w_R, for α-particles remained unchanged at 20 from ICRP 26. The ICRP did not retain use of the non-stochastic effects term, but rather changed it to "deterministic" effects. Organ/tissue weighting factors, w_T, were modified from ICRP 26, as listed in Table 4-9. Key changes from ICRP 26, with respect to plutonium exposures, is the drop in the weighting factor for the bone surfaces by a factor of 3. The liver only had a minor change from 0.06 to 0.05, from ICRP Report 26 to 60. Table 4-10 contains the ICRP dose limits. Due to the drop in the annual limit, a committed equivalent dose to individual organ/tissue was no longer deemed necessary because deterministic effects were sufficiently covered by the effective dose limit for stochastic effects, with the exception of the lens of eye, skin, hands, and feet, as noted in Table 4-10.

ICRP Publication 61 (ICRPa 1991) listed annual limits on intake, based on ICRP 30/48 biokinetic modeling, and ICRP 60 dose limits and tissue weighting factors. Due to the same biokinetic model, the relationship between organ doses and intakes, i.e., commonly called dose conversion factors (DCFs), did not change. However, due to changes in the annual limits and tissue weighting factors, changes in the ALIs were observed for many radionuclides, including plutonium. Table 4-10 contains a summary of ALI values for inhalation and ingestion intakes for occupational exposures from ICRP Reports 26 through 68. Because there was no change in the lung tissue weighting factor, the only effective change from ICRP Reports 26/30/48 to ICRP Reports 30/48/60/61 for inhalation Class Y compounds was the change in the annual limit for CEDE to effective dose, *E*, a factor of 2.5. For inhalation Class W compounds only a minor change occurred in the ALI, even though there was a drop of a factor of 2.5 between the CEDE of ICRP 26 and the effective dose of ICRP 60. This was due to the three-fold drop in the bone surface weighting factor.

TABLE 4-9. 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 4-10. ICRP 60 Dose 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)	-

ICRP Publication 68 (ICRPa 1994) was an update to ICRP 61's annual limits on intake to workers, based on the newer lung biokinetics model in ICRP 66 (ICRPb 1994) and updates to the metabolism of many elements, including plutonium in ICRP 67 (ICRP 1993). ICRP 67 dropped the relatively high f_1 value of 10^{-3} for unspecified plutonium compounds to 5×10^{-4}. The new lung model was considerably more detailed than the previous model. The ICRP 30 inhalation class system of D, W, and Y was changed to near equivalents of F, M, and S in ICRP 66. As observed in Table 4-10, the new lung model

and changes in plutonium metabolism increased the ALI's from ICRP 30/48/60/61 to the ICRP 60/66/68 recommendations, though the effective dose limit remained the same between the sets of recommendations. For inhalation Class Y (Type S) compounds, i.e., PuO_2, the ALI for inhalation exposures was raised by a factor of 4.5, and 1.5 for inhalation Class W (Type M) compounds. Overall, for inhalation of Class Y compounds under ICRP 26/30/48, compared to Class S under ICRP 60/66/68, the ALI was increased by a factor of about two, though the dose limitation endpoint was decreased by a factor of 2.5 between the two sets of recommendations. For the comparable inhalation Class W (Type M) compounds, the ALI increased by 20% for inhalation intakes.

TABLE 4-11. ICRP 26/30/48, ICRP 60/61, ICRP 60/66/68 Annual Limits on Intake for $^{239+240}$Pu.

Exposure	Inhalation Class (Type)	ALI (μCi) for Respective ICRP Reports						
		26/30/48	f_1	Limiting Criterion	30/48/60/61	f_1	60/66/68	f_1
Inhalation	W (M)	0.006	10^{-3}	Bone Surface	NA	NA	NA	NA
		0.01	10^{-3}	CEDE	0.008	10^{-3}	0.012	5×10^{-4}
	Y (S)	0.02	10^{-5}	CEDE	0.008	10^{-5}	0.036	10^{-5}
Ingestion	W (M)	0.8	10^{-3}	Bone Surface	NA	NA	NA	NA
		1.0	10^{-3}	CEDE	NA	NA	2.2	5×10^{-4}
		8.0	10^{-4}	Bone Surface	1.1	10^{-3}	10	10^{-4}
	Y (S)	80	10^{-5}	Bone Surface	8.1	10^{-5}	60	10^{-5}

For limiting criterion of bone surface, the limit is 50 rem CED, for CEDE limit under ICRP 26 the limit is 5 rem in a year. For ICRP 60, *E* of 5 rem in a year is the limit.

4.4.6 Environmental Protection Agency (EPA) Proposed Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment (1977).

In 1972, the State of Colorado raised interest in the acceptable levels of plutonium in soils in regard to the utilization of land in the vicinity of the Rocky Flats site (EPA 1977). As an interim measure in 1973, the State of Colorado adopted a plutonium activity concentration limit of 2 disintegrations per minute per gram (dpm g^{-1}) [0.9 pCi g^{-1}], as averaged over the top 1/8 inch (~ 3 mm) soil as a guide for protection of construction workers building homes (EPA 1977). The interest at this site, among many others in the AEC complex, prompted the EPA to develop guidance for exposures in the general environment. The guidance was developed with the expectation that it would guide remedial actions for sites contaminated with transuranics.

The EPA made the following recommendations (EPA 1977):

1) The annual alpha radiation dose rate to members of the critical segment of the exposed population as the result of exposure to transuranium elements in the general environment should not exceed either:

a) 1 mrad per year to pulmonary lung [bronchioles, alveolar ducts, atria, alveoli, and alveolar sacs] or

b) 3 mrad per year to the bone [dose rate attained after 70-y of chronic exposure].

2) For newly contaminated areas, control measures should be taken to minimize both residual levels and radiation exposures of the general public.

3) The recommendations are to be used only for guidance on possible remedial actions for the protection of the public in instances of presently existing contamination or of possible future unplanned releases of transuranium elements.

The EPA recognized that the radiation risk due to inhalation exposures is primarily lung cancer, with lower risk contributions to the liver, bone, and gonads after translocation of material from the lung. The EPA predicted that an exposure of 70-y would contribute to a risk of 10 premature deaths in 100,000 persons, or about 10^{-6} per person-year. Due to the dominance of the inhalation exposure pathway over ingestion from plutonium in surface soils, the dose to lung would be the limiting criterion.

In addition to the dose limiting criteria, the EPA also developed soil screening levels and air concentrations using conservative assumptions (EPA 1977a). The EPA noted that the screening level should not be used as a remedial action criterion, due to the conservative nature of the assumptions made in the calculations. The following criteria were used in developing the screening level:

1) mass loading of 100 $\mu g\ m^{-3}$ from ambient aerosols from resuspended dust,

2) soil is enriched with activity in the respirable range relative to the soil as a whole,

3) the contamination is widely dispersed and a correction for area size is not appropriate, and

4) no land use restrictions.

Table 4-12 contains the EPA proposed screening levels for transuranics, with additional detail in Table D-6. The basic soil criterion was 0.2 $\mu Ci\ m^{-2}$, as averaged over the top centimeter of soil and for particles of size less than 2 mm. Assuming a soil density of 1.5 g cm^{-3}, the criterion is 13.3 pCi g^{-1}. A similar criterion, 13.5 pCi g^{-1}, was provided by the EPA as interim guidance for soils in 1987 (EPA 1987). This was one remedial action criterion establish for soils on Johnston Island (Geo-Centers 2002). In 2000, Defense Threat Reduction Agency (DTRA) requested concurrence from the AF, US Fish and Wildlife Service, and the EPA on a 40 pCi g^{-1} criterion for soils, based on a 10^{-4} lifetime risk of cancer morbidity (Geo-Centers 2002). Nevertheless, though the AF concurred, DTRA based final corrective actions on the 13.5 pCi g^{-1} criterion (DTRA 2002). In the case of either criterion, the limit was based on a lifetime residential occupancy, though DTRA noted the unlikelihood of an exposure of this nature. In the remediation of Enewetak Atoll, residential areas were remediated to 40 pCi g^{-1} of transuranics (DNA 1981), however, in the case of this island, the areas were inhabited post remediation.

TABLE 4-12. EPA Proposed Screening Levels for Transuranics (EPA 1977).

Application	Criterion (Total α)	Units	Equivalent
Soil Screening	0.2 (top 1 cm)	$\mu Ci\ m^{-2}$	13.3 pCi g^{-1} (ρ = 1.5 g cm^{-3})
Air Concentration	1 (averaged over year or more)	fCi m^{-3}	37 $\mu Bq\ m^{-3}$

5.0 Radiological Surveillance Activities and Restoration Activities on Johnston Atoll

5.1 General. Plutonium contamination created during the 1962 Operation Dominic launch failures was mitigated by a number of methods over 40 y, with the last action being a 2002 on-site burial of the higher concentration residuals from the soil sorting operation. The Island was deserted by the military in 2004, with intermittent visits by the US Fish and Wildlife Service personnel after this time. Since the 1962 mishaps, radiological surveys were accomplished on the Island. Some were on a routine basis, while others were special purpose surveys where personnel travelled to the Island to conduct their work. In addition to the survey of soil, building surfaces, and equipment, a substantial amount of air sampling was conducted. Air sampling is a key index of exposure potential for plutonium because inhalation is generally the most significant pathway of exposure to individuals in plutonium-contaminated environments. A radiological survey conducted in 1980 was the most extensive and provides perhaps the best evaluation of residual plutonium on the Island after the 1962 mishaps, with the exception of small-scale contamination removal activities that were conducted prior to this survey. In the mid-1980's, mitigation activities were conducted on buildings and other structures within the Radiation Control Area (RCA) that was established initially on the boundaries of LE-1, but was expanded in 1975 when contaminated areas were identified outside the confines of the RCA (Dooley et al. 1986).

5.2 Mitigation Shortly after the Bluegill Prime Mishap.

The failure of the Bluegill Prime launch occurred on the launch pad. During the mishap, a fire engulfed the missile and the nuclear warhead was intentionally destroyed by the Range Safety Officer (CJTF 1964). Figure 5-1 contains a photograph of a Thor missile on LE-1 before the Bluegill Prime mishap. Extensive radioactive contamination to the launch pad occurred as a result of this mishap. A photograph of LE-1 shortly after the mishap is shown in Figure 5-2. Clear from the photograph is the blackened area on the soil adjacent to the launch pad, and the launch emplacement structures and infrastructure. The cable trenches that extended to the north and south directions from the launch pad contained a significant amount of soot from the fuel flow during the mishap. The explosions caused the scattering of contaminated debris throughout the launch emplacement (CJTF 1964). During the mishap, the prevailing winds were 15 knots from 110°, i.e. to the west-northwest, which carried airborne contaminants to the lagoon of the Atoll (CJTF 1964). From Figure 5-2, a darkened soil area is observable extending from the launch pad to the upper section of the photograph, which could be attributed to the effect of the explosion and/or wind-based transport, but unlikely due to fuel flow.

After the flames from the burning missile fuel had subsided, three "Rad-Safety" members from the DCT entered LE-1 with fire crew members (Holmes and Narver 1963). The team noted that with the exception of a few missile fragments identified outside the concertina-wired emplacement, contamination was limited to the immediate vicinity of the launch pad (Holmes and Narver 1963). According to Holmes and Narver (1963), fragments identified outside LE-1 were moved by the DCT to a safe location within 48 hours of the mishap. Further, it was reported that buildings, to include living quarters, and the mess hall were also monitored with portable radiation detection equipment, with negative findings. This finding is logical due to the prevailing wind direction during the mishap (from the east), and generally for most time periods, consistent with trade wind patterns for this region of the Pacific Ocean.

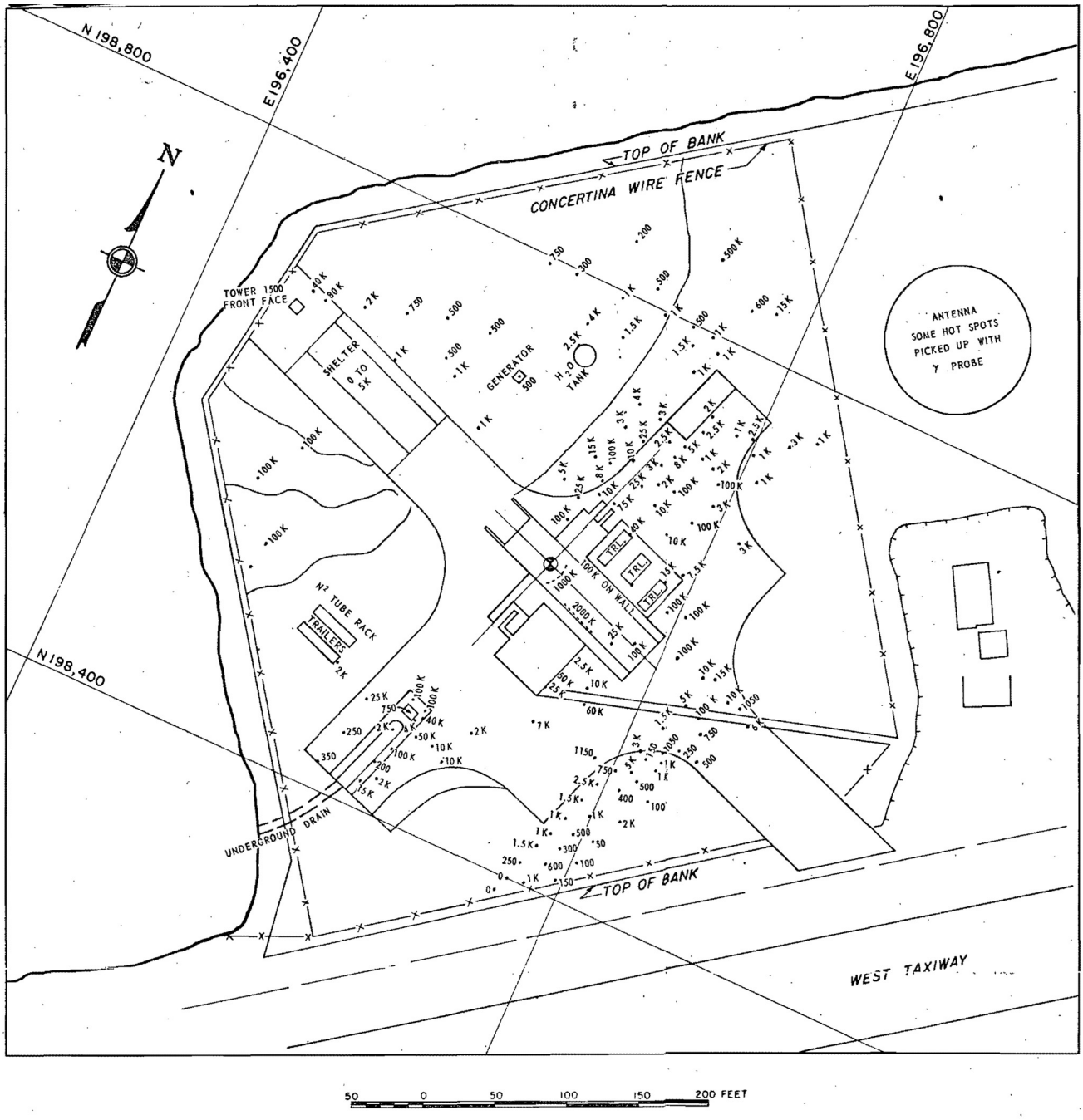
Figure 5-1. Aerial Photograph of LE-1 Prior to Bluegill Prime Mishap, June 1962 (View from North).

Figure 5-2. Photograph of LE-1 After Bluegill Prime Mishap, July 1962 (View from Southeast).

Due to the contamination of the launch pad, a pause in test operations was necessary until LE-1 could be rehabilitated for safe use (Berkhouse et al. 1983). During this period of time most personnel returned to their home bases of assignment until testing resumed (Berkhouse et al. 1983). Entries into the contaminated LE-1 were closely controlled, with personnel leaving the contaminated zone being processed through a decontamination center, which consisted of a "hot" tent with laundry, two showering compartments, a "clean" tent for clothing issue and the radiological monitoring of personnel prior to exiting the contaminated zone (Holmes and Narver 1963). The decontamination center was located on the northeast corner of LE-1. The following morning after the mishap, DCT personnel surveyed ground areas, structures, and buildings in LE-1 for α-radiation contamination with Eberline Models PAC-1S (i.e, portable alpha counter, scintillator type) and PAC-3G (i.e., portable alphas counter, gas- flow proportional). Results of the survey are contained in Figure 5-3 from Holmes and Narver (1963). The count rates noted on the Figure range from 0 to 2,000 kilo counts per minute (kcpm), though the peak measurement of the PAC-1S and PAC-3G was 2,000 kcpm and 100 kcpm, respectively. It is possible that part of the PAC -3G's detector entrance window was covered to extend the effective measurement range, or simply the measurements in the more highly contaminated areas were collected with the PAC-1S. Each detector has an approximate 60 cm^2 entrance window and a 4π detection efficiency of about 20% (Ello 1966). The DoD used the AN/PDR-60 designation for the PAC-1S and AN/PDR-54 for the PAC-3G (Jaycor 1985). Due to the irregularity of ground contamination, as is evident from inspection of the count rates in Figure 5-3, no attempt was made to draw iso-contamination curves (CJTF 1964). All personnel working in the contaminated zone during the rehabilitation of LE-1 were required to wear canvas or rubber booties, respirators, and protective clothing (CJTF 1964), as illustrated by the personnel inspecting the Thor rocket engine in Figure 5-4.

Restoration of the contaminated LE-1 took approximately two and a half weeks to reduce α-radiation contamination levels to a point that did not constitute a health hazard to unprotected personnel supporting the operation (Berkhouse et al. 1983). The majority of the work-force that accomplished the restoration and accompanying radiation safety support was provided by Holmes and Narver, an AEC contractor (Berkhouse 1983). The restoration plan encompassed the 1) removal of debris and contaminated topsoil (coral), 2) the addition of clean replacement top soil (coral), 3) decontamination of the revetments and paved areas, 4) fixation of contamination on surfaces with a surface coating (primarily paint), and 5) disposal of the waste at sea. Holmes and Narver (1963) listed the number of personnel on a daily basis processing through the control point during restoration of LE-1, as reported in Table 5-1.

Diesel oil was sprinkled over contaminated soil to minimize resuspension of radiological contamination prior to the scraping of approximately 2 inches (5 cm) of contaminated soil (Holmes and Narver 1963). The contaminated coral was piled in the northeast corner of LE-1 prior to it being transported to sea (along with other debris) by landing craft from this point in LE-1 (Holmes and Narver 1963). Some of the contaminated coral aided as fill material supporting a ramp to the loading craft, but ultimately was washed out to sea (Holmes and Narver 1963). R.C. Harbert, the General Manager of Holmes and Harver in 1973, reported that it was possible that material which formed the ramp may have been "covered during the subsequent dredging operation [i.e., the 1964 expansion] that enlarged the island" (Geo-Centers 2000). Though this was an issue of interest of discussion in the 2000 radiological survey of the RCA (Geo-Centers 2000), regardless of the fate of this material: 1) washed away to sea, 2) covered during the expansion of the Island in 1964, or 3) potentially dredged and used as fill during the 1964 expansion of the Island, if the contaminated soil was not on the surface and available for



PLOT PLAN - LAUNCH PAD NO. 1

Figure 5-3. Radiological Survey of LE-1, 26 July 1962, Ten Hours Post Bluegill Prime Mishap, Readings in Count per Minute, Eberline PAC-3G's (Holmes and Narver 1963).

resuspension, it presented no practical exposure pathway to personnel on the Island after the restoration. On 4 August, "hot areas" were afforded additional surface scraping (Holmes and Narver 1963).

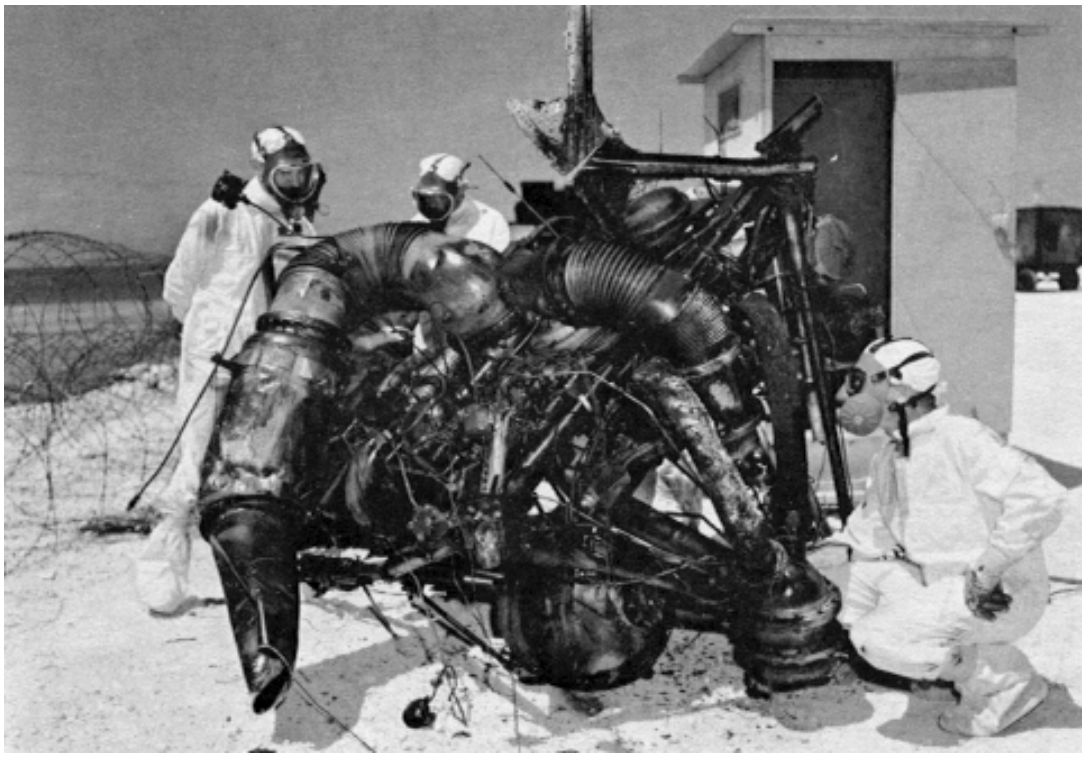


Figure 5-4. Photograph of Thor Rocket Engine after Bluegill Prime Mishap, July 1962.

TABLE 5-1. Number of Personnel on a Daily Basis Processed Through the Control Point During Restoration Phase of Bluegill Prime Mishap (Holmes and Narver 1963).

Date	Number	Date	Number	Date	Number
29 July 1962	13	3 August	62	8 August	20
30 July	88	4 August	56	9 August	54
31 July	33	5 August	61	10 August	80
1 August	37	6 August	57	11 August	NA
2 August	63	7 August	28	12 August	38

Damaged and contaminated cables and equipment were staged downwind from the launch pad in preparation for sea disposal (Holmes and Narver 1963). Concrete and building surfaces were scrubbed with "Gunk" and other solvents in an effort to remove surface-deposited contamination (CJTF 1964). Figure E-1 contains a plot of initial α-radiation contamination levels on structural components. The inside walls of the two buildings abutting the launch pad ranged between 1,000 and 3,000 cpm, while many exterior surfaces had surface contamination levels reading many hundred thousand cpm. After repeated attempts at removal, if a surface retained contamination, surface swipes samples were used to assess the removable fraction of the contamination (Holmes and Narver 1963). After it was determined that the contamination was fixed, concrete surfaces were fixed with fire-retardant paint, except the base of the launch mount, which was coated with epoxy paint (Holmes and Narver 1963). Contaminated wooden rail ties were covered with concrete, cable conduits were grouted with concrete or steel plates,

and the bottoms of cable trenches were covered with concrete (Berkhouse et al. 1983). Blast and fire from subsequent missile launches re-exposed contaminated surfaces, which necessitated recoating after each launch (Holmes and Narver 1963) and the recovery and disposal of paint chips as radioactive waste well into the mid-1970's. Painters chipping paint or repainting contaminated surfaces were required to wear full "Rad-Safe" gear, including respirators (Holmes and Narver 1963). There was only one more launch of a Thor missile from LE-1 during Operation Dominic I, on 26 October, thought LE-1 was used for seven more Thor launches between 14 February 1964 and 27 March 1970, as listed in Table B-1. Figure E-2 contains a plot of α-radiation contamination levels from a 23 November 1962 survey, which was conducted after the 26 October Thor launch. Notable are the "zero" readings in soil areas, though some moderate activity existed on the revetments, which were attributed to locations that involved peeling paint. These areas required repainting, per the surveillance and control policies instituted by the AEC (Holmes and Narver 1963). The US PHS collected swipe samples at a number of locations on LE-1 on 20 December 1962, after the last launch during Operation Dominic I. The results are summarized in Table E-1. The majority of the swipes had "zero" reported activity, with about one-third having activity concentrations between 4 and 28 dpm per 100 cm^2, and one sample at 204 dpm per 100 cm^2. The average was 17 dpm per 100 cm^2, which is on par with removable contamination levels for unrestricted release of contaminated materials in the current American National Standards Institute (ANSI) Report N13.12 (ANSI 2010).

Extensive high-volume air sampling was conducted during the restoration activities, with continuing sampling on the launch pad for many months after restoration activities were completed. Table E-2 contains a summary of the sampling results. During the restoration phase, three air sampling stations were established. One was placed in the hot area, on the northwest portion of LE-1, downwind from the launch pad and where contaminated soil and debris were staged prior to ocean disposal. A second one was placed at the decontamination tent, which was just outside the LE-1 concertina-wired boundary on the northeast, in an upwind area. A third one was placed at the launch pad area, which initially contained the most significant levels of contamination. The samples were collected with a Staplex High Volume Air Sampler, with an inventory of 12 available for use (Holmes and Narver 1963). A summary of the air sampling results are in Appendix E, Table E-2. The established MPC (40-hour week) for personnel was 2 $\mu\mu$Ci m^{-3} (2 pCi m^{-3}) for restoration activities (Holmes and Narver 1963), equivalent to the MPC in NBS Handbook 69, based on soluble forms of plutonium and bone as the critical organ (see Table D-2). As discussed above in the discussion of exposure standards, it was noted that this value was commonly used for personnel in nuclear weapon accident response; however, PuO_2 forms are expected in accidents of this type where plutonium metals are subjected to high temperatures in oxygen-rich environments. The MPC for $^{239}PuO_2$ was 30 $\mu\mu$Ci m^{-3} under NBS Handbook 69. In comparison, the ICRP 26/30/48 DAC levels are 3 and 7 pCi m^{-3}, respectively for Class W and Y compounds.

Air sampling was first conducted in the hot area on 28 July, while it was initiated on 31 July at the decontamination tent and on 3 August on the launch pad. The sample with the highest α-radiation concentration was collected on 2 August in the hot area, with an average concentration of 1,100 pCi m^{-3}. Around this period, many of the higher air concentrations were observed in the hot zone, 280 (30 July), 170 and 160 (31 July), 250 and 220 (1 August) pCi m^{-3}. After the end of July and the first week of August, however, concentrations in the hot zone greatly diminished, as observed from the data in Table E-2. The reduction could be attributed to a number of factors. First, the soil scraping operation that was initiated at the end of July and completed during early August would have aided the resuspension of contamination. Without this activity, resuspended contamination levels would have been lower.

Second, prior to the removal of contamination of surface soils, these contaminated surfaces remained as a source of resuspension from existing surface wind activity. Though it was noted that some of this contaminated coral was placed on the edge of the Island - in the lagoon as a ramp for landing craft, the material would have been partially saturated by sea water and encompassed a substantially smaller surface area available for resuspension. If resuspended, the contamination would have been carried to the lagoon, an uninhabited area. Also, the first phase of contaminated debris disposal at sea was accomplished between 2 and 10 August, which is listed in Table E-3. Later in August, additional sea disposals were accomplished, but with significantly less material than disposed in the first phase. A summary of this disposal action is also listed in Table E-3. Air sampling was discontinued in the hot area on 20 August, a day before the last sea disposal action was conducted in August. All the air samples collected in this area after 10 August were below the 2 pCi m^{-3} criterion established for personnel during restoration. Air samples collected at the decontamination tent had the lowest concentrations among the three sampler stations. The vast majority of the samples had α-radiation concentrations less than 0.1 pCi m^{-3}, with the highest at 1.6 pCi m^{-3}, collected on 7 August. Air sampling was discontinued at this sampling location the end of August. Air samples collected from the launch pad did not begin until 3 August. This sampler arguably provided the best estimate of airborne contamination personnel received working within LE-1 during the restoration period and after, as the bulk of the infrastructure was contained in the center of LE-1 at the launch pad location. Up until 12 August, personnel wore full protective gear while working in LE-1. After this point in time, most protective precautions were removed, with the exception of personnel that scraped, removed contaminated paint, and repainted contaminated surfaces in the launch pad area (Holmes and Narver 1963). The highest α-radiation concentration on a sample collected at this location prior to 12 August was 4.01 pCi m^{-3}, though the other samples were well below this level, with many below 0.2 pCi m^{-3}.

Air sampling results from LE-1 are plotted in Figures 5-5 and 5-6. Figure 5-5 contains result for the period of 10 August 1962 to 20 April 1963. During the early part of this period, samples were collected on an AM/PM basis, which appeared to encompass two work periods. In the beginning of August, there was almost 13 hours of daylight, which could have afforded about 6 to 7 hours per sample if work was accomplished during the daylight period. After 14 August, only single daily samples were collected, where from the review of actual individual sample data sheets, it is apparent that most were for a 24-hour period. Some apparently covered two or three days, during periods where no work was accomplished or access to LE-1 was restricted because of a launch on LE-2, where the majority of support personnel were evacuated from the Island prior to launch. For the lone launch from LE-1 after the Bluegill Prime launch failure within Operation Dominic I occurred on 26 October, only a day of sampling was missed. It is assumed that in this case, the sampler would have been removed prior to the launch, with resumption of sampling after the successful launch of Bluegill Triple Prime. In the plots, for simplicity, the days without a sampling result, the air concentration was assumed to be equal to that recorded on the next day. A number of the samples had a "zero" recorded for the air concentration. From a review of individual data sheets, the minimal detectable concentration (MDC) was around 0.02 pCi m^{-3}.

Over the 10 August 1962 to 20 April 1963 period, only seven samples from the launch pad had an average α-radiation activity concentration greater than the 2 pCi m^{-3} MPC (40-hour week) established for the restoration. The highest concentration was for the air sample collection that ended on 2 October 1962, 22.2 pCi m^{-3}. The duration of the sampling period for this sample is not known, but as noted above, it is assumed that the sample encompassed three days of collection. The activity concentration

for this sample was unusually high, compared to other samples collected around this time period on the launch pad. The sample with the next highest activity concentration among samples collected over this period of time was 4.2 pCi m^{-3}, with sample collection completed on 11 October. Generally, over time the air concentrations decreased. Some of the decrease observed in fall 1963 could be attributed to the reduced activity on the Thor launch emplacements with the completion of Thor launches during Operation Dominic I. However, re-suspension of surface-deposited contaminants will naturally decrease over time, as contaminants attach to particles in the host soil matrix and migrate to greater depth in surface soil. Some discussion of this phenomenon will be discussed later in this report.

Figure 5-6 contains air sampling results from 1 November 1962 to 20 April 1963, and allows a better view on the lower concentrations observed in 1963, due to the lower scale of the plot. After mid-January 1963, all of the samples were less than 5% of the established MPC, with the vast majority of the samples having activities below the MDC. No additional air sampling results were located in the DTRIAC archives for the 1963 calendar year after 20 April, though it is possible that sampling was continued beyond this date, as JTF Eight maintained control of the Island through 1964.

5.3 1964 US Public Health Service (PHS) Radsafe Status Report.

Two US PHS officers were assigned to the AEC from 13 May to 10 September 1964, with duty at Johnston Island (Martin 1964). The two officers were health physicists and had a primary role of filling a temporary manning gap for a professional health physicist on the Holmes and Narver staff. The officers provided some recommendations for refinement of the program (Martin 1964). Some of the most important information from the US PHS report is a description of the current radiation safety program implemented at that time.

5.3.1 Air Sampling. Air sampling was being accomplished on a daily basis in LE-1 through high-volume air samplers and paper filter media, with a recommended change to glass membrane filters with low-volume samplers. The change was recommended to improve detection efficiency in assessment of the samples, which was currently being conducted with portable survey instruments. Martin (1964) noted that the sensitivity of the method achieved a sensitivity of about "$1/100^{th}$ of the ICRP [Report 2] MPC," 0.02 pCi m^{-3}. Results for air sampling conducted in the summer of 1965 are listed in Table E-5, using the recommended changes in sampling. The majority of the samples were accomplished over a single day, with total sample volumes of 1,400 m^3. A small number of two day samples were collected over weekends and had 2,800 m^3 volumes. For the single day samples, the majority had activity concentrations below 7 fCi m^{-3}, the presumed MDC, while the samples collected over two days had activity concentrations below 3 fCi m^{-3}. Special, task-related monitoring was also accomplished, though collection volumes were 400 m^{-3}, covering about 7 h of time, assuming a similar volumetric flow rate as the daily samples. None of these samples had reported airborne α-radiation concentrations above the MDC, though the MDC was typically 20 fCi m^{-3} for these samples. The sample collected on 2 August was reported at < 4,000 fCi m^{-3}, and as noted in the Table, it is believed that this sample was mis-reported, as the MDC is two to three orders of magnitude higher than other samples with equivalent collection volume. Overall, the observation from these samples is that activity concentrations of the plutonium contaminant were very low, consistent with that found in April 1963. It is our belief that air sampling in LE-1 was a common health and safety practice conducted for many years after the Bluegill Prime launch failure, though more air sampling data summary reports were not found in DTRIAC archives, as was the case for the 1965 sampling results discussed here.

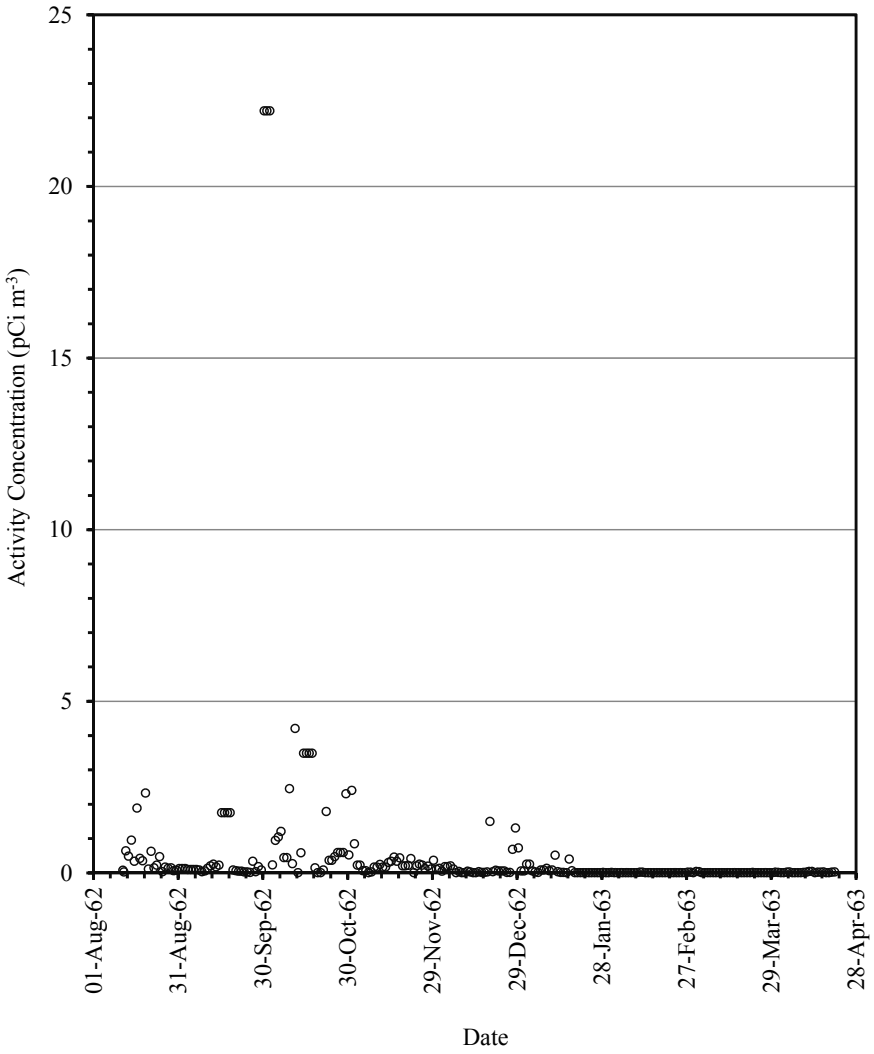


Figure 5-5. LE-1 Launch Pad High-Volume Air Sampling Results (10 Aug 62 – 20 Apr 63).

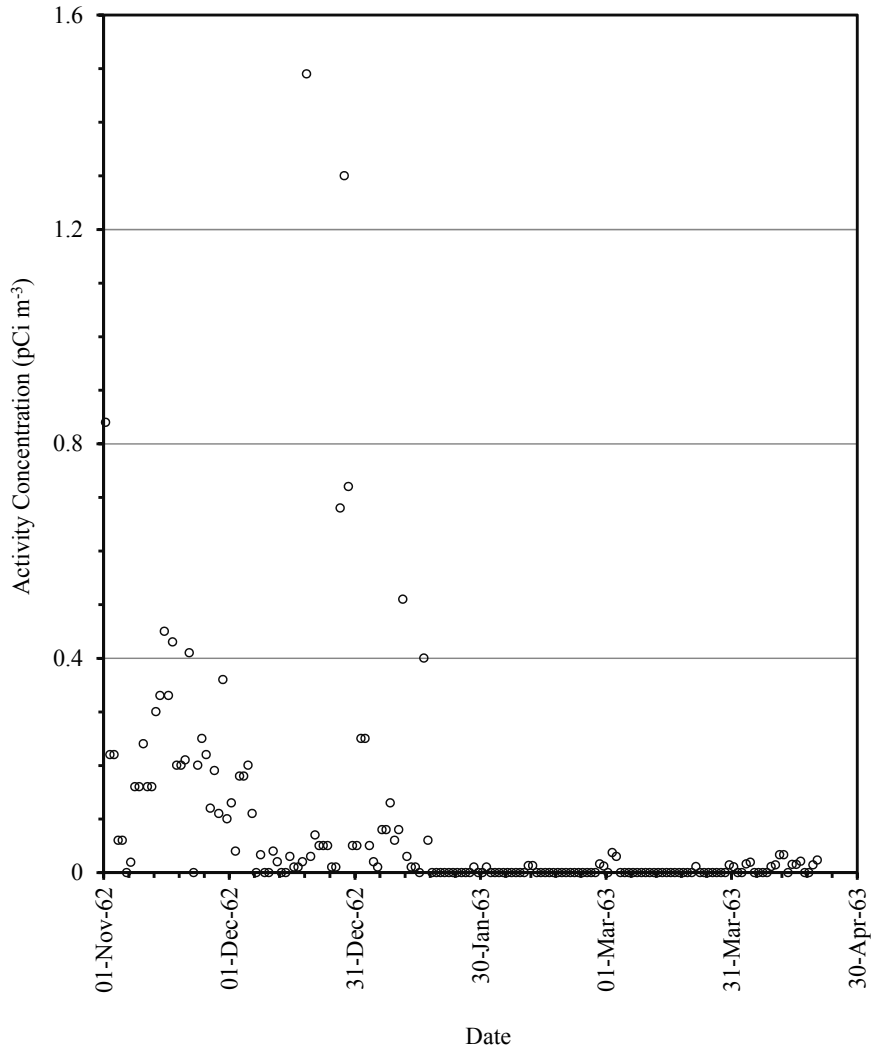


Figure 5-6. LE-1 Launch Pad High-Volume Air Sampling Results (1 Nov 62 – 20 Apr 63).

5.3.2 Swipe Samples. Swipe sampling had already been accomplished routinely on surfaces in LE-1 with collections over an industry-standard 100 cm^2 area. The US PHS added the mess hall and post office to the routine surveillance, as these two areas were considered, "high movement areas" (Martin 1964). The criterion for further investigation of the samples from outside LE-1 was based on a net count rate of 2 cpm and 10 cpm for samples collected within LE-1. Applying a 25% α-radiation detection efficiency, this leads to respective criteria of 8 and 40 dpm per 100 cm^2, which are on par with removable contamination levels for unrestricted release of contaminated materials in the current ANSI Report N13.12 (ANSI 2010). Areas that exceeded these levels were afforded decontamination or fixation by paint, which was common in the revetment area of the LE-1.

5.3.3 Urinalysis. The US PHS made a recommendation that employees working in LE-1 be afforded periodic urinalysis to document body burdens of plutonium. It is not known if urinalysis was performed on Holmes and Narver employees that provided support to the Island. However, due to the low airborne concentrations of α-radiation that existed in LE-1 after the pad restoration and the relative insensitivity of the method for detecting urinary excretions of PuO_2 respiratory intakes, it is unlikely that any positive detection would have occurred in monitored personnel. Current occupational standards do not generally require bioassay monitoring unless a worker has the potential to exceed 10% of the ALI, which would be equal to 10% of the DAC (i.e., MPC, under ICRP 2), in a 2,000 h work year. Airborne concentrations were below 1% of the established MPC, based on the 1965 air sampling data.

5.4 1966 US Public Health Service Assessment of Plutonium on LE-1.

In 1966, the US PHS service was asked to assess plutonium contamination on LE-1, which was being used by the Air Force to support nuclear-tipped, Thor missiles on alert status (Martin 1966). US PHS concluded that the radiological contamination situation was relatively minor.

Jaffe and Tipton (1982) in a report describing the results of a 1979 radiological survey of the Island noted, "In 1964, the US PHS conducted a portable alpha meter survey, at which time about 400 55-gallon drums of contaminated debris were disposed of off the island. A survey using x-ray meters in 1965 yielded an additional 50 drums of contaminated debris." This information contrasts Holmes and Narver disposal logs, as accessed from DTRIAC archives, and summarized in Table E-4. According to these documents, only a small number of contaminated office items were disposed in 1963. Two disposal efforts were conducted in 1964, 9 March and 4 June. Numerous individual debris items are listed among the two disposal actions, though only 10 and 64 55-gallon drums are listed in the two respective actions. The materials in the drums were listed as contaminated coral paint scrapings, concrete chips, worn and torn protective gear, and small metal parts from shelter. These disposal actions are consistent with precautionary health and safety practices established during the initial restoration, where contaminated paint chips were collected and prepared for disposal, and protective equipment was worn by personnel performing these actions. In 1965, two separate disposal actions were completed. On 27 January, 63 drums of contaminated coral from LE-1 were disposed, while on 23 March, 55 drums were disposed. The volume of the drums was not listed, though for one disposal description, it was noted that the drums were a third full. It is likely that the drums were 55-gallon capacity, and likely for handling considerations, were only partially full. Sixty-three 55-gallon drums of contaminated coral, a third full, is about 4.3 m^3 in volume. Jaffe and Tipton (1982) noted that the use of an x-ray meter yielded an additional 50 drums. Thin-crystal detectors, i.e., NaI(Tl) and CaF_2, were developed in the mid-1960's specifically for the detection of low-energy photons emitted from WGP. Eberline

manufactured the PG-1 and PG-2 probes, which respectively had one and two inch diameter, thin-crystal NaI(Tl), while the AN/PDR-56 had an auxiliary thin-window, thin-crystal NaI(Tl) (DASA 1966). The FIDLER (field instrument for the detection of low energy radiation), which had a 12.7 cm diameter, 1.6 mm thick NaI(Tl) crystal was not fielded until 1968, when deployed to the nuclear weapon accident at Thule AB (DAGIG 1970). It is very reasonable that use of these detectors afforded additional volumes of contaminated coral, over the materials collected with the aid of only α-radiation scintillators or gas-proportional detectors. For detection with the latter type of detectors, materials are required to be present on the surface, as α-particles are readily absorbed, having a penetration range in water of only 42 μm. Degradation of the contamination on surfaces rapidly decreases the detectability by α-radiation measurement techniques, as illustrated in Figure 5-7 (FC DASA 1968). For soils, a degradation factor of 10 is expected after 8 days, while at 100 days the degradation factor is 72, with only about 1.4% of the initial deposition detectable by α-radiation techniques.

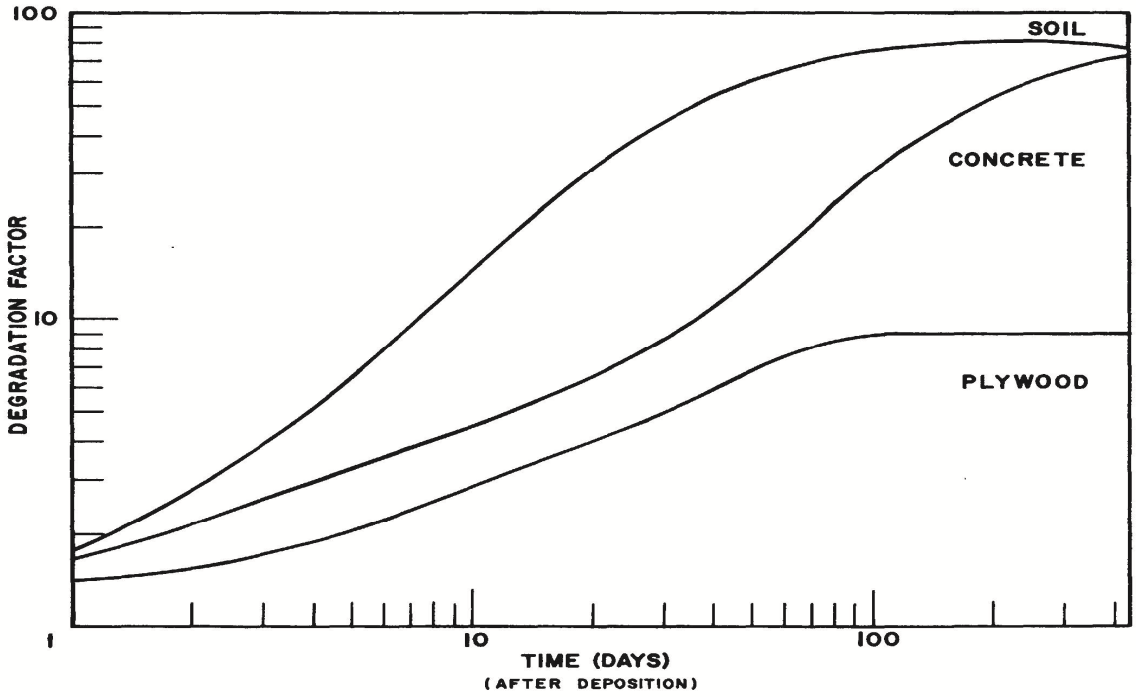


Figure 5-7. Activity Degradation Apparent to α-Radiation Survey Instruments, based on Project 57 Test Reports (FC DNA 1968).

Systems that detect low-energy photons are effective at locating contamination at depth. It is important to note the primary radiological safety concern is due to the inhalation exposure pathway, which is linked to the resuspension of loose contaminated materials on solid surfaces and the upper few mm of soil. As such, while the removal of contaminated material at depth is consistent with good health and safety practice, it is unlikely to have much effect on airborne concentrations in the short-term. Sea disposal of contaminated debris continued through 1972. AEC policy changed with the impending Marine Protection, Research, and Sanctuaries Act of 1972 that added regulation of ocean dumping of materials that adversely affected the marine environment, among other affects (Public Law 1972). The primary materials disposed were 55-gallon drums, which presumably contained primarily paint chips.

5.5 AEC Nevada Operations Office 1973 Survey.

Between 7 and 10 August 1973, the Nevada Operations Office of the AEC performed in-situ surveys with a FIDLER to assess low-energy photon emissions from soils (AEC 1974). A survey was conducted on Johnston Island, with detailed attention to LE-1, and Sand Island. Use of FIDLER detectors provided better sensitivity over the x-ray probes used in the 1966 survey performed by the US PHS due to disparity in detector area. The survey confirmed the presence of residual contamination outside the fenced area of LE-1 and on Sand Island. Specific note was made of discrete particles of contamination that have been termed "hot" particles by some authors. It was noted that the practice of repairing chipped paint and concrete with new coatings had deteriorated. It was recommended to increase the size of the LE-1 exclusion area and that further decontamination efforts be accomplished to remediate "hot spots" of contamination on Johnston and Sand Islands. A plot of FIDLER survey measurements conducted in LE-1 is in Figure E-3. Eight hot spots identified on the outside of LE-1 on Johnston Island and nine on Sand Island were removed (Jaffe and Tipton 1982). The most notable feature of the contamination was the higher concentrations to the north of the launch pad.

5.6 USAF Hospital Radiological Survey, 1974.

Prompted by the cursory survey conducted by the AEC in 1973, Field Command, DNA (FC DNA) requested the USAF Hospital, AF Special Weapons Center, Kirtland AFB to conduct a radiological survey of Johnston and Sand Islands (Kinsley 1973). The survey consisted of scanning surveys with an array of FIDLER detectors on the back of a motorized vehicle, extensive swipe sampling, and air sampling. The survey was accomplished over a 25 d period in February and March 1974.

The three air samples collected within LE-1 on 19 March had sampling volumes of 102 m^3. All samples had reported airborne activity concentrations less than 2.2 fCi m^{-3}, with the summary in Table E-6.

Two-hundred thirty-six swipe samples were collected in the Johnston Island main dining hall (including the roof), the hospital, the LE-1 office, the LE-1 missile floor pad, and Sand Island quarters and dining area. In addition miscellaneous samples were collected at a number of other buildings, but at a substantially smaller number per building than the buildings listed above. The results of the swipe samples are summarized in Table E-7. Among the locations wiped, the sample with the highest activity was collected on the LE-1 missile launch pad floor, and had an activity of 27 dpm, over an assumed wipe area of 100 cm^2. The average activity for the 50 samples collected on the pad, however, was only 2.7 dpm. The maximum activity on swipes collected in areas outside LE-1 was found in one sample from the interior of the dining hall, but was only 4.6 dpm, with an average among samples collected in this building of only 0.3 dpm. The other samples collected in buildings outside LE-1 were unremarkable, with negligible α-radiation contamination. In light of the relatively low removable contamination levels identified on LE-1 swipe samples, concerns expressed in the 1973 AEC report were somewhat diminished.

The survey identified several radioactively-contaminated metal pieces on Sand Island on the eastern and western portions of the Island, but not on the causeway strip of land connecting the two larger land masses. The western land mass contained the primary buildings, work, and recreation areas, while the eastern land mass possessed a large ground antenna, and associated structural support wires. In the report, this land mass was referred to as Bird Island. The surveys identified 22 areas of isolated

contamination and 40 metal parts. These areas were marked for removal. The contamination found at these locations on Sand Island were logically attributed to the Starfish mishap, which occurred five weeks before the Bluegill Prime mishap, but released contamination from an altitude of 10.6 km (see Table 2-1). The authors noted, "The roof areas were monitored and found to be free of localized hot spots [isolated contamination] but the overall readings were several magnitudes above background." While the surveys accomplished on the roof tops with a FIDLER were likely valid, a conclusion that the detector response was attributed primarily to plutonium deposition is likely false. FIDLER measurements inside concrete buildings on Johnston Island commonly afforded substantially higher background count rates than outdoor areas where terrestrial background is dominated by the photon emission from coral (i.e., mostly $CaCO_3$). The constituents of concrete used to construct buildings on Johnston Island were known to possess substantially greater concentrations of primordial radionuclides (i.e., ^{232}Th and decay chain, ^{238}U and decay chain, and ^{40}K) than coral. As well, the FIDLER, as set to record energy deposition events around 60 keV (i.e., γ-ray emitted by ^{241}Am), will have negligible response to cosmic radiations which have a concentration of energy deposition around 1.2 MeV for a 1.6 mm thick NaI(Tl) crystal, using the analysis approach in Rademacher (2013).

In the survey of Johnston Island with FIDLERs, similar contamination patterns identified in LE-1 as was noted in the 1973 AEC survey, with a similar finding that hot spots of contamination existed on the outside of the LE-1 fenced area. One specific area on the northwest boundary of LE-1 was part of the storage and inspection area, which was partially on land that existed prior to the 1963-1964 Island expansion and newly created land. It was noted, however, that the contamination existed on the pre-existing section of land, with the conclusion that the contamination was likely from the initial dispersal in the Bluegill Prime mishap, rather than from contamination deposited in the lagoon and added to the Island from dredging operations. Some hot spots were also identified in LE-2.

The report made a number of recommendations. A recommendation for urine bioassay monitoring was made for individuals working on Sand Island and with LE-1, and in contamination cleanup tasks, similar to the earlier US PHS recommendation. However, the authors noted that it was "most unlikely" that a positive result would appear among those monitored. A recommendation to remove "hot spots" with simple shovel and lined 55-gallon drums was made, though it was noted in a letter to Island residents the "plutonium residual being identified is below the surface and not accessible nor does it approach danger unless excavated." A recommendation to repaint the LE-1 shelter floor was made and a recommendation to add an additional 3-5 inches of coral on LE-1 if missile firings occurred. The ASAT mission, however, was terminated later in 1974, though "alert status" of Thor missiles ended in 1970. Two Thor launches from LE-1 were made in 1975, but unrelated to ASAT. Prior to these last Thor launches on the Island, the last previous test was conducted in 1970. The recommendation was made to make the LE-1 a RCA. The fenced area around LE-1 was increased by about 60% and the hot spots outside LE-1 were excised and placed in storage (Jaffe and Tipton 1982).

5.7 Mid-1970's Radiation Monitoring Program Initiation.

5.7.1 General. In 1975, FC DNA initiated more extensive radiological contamination surveillance on the Island. LE-1 was made a RCA, with tighter monitoring controls upon exiting the facility and a log of entries into the area. This would have only a minor impact on operations, as the Thor launch emplacements were no longer in use by the end of 1975. Though radiological monitoring was periodically accomplished in areas outside LE-1, as noted above, continuous air sample monitoring was

accomplished at a number of locations on the Island outside LE-1. A routine swipe collection program was initiated for areas outside LE-1, potable water sampling, and a periodic "hot spot" removal practice.

5.7.2 Air Sampling.

In the fall of 1975, high-volume air sampling was initiated at three locations outside LE-1: the storage and inspection (S&I) area (adjacent and downwind from LE-1), building 45 (on the east side of the Island), and the dining hall (upwind from LE-1 in the middle of the Island). Table 5-2 contains a summary of the sampling locations, maximum measured concentrations, typical concentrations, date of sampling start for a location, and the ending date of sampling for a location. Figure 5-8 contains annotation of sampling locations. Most samples were collected for about a week and had collection volumes between about 50 and 180 m^3 per day, dependent on the sampler. Over the years, some locations were dropped, while others were added. Among the notable locations that were outside LE-1 and were sampled until 1990 were the S&I area, the swimming pool, and the bowling alley. Some locations were added within the Thor launch complex, and were subject to long-term sampling as well: building 786, building 795, LE-1 pad shack, and the southwest corner of LE-1, which was downwind from the launch pad. Most of these locations were added in conjunction with restoration activities that were conducted in the Thor launch emplacement area in the early 1980's. Sampling at building 45 was discontinued in 1977, while sampling at bunker 202 was initiated in 1978. Sampling at bunker 202 was ended in 1984, but was started at an adjacent building, the bowling alley, at the same time. For a few months, a sampler was also placed on Sand Island.

The vast majority of samples were screened on-site for gross α-radiation, with the vast majority having activity indiscriminant from background. The majority of the samples were also analyzed for isotopic plutonium at Wright-Patterson AFB, by the Radiological Health Laboratory (RHL), and later when the Laboratory became a part of the Occupational, Environmental Health Laboratory (OEHL). In the later 1980's, it became a practice to screen most samples by gross α-radiation on-site prior to being sent to OEHL where most samples were analyzed for isotopic plutonium by α-spectrometry. With the exception of a few air samples collected outside LE-1, the majority were unremarkable, having activity concentrations around 1 fCi m^{-3} or below. Many of the highest readings observed in samples collected at locations outside LE-1 were attributed to samples that had only a gross α-radiation analysis at OEHL. For example, the 22.0 ± 2.6 fCi m^{-3} maximum activity concentration for a sample at the swimming pool was attributed to a gross α-radiation laboratory measurement, while the highest concentration reported for all samples analyzed for isotopic plutonium had a concentration of only 3.6 ± 1.0 fCi m^{-3}. For samples with both analyses, most gross α-radiation results were much higher than the MDC for either ^{239}Pu or ^{238}Pu. Table 5-3 provides a listing of gross α-radiation, ^{239}Pu, and ^{238}Pu for samples collected at the southwest corner of LE-1. For the four samples with reported gross α-radiation concentrations, all isotopic plutonium analyses did not have results above the MDC. The highest reported result at S&I was 14.6 ± 1.6 fCi m^{-3}, but was observed during a 1984 period of restoration in LE-1. A similar finding existed for comparisons of paired isotopic plutonium and gross α-radiation analyses for other locations, but for brevity sake are not detailed in this report. The sample with the next highest activity concentration, however, was only 3.0 ± 0.2 fCi m^{-3}. This sample was collected in January 1976, which had a sampling volume of 686.4 m^3. The total $^{239+240}Pu$ activity for the sample was only 2 pCi, which had volume- and aerodynamic-dynamic diameters of 1.7 and 5.7 μm, respectively, if due to a single, pure PuO_2 particle in a spherical geometry (see Figure E-6 for additional detail). As such, it is plausible that a single particle dominated the total sample activity.

TABLE 5-2. Results for Weekly High-Volume Air Sampling Conducted by Field Command, Defense Nuclear Agency from 1975 – 1989[1,2,5] (DTRIAC Archives).

Location	Sampling Start	Sampling End	Airborne Concentration (fCi m^{-3})	
			Maximum	Typical
Storage & Inspection Area (Bldg 787)	19 Nov 75	1 Oct 90	19.8 ± 2.9[3]	< 0.1
Building 45	24 Nov 75	14 Nov 77	2.7 ± 0.4	< 0.1
Swimming Pool[7]	14 Nov 77	2 Jul 90	22.0 ± 2.6[5]	< 0.1
Building 786 Count Pad	8 Oct 84	18 Oct 84	< 0.01	< 0.05
	24 Aug 87	7 Nov 88	< 0.03	< 0.03
Building 795	7 Apr 85	14 Apr 85	< 0.3	< 0.3
	10 Feb 86	23 Aug 87	$1{,}100 \pm 140$[6]	0.1
Mess Hall (Bldg 519)	24 Nov 75	16 Oct 89	4.5 ± 0.2	< 0.1
Sand Island	21 Nov 77	20 Feb 78	< 0.013	< 0.01
Bowling Alley (Bldg 206)[7]	3 Jan 84	2 Jul 90	1.7 ± 1.4[5]	< 0.1
LE-1 Southwest Corner	20 Dec 81	1 Oct 90	3.2 ± 1.0	< 0.1
LE-1 Pad Shack	14 Apr 80	5 May 80	< 0.004	< 0.004
	24 Sep 84	10 Dec 84	< 0.05	< 0.05
Beacon Building	9 Jul 76	14 Nov 77	< 0.2	< 0.1
Bunker (Bldg 202)	6 Nov 78	3 Jan 84	0.19 ± 0.11	< 0.1
LE-2	24 Oct 88	1 Oct 90	29 ± 10	< 1.2

Notes: 1. 4th Quarter of 1979, weekly samples were composited for isotopic Pu analysis.
2. Large fraction of samples analyzed off-site by isotopic Pu analysis in addition to on-site gross α-counting.
3. Concentration was observed for19-26 Nov 1984, during restoration of LE-1. Excepting the LE-1 restoration period, the highest was 3.0 ± 0.2, for the 19-26 Jan 1976 sample.
4. In 1988, off-site laboratory analyses used gross α-radiation screening analysis, with some sample receiving follow-up isotopic plutonium analyses. Follow-up isotopic plutonium analyses discontinued summer 1988, but resumed for some samples summer 1989.
5. Gross α-radiation screening analysis only basis for maximum result, no isotopic-specific plutonium analysis. For the swimming pool, the highest isotopic-specific plutonium was 3.6 ± 1.0 fCi m^{-3}.
6. Concentration for 31 Mar – 7 Apr 1986, next highest 0.20 + 0.07 fCi m^{-3}. Validity of result questioned - sample screening on Johnston Island, prior to submission to OEHL, reported negligible activity.
7. Bowling alley & swimming pool had quarterly composite sample analyses for 4th Quarter 1989, 2nd Quarter 1990.

Nevertheless, airborne plutonium in areas sampled outside LE-1 was very low, with the average at measured locations expected to be well below 1 fCi m^{-3}. It is plausible that some of the plutonium existing in these samples could be attributed to world-wide fallout. A plot of world-wide ^{239}Pu fallout is contained in Figure E-4. The Mauna Loa, Hawaii location is most representative of the Johnston Island latitude. In the early 1960's, world-wide fallout in the northern hemisphere measurement locations was nearly 1 fCi m^{-3}, equivalent to the 1977 EPA proposed screening level for air (EPA 1977). In the summer and fall of 1976, FC DNA split some air samples with the McClellan Central Laboratory, where thermal ionization mass spectrometry analyses were performed. This method had much better sensitivity than the isotopic plutonium analyses performed at RHL using α-spectrometry. The results are in Table E-8. All results were below the MDC, which ranged from 2.64 to 31.84 aCi m^{-3}.

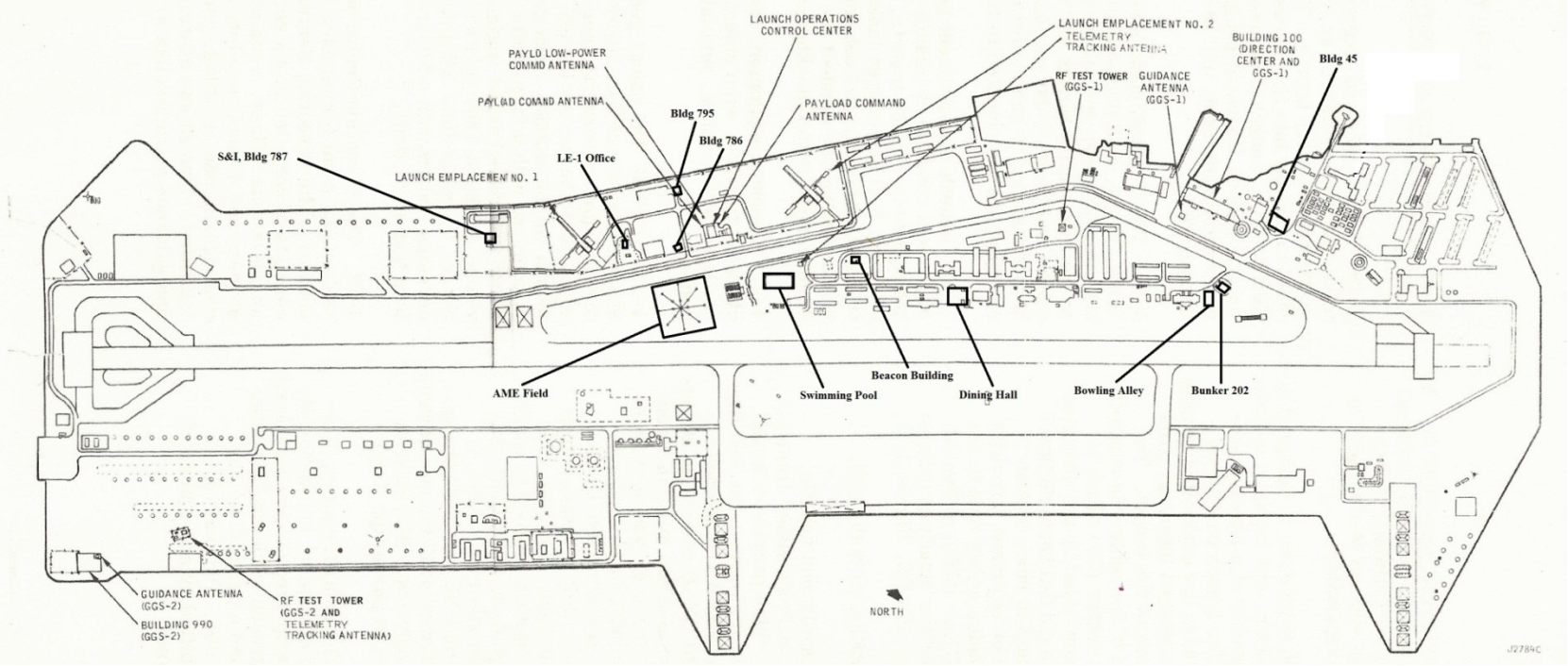


Figure 5-8. Map of Johnston Island, Showing Air Sampling Locations and Other Features.

Buildings 786 and 795 are contained within the Thor launch emplacement complex. Air sampling at these locations was initiated due to the proximity to operations supporting remediation of LE-1. Results from these samples, as well as single day sampling with the Thor launch complex will be discussed later in this report. Important in regard to samples collected in conjunction with these operations was full respiratory protection provided to personnel supporting the work.

5.7.3 Water Sampling. Distilled saltwater was used as a source of fresh drinking water at Johnston Island until the later 1980's when a reverse osmosis system was installed. Sampling and laboratory analysis for isotopic plutonium was performed by α-spectrometry was initiated in early 1976 on a monthly basis. In 1979, FC DNA switched over to quarterly sampling and analysis. The results are in Table E-9. The vast majority of the results are below the MDC, with those samples having positive detects all below 0.07 ± 0.03 pCi L^{-1}. For

comparison, the acceptable gross α-radiation limit under the EPA Safe Drinking Water Act is 15 pCi L^{-1}. Nevertheless, distillation or reverse osmosis would be effective at the removal of plutonium.

TABLE 5-3. Gross α-Radiation and Isotopic Plutonium for Air Samples Collected from Southwest Corner of LE-1, as Analyzed by OEHL.

Period		Volume	Airborne Concentration (fCi m^{-3})		
Start	End	(m^3)	Gross Alpha	Pu-239	Pu-238
18-Apr-88	25-Apr-88	1012	< 0.15	< 0.05	< 0.04
27-Jun-88	4-Jul-88	1048	0.09 ± 0.09	< 0.005	< 0.003
27-Jun-89	3-Jul-89	346	< 1.0	< 0.17	< 0.17
4-Jul-89	10-Jul-89	308	7.6 ± 1.2	< 0.11	< 0.24
10-Jul-89	16-Jul-89	308	7.6 ± 1.4	< 0.11	< 0.24
11-Jul-89	17-Jul-89	327	< 1.1	1.1 ± 0.8	< 0.047
18-Jul-89	24-Jul-89	324	< 1.1	< 0.38	< 0.21
25-Jul-89	31-Jul-89	327	< 1.1	< 0.14	< 0.08
1-Aug-89	8-Aug-89	354	< 1.0	< 0.29	< 0.19
9-Aug-89	15-Aug-89	320	< 1.1	< 0.26	< 0.26
21-Aug-89	29-Aug-89	285	9.1 ± 1.8	< 0.65	< 0.22
29-Aug-89	5-Sep-89	366	< 0.97	< 0.6	< 0.2
5-Sep-90	11-Sep-89	313	< 1.1	< 0.16	< 0.08
11-Sep-89	18-Sep-89	269	< 0.95	< 0.71	< 0.42
18-Sep-89	25-Sep-89	316	< 1.1	< 0.79	< 0.40
25-Sep-89	1-Oct-89	269	< 1.3	< 1.3	< 0.70

5.7.4. "Hot Spot" Removal.

Survey for and the removal of "hot spot" areas initiated in 1975 was conducted in a similar manner to the practice that was used during the 1974 survey. The removal process occurred in areas outside LE-1. Jaffe and Tipton (1982) reported that from June 1975 to March 1980, over 500 spots were located and removed, with most coming from the Redstone launch pad area. DTRIAC archives contained a log of removals up to November 1978, which is summarized in Table E-10 based on an August 1979 Holmes & Narver letter (Munk 1979). The Table contains the date found, approximate location, FIDLER count rate, the minimum ^{241}Am activity, based on the assumption that the particle was on the surface, and an estimate of the of $^{239+240}$Pu, based on the estimated time-varying $^{239+240}$Pu to ^{241}Am ratio to be discussed later in this report. The table lists 81 particles, while Jaffe and Tipton (1982) noted that over 500 particles were removed up to March 1980. It is possible 400+ particles were removed between August 1979 and March 1980, but this seems unlikely. Among the particles noted on Table E-10, most were in the middle part of the Island, between the runway and the taxiway boundary on the north, and not in the Redstone launch area, which was on the eastern portion of the Island that existed prior to the 1963/1964 expansion. It is possible that the Redstone launch area had particle removal activities conducted between August 1979 and March 1980. The Redstone launch area did not support other missions after its use in Hardtack I. This area is about 400 feet east of Bunker 202 (see Figure 5-8).

Less than 20% of the particles removed, as listed in Table E-10, provided a FIDLER count rate in excess of 100 kcpm, with the vast majority providing a count rate less than 10 kcpm. Assessment of activity of individual particles is affected by the depth of the particle in soil. There is no way to know the precise depth for any of the particles removed, unless details are provided in the removal process. The particles deposited outside LE-1 were not intentionally covered in a layer of clean coral, as was the case for residual contamination within LE-1. If the particles did not lie on or very near the surface, the estimated activity would be higher, as the detection efficiency would be lower due to scattering and absorption of the low-energy γ-rays emitted by ^{241}Am. However, material at depth does not provide much exposure risk compared to material on the surface, which has the potential for resuspension and subsequent inhalation. The particles found and removed in 1978 had low associated count rates, which is logical for a process to remove particles with the greatest activity earlier, as they are more readily located.

The particles found outside LE-1 had a number of possible origins. For the particles found closer to LE-1, it is possible that the original explosion and turbulence afforded airborne transport and deposition, while this was much less the case for contamination located near the Redstone launch area, due to the much greater distance. Contamination in this area was most likely from the Starfish mishap, which was purposely detonated by the range safety officer at an altitude of 10.6 km (see Table 2-1), and did have identifiable debris on Johnston Island (see Figure 5.9 below). As well, logically the plutonium deposition on Sand Island was also from Starfish. To a lesser degree, some plutonium may have been trans-located over the years from air resuspension, and foot and vehicle traffic. Based on an extensive computer modeling analysis of debris patterns from the Starfish and Bluegill Double Prime mishaps that occurred at high altitudes, the predicted debris pattern from Starfish was more highly concentrated in the vicinity of Johnston Island than that from the Bluegill Double Prime mishap (Geocenters 2000).

The discrete particle removal actions were part of the overall ALARA practice - part of a good radiation safety program. However, the process accomplished outside the LEs likely had a small overall impact on airborne concentrations of plutonium in areas outside the launch emplacements. This is due to the fact that the particles subject to the removal were aerodynamically too large for resuspension in the atmosphere under normal outdoor conditions, and also too large to reach the pulmonary and tracheobronchial regions of the human respiratory system. Figure E-5 contains a plot of the minimum

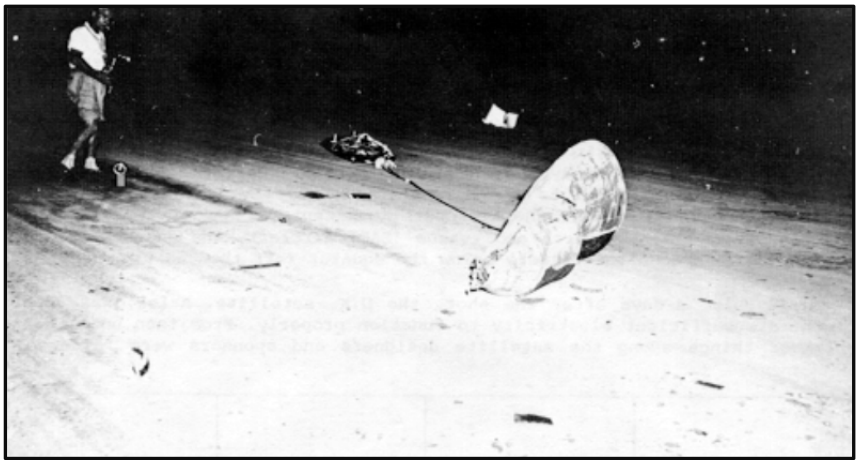


Figure 5-9. Debris that Fell on Johnston Island from Starfish Launch (Berkhouse et al. 1983).

$^{239+240}PuO_2$ particle diameter (volume equivalent) for WGP with an approximate α-particle emission partition 80:20 for ^{239}Pu and ^{240}Pu, with an assumed density of 11.5 g cm^{-3}. Particles mixed with inert materials would have larger diameters, while pure a PuO_2 is assumed in Figure E-5. A 1995 scanning electron microscopy (SEM) study of discrete radioactive particles from Johnston Island found that plutonium was present within crystalline and amorphous aluminum oxide and ferrous compounds (Buck et al. 1995). Particles visible to the naked eye were also identified by FIDLER scans in LE-1 and readily isolated on filter papers. Figure E-6 contains example images from Rademacher (1999c). Most particles having radioactive emissions appear black in color, with appearance like course ground black pepper. For the range of FIDLER response count rates listed in Table E-10, 1.5 to 500 kcpm, the minimum volume equivalent diameters would be 31 and 225 μm, respectively, if on the soil surface, based on Figure E-5. Figure E-5 contains a plot of aerodynamic equivalent diameters versus maximum particle activity ($^{239+240}Pu$) with associated details on deposition regions in the human respiratory tract and re-suspension in air, set at 30 μm per EPA guidance. Clear from the plot is a threshold for resuspension at 300 pCi for pure PuO_2 spherical particles, and 605 pCi for a particle with a shape factor of 1.6, i.e., oblong in shape. Though individual particles with activity greater than the upper-bound for resuspension would not be available for respiratory intakes, some potential for ingestion intakes exist.

5.7.5. Other Surveys. From 1975 to the later 1980's, radiological screening of occupied buildings was performed on an annual basis. Notably, surveys were not conducted in 1985, due to the heavy workload associated with health physics support to LE-1 restoration efforts. The surveys consisted of floor screens with FIDLER instruments and swipe sampling. Details of the surveys are contained in DTRIAC archives. FIDLER surveys were unremarkable, with measurements within background count rates. Swipe sampling on an annual basis was quite extensive, with annual sampling typically above 500 samples. For example, the 1983 survey consisted of 574 individual swipe samples, with the sample having the highest removable contamination identified at 7 dpm. In comparison, the 1976 survey consisted of 572 individual swipe samples, with the highest at 20 dpm. In both cases, the swipe area is assumed to be 100 cm^2, with a conclusion that the contamination was at negligible levels from a radiation health perspective.

5.8 1980 EG&G (DOE Remote Sensing Laboratory) Radiological Survey.

5.8.1 General. EG&G performed the most extensive radiological survey to date in 1980 on soil with the purpose to locate and quantify residual plutonium and americium from the three Thor missile aborts that occurred in 1962 (Jaffe and Tipton 1982). The survey used a high-purity germanium planar detector, suspended by a boom to collect the measurements. This detector and measurement geometry offered better sensitivity than the FIDLER's that had been used to conduct measurements of soil in the 1973 and 1974 surveys, and hot particle identification and removal efforts. The survey instrumentation was designed and built for radiological surveys at Enewetak Atoll (Jaffe and Tipton 1982). Soil sampling and analysis that accompanied this survey was reported by Powell (1981) and will also be discussed in this section of the report.

5.8.2 In-situ Survey Approach.

Land areas on Johnston Island in existence during the Operation Dominic tests were surveyed on a 100-foot rectilinear grid, while parts of the Island that were formed from the 1963/1964 dredging operation were surveyed in a similar manner, but with a 200-foot spacing convention. The majority of the

measurements were conducted with the detector at 24 feet above ground level. Areas that contained survey measurements identifying ^{241}Am above the MDA were subjected to additional measurement on a 50-foot grid pattern and with the use of a collimator to restrict the field-of-view of the detector to a circular ground surface area of 80 feet in diameter (Jaffe and Tipton 1982). Results of the survey measurements were reported as equivalent surface contamination in nCi m^{-2}. North, East, and the western portion of Sand Islands were also surveyed. The eastern portion of Sand Island, commonly referred to as Bird Island was not surveyed due to the electromagnetic interference from the Loran C antenna. This is deemed of little consequence, as this part of the Sand Island had very limited occupancy compared to the western portion.

5.8.3 Soil Sampling Approach. The authors noted that in previous surveys of Johnston Island, contamination would exist as discrete particles, which contained highly-localized activity, while other contamination in soil would be "spread out as a continuum" (Jaffe and Tipton 1982). Samples that are somewhat homogeneous could in essence be subdivided into small samples, yet carry nearly the same activity concentration as the whole. Three types of soil samples were obtained, 1) those used to assess the $^{239+240}$Pu to ^{241}Am activity concentration ratio, 2) those used to assess the ^{241}Am activity concentration in areas believed to have a somewhat homogeneous distribution of plutonium, and 3) those used to assess the elemental composition of soils.

5.8.4 Survey Results.

5.8.4.1 North and East Island. Figures E-8 and E-9, respectively, contain the in-situ measurement points for the surveys on North and East Islands. None of the measurements on either island had a positive detect for ^{241}Am. A large area composite soil sample was collected on each island. The sample collected on East Island had a negative FIDLER pre-screen result and was not subjected to laboratory analysis. The North Island sample had very low-levels of $^{239+240}$Pu and ^{241}Am, with a $^{238+239+240}$Pu to ^{241}Am activity ratio of 3.4. This value is typical for ratios observed from global fallout, but less than half the ratio expected for the un-fissioned plutonium fuel in the Starfish and Bluegill Prime weapons. Jaffe and Tipton (1982) concluded that neither of these island had ^{241}Am, based on the MDC established for in-situ measurements. This is logical since both of these islands were formed from the 1963/1964 dredge operation and did not exist at the time of the Operation Dominic I launch mishaps.

5.8.4.2 Sand Island. Seventy-nine in-situ measurements were collected on Sand Island, with 17 having positive indication of ^{241}Am in soils. The projected areal contamination concentrations for these locations with positive indications of ^{241}Am were estimated to range between 6 and 15 nCi m^{-2}. The upper value of this range is only equal to 2.1 pCi g^{-1} of $^{238+239+240}$Pu , as averaged over the top 3 cm of surface soils with an assumed $^{238+239+240}$Pu to ^{241}Am activity concentration ratio of 7.17. The 3 cm thickness was used to allow a comparison to soil samples that were collected over this thickness. The upper areal concentration value is less than a tenth the EPA recommended soil concentration screening level of 0.2 μCi m^{-2} (see Table 4-11), but is subject to additional discussion later in this report, as the EPA screening criterion is based on the areal concentration over the top cm, while EG&G reported them in terms of equivalent surface concentration. The average $^{238+239+240}$Pu activity concentration among six samples collected for the purpose of estimating the continuum concentration was 2.55 pCi g^{-1}, with the highest being 11.6 pCi g^{-1}. The soil samples were collected at locations that produced negative and positive detects for ^{241}Am, with samples from the negative detect locations biased low by a factor of two. As such, the average $^{238+239+240}$Pu concentration is likely about a half of 2.55 pCi g^{-1}, or 1.3 pCi g^{-1}.

5.8.4.3 Johnston Island, Area Outside LE-1.

A plot of the final in-situ measurement grid used for the Johnston Island phase of the survey is shown in Figure E-10. All of the land areas that were created by the 1963/1964 dredging operation were initially screened on a 200-foot grid convention. None of the measurements in these areas had an in-situ measurement above the ^{241}Am MDC, and per the set protocol did not receive additional measurements. Among land areas existing during Operation Dominic I, about one-third received additional in-situ measurements on the 50-foot grid convention, while the other two-thirds did not have measurements with ^{241}Am above the MDC upon completion of measurement on the 100-foot grid convention. The largest area receiving the more detailed measurements was within the boundaries of LE-1, LE-2, and just south of LE-1. A number of much smaller areas were located along the long axis of the runway, with the eastern-most area by the Redstone launch pad. Figure E-11 contains a plot of the final ^{241}Am in-situ measurement results. These smaller areas of contamination along the runway were likely along a debris pattern from the Starfish failure. Figure E-12 contains in-situ measurements excerpted from Grid Map 32 of Jaffe and Tipton (1982) for the Redstone pad area. The majority of the measurements in the area were below the sensitivity for ^{241}Am, with a high measurement of 37 nCi m^{-2}. This location was chosen for a ratios soil sample. After the sample was collected, a re-measurement with the in-situ system yielded only 15 nCi m^{-2}, indicative that a discrete particle was likely responsible for over half the detector response. Three composited continuum soil samples yielded a $^{238+239+240}$Pu activity concentration of 8.5 pCi g^{-1}.

Positive in-situ measurements were also observed in the vicinity of the mess hall, building 591, as shown in Figure E-13. The two highest measurements were 32 and 29 nCi m^{-2}. Each measurement location was subjected to a ratios and a continuum sample. The average $^{238+239+240}$Pu activity concentration for the continuum samples was 11.6 pCi g^{-1}. At one location, after the sample was collected, a re-measurement with the in-situ system yielded only 11 nCi m^{-2}, indicative that a discrete particle was likely responsible for over half the detector response, while for the second location, the after sampling repeat in-situ measurement only had a modest drop from 32 to 26 nCi m^{-2}.

Another smaller area of contamination was southeast of the swimming pool, with a composited plot of in-situ measurements from Grid Maps 18 and 24 from Jaffe and Tipton (1982) in Figure E-14. The authors referred to this region as the Sandia Bunker Area. There were a number of high readings in the area, with the highest at 43, 35, 34, and 32 nCi m^{-2}. The location with the highest in-situ measurement was sampled, having an average $^{238+239+240}$Pu activity concentration of 547 pCi g^{-1} in close proximity to a discrete particle, based on FIDLER screening. After sampling, however, the repeat in-situ measurement dropped to < 15 nCi m^{-2}, indicative that discrete particles were likely responsible for most of the detector response. The three other continuum composited samples had an average $^{238+239+240}$Pu activity concentration of 12.6, 0.57 and 0.49 pCi g^{-1}. The range of $^{238+239+240}$Pu activity concentration among the three composite samples is evidence of heterogeneity effects, with the average being 4.6 pCi g^{-1}.

5.8.4.3 Johnston Island, Inside LE-1 and Surrounding Area.

The vast majority of contamination was identified inside LE-1, with lower concentrations extending eastward to include portions of LE-2 and southeast of LE-1. The highest in-situ measurement was in LE-1, at 3,220 nCi m^{-2}, surface equivalent ^{241}Am. For the 2,500 ft^2 area (square, i.e., on a 50-foot grid) around LE-1 had an average ^{241}Am activity concentration of 977 nCi m^{-2}, about a third of the maximum

in LE-1. A plot of in-situ measurements of LE-1 and the area to the southeast of LE-1 is in Figure E-15. As observed from previous surveys of this area, contamination levels were noticeably high directly north of the launch pad. Although, there is clear contamination to the southeast of the LE-1, on the outside of the original launch emplacement boundary, contamination levels are substantially lower. One important difference between the contaminant in these two areas is that the contamination within LE-1 was purposely covered with clean coral in 1962 after the Bluegill Prime launch failure, while that outside LE-1 is largely expected to be undisturbed, with the exception of construction activities. Nine soil samples were collected from this area. The highest two had $^{238+239+240}$Pu activity concentrations of 43.3, 20.5 and 20.0 pCi g^{-1}, with respective in-situ measurements of 76, 128, and 49 nCi m^{-2}. The other samples had activity concentrations below 10 pCi g^{-1}, with an average $^{238+239+240}$Pu among the nine at 10.7 pCi g^{-1}. An important point regarding this area is that it is downwind of the key facilities that existed in the middle part of the Island, near the runway. Occupancy in this area would have been intermittent, primarily for individuals transiting to work areas on the western part of the Island.

The maximum in-situ measured ^{241}Am activity concentration in the LE-2 launch pad area was 157 nCi m^{-2}, with the average in the 2,500 ft^2 area (square) around LE-2 of 19.1 nCi m^{-2}. For the five locations with ^{241}Am below the MDC, the concentration was assumed to be at the MDC value for calculation of the average. One in-situ measurement location, just outside the LE-2 boundary to the east had an ^{241}Am activity concentration of 185 nCi m^{-2}. A composited continuum soil sample at this location had a $^{238+239+240}$Pu activity concentration of 15.9 pCi g^{-1}.

5.8.4.4 Overall Activity on Johnston Island.

Figure 5-10 contains a histogram of ^{241}Am activity concentration values for in-situ measurements having reported activity concentrations above the MDC. Overall, 599 locations had measurements above the MDC from our review. The < 100 nCi m^{-2} bin contained 512 measurement locations. With the exception of three locations, all measurements above 100 nCi m^{-2} were within either the LE-1 and LE-2 areas. Two, with concentrations of 128 and 165 nCi m^{-2}, were just south of the LE-1 boundary, while the other, 184 nCi m^{-2}, was on the eastern boundary of LE-2. Among the 84 locations with ^{241}Am activity concentrations above 100 nCi m^{-2}, only two were within LE-2, both at adjacent measurement locations to that where the 184 nCi m^{-2} activity concentration was observed just outside the LE-2 boundary. Integration of the activity over locations with a positive ^{241}Am in-situ reading provided an estimated total ^{241}Am of 0.015 Ci. This value is based on activity being on the surface and a negligible contribution from areas with in-situ measurements below the MDC. It should be noted that Jaffe and Tipton (1982) had 616 in-situ measurement locations with positive ^{241}Am, 17 higher than our review of their report possessed. The discrepancy is believed to be related to how locations were categorized in relation to pre- and post-sampling, and some additional measurements were collected off the standard 50-foot grid. For some measurement locations, a pre-sampling measurement may have had a positive indication of ^{241}Am, while the post-sampling measurement may have been negative, and vice-versa.

Jaffe and Tipton (1982) provided conversion factors for conditions where contamination was covered by an un-contaminated coral overburden, as listed in Table 5-4. The conversion is most appropriate for areas in LE-1 that were purposely covered, but to a lesser degree in other areas. Jaffe and Tipton (1982) noted that source distribution studies while collecting ratio sample provided a median depth of 1.1 cm, which would provide a conversion factor of about 2.25, based on a smooth-fit to the factors listed in Table 5-4. However, it is important to note that the vast majority of the ratio samples were collected

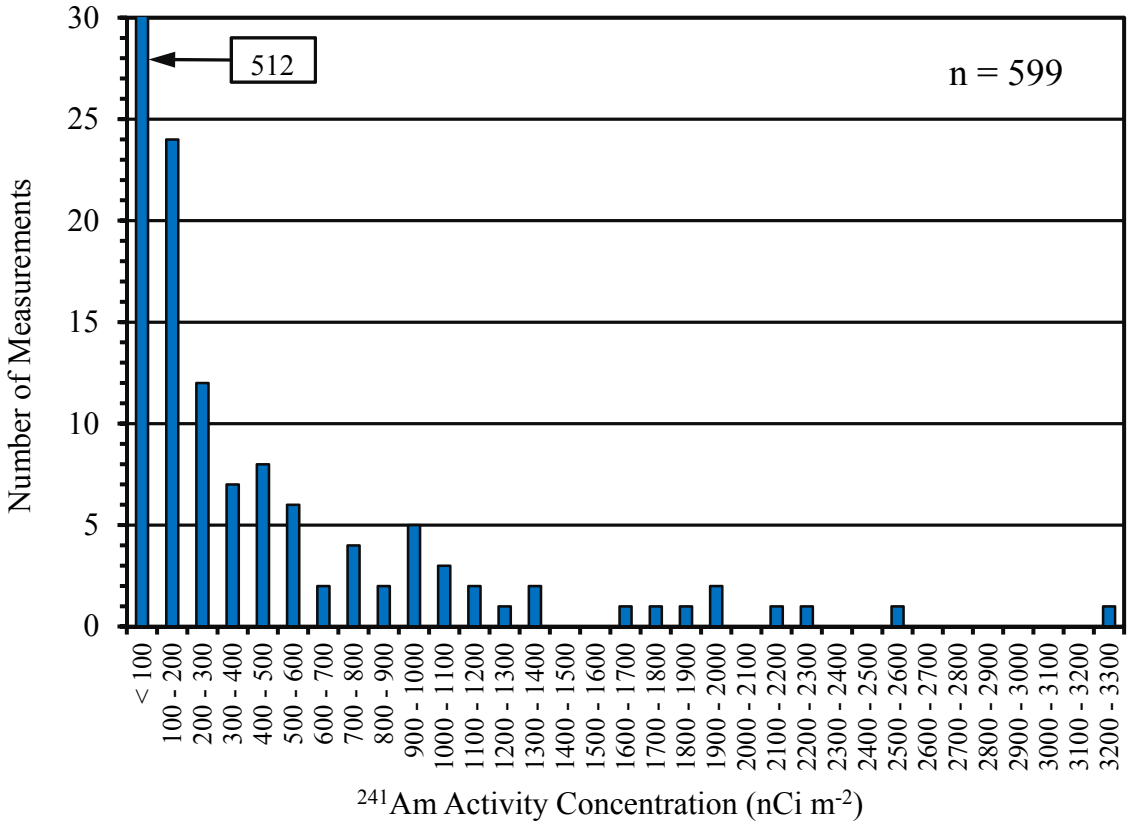


Figure 5-10. Histogram of ^{241}Am Activity Concentrations for In-Situ Measurements Greater than the MDC, Data from Jaffe and Tipton (1982).

outside LE-1, which would underestimate the overburden for contamination in LE-1. Jaffe and Tipton (1982) also provided conversion factors to estimate the average concentration in the top 3 cm of soils, based on in-situ measurements and varied relaxation lengths (exponential model) for the contaminant distribution. Application of the conversion factor for a 3.0 cm cover to the integrated ^{241}Am estimate of 0.015 Ci for zero cover raises the estimate by a factor of 8.7. Additionally, application of a $^{238+239+240}$Pu

TABLE 5-4. Conversion Factors for Varied Contaminant Distributions (Jaffe and Tipton 1982).

Soil Overburden (cm)	Conversion Factor	Relaxation Length (cm)	Conversion Factor for Average Activity Concentration in Top 3 cm of Soil (pCi m^2 nCi^{-1} g^{-1})
0	1	1	0.0329
0.75	1.8	2	0.0376
1.5	3.0	5	0.0410
2.25	5.3	10	0.0420
3.0	8.7	10,000	0.0424

to ^{241}Am activity concentration ratio of 7.17, provides for about 1 Ci $^{238+239+240}$Pu. With a specific activity of 0.072 Ci g^{-1}, it is equivalent to 14 g.

The amount of WGP in the Bluegill Prime warhead remains classified. Masses and fractions noted are for illustration purposes only. If the warhead had 1 kg plutonium, the estimated 14 g residual would be 1.4% of the original mass. If the warhead had 2 kg plutonium, the estimated 14 g residual would be 0.7% of the original mass. For comparison, the BOMARC missile accident that occurred in 1960 had an estimated plutonium residual of 300 g, which was remediated in the 2000's (Rademacher 2010). After completion of the plutonium mining (remediation) project in the later 1990's at Johnston Island, estimates of $^{239+240}$Pu residuals in coral soils could have been as high as 13 Ci, 180 g (DTRA 2002). However, this is based on conservative assumptions in the estimation of activity from the radiological scanning of soil during processing through the segmented gate system (SGS).

5.8.4.5 Isotopic Ratios.

During the 1980 survey, numerous samples were collected to assess the isotopic plutonium to ^{241}Am ratios, as well as four samples that were subjected to mass spectrometry. The mass spectrometry samples provided the ^{239}Pu to ^{240}Pu partitioning, as the α-spectrometry method is unable to resolve the α-particle energies of the two isotopes. The samples analyzed by mass spectrometry also had uranium quantifications. The results of the mass spectrometry data is contained in Table 5-5. Overall, there was a wide range of variability between the various isotopes of uranium and total uranium compared to ^{239}Pu. LANL noted, "With a low order explosion such as happened to Bluegill Prime, the

TABLE 5-5. Isotopic Uranium, Plutonium, and ^{241}Am Relationships from Four Samples Analyzed by Mass Spectrometry, Los Alamos National Laboratory, 28 December 1980 (Knobeloch 1981).

Sample	Mass Ratios				Plutonium Mass Fractions			
	U-235 / Pu-239	U-238 / U-235	Total U / Pu-239	Am-241 / Pu-238+239+240	Pu-238	Pu-239	Pu-240	Pu-241
2905	0.36	14.3	5.55	0.00302	7.86E-5	0.9427	0.0554	0.0018
2906	5.8	0.801	10.51	0.00283	7.95E-5	0.9427	0.0554	0.0018
2907	0.696	0.208	0.85	0.00341	8.36E-5	0.9392	0.0588	0.0019
2908	0.394	3.28	1.69	0.00293	8.04E-5	0.9424	0.0557	0.0018
				Mean	8.05E-5	0.9418	0.0563	0.00181

Sample	Activity Ratios			
	U-234+235+238 / Pu-239	U-234+235+238 / Pu-238+239+240	Am-241 / Pu-238+239+240	Pu-238+239+240 / Am-241
2905	0.00385	0.00310	0.145	6.87
2906	0.00670	0.00539	0.136	7.33
2907	0.00084	0.00067	0.163	6.15
2908	0.00044	0.00036	0.141	7.11
Mean	0.00296	0.00238	0.146	6.87
Median	0.00235	0.00189	0.143	6.99

fractionation of such different types of components should make it possible to find samples containing almost any mixture" (Knobeloch 1981). Most importantly among the samples, the uranium activity was very small compared to the ^{239}Pu or $^{238+239+240}$Pu, and of negligible health consequence compared to that from the plutonium. The same conclusion was made upon review of the original warhead composition, though specific details cannot be provided here, because the composition of the warhead remains classified. The isotopic plutonium fractions were fairly consistent among the four samples, with mean values listed in the table.

LANL noted that the data supported a common source for the plutonium, with an estimate that it was purified for fabrication in 1960 (Knobeloch 1981). The two short-lived isotopes of plutonium, ^{238}Pu and ^{241}Pu, had respective mean mass fractions of 8.05×10^{-5} and 1.81×10^{-3} in 1980. Decayed back to 1960, the fractions would have been 9.3×10^{-5} and 4.75×10^{-3}. In 1960, ^{238}Pu would have contributed about 2% of the total α-radiation emissions from the plutonium, with its contribution slowly decreasing over time. While ^{241}Pu only emits low-energy β-particles and is negligible in radiological hazard compared to the α-particle emissions, it decays to ^{241}Am (an α-particle emitter), as discussed above in Section 4.1. Because, ^{241}Am has a longer half-life than ^{241}Pu, it is in transient equilibrium with ^{241}Pu, having activity relative to ^{241}Pu, as shown in Figure 5-11. The ^{241}Am reached 68% of its peak value by the 1980 soil sampling event. The ^{241}Am is an important radionuclide in WGP, as it is has a more easily quantified photon in field conditions than the photon emissions from the plutonium isotopes. From these four samples, the $^{238+239+240}$Pu to ^{241}Am ratio had a mean and median about seven. Eighty-one samples, including ratios and continuum samples, had reported activity concentrations from α-spectrometry analyses for ^{241}Am and plutonium isotopes. Nine samples had reported activity concentrations for $^{239+240}$Pu, but with ^{241}Am below the MDA, which necessitated removing these samples from the analysis. The individual samples had $^{238+239+240}$Pu to ^{241}Am ratios ranging from 0.42 to 21.4, with a mean of 7.47, and a median of 7.17. In previous analysis of $^{239+240}$Pu to ^{241}Am ratios for WGP at the BOMARC and Rocky Flats sites, the AF Safety Center deemed the median ratio a better estimate of the true ratio than the arithmetic average [Rademacher(b) 1999]. As such, this value was chosen as the best

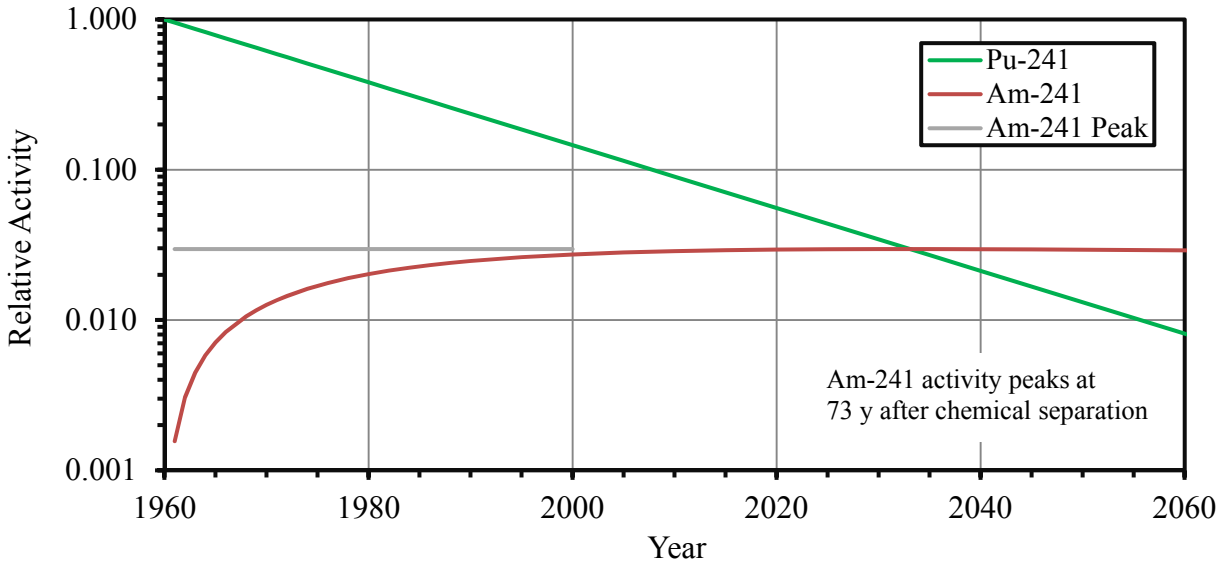


Figure 5-11. Relative Activity of ^{241}Am to ^{241}Pu after Chemical Separation in 1960.

estimate for the relationship in 1980. The estimated isotopic relationships among the key α-emitting isotopes of the Bluegill Prime WGP between 1960 and 2005 are displayed in Figure 5-12. The $^{238+239+240}$Pu to ^{241}Am ratio in 1962 was estimated at 47.7, but only 5.2 in 2005. At the time of chemical separation, estimated at 1960, the α-emissions from the WGP are solely from plutonium, while in 1980 and 2005, ^{241}Am accounts for 12 and 16%, respectively, based on the figure.

5.8.4.6 Test Remediation. During the 1980 radiological survey, EG&G, with assistance from DOE, Nevada Operations Office, and FC DNA, performed test remediation in a contaminated area around N198150 – E196400, as shown in Figure E-15 centered on the purple-colored circle. A 50 x 50 foot square area was carefully surveyed with a FIDLER on a two-foot serpentine survey pattern and wand flagged at each location with an identified hot spot. In conjunction to the FIDLER survey, an additional in-situ measurement was collected with the HpGe system, but at half the standard height used for other measurements. The measurement at 7.2 m above ground level, yielded 58 nCi m^{-2}, while at the 3.6 m height the measurement yielded 99 nCi m^{-2}. The FIDLER survey identified 34 separate hot spots. The hot spots were removed, with a post removal in-situ measurement yielding 40 nCi m^{-2} at a 3.6 m measurement height. After the removal action, the continuum sample was obtained from the area, which yielded a $^{238+239+240}$Pu activity concentration of 11.8 pCi g^{-1}. Clear from this discrete particle removal activity and associated measurements is the substantial contribution to detector response, ~ 60%, from the discrete particles rather than the diffusely-contaminated continuum.

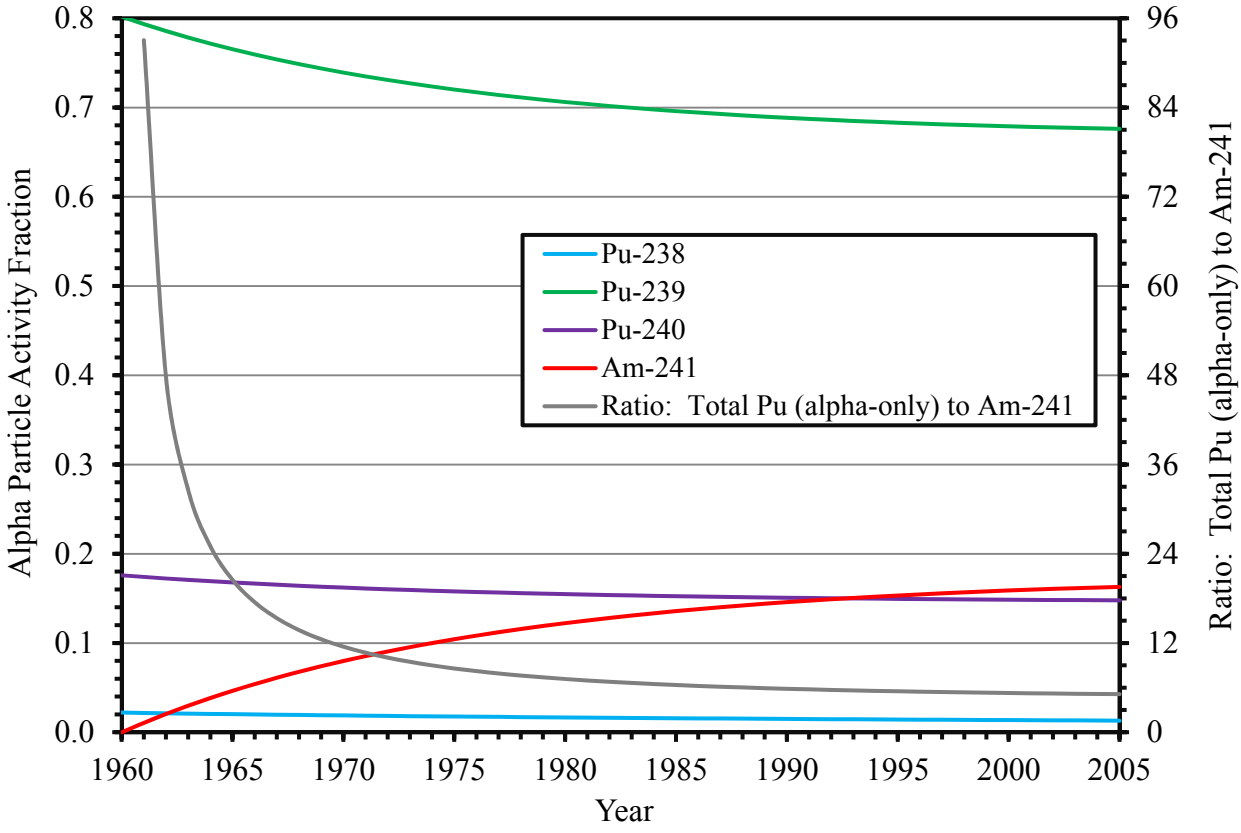


Figure 5-12. Estimated α-Particle Emitting Isotopic Fractions for Bluegill Prime Plutonium.

5.8.4.7 Other Radionuclides. EG&G evaluated other radionuclides in the in-situ spectra, with identification of ^{234}Th, ^{235}U, ^{214}Bi, and ^{137}Cs. The first three were associated with a natural terrestrial uranium source, while the latter was associated with concentrations expected in surface soils from global fallout of atmospheric nuclear weapons testing (Jaffe and Tipton 1982), which to varying degree impacted all surface soils.

5.8.4.8 External Radiation from Dispersed WGP.

External radiation emissions from the low-levels of ground-deposited WGP and uranium emits insignificant levels of external radiation in comparison to natural terrestrial and cosmic radiation sources. To illustrate this point, an estimate of external dose rates were made, based on upper-end ^{241}Am activity concentrations in LE-1, based on the 1980 EG&G survey (Jaffe and Tipton 1982). In review of Figure E-15, 1,000 nCi m^{-2} was deemed a reasonably high estimate of the activity concentrations in the vicinity of the launch pad. As noted earlier in this report, activity concentrations in other contaminated areas on Johnson Island were substantially lower. Although most of the contamination was likely covered by varying thickness of clean coral, the EG&G values reported represent equivalent levels of surface contamination. External dose coefficients for ^{241}Am, ^{238}Pu, ^{239}Pu, and ^{240}Pu are contained in Table 5-6, with activity ratios of the plutonium isotopes to ^{241}Am and calculated dose equivalent rates for each isotope. ^{241}Am contains the vast majority of the contribution to the total dose equivalent rate among the isotopes at the time chosen. Based on Figure 5-10, the ^{241}Am concentrations are only about two-thirds of their peak concentration, with the concentrations were near the peak in 2000, and concentrations prior in 1980 progressively less for earlier times, and insignificant in 1962. The changes in ^{241}Am concentrations over time are somewhat balanced by the distribution in depth. In 2000, ^{241}Am would be about 50% higher than in 1980, but would have migrated to greater depths, and with associated higher photon attenuation. Similarly, prior to 1980, the ^{241}Am being progressively less abundant for early times, the material would have also been subjected to less time-dependent weathering and would have been closer to the surface.

The total dose equivalent rate of 0.41 μrem h^{-1} is small compared to an estimated background of 5 μrem h^{-1} for Johnston Island from natural terrestrial and cosmic sources. For a 2,000 h exposure period in LE-1, this would equate to only 0.8 mrem.

TABLE 5-6. Estimate of External Dose Levels for WGP at 1,000 nCi m^{-2} ^{241}Am on Ground Surface in 1980 with Federal Guidance Report 12 Dose Equivalent Values (EPA 1993).

Radionuclide	Activity Ratio to ^{241}Am in 1980 (from Figure 5-11)	Dose Coefficient (Effective) (Sv-m^2 s-Bq^{-1})	Dose Equivalent Rate (μrem h^{-1})
Am-241	1	2.75 x 10^{-17}	0.366
Pu-239	5.79	3.67 x 10^{-19}	0.028
Pu-240	1.27	8.03 x 10^{-19}	0.013
Pu-238	0.14	8.38 x 10^{-19}	0.0015
Total	NA	NA	0.41

5.9 Thor Missile Site Remediation.

5.9.1 General. The Thor launch facility was decommissioned in 1977 (Dooley et al. 1986), two years after the last Thor launch from Johnston Island. By 1980, the site had suffered significant degradation due in part to the marine environment, with concern that a strong typhoon would destroy the facility and redistribute radiological contamination (Dooley et al. 1986). Around the time of the EG&G survey in 1980, the large steel revetments and 610 m^3 of debris was placed inside the missile shelter, which was assessed to provide better stability than that in open outdoor areas (Dooley et al. 1986). In 1983, a decision was made to remediate the site. The first phase planned was the disposal of contaminated structures, the second phase planned was the consolidation of contaminated soils into the RCA, and the final phase planned was the recovery of plutonium from the soils that implemented a SGS to reduce contaminated soil volumes. This process was deemed more cost efficient than soil removal.

5.9.2 1984 Infrastructure Decontamination and Demolition Inside LE-1.

Dooley et al. (1986) detailed the 1984 activities to remove structures and other debris from LE-1. The operation was accomplished inside the confines of the RCA, but involved activities on debris in LE-1. Similar to operations that were accomplished in the remediation of LE-1 in 1962 after the Bluegill Prime launch failure, a full hot-line was established for workers, at 46 m up-wind of the work area on the LE-1 pad, with workers wearing air-purifying respirators and anti-contamination clothing. Air sampling was also conducted at numerous locations in the RCA, as summarized in Table E-11.

The work that was accomplished breaking concrete and steel into smaller, more manageable sizes implemented the use of acetylene torches, saws, and chipping hammers, while the large concrete pads were scabbled to remove surface contamination (Dooley et al. 1986). These operations notably produced the highest concentrations of airborne contamination, based on a review of air sampling data. For five of the daily samples, the average concentration of a downwind air sampler from LE-1 pad had an airborne $^{239+240}Pu$ concentration greater than 2,000 fCi m^{-3} (2 pCi m^{-3}), while for 21 daily air samples the concentration ranged between 200 and 2,000 fCi m^{-3}. One-hundred seventeen daily air samples though had airborne $^{239+240}Pu$ concentration less than 200 fCi m^{-3}. Building 786 was at the entry control point (ECP) to the RCA (see Figure 5-8), and represented a location in the RCA upwind from the primary work zone. This is the area that debris was taken to be assessed for contamination content, as this area within the RCA was known to have relatively little radiological impact from the Bluegill Prime launch failure and had a large concrete pad for arranging debris-laden pallets (Dooley et al. 1986). After debris was assessed, it was packaged into shipping containers (Dooley et al. 1986). The highest airborne concentration measured at this location was 246 fCi m^{-3}, with the next highest at 124 fCi m^{-3}. This area overall had lower concentrations of contamination than the two samplers downwind of the LE-1 pad. Two long-term air samples were collected at this location at the beginning of the project, 8 – 18 Oct 84, having negligible results listed in Table 5-2 (above), where summaries of other long-term air samples are contained. Weekly samples were also collected at this location between August 1987 and November 1988 as well, with negligible results listed in the same table.

While a number of samples collected in LE-1 during the restoration activity were in excess of 10% of the 2 pCi m^{-3} MPC limit established for occupational exposure to plutonium on Johnston Atoll, it is important to note that actual inhalation exposures to workers would have been much less, as personal protective equipment (PPE), including respirators was used for work in the RCA during this project.

The nearly 200 workers that contributed to this project were monitored with thermo-luminescent dosimetry (TLD), screened upon exiting the hot zone for α-radiation contamination, underwent isotopic plutonium analysis of pre- and post-project urine samples. No external or internal radiation dose from the work was detected for any of the workers (Dooley et al. 1986).

The closest downwind worksite from the RCA was within the S&I area. As detailed in Table 5-2, this location had continuous air sampling between November 1975 and October 1990. Airborne concentrations at this location were typically well below 0.1 fCi m^{-3}. It is notable that the highest average activity concentration observed at this sampling location was for 18-26 November 1984, 19.8 ± 2.9 fCi m^{-3} during this remediation activity. Table 5-7 lists air sampling results for this location over the duration of the LE-1 work in fall 1984. Elevated readings were observed from the three sampling periods between 19 November and 3 December, though the concentrations were all below 1% of the 2 pCi m^{-3} MPC established for occupational exposures to plutonium on Johnston Atoll.

The decontamination and demolition project required 27 dry cargo shipment containers, with an estimated waste mass of 455 metric tons, 455,000 kg (Dooley et al. 1986). Twenty-one were filled with structural debris, 5 were filled with surface-contaminated gunited concrete, and one was filled with 55-gallon drums of material (Dooley et al. 1986). The waste was shipped to the Nevada Test Site for disposal.

TABLE 5-7. Weekly Air Sampling Results for S&I During the 1984 LE-1 Decontamination and Demolition (DTRIAC Archives).

Collection Dates	Volume (m^3)	$^{239+240}$Pu (fCi m^{-3})	OEHL Sample Number	Collection Dates	Volume (m^3)	$^{239+240}$Pu (fCi m^{-3})	OEHL Sample Number
24 Sep-1 Oct	867	1.0 ± 0.2	18401160	12-19 Nov	865	15 ± 2	18500169
1-8 Oct	866	0.6 ± 0.2	18401163	19-26 Nov	863	20 ± 3	18500170
8-15 Oct	864	1.9 ± 0.3	18401164	26 Nov-3 Dec	866	19 ± 2	18500171
15-22 Oct	875	4.8*	18500165	3-10 Dec	870	1.4 ± 0.2	18500172
22-29 Oct	867	2.2*	18500166	10-17 Dec	164	0.4 ± 0.3	18500173
29 Oct-5 Nov	872	0.2*	18500167	17-24 Dec	873	0.03 ± 0.03	18500174
5-12 Nov	862	0.16 ± 0.06	18500168	24-31 Dec	868	0.05 ± 0.04	18500175

* Value not listed in DTRIAC archive, values scaled from daily air sampling in LE-1 (see § 6.2.5.1 for details)

5.9.3 1985 Coral Grading Operation Outside LE.

In 1985, radiologically-contaminated soil outside the RCA was removed and consolidated into LE-1. The areas subject to removal were those southeast of LE-1. In a similar manner to the work accomplished in LE-1 during 1984, air sampling was accomplished during the activities, with a summary of the results in Table E-12. High-volume air sampling was accomplished at Arnold Ave. and the Angle Measurement Equipment (AME) field. Arnold Ave. is south of the swimming pool. The AME field is noted on Figure 5-8 around the radar measurement equipment, presumably key to tracking missile launches. In addition, lapel monitoring was accomplished, where the measurements are listed under the categories: grader, back hoe, and Arnold [Ave]. On some air sampling forms, where Arnold

Ave. was listed for a lapel sampler, the location was also listed as an end loader. It is our assumption that this is where contaminated soil was loaded on a dump truck for eventual transport to LE-1.

The highest concentration recorded for the high-volume air samples was 15 $\pm$ 2 fCi m^{-3} on 3 December. The vast majority of the high-volume air samples had activity concentrations below 1 fCi m^{-3}. The largest lapel air sampler had a collection volume of 1.3 m^3, substantially less than the high-volume air samples, which had 67 m^3 as the lowest volume collected. The low collection volumes severely hampered sensitivity. The lowest individual sample MDA was 10 fCi m^{-3}, for the sample with the 1.3 m^3 volume, while the highest MDA was 180 fCi m^{-3}, for the sample with volume of 0.1 m^3. The latter volume is equivalent to the volume inhaled by a worker over a 5 minute period under light activity conditions. Only one lapel sample had a reported concentration, 60 $\pm$ 50 fCi m^{-3}, for 20 September. Overall, the lapel samplers had poor detection sensitivity due to the low collection volumes. Due to the relatively low plutonium activity levels in the soils in these areas, airborne radioactivity levels would not be expected to be significant, as evidenced by the high-volume air sample results.

5.9.4 1988 Operation in LE-2. The DTRIAC archives also contained high-volume air sampling results for three days in October 1988. For each of the samples, the collection was only over a portion of one day, with the volumes ranging between 61 and 88 m^3. The three samples were analyzed by OEHL for gross α-radiation content. It is our assumption that these samples may have been conducted during demonstration of a test soil cleanup plant operation in the RCA in 1988 (Wilson-Nichols et al. 1988). Details were not located in the DTRIAC archived records on the activity that prompted the collection of these samples. Nevertheless, the activity concentrations were unremarkable, with the highest concentration among the three at only 11 $\pm$ 6 fCi m^{-3}.

5.9.5 Soil Sorting – Volume Reduction.

The soil volume reduction phase of the radiological restoration of Johnston Atoll began with operation of a pilot plant operated in the first half of 1986 (Bramlitt 1988), with full-scale operations initiated in January 1992. Prior to the pilot plant operation, test soils were sent to the Rocky Flats Plant in Colorado for suitability tests (Bramlitt 1988). The operating concepts are detailed in Bramlitt (1986), and are outside of the scope of this report. One weekly air sample, 31 March – 7 April 1986, collected at building 795 during operations of the pilot plant had an airborne $^{239+240}$Pu concentration of 1,110 $\pm$ 140 fCi m^{-3}. As noted in Table 5-2, the result is believed to be a reporting error, as the radiological screen of the sample on Johnston Island was less than the MDA. All other weekly samples collected during operation of the pilot plant were unremarkable.

Some operating principles of the pilot plant were eventually merged with a SGS that preferably removed contaminated soil transported on a conveyor belt subjected to real-time radiological monitoring of the material under transport (Moroney 1995). DNA had established a 13.5 pC g^{-1} release criteria for soils, which was incorporated into operational parameters of the system (Moroney 1995). A 135 nCi discrete particle criterion was also incorporated into the screening process for the unrestricted release of soil (Moroney 1995). This criterion was established based on the detection capability of the system, as a particle of this activity has a minimum volume equivalent diameter of about 67 μm (see Figure E-5) and does not represent an airborne resuspension hazard. Weight reductions of contaminated soils were estimated at about 98.1% (Moroney 1995). The system was set-up near building 795, within LE-1, near

the seawall. This location provided minimal impact of suspended aerosols from the operation to personnel in uncontrolled areas, as the lagoon was immediately downwind of the operation.

Processing of soils through the SGS ended in 1996. At the end of 1996 into 1997, efforts to further reduce the volume of the soils with concentrations above the criterion were attempted, however, this effort was ceased after it became clear that the technology failed to meet demonstration goals (DTRA 2002). The SGS process ended up producing a pile with concentration above the release criteria estimated at 45,000 m^3, with an estimated average $^{239+240}Pu$ concentration of 200 pCi g^{-1}. The pile with soil below the release criteria had an estimated volume of 120,000 m^3, with an estimated $^{239+240}Pu$ concentration of 7.7 pCi g^{-1}. Moroney et al. (1995) reported densities of feed material ranging between 1.07 and 1.56 g cm^3. Assuming an average density of 1.32 g cm^3, these piles encompassed an estimated $^{239+240}Pu$ activity of 13 Ci.

THERMO NUtech, the contractor operating the contaminated soil cleanup project, conducted a comprehensive radiation safety monitoring program, which consisted of air sampling, surface contamination and FIDLER scan surveys in building 795, contamination control surveys of personnel exiting the RCA or entering building 795, and urine bioassay samples (Doane 1996). An administrative limit for airborne α-radiation activity concentrations was established at 20% of the 10 CFR 20 DAC (7×10^{-12} μCi cm^{-3}), i.e., 1.4×10^{-12} μCi cm^{-3} and 1.4 pCi m^{-3} (Doane 1996). Access to areas exceeding this level required the use of respiratory protection. High-volume air samples were collected throughout processing in the plant, and as such, represented concentrations in the work for individuals supporting the processing operations. Monitoring results for three months in 1994 are provided in Figure E-17 as an example. For February, concentrations were typically around 0.02×10^{-12} μCi cm^{-3} (20 fCi m^{-3}), with the high sample having a concentration of 0.1×10^{-12} μCi cm^{-3}. Concentrations in March and April were higher than February, though below the administrative limit of 1.4×10^{-12} μCi cm^{-3} (pCi m^{-3}). For March, the peak concentration was 0.48×10^{-12} μCi cm^{-3}, while for April it was 1.3×10^{-12} μCi cm^{-3}, just below the administrative limit, though typical values were much less, $\sim 0.1 \times 10^{-12}$ μCi cm^{-3}. Air sampling results for other periods of operations are contained in other archived DTRA reports.

Lawrence Livermore National Laboratory (LLNL) in 1992 performed air sampling analysis in proximity to the soil sorting operation for one month, 14 October – 14 November 1992 (Shinn et al. 1994). LLNL sampled at three locations around the operation, with a high-volume cascade impactor (CI) paired with a high-volume air sampler. Two paired high-volume air samplers were upwind of the operation to assess background conditions. Each sampler had a flow rate of about 34 m^3 h^{-1}. The locations were the "spoils pile," in vicinity of the location the stock is fed onto the conveyor belt, the "plant area" where the soils above the criteria are removed from the conveyor belt, and the "clean pile" that had soils presumably below the screening criteria. A summary of the air sampling results are in Table 5-8. The median specific activity of $^{239+240}Pu$ in the suspended aerosols was 3.64 pCi g^{-1}, with the high-volume sampler at the clean pile having an activity concentration about six-fold higher than the median. Overall, however, airborne activity concentrations were very low compared to the occupational limit established at that time for $^{239+240}Pu$, 7 pCi m^{-3}, consistent with 10 CFR 20 (1992). The air sampling data also provides some important information regarding the aerosol. The activity median aerodynamic diameter (AMAD) and the mass median aerodynamic diameter (MMAD) are much higher than the default AMAD of 1 μm that is commonly used for occupational exposure settings. Among the six samples, the mass loading ranged between 71 and 196 μg m^{-3}, whereas the background was only 41.4 μg m^{-3}. The elevated mass loading in the work zones over that observed at the background sampling location is expected, due to the

TABLE 5-8. LLNL Air Sampling Results, 14 October – 14 November 1992, (Shinn et al. 1994).

Location	Sampler	$^{239+240}$Pu Activity Concentration (pCi g^{-1})	$^{239+240}$Pu Activity Concentration (fCi m^{-3})	Mass Loading (μg m^{-3})	Activity Median Aerodynamic Diameter (μm)	Mass Median Aerodynamic Diameter (μm)
Spoils Pile	CI	4.75	0.93	196	3.59	3.25
	HV	3.32	0.53	160	IND*	13.0*
Plant Area	CI	3.20	0.31	96.8	3.64	3.98
	HV	3.87	0.35	89.5	9.1*	7.7*
Clean Pile	CI	3.19	0.28	87.9	2.62	3.26
	HV	21.2	1.5	71.0	12.5*	8.5*
All Sites	Median	3.64	0.40	0.11	3.3	3.5
	CV	0.54	0.68	0.41	0.58	0.42
Bkgd	HV	0.14	0.0058	41.4	NA	NA

* Observed geometric standard deviations IND = Indeterminate

loading and processing of soil. The background mass loading is typical for the average in the eastern US, as seen from EPA data in Figure 5-13.

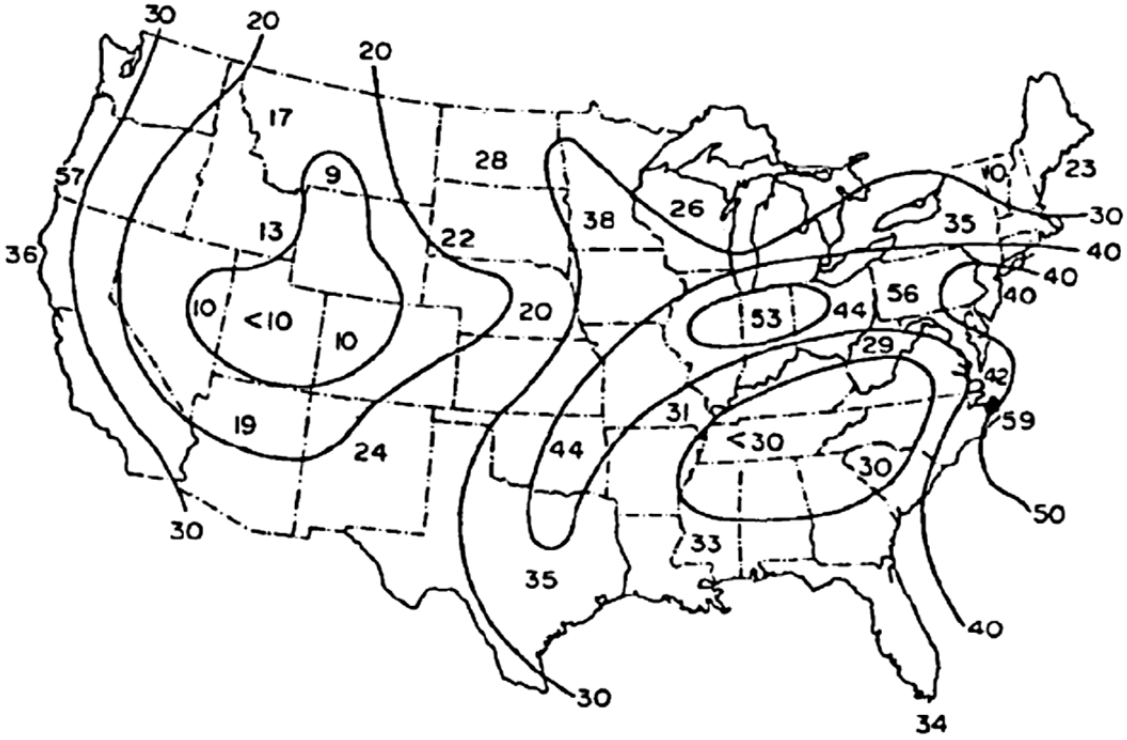


Figure 5-13. Annual Mean Mass Concentrations (μg m^{-3}) of Airborne Particles from Non-Urban Stations of the U.S. National Air Sampling Network (Figure A2-2 from EPA 1977).

6.0 Dose Assessment Modeling

6.1 Applicability.

Military service members with onsite participation during the operational period of atmospheric tests during Operations Hardtack I and Dominic I that have radiogenic diseases listed in Table A-1 are presumptive for service connection under VA adjudication procedure. As well, the period of coverage extends for six months after the end of the operational period of the tests. For Hardtack I, the period extends from 28 April 1958 to 30 April 1959, while for Dominic I, the period extends from 25 April 1962 to 30 June 1963. Hence, for service members assigned to Johnston Island during these periods, dose assessments from dosimetry records or modeling are not required to adjudicate a claim.

There is the potential for some VA claims to originate from individuals that participated in Hardtack I and Dominic I from Johnston Island, yet do not have a radiogenic disease on the VA list for presumptive connection (see Table A-1). VA cases of this type are normally evaluated for radiation exposure potential by DTRA/NTPR. DTRA/NTPR would normally refer to external dosimetry information in Gladeck et al. (1982) and Berkhouse et al. (1983) for these claims. With the exception of a small number of individuals assigned to duties at Johnston Atoll during these two test series, external radiation exposure potential was very low. While the Berkhouse et al. (1983) work is specific to Dominic I tests, it does not contain detailed information on airborne plutonium levels observed during the restoration of the LE-1, though the report details protection afforded to workers and details on restoration activities. Evaluation of VA cases with non-presumptive diseases requires evaluation of internal exposure potential from WGP released from the Thor missile mishaps. Nevertheless, as detailed in this report, exposure to airborne plutonium presents internal exposure hazard, with predominant deposition and retention in the lungs, bone surfaces, and liver. The deposition and retention has been substantiated in animal and human studies, with cancer risks to these tissues from epidemiological studies of occupational exposures to high-levels of plutonium. Primary cancers in the lung, liver, and bone are recognized by the VA as presumptive radiogenic diseases. Hence, there is not a strong scientific link between non-presumptive diseases, which are not also on the presumptive list, and internal exposure from WGP exposure. Claims of this type follow the procedures in 38 CFR § 3.311, where an "assessment will be made as to the size and nature of the radiation dose or doses." DTRA/NTPR currently uses Standard Operating Procedure RA02 to assist in these claims (DTRA 2014). The list of radiogenic diseases under § 3.311 is larger than the list under § 3.309, and also lists "other cancers," which a few years ago added consideration for chronic lymphocytic leukemia (CLL). CLL had traditionally been considered non-radiogenic.

Service members working on Johnston Atoll outside the operational periods covered under Operations Hardtack I and Dominic I would have had exposure potential from the dispersed WGP. Claims of this type, also follow 38 CFR § 3.311, and require an assessment of dose. While low-levels of ground-deposited WGP and uranium emit γ-radiation and x-rays, their contributions to external radiation are negligible compared to existing natural terrestrial and cosmic radiation sources, as demonstrated in calculations provided in Section 5.8.4.8 of this report. Because the Atoll was not impacted by fission product fallout from the tests conducted from the Atoll, external radiation exposures would have been insignificant for individuals on the Atoll outside the operational periods of Operations Hardtack I and Dominic I. Therefore, no further analysis of external radiation exposures will be contained in this report, as they are deemed negligible. All dose assessments will evaluate internal radiation exposures.

Also, the analysis of internal exposures from uranium released from the Thor mishaps are deemed negligible, and well within the uncertainties that exist in the estimation of doses from WGP. Internal exposures from ground-deposited WGP generally consider the following exposure pathways: inhalation of resuspended contamination, ingestion of contaminated dusts/soils, consumption of contaminated water, consumption of plants grown on contaminated soils, and consumption of animals grazing contaminated areas or grazing on fodder grown in contaminated areas. The last two categories are applicable to contaminated land areas that are involved in agriculture or support a household garden. Since neither of these activities was applicable to Johnston Atoll, these pathways were not considered. In scenarios where these pathways are applicable, however, the relative contribution to total dose is generally low, due to the relative insolubility of PuO_2 and subsequent poor uptake in plants. Up until 1986, Johnston Island produced potable water by distillation, while after 1986, it used reverse osmosis. Both of these methods would have been effective at removal of plutonium. Nevertheless, routine radiological monitoring of drinking water was accomplished, as discussed above, with unremarkable results. As such, this pathway is not considered applicable to WGP exposures on Johnston Atoll. Therefore, the only reasonable internal exposure pathways are inhalation and ingestion of dusts/soils.

6.2 Inhalation Exposure Pathway.

6.2.1 Methodologies. 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. A number of assumptions are made in the estimate of inhalation intakes from air sampling data. Key assumptions are: the rate of inhalation, inhalation period, aerosol size characteristic, and the chemical form of the WGP. Some air samples collected during operation of the SGS provided aerosol characteristics through use of cascade impactors. Airborne concentrations can be predicted from the concentrations of contaminants in surface soils. Modeling codes like Residual Radiation (ResRad) was developed and is maintained by the Environmental Assessment Division Office at Argonne National Laboratory. This code uses a mass loading approach for estimating airborne concentrations. Urine bioassay analysis can be used to estimate body burdens of plutonium, and indirectly from this data, estimates can be made of a potential intake. Bioassays are normally accomplished to demonstrate compliance with occupational exposure standards and evaluate the effectiveness of a radiation safety program. However, due to the cost and burden of collecting samples, samples are often collected infrequently, compared to air sampling. As a result, assumptions must be made regarding the time of potential intake, which can have a significant influence on the estimate of intake. Urinalysis for WGP, however, is not sufficiently sensitive to estimate inhalation intakes at a small fraction of the ALI.

6.2.2 Resuspension Models.

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 average 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:

$$C = E_f S_o M.$$

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 average 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 [Palomares, Tonopah] and at large distances from fission events [Bikini, Maralinga]." 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.

The resuspension 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:

$$C = S_f D.$$

Anspaugh et al. (1974) summarized some early models for temporal changes in resuspension factors, as summarized in Figure 6-1. Also noted on the plot is a model described in 1982 by Smith et al. The Kathren and Anspaugh et al. model 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 NRC (1975) use. The Smith model as used by the NRC (1975) and Anspaugh 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.

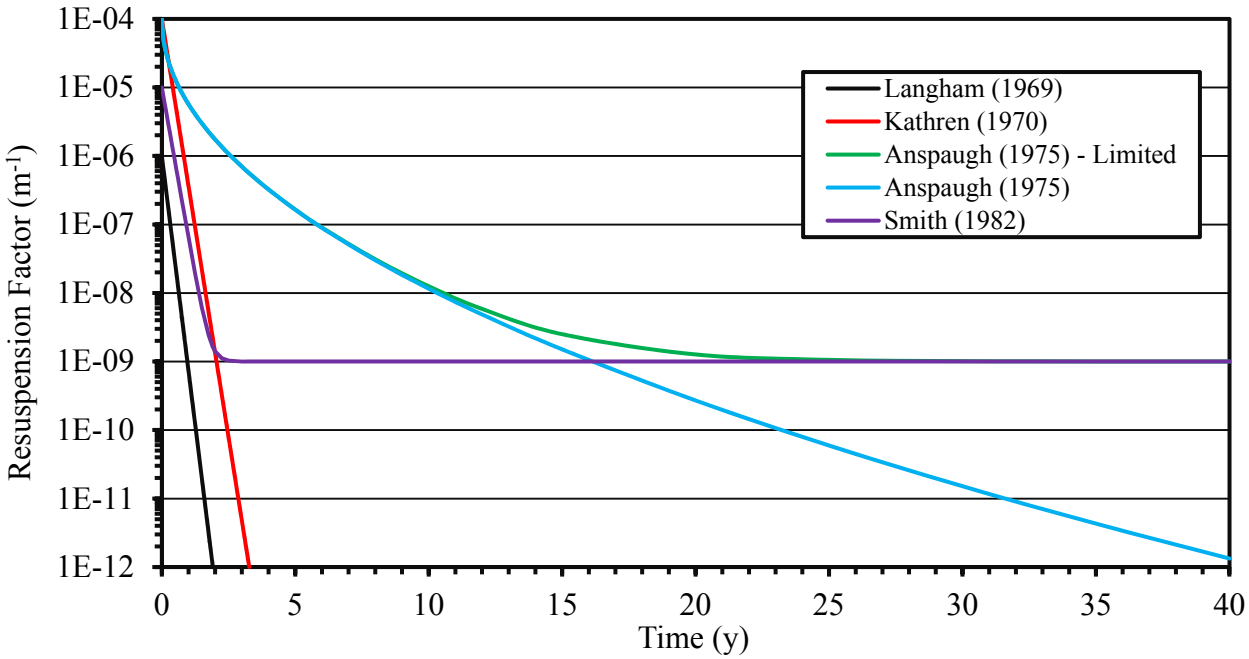


Figure 6-1. Resuspension Factors based on Anspaugh et al. (1975) and Smith et al. (1982).

The variability in the models results from differences in the periods of time 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) more recently 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 6-2. 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 long periods, consistent with the Smith

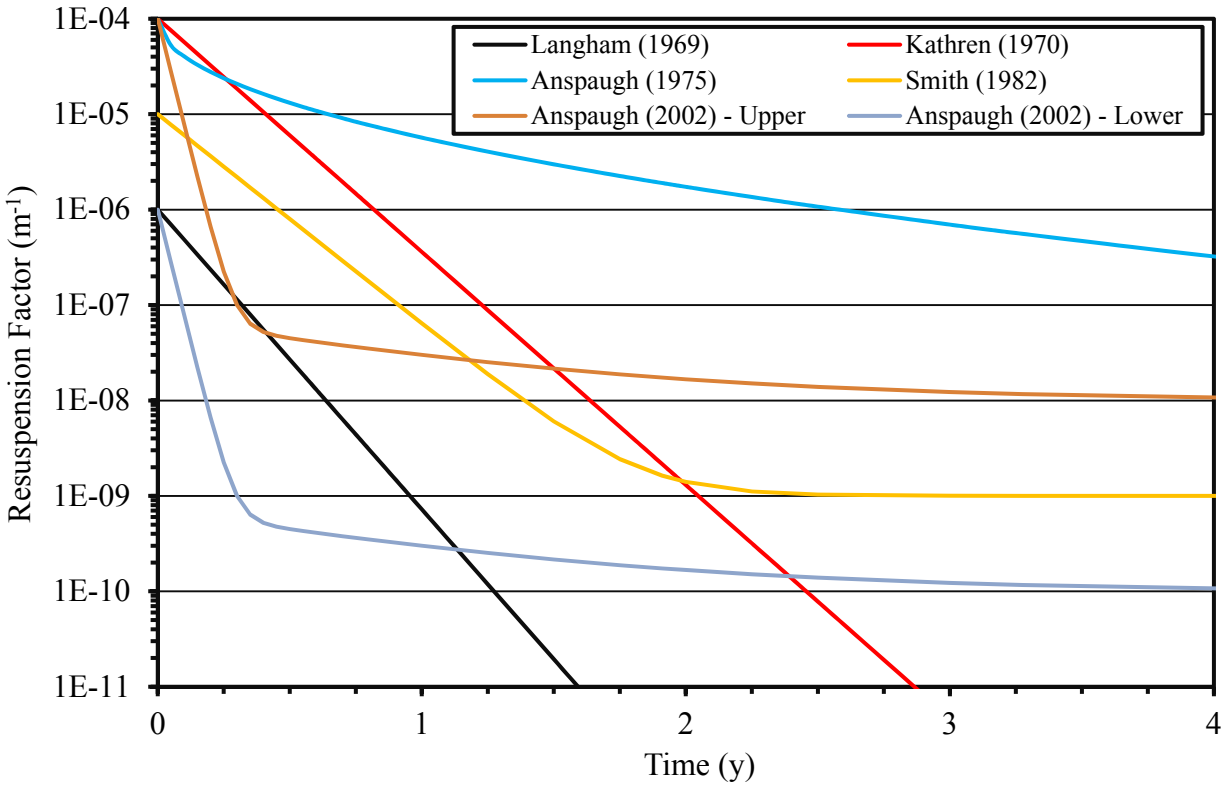


Figure 6-2. Resuspension Factors based on Anspaugh et al. (2002), with Previous Models.

et al. (2002) model and the Anspaugh et al. (1975) model. The early reduction in resuspension factors predicted by this model is greater than that of the 1969 Langham model. The Smith et al. (1982) model, with the use of parameters used by the NRC, is more conservative than the most recent Anspaugh et al. model, but this is expected due to the NRC's regulatory role and inherent conservative assumptions. 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).

An important point regarding plutonium dispersed in an accidental fire or detonation is that the majority of plutonium is not released in a respirable form, and subsequently would overall have poor resuspension potential compared to tests on the deposition of other aerosols, i.e., world-wide fallout, where the majority of the deposited aerosol is respirable and readily resuspend able upon initial deposition. For fires, plutonium released in respirable form is expected to be less than 2% based on experimental data and computer modeling (Condit 1993). Stephens' (1995) best estimate of the expected value of respirable fraction from plutonium involved in a fuel fire was only 0.05%, with an estimate of the upper bound of only 0.5%. For the high-explosive (HE) detonations of plutonium from Operations Plumbbob and Roller Coaster, it was conservatively assumed that 20% of the plutonium subject to the HE detonation was dispersed in a respirable form (Stephens 1995), though these assessments were for areas well beyond the blast zone. These tests involved high-order detonations, while the Bluegill Prime test warhead was involved in a low-order detonation. Hence, due to aerosol characteristics produced in plutonium accidents involved in fires or HE detonations, resuspension rates upon initial deposition are likely to be on the lower-end of proposed models for resuspension. This conclusion is well supported by the observed heterogeneity from the numerous accidents involving plutonium, where discrete particles of physical dimension on par with tens to hundreds of microns were found in abundance. This is prior to any subsequent attachment to soil particles.

6.2.3 Air Sampling Data.

A vast amount of air sampling was conducted on Johnston Island. This data is considered superior for the purposes of estimating respiratory intakes by personnel. Extensive air sampling data was collected on LE-1 during the site restoration conducted immediately after the Bluegill Prime mishap until 20 April 1963. It is believed that sampling was collected past this point in time; however, records were not found in DTRIAC archives. An air sampling data set was in DTRIAC archives for a few months in 1965, but additional air sampling data within LE-1 past this time did not exist in archived files until 1974 and beyond. The air sampling data beyond 1975 was predominated by time periods where there was very little activity in the RCA or during time periods where active restoration was being accomplished. During the latter periods, extensive radiological safety monitoring was accomplished, along with PPE that would have greatly reduced inhalation intakes from the ambient airborne concentrations. NRC assigned respiratory protection factors for solid aerosols are contained in Figure F-1. For the full-facepiece, air-purifying respirator, the assigned protection factor is 100. This type of respirator is the most common provided to military members for response to nuclear incidents, and was the type worn by individuals during the restoration of the LE-1 immediately after the Bluegill Prime mishap.

Air sampling was apparently not collected in other areas of Johnston Island until 1975 when DNA greatly expanded its radiological monitoring program. The air sampling program started in 1975 contained extensive monitoring data for areas outside the RCA. This data is well suited for estimation

of inhalation intakes. For time periods prior to 1975, it is possible to extrapolate air sampling data back to 1962 through use of resuspension factors and estimates of surface soil plutonium concentrations from the 1980 EG&G survey (Jaffe and Tipton 1982). Nevertheless, this process is largely academic, due to low-concentrations of plutonium in areas outside the RCA and limited occupancy in those same areas that had the highest ^{241}Am concentrations.

6.2.4 Inhalation Exposure Factors.

The inhalation rate is a key factor in estimates of inhalation intakes. ICRP 66 lists inhalation rates for adults based on various activities, as listed in Table 6-1. The ICRP and EPA have alternate inhalation rates for children. These values are not considered in this report, as children did not accompany military or civilians to Johnston Atoll. The ICRP does not recommend assigning more than two hours of a work day to heavy exercise. For the purposes of evaluating inhalation rates during work periods, it is assumed that individuals have two hours of heavy exercise and six hours of light exercise, for a total volume of 15 m^3, as listed in Table 6-2. For non-duty portions of work days, it is assumed that individuals are engaged in an hour of heavy exercise, with three hours of light exercise, four hours of sitting, and eight hours assigned to sleeping. For most individuals, this is a high degree of activity for an eight hour period, as it does not include any sitting time, which has a substantially lower assumed breathing rate.

TABLE 6-1. Activity-Based Inhalation Rates (ICRPb 1994).

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

TABLE 6-2. Hours Assigned to Various Activities for Personnel Assigned to Johnston Atoll.

Type of Day	Time Period	Sleeping	Sitting	Light Exercise	Heavy Exercise	Volume (m^3)
Work	Work	0	0	6	2	15
	Off-Duty	8	4	3	1	13.3
Non-Work	Off-Duty	8	4	10	2	26.8

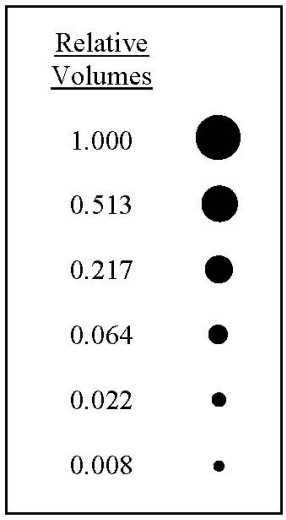
The aerosol characteristic has a bearing on uptake from inhalation exposures. During the three Thor launch mishaps that were responsible for release of plutonium on Johnston Atoll, individuals were either evacuated from the Atoll or sheltered indoors, with the exception of an undocumented claim by a Navy veteran that some personnel were inadvertently left in the open, near the flightline (Murray 2015). The presence of most personnel at these mishaps would have been after deposition of fallout. It is therefore a reasonable assumption that aerosols subject to inhalation were the result of resuspension, and were in particulate form, either as pure plutonium compounds, plutonium mixed with other materials during the mishaps, i.e., uranium, Fe, or as a plutonium compound attached to soil particles. The size distribution

of an aerosol is commonly defined in terms of the AMAD, where the total activity in the aerosol is distributed equally above and below the value. Generally, most aerosols are assumed to be log-normally distributed. For radionuclides where the lung is an organ of concern from inhalation exposures, use of a 1 μm AMAD aerosol distribution affords high deposition in the pulmonary portion of the respiratory tract, compared to aerosol distribution with higher or lower AMAD values. As noted earlier, LLNL found from air sampling conducted in 1992, AMAD values of sample aerosols about 3.4 μm (Shinn et al. 1994). DTRA uses an AMAD of 20 μm for some dose reconstruction, notably for ^{131}I inhalation intakes, because it maximizes dose to the thyroid (NAS 2003). For most, however, it uses an AMAD of 1 μm (NAS 2003). For inhalation intakes in this report, aerosol distributions are assumed to be log-normal with an AMAD of 1 μm. For inhalation of insoluble Pu and Am, this is a conservative assumption.

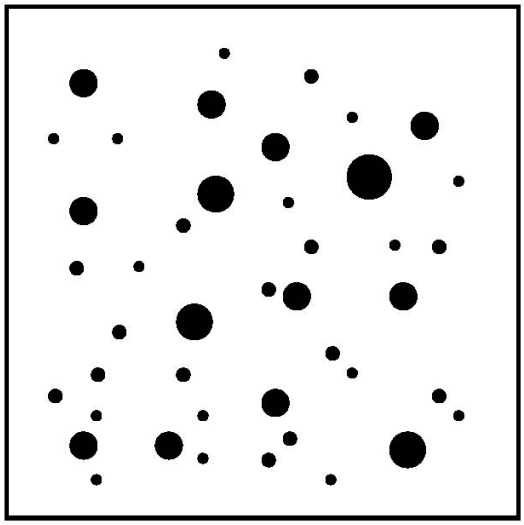
Distribution of inhaled radioactive materials from initial deposition in the respiratory tract to other organs or tissues is dependent on the location of deposition in the respiratory tract and the relative biological mobility of the compound in the body that is dictated by chemical form. Plutonium involved in fires and high explosive detonations is expected to be in a residual dioxide form (Condit 1993; Langham et al. 1966). Over time, as a contaminant in soils, the plutonium can be converted into other chemical forms, dependent on the characteristics of the soil, i.e., pH, oxidation potential, organic content, moisture content, and other factors. The change in chemical form can influence transport in the environment and the initial biological mobility if an intake occurs in humans. Wolf et al. (1997) studied a sample of plutonium-contaminated soil in conjunction with remediation activities conducted on soils at Johnston Island in the 1990s. The primary purpose was to study the distribution of contamination within the sample and assess their chemical characteristics. For the sample analyzed, they found > 99% of the radioactivity in the sample attributed to nine discrete particles in the soil matrix, having isotopic relationships consistent with expectations for a 1960 plutonium purification date and no significant fractionation of the Am and Pu. The nine discrete particles had varying compositions of oxidized Pu and U, along with varying levels of radiologically-inert Al, Si, Mg, Fe, Ti, Cr, Cu, and Ni. The particles were covered with $CaCO_3$, the primary constituent of coral. Other portions of the soil sample, which were apparently devoid of discrete particles based on detailed analysis, had diffusely-distributed Pu and U that apparently had, in part, undergone in-situ conversion from insoluble oxides to more soluble actinyl oxides and/or actinyl carbonate complexes. This was attributed to weathering from the ingress of water and carbonate (Wolf et al. 1997). This was proposed as a mechanism for greater rates of transport of plutonium in the environment, over a physical migration mechanism for PuO_2 particles.

The scale in Figure 6-3a provides the approximate relative volume encompassed by individual particles. Figure 6-3b contains a conceptual diagram of a heterogeneous distribution of plutonium at formation. Upon initial formation, these particles are assumed to be in a dioxide form, which under the ICRP 66 lung model would be inhalation Type S, and Class Y under ICRP 30. The more soluble actinyl oxides and actinyl carbonates would more appropriately be inhalation Type M and Class W, respectively under ICRPs 66 and 30. Figure 6-3c contains a conceptual diagram of plutonium in soils that have undergone environmental weathering, in line with the findings of Wolf et al. (1997). The gray background in the individual cells depicts plutonium that has been solubilized and diffusely-distributed, with adherence on coral. Figure 6-3d contains a depiction of the same condition, as in Figure 6-3c, except that there is some fine particle retention of plutonium that have retained their initial PuO_2 chemical character, albeit with some dissolution losses. A number of the Pu-contaminated soil samples collected from the BOMARC site in 2000 exhibited characteristics similar to Figure 6-3d, where a range of activities

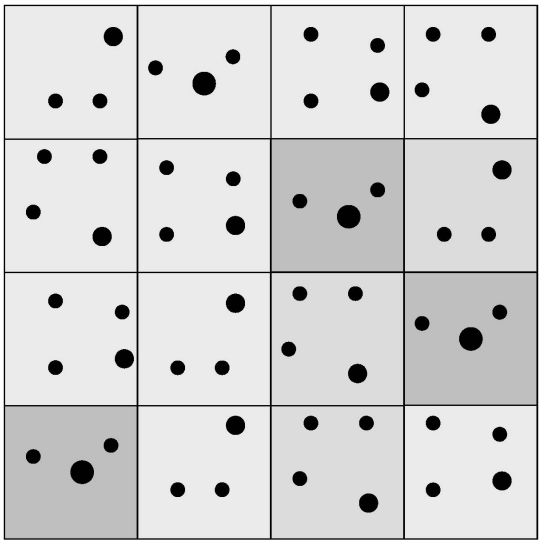
existed among discrete particles, yet a diffuse component. Figure 6-4 displays an example of one sample, among the sample set from Rademacher (2001), which also contained Figures C-1 and C-2.



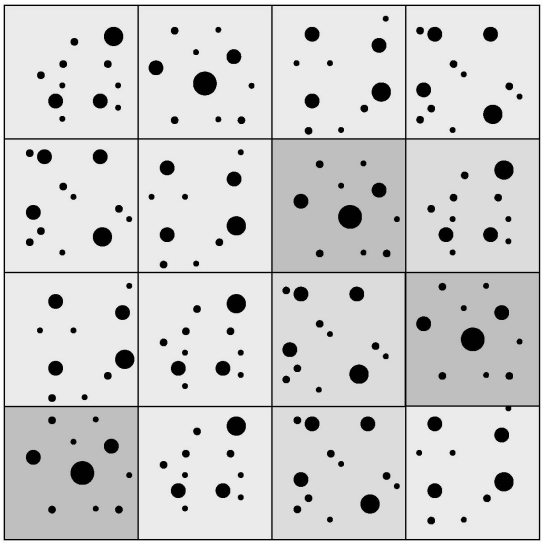
a. Relative Particle Volume Scale.



b. Conceptual Initial Discrete Particle Distribution.



c. Conceptual Late Distribution, No Residual Fine Particles.



d. Conceptual Late Distribution, Residual Fine Particles.

Figure 6-3. Conceptual Distribution Diagrams of Plutonium in Soils.

The average $^{239+240}$Pu activity concentration among all eight aliquots was 7.5 pCi g^{-1}, with 48% of the contribution from activity in aliquot number 3. If the excess activity in this aliquot is due to a discrete

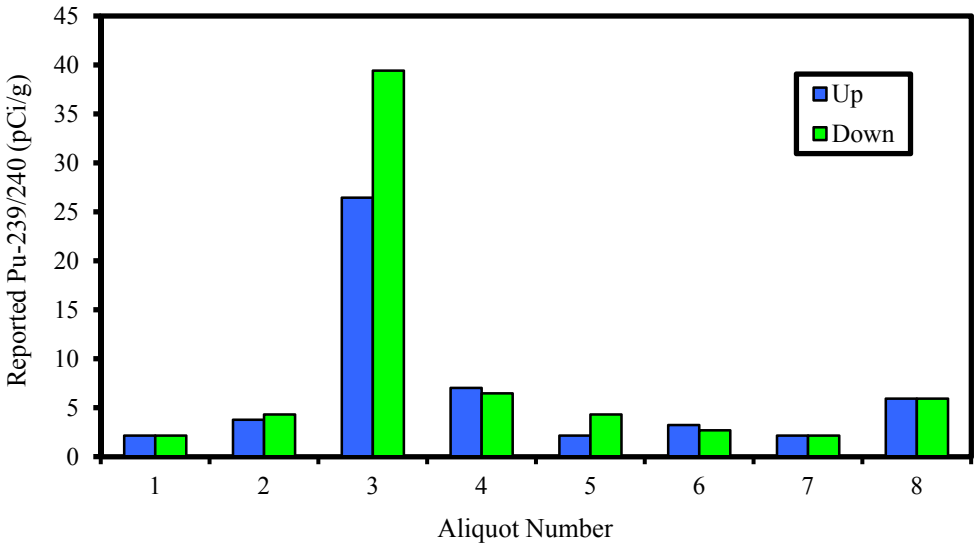


Figure 6-4. Sample 685 $^{239+240}$Pu Activity Concentration for Individual Aliquots, from Rademacher (2001).

particle, it would contain about 5.8 nCi $^{239+240}$Pu, and have a minimum volume equivalent diameter of 23 μm (see Figure E-5) and aerodynamically too large for air resuspension. Due to the high disparity in the estimated activity between the conjugate assessments (i.e., up vs. down) of the plane-symmetrical, petri dish sample container, it is highly improbable that the activity is homogenous, but likely dominated in total activity by a single particle.

In summary, the WGP dispersed on Johnston Atoll from the two missile mishaps in 1962 was dispersed as discrete PuO_2 particles. Over time, some of the material was solubilized, affording a more uniformly distributed contaminant. However, an overwhelming fraction was retained in discrete PuO_2 particles. The relative effect on the chemical form of the materials subject to resuspension and inhalation at time periods past the initial deposition is not unequivocally established. It is reasonable to assume that over time, the fraction of resuspended plutonium subject to inhalation in more soluble chemical compounds increased, as the plutonium redistributed by solubilization preferably adhered to smaller particles. This is due to the greater surface to volume ratio of small particles compared to large ones.

It is common for dose reconstructions to choose the plausible chemical form that produces the greatest dose impact for individuals in the dose reconstruction process. In the case of plutonium inhalation, however, neither the assumption of an inhalation Type M or Type S (ICRP 66) maximizes committed effective dose (CED) to key organs, as shown in Figure 6-5 (data in Table D-5). The assumption of Type S maximizes CED to the lung, while Type M maximizes CED to bone surfaces, red bone marrow, and liver. Of these, however, key doses are to bone surfaces, liver, and lung, as plutonium deposition in these organs has been attributed to increased risk of primary cancers in the bone, lung, and liver from animal exposure studies and human epidemiological studies.

For dose reconstructions, based on inhalation of fallout products, DTRA generally used an ICRP 30 inhalation Class Y, with some exception (NAS 2003). This is primarily due to the fact that dose assessments are for the presence of individuals on sites shortly after detonation, where many of the

fission and activation products, and un-burned fissionable materials are in oxide chemical forms. Overall, for dose reconstructions, maximizing lung dose will have a greater benefit, as primary lung cancers are observed in much greater frequency than either primary bone (osteosarcomas) or liver cancers. Primary bone cancers are only 0.2% of new cancers diagnosed every year in the US, but with over 40% observed in individuals less than 34 years in age (NCI 2014). Primary liver and intrahepatic bile duct cancers are about 2% of new cancers diagnosed every year in the US (NCI 2014). In contrast, primary cancers in the lung and bronchus are 13.5% of new cancers in the US (NCI 2014).

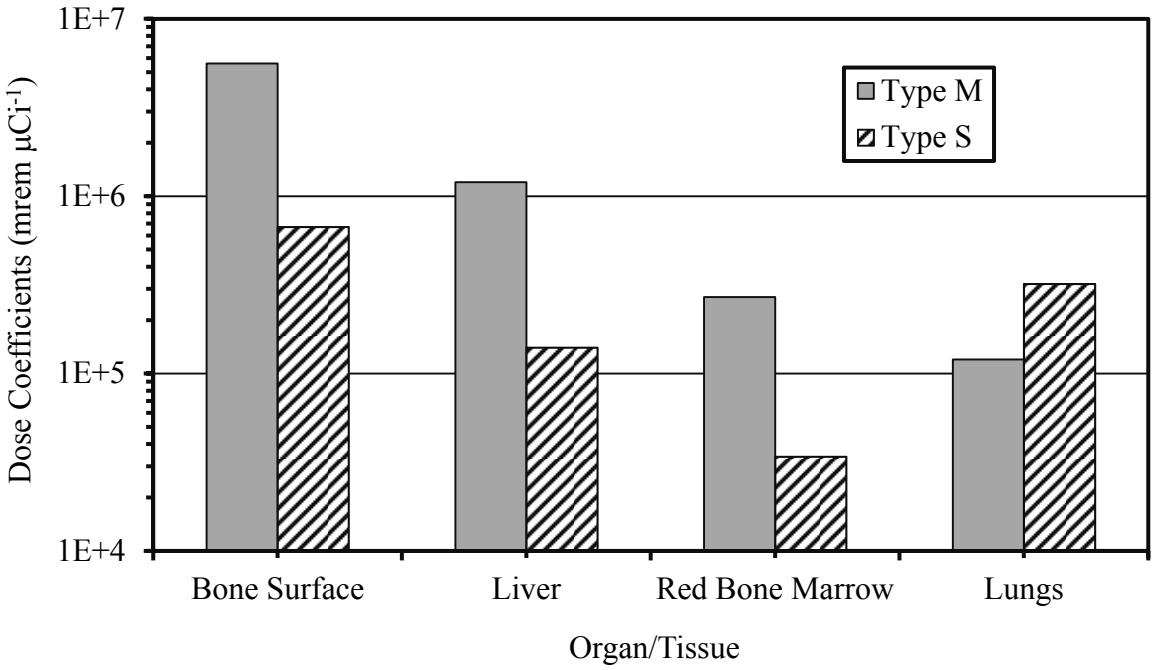


Figure 6-5. Histogram of ICRP 68 Dose Coefficients for ^{239}Pu, Inhalation Types M and S.

6.2.5 Concentration of Radiological Contaminants in Air Available for Inhalation.

6.2.5.1 RCA.

The last air sampling data found in the DTRIAC archives during JTF Eight operations within the RCA ended 20 April 1963. For sampling in the month of April 1963, the mean reported activity concentration was 13.3 $\pm$ 9.3 fCi m^{-3}, assuming that zero values were one-half of the approximate MDC of 10 fCi m^{-3}. The full data set is in Table E-2. DTRA archives contained air sampling data from the summer of 1965 (summary in Table E-5). Many of the samples were high volume samples, > 1200 m^3, while a smaller number were task oriented samples, having volumes of only 400 m^3, and had overlap with the high volume samples collected in the LE-1 shelter area. All samples had $^{239+240}$Pu activity levels below the MDC, as low as 3 fCi m^{-3} for samples collected over two days, 7 fCi m^{-3} for samples collected over a day, and 20 fCi m^{-3} for most of the task-related samples. While a precise estimate of the airborne activity concentration cannot be inferred from the data, it is reasonably conservative to assume that the average concentration is equal to 7 fCi m^{-3}. This value is less than the average concentrations reported

for April 1963, which is logical considering weathering effects. It is important to note that these samples and those collected in the fall and spring of 1963 were collected on the LE-1 launch pad. Personnel supporting activities in the RCA would likely have split time in LE-2, which had substantially lower Pu contamination than LE-1. Three high volume air samples were collected by an AF survey team in 1974, with all samples having less than 2.2 fCi m^{-3} α-particle activity. After this period, little activity occurred in the RCA, with the exception of radiological surveillance activities and restoration.

The air samples collected in LE-1 up to 1974, used α-detection technology for assessment of activity on filters. Conservatively, a correction factor of two is recommended to account for filter self-absorption. A summary of recommended air concentrations in the RCA are in Table 6-3 for non-restoration periods.

TABLE 6-3. Recommended Airborne Concentrations in RCA for Non-Restoration Periods.

Period	α-Radiation (fCi m^3)	Notes
27 July 1962 to April 1963	Table E-2	Highly-varied concentrations. Values in Table E-2 should be used with respiratory protection factors in F-1, if applicable. Cancers related to internal plutonium exposures subject to presumptive compensation for this exposure period, and until 30 June 1963. External exposure issues not detailed in report.
April 1963 to Summer 1965	26.6	Increasingly conservative later times in the period.
Summer 1965 to 1975	14	Increasingly conservative later times in the period.
1975 to 1992	Duty Dependent	Most individuals entering area had duties related to monitoring and restoration, where extensive monitoring and respiratory protection was typically applied. For entries during non-restoration activities, conservative to apply airborne concentration recommended for summer 1965 to 1975.
Beyond 1992	Special Evaluation	Most individuals entering area had duties related to monitoring and restoration, where extensive monitoring and respiratory protection was typically applied. Beyond current scope of this report.

Restoration activities had rigorous radiological monitoring and protective measures, which have been previously discussed in this report. For the work being accomplished, airborne radioactivity levels were well below occupational exposure standards for unprotected individuals, with the exception of some samples collected in 1984, though based on the DAC associated with the most conservative chemical form. Nevertheless, respiratory protection was provided to workers, which would have reduced respiratory intakes by a factor of 100 using NRC values (see Table F-1). For example, the fall 1984 restoration activities encompassed 71 days, with 63 being work days, based on air sampling data in Table E-11. For the air sampler at "LE-1 + 50 m", the average among the 63 samples was 123.5 fCi m^{-3}, a standard deviation of 363.8 fCi m^{-3} among the samples, and maximum and minimums of 2,400 and

0.12 fCi m^{-3}, respectively. Applying a 100-fold protective factor, the average concentration would have been 1.2 fCi m^{-3}. No correction factor is recommended for these samples, as they were either wet- or dry-ashed with extraction of the plutonium. Individuals involved with these activities also participated in a urine bioassay. The current edition of this report does not contain the results of these analyses, but could be included in a future edition. Also, from 1992 to 1997, the SGS was operational, with access to this area restricted to individuals supporting the project. The majority of the individuals were contract employees supporting THERMO NUtech, formerly TMA/Eberline. Similar to restoration activities conducted in LE-1 in the mid-1980's, extensive occupational monitoring was provided. These exposures would be most appropriately evaluated by the employers.

6.2.5.2 Areas Outside the RCA.

The DTRIAC archives did not contain records of air sampling outside LE-1 until 1975 when the radiological monitoring program was greatly expanded. As listed in Table 5-2, with only a few exceptions, air samples had activity concentrations well below 1 fCi m^{-3}. Some of the sampling locations listed in Table 5-2 were for sampling locations within the RCA. One notable exception was for air sampling in the S&I area during the fall 1984 restoration in LE-1, as listed in Table 5-7, where the three high weekly samples were 15, 19, and 20 fCi m^{-3} for 12 Nov – 3 Dec. The S&I area is the closest work location outside the RCA that is downwind of the RCA. This location was not constructed until after the 1963-1964 expansion of the land area of Johnston Island.

Table 5-7 contains weekly airborne concentrations in the S&I area during restoration of LE-1 in 1984, while Table E-11 contains daily airborne concentrations within LE-1 during the same period. The three week period of time, 12 November – 3 December 1984, had the highest average concentrations during the LE-1 restoration. A comparison between the average concentration at the LE-1 + 20m sampling station and the one at the S&I, about 180 m downwind is predictive of the dilution of airborne contamination created by resuspension within LE-1, yet observed by sampling in the S&I area. During this period, work was accomplished on 20 of 22 days, with an assumption that the air samples collected at LE-1 + 20m operated for eight hours. The average among the samples was 752.7 fCi m^{-3}. For the three weekly samples collected at S&I, the average concentration was 18 fCi m^{-3}. Assuming that the activity collected at this station was dominated by aerosols created during work periods, with negligible concentrations during non-work periods, the average concentration adjusted to a 160-hour period (20 days x 8 hours per day) is 56.7 fCi m^{-3}. Therefore, the estimated dilution factor for airborne concentration observed at LE-1 + 20m versus the S&I air sampling location is 12.8. As such, since the S&I area was not available for occupancy until after the 1963/1964 Johnston Island area expansion, it is assumed that this location was not occupied until the summer of 1965. As discussed above, air sampling within LE-1 in 1965, had a conservatively estimated airborne concentration of 7 fCi m^{-3}. Applying the 12.8 dilution factor, it is conservatively estimated that airborne concentrations at the S&I sampling site would have averaged only about 0.55 fCi m^{-3}, though the S&I area was constructed on clean coral. For other areas further downwind from the S&I, i.e., the western part of Johnston Island, concentrations would have been even lower.

An air sampling station was placed at the Mess Hall since late 1975. Besides two samples with reported activity concentration greater than 1 fCi m^{-3}, within the first few months of sampling at this location, all other samples were a small fraction of 1 fCi m^{-3}. As noted earlier in this report, this location had the greatest amount of contamination outside the RCA in an area with reasonably-continuous occupancy by

individuals on Johnston Island. For time periods in 1975 and beyond, it is reasonable to assume that the average airborne concentrations of $^{238+239+240}$Pu were a small fraction of 1 fCi m^{-3}. For previous periods, air sampling was not conducted at this location. There are a few methods available to estimate the concentrations in earlier times. Airborne concentrations could be estimated from the difference in resususpension rates in 1975/1976 to previous times using data from Figures 6-1 and 6-2. However, most of the air samples collected in 1975 and 1976 have activity concentrations well below 1 fCi m^{-3}, and at levels below the MDC for the method. Further, due to the relatively low $^{238+239+240}$Pu activity concentrations in soils for this area, it was speculated that some activity observed on samples was due to world-wide fallout, and not resuspension of ground-deposited plutonium. Another method implements use of the 1980 EG&G in-situ measurements to estimate the initial deposition in the vicinity of the Mess Hall. The small cluster of ^{241}Am measurements with reported concentrations greater than 5 nCi m^{-2}, as displayed in Figure E-10, are listed in Table 6-4. The average ^{241}Am activity concentration predicted by the measurements is 12.4 nCi m^{-2}, assuming that half of the values with ^{241}Am below the detection limit are equal to that level. The estimated $^{238+239+240}$Pu concentration is 7.17-fold higher, 89 nCi m^{-2}. One year after the Starfish mishap, 19 June 1963, predicted airborne concentrations ranged between 0.03 and 5.7 fCi m^{-3}, respectively, for the lower end of the Anspaugh et al. (2002) and Smith (1982) models, as shown in Figure 6-2. The other models were dispelled by Anspaugh et al. (2002) and Shinn et al. (1998) for being overly conservative at early times after deposition. Also, the area soil concentrations were averaged over only about 3,200 m^2, while these resuspension models assume much larger contaminated areas. It is important to point out that world-wide airborne $^{239+240}$Pu concentrations for the monitoring station at Moana Loa, HI, in 1963 was 0.89 fCi m^{-3} (see Figure E-4). Thus, world-wide fallout would have had a reasonably high contribution to the total airborne plutonium in this area. Airborne concentrations were not estimated for time period prior to June 1963, as individuals assigned to duties on Johnston would be presumptively compensated for cancers plausibly connected to internally-deposited plutonium.

TABLE 6-4. Reported ^{241}Am from In-situ Measurements, East of Mess Hall (nCi m^{-2}), [East-West & North-South Coordinates in Units of Feet] (Tipton and Jaffe 1982).

North-South	East-West									
	198700	198750	198800	198850	198900	198950	199000	199050	199100	199150
199250	-	-	-	< 14	< 9	29	7	11	7	< 11
199200	< 13	< 15	10	15	< 8	13	12	-	-	-

EG&G in their 1980 in-situ γ-radiation survey of Sand Island (Jaffe and Tipton 1982) had positive ^{241}Am on 17 measurements, with predicted activity concentrations in the 6 – 15 nCi m^{-2} range, while 62 were less than 6 nCi m^{-2}. Forty-eight of the 62, however, were on the main portion of Sand Island, i.e., the western major land mass, while 13 were on the causeway, and one on Bird Island. At most, the average concentration on the western land mass of Sand Island is 7.6 nCi m^{-2}. Following the sampling method as applied to the surface soil concentrations east of the Mess Hall, the predicted airborne concentrations in June 1963 range between 0.02 and 3.5 fCi m^{-3}. No air sampling results were located in DTRIAC archives for sampling on Sand Island, except for a three month period at the end of 1977 to early 1978. After a couple of additional years of presence in the environment, the airborne activity

concentrations on Sand Island would reasonably be expected to drop by another order of magnitude, based on resuspension factors around 10^{-9} m^{-1}. This is also the case for the area around the Mess Hall.

Table 6-5 contains a summary of recommended airborne concentrations in areas outside the RCA, per the discussion above. The values are conservative based on air sampling data, the heterogeneous nature of the plutonium contaminant, and theoretical models described above. Air concentration data for the general areas of Johnston Island that existed in 1962 was based on those conservatively estimated for the Mess Hall area. For most individuals occupying these areas, airborne concentrations will be substantially lower due to the negligible plutonium soil concentrations in the majority of locations considered general areas of Johnston Island. In addition, indoor concentrations will be much lower than those predicted for outdoor occupancy (Fogh et al. 1997). Most individuals in this part of Johnston Island would have been indoors at least eight hours a day. A similar approach was used for estimates of airborne concentration on Sand Island. Airborne concentrations post-1975 are assumed to be similar to that at the Mess Hall and S&I air sampling stations, though the plutonium concentrations in soils on the western land mass of Sand Island are lower than those in the vicinity of the Mess Hall. In land areas created after the 1963/1964 land expansion on Johnston Island, airborne concentrations of $^{238+239+240}$Pu are expected to be negligible, with exception to the S&I area, which is directly downwind of LE-1.

TABLE 6-5. Recommended Airborne Concentrations of $^{238+239+240}$Pu in Areas Outside RCA (fCi m^{-3}).

Period	Sand Island	General Areas of Johnston Island (1962 Existing Land)	S&I	Post-1963/1964 Land Areas, Except S&I
June 1963 Summer 1965	3.5	5.7	NA	NA
Summer 1965 to Fall 1975	0.35	0.57	0.55	<< 0.55
26 September to 6 December 1984	NA	NA	20*	<< 20
Later than 1975**	0.1	0.1	0.1	Negligible

* Scaled from Table 5-7 values using method in § 6.2.5.1 for 8-hour work periods to 168-hour weekly sampling period.
** Except 26 September to 6 December 1984 for S&I.

6.3 Soil/Dust Ingestion Exposure Pathway.

6.3.1 General.

Individuals inhabiting an area are subject to incidental and intentional ingestion of soil constituents. Incidental ingestion can be incurred through the handling of food, drink, and cigarettes with hands that have been in contact with surfaces containing soil/dust. For children, potential ingestion rates are expected to be higher due to their greater propensity to place their hands in the mouth, and in some cases the ingestion of soil and other non-food materials is intentional, which is termed pica. For the purposes of this report, however, exposures to children are not applicable.

6.3.2 Ingestion Rates.

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). For assessment of soil ingestion rates of adults under Operation Tomodachi, the DoD's humanitarian assistance/disaster relief effort after the Fukushima Daiichi Nuclear Power Station disaster, a highly conservative estimate of 200 mg d^{-1} was made for adults (Cassata et al. 2012). However, this value was based on the assumption of a high fraction of duty time involved with heavy work for the 60-day period covered by the assessment – a practice deemed less appropriate for work on Johnston Atoll. For the assessments covered in this report, a daily ingestion rate of 100 mg d^{-1} will be made. For work days, half of the exposure will be assumed to occur at the workplace, while the other in general areas of Johnston Atoll. For simplicity, soil contamination levels will be estimated for two areas: general areas on Johnston Island and within the RCA. Thus, for individuals that did not work within the RCA, all soil ingestion will be assumed to originate from soils in general areas on Johnson Island.

6.3.3 Physical and Chemical Form of Pu for Ingestion Assessments.

As noted above, plutonium dispersed from the 1962 missile mishaps is assumed to be released as PuO_2 in a discrete particle form, though over time some plutonium was more uniformly distributed in soil, aided by dissolution. The heterogeneously-distributed portion of the contaminant logically would have an associated GI tract uptake fraction for dioxides, which would be assigned a 10^{-5} fraction under ICRPs 30 and 68. ICRP 67 contains dose conversion factors for ingestion of radionuclides. In this report, ICRP conservatively assumes that GI uptake fractions for Am and Pu are 5×10^{-4}, based on values more appropriate for ingestion of Pu and Am incorporated into food (ICRP 1993), rather than in soil. Dose coefficients from ICRP Report 67 are contained in Table F-2, and are a companion to inhalation coefficients in Table D-5. For internal organs, use of the 5×10^{-4} GI tract uptake fraction provides a 50-fold higher committed dose than use of 10^{-5} for PuO_2.

Dose modeling of soil ingestion assumes that contaminants are uniformly distributed in soils or dust. The plutonium contaminant has had varying degrees of heterogeneity from its dispersal in 1962 to final burial of residuals in 2002. In assessments of risk for residual plutonium at the BOMARC, the Air Force Safety Center evaluated the effect of the stochastic intake paradigm for ingestion of soil (Rademacher 2010). The assessment assumed that the residual soil was comprised of 17 nCi $^{239+240}Pu$ particles, at an average activity concentration in soils of 3.24 pCi g^{-1}. Over 70-y of occupancy, at an average annual ingestion rate of 35 g y^{-1}, it was found that mean probability of ingesting a single particle was 0.293, two – 0.068, and three – 0.011. The 70-y effective dose equivalent was less than 1 mrem under ICRP 68 using a 10^{-5} GI uptake fraction for ingestion of a single particle. Placing the activity in a lower number of proportionately higher activity particles subsequently lowered the probability of ingestion, yet increased the probability of health detriment on an individual particle intake basis. The key point to this evaluation was that concern over ingestion intakes of discrete particles of high activity are diminished by low GI uptake fractions due to the dioxide form and the low probability of ingestion. There is no reasonable mechanism for Johnston Island soil to concentrate plutonium in soluble, discrete particle forms to the degree of concentration that existed as PuO_2 after the initial dispersal to the environment. A parallel, but different argument exists for concerns over the inhalation of high-activity

discrete particles. High-activity particles are unable to penetrate and deposit in the deep portions of the respiratory tract, due to an associated high, minimum aerodynamic diameter and likelihood for removal by physical settling or impaction in the upper portions of the respiratory tract. In addition, due to their large aerodynamic diameter they have low probability for airborne resuspension.

6.3.4 Concentration of Radiological Contaminants in Soils Available for Ingestion.

6.3.4.1 General.

Precise assessment of the radiological contaminants in soils available for ingestion is complicated by a number of factors. First, based on the historical aspects of the release and the 1980 EG&G radiological survey of Johnston Atoll, there is a highly varied concentration of contaminants across the Johnston Island. The RCA that was established in 1975 contains LE-1, LE-2, and an extension of the original Thor launch emplacement fence to the southeast of LE-1, and contains the vast majority of residual plutonium contamination (see Figures E-9 and E-10). Some areas, primarily in the LE-2 portion of the RCA, did not have detectable levels of ^{241}Am, while the areas around LE-1, overwhelmingly had the greatest levels of contamination. The region southeast of LE-1 and along both sides of the western end of the runway (that existed in 1962) contained a broad area of low-level contamination, which was believed to have been the result of the Bluegill Prime mishap that occurred on the LE-1 pad. It is believed that contamination would have also deposited on the runway, between these two soil areas, but was transported via rain water run-off to the adjacent soil areas. Upon examination of Figure E-10, a number of smaller areas of contamination existed to the east of the LE-1 pad – one southwest of the swimming pool, two areas around the mess hall, and a few small areas around the Redstone pad area.

Second, variations in the vertical distribution of the contaminant complicate the assessment. WGP deposited outside of LE-1, whether it was from the Starfish or Bluegill Prime mishap, was not intentionally disturbed, with the exception of the soil relocation project in 1985. The 1980 EG&G survey reported the median contaminant depth of only about a centimeter (Jaffe and Tipton 1982). Residual contamination in LE-1, post soil scraping, was purposely covered with clean coral.

Third, the vertical distribution of the contaminant changed over time due to weathering which would be expected to slowly carry contamination to greater depth, and surface disruptions by vehicle traffic and construction. The latter process may have been responsible for some redistribution of soil in LE-1, uncovering some previously covered contaminated coral. Fourth, individuals did not spend all of their time in one area on Johnston Atoll. This would have created varied exposure potential, primarily dependent on an individual's primary work area. Fifth, some contaminated soil was removed from LE-1 in the 1960's, well after the initial remedial action conducted in 1962, as well as discrete particle removals in the mid- to later 1970's.

6.3.4.2 RCA.

After the completion of JTF Eight's support to Operation Dominic I in 1963, the primary access to the Thor launch areas would have been for individuals supporting the USAF ASAT mission until 1975. After this point in time, primary access would have been in support of restoration activities.
Due to the complicating factors of estimating the activity concentration in the top centimeter of soil, which is expected to be the primary contributor to soil and dust ingestion, we have conservatively

estimated the average in the top centimeter as the average in surface soils remediated by the SGS in the 1990's. The average activity concentration in the estimated 165,000 m^3 of soil processed is 60 pCi g^{-1}, about 4-fold higher than the EPA's screening criterion of 13.3 pCi g^{-1}. To account for contaminated soil removed in 1965, and the weathering processes that occurred over a 30 year period of time between the accident and soil soring initiated in the early 1990's, the average concentration will be conservatively doubled to 112 pCi g^{-1}, as a better estimate of the average concentration in the mid-1960's.

6.3.4.3 Areas Outside the RCA.

There are four primary areas outside the RCA that had detects for ^{241}Am in the 1980 EG&G survey:

1) the area southeast of LE-1, on either side of the runway,
2) the area southwest of the swimming pool, vicinity of the Sandia Bunkers,
3) the Redstone pad area, vicinity of Bunker 202, and
4) two small regions around the mess hall.

The largest area among the four is the area southeast of LE-1, but occupancy in this area would have been intermittent, primarily for individuals transiting to work areas on the western part of the Island. The AME field is within this area; however, no buildings or workplaces are in the vicinity of this area. Most of these areas were fenced-off in 1975, with the area adjacent to the Thor launch area being incorporated into the RCA. In 1985, a soil relocation project was accomplished in this area, which was discussed earlier in this report. As such, past 1985, contamination in this area would have been greatly reduced. Soil samples collected in this area during the EG&G survey (Jaffe and Tipton 1982) had an average $^{238+239+240}$Pu of 10.7 pCi g^{-1}.

The Redstone pad area and the area southwest of the swimming pool also would have had only intermittent occupancy. The Redstone pad area is upwind of Bunkers 202 and 206, but is not near any buildings that supported extended occupancy. The average $^{238+239+240}$Pu concentration of the soil samples collected by EG&G in 1980 was 8.5 pCi g^{-1}. The average $^{238+239+240}$Pu concentration of samples collected from the area southwest of the pool was 4.6 pCi g^{-1}. This area is in close proximity to the Sandia Bunker, though this structure would have had only intermittent occupancy.

The regions around the mess hall had an average $^{238+239+240}$Pu concentration of 11.6 pCi g^{-1} among the soil samples collected in this area by EG&G in 1980. Among all of the areas outside LE-1, this area has greatest potential for occupancy by individuals on a daily basis for dining and personnel that worked at the facility. However, the two regions around the mess hall that had detects for ^{241}Am from the 1980 EG&G survey perhaps only represent about 10% of the soil in this area, making the area average $^{238+239+240}$Pu about 1.2 pCi g^{-1} in 1980. This value will be used to represent average soil concentrations for locations outside LE-1, but only in areas that existed prior to the 1963-1964 Johnston Island land expansion. Use of this value is very conservative, especially for individuals that worked near the piers, on the northern-most part of Johnston Island.

Some workplace areas were constructed on post 1963-1964 land. The Joint Operations Center, constructed in 1965, is on the east side of Johnston Island (see Figure E-9). A 41-acre site was constructed on the southwest portion of Johnston Island in 1971 to store chemical munition, under the "RED HAT" program. Just north of this location, 25,000-plus 55-gallon drums of Agent Orange were

stored, starting in 1972. The JACADS system was installed adjacent to the RED HAT area, with operational testing initiated in 1991. It is assumed for the purposes of this report, that these locations had negligible levels of WGP in soils. One exception to this assumption is for individuals that worked in the S&I area, that is directly southwest of LE-1. Due to the proximity to LE-1, some resuspension and deposition of WGP would have occurred, though the concentrations would have been low.

6.3.4.4 Sand Island. The estimated average $^{238+239+240}$Pu activity concentration in soils from the EG&G 1980 survey was 1.3 pCi g^{-1}, as noted in Section 5.8.4.2 above.

6.3.4.5 Surface Soil Concentrations in Time Periods Previous to the 1980 EG&G Survey. As discussed in Jaffe and Tipton (1982), ^{241}Am activity initially deposited to the surface of soils will slowly migrate to greater depths. Table 5-4 above, provides correction factors for in-situ measurements, based on varied relaxation lengths, assuming an exponential distribution. Figure F-1 contains a plot of the fraction of activity in the vertical soil column from the surface to varying depths versus relaxation length. For soils outside LE-1, which have not been disturbed, it is deemed reasonably conservative to assume a relaxation length of 5 cm for the ^{241}Am and plutonium contaminants in 1980. This would be based on an 18 y time period between the initial deposition in 1962 and 1980. Soil samples collected in 1980 by EG&G were over a depth of 3 cm (Jaffe and Tipton 1982). Based on the plot in Figure F-1, the fraction of activity contained in the top 3 cm is 0.45, based on an interpolation between the 4 and 6 cm relaxation length curves. Thus, it is estimated that in 1962 the vertical soil columns would contain about a 2.2-fold higher activity, compared to that based on a 1980 sample collected over the top 3 cm. Also, using the EPA recommendation of considering activity in the top 1 cm, as a basis for comparison to screening levels, a modifying factor of 3 is appropriately applied for a total correction of 6.5-fold. Table 6-6 contains estimated $^{238+239+240}$Pu activity concentrations in the top 1 cm for 1962, 1971, and 1980, based on estimated activity concentrations in soil samples collected by EG&G in 1980 and

TABLE 6-6. Estimated $^{238+239+240}$Pu Activity Concentrations in the Top Soil from 1980 EG&G Soil Sampling, Assuming a 5 cm Relaxation Length in 1980 (Jaffe and Tipton 1982).

Area	Average $^{238+239+240}$Pu Concentration (pCi g^{-1})			
	Top 3 cm (1980)	Top 1 cm (1980)	Top 1 cm (1971)*	Top 1 cm (1962)
Sand Island	1.3	1.6	5.6	8.5
Mess Hall	1.2	1.4	5.2	7.8
SE LE-1**	10.7	12.9	45.9	69.7

* Assuming a relaxation length of 2.5 cm, based on a linear change in time between 1962 and 1980.
** Area outside RCA, on either side of runway, and including AME field.

values from Figure F-1. Values are for Sand Island, the area around the Mess Hall, which was deemed a reasonably conservative model for areas outside the RCA that existed in 1962 and have reasonable high occupancy by individuals on Johnston Island. The area southeast of LE-1 and outside the RCA is also shown for informational purposes, yet deemed unreasonable for any prolonged occupancy, with the exception for relocation of surface soil from this area to LE-1 in 1985. It is noteworthy that the estimated average activity concentration in the top 1 cm for this area in 1962, 69.7 pCi g^{-1}, is about 60% of the conservative estimate for the average soil concentration in the RCA in 1962. Estimated values are also provided for 1971, assuming a linear change in relation length between 1962 and 1980.

7.0 Example Exposure Evaluations

7.1 Veteran Served at Thor Missile Launch Site in 1966.

This example is for an individual that was assigned duties on Johnston Island for one year, in 1966, with duties as a Thor missile technician under the ASAT program. The first Thor missile launch from Johnston Island under this program occurred on 14 February 1964, with the last on 24 September 1970. Many of the personnel that supported this program served on a rotational basis from their permanent assignment to Vandenburg AFB. A one year total assignment period could have been comprised of multiple shorter duration duty rotations to the Atoll. For this example, it is assumed that the veteran worked in the LE-1 and LE-2 Thor launch area eight hours a day, with the remainder of the day in general areas of Johnston Island. For conservative measure, it is assumed that the veteran worked six days a week, as detailed with other exposure parameters in Table F-3. For this example, the assumed airborne and soil concentrations of $^{238+239+240}$Pu are substantially higher in the veteran's work area than general areas. Hence, the total inhalation and ingestion intakes are dominated by work periods.

Calculated committed equivalent dose (CED) for organs and tissues under ICRP 60/66 are contained in Table F-4. Separate calculations are for ICRP 66 inhalation of Type S and M material. The calculations are for $^{238+239+240}$Pu, ^{241}Pu, and ^{241}Am, with $^{238+239+240}$Pu intake values from Table F-3, and ^{241}Pu and ^{241}Am concentrations based on the respective relationships to $^{238+239+240}$Pu listed for 1966 in Table F-5. Table F-5 is based on the ratios established in Section 5.8.4.5 above. Histograms of the data from Table F-4 are in Figures 7-1 and 7-2, respectively, for inhalation Type S and M. Selection of inhalation Type M greatly increases CED to all organs except the respiratory tract. Dose to the respiratory tract is maximized through selection of inhalation Type S. Based on historical studies of accidents involving plutonium, the characteristics of this accident, and the observed heterogeneity, selection of inhalation Type S is more readily defensible, especially for earlier times after the accident. Nevertheless, for conservativeness, calculations for both inhalation types are provided, as Type M is more favorable for adjudication of claims for tissues/organs other than those associated with the respiratory tract, as Type M materials have greater systemic uptake, i.e. distribution through the bloodstream and deposition on the bone surfaces, liver, and other internal organs. As well, for Type M materials cleared from the respiratory tract to the GI tract, there is the assumption of greater uptake in the GI tract than in the case of Type S materials. This is consistent with the VA's policy of providing benefit of doubt to veterans.

For the calculations performed here, $^{239+240}$Pu dose conversion factors were used for ^{238}Pu to simplify calculations. The simplification is conservative, as the ^{238}Pu conversion factors are lower than $^{239+240}$Pu, but overall has a negligible impact on calculated doses, as ^{238}Pu only contributes a small fraction of the total α-particle emission rate. Figure 7-3 contains the relative contributions of $^{238+239+240}$Pu, ^{241}Pu, and ^{241}Am to CED to the bone surfaces, for Type M. About 85% of the CED is from the α-emitting Pu isotopes. Calculations of dose under identical circumstances, except using isotopic compositions for the radiological contaminant in 1975, the CED to the bone surfaces only increased by 2.6% over the calculations made with isotopic composition for 1966. The relative contribution to CED from $^{238+239+240}$Pu decreased slightly to 0.834, with the contribution from ^{241}Pu dropping to 0.058 and ^{241}Am increasing to 0.109. Effectively, the relative increase in contribution to CED to bone surfaces from ^{241}Am is compensated by the decrease in contribution from ^{241}Pu, though ^{241}Am has about a 10% higher conversion factor [for dose] than $^{239+240}$Pu, the majority of which is due to ^{241}Am's higher α-particle energy.

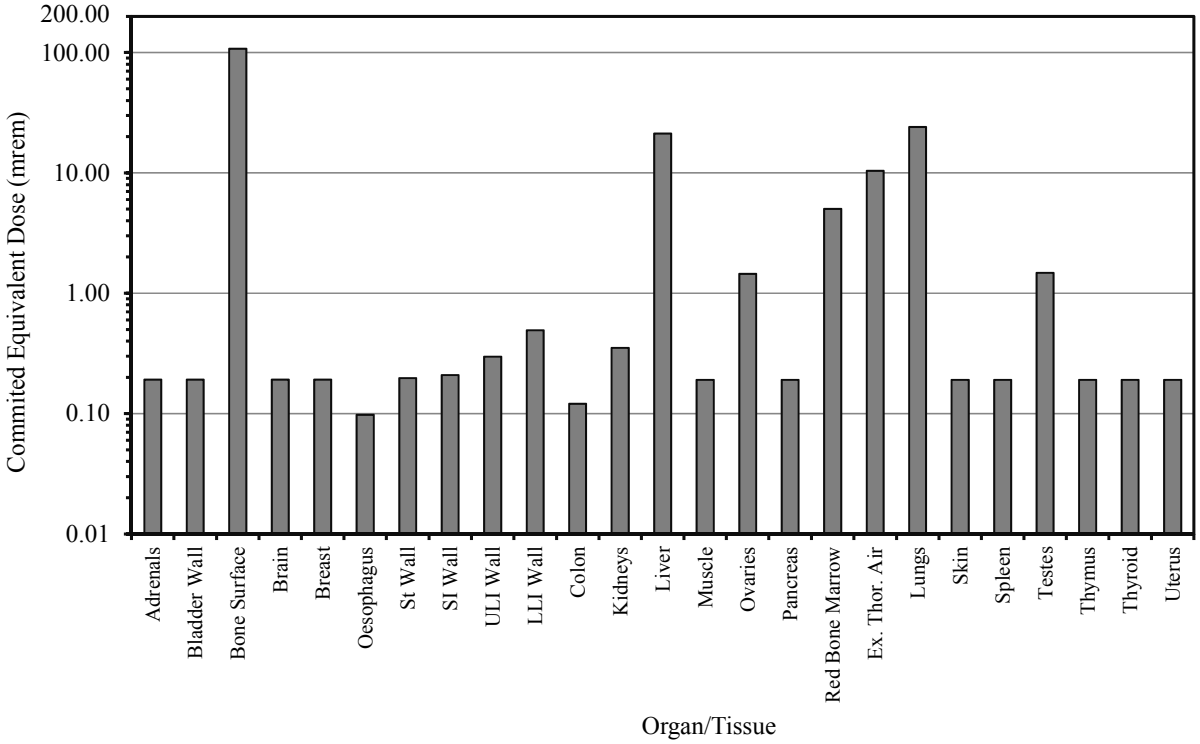


Figure 7-1. Histogram of CED for Organs and Tissues, Inhalation Type S, Thor Worker, 1966.

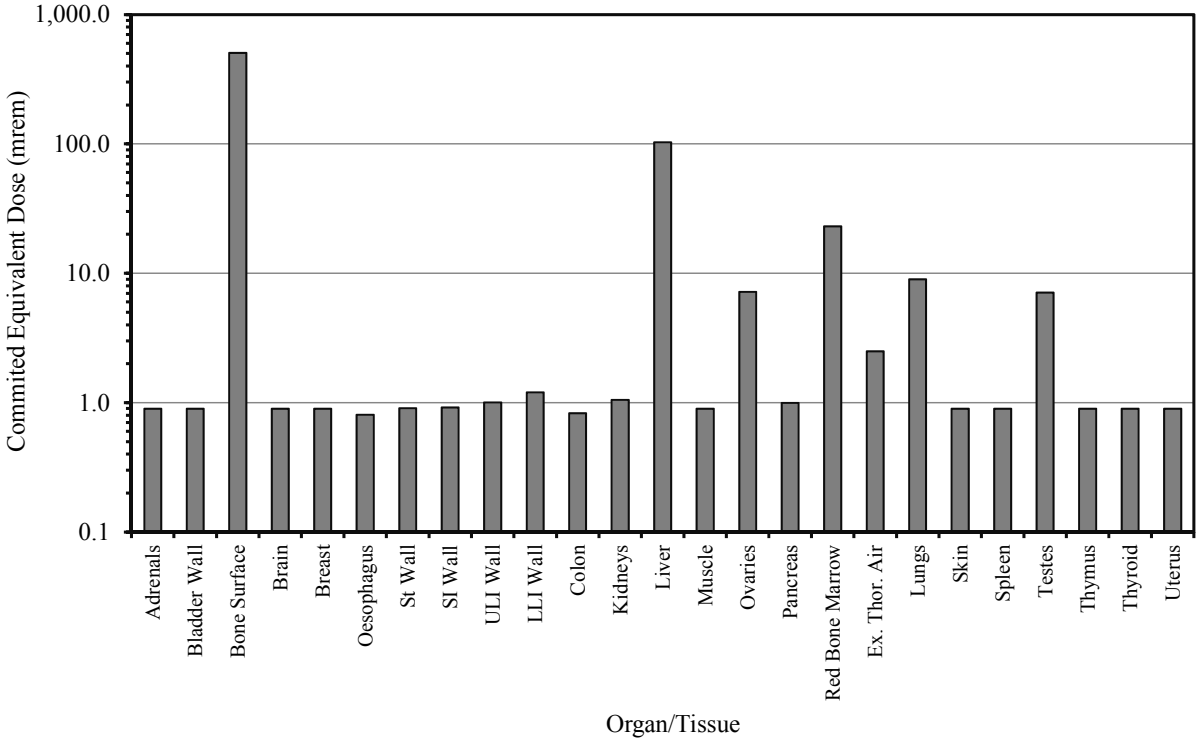


Figure 7-2. Histogram of CED for Organs and Tissues, Inhalation Type M, Thor Worker, 1966.

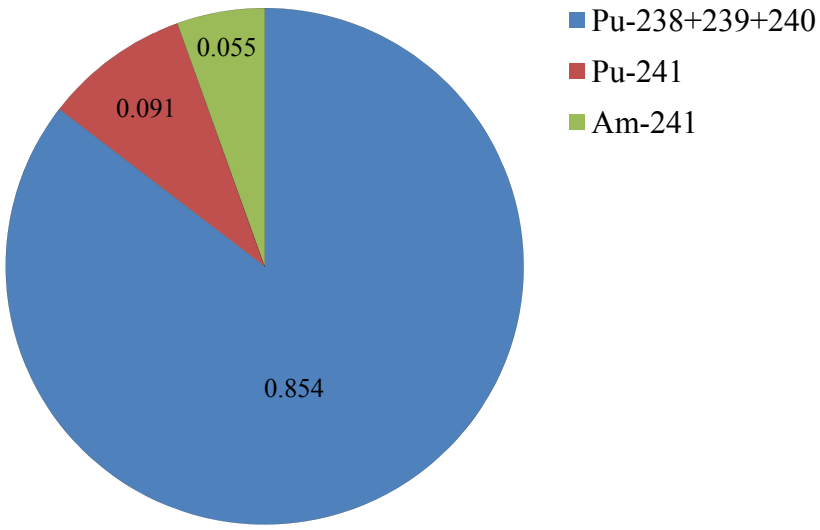


Figure 7-3. Piechart of Relative Contribution of $^{238+239+240}$Pu, ^{241}Pu, and ^{241}Am to CED for Bone Surfaces, Inhalation Type M, 1966.

7.2 Veteran Served on Johnston Island in 1964, Worked in General Areas.

This example is for an individual that was assigned duties on Johnston Island for one year, in 1964, with duties in general areas of Johnston Island. Intake summary parameters for this example are contained in Table F-6. Calculated CED for organs and tissues under ICRP 60/66 are contained in Table F-7. Overall, the CEDs for organs/tissues are lower than the example case above. Although this example was for an individual not working in the Thor launch area, the doses were not significantly lower than the previous example. This is due to the fact that inhalation rates in general areas of Johnston Island are assumed to be higher for this time period compared to 1966. The assumption was highly conservative, as it premised an individual spent the majority of their time in the vicinity of the Mess Hall, downwind from a small area of contamination. Actual exposures are expected to be significantly less.

7.3 Veteran Served on Johnston Island in 1964, Worked in General Areas, Including RCA.

This example is for an individual that was assigned duties on Johnston Island for one year, in 1964, with duties in general areas of Johnston Island, but also some in the RCA. Note: the RCA term had not been used for this area before 1975. This type of exposure scenario would be appropriate for an individual performing general construction and maintenance, with duties throughout Johnston Island. For this scenario, it is assumed that the individual spent 20% of his working duty time in the RCA, with 80% in other areas of Johnston Island. Intake summary parameters for this example are contained in Table F-8. Calculated CED for organs and tissues under ICRP 60/66 are contained in Table F-9. As expected, CEDs are higher than those in the previous example, due to time spent in the RCA. The maximum CED values for key organs: bone surfaces - 531, liver - 110, and lungs – 26.8 mrem, however, were fairly low compared to the current annual organ dose limit of 50,000 mrem. Figure 7-6 contains the relative contributions of $^{238+239+240}$Pu, ^{241}Pu, and ^{241}Am to CED to the bone surfaces, for inhalation Type M. About 86% of the CED is from the α-emitting Pu isotopes.

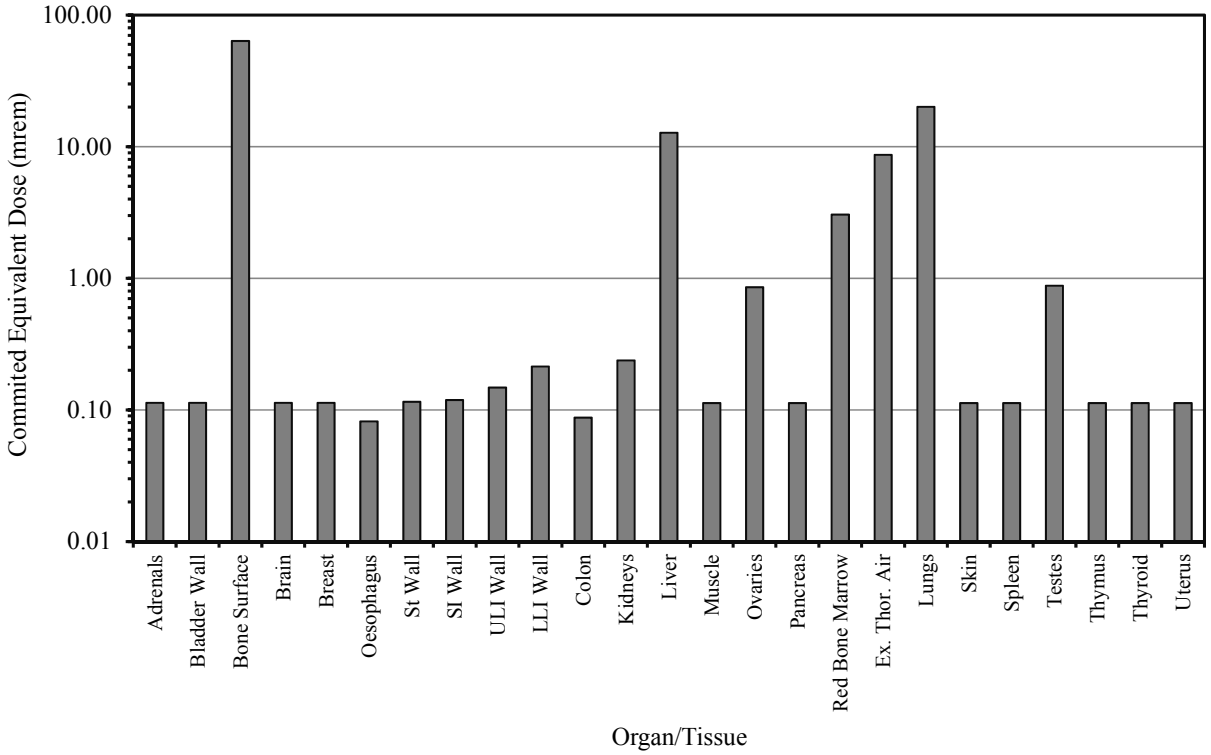


Figure 7-4. Histogram of CED for Organs and Tissues, Inhalation Type S, General Areas, 1964.

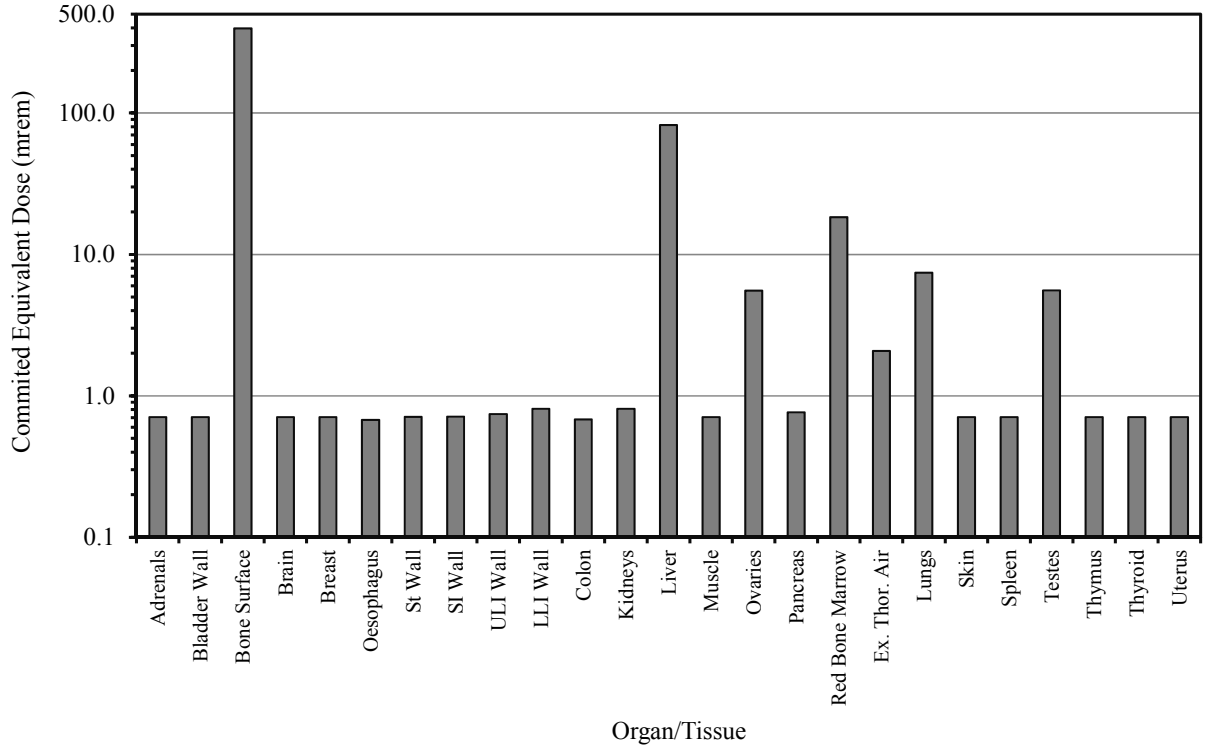


Figure 7-5. Histogram of CED for Organs and Tissues, Inhalation Type M, General Areas, 1964.

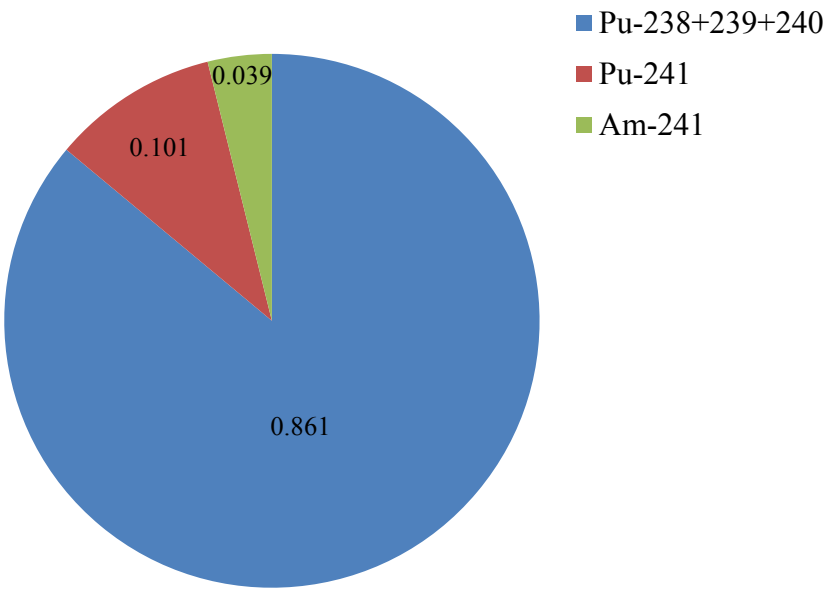


Figure 7-6. Piechart of Relative Contribution of $^{238+239+240}$Pu, ^{241}Pu, and ^{241}Am to CED for Bone Surfaces, Inhalation Type M, 1964.

7.4 Veteran Served on Johnston Island, Worked at JACADS.

This example is for an individual that was assigned duties on Johnston Island for one year, in 1993, with duties at the JACADS. The CEDs would be applicable for all of the years, albeit with minor changes in the ^{241}Am and ^{241}Pu contributions. In the early 1990's, ^{241}Am was near its peak concentration in relation to $^{239+240}$Pu. It is notable that soil concentrations available for soil ingestion and inhalation are the same as those applicable to 1980 and 1975, respectively. No effort was made in this report to predict further dilution of surface soil concentrations of $^{238+239+240}$Pu after the 1980 EG&G survey. As well, most resuspension models predict a lower-end (asymptote) resuspension for long periods of time after deposition. Also, in the extensive air sampling data set that was available for 1975 – 1992, due to low airborne concentrations of $^{238+239+240}$Pu, it was impossible to infer any temporal changes in airborne concentrations. This exposure example is appropriate for a significant number of individuals that were assigned to Johnston Island in its latter years of use.

Intake summary parameters for this example are contained in Table F-10. Most important for this example is the lack of assumed inhalation and ingestion of $^{238+239+240}$Pu during work periods. This is reasonable considering the fact that the JACADS was built on the southwestern part of Johnston Island, on land created after the 1962 mishaps. Calculated CED for organs and tissues under ICRP 60/66 are contained in Table F-11, with histograms in Figures 7-7 and 7-8, respectfully, for inhalation Types S and M. The CED to key organs was very low, only a small fraction of annual organ dose acquired from background sources. The distribution of CED to key organs for inhalation Type M is shown in Figure 7-9. Overall, due to the low residuals of ^{241}Pu compared to $^{238+239+240}$Pu, ^{241}Pu provides only a small fraction to CED to the bone surfaces and liver, while a negligible contribution to the lungs. In the latter organ, the contribution is negligible due to the relatively fast clearance compared to the radiological

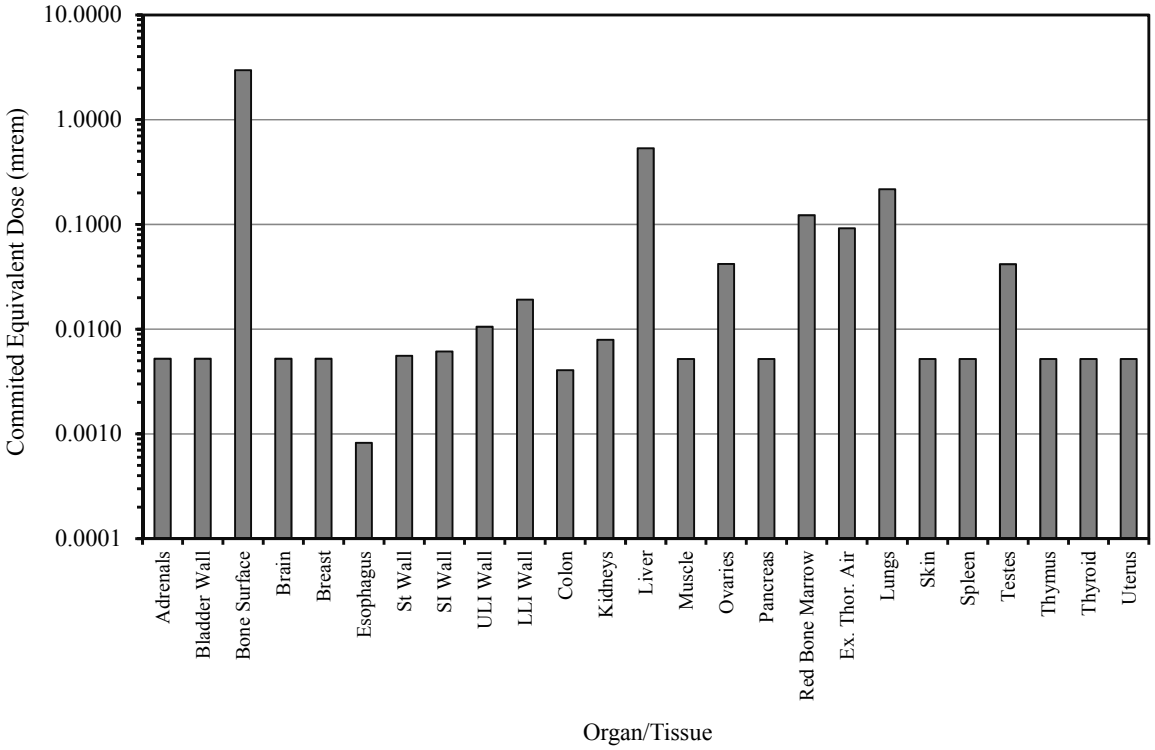


Figure 7-7. Histogram of CED for Organs and Tissues, Inhalation Type S, JACADS Worker, 1993.

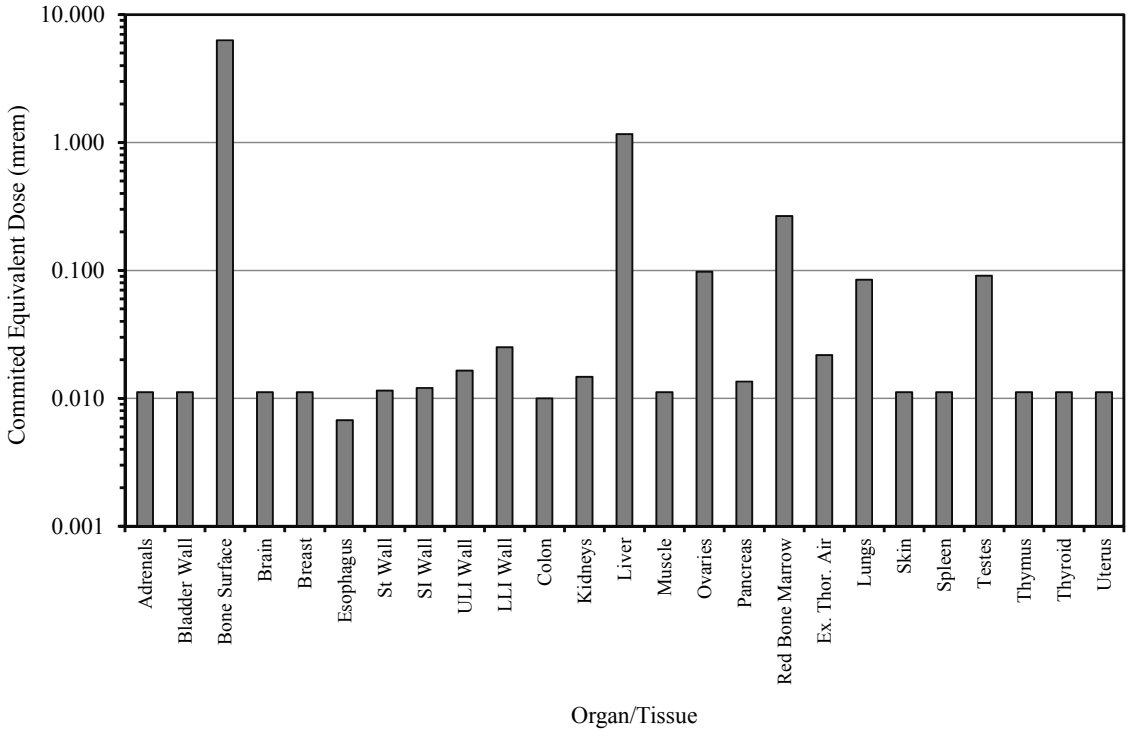


Figure 7-8. Histogram of CED for Organs and Tissues, Inhalation Type M, JACADS Worker, 1993.

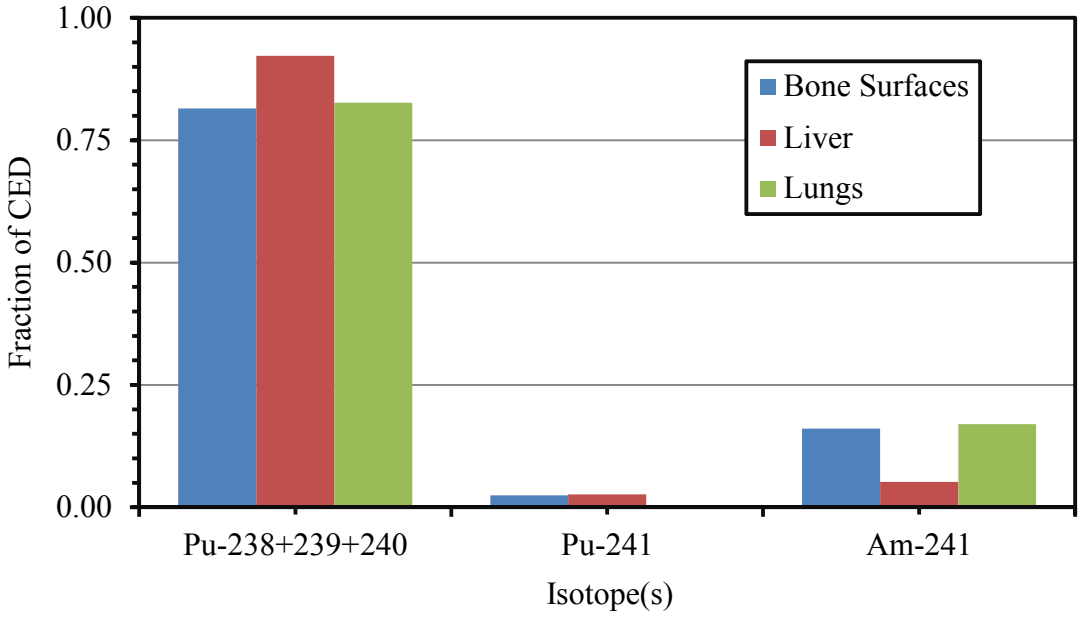


Figure 7-9. Histogram of Relative Contribution of $^{238+239+240}$Pu, ^{241}Pu, and ^{241}Am to CED of Key Organs, Inhalation Type M, 1993.

half-life of ^{241}Pu, 14.4 y. In the case of the bone surfaces and liver, the modeled biological retention in these organs is much longer than the half-life of ^{241}Pu. The assumption of inhalation Type S increases the fraction of contribution of ^{241}Pu to CED to the lungs, due to the longer modeled retention for Type S compounds compared to Type M. However, the fraction still remains negligible.

7.5 Veteran Served as Thor Missile Launch Site in 1964.

This case is the same as that presented in Section 7.1 above, except that it applies airborne concentrations that are assumed to exist between April 1962 to the summer of 1965. Due to the limited duration of this time period, it is expected to apply to a much smaller number of personnel as covered by the evaluation in Section 7.1. Intake summary parameters for this example are contained in Table F-12. Calculated CED for organs and tissues under ICRP 60/66 are contained in Table F-13. The histograms in Figures 7-10 and 7-11 display the distributions of CED for the data in the tables, respectively, for inhalation Types S and M. Among the exposure examples provided in this report, covering periods past 30 June 1964, this example provides the greatest overall organ/tissue doses for a year. The maximum CED to the bone surfaces is 885 mrem (for inhalation Type M), which would be 1,770 mrem for a two year time period, the maximum period covered under these exposure assumptions. Due to crew rotations, a two-year exposure duration may be unreasonable for the majority of individuals assigned for duties in the Thor missile launch site.

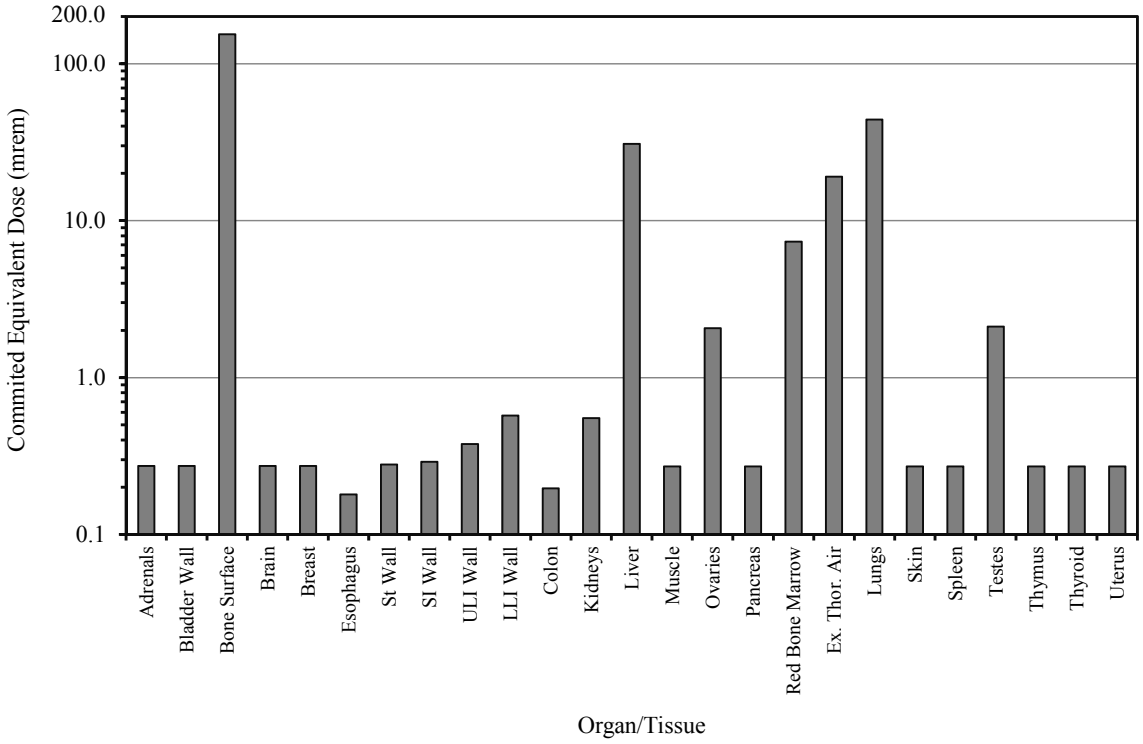


Figure 7-10. Histogram of CED for Organs and Tissues, Inhalation Type S, Thor Worker, 1964.

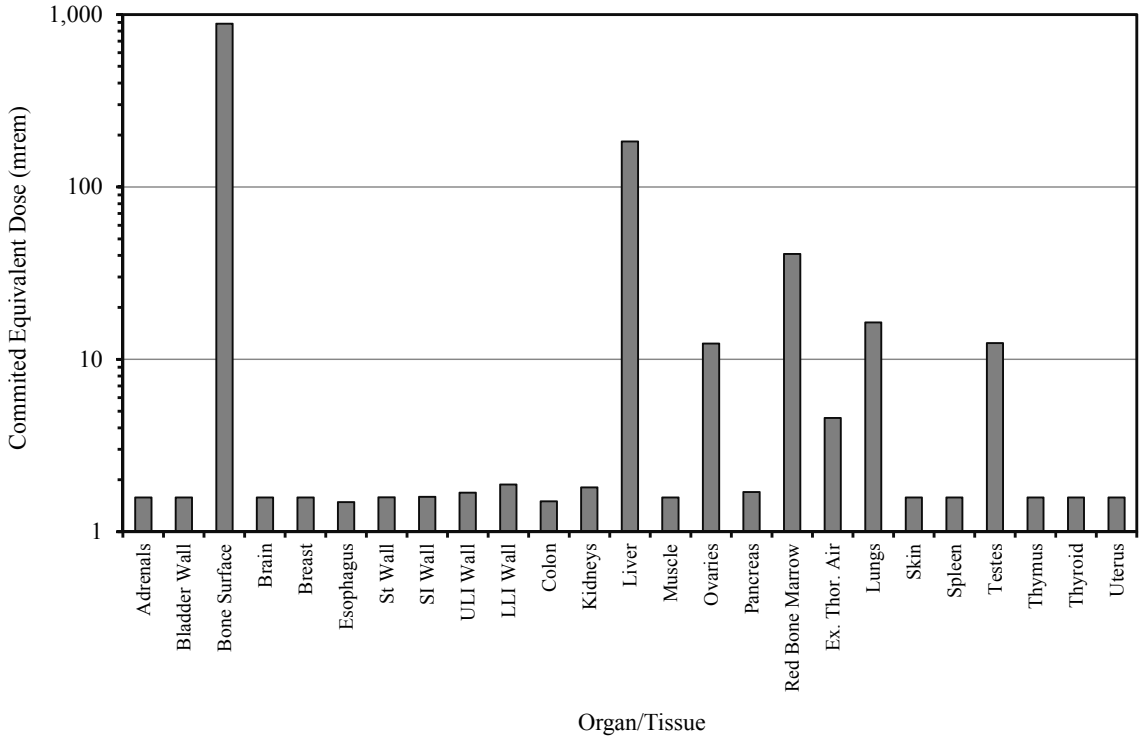


Figure 7-11. Histogram of CED for Organs and Tissues, Inhalation Type M, Thor Worker, 1964.

7.6 Summary. Table 7.1 contains a summary of CED to key organs for the example exposure evaluation provided above. The data is from the tables contained in Appendix F. The table only contains CED from the inhalation type that provided the highest CED to the specific organ. The examples given in this section were made to illustrate the magnitude of exposure potential for various work locations and assignment times. For brevity's sake, the evaluations provided here were small in number. The methodology provided, however, could be extended to a vast number of additional exposure evaluations, based on individual exposure conditions.

TABLE 7-1. Summary of CED to Key Organs for Example Exposure Evaluations.

Example Exposure Evaluation (One Year Duration)	Organ CED (mrem) [Inhalation Type]				
	Bone Surfaces [M]	Liver [M]	Red Bone Marrow [M]	Extra-thoracic Airways [S]	Lungs [S]
Thor missile technician, 1966	504	103	23.1	10.4	24.1
Working in general areas, 1964	397	82.2	18.3	8.67	20.1
Work in general areas, some duties in RCA, 1964	531	110	24.5	11.6	26.8
Working at JACADS, 1993	6.31	1.17	0.267	0.0915	0.217
Thor missile technician, 1964	885	183	40.9	19.0	44.1

8.0 Probability of Causation (PC) and Interactive RadioEpidemiological Program (IREP)

8.1 General.

Some radiogenic disease compensation claims handled by the VA are evaluated by the Interactive RadioEpidemiological Program (IREP) computer software (Kocher and Apostoaei 1997). Notably, claims meeting the presumptive compensation requirements in 38 CFR 3.309 would not normally require a dose assessment and an IREP evaluation. The IREP code used by the VA was developed by the National Institutes of Health (NIH), an agency currently in the Department of Health and Human Services (HHS). A similar IREP code was later developed by the National Institute for Occupational Safety and Health (NIOSH), also part of HHS. The NIOSH code was similar to the existing NIH code, though it was developed for use by the Department of Labor (DOL) in assessment of claims under the Energy Employees Occupational Illness Compensation Program Act (EEOICPA). In the mid- to the later 2000's the VA began using the NIOSH version of IREP for most medical opinions (Ochin 2007). IREP calculates a probability of causation (PC) distribution for specific cancer induction sites, based on radiation exposure estimates. PC values vary by age at exposure and the time between the age at exposure and malignancy diagnosis, commonly termed the latency period. Land et al. (2003) define the "probability that a cancer in an individual was caused by prior exposure to ionizing radiation" - PC as:

$$PC = {}^{R}/_{(R+B)},$$

where R is the probability of incurring a specific cancer due to the radiation exposure and B is the baseline (background) probability of incurring the cancer, absent the radiation exposure. On this issue, it is important to note that the specific cause of any cancer is not known, even if an individual has

known risk factors. Though many cancer types have well known risk factors, i.e., high radiation exposure, high indoor radon concentrations, tobacco use, genetic links, poor diet, occupational exposure to chemicals, baseline risk factors for some cancer types have not been well established by medical and epidemiological studies.

IREP calculates PC on an "estimate of the excess relative risk (ERR) associated with a given radiation dose to an organ or tissue in which a cancer occurred" (Kocher and Apostoaei 2007). ERR values are based on estimates obtained from epidemiological studies of populations exposed to radiation. The Japanese atomic bomb survivor follow-up studies have been the primary source of risk data. IREP applies a radiation effectiveness factor (REF) to the type of radiation absorbed in the organ of interest. It is important to note CED values provided in the previous section of this report use radiation weighting factors from ICRP Report 60, which uses a factor of 20 for the absorption of α-particles energy in tissue. IREP uses a probability distribution of REF for α-particles, as compared to high-energy photons. For individuals using CED values from this report, it is reasonable to assume that the vast majority of CED is attributed to the absorption of α-particle energy. Over 99.8% of the energy emitted in the decay of ^{239}Pu and ^{240}Pu is due to α-particles, while for ^{241}Am over 98.5%. Hence, dose values are simply 1/20th of the CED.

8.2 Example PC Screening Values.

In adjudication of claims made by veterans to the VA, in the absence of direct radiation monitoring data, it has generally been the responsibility of the individual DoD component to assess radiation exposure potential. Based on the radiation exposure, or credible estimates, the VA assesses PC based on IREP calculations. Under VA and EEOICPA methods, claims are evaluated against a 50% or greater probability at the 99% credibility limit from radioepidemiological tables. This approach for assessing claims under EEOICPA was formalized in a 2002 HHS rule-making (CFR 2002). The VA uses this approach as well (Ochin 2007). Doses reported at this level of credibility are typically about 10-fold higher than the 50% credibility level, but are varied dependent on the cancer type, latency, and other factors. This factor adds another significant level of conservatism in the process of adjudicating claims.

Kocher and Apostoaei (2007) developed "screening doses" for assessment of PC for exposure to photons of energy greater than 250 keV. The primary purpose of the Kocher and Apostoaei (2007) work was to aid DTRA and the VA in more readily evaluating claims under the NTPR program. Although their work listed PC values at the upper 99% credibility limit for cancers in numerous tissues/organs, it was deemed most beneficial in aiding in the adjudication of claims for cancers that did not fall under the presumptive compensation provision in 38 CFR 3.309(d)(2). Specifically, skin and prostate cancers were noted as the most common non-presumptive cancers of interest (Kocher and Apostoaei 2007). The values were calculated from Version 5.4 of the NIOSH-IREP code. Screening values for key organs and tissues with respect to internal exposures to plutonium from the Kocher and Apostoaei (2007) report are provided in Appendix G of this report as an aid to the reader to place into context the exposure estimates against screening levels. Within this context, it is important to note:

1) the screening doses were calculated for high energy photons and there is expected to be some difference for α-particle dose that is dominant for internal exposure to plutonium,

2) PC values for adjudicating individual veteran claims based on assigned duties to Johnston Island would be determined by the VA,

3) values from the Kocher and Apostoaei (2007) report were listed here as a matter of convenience, with detailed example calculations for α-particle dose beyond the primary scope of this this report, and

4) the NIOSH-IREP code is subject to changes over time with availability of new epidemiological and medical information.

Tables G-1 through G-4 are excerpts from Kocher and Apostoaei (2007) for the liver, lung, and bone, the three organs that have been linked to internal exposures to WGP from animal and human epidemiological studies. All values are based on estimated PC of 50% at the upper 99% credibility limit. Kocher and Apostoaei (2007) list two sets of screening doses for lung cancers which use different risk models (Tables 7-2 and 7-3). The authors noted that the screening doses in Table 7-3 are often substantially lower for individuals exposed at a younger age and for lower latency periods. For more details on the differences, Kocher and Apostoaei (2007) should be reviewed. PC calculations for the lung are highly varied based on the smoking status of an individual. Smoking is a well-established synergist for lung cancer induction with other agents of known risk for cancer induction.

Among the screening dose levels for key organs with respect to internal plutonium exposure, generally the lowest levels were for the liver. For cancer to the liver, the lowest screening level was 4.0 rem for an assumed exposure age of 18 y, with a latency period to diagnosis of 10 y. For the same exposure age, but a latency of $\geq$ 30 y, the screening dose more than doubles to 11 rem. For the liver, the worst-case annual exposure, among the examples provided above, was for an individual working in the Thor launch area in 1964. The 50-y CED to the liver was 183 mrem. It would take 22 y of exposure at this same level to acquire this CED. As discussed above, the assumed airborne concentrations in the Thor launch area for 1964 were projected for a two year period of time. A 1965 air sampling data set, did not allow justification for the overly-conservative estimate for 1965 and beyond. As such, subsequent years up to 1975 had almost half the assumed airborne concentrations of $^{238+239+240}$Pu. Also, individuals that worked in this area were typically rotated on a 90 d basis, with individuals performing at most a handful of rotations. Hence, by virtue of the environmental data documented in this report, conservative exposure assumptions, duty assignment practices of that time, and IREP-modeled PC's, all reasonable exposures would produce estimated CED's below the listed screening levels for the liver.

The highest estimated annual CED to the bone surfaces was 885 mrem for an individual working in the Thor launch area in 1964, while the lowest screening level for bone cancer was 10 rem for an exposure at 18 y and a latency period of 5 y. It would take over 11 y of exposure at this same level to acquire a CED of 10 rem. For similar reasons noted above for liver cancer induction, an exposure of this magnitude is not plausible.

The highest estimated annual CED to the lung was 44.1 mrem for an individual working in the Thor launch area in 1964, while the lowest screening level for lung cancer was 18 rem for an exposure at 18 y and a latency period of 10 y, for a "never smoker." For similar arguments provided above for liver and bone cancers, probability of attribution of a lung cancer to an exposure at Johnston Island is very low.

Screening doses for malignancies of the blood and lymphatic systems are listed in Tables G-5 (lymphoma and multiple myeloma), G-6 (acute lymphocytic leukemia), G-7 (acute myeloid leukemia), G-8 (chronic myeloid leukemia), and G-9 (leukemia). Dose to the red bone marrow (RBM) is generally considered the important dose index for evaluating PC for these malignancies, with the exception of lymphomas, which will be discussed later in this report. Table 8-1 contains a list of the lowest screening doses among Tables G-5 – G-9. The lowest dose is 240 mrem, for acute lymphocytic leukemia (ALL), while the highest minimum screening dose is 22 rem for lymphomas and multiple myeloma. In the case of ALL, the minimum is for an exposure at 18 y, with a latency period of 5 y. However, for individuals $\geq$ 20 y at the time of exposure, the screening dose is 16 rem or higher. Increased risk for leukemia and lymphomas were not identified in animal studies or human epidemiological studies. Nevertheless, the data tables are provided here for informational purposes. The highest estimated annual CED to the RBM was 40.9 mrem for an individual working in the Thor launch area in 1964. At this rate, it would take a six year exposure period to meet the minimum screening level of 240 mrem for ALL, which is interesting in that the latency period for this screening dose is only 5 y, less than the total exposure time. For an 18 y old person at the time of exposure and a 10 y latency period, the screening dose increases to 0.91 rem. As noted above, multiple years of exposure at this level, however, is not possible. Outside of this unique minimum screening dose, all the others for the blood and lymphatic system malignancies are substantially higher, with probability of attribution to internal WGP exposure being very low.

TABLE 8-1. Lowest Screening Dose (rem) Calculated with IREP, for Malignancies of the Blood-Forming Organs and Lymphatic System [Kocher and Apostoaei 2007)].

Malignancy Type	Screening Dose (rem)	Malignancy Type	Screening Dose (rem)
Lymphoma and multiple myeloma	22	Acute lymphocytic leukemia	0.24
Leukemia, excluding chronic lymphocytic*	1.9	Acute myeloid leukemia	5.8
Chronic myeloid leukemia	1.4		

* Chronic lymphocytic leukemia (CLL) has traditionally not been considered a radiogenic cancer, however, is now evaluated for compensation in VA and EEOICPA radiation exposure cases.

8.3 Temporal Accumulation of Dose from Internal Exposure to Plutonium.

Contrasting external exposures to penetrating ionizing radiation and internal exposures to short-lived radionuclides and/or radionuclides with short biological retention, internal exposure to the long-lived radionuclides of Pu and Am distribute dose to key tissues over long periods of time after an acute intake. The retention function plots in Figures G-1 and G-2, respectively, for inhalation of Type M and S stable plutonium under ICRP 68 illustrates the concept for the whole-body and the lung. There is a rapid clearance of material deposited in some portions of the respiratory tract, which is readily cleared within a few days after exposure; however, in the thoracic portion of the lung, there is a fraction of the initial intake that is retained for a long period of time. Some is translocated to the thoracic lymph nodes where the material is retained for nearly an indefinite period. The liver, under ICRP 68. has a two compartment model, where retention in one compartment is modeled to have a retention half-life of 2.1 y and the other 18.7 y (ICRPa 1994). The bone, similar to the liver, has long-term retention, though the ICRP has a more complex six-compartment model for this organ.

The temporal accumulation of dose from internal exposure to plutonium complicates PC assessments. The current radiation protection practice under the ICRP and NCRP schemes of assigning committed internal doses to the year of intake is a conservative approach. For occupational exposures, 50-y committed doses are used, while 70-y is used for exposures received by members of the public. For bronchial/alveolar tissues of the lung, the liver, bone surfaces, and red bone marrow, dose rates are highest shortly after an inhalation intake, with a gradual decrease in the rate over time. The peak dose rates to the thoracic lymph nodes, however, are delayed due to the relatively slow translocation of material deposited in the bronchial/alveolar region to the lymph nodes. Hence, for individuals being evaluated for PC with a malignancy diagnosis within 5 y may have accumulated only a small fraction of the 50-y committed dose. This is especially key in the evaluation of ALL, which has a minimum screening dose of 0.24 rem for an individual exposed at an age of 18 (see Tables G-6 and 8-1), which was the subject of discussion above. In the discussion above, it was noted that an individual would have had to work under the worst-case exposure condition for six-years to acquire a CED to the RBM at the minimum CED for ALL. The conditions for this exposure, however, were only modeled for two years, with subsequent exposure conditions much lower in the Thor launch area for subsequent exposure years. The discussion provided above did not consider the temporal accumulation of dose to the RBM. Under these considerations, applicability of the minimum screening dose listed in the referenced tables for ALL to internal WGP exposure conditions at Johnston Island are deemed even less appropriate.

Kocher and Apostoaei (2007) contained a discussion for consideration of dose from exposure acquired in more than one year and application of screening doses. In some respects, an internal dose commitment can be expressed as a dose received over multiple years. The authors noted multiple approaches to evaluating an exposure to screening doses. Because the screening doses were provided in this report for informational purposes only, no additional detail will be provided from Kocher and Apostoaei (2007).

Due to the low projected CED's to organs/tissues from Pu exposures on Johnston Island compared to screening doses, no effort was made in the current edition of this report to quantify annual dose acquired by individual organs/tissues over time based on a single acute intake. Computer codes, for example, the Integrated Modules for Bioassay Analysis (IMBA) developed by the UK Health Protection Agency can be used to calculate organ/tissue doses using the ICRP models.

9.0 Discussion of Special Issues

9.1 General. Internal radiation exposure to plutonium has some special issues compared to exposures from relatively uniform external sources and other internal emitters, i.e., Cs-137 and H-3, which produce a fairly uniform irradiation to tissues of the body as compared to plutonium. With respect to plutonium exposure, this issue complicates assessment of PC for lymphatic system neoplasms and has historically created a significant amount of debate regarding the relative effectiveness of lung-deposited plutonium in discrete particle form in induction of lung cancer as compared to a more uniform irradiation of the lung. This section also provides a brief discussion of lung fibrosis, which has more recently received attention among individuals employed in the former AEC complex working in environments with airborne plutonium. Brief comment is also provided for prostate cancer. The prostate organ is not very radiosensitive, however, prostate cancer incidence is common among older men, which is coincident with many of the individuals that were assigned duties to Johnston Island in the 1960's and 1970's.

9.2 Lymphatic System.

The human lymphatic system functions as an accessory route for transport of fluids in the body back to the blood stream and an important part of the immune system. The lymphatic system is comprised of the lymphatic organs, vessels, and the circulating lymph tissue. Under ICRP 23, the lymphatic system has a mass of 2,200 g, which excluding the spleen, thymus, and tonsils has a mass of 1,996 g. The thymus and bone marrow are responsible for the production of lymphocyte tissue. In contrast to most solid tumors, for lymphomas, the location of irradiation is not always linked to the site of metastasis. This is particularly the case for circulating cells in the lymphatic system. With respect to inhalation exposures to insoluble chemical forms of plutonium, i.e., inhalation Type S (ICRP 66) and Class Y (ICRP 30), dose to thoracic lymph nodes [LN(TH)] is high compared to even the lung, liver, and bone surface, though these lymph nodes comprise only about 1.5% of the mass of entire lymphatic system. This is due to the long-term retention of plutonium deposited in the LN(TH). Among other organs in the lymphatic system, dose to the RBM is relatively high from internal plutonium exposures, while the spleen, thymus, and lymph nodes (outside the respiratory tract) do not have a proclivity for retention of plutonium or americium, and subsequently substantially lower dose than that received by the RBM.

For dose assessments under ICRP 68, only a 0.001 tissue-weighting factor for the dose contribution to the lymph nodes is used in calculation of dose to the ET and thoracic airways, because they are assumed to have a very low radiation detriment (Eckerman 2012). Mettler and Upton (1995) categorize malignancies to the lymphatic system in the group of tissues with very low or absent susceptibility to radiation induction. This was noted previously in this report from a comment by Stannard (1988) on earlier ICRP documents.

In ICRP 103 (ICRP 2007), the lymphatic nodes are handled as a separate remainder tissue that is one of 13 for each gender. Nevertheless, with averaging of the 13 remainder tissues, each remainder tissue receives an effective weighing factor of ~ 0.01. Further, with the LN(TH) comprising only about 1.5% of the total lymph tissue mass outside of the spleen, thymus, and tonsils, dose to the LN(TH) is deemed relatively insignificant compared to other detriment from internal WGP dose. ICRP recognized that for many circumstances dose was distributed in a heterogeneous manner, but deems detriment from stochastic effects (i.e., cancer, genetic effects) in all parts of that organ or tissue can be correlated with dose averaged over the entire tissue with sufficient accuracy (ICRP 2007). For unique circumstances like radon daughter product deposition on the bronchial mucosa or plutonium deposited on bone surfaces, the ICRP addressed these issues in specific organ (i.e., skeleton) or system (i.e., respiratory tract) models (ICRP 2007).

Historically, under the EEOICPA, cases where a worker has a lymphoma, medical reviews were performed, without specification of a specific organ dose (ORAU 2003). More recent guidance for EEOICPA cases (ORAU 2012) contains internal dose target organs for consideration, based on the site of metastasis in the lymphatic system and the metastasis type. A summary is provided in Table G-10. Various forms of leukemia are also included in this table, though these metastases, with the exception of CLL, are linked to radiation dose to the bone marrow. The VA approach in evaluating cases of lymphoma may have some similarities and differences in the manner used under EEOICPA cases.

The recent addition of CLL cases under the EEOICPA involved a detailed review of the lymphatic system to radiation dosimetry for CLL by Specialists in Energy, Nuclear and Environmental Sciences

(SENES), Oak Ridge, TN (Apostoaei and Trabalka 2012). The Apostoaei and Trabalka (2012) work concentrated on potential dose to precursor B-cells, as this group of cells were deemed to represent those cells within the lymphatic system that were potential precursors to CLL. In review of Table G-10, precursor B-CLL cells are also believed to be precursors for many lymphoma types. Because these cells are located throughout the lymphatic system, assessment of dose and ultimately PC is complicated by the varied distribution among individuals, affected by age, gender status, and other factors (Apostoaei and Trabalka 2012).

A brief review of some information from this work is useful in illustrating the problem. Dose coefficient (DC) values for organs key to internal plutonium exposure and the lymphatic system from inhalation of Type S $^{239+240}$Pu are listed in Figure 9-1. Obvious is the ten-fold higher DC for the LN(TH) as compared to the lungs, yet the very low DC's for other organs/tissues in the lymphatic system – thymus, spleen, remainder lymph nodes, other. Figure 9-2 contains a point estimate of percentage of precursor B-CLL cells in various organs/tissues, though the Apostoaei and Trabalka (2012) work treated the distribution in a probabilistic manner. Among the organs/tissues with the largest fraction of precursor B-CLL cells, only the RBE was among those organs with a reasonably high DC for inhalation of Type S $^{239+240}$Pu. The results of the Apostoaei and Trabalka (2012) probabilistic evaluation of inventory-weighted 50-y CED DC's for precursor B-CLL cells and B-cells are shown in Figure 9-3 against DC's for key organs. The plot demonstrates the high variability in potential DC factors for calculation of PC's for CLL. Use of the DC for LN(TH) for calculation of PC in CLL cases is highly conservative, but unrealistic and lacking scientific defense (Apostoaei and Trabalka 2012). Application of the LN(TH) DC in PC calculation for some lymphomas may have a similar shortcoming. The discussion here helps illustrate the complications in assessment of PC for lymphatic metastases.

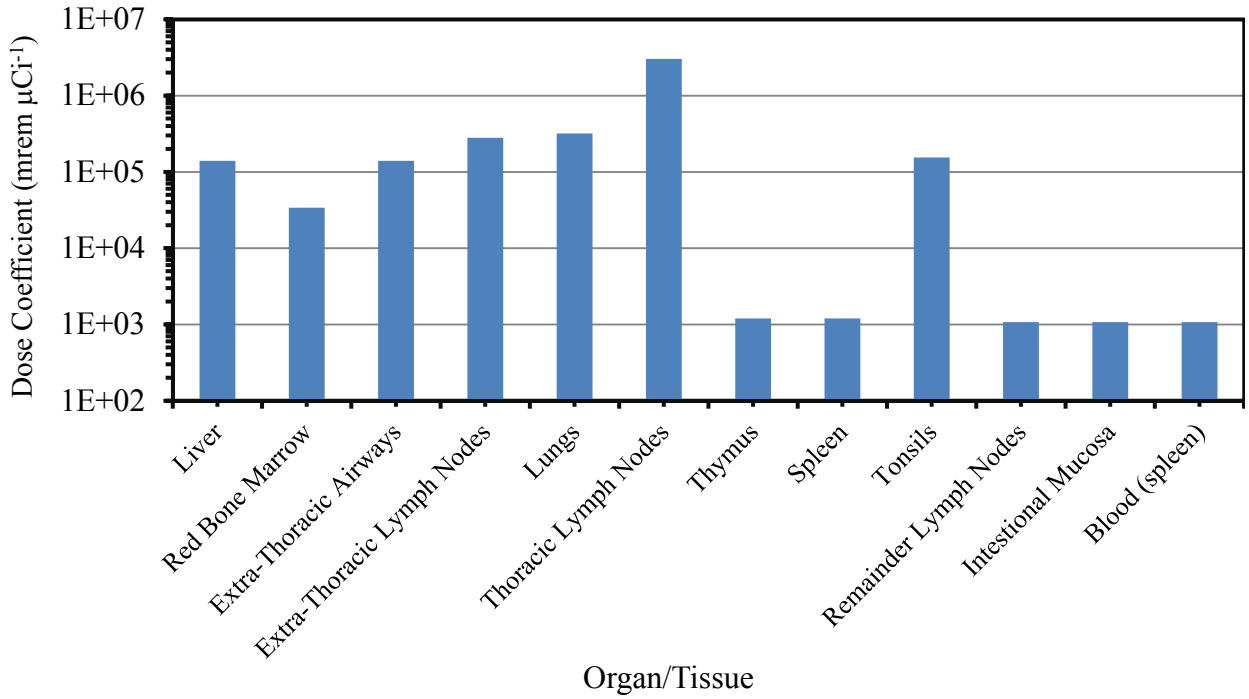


Figure 9-1. Dose Coefficients for Organs Key to $^{239+240}$Pu Internal Exposure and the Lymphatic System, data from Apostoaei and Trabalka (2012) for Inhalation Intakes, Type S.

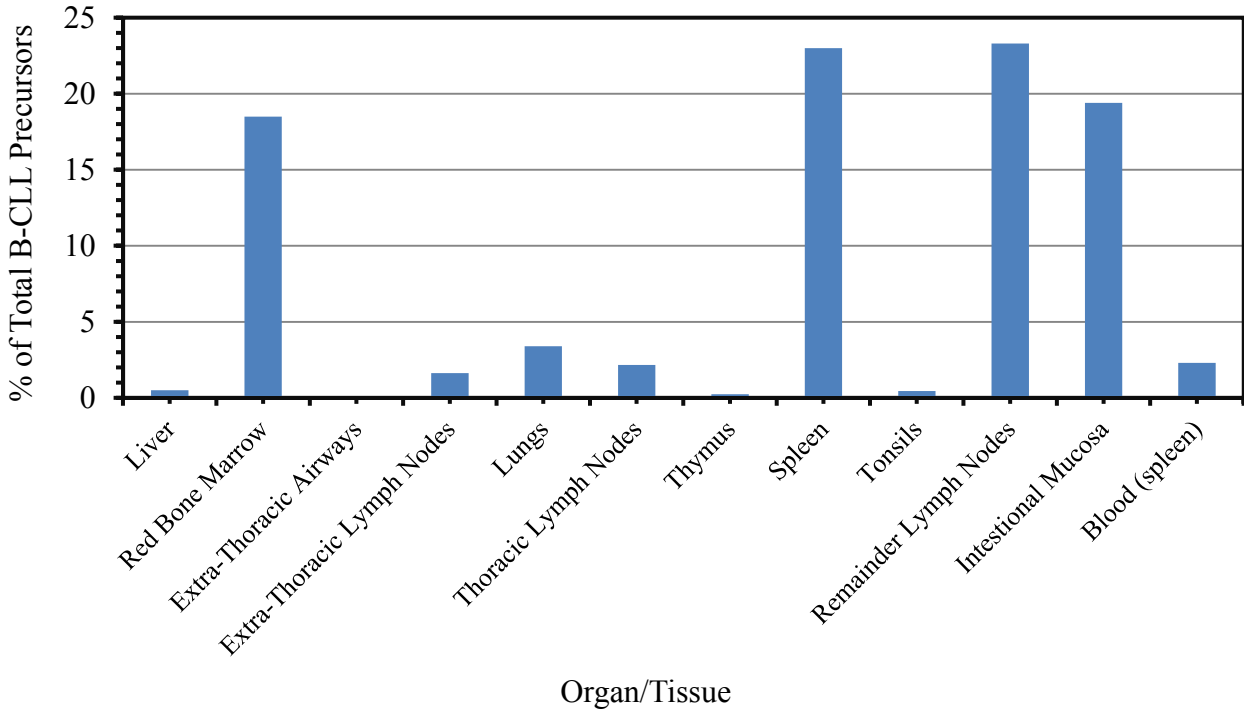


Figure 9-2. Point Estimate, Percent of Total B-CLL Precursors to Organs Key to Internal Plutonium Exposure and the Lymphatic System, data from Apostoaei and Trabalka (2012).

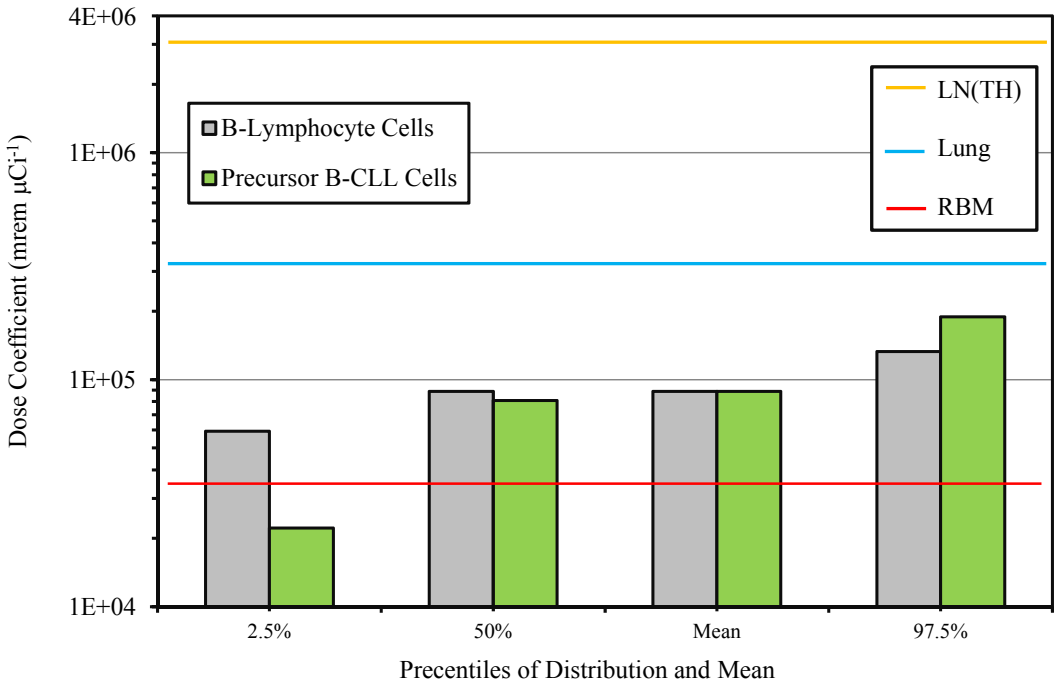


Figure 9-3. Percentiles of Probabilistic Inventory-Weighted Average 50-y CDE Dose Coefficient Distributions for B-Cells and Precursor B-CLL Cells, and Key Organ Dose Coefficients for Inhaled $^{239+240}$Pu, Type S, data from Apostoaei and Trabalka (2012).

9.3 Spatial Distribution of Dose to Lung from α-Emitting Radionuclides.

Special interest in the heterogeneous distribution of dose to lung tissue was raised about 30 y ago by the National Resources Defense Council [NRDC] (Tamplin and Cochran 1974; Stannard 1988) and the NAS (Richmond 1975). The premise of the NRDC and NAS was that discrete particles deposited were uniquely carcinogenic to lung tissue as compared to homogenously dispersed radiological contaminants and that standards of the day were 115,000-fold too low (Stannard 1988). Stannard (1988) noted that attention to this problem was the "most diversionary, most divisive, and most expensive" creating undue concern in the US and among European countries. Though this issue covered other elements, its primary focus was on plutonium.

Stannard (1988) and Richmond (1975) noted in extensive detail that a significant amount of work had already accomplished in study of this issue through animal research, though it generated readdress to the work by numerous investigators in both theoretical and evaluation of animal study data. Nevertheless, ICRP and NCRP reiterated the validity of the practice of averaging dose over the lung tissue in estimation of stochastic cancer risks (Stannard 1988). Substantial details on this issue can be found in Stannard (1988), NCRP Report 46 (NCRP 1975), Richmond (1975), and work referenced in these documents.

9.4 Lung Fibrosis at High Lung Dose from Plutonium Inhalation.

High lung doses from inhalation of plutonium created chronic inflammatory lung diseases and delayed-onset pulmonary fibrosis (Newman et al. 2005). This finding was discussed earlier in this report. Newman et al. (2005) were prompted to study a population of Rocky Flats plutonium workers for lung fibrosis, based on suggested effects in Mayak workers. Their study evaluated 326 workers exposed to plutonium as part of their work with 194 unexposed workers. Cumulative lung doses were evaluated under ICRP 30 modeling and pulmonary fibrosis was evaluated with chest radiographs. Correlations between evidence of fibrosis and cumulative lung dose was evaluated by univariate and multivariate regression models, with the latter model including age, smoking status, and age at time of evaluation. Individuals having a cumulative dose equivalent to the lung between 500 and 1,000 rem had a 1.7-fold higher odds ratio of having an abnormal chest x-ray profusion score compared to the unexposed group. Individuals having a cumulative dose equivalent to the lung greater than 1,000 rem had a 5.3-fold higher odds ratio of having an abnormal chest x-ray profusion score compared to the unexposed group, which was statistically significant. An important factor in the multivariate analysis was smoking history, which was divided between "never smokers" and "ever smokers" for the analysis. Ever smokers had a 4.2-fold higher odds ratio of having an abnormal chest x-ray profusion score compared to never smokers.

Due to the high, cumulative dose equivalent levels that the increased risk of abnormal x-rays was observed in this study, the findings are of no consequence to personnel that were assigned duties at Johnston Atoll, due to the substantially lower potential lung doses. For the Rocky Flats worker study, there were only 38 individuals with cumulative lung dose equivalent to the lung greater than or equal to 500 rem among the 326 plutonium-exposed workers in the study (~ 12%). EEOICPA compensates eligible individuals with non-malignant respiratory conditions, i.e., pneumoconiosis and fibrosis of the lung, but only for individuals that had jobs in uranium mining, milling, and ore transport. The epidemiology that supported compensation for non-malignant respiratory conditions for these cohorts of

workers did not differentiate among the various risk factors: radon daughter dose to the lung, dose to the lung from deposited uranium particles, or the high dust loading conditions (NAS 2005).

9.5 Prostate Cancer.

Prostate cancer is the most common cancer among men after skin cancer, with over 50% of new cases diagnosed after 65 y of age. While prostate cancer is listed by the VA as radiogenic (Table A-2), the prostate is relatively insensitive to ionizing radiation, as compared to other tissues (Mettler and Upton 1995). IREP treats the prostate gland under the collective group of male genitalia. The minimum screening dose for this tissue group by Kocher et al. (2007) is 27 rem. Under EEOICPA, it is recommended to apply dose received by the organ with highest dose among those that do not have specific-metabolic models for the radionuclide of interest, i.e., plutonium and americium. For internal dose from plutonium and americium, the appropriate "surrogate" organ would be the testes. Hence, due to the very low CEDs to the testes for all examples provided here, likelihood of prostate cancer induction from plutonium exposures is negligible.

10 Conclusions

Johnston Atoll supported U.S. atmospheric nuclear weapons testing under Operations Hardtack I and Dominic I. The most significant incidents occurring during these Operations impacting the Atoll were three Thor missile launch mishaps under Dominic I: Starfish (19 June 1962), Bluegill Prime (25 July 1962), and Bluegill Double Prime (15 Oct 62). The most important of these mishaps was Bluegill Prime, responsible for dispersal of WGP, HEU, and DU on the Thor LE-1 pad and vicinity, due to a low-order detonation and fire to the nuclear warhead on the pad. The Starfish mishap, while involving a high-altitude conventional detonation of the nuclear warhead, did have impact of the same radiological contaminants to the Atoll, but to a significantly lesser degree. The vast majority of the plutonium deposited on land within the vicinity of the LE-1 pad was remediated shortly after the Bluegill Prime mishap during Operation Dominic I.

Ionizing radiation exposures related to atmospheric testing had the potential for health effects on military veterans and other personnel supporting the testing program. While some acute radiogenic effects may have occurred, i.e., skin burns from fallout, the most significant concern for individuals supporting the tests is from the delayed effect of cancer induction. The VA has a number of radiogenic cancers that are presumptively compensated if the veteran has one of these cancer types and was an on-site participant during testing. Key cancers attributed to high-level, internal plutonium exposure: lung, bone, and liver are on the VA list of presumptive radiogenic cancers (38 CFR §3.309d).

While the vast majority of the plutonium deposited in the vicinity of LE-1 was remediated during Operation Dominic I, some low-level residuals persisted. Significant radiological monitoring was accomplished during the initial remedial action and continued for decades until the Atoll no longer supported military operations in 2004. As well, a number of significant remedial actions were accomplished on plutonium contamination after Operation Dominic I until 2002, when the pile of higher-levels of plutonium was buried on Johnston Island. This report documented radiological sampling and surveys accomplished on Johnston Atoll from the Bluegill Prime mishap through the mid-1990s. The data generated demonstrated that potential radiological exposures to individuals from residual contamination were very low compared to U.S. and internationally-accepted standards of earlier times and today. These standards have evolved over many decades, but are very similar in acceptable plutonium exposure levels that existed at the time of the Thor missile mishaps in 1962.

Veterans present on the Atoll after Operation Dominic I, 30 June 1962, have exposures evaluated under the provisions of 38 CFR §3.311b, where the VA calculates a probability of causation (PC) for individual cancer types from a radiation dose estimate. For example exposure scenarios evaluated in this report, favorable PC values for key plutonium-related cancers are not apparent based on comparison with screening dose levels documented by DTRA. Highly-conservative assumptions were used in the estimate of doses for the scenarios evaluated. Actual doses to individuals are expected to be substantially lower.

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Appendix A

Information of Radiogenic Diseases, Veterans Administration and Bioassay Information on Occupational Exposure to Plutonium Case

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TABLE A-1. VA Presumptive Radiogenic Diseases under 38 CFR §3.309d.

Cancer of the Bile Ducts	Cancer of the Gall Bladder	Pancreatic Cancer
Bone Cancer	Leukemia (except CLL)	Cancer of the Pharnyx
Brain Cancer	Liver Cancer*	Salivary Gland Cancer
Breast Cancer	Lung Cancer	Cancer of the Small Intestine
Bronchio-Alveolar Cancer	Non-Hodgkins Lymphomas	Stomach Cancer
Colon Cancer	Multiple Myeloma	Thyroid Cancer
Esophageal Cancer	Ovarian Cancer	Urinary Tract Cancers**

* Except if cirrhosis or hepatitis B is indicated. ** Kidneys, renal pelves, ureters, urinary bladder, and urethra.

TABLE A-2. VA Non-Presumptive Radiogenic Diseases under 38 CFR §3.311b.

Bone Cancer	Liver Cancer	Posterior Subcapsular Cataracts
Brain Cancer	Lung Cancer	Prostate Cancer
Breast Cancer	Non-Hodgkins Lymphomas	Rectum Cancer
Central Nervous System Tumors	Multiple Myeloma	Salivary Gland Cancer
	Non-Malignant Thyroid Nodular Disease	Skin Cancer
Colon Cancer		Stomach Cancer
Esophageal Cancer	Ovarian Cancer	Thyroid Cancer
Kidney Cancer	Pancreatic Cancer	Urinary Tract Cancers
Leukemia (except CLL)	Parathyroid Adenoma	Other Cancers

TABLE A-3. Partial Radioanalysis and Nasal Swab Data on USTR Case #193 (McInroy et al. 1991).

Date	Pu-239 in Urine (mBq in 24 h)	Nasal Swab (cpm)	
		First	Second
27-Mar-45		168	23
20-Apr-45	-3.7		
12-Jun-45		306	187
14-Jun-45		225	40
6-Jul-45		800	616
16-Jul-45		186	
31-Jul-45		168	146
1-Aug-45		156	50
3-Aug-45		153	26
12-Aug-45		1562	156
20-Aug-45		7696	4598
28-Aug-45		124	106
30-Aug-45		374	88
6-Sep-45	102		
13-Feb-46		224	

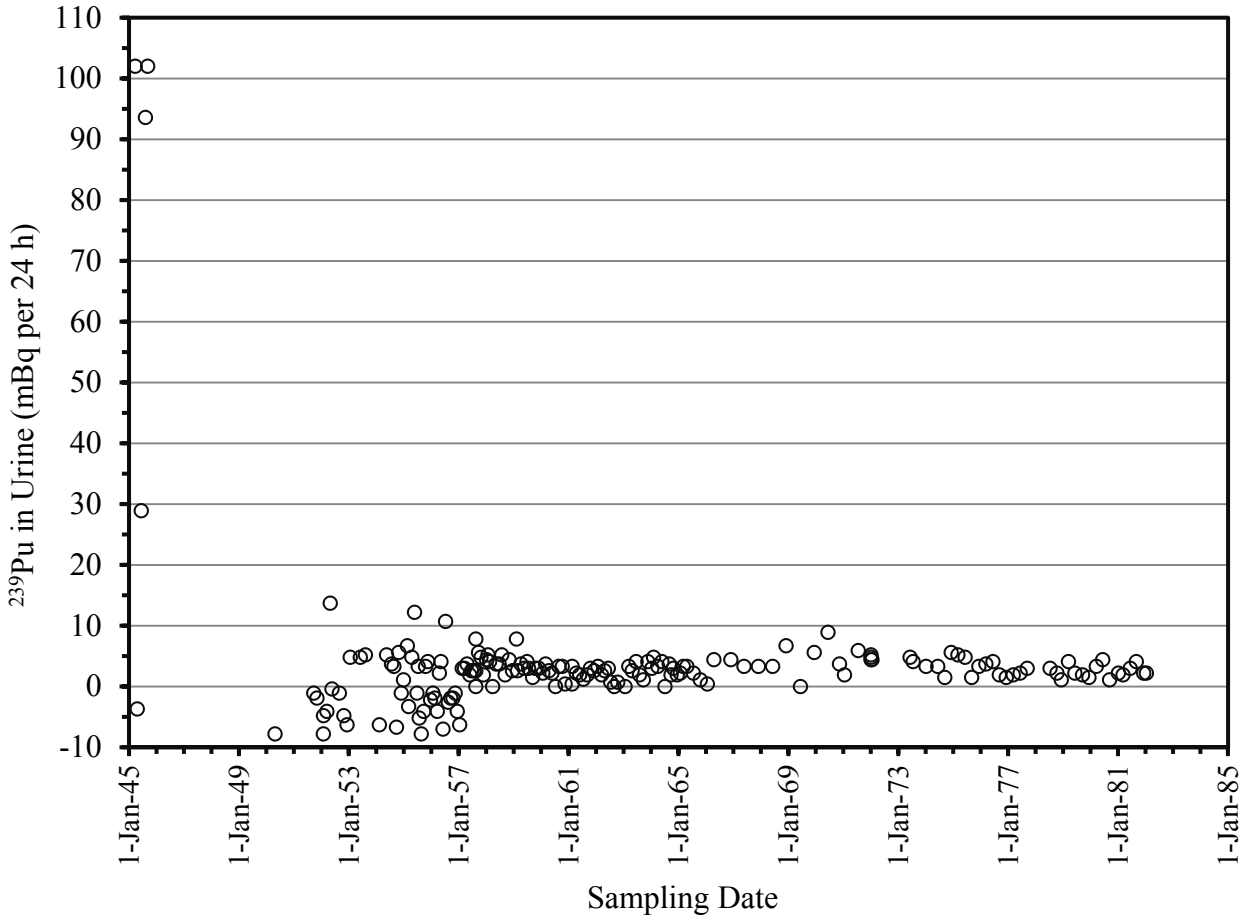

Figure A-1. Urine Radioanalysis Data on USTR Case #193 (McInroy et al. 1991).

Appendix B

Missile Launch Data for Johnston Island

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Table B-1. Summary of Missile Launches from Johnston Island (DOE 2000 and AF 2014).
[Dates based on Coordinated Universal Time (UTC).]

Date	Number	Launch Vehicle	Launch Site	Notes
1 Aug 58	13	Asp – Sounding Rocket	Johnston Island South	Lawrence Radiation Laboratory, aeronomy mission associated with Operation Hardtack
	1	Redstone	Launch Complex 1 (Eastern Area on Island)	High altitude (76.8 km) nuclear weapon detonation test under Operation Hardtack (Test Teak, 3.8 MT)
	8	Doorknob	Johnston Island South	Sandia Corp, aeronomy mission associated with Operation Hardtack
11 Aug 58	8	Doorknob	Johnston Island South	Sandia Corp, aeronomy mission associated with Operation Hardtack
12 Aug 58	14	Asp – Sounding Rocket	Johnston Island South	Lawrence Radiation Laboratory, aeronomy mission associated with Operation Hardtack
	1	Redstone	Launch Complex 1	High altitude (43 km) nuclear weapon detonation test Operation Hardtack (Test Orange, 3.8 MT)
2 May 62	1	Thor DSV-2E	Launch Emplacement 1	Tigerfish High Altitude (481 km) Launch Test, non-nuclear payload
1 Jun 62	1	Nike Cajun	Johnston Island South	AF aeronomy mission associated with Operation Dominic
3 Jun 62	1	Thor DSV-2E	Launch Emplacement 1	High altitude test under Operation Dominic (Test Bluegill), missile destroyed by range safety officer shortly after launch due to radar failure, no nuclear detonation or radiological contamination
19 Jun 62	1	Nike Cajun	Johnston Island South	AF aeronomy mission associated with Operation Dominic
20 Jun 62	1	Thor DSV-2E	Launch Emplacement 1	High altitude nuclear weapon detonation test under Operation Dominic (Test Starfish), Stage 1 missile failure, range safety officer initiated self-destruct 59 s after launch, single-point detonation of warhead conventional high explosives at 10.6 km altitude

Table B-1. Summary of Missile Launches from Johnston Island, continued

Date	Number	Launch Vehicle	Launch Site	Notes
1 Jul 62	1	Nike Cajun	Johnston Island South	AF aeronomy mission associated with Operation Dominic
8 Jul 62	1	Nike Cajun	Johnston Island South	AF aeronomy mission associated with Operation Dominic
9 Jul 62	6	Nike Cajun (4) & Javelin (2)	Johnston Island South	AF aeronomy mission associated with Starfish Prime Test
	1	Thor DSV-2E	Launch Emplacement 1	High altitude (400 km) nuclear weapon detonation test under Operation Dominic (Test Starfish Prime, 1.4 MT)
	5	Strypi Antares	Launch Complex 1	DASA Project associated with Starfish Prime Test
	10	Nike Apache	Launch Complex 1	DoD Project associated with Starfish Prime Test
	2	Honest John Nike	Johnston Island South	AF aeronomy mission associated with Starfish Prime Test
	3	Javelin	Launch Complex 1	AF aeronomy mission associated with Starfish Prime Test
10 Jul 62	1	Nike Cajun	Launch Complex 1	AF aeronomy mission associated with Starfish Prime Test
19 Jul 62	1	Nike Cajun	Johnston Island South	AF aeronomy mission
23 Jul 62	2	Nike Cajun and Javelin	Johnston Island South	AF aeronomy mission
26 Jul 62	1	Thor DSV-2E	Launch Emplacement 1	High altitude nuclear weapon detonation test under Operation Dominic (Test Bluegill Prime), Stage 1 missile failure prior to lift-off, range safety officer initiated self-destruct on launch pad, explosions and fire engulfed the missile, dispersed radiological contamination to local area
1 Aug 62	1	Nike Hercules	Johnston Island South	AF certification test
1 Sep 62	1	Nike Hercules	Johnston Island South	AF certification test

Table B-1. Summary of Missile Launches from Johnston Island, continued

Date	Number	Launch Vehicle	Launch Site	Notes
16 Oct 62	1	Thor DSV-2E	Launch Emplacement 2	High altitude nuclear weapon detonation test under Operation Dominic (Test Bluegill Double Prime), Booster stage missile failure at 86 s after launch, range safety officer initiated self-destruct 95 s after launch, but prior to nuclear detonation
20 Oct 62	1	Castor-Recruit	Johnston Island South	High altitude nuclear weapon detonation test Operation Dominic (Test Checkmate, Low Yield)
	2	Strypi Antares	Johnston Island South	DASA Project associated with Checkmate Test
	1	Nike Cajun	Johnston Island South	AF aeronomy mission associated with Checkmate Test
25 Oct 62	1	Nike Cajun	Johnston Island South	AF aeronomy mission
26 Oct 62	1	Javelin	Johnston Island South	AF aeronomy mission associated with Bluegill Triple Prime Test
	3	Nike Cajun	Johnston Island South	AF aeronomy mission associated with Bluegill Triple Prime Test
	1	Thor DSV-2E	Launch Emplacement 1	High altitude nuclear weapon detonation test Operation Dominic (Test Bluegill Triple Prime, Sub-megaton Yield)
	4	Honest John Nike	Johnston Island South	AF aeronomy mission associated with Bluegill Triple Prime Test
27 Oct 62	1	Nike Cajun	Johnston Island South	AF aeronomy mission
1 Nov 62	1	Thor DSV-2E	Launch Emplacement 2	High altitude nuclear weapon detonation test Operation Dominic (Test Kingfish, Sub-megaton Yield)
	4	Honest John Nike	Johnston Island South	AF aeronomy mission associated with Kingfish Test
	1	Nike Cajun	Johnston Island South	AF aeronomy mission associated with Kingfish Test
2 Nov 62	1	Nike Cajun	Johnston Island South	AF aeronomy mission
3 Nov 62	1	Nike Cajun	Johnston Island South	AF aeronomy mission

Table B-1. Summary of Missile Launches from Johnston Island, continued

Date	Number	Launch Vehicle	Launch Site	Notes
4 Nov 62	2	Nike Cajun	Johnston Island South	AF aeronomy mission
4 Nov 62	1	Nike Hercules	Johnston Island South	AF aeronomy mission associated with Tightrope Test
	1	Nike Hercules	Johnston Island South	High altitude nuclear weapon detonation test Operation Dominic (Test Tightrope, Low Yield)
27 Nov 62	1	Javelin	Johnston Island South	AF aeronomy mission
14 Feb 64	1	Thor DSV-2J	Launch Emplacement 1	AF Program 437 demonstration (Squanto Terror)
1 Mar 64	1	Thor DSV-2J	Launch Emplacement 1	AF Program 437 demonstration (Squanto Terror)
23 Apr 64	1	Thor DSV-2J	Launch Emplacement 2	AF Program 437 combat training launch (CTL)
28 May 64	1	Thor DSV-2J	Launch Emplacement 2	AF Program 437 CTL
16 Nov 64	1	Thor DSV-2J	Launch Emplacement 1	AF Program 437 CTL
5 Apr 65	1	Thor DSV-2J	Launch Emplacement 2	AF Program 437 CTL
7 Dec 65	1	Thor DSV-2J	Launch Emplacement 2	AF Program 437 CTL
18 Jan 66	1	Thor DSV-2J	Launch Emplacement 2	AF Program 437 CTL
12 Mar 66	1	Thor DSV-2J	Launch Emplacement 2	AF Program 437 CTL
2 Jul 66	1	Thor DSV-2J	Launch Emplacement 2	AF Program 437 CTL
19 Sep 66	1	Nike Tomahawk	Johnston Island South	Sandia Corp aeronomy mission
20 Sep 66	1	Nike Tomahawk	Johnston Island South	Sandia Corp astronomy mission
22 Sep 66	1	Nike Tomahawk	Johnston Island South	Sandia Corp astronomy mission
31 Mar 67	1	Thor DSV-2J	Launch Emplacement 1	AF Program 437 CTL
21 Sep 67	1	Terrier Sandhawk	Johnston Island South	Sandia Corp aeronomy mission
25 Sep 67	1	Tomahawk Sandia	Johnston Island South	Sandia Corp aeronomy mission
27 Sep 67	1	Terrier Sandhawk	Johnston Island South	Sandia Corp aeronomy mission
29 Sep 67	1	Nike Tomahawk	Johnston Island HAD23	Sandia Corp aeronomy mission
2 Oct 67	1	Nike Tomahawk	Johnston Island South	Sandia Corp astronomy mission
3 Oct 67	1	Terrier Tomahawk	Johnston Island South	Sandia Corp aeronomy mission
14 May 68	1	Thor DSV-2J	Launch Emplacement 1	AF Program 437 CTL
1 Oct 68	1	Terrier Tomahawk	Johnston Island South	Sandia Corp aeronomy mission
29 Oct 68	1	Terrier Sandhawk	Johnston Island 6 UL	Sandia Corp astronomy mission

Table B-1. Summary of Missile Launches from Johnston Island, continued

Date	Number	Launch Vehicle	Launch Site	Notes
7 Nov 68	1	Terrier Sandhawk	Johnston Island UL6	Sandia Corp astronomy mission
20 Nov 68	1	Thor DSV-2J	Launch Emplacement 1	AF Program 437 CTL
27 Mar 70	1	Thor DSV-2J	Launch Emplacement 1	AF Program 437 CTL
24 Apr 70	1	Thor DSV-2J	Launch Emplacement 2	ASAT Test
24 Sep 70	1	Thor DSV-2J	Launch Emplacement 2	Astronomy Test
19 Sep 75	1	Thor DSV-2J	Launch Emplacement 2	
6 Nov 75	1	Thor DSV-2J	Launch Emplacement 2	

Table B-2. Nuclear Detonations in the Vicinity of Johnston Island.

Date	Test Name	Test Series	Test Type	Yield*	DNA Report	Notes
1 Aug 58	Teak	Operation Hardtack I	Missile	3.8 Mt	DNA 6038F	Detonation occurred at an altitude of 76.8 km over Johnston Island, non-essential personnel were evacuated by ship to an area 50 to 70 nmi (93 to 130 km) northeast of Johnston Island during the shot, ~ 175 remained on Island during launch, no detectable increase in background radiation conditions on the Island
12 Aug 58	Orange		Missile	3.8 Mt	DNA 6038F	Detonation occurred at an altitude of 43 km, 41.6 km south of Johnston Island, total slant distance ~ 60 km to island, non-essential personnel were evacuated by ship to an area 67 nmi (125 km) northeast of Johnston Island during the shot, ~ 145 remained on Island during launch

* DOE (2000)

Table B-2. Nuclear Detonations in the Vicinity of Johnston Island, continued

Date	Test Name	Test Series	Test Type	Yield*	DNA Report	Notes
9 Jul 62	Starfish Prime	Operation Dominic I	Missile	1.4 Mt	DNA 6040F	Detonation occurred at an altitude of 400 km, 25 km SW of Johnston Island, 559 non-essential personnel were evacuated from Johnston Island prior to the test
2 Oct 62	Androscoggin		Airdrop	75 kt	DNA 6040F	Detonation occurred 480 km SW of Johnston Island, 3.1 km altitude
6 Oct 62	Bumping		Airdrop	11.3 kt	DNA 6040F	Detonation occurred 290 km SE of Johnston Island, 3.1 km altitude
18 Oct 62	Chama		Airdrop	1.6 Mt	DNA 6040F	Detonation occurred 290 km SE of Johnston Island, 3.6 km altitude
20 Oct 62	Checkmate		Missile	Low	DNA 6040F	Detonation occurred at high altitude, 80 km SSW of Johnston Island, 787 non-essential personnel were evacuated from Johnston Island prior to the test
26 Oct 62	Bluegill Triple Prime		Missile	Sub- Mt	DNA 6040F	Detonation occurred at high altitude, 37 km SE of Johnston Island, 803 non-essential personnel were evacuated from Johnston Island prior to the test
27 Oct 62	Calamity		Airdrop	800 kt	DNA 6040F	Detonation occurred 280 km SE of Johnston Island, 3.6 km altitude
30 Oct 62	Housatonic		Airdrop	8.3 Mt	DNA 6040F	Detonation occurred 490 km SE of Johnston Island, 3.7 km altitude
1 Nov 62	Kingfish		Missile	Sub- Mt	DNA 6040F	Detonation occurred at high altitude, 80 km SE of Johnston Island, 787 non-essential personnel were evacuated from Johnston Island prior to the test
4 Nov 62	Tightrope		Missile	Low	DNA 6040F	Detonation occurred at high altitude, 18 km NW of Johnston Island, 633 non-essential personnel were evacuated from Johnston Island prior to the test

Appendix C

Information on Heterogeneity of Plutonium from Accidental Releases to the Environment

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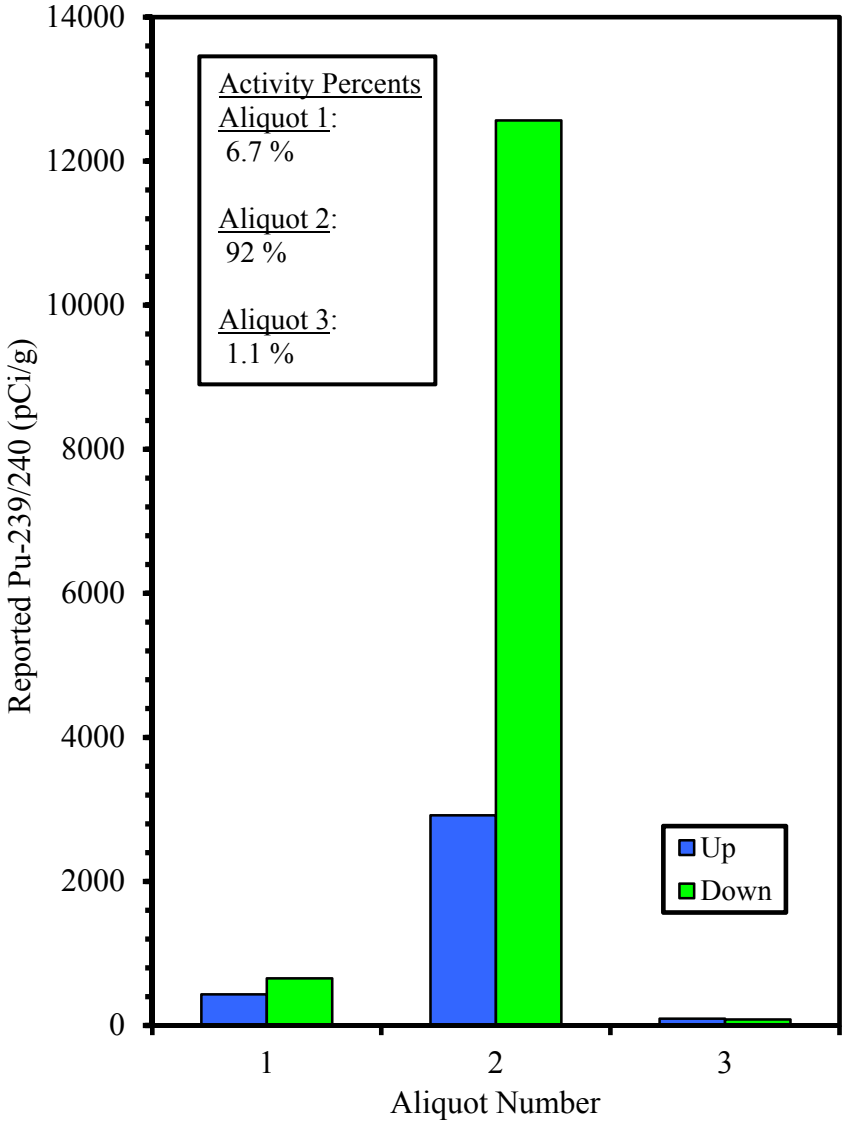


Figure C-1. Sample 14 $^{239+240}$Pu Activity Concentration for Individual Aliquots, from Rademacher (2001).

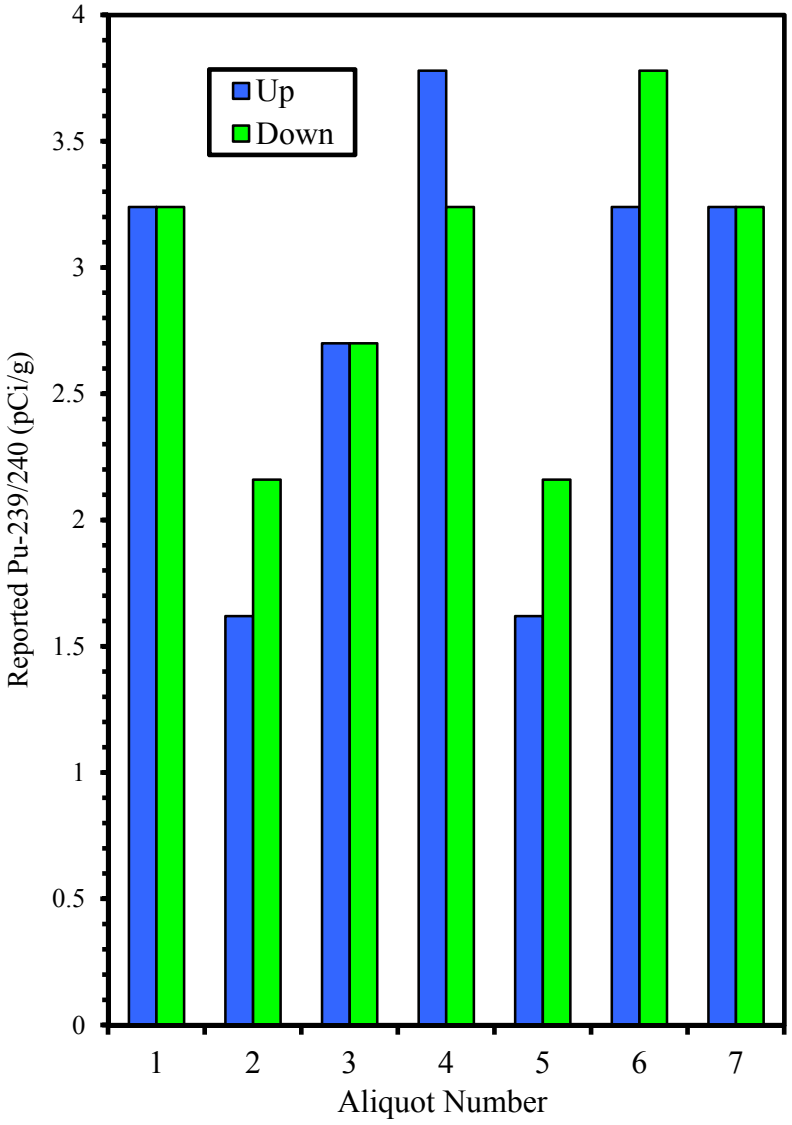
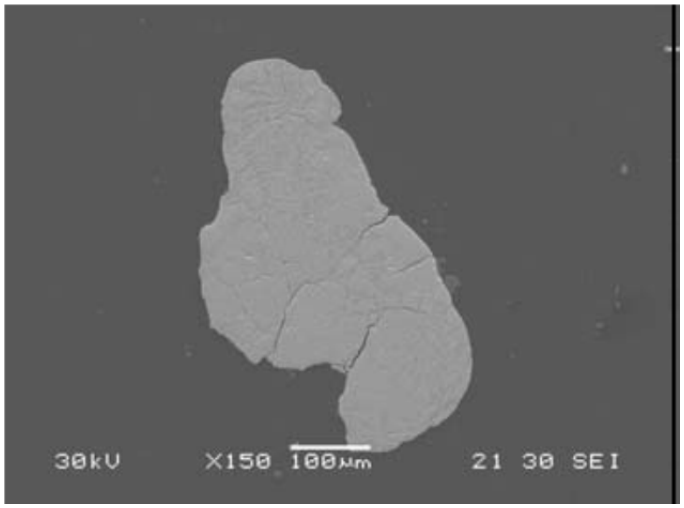
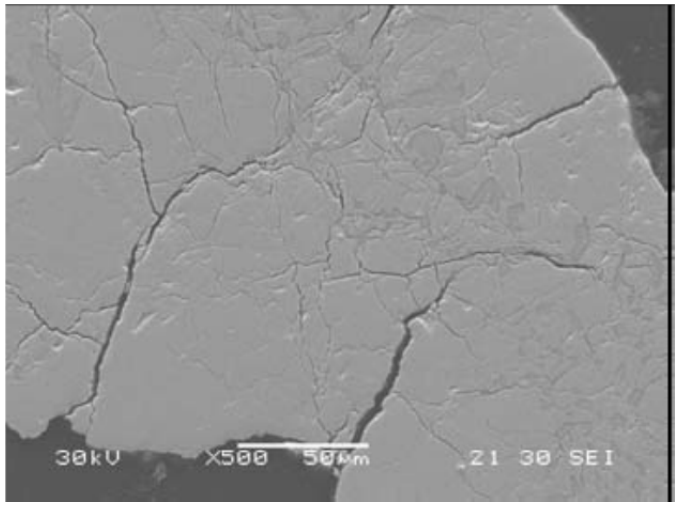


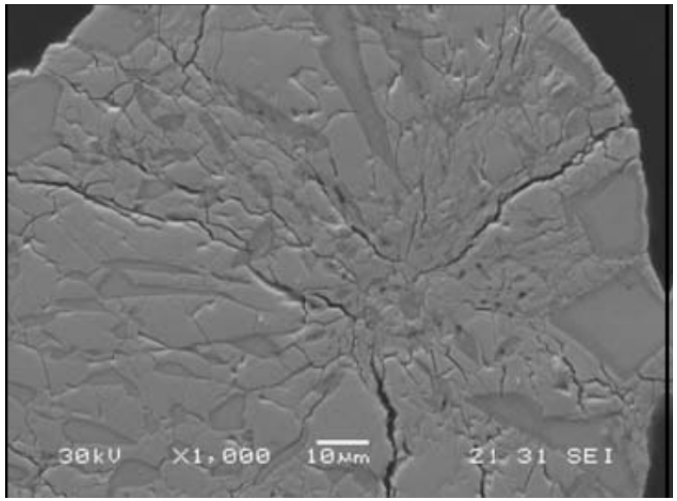
Figure C-2. Sample 686 $^{239+240}$Pu Activity Concentration for Individual Aliquots, from Rademacher (2001).



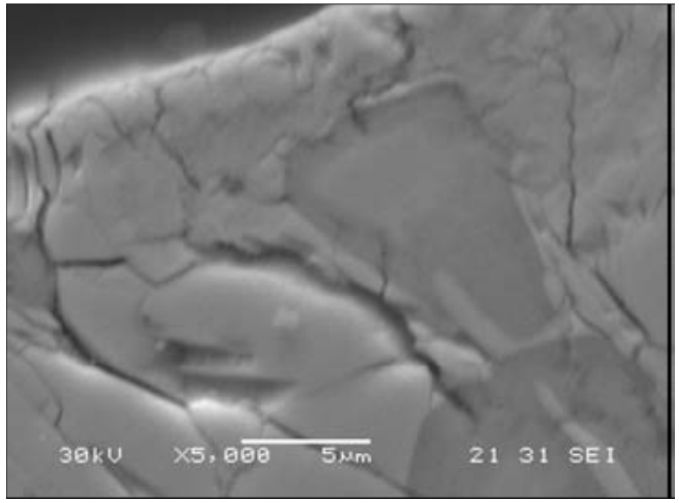
a. SEI x150



b. SEI x50



c. SEI x1000



d. SEI x5000

Figure C-3. Secondary Electron Imaging (SEI) Analysis of 0.8 µCi $^{239+240}$Pu Particle Evaluated by Radiochemistry Research Group, Harry Reid Center and Department of Chemistry, University of Nevada, Las Vegas, NV [Figure 13, Appendix E, (Cabrera 2006c)].

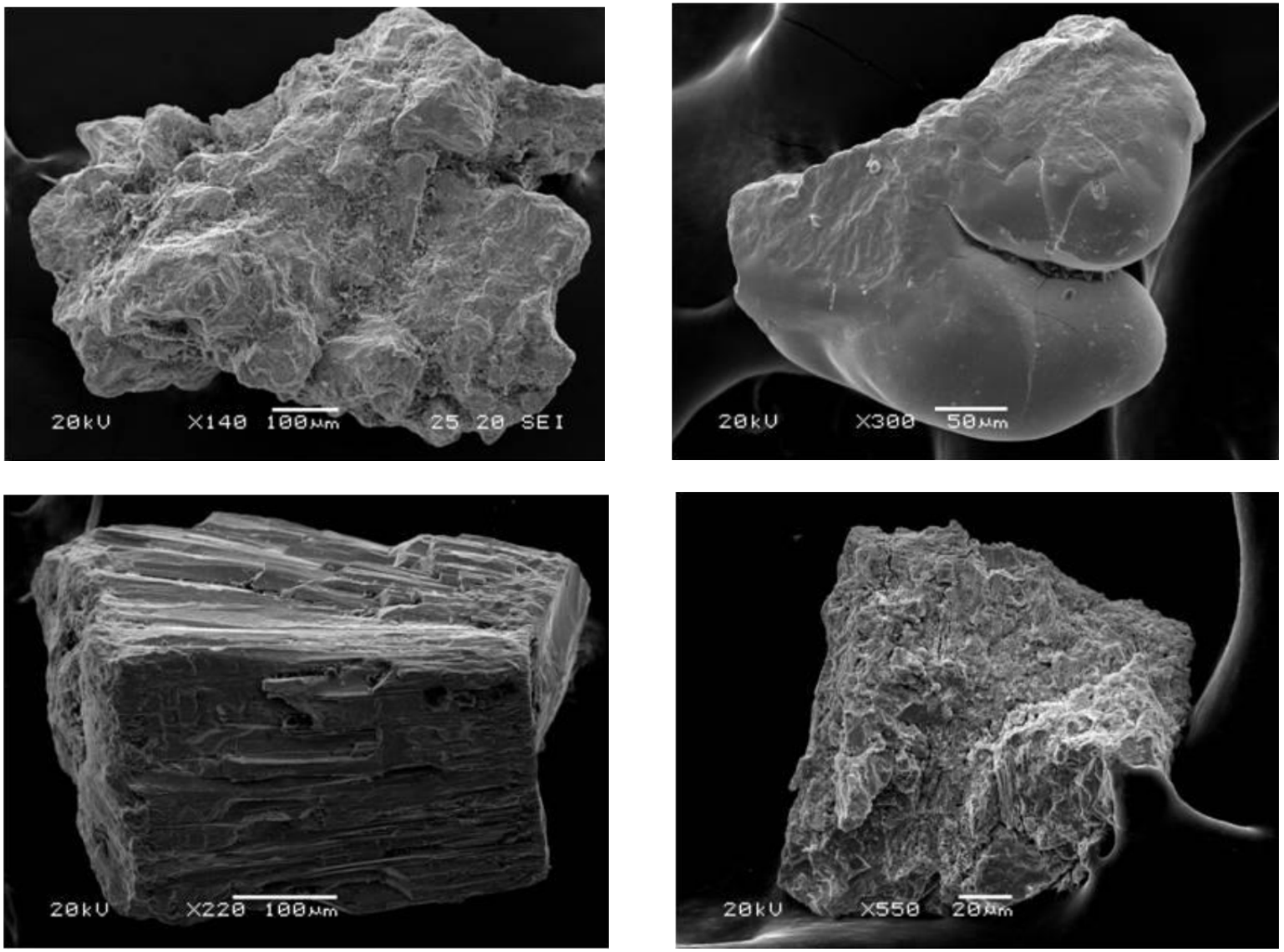


Figure C-4. Additional SEI Images of Discrete Particles Evaluated by Radiochemistry Research Group, Harry Reid Center and Department of Chemistry, University of Nevada, Las Vegas, NV (Gostic 2010), with permission.

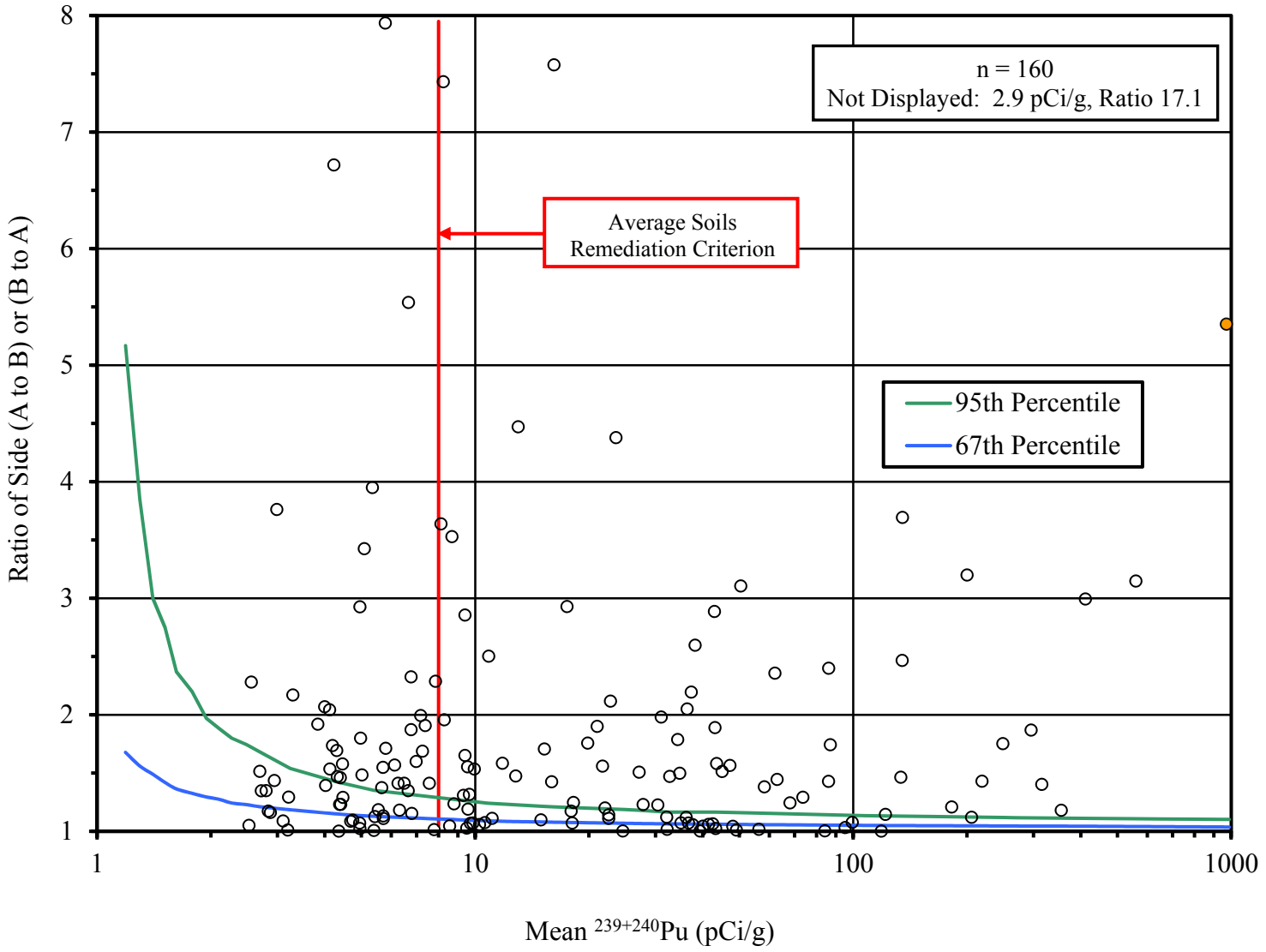


Figure C-5. Ratios of Activity Concentration for Conjugate Assessment of Select Final Status and Biased Soil Samples (Rademacher 2010).

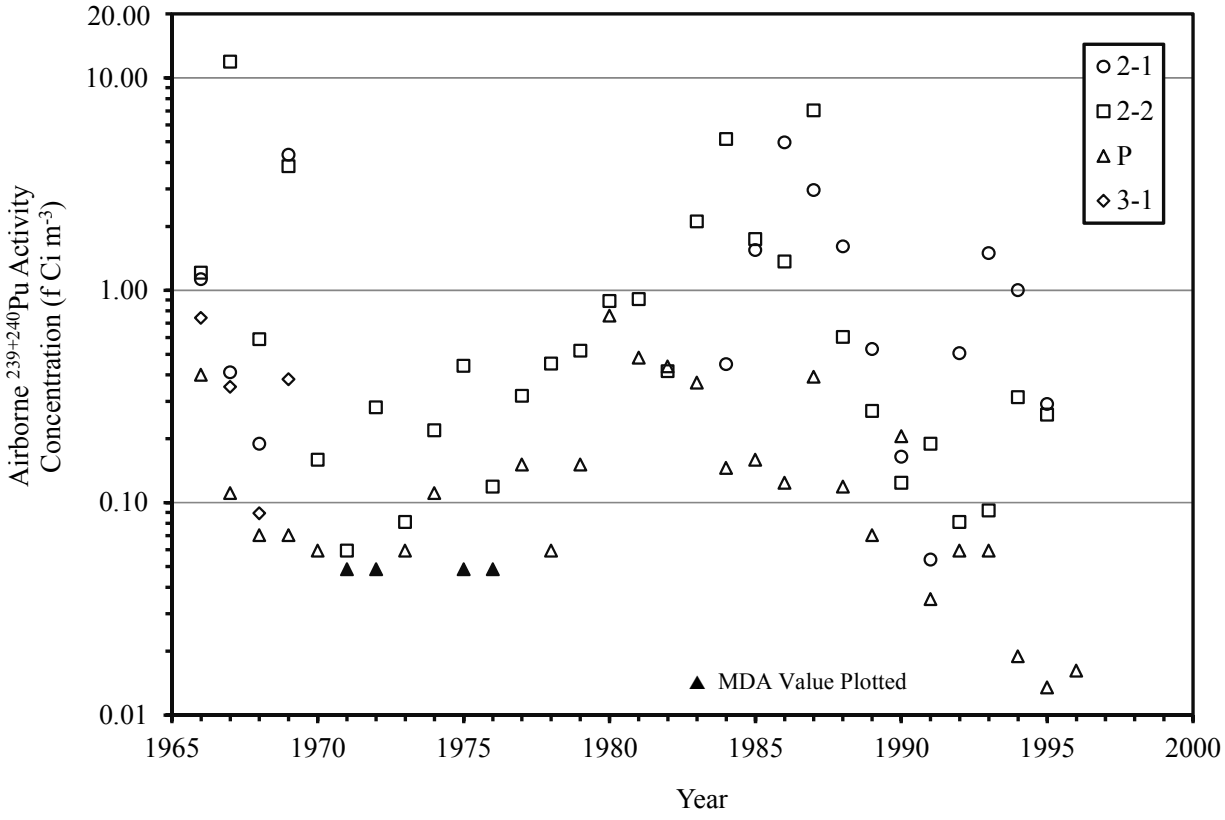


Figure C-6. Average Annual Airborne $^{239+240}$Pu Activity Concentration at Four Monitoring Locations in Palomares, Spain, Data from Iranzo et al. (1998).

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Appendix D

Exposure Standards

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TABLE D-1. Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water for Continuous Exposure, Excerpts from TABLE 3, Subsection A, Common Isotopes that are Alpha Emitters, NBS Handbook 52 (NBS 1953).

Element	Organ (g)	Activity in Total Body (μCi)	Activity Concentration in Water (μCi ml^{-1})	Activity Concentration in Air (μCi ml^{-1})
Pu-239 (soluble)	Bone - 7,000	0.04 (2,5)	1.5×10^{-6} (5)	2×10^{-12} (5)
Pu-239 (insol)	Lungs - 1,000	0.008 (9)		2×10^{-12} (3,5)
U-nat (soluble)*	Kidneys - 300	0.2 (8)	7×10^{-5} (9)	1.7×10^{-11} (3,4)
U-nat (insol)*	Lungs - 1,000	0.009 (7)		1.7×10^{-11} (3,4)
Ra-226 + daughters (50% equilibrium)	Bone - 7,000	0.1 (1,2,3,5,6)	4×10^{-8} (3,4,9)	8×10^{-12} (5,6)
Po-210 (soluble)	Spleen - 150	0.02 (7)	3×10^{-6} (9)	2×10^{-10} (8)
Po-210 (insoluble)	Lungs - 1,000	0.007 (7)		7×10^{-11} (8)

* Based on chemical toxicity

Notes:

1. Values agreed upon by Advisory Committee on X-ray and Radium Protection (1941)
2. Values agreed on by the Subcommittee on Permissible Internal Dose of the NCRP (Feb 9 & 10, 1950)
3. Values suggested by the Chalk River, Canada, Conference (Sep 29 & 30, 1949) with US, Great Britain, and Canada
4. Values agreed upon at a meeting in Rochester, N.Y. (Sep 29, 1949) between Rochester Atomic Energy Project and members of the AEC to discuss uranium toxicity and establish interim values for permissible concentration in air of soluble and insoluble compounds of uranium
5. ICRP at the Sixth International Congress of Radiology, meeting in London during July 1950, noted: "While the Commission does not, at the moment, consider that there is sufficient information to make firm recommendations concerning maximum permissible exposures to internal radiation from radioactive isotopes, it brings to the notice of uses of radioactive isotopes values which are commonly used, at the present time, in the US, Canada, and Great Britain.
6. Values agreed upon by the American Standards Association, Subcommittee on Radium Dust, Radon Gas, and Gamma Ray Exposure (Z-37, 1950)
7. Calculated with Equation G4 of NBS Handbook 52
8. Calculated with Equation G5 of NBS Handbook 52
9. Calculated with Equation G6 of NBS Handbook 52

TABLE D-2. Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposures, Excerpts from Table 1, NBS Handbook 69 (NBS 1963). [NCRP Report 22/ICRP 2].

Radionuclide	Solubility Class	Organ of Reference (Critical Organ in Boldface)	Maximum Permissible Concentrations (MPC)				Maximum Permissible Burden in Total Body (μCi)
			40-h week (μCi cm^{-3})		168-h week (μCi cm^{-3})		
			Water	Air	Water	Air	
Pu-238	Soluble	**Bone**	**10^{-4}**	**2×10^{-12}**	**5×10^{-5}**	**7×10^{-13}**	0.04
		Liver	6×10^{-4}	8×10^{-12}	2×10^{-4}	3×10^{-12}	0.2
		Total Body	10^{-3}	10^{-11}	4×10^{-4}	5×10^{-12}	0.3
	Insoluble	**Lung**		**3×10^{-11}**		**10^{-11}**	
		GI (LLI)	**8×10^{-4}**	2×10^{-7}	**3×10^{-4}**	5×10^{-8}	
Pu-239/240	Soluble	**Bone**	**10^{-4}**	**2×10^{-12}**	**5×10^{-5}**	**6×10^{-13}**	0.04
		Liver	5×10^{-4}	7×10^{-12}	2×10^{-4}	2×10^{-12}	0.4
		Total Body	10^{-3}	10^{-11}	3×10^{-4}	5×10^{-12}	0.4
	Insoluble	**Lung**		**4×10^{-11}**		**10^{-11}**	
		GI (LLI)	**8×10^{-4}**	2×10^{-7}	**3×10^{-4}**	5×10^{-8}	
Am-241	Soluble	**Kidney**	**10^{-4}**	**6×10^{-12}**	**4×10^{-5}**	**2×10^{-12}**	0.1
		Bone	**10^{-4}**	**6×10^{-12}**	7×10^{-5}	**2×10^{-12}**	0.05
		Liver	2×10^{-4}	9×10^{-12}	7×10^{-5}	3×10^{-12}	0.4
		Total Body	4×10^{-4}	2×10^{-11}	10^{-4}	5×10^{-12}	0.3
	Insoluble	**Lung**		**10^{-10}**		**4×10^{-11}**	
		GI (LLI)	**8×10^{-4}**	10^{-7}	**2×10^{-4}**	5×10^{-8}	
U-natural	Soluble	**GI (LLI)**	**5×10^{-4}**	10^{-7}	**2×10^{-4}**	4×10^{-8}	
		Kidney	**2×10^{-3}**	**7×10^{-11}**	6×10^{-4}	**3×10^{-11}**	5×10^{-3}
		Bone	6×10^{-3}	3×10^{-10}	2×10^{-3}	10^{-10}	0.03
		Total Body	0.02	8×10^{-10}	7×10^{-3}	3×10^{-10}	0.2
	Insoluble	**Lung**		**6×10^{-11}**		**2×10^{-11}**	
		GI (LLI)	**5×10^{-4}**	8×10^{8}	**2×10^{-4}**	3×10^{-8}	

Annual Dose Limits: 30 rem (critical organs of thyroid and skin), 5 rem (critical organ of whole body or gonads), 15 rem (most organs, GI (LLI), Kidney, and Liver), bone-seeking radionuclides have additional limits based on distribution of internal deposition, the relative biological effectiveness (RBE) of the radionuclide, and a comparison of the energy released in the bone with energy release delivered by a maximum body burden of 0.1 μg Ra-226 + daughters. Annual dose limits based on 18 year old employee, due to impracticality in setting multiple MPC values.

TABLE D-3. 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, 1982), 48 (1986)].

Radionuclide	Inhalation Class	Occupational Limit (source of limit)				Effluent Concentrations	
		Oral Ingestion		Inhalation		Air (μCi cm^{-3})	Water (μCi cm^{-3})
		f_1	ALI (μCi)	ALI (μCi)	DAC(μCi cm^{-3})		
Pu-238	W	*10^{-3}	0.9 (Bone Surface)	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)	2×10^{-2} (Bone Surface)	8×10^{-12} (Bone Surface)		
		*10^{-5}	90 (CEDE)	2×10^{-2} (CEDE)		2×10^{-14}	
Pu-239/240	W	*10^{-3}	0.8 (Bone Surface)	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)	2×10^{-2} (Bone Surface)	7×10^{-12} (Bone Surface)		
		*10^{-5}	80 (CEDE)	2×10^{-2} (CEDE)		2×10^{-14}	
Am-241	W	10^{-3}	0.8 (Bone Surface)	6×10^{-3} (Bone Surface)	3×10^{-12} (Bone Surface)		
			1.0 (CEDE)	10^{-2} (CEDE)		2×10^{-14}	2×10^{-8}

* From Federal Guidance Report 11 (EPA 1988).
Annual Occupational Dose Limits: 5 rem for CEDE-based values, 50 rem committed effective dose (CDE) for bone surface
Annual Individual of the Public Dose Limits: 0.1 rem CEDE (effluent concentrations)
Inhalation Class W: all compounds except PuO_2 Inhalation Class Y: PuO_2
Small Intestine Uptake Fraction (Ingestion): Oxides - 10^{-5}, Nitrates - 10^{-4}, Others – 0.001

TABLE D-4. Dose Conversion Factors, Federal Guidance Report 11 (EPA 1988).

Radionuclide	Small Intestine Uptake Fraction, f_1	Committed Dose Equivalent (mrem μCi^{-1}) from Inhalation Exposures							
		Gonads	Breast	Lung	Red Bone Marrow	Bone Surface	Thyroid	Remainder	Effective
Pu-238	W (0.001)	1.04×10^5	3.70	6.81×10^4	5.62×10^5	7.03×10^6	3.55	2.60×10^5	3.92×10^5
	Y (10^{-5})	3.85×10^4	1.63	1.18×10^6	2.15×10^5	2.68×10^6	1.43	1.01×10^5	2.88×10^5
Pu-239/240	W (0.001)	1.18×10^5	3.52	6.40×10^4	6.25×10^5	7.81×10^6	3.35	2.80×10^5	4.29×10^5
	Y (10^{-5})	4.44×10^4	1.60	1.20×10^6	2.43×10^5	3.04×10^6	1.39	1.12×10^5	3.08×10^5
Am-241	W (0.001)	1.20×10^5	9.88	6.81×10^4	6.43×10^5	8.03×10^6	5.92	2.83×10^5	5.18×10^5

Radionuclide	Small Intestine Uptake Fraction, f_1	Committed Dose Equivalent (mrem μCi^{-1}) from Ingestion Exposures							
		Gonads	Breast	Lung	Red Bone Marrow	Bone Surface	Thyroid	Remainder	Effective
Pu-238	0.001	862	3.11×10^{-2}	3.14×10^{-2}	4.70×10^4	5.85×10^4	2.96×10^{-2}	2.22×10^3	3.20×10^3
	10^{-4}	86.2	3.11×10^{-3}	3.14×10^{-3}	4.70×10^3	5.85×10^3	2.96×10^{-3}	222	320
	10^{-5}	8.62	3.11×10^{-4}	3.14×10^{-4}	470	585	2.96×10^{-4}	22.2	32.0
Pu-239/240	0.001	977	2.85×10^{-2}	2.86×10^{-2}	5.22×10^3	6.51×10^4	2.96×10^{-2}	2.38×10^3	3.54×10^3
	10^{-4}	97.7	2.85×10^{-3}	2.86×10^{-3}	522	6.51×10^3	2.96×10^{-3}	238	354
	10^{-5}	9.77	2.85×10^{-4}	2.86×10^{-4}	52.2	651	2.96×10^{-4}	23.8	35.4
Am-241	0.001	999	9.69×10^{-2}	0.124	5.37×10^3	6.70×10^4	4.88×10^{-2}	2.46×10^3	3.64×10^3

Small Intestine Uptake Fraction: Oxides - 10^{-5}, Nitrates - 10^{-4}, Others – 0.001

Aerosol Distribution: based on 1 μm activity median aerodynamic diameter (AMAD)

TABLE D-5. Inhalation Dose Coefficients, ICRP Reports 68 and 71 (ICRPa 1994 and ICRP 1995).

Organ/Tissue		Committed Equivalent and Effective Doses (mrem μCi^{-1}) for 1 μm AMAD								
		Pu-238			Pu-239/240			Am-241		
		Type F	Type M	Type S	Type F	Type M	Type S	Type F	Type M	Type S
Adrenals		2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.4×10^{3}
Bladder Wall		2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.4×10^{3}
Bone Surface		1.3×10^{7}	5.2×10^{6}	5.9×10^{5}	1.5×10^{7}	5.6×10^{6}	6.7×10^{5}	1.6×10^{7}	6.3×10^{6}	7.8×10^{5}
Brain		2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.4×10^{3}
Breast		2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.4×10^{3}
GI Tract	Esophagus	2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.4×10^{3}
	St Wall	2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.4×10^{3}
	SI Wall	2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.4×10^{3}
	ULI Wall	2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.4×10^{3}
	LLI Wall	2.3×10^{4}	8.9×10^{3}	1.1×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.4×10^{3}
	Colon	2.3×10^{4}	8.9×10^{3}	1.1×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.4×10^{3}
Kidneys		5.6×10^{4}	8.9×10^{3}	1.0×10^{3}	5.9×10^{4}	2.4×10^{4}	3.0×10^{3}	8.1×10^{4}	3.2×10^{4}	4.1×10^{3}
Liver		2.8×10^{4}	1.2×10^{6}	1.3×10^{5}	3.1×10^{6}	1.2×10^{6}	1.4×10^{5}	1.0×10^{6}	3.7×10^{5}	4.8×10^{4}
Muscle		2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.2×10^{3}
Ovaries		1.7×10^{5}	6.7×10^{4}	7.8×10^{3}	1.9×10^{5}	7.4×10^{4}	8.9×10^{3}	3.2×10^{5}	2.1×10^{5}	1.5×10^{4}
Pancreas		2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	3.5×10^{4}	1.2×10^{3}
Red Bone Marrow		6.7×10^{5}	2.6×10^{5}	3.1×10^{4}	7.0×10^{5}	2.7×10^{5}	3.4×10^{4}	5.6×10^{5}	1.4×10^{5}	2.7×10^{4}
Respiratory Tract	Ex. Thor. Air	2.3×10^{4}	3.3×10^{5}	1.4×10^{5}	2.6×10^{4}	3.3×10^{4}	1.4×10^{5}	2.7×10^{4}	3.5×10^{4}	1.4×10^{5}
	Lungs	2.3×10^{4}	1.4×10^{5}	3.4×10^{5}	2.6×10^{4}	1.2×10^{5}	3.2×10^{5}	2.7×10^{4}	1.4×10^{5}	3.5×10^{5}
Skin		2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.2×10^{3}
Spleen		2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.2×10^{3}
Testes		1.8×10^{5}	7.0×10^{4}	8.1×10^{3}	2.0×10^{5}	7.8×10^{4}	9.3×10^{3}	3.1×10^{5}	1.2×10^{5}	1.5×10^{4}
Thymus		2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{-4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.0×10^{4}	1.2×10^{3}
Thyroid		2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{-4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.2×10^{3}
Uterus		2.3×10^{4}	8.9×10^{3}	1.0×10^{3}	2.6×10^{-4}	1.0×10^{4}	1.2×10^{3}	2.7×10^{4}	1.1×10^{4}	1.2×10^{3}
Remainder		2.3×10^{4}	9.3×10^{3}	1.1×10^{3}	2.6×10^{4}	1.0×10^{4}	1.3×10^{3}	2.8×10^{4}	1.1×10^{4}	1.3×10^{3}
Effective Dose		4.1×10^{5}	1.7×10^{5}	5.9×10^{4}	4.4×10^{5}	1.9×10^{5}	6.0×10^{4}	3.6×10^{5}	1.6×10^{5}	6.0×10^{4}
Effective (5 μm AMAD)		-	1.2×10^{5}	4.3×10^{4}	-	1.3×10^{5}	3.1×10^{4}	-	1.1×10^{5}	-

Table D-6. Environmental Protection Agency 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 70^{th} 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 70^{th} 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*, breathing rate of 2.3×10^4 L d^{-1}, annual intake of 8.4 pCi.
0.2 μCi 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 μg 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}.

* Choice of 0.1 μm AMAD related to expected aerosol distribution for stack release conditions (EPA 1978).

Appendix E

Radiological Data for Johnston Atoll

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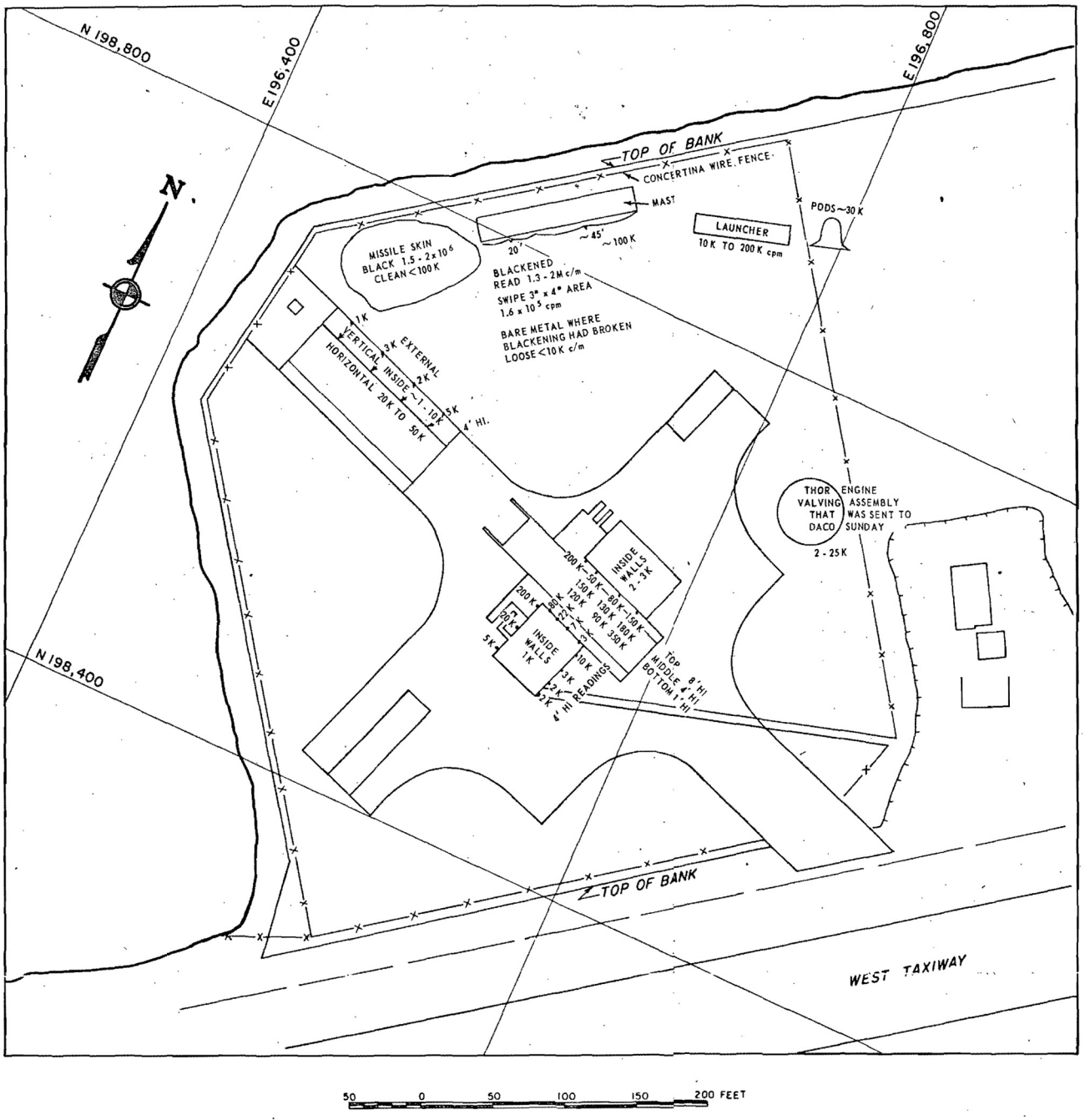
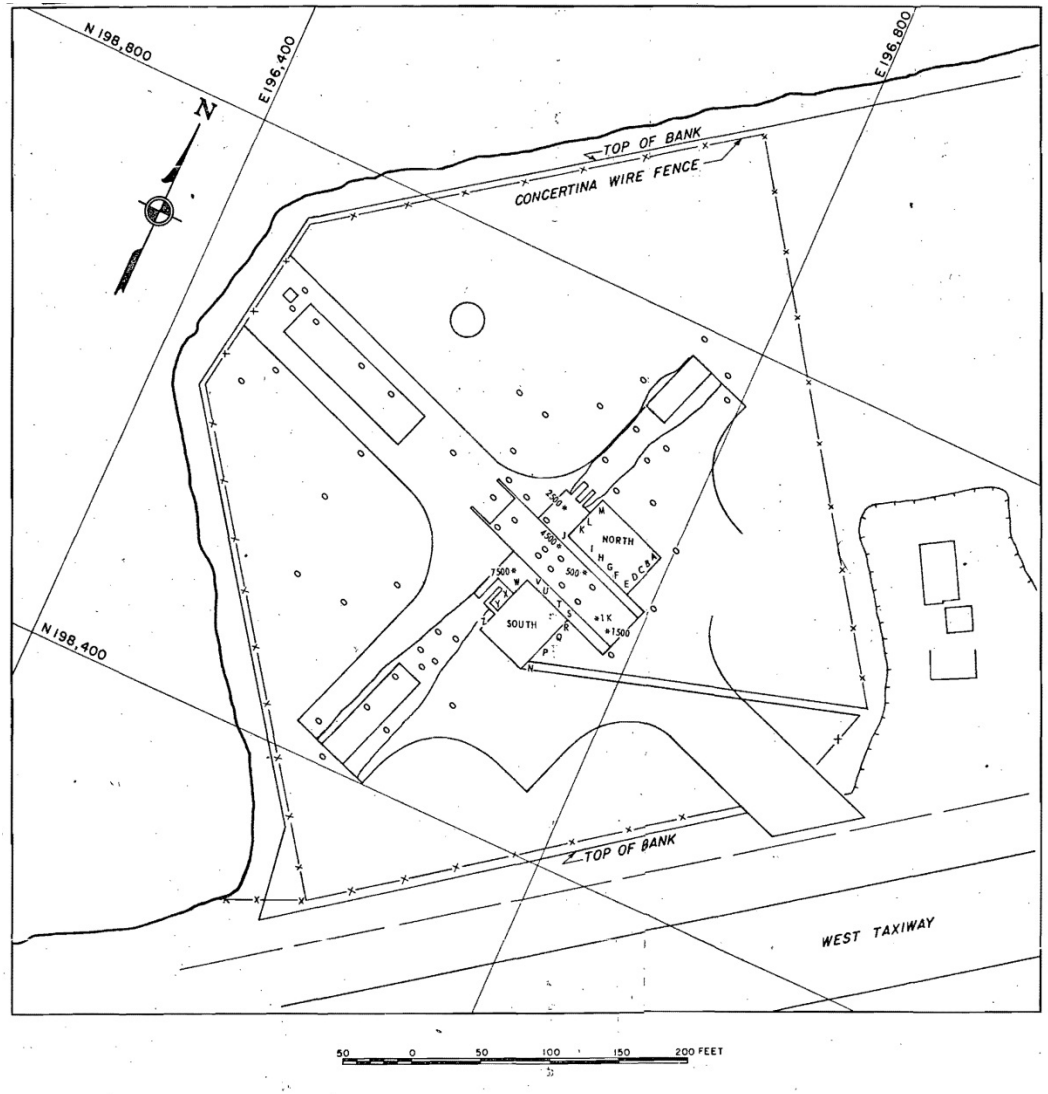


PLOT PLAN - LAUNCH PAD NO. 1

Figure E-1. Radiological Survey of LE-1, 31 July 1962, Structural Components Post Bluegill Prime Mishap, Readings in Count per Minute, Eberline PAC-1S (Holmes and Narver 1963).



NOVEMBER 23, 1962

INSTRUMENT USED: EBERLINE PAC-3G

ALL FIGURES: COUNTS PER MINUTE OF ALPHA CONTAMINATION

NORTH REVETMENT

POSITION ON MAP	BOTTOM CPM	MIDDLE CPM	TOP CPM
A	0	0	0
B	0	0	0
C	0	0	0
D	0	0	0
E	4,000	100	1,000
F	6,000	0	0
G	20,000	4,000	2,500
H	8,000	7,500	15,000
I	10,000	0	10,000
J	150	0	850
K	0	4,500	2,500
L	1,150	0	3,000
M	4,000	0	3,000

SOUTH REVETMENT

POSITION ON MAP	BOTTOM CPM	MIDDLE CPM	TOP CPM
N	0	0	0
P	0	0	0
Q	0	0	0
R	0	0	0
S	150	0	650
T	2,500	0	0
U	0	15,000	0
V	0	16,000	500
W	0	0	1,000
X	9,000	0	1,000
Y	0	0	0
Z	0	0	500

* APPROXIMATE POINT LOCATION OF READING SHOWN

O APPROXIMATE POINT LOCATION OF A ZERO (e.g. BACKGROUND) READING

NOTE: THIS FIGURE FURNISHED BY HEADQUARTERS JOINT TASK FORCE EIGHT.

PLOT PLAN - LAUNCH PAD NO. 1

Figure E-2. Radiological Survey of LE-1, 23 November 1962, Soil & Revetment Survey Post Bluegill Prime Mishap, Readings in Count per Minute, Eberline PAC-1S (Holmes and Narver 1963).

TABLE E-1. Swipe Samples Collected on LE-1 by US Public Health Service on 20 December 1962, Post Missile Launches during Operation Dominic I. (Defense Threat Reduction Information Analysis Center [DTRIAC] Archives, Kirtland AFB, NM).

Sample Number	Location of Sample Collection	Activity* (disintegration min^{-1})
1	Exterior rusted area	4
2	LH5NC tank fill valve	0
3	LH6NC tank fill valve – main line bypass valve	16
4	Liquid oxygen pressure system surge regulator dials	8
5	Dining hall, south side of complex	0
6	Exterior rusted area, southeast corner of launch pad	28
7	Exterior rusted area, northeast corner of launch pad	0
8	Interior hall of launch complex building	24
9	NP3NC pressure valve	0
10	NH-37 valve	0
11	NH-21	4
12	NH-39	0
13	NH-38	0
14	Tank vent shut-off	0
15	Storage tank vent valve	0
16	Interior wall of launch complex building, northwest corner	24
17	Exterior floor	20
18	Exterior valve	0
19	Between liquid oxygen tank and complex boundary	0
20	West corner of LE-1 pad	204

*Total Alpha Particle Activity per Smear, 100 cm^2 Area, Assumed Detection Efficiency = 0.25.

TABLE E-2. Air Sampling Data for LE-1 after Bluegill Prime Launch Failure (Holmes and Narver 1963; DTRIAC Archives, Kirtland AFB, NM).

Sample End Date	Alpha Particle Activity Concentration (pCi m^{-3})					
	Hot Area		Decontamination Tent		Launch Pad	
	AM	PM	AM	PM	AM	PM
27 Jul 62	-	-	-	-	-	-
28 Jul 62	84	-	-	-	-	-
29 Jul 62	-	-	-	-	-	-
30 Jul 62	280	-	-	-	-	-
31 Jul 62	58	-	-	-	-	-
31 Jul 62	170	160	0.2	0.1	-	-
1 Aug 62	250	220	0	0	-	-
2 Aug 62	87	1100	0.07	0.03	-	-
3 Aug 62	16	49	0.03	0.00	0.022	-
4 Aug 62	7.6	26	0.12	0.026	0.017	-
5 Aug 62	7.7	9	-	-	0.02	-
6 Aug 62	7.4	7	0.033	0.055	0.026	-
7 Aug 62	2.5	14.2	0.13	1.6	0.014	-
7 & 8 Aug 62	-	0.74	-	0.14	-	-
8 Aug 62	1.35	5.15	0.036	0.052	-	-
8 & 9 Aug 62	-	0.26	-	0.055	-	-
9 Aug 62	2.43	12.1	0.069	0.022	4.01	-
10 Aug 62	0.19	-	0.022	-	0.49	-
11 Aug 62	0.36	1.15	0.41	0.06	0.07	0.025
12 Aug 62	1.16	-	0.027	-	0.64	-
13 Aug 62	0.23	-	0.017	0.032	0.48	-
14 Aug 62	0.3		0.045		0.95	
15 Aug 62	0.34		0.014		0.33	
16 Aug 62	0.17		0.013		1.88	
17 Aug 62	0.09		0.014		0.42	
18 Aug 62	0.56		0.028		0.35	
19 Aug 62	0.82		0.022		2.32	
20 Aug 62	0.71		0.084		0.11	
21 Aug 62	Sampling Discontinued for This Area		0.030		0.62	
22 Aug 62			0.036		0.14	
23 Aug 62			0.04		0.22	
24 Aug 62			0.074		0.47	
25 Aug 62			0.044		0.032	
26 Aug 62			0.049		0.16	
27 Aug 62			0.044		0.13	
28 Aug 62			0.031		0.14	
29 Aug 62			0.015		0.054	
30 Aug 62			0.025		0.069	
2 Sep 62			Discontinued		0.12	

TABLE E-2. continued.

Sample End Date	Alpha Particle Activity Concentration on Launch Pad (pCi m^{-3})	Sample End Date	Alpha Particle Activity Concentration on Launch Pad (pCi m^{-3})	Sample End Date	Alpha Particle Activity Concentration on Launch Pad (pCi m^{-3})
6 Sep 62	0.09	28 Oct 62	0.59	10 Dec 62	0
7 Sep 62	0.08	29 Oct 62	2.30	11 Dec 62	0.04
8 Sep 62	0.03	30 Oct 62	0.52	12 Dec 62	0.02
9 Sep 62	0.05	31 Oct 62	2.40	13 Dec 62	0
10 Sep 62	0.13	1 Nov 62	0.84	14 Dec 62	0
11 Sep 62	0.2	3 Nov 62	0.22	15 Dec 62	0.03
12 Sep 62	0.25	5 Nov 62	0.06	17 Dec 62	0.01
13 Sep 62	0.17	6 Nov 62	0	18 Dec 62	0.02
14 Sep 62	0.22	7 Nov 62	0.019	19 Dec 62	1.49
18 Sep 62	1.75	8 Nov 62	0.16	20 Dec 62	0.03
19 Sep 62	0.075	9 Nov 62	0.16	21 Dec 62	0.07
20 Sep 62	0.06	10 Nov 62	0.24	22 Dec 62	0.05
22 Sep 62	0.04	12 Nov 62	0.16	24 Dec 62	0.05
24 Sep 62	0.02	13 Nov 62	0.3	26 Dec 62	0.01
25 Sep 62	0.01	14 Nov 62	0.33	27 Dec 62	0.68
26 Sep 62	0.33	15 Nov 62	0.45	28 Dec 62	1.3
27 Sep 62	0.028	16 Nov 62	0.33	29 Dec 62	0.72
28 Sep 62	0.18	17 Nov 62	0.43	31 Dec 62	0.05
29 Sep 62	0.08	19 Nov 62	0.20	2 Jan 63	0.25
2 Oct 62	22.2	20 Nov 62	0.21	3 Jan 63	0.05
3 Oct 62	0.23	21 Nov 62	0.41	4 Jan 63	0.02
4 Oct 62	0.94	22 Nov 62	0	5 Jan 63	0.01
5 Oct 62	1.04	23 Nov 62	0.20	7 Jan 63	0.08
6 Oct 62	1.2	24 Nov 62	0.25	8 Jan 63	0.13
8 Oct 62	0.44	25 Nov 62	0.22	9 Jan 63	0.06
9 Oct 62	2.45	26 Nov 62	0.12	10 Jan 63	0.08
10 Oct 62	0.26	27 Nov 62	0.19	11 Jan 63	0.51
11 Oct 62	4.2	28 Nov 62	0.11	12 Jan 63	0.03
12 Oct 62	0.00	29 Nov 62	0.36	14 Jan 63	0.01
13 Oct 62	0.58	30 Nov 62	0.1	15 Jan 63	0
16 Oct 62	3.48	1 Dec 62	0.13	16 Jan 63	0.04
18 Oct 62	0.14	2 Dec 62	0.04	17 Jan 63	0.06
19 Oct 62	0.00	3 Dec 62	0.18	18 Jan 63	0
20 Oct 62	0.00	4 Dec 62	0.18	19 Jan 63	0
21 Oct 62	0.08	5 Dec 62	0.20	21 Jan 63	0
22 Oct 62	1.78	6 Dec 62	0.11	22 Jan 63	0
24 Oct 62	0.36	7 Dec 62	0	23 Jan 63	0
25 Oct 62	0.47	8 Dec 62	0.033	24 Jan 63	0

TABLE E-2. continued.

Sample End Date	Alpha Particle Activity Concentration on Launch Pad (pCi m^{-3})	Sample End Date	Alpha Particle Activity Concentration on Launch Pad (pCi m^{-3})	Sample End Date	Alpha Particle Activity Concentration on Launch Pad (pCi m^{-3})
25 Jan 63	0	23 Feb 63	0	25 Mar 63	0
26 Jan 63	0	25 Feb 63	0	26 Mar 63	0
28 Jan 63	0.01	26 Feb 63	0	27 Mar 63	0
29 Jan 63	0.00	27 Feb 63	0.016	28 Mar 63	0
30 Jan 63	0.06	28 Feb 63	0.012	29 Mar 63	0
31 Jan 63	0.01	1 Mar 63	0	30 Mar 63	0.014
1 Feb 63	0	2 Mar 63	0.037	1 Apr 63	0.0106
2 Feb 63	0	4 Mar 63	0.03	2 Apr 63	0
4 Feb 63	0	5 Mar 63	0	3 Apr 63	0.016
5 Feb 63	0	6 Mar 63	0	4 Apr 63	0.019
6 Feb 63	0	7 Mar 63	0	5 Apr 63	0
7 Feb 63	0	8 Mar 63	0	6 Apr 63	0
8 Feb 63	0	9 Mar 63	0	8 Apr 63	0
9 Feb 63	0	11 Mar 63	0	9 Apr 63	0.011
11 Feb 63	0.013	12 Mar 63	0	10 Apr 63	0.014
12 Feb 63	0	13 Mar 63	0	11 Apr 63	0.033
13 Feb 63	0	14 Mar 63	0	12 Apr 63	0.033
14 Feb 63	0	15 Mar 63	0	13 Apr 63	0
15 Feb 63	0	16 Mar 63	0	15 Apr 63	0.015
16 Feb 63	0	18 Mar 63	0	16 Apr 63	0.021
18 Feb 63	0	19 Mar 63	0	17 Apr 63	0
19 Feb 63	0	20 Mar 63	0	18 Apr 63	0
20 Feb 63	0	21 Mar 63	0	19 Apr 63	0.014
21 Feb 63	0	22 Mar 63	0.011	20 Apr 63	0.023
22 Feb 63	0	23 Mar 63	0		
	Thor launch on LE-2				
	Value reported in original document was lower than calculated for net count rate and displayed here.				

- Air samples were counted on an Eberline Model PC404 proportional chamber with a Model PC6-1 six decade scaler. Alpha particle counting efficiency was assumed at 0.25, based on calibration standard.
- The "Hot Area" air sampling station was set-up on the northwest corner of the LE-1 launch complex where contaminated debris was staged for ultimate disposal, downwind of all activities.
- The "Decontamination Tent" air sampler was on the northeast location of the LE-1 launch complex, upwind of all restoration activities.
- The "Launch Pad" air sampler was on the downwind section of the pad.

TABLE E-3. Disposal of Contaminated Materials and Equipment (Holmes and Narver 1963).

Date	Number	Description
2 Aug 62	16	Pallets, electrical cable
3 Aug 62	15	Pallets, electrical cable
	1	Trailer – air conditioned, 10-foot
	1	Flat skid (valve shed for JP-4 fuel tank)
4 Aug 62	1	Skid – valve mounting for LOX
	1	Skid – valve mounting for filtration
	1	Metal electric switch box
	1	Metal beam, 8 in x 12 ft
	8	Metal plates, 3 ft x 2 ft
	3	Metal stands, 6 ft high
	1	Metal pipe, "L", 8 in diameter
	1	Upper launch mount
	1	Fuel filter on 4 wheel cart
	1	Metal electrical cabinet, with drawers
5 Aug 62	1	Lower louver launch assembly
	1	Pipe, 8 in diameter
	1	Pallet, assorted pipe
	1	Metal trough, 5 ft x 2 ft x 1.5 in
	1	50 ft. boom for fuel loading
	1	Air conditioner
	5	Pallets, metal plates, 2 ft x 2.5 in x ½ in
	1	Fog horn
	1	Telescope instrument, Keuffel & Esser
	1	1 hp electric motor
	1	Large base mounting for launcher
6 Aug 62	Multiple	Miscellaneous Bluegill-Prime missile skin and parts
	8	Pieces LOX piping
	3	Pallets, electrical cable
	1	Lower louver launch mount
7 Aug 62	Multiple	Miscellaneous Starfish missile skin and parts
	Multiple	Miscellaneous Bluegill-Prime skin and parts
	Multiple	Miscellaneous LOX piping
	2	Pallets, cable and pipe
8 Aug 62	38	Barrels, miscellaneous small parts, debris and missile skin
	1	8 wheel trailer
	1	General trailer with generator
10 Aug 62	32	Barrels, miscellaneous missile skin and parts
	2	Pads, encased in concrete box
	3	Pod lids, encased in concrete
	1	Air-conditioner
	2	Floodlights
	5	Pallets, miscellaneous equipment

TABLE E-3. continued.

Date	Number	Description
10 Aug 62	3	Carts, portable fire-fighting with tanks
	1	Metal cabinet
	2	Metal wall shelving
	1	Box, scrapings, sealed with concrete 5 ft x 5 ft x 5 ft
	3	Stands, LOX pipe
	1	Piece pipe, LOX stainless steel, 15 ft long, flexible
21 Aug 62	1	24 ft trailer – Douglas controller, hydro pneumatic systems, trailer mounted
	1	24 ft trailer – Douglas checkout station, ballistic missile system, trailer mounted TTU-92/M
22 Aug 62	1	Pod, encase and filled with concrete
	6	55 gallon drums, miscellaneous missile skin, wiring, debris and contaminated dirt
	1	Wooden box, 4 ft x 4 ft x 4 ft, tools and tool kits
	1	Pallet, electrical cable
	2	Large aluminum lids, 4 ft diameter
	1	Pallet, painters spray hoses and nozzles
	24	Anti-aircraft searchlight unit
	3	Television camera mounts
	2	Loud speakers
	1	Copper nose cone
	1	Section stainless steel pipe connection for rocket fuel
	1	Battery charger
	2	Valves, 12 in diameter

TABLE E-4. Disposal of Contaminated Materials and Equipment, Holmes and Narver, Inc., Radiological Health Physics Department, Environmental Sample Data Form (DTRIAC Archives, Kirtland AFB, NM).

Date	Number	Description
18 Nov 62	1	Vacuum cleaner
	1	Vacuum pump
	2	T.R. electronic tubes
	1	Drum silica gel
	3	Stools, miscellaneous office equipment
	9	Drums contaminated waste
22 Jun 63	1	Water cooler
	1	Executive desk
	1	Executive chair
	2	Wood desks
	2	Straight back metal chairs
	1	Four drawer file cabinet
	1	Five drawer file cabinet
9 Mar 64	5	Nitrogen semi-trailers
	10	55-gallon drums contaminated coral paint scrapings
	1	Floor scrubber
	6	Pipe supports, metal tripod
	1	Five foot air conditioning duct pipe
	1	Cable, 20 feet
	6	Metal strips
	3	Pipe sections, stainless steel
4 Jun 64	1	Long range electrotheodolite azimuth alignment machine
	64	55 gallon barrels contaminated paint scrapings, concrete chips, worn and torn protective gear, small metal parts from shelter
	5	Pallets of concrete blocks
	2	Pallets electrical cable
	1	Flood light
	2	Telephone communications boxes
	1	Horn assembly
	12	Pieces of corrugated roofing from theodolite tower
	1	Small theodolite tower
	1	Pipe, stainless steel 26 feet long
	1	Table, metal with masonite top
	1	Refrigerator
	3	Sections of device for shelter movement
27 Jan 65	63	Drums of contaminated coral from LE-1 (1/3rd full)
23 Mar 65	55	Drums of contaminated coral, assorted metal components
23 Mar 66	4	Liquid oxygen storage tank mounts
	39	55 gallon drums
	24	Shelter panels

TABLE E-4. continued.

Date	Number	Description
6 Jun 66	3	Concrete manholes containing dismantled theodolite tower
7 Sep 66	1	Contaminated trailer
18 Jan 67	12	55 gallon drums
10 May 67	20	55 gallon drums
Jul 67	3	55 gallon drums
11 Nov 67	3	Uniforms
	1	Pair boots
Nov 68	5	55 gallon drums
Jul 70	4	55 gallon drums
23 Aug 71	3	Drums containing metal rails, concrete and paint chips
5 Jan 72	2	Drums, paint chips

TABLE E-5. Air Sampling Data for LE-1, Holmes and Narver, Inc., Radiological Health Physics Department, Environmental Sample Data Form (DTRIAC Archives, Kirtland AFB, NM).

Sampling Date(s)	Location	Volume (m^3)	Concentration (fCi m^{-3})
1 Jun 65	Between revetment & shelter	1400	< 7
2 Jun 65	Between revetment & shelter	1460	< 7
3 Jun 65	Between revetment & shelter	1420	< 7
4 Jun 65	Between revetment & shelter	1430	< 7
5 & 6 Jun 65	Between revetment & shelter	2800	< 3
7 Jun 65	Between revetment & shelter	1400	< 7
8 Jun 65	Between revetment & shelter	1400	< 7
9 Jun 65	Between revetment & shelter	1400	< 7
10 Jun 65	Between revetment & shelter	1400	< 7
11 Jun 65	Between revetment & shelter	1400	< 7
12 & 13 Jun 65	Between revetment & shelter	2800	< 3
14 Jun 65	Between revetment & shelter	1400	< 7
15 Jun 65	Between revetment & shelter	1400	< 7
16 Jun 65	Between revetment & shelter	1400	< 7
17 Jun 65	Between revetment & shelter	1400	< 7
18 Jun 65	Between revetment & shelter	1400	< 7
19 & 20 Jun 65	Between revetment & shelter	2800	< 3
21 Jun 65	Between revetment & shelter	1400	< 7
22 Jun 65	Between revetment & shelter	1400	< 7
23 Jun 65	Between revetment & shelter	1400	< 7
24 Jun 65	Between revetment & shelter	1400	< 7
25 Jun 65	Between revetment & shelter	1400	< 7
26 & 27 Jun 65	Between revetment & shelter	1400	< 7
28 Jun 65	Between revetment & shelter	1400	< 7

TABLE E-5. continued.

Sampling Date(s)	Location	Volume (m^3)	Concentration (fCi m^{-3})
29 Jun 65	Between revetment & shelter	1400	< 7
30 Jun 65	Between revetment & shelter	1400	< 7
1 Jul 65	Between revetment & shelter	1400	< 7
1 Jul 65	Downwind of sandblasting	400	< 20
1 Jul 65	North side water tank-trenching	400	< 20
1 Jul 65	South side water tank-trenching	400	< 20
1 Jul 65	West side water tank-trenching	400	< 20
2 Jul 65	Shelter area	400	< 20
2 Jul 65	Downwind of sandblasting	400	< 20
2 Jul 65	West of trenching operation	400	< 20
3 Jul 65	Downwind of sandblasting	400	< 20
3 Jul 65	Downwind of sandblasting	400	< 20
3 & 4 Jul 65	Shelter area	2800	< 3
5 Jul 65	Shelter area	1400	< 7
6 Jul 65	Shelter area	400	< 20
7 Jul 65	Shelter area	1400	< 7
7 Jul 65	North of east revetment	400	< 20
8 Jul 65	North of east revetment	400	< 20
8 Jul 65	Shelter area	1400	< 7
9 Jul 65	Shelter area	1400	< 7
9 Jul 65	North of east revetment	400	< 20
10 Jul 65	Downwind of sandblasting	400	< 20
10 & 11 Jul 65	Shelter area	2800	< 3
12 Jul 65	Shelter area	1400	< 7
12 Jul 65	Downwind of sandblasting	400	< 20
13 Jul 65	Shelter area	1400	< 7
14 Jul 65	Shelter area	1400	< 7
15 Jul 65	Shelter area	1400	< 7
18 Jul 65	Shelter area	1400	< 7
20 Jul 65	Shelter area	1220	< 4
21 Jul 65	Shelter area	1270	< 4
22 Jul 65	Shelter area	1220	< 40
23 Jul 65	Shelter area	1220	< 4
24 Jul 65	Shelter area	1220	< 4
26 Jul 65	Shelter area	1220	< 40
27 Jul 65	Shelter area	1641	< 7
28 Jul 65	Shelter area	1641	< 40
30 Jul 65	Shelter area	1641	< 40
31 Jul 65	Shelter area	1641	< 40
2 Aug 65	Shelter area	1641	< 4000
3 Aug 65	Shelter area	1641	< 4
4 Aug 65	Shelter area	1641	< 40

TABLE E-5. continued.

Sampling Date(s)	Location	Volume (m^3)	Concentration (fCi m^{-3})
5 Aug 65	Shelter area	1640	< 4
6 Aug 65	Shelter area	1640	< 4
7 Aug 65	Shelter area	1640	< 40
10 Aug 65	Shelter area	1640	< 4
	Value believed to be in error in the tens units, as high volume air sample would have had sufficient sensitivity to have a reported value at 4000 fCi m^{-3} rather than a less than value.		

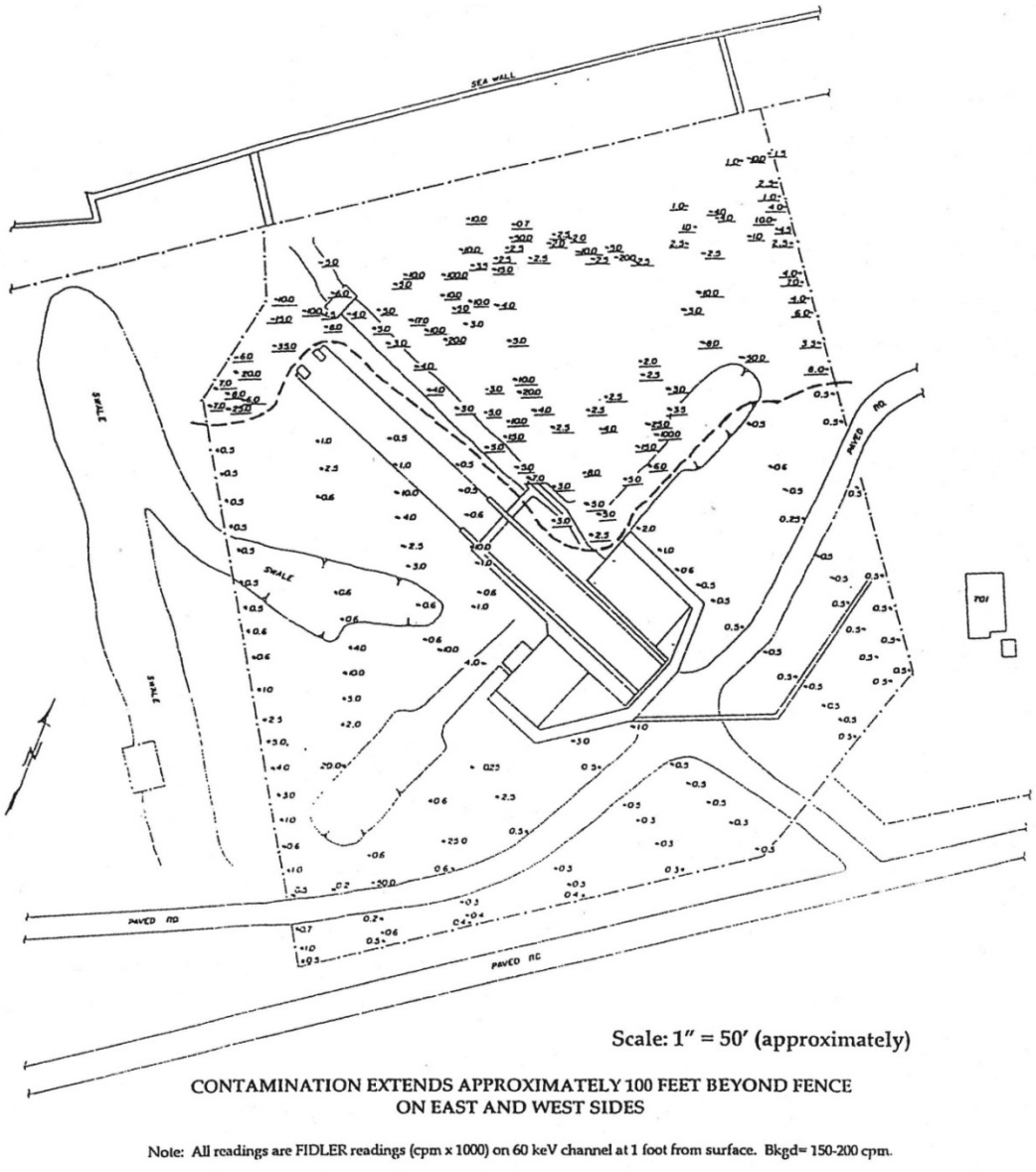


Figure E-3. AEC August 1973 Survey of LE-1 (AEC 1974).

TABLE E-6. Air Sampling Data for LE-1 (Kinsley 1974).

Date	Location	Volume (ft^3 / m^3)	α-Radiation Activity (count min^{-1})	α-Radiation Concentration in Air (fCi m^{-3})
19 Mar 74	90 ft from seaward fence	3600 / 102	0.15	< 2.2
19 Mar 74	150 ft from seaward fence	3600 / 102	0.20	< 2.2
19 Mar 74	210 ft from seaward fence	3600 / 102	0.70	< 2.2

TABLE E-7. Swipe Sampling Results for Removable α-Radiation (Kinsley 1974).

Location	Sample Number	Net α-Radiation Activity (dpm)*		
		Maximum	Minimum	Mean
LE-1 missile launch pad floor	50	27	< MDA	2.7
Dining hall interior	30	4.6	< MDA	0.3
LE-1 office building interior	10	2.7	< MDA	0.5
Dining hall roof	43	2.2	< MDA	0.2
Hospital interior and roof locations	24	0.7	< MDA	-0.04
LE-2 office building interior	10	1.2	< MDA	0.3
Sand Island mess hall	22	1.1	< MDA	0.2
Miscellaneous: library, hobby shop, laundry, weight room, sauna bath, Joint Operations Center, BX, bowling alley, NCO club, tailor shop, package store, and Bldgs 520, 521, 691A, 691C, 691E, 691F, 696B, 698A, 697, 694, 690, 418, 414, 294A, 294C, 294F, 291C-D, 293B, 293C, 293F, 294E, 290E, 291A, 291E, 697A, 205A, 206B, 201A, 18, 201A	46	2.7 (tailor shop)	< MDA	-0.54

* 100 cm^2 swipe area presumed

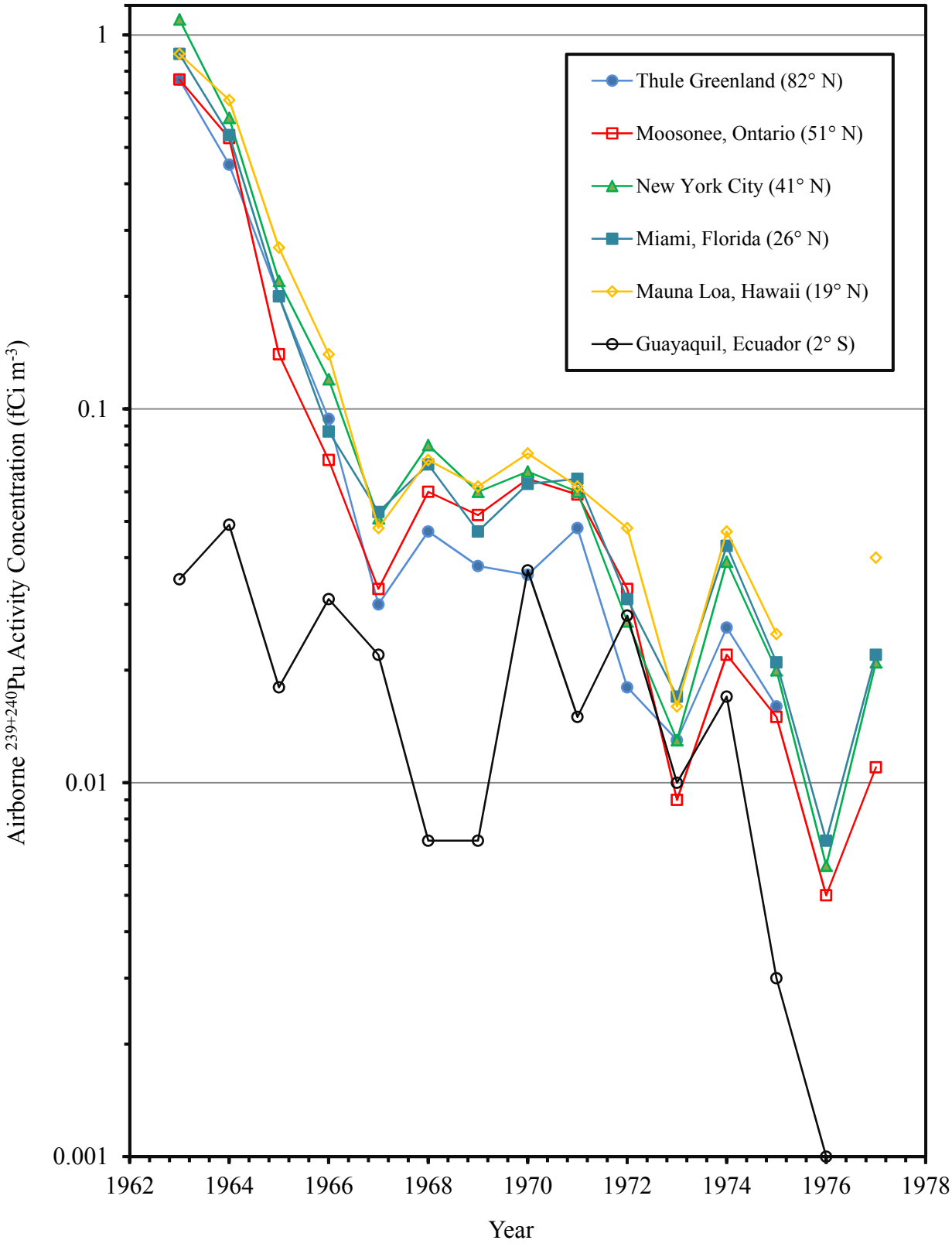


Figure E-4. Worldwide Concentrations of Plutonium (Harley 1980).

TABLE E-8. Thermal Ionization Mass Spectrometry Analysis of Johnston Island Air Samples for ^{239}Pu (Elliott 1977).

Location	Air Sampling Period	Volume (m^3)	^{239}Pu* Activity Concentration in Air ($aCi\ m^{-3}$)
Herbicide Orange Storage Area**	9 Aug – 6 Sep 76	742	< 3.48
	6 Sep – 4 Oct 76	742	< 2.84
	4 Oct – 1 Nov 76	742	< 31.84
Storage & Inspection Area	31 May – 28 Jun 76	1370	< 4.31
	6 Jun – 26 Jul 76	1370	< 4.45
	26 Jul – 30 Aug 76	1370	< 7.10
	30 Aug – 27 Sep 76	1370	< 3.40
	27 Sep – 1 Nov 76	1712	< 13.10
Dining Hall	31 May – 28 Jun 76	1370	< 4.12
	28 Jun – 26 Jul 76	1370	< 3.79
	26 Jul – 23 Aug 76	1370	< 3.52
	23 Aug – 20 Sep 76	1370	< 51.23
	20 Sep – 11 Oct 76	1027	< 6.78
	11 Oct – 1 Nov 76	1027	< 3.57
Distillation Plant	31 May – 28 Jun 76	742	< 5.48
	28 Jun – 26 Jul 76	742	< 4.23
	26 Jul – 23 Aug 76	742	< 4.39
	23 Aug – 20 Sep 76	742	< 2.64
	20 Sep – 11 Nov 76	556	< 8.79
	11 Oct – 1 Nov 76	556	< 6.57

* MDC assessment based on ^{239}Pu – for analogous $^{239+240}$Pu MDC multiple by 1.22, per ratios in Figure 5.12

** Agent Orange was stored at Johnston Island between 1972 and 1977 at the northwest portion of the Island

TABLE E-9. Results for Water Samples at Dining Hall, Analyzed by USAF Radiological Health Laboratory and Occupational and Environmental Health Laboratory (DTRIAC, Kirtland AFB, NM).

Date Sample Received	Date Completed	$^{239+240}$Pu (pCi L^{-1})	Date Sample Received	Date Completed	$^{239+240}$Pu (pCi L^{-1})
9 Feb 76	12 Feb 76	< 0.02	02 Mar 79*	21 Mar 79	< 0.02
9 Feb 76 (D)	12 Feb 76	< 0.02	02 Mar 79*	21 Mar 79	< 0.03
8 Mar 76	13 Mar 76	< 0.04	02 Mar 79*	21 Mar 79	< 0.02
6 Apr 76	14 Apr 76	< 0.03	14 Jun 79	10 Aug 79	< 0.02
19 Apr 76	27 Apr 76	< 0.02	17 Oct 79	24 Jan 80	< 0.01
17 Jun 76	7 Jul 76	< 0.03	22 Oct 80	04 Nov 80	< 0.02
22 Jun 76	14 Jul 76	< 0.02	11 Feb 80	29 Feb 80	< 0.03
23 Jul 76	5 Aug 76	< 0.1	22 Apr 80	22 May 80	< 0.03
25 Aug 76	1 Sep 76	< 0.02	08 Jul 80	24 Jul 80	< 0.04
20 Sep 76	28 Sep 76	< 0.02	22 Jan 81	11 Feb 81	< 0.01
23 Oct 76	1 Nov 76	< 0.02	8 Apr 81	16 Apr 81	< 0.02
15 Nov 76	24 Nov 76	< 0.02	28 Jul 81	12 Aug 81	< 0.01
20 Jan 77	1 Feb 77	< 0.03	15 Oct 81	16 Nov 81	< 0.01
26 Jan 77	21 Feb 77	< 0.03	15 Oct 81 (D)	16 Nov 81	< 0.01
26 Jan 77 (D)	2 Feb 77	< 0.03	25 Jan 82	2 Feb 82	< 0.05
17 Feb 77	1 Mar 77	< 0.03	12 Apr 82	24 May 82	< 0.02
17 Feb 77 (D)	24 Feb 77	< 0.03	25 Jul 82	20 Aug 82	< 0.01
17 Mar 77	6 Apr 77	< 0.03	15 Oct 82	12 Nov 82	< 0.01
17 Mar 77 (D)	6 Apr 77	< 0.03	18 Jan 83	10 Mar 83	0.03 $\pm$ 0.02
11 Apr 77	19 Apr 77	< 0.04	20 Apr 83	20 May 83	< 0.02
11 Apr 77 (D)	19 Apr 77	< 0.04	12 Aug 83	12 Aug 83	< 0.02
16 May 77	27 May 77	< 0.03	23 Dec 83	23 Dec 83	< 0.02
16 May 77 (D)	27 May 77	< 0.03	17 Feb 84	28 Feb 84	< 0.01
13 Jun 77	27 Jun 77	< 0.03	25 Apr 84	4 May 84	< 0.02
13 Jun 77 (D)	27 Jun 77	< 0.03	17 Jul 84	26 Jul 84	< 0.01
8 Jul 77	20 Jul 77	< 0.03	17 Oct 84	28 Nov 84	0.02 $\pm$ 0.01
8 Jul 77 (D)	20 Jul 77	< 0.04	24 Jan 85	11 Feb 85	< 0.01
12 Aug 77	8 Sep 77	< 0.03	17 Apr 85	31 May 85	< 0.01
19 Sep 77	26 Sep 77	< 0.03	17 Jul 85	23 Aug 85	0.07 $\pm$ 0.03
10 Sep 77 (D)	26 Sep 77	< 0.03	21 Oct 85	5 Jan 86	0.02 $\pm$ 0.02
17 Oct 77	23 Dec 77	< 0.03	22 Jan 86	7 Mar 86	< 0.01
17 Oct 77 (D)	23 Dec 77	< 0.03	14 Apr 86	9 May 86	0.0044 $\pm$ 0.0005
23 Jan 78	15 Feb 78	< 0.03			
7 Apr 78	25 May 78	< 0.03	24 Jul 86	22 Aug 86	0.02 $\pm$ 0.02
7 Apr 78(D)	25 May 78	< 0.03	14 Nov 86	04 Mar 87	0.02 $\pm$ 0.02
8 Nov 78	09 Jan 79	< 0.02	1 Jan 87	4 Mar 87	0.03 $\pm$ 0.02
22 Jan 79	13 Feb 79	< 0.03	1 Jun 87	10 Jul 87	< 0.05
02 Mar 79*	21 Mar 79	< 0.02	* Fire-fighting water tanks		

D - duplicate

TABLE E-10. Location and Intensity of Hot-Spots (Ground Areas Outside Buildings) Removed between June 1975 and November 1978 [Holmes and Narver 1979].

Number	Date Found	Building/Apt Number	Direction from Building	FIDLER Count Rate Prior to Removal (cpm)	Minimum ^{241}Am Activity* (pCi)	Minimum $^{239+240}Pu$ Activity (pCi)
1	11 Jun 75	698D	North	500K	5.6×10^5	5.0×10^6
2	11 Jun 75	695F	North	100K	1.2×10^5	9.9×10^5
3	11 Jun 75	698B	North	50K	5.8×10^4	5.0×10^5
4	11 Jun 75	695-696	Between	50K	5.8×10^4	5.0×10^5
5	11 Jun 75	696F	North	10K	1.2×10^4	9.9×10^4
6	16 Jun 75	691B	North	30K	3.5×10^4	3.0×10^5
7	16 Jun 75	691F	South	10K	1.2×10^4	9.9×10^4
8	16 Jun 75	691F	South	95K	1.1×10^5	9.4×10^5
9	16 Jun 75	691F	South	10K	1.2×10^4	9.9×10^4
10	16 Jun 75	691D	South	90K	1.0×10^5	8.9×10^5
11	18 Jun 75	520	West	250K	2.9×10^5	2.5×10^6
12	18 Jun 75	520	South	5K	5780	5.0×10^4
13	18 Jun 75	520	South	30K	3.5×10^4	3.0×10^5
14	18 Jun 75	521	South	100K	1.2×10^5	9.9×10^5
15	18 Jun 75	521	South	> 500K	5.6×10^5	5.0×10^6
16	18 Jun 75	521	South	15K	1.7×10^4	1.5×10^5
17	18 Jun 75	520-521	Between	175K	2.0×10^5	1.7×10^6
18	19 Jun 75	521	East	5K	5780	5.0×10^4
19	25 Jun 75	521	West	30K	3.5×10^4	3.0×10^5
20	26 Jun 75	697F	South	25K	2.9×10^4	2.5×10^5
21	26 Jun 75	697B	North	7K	8090	6.9×10^4
22	26 Jun 75	697B	West	5K	5780	5.0×10^4
23	26 Jun 75	697B	North	> 500K	5.6×10^5	5.0×10^6
24	27 Jun 75	694D	North	2.5K	2890	2.5×10^4
25	27 Jun 75	694D	North	10K	1.2×10^4	9.9×10^4
26	27 Jun 75	694D	North	100K	1.2×10^5	9.9×10^5
27	27 Jun 75	694D	North	10K	1.2×10^4	9.9×10^4
28	27 Jun 75	694F	North	25K	2.9×10^4	2.5×10^5
29	27 Jun 75	694F	North	20K	2.3×10^4	2.0×10^5
30	27 Jun 75	694F	North	10K	1.2×10^4	9.9×10^4
31	1 Jul 75	694D	North	100K	1.2×10^5	9.9×10^5
32	1 Jul 75	694F	North	2.5K	2890	2.5×10^4
33	2 Jul 75	694F	South	10K	1.2×10^4	9.9×10^4
34	7 Jul 75	Nat'l Park	East	100K	1.2×10^5	9.9×10^5
35	7 Jul 75	Tennis Crt	South	200K	2.3×10^5	2.0×10^6
36	8 Jul 75	520 Park Lot	Across	60K	6.9×10^4	6.0×10^5

* Assumption particle is on surface and FIDLER detection efficiency is 0.39.

TABLE E-10. continued.

Number	Date Found	Building/Apt Number	Direction from Building	FIDLER Count Rate Prior to Removal (cpm)	Minimum ^{241}Am Activity* (pCi)	Minimum $^{239+240}$Pu Activity (pCi)
37	8 Jul 75	520 Park Lot	Across	75K	8.7×10^4	7.4×10^5
38	25 Sep 75	294B	South	50K	5.8×10^4	5.0×10^5
39	6 Oct 75	203	North	25K	2.9×10^4	2.5×10^5
40	13 Nov 75	327	South	15K	1.7×10^4	1.5×10^5
41	3 Dec 75	304	South	200K	2.3×10^5	2.0×10^6
42	4 Dec 75	370	West	100K	1.2×10^5	9.9×10^5
43	6 Apr 77	48	North	400K	4.6×10^5	3.7×10^6
44	15 Dec 77	Sand Is, W. of Gener. Bldg		75K	8.7×10^4	6.9×10^5
45	16 Feb 78	Sand Is, N. of Old Kitchen		25K	2.9×10^4	2.2×10^5
46	6 Nov 78	South of Old Taxiway Across from Motor Pool		7K	8090	6.2×10^4
47	6 Nov 78			4.5K	5200	4.0×10^4
48	6 Nov 78			3K	3470	2.6×10^4
49	6 Nov 78			3.5K	4040	3.1×10^4
50	6 Nov 78			6K	6930	5.3×10^4
51	6 Nov 78			7K	8090	6.2×10^4
52	6 Nov 78			1.5K	1730	1.3×10^4
53	6 Nov 78			7K	8090	6.2×10^4
54	6 Nov 78			1.5K	1730	1.3×10^4
55	6 Nov 78			2.5K	2890	2.2×10^4
56	6 Nov 78			2K	2310	1.8×10^4
57	6 Nov 78			6.5K	7510	5.7×10^4
58	7 Nov 78			4.5K	5200	4.0×10^4
59	7 Nov 78			5K	5780	4.4×10^4
60	7 Nov 78			5K	5780	4.4×10^4
61	7 Nov 78			4K	4620	3.5×10^4
62	7 Nov 78			5K	5780	4.4×10^4
63	7 Nov 78			6K	6930	5.3×10^4
64	7 Nov 78			7K	8090	6.2×10^4
65	7 Nov 78	Bunker 202	Southeast	5K	5780	4.4×10^4
66	8 Nov 78	South of Old Taxiway Across from Motor Pool		5K	5780	4.4×10^4
67	8 Nov 78			6K	6930	5.3×10^4
68	8 Nov 78			2.5K	2890	2.2×10^4
69	8 Nov 78			2K	2310	1.8×10^4
70	8 Nov 78			7.5K	8660	6.6×10^4
71	8 Nov 78			5K	5780	4.4×10^4
72	8 Nov 78			5K	5780	4.4×10^4
73	8 Nov 78			6K	6930	5.3×10^4
74	8 Nov 78			3K	3470	2.6×10^4

TABLE E-10. continued.

Number	Date Found	Building/Apt Number	Direction from Building	FIDLER Count Rate Prior to Removal (cpm)	Minimum ^{241}Am Activity* (pCi)	Minimum $^{239+240}Pu$ Activity (pCi)
75	8 Nov 78	South of Old Taxiway Across from Motor Pool		2K	2310	1.8×10^4
76	8 Nov 78			5K	5780	4.4×10^4
77	8 Nov 78			6K	6930	5.3×10^4
78	8 Nov 78			4.5K	5200	4.0×10^4
79	8 Nov 78			5K	5780	4.4×10^4
80	8 Nov 78			5K	5780	4.4×10^4
81	8 Nov 78			5K	5780	4.4×10^4

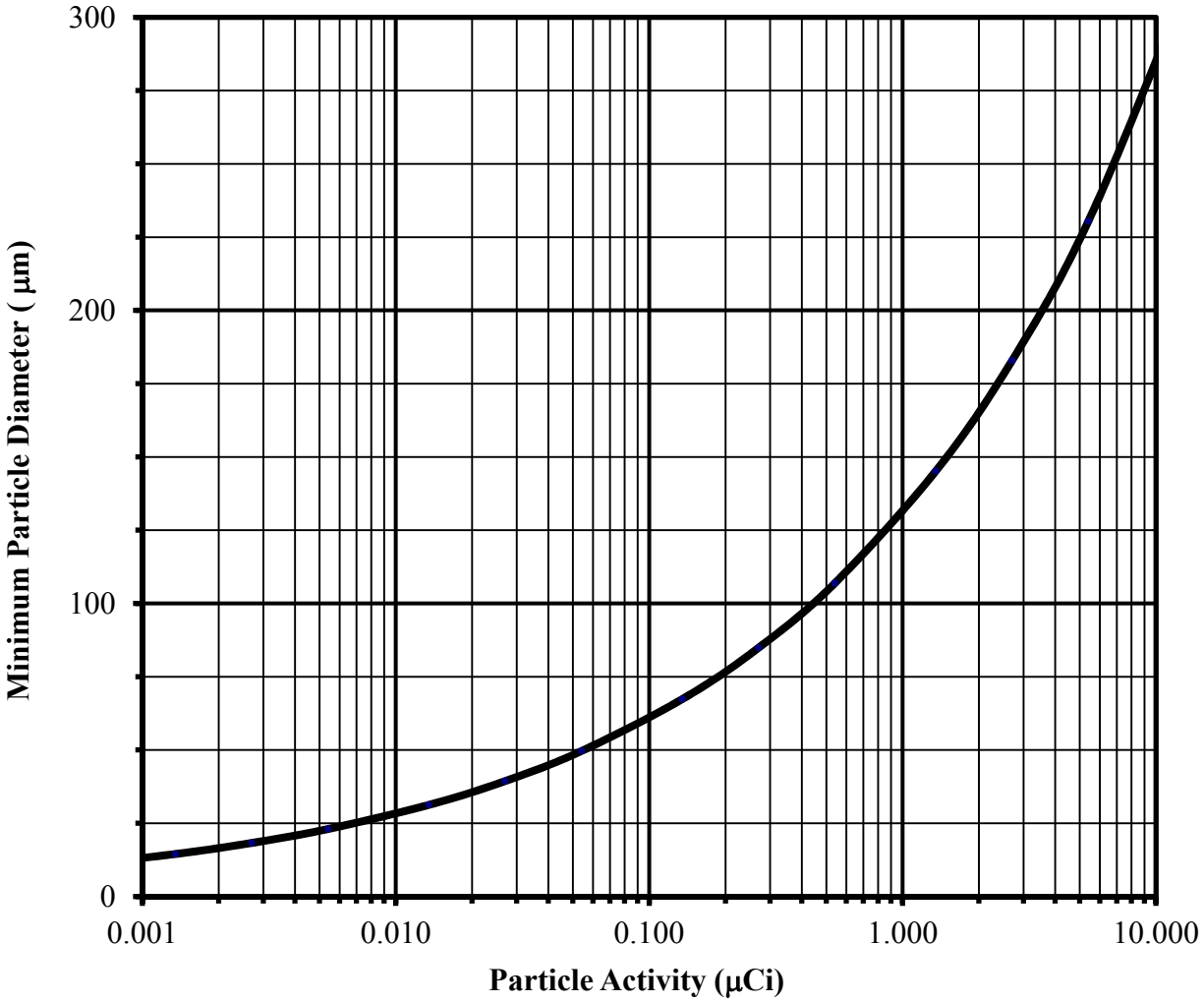


Figure E-5. Minimum $^{239+240}PuO_2$ Particle Diameter vs. Activity.

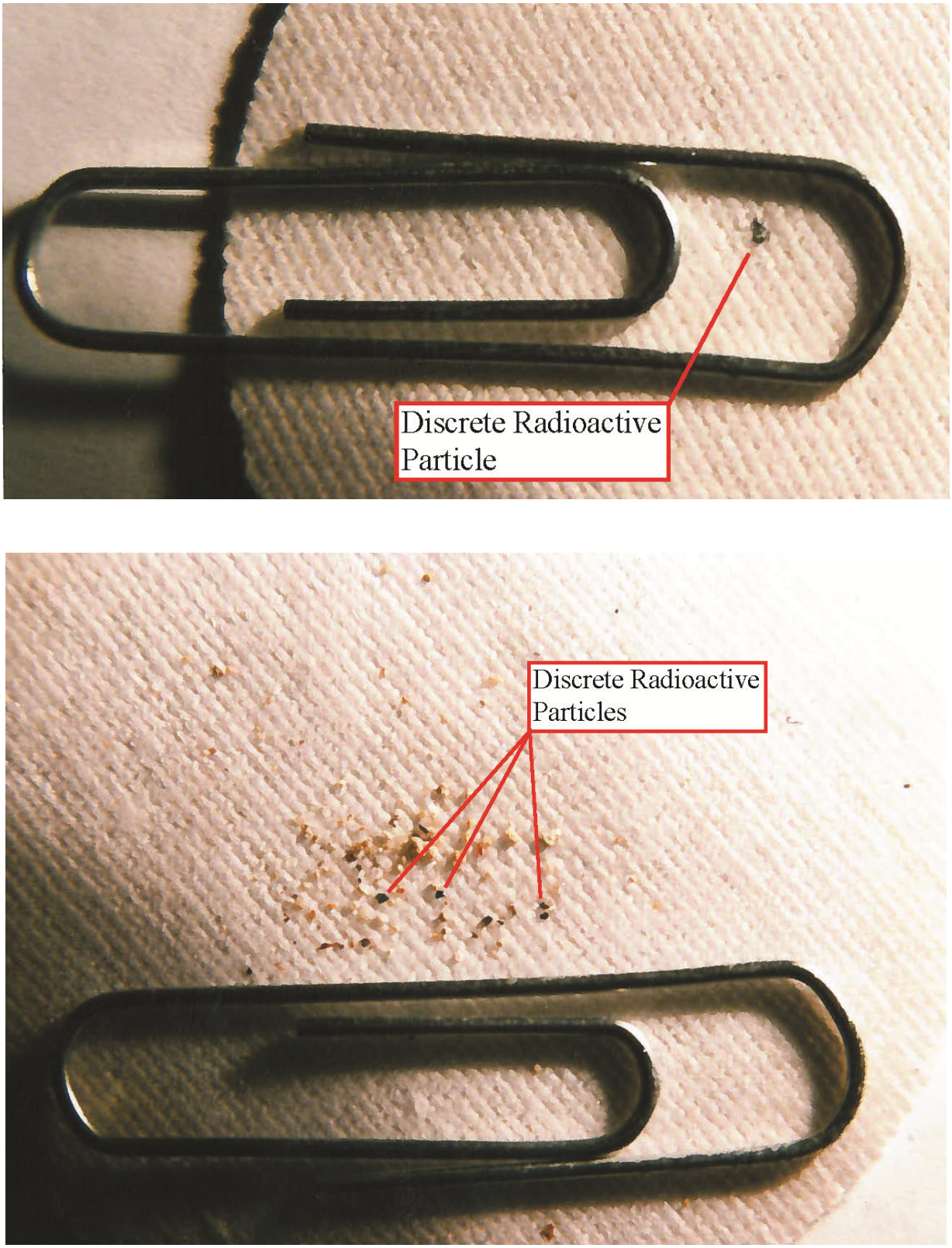


Figure E-6. Images of Discrete Radioactive Particles Visible to the Naked Eye, as Identified by FIDLER Scanning Survey in LE-1 (Rademacher 1999c).

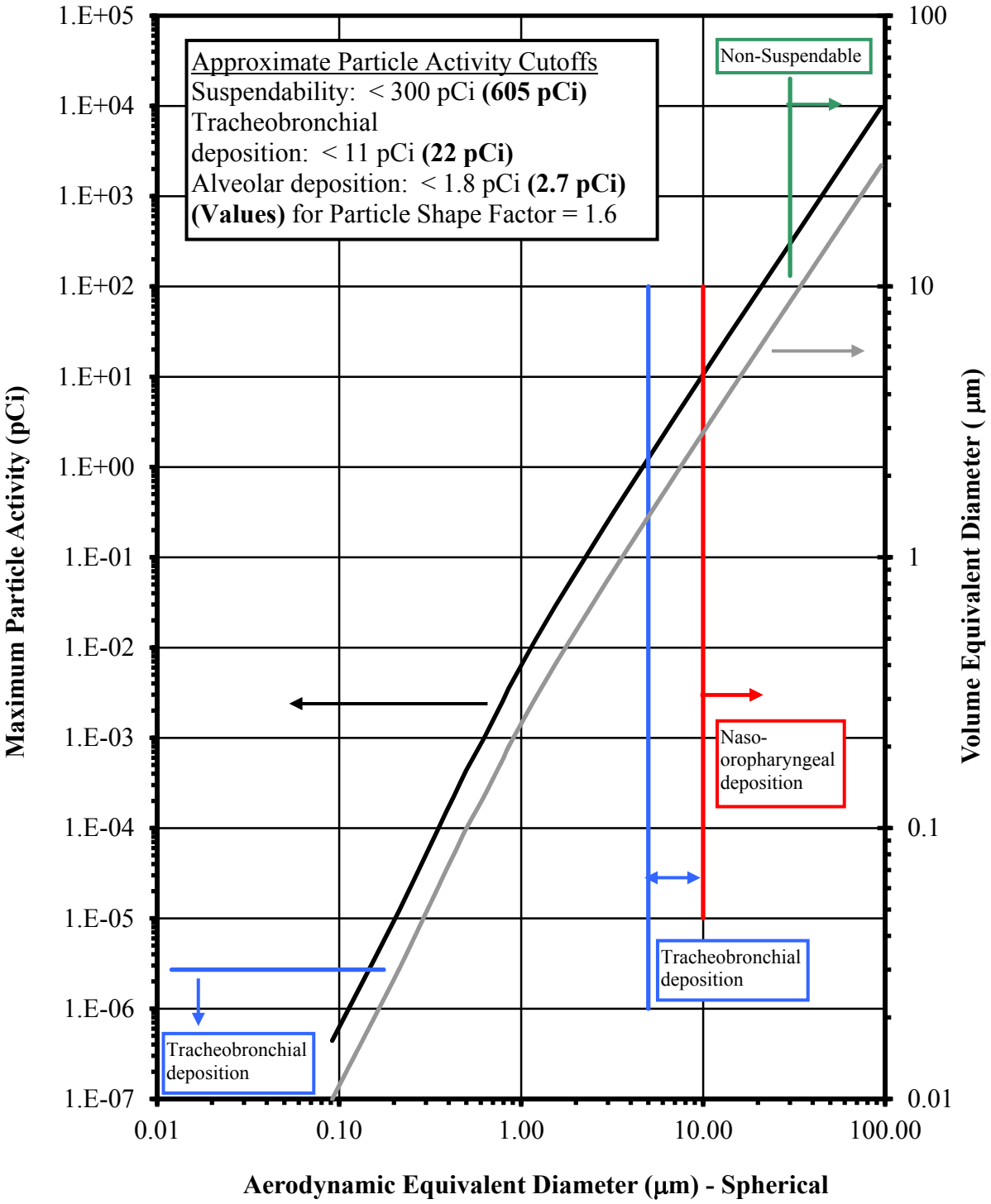


Figure E-7. Maximum Particle Activities and Volume Equivalent Diameters vs. Aerodynamic Equivalent Diameter (Spherical) $^{239+240}PuO_2$ Particles, and Respiratory Deposition Regions versus Aerodynamic Equivalent Diameter (Rademacher 2009).

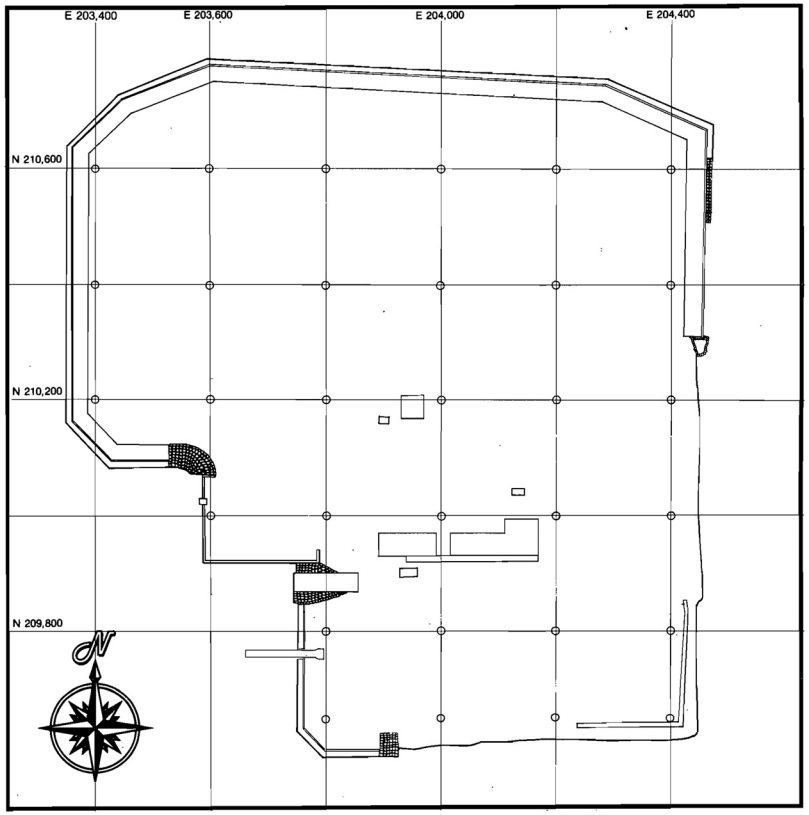


Figure E-8. EG&G In-Situ Measurement Locations on North Island (Jaffe and Tipton 1982).

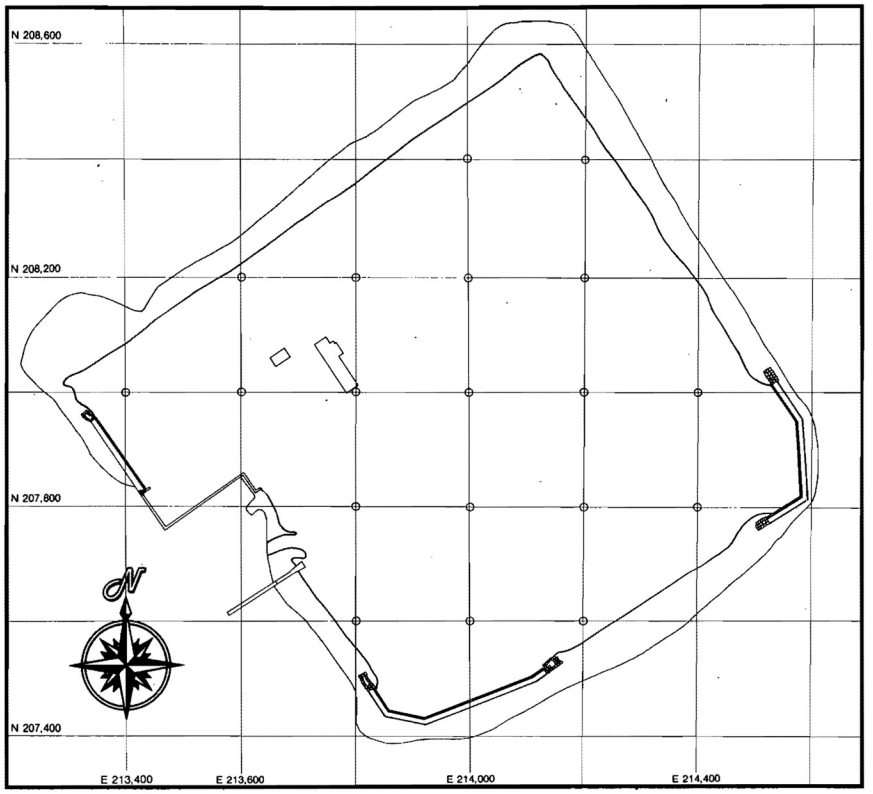


Figure E-9. EG&G In-Situ Measurement Locations on East Island (Jaffe and Tipton 1982).

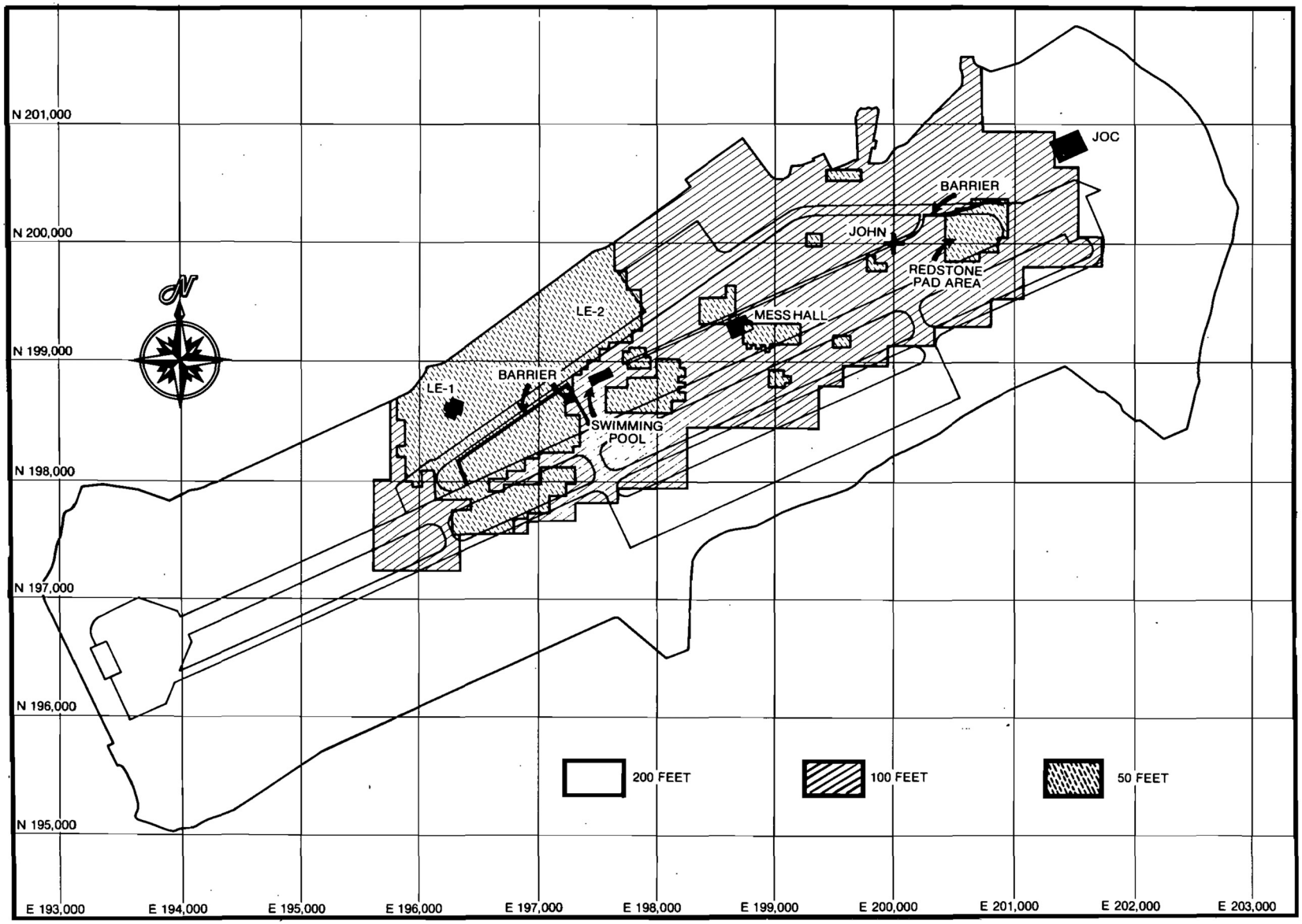


Figure E-10. Final In-Situ Measurement Grid for Johnston Island (Jaffe and Tipton 1982).

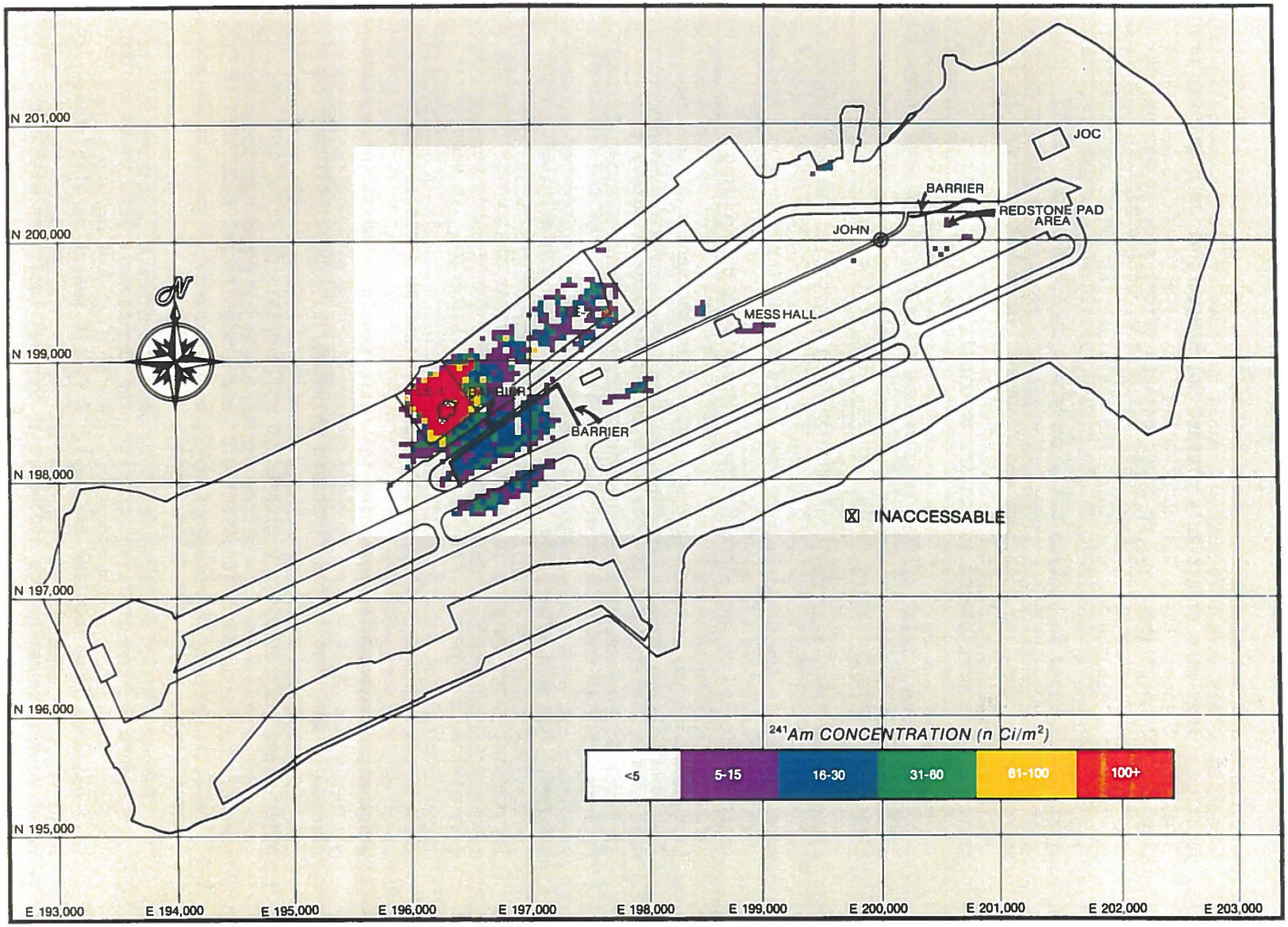


Figure E-11. Final ^{241}Am In-Situ Measurement Results for Johnston Island (Jaffe and Tipton 1982).

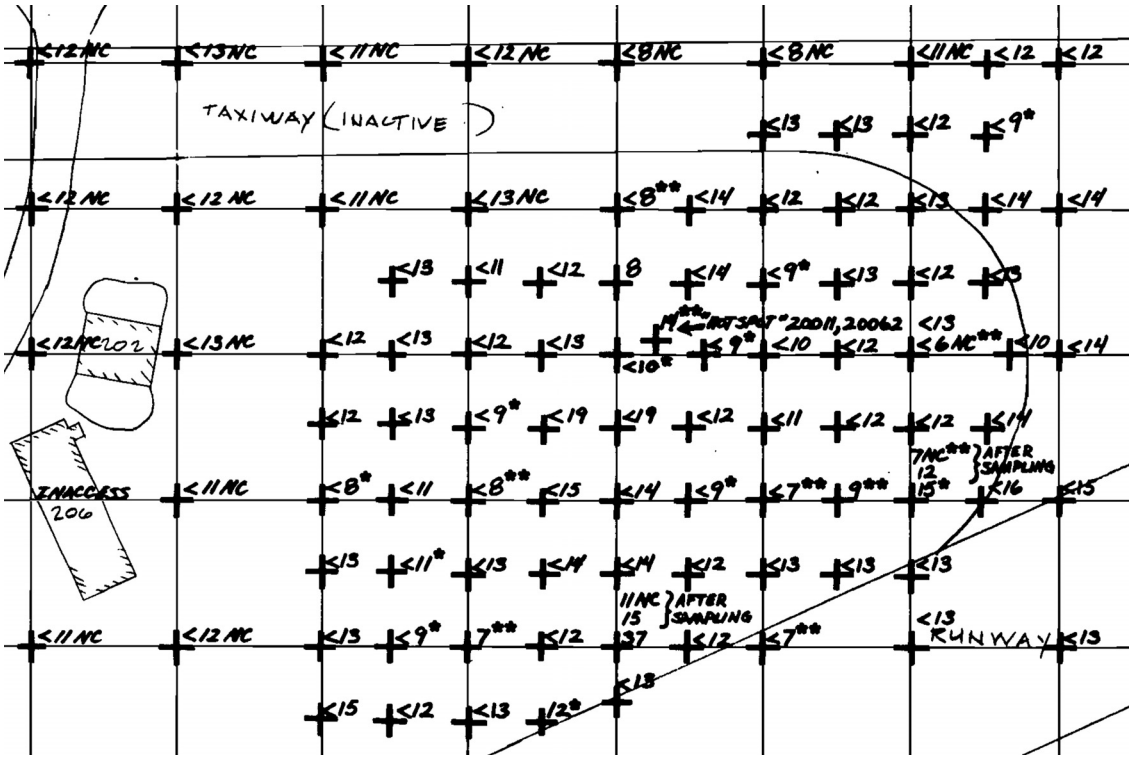


Figure E-12. Grid Map 32, Redstone Pad Vicinity (Jaffe and Tipton 1982).

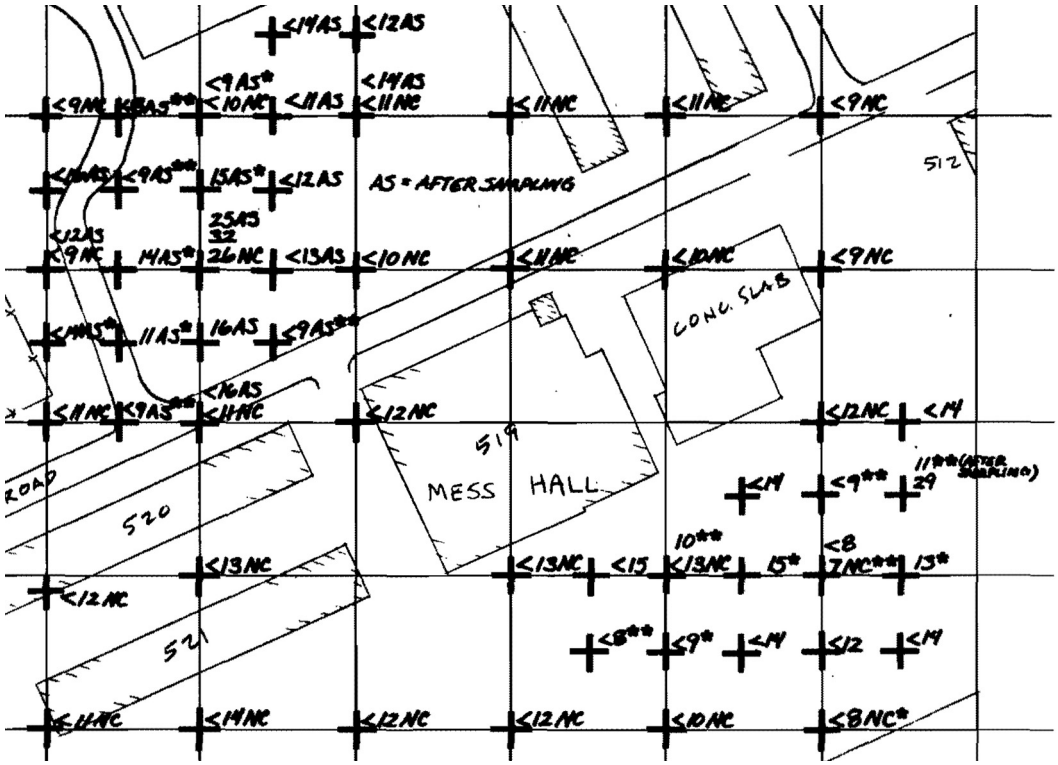


Figure E-13. Grid Map 23, Mess Hall Area (Jaffe and Tipton 1982).

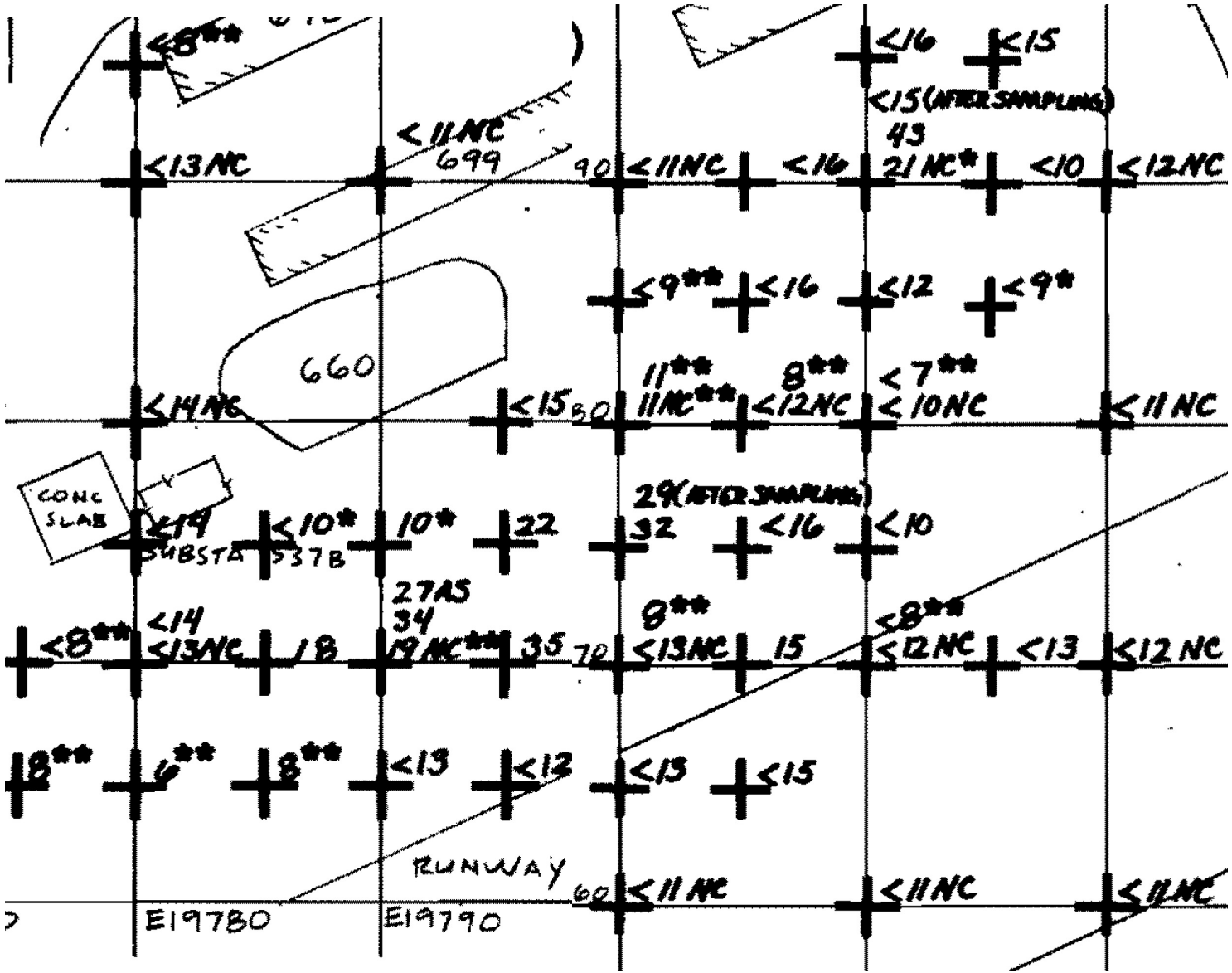


Figure E-14. Grid Maps 18 and 24, Southwest of Pool (Jaffe and Tipton 1982).

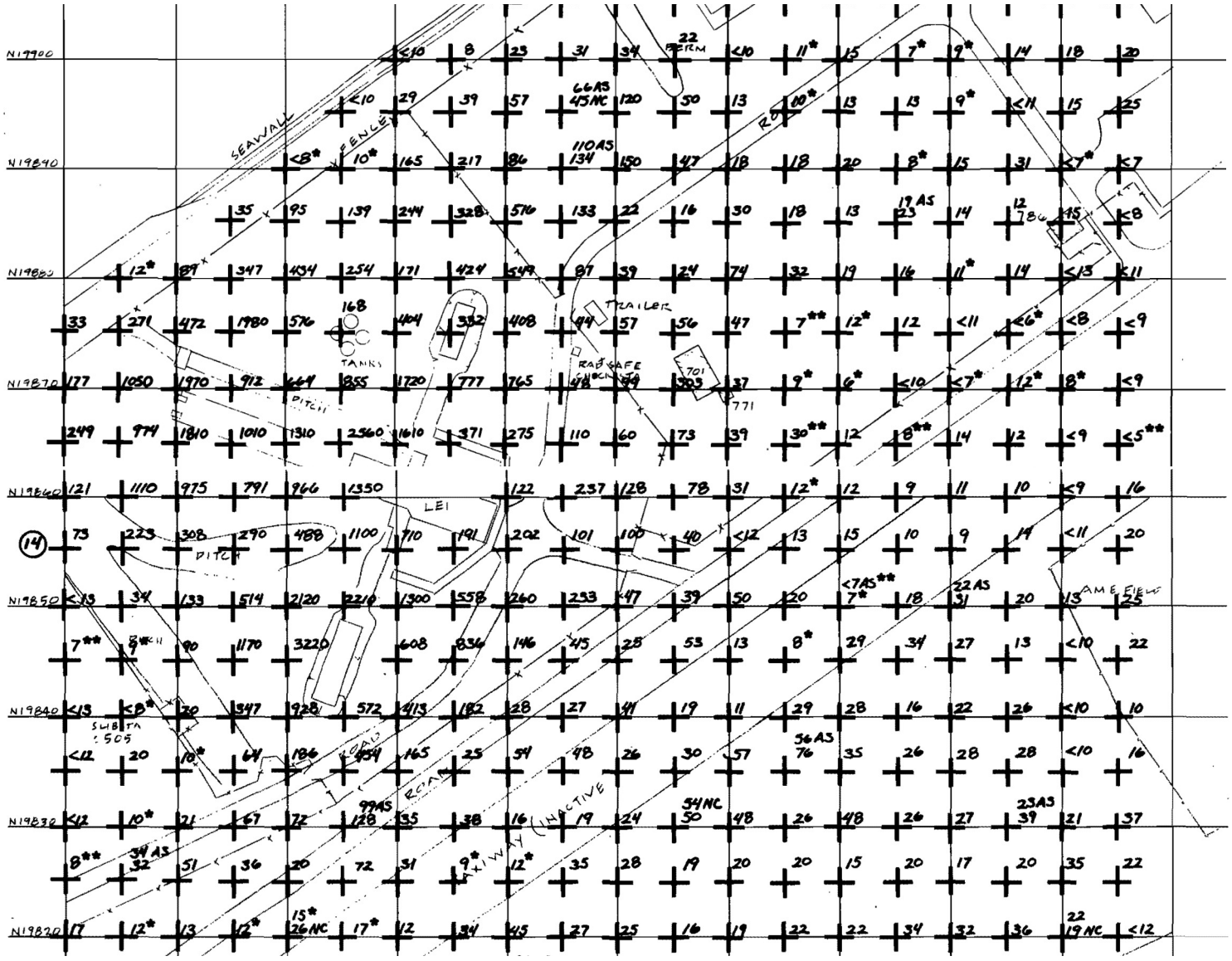


Figure E-15. Grid Maps 13 and 14, LE-1 and Area Southeast of LE-1 (Jaffe and Tipton 1982).

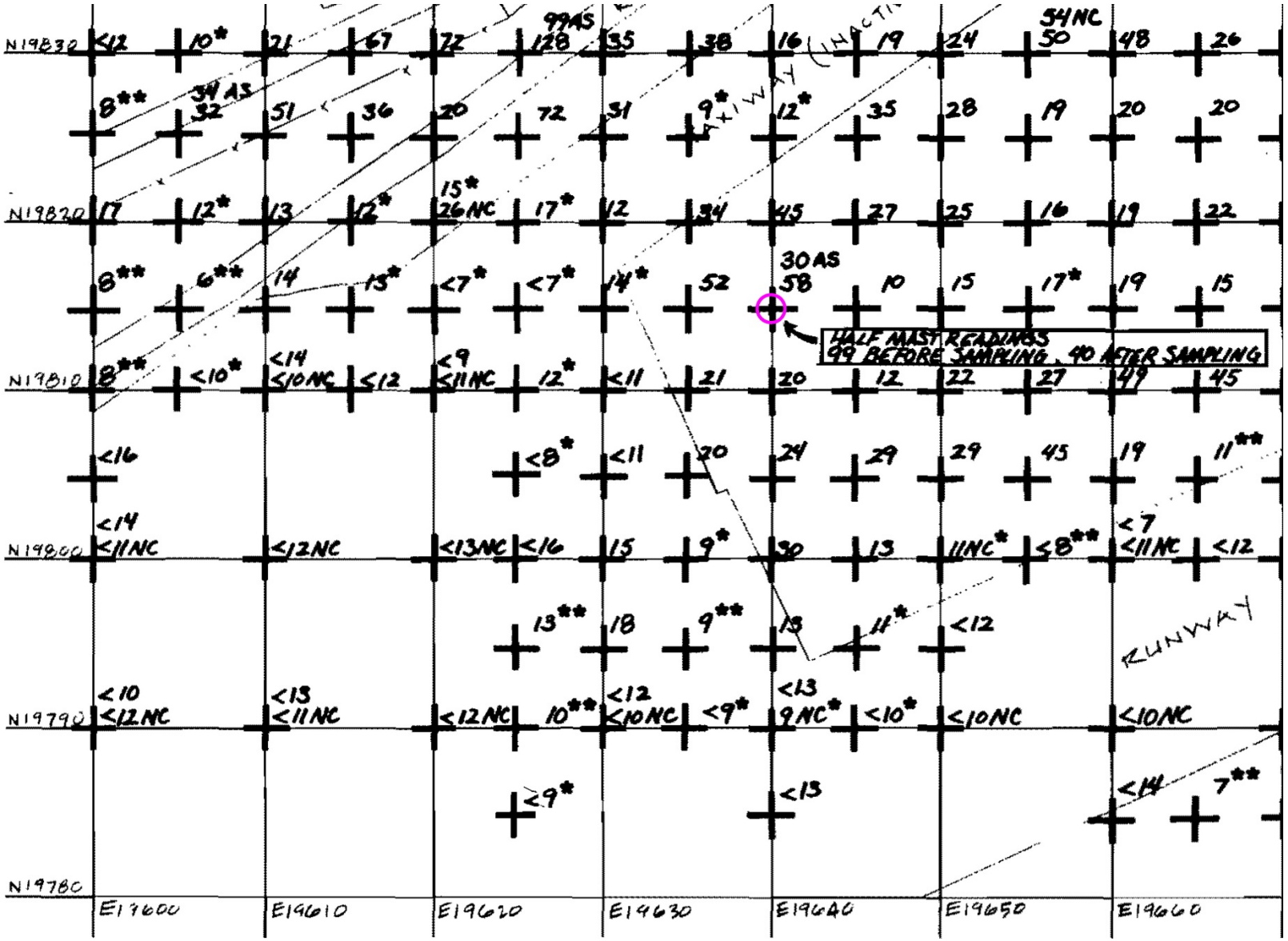


Figure E-16. Grid Map 14, Area Southeast of LE-1, Test Remediation Site (Jaffe and Tipton 1982).

TABLE E-11. Air Sampling Conducted During 1984 LE-1 Work (DTRIAC Archives).

Collection Date	Volume (m^3)	$^{239+240}Pu$ ($fCi\ m^{-3}$)	Location	OEHL Sample Number
26-Sep-84	432	3.6 ± 0.6	LE-1 + 50 m	18401136
26-Sep-84	574	0.36 ± 0.08	LE-1 + 20 m	18401124
27-Sep-84	573	7.1 ± 0.8	LE-1 + 50 m	18401125
27-Sep-84	364	0.02 ± 0.02	LE-1 + 20 m	18401128
28-Sep-84	574	4.9 ± 0.05	LE-1 + 50 m	18401129
28-Sep-84	375	0.6 ± 0.1	LE-1 + 20 m	18401127
29-Sep-84	520	23.6 ± 2.2	LE-1 + 50 m	18401130
29-Sep-84	375	2.3 ± 0.3	LE-1 + 20 m	18401123
1-Oct-84	449	28.3 ± 2.7	LE-1 + 50 m	18401131
2-Oct-84	483	5.7 ± 0.5	LE-1 + 50 m	18401132
3-Oct-84	597	4.2 ± 0.4	LE-1 + 50 m	18401133
4-Oct-84	583	4.5 ± 0.05	LE-1 + 50 m	18401134
5-Oct-84	622	2.7 ± 0.3	LE-1 + 50 m	18401135
6-Oct-84	605	0.36 ± 0.08	LE-1 + 50 m	18401136
8-Oct-84	436	340 ± 0.04	LE-1 + 50 m	18401528
9-Oct-84	433	15 ± 11	LE-1 + 50 m	18401529
10-Oct-84	400	0.36 ± 0.11	LE-1 + 50 m	18401130
11-Oct-84	448	50.5 ± 4.3	LE-1 + 50 m	18401131
12-Oct-84	414	855 ± 69	LE-1 + 50 m	18401132
13-Oct-84	505	29.7 ± 2.4	LE-1 + 50 m	18401133
15-Oct-84	510	0.6 ± 0.1	LE-1 + 50 m	18401534
16-Oct-84	549	14.1 ± 1.9	LE-1 + 50 m	18401535
17-Oct-84	604	36.3 ± 3.5	LE-1 + 50 m	18401536
18-Oct-84	721	0.18 ± 0.07	LE-1 + 50 m	18401537
19-Oct-84	757	0.8 ± 0.2	LE-1 + 50 m	18401538
20-Oct-84	285	< 0.13	LE-1 + 50 m	18401539
20-Oct-84	274	1.3 ± 0.7	LE-1 + 20 m	18401496
20-Oct-84	187	4.1 ± 1.0	Bldg 786 Pad	18401571
22-Oct-84	302	5.4 ± 1.2	LE-1 + 50 m	18401549
22-Oct-84	302	< 0.3	LE-1 + 20 m	18401497
22-Oct-84	367	0.2 ± 0.1	Bldg 786 Pad	18401572
23-Oct-84	287	0.12 ± 0.09	LE-1 + 50 m	18401541
23-Oct-84	313	0.7 ± 0.4	LE-1 + 20 m	18401498
23-Oct-84	732	< 0.04	Bldg 786 Pad	18401573
24-Oct-84	310	4.9 ± 0.7	LE-1 + 50 m	18401542
24-Oct-84	316	47.6 ± 5.9	LE-1 + 20 m	18401499
24-Oct-84	440	2.6 ± 0.2	Bldg 786 Pad	18401574
25-Oct-84	300	0.6 ± 0.2	LE-1 + 50 m	18401543
25-Oct-84	306	0.9 ± 0.05	LE-1 + 20 m	18401500
25-Oct-84	373	0.3 ± 0.2	Bldg 786 Pad	18401575
26-Oct-84	303	38.7 ± 3.8	LE-1 + 50 m	18401544

TABLE E-11, continued.

Collection Date	Volume (m^3)	$^{239+240}Pu$ ($fCi\ m^{-3}$)	Location	OEHL Sample Number
26-Oct-84	309	121 ± 19	LE-1 + 20 m	18401501
26-Oct-84	310	0.8 ± 0.4	Bldg 786 Pad	18401576
27-Oct-84	286	368 ± 31	LE-1 + 50 m	18401545
27-Oct-84	293	501 ± 81	LE-1 + 20 m	18401502
27-Oct-84	363	0.5 ± 0.2	Bldg 786 Pad	18401577
29-Oct-84	310	30.4 ± 2.6	LE-1 + 50 m	18401546
29-Oct-84	331	2.7 ± 1.0	LE-1 + 20 m	18401503
29-Oct-84	352	0.6 ± 0.2	Bldg 786 Pad	18401578
30-Oct-84	284	13.9 ± 1.5	LE-1 + 50 m	18401547
30-Oct-84	284	8.7 ± 1.5	LE-1 + 20 m	18401504
30-Oct-84	329	0.2 ± 0.1	Bldg 786 Pad	18401579
31-Oct-84	308	1.8 ± 0.4	LE-1 + 50 m	18401548
31-Oct-84	314	8.9 ± 1.9	LE-1 + 20 m	18401505
31-Oct-84	358	< 0.1	Bldg 786 Pad	18401580
1-Nov-84	302	5.4 ± 1.2	LE-1 + 50 m	18401549
1-Nov-84	330	13 ± 2	LE-1 + 20 m	18401506
1-Nov-84	294	3.4 ± 0.6	Bldg 786 Pad	18401581
2-Nov-84	309	4.3 ± 0.9	LE-1 + 50 m	18401550
2-Nov-84	335	9.5 ± 1.7	LE-1 + 20 m	18401507
2-Nov-84	372	0.26 ± 0.12	Bldg 786 Pad	18401582
3-Nov-84	294	0.9 ± 0.3	LE-1 + 50 m	18401551
3-Nov-84	306	3.4 ± 0.8	LE-1 + 20 m	18401508
3-Nov-84	328	< 0.08	Bldg 786 Pad	18401583
5-Nov-84	284	4.5 ± 0.7	LE-1 + 50 m	18401552
5-Nov-84	309	13 ± 2	LE-1 + 20 m	18401509
5-Nov-84	368	< 0.06	Bldg 786 Pad	18401584
6-Nov-84	220	3.4 ± 0.6	LE-1 + 50 m	18401553
6-Nov-84	312	0.6 ± 0.4	LE-1 + 20 m	18401510
6-Nov-84	335	0.2 ± 0.1	Bldg 786 Pad	18401585
7-Nov-84	290	3.8 ± 0.6	LE-1 + 50 m	18401554
7-Nov-84	331	5.0 ± 0.7	LE-1 + 20 m	18401511
7-Nov-84	377	0.075 ± 0.073	Bldg 786 Pad	18401586
8-Nov-84	303	4.3 ± 0.6	LE-1 + 50 m	18401555
8-Nov-84	335	969 ± 421	LE-1 + 20 m	18401512
8-Nov-84	362	< 0.08	Bldg 786 Pad	18401587
9-Nov-84	290	21 ± 2	LE-1 + 50 m	18401556
9-Nov-84	362	791 ± 643	LE-1 + 20 m	18401513
9-Nov-84	384	< 0.11	Bldg 786 Pad	18401588
10-Nov-84	296	7.4 ± 0.7	LE-1 + 50 m	18401557
10-Nov-84	333	948 ± 126	LE-1 + 20 m	18401514
10-Nov-84	367	0.38 ± 0.17	Bldg 786 Pad	18401589

TABLE E-11, continued.

Collection Date	Volume (m^3)	$^{239+240}Pu$ ($fCi\ m^{-3}$)	Location	OEHL Sample Number
12-Nov-84	296	14 ± 1	LE-1 + 50 m	18401558
12-Nov-84	283	820 ± 75	LE-1 + 20 m	18401515
12-Nov-84	384	2.3 ± 0.4	Bldg 786 Pad	18401590
13-Nov-84	398	0.7 ± 0.2	Bldg 786 Pad	18401591
13-Nov-84	251	10.3 ± 0.9	LE-1 + 50 m	18401559
13-Nov-84	235	117 ± 17	LE-1 + 20 m	18401516
14-Nov-84	359	0.5 ± 0.2	Bldg 786 Pad	18401592
14-Nov-84	244	38 ± 4	LE-1 + 50 m	18401560
14-Nov-84	278	785 ± 63	LE-1 + 20 m	18401517
15-Nov-84	442	1.1 ± 0.2	Bldg 786 Pad	18401593
15-Nov-84	317	253 ± 27	LE-1 + 50 m	18401561
15-Nov-84	315	509 ± 42	LE-1 + 20 m	18401518
16-Nov-84	374	14 ± 1	Bldg 786 Pad	18401594
16-Nov-84	274	35 ± 4	LE-1 + 50 m	18401562
16-Nov-84	266	1150 ± 93	LE-1 + 20 m	18401519
17-Nov-84	247	21 ± 3	LE-1 + 50 m	18401563
17-Nov-84	232	3910 ± 259	LE-1 + 20 m	18401520
18-Nov-84	285	0.4 ± 0.2	Bldg 786 Pad	18401595
18-Nov-84	519	7 ± 1	LE-1 + 50 m	18401564
18-Nov-84	740	50 ± 4	LE-1 + 20 m	18401521
19-Nov-84	421	124 ± 13	Bldg 786 Pad	18401596
19-Nov-84	291	44 ± 7	LE-1 + 50 m	18401565
19-Nov-84	259	472 ± 40	LE-1 + 20 m	18401152
20-Nov-84	361	32.5 ± 3.3	Bldg 786 Pad	18401597
20-Nov-84	231	165 ± 22	LE-1 + 50 m	18401566
20-Nov-84	259	610 ± 50	LE-1 + 20 m	18401523
21-Nov-84	421	19.6 ± 1.9	Bldg 786 Pad	18401598
21-Nov-84	207	2400 ± 400	LE-1 + 50 m	18401567
21-Nov-84	314	220 ± 20	LE-1 + 20 m	18401524
22-Nov-84	365	59 ± 5	Bldg 786 Pad	18401599
22-Nov-84	204	105 ± 19	LE-1 + 50 m	18401568
22-Nov-84	254	230 ± 20	LE-1 + 20 m	18401525
23-Nov-84	349	16.4 ± 0.2	Bldg 786 Pad	18401600
23-Nov-84	251	1200 ± 100	LE-1 + 50 m	18401569
23-Nov-84	278	320 ± 30	LE-1 + 20 m	18401526
24-Nov-84	342	21 ± 2	Bldg 786 Pad	18401601
24-Nov-84	273	61 ± 7	LE-1 + 50 m	18401570
24-Nov-84	280	210 ± 20	LE-1 + 20 m	18401527
26-Nov-84	324	246 ± 22	Bldg 786 Pad	18500096
26-Nov-84	263	12.3 ± 1.4	LE-1 + 50 m	18500075
26-Nov-84	284	11.9 ± 1.3	LE-1 + 20 m	18500074

TABLE E-11, continued.

Collection Date	Volume (m^3)	$^{239+240}Pu$ ($fCi\ m^{-3}$)	Location	OEHL Sample Number
27-Nov-84	364	59 ± 5	Bldg 786 Pad	18500097
27-Nov-84	252	4.3 ± 0.9	LE-1 + 50 m	18500077
27-Nov-84	245	3.8 ± 0.6	LE-1 + 20 m	18500076
28-Nov-84	317	52 ± 5	Bldg 786 Pad	18500098
28-Nov-84	193	22 ± 3	LE-1 + 50 m	18500079
28-Nov-84	214	32 ± 3	LE-1 + 20 m	18500078
29-Nov-84	210	795 ± 70	LE-1 + 50 m	18500081
29-Nov-84	237	2300 ± 200	LE-1 + 20 m	18500080
30-Nov-84	156	178 ± 16	LE-1 + 50 m	18500083
30-Nov-84	224	3000 ± 200	LE-1 + 20 m	18500082
1-Dec-84	198	546 ± 47	LE-1 + 50 m	18500085
1-Dec-84	239	183 ± 14	LE-1 + 20 m	18500084
3-Dec-84	222	11.0 ± 1.3	LE-1 + 50 m	18500087
3-Dec-84	430	120 ± 11	LE-1 + 20 m	18500086
4-Dec-84	183	20 ± 2	LE-1 + 50 m	18500089
4-Dec-84	248	45 ± 5	LE-1 + 20 m	18500088
5-Dec-84	195	172 ± 16	LE-1 + 50 m	18500091
5-Dec-84	237	126 ± 11	LE-1 + 20 m	18500090
6-Dec-84	207	58 ± 5	LE-1 + 50 m	18500093
6-Dec-84	290	123 ± 10	LE-1 + 20 m	18500092
	Air Concentration ≥ 200, < 2,000 $fCi\ m^{-3}$			
	Air Concentration ≥ 2,000 $fCi\ m^{-3}$			

TABLE E-12. Air Sampling Conducted During Contaminated Soil Relocation Work (DTRIAC Archives, Kirtland AFB, NM).

Collection Date	Volume (m^3)	$^{239+240}Pu$ ($fCi\ m^{-3}$)	Location	OEHL Sample Number
25-Feb-85	262	2.4 ± 0.4	Arnold Ave.	18500531
26-Feb-85	271	2.5 ± 0.5	Arnold Ave.	18500532
27-Feb-85	275	0.2 ± 0.1	Arnold Ave.	18500533
28-Feb-85	276	< 0.1	Arnold Ave.	18500094
21-Mar-85	241	1.3 ± 0.3	Arnold Ave.	18500534
22-Mar-85	230	0.3 ± 0.1	Arnold Ave.	18500535
3-Apr-85	430	0.2 ± 0.1	Arnold Ave.	18500536
4-Apr-85	112	< 0.2	Arnold Ave.	18500537
6-Apr-85	187	0.19 ± 0.18	Arnold Ave.	18500538
19-Aug-85	198	< 0.11	AME	18501462
20-Aug-85	320	< 0.11	AME	18501463
21-Aug-85	368	< 0.05	AME	18501464
22-Aug-85	415	< 0.04	AME	18501465
23-Aug-85	318	< 0.04	AME	18501466
24-Aug-85	380	< 0.05	AME	18501467
26-Aug-85	351	< 0.05	AME	18501468
27-Aug-85	361	0.4 ± 0.2	AME	18501469
28-Aug-85	361	0.6 ± 0.3	AME	18501470
29-Aug-85	386	2.6 ± 0.6	AME	18501471
30-Aug-85	305	5.4 ± 0.7	AME	18501472
3-Sep-85	495	0.16 ± 0.13	AME	18501473
4-Sep-85	179	< 0.5	AME	18501474
5-Sep-85	79	< 0.5	AME	18501475
6-Sep-85	174	< 0.7	AME	18501476
7-Sep-85	163	< 0.22	AME	18501477
9-Sep-85	173	0.17 ± 0.14	AME	18501478

TABLE E-12, continued.

Collection Date	Volume (m^3)	$^{239+240}Pu$ ($fCi\ m^{-3}$)	Location	OEHL Sample Number	Volume (m^3)	$^{239+240}Pu$ ($fCi\ m^{-3}$)	Location	OEHL Sample Number	Volume (m^3)	$^{239+240}Pu$ ($fCi\ m^{-3}$)	Location	OEHL Sample Number
10-Sep-85	185	0.3 ± 0.3	AME	18501479					0.6	< 30	Arnold	18501449
11-Sep-85	90	0.14 ± 0.13	AME	18501480	0.7	< 30	Grader	18501444	0.7	< 40	Arnold	18501450
12-Sep-85	87	0.8 ± 0.5	AME	18501482	0.3	< 80	Grader	18501445	0.4	< 40	Arnold	18501451
13-Sep-85	67	< 0.4	AME	18501484	0.6	< 80	Grader	18501446				
14-Sep-85	379	< 0.08	AME	18501486	0.2	< 70	Grader	18501447	0.2	< 70	Arnold	18501452
16-Sep-85	271	< 0.14	AME	18501487					0.7	< 71	Arnold	18501453
17-Sep-85	361	0.09 ± 0.09	AME	18501488					0.1	< 180	Arnold	18501454
18-Sep-85	286	0.08 ± 0.07	AME	18501489	0.8	< 20	Grader	18501448	0.6	< 40	Arnold	18501455
19-Sep-85	357	< 0.14	AME	18501490								
20-Sep-85	245	0.14 ± 0.13	AME	18501491					0.8	60 ± 50	Arnold	18501456
21-Sep-85	361	< 0.1	AME	18501492								
23-Sep-85	289	0.14 ± 0.12	AME	18501493								
25-Sep-85	121	< 0.56	AME	18501494					0.2	< 80	Arnold	18501457
26-Sep-85	286	0.26 ± 0.21	AME	18501495								
27-Sep-85	397	< 0.11	AME	18501496								
28-Sep-85	312	< 0.16	AME	18501497					0.9	< 50	Arnold	18501458
30-Sep-85	371	0.11 ± 0.09	AME	18501498					0.9	< 20	Arnold	18501459
1-Oct-85	390	< 0.11	AME	18501499	0.3	< 50	Back Hoe	18501460				
2-Oct-85	299	0.19 ± 0.11	AME	18501500								
3-Oct-85	280	0.52 ± 0.19	AME	18501501	0.8	< 30	Back Hoe	18501461				
7-Oct-85	256	0.2 ± 0.1	AME	18600125	0.8	< 50	Grader	18600165				
8-Oct-85	258	0.2 ± 0.1	AME	18600126	0.9	< 30	Grader	18600166				
9-Oct-85	212	0.2 ± 0.1	AME	18600127	0.8	< 40	Grader	18600167				
10-Oct-85	237	0.38 ± 0.14	AME	18600128	0.7	< 40	Grader	18600168				
11-Oct-85	196	0.06 ± 0.06	AME	18600129	0.9	< 60	Grader	18600169				
14-Oct-85					0.9	< 20	Grader	18600170				
15-Oct-85					0.8	< 50	Grader	18600171				

TABLE E-12, continued.

Collection Date	Volume (m^3)	$^{239+240}Pu$ (fCi m^{-3})	Location	OEHL Sample Number	Volume (m^3)	$^{239+240}Pu$ (fCi m^{-3})	Location	OEHL Sample Number	Volume (m^3)	$^{239+240}Pu$ (fCi m^{-3})	Location	OEHL Sample Number
16-Oct-85	295	0.08 ± 0.05	AME	18600130					0.9	< 30	Arnold	18600172
17-Oct-85	343	0.12 ± 0.06	AME	18600131					0.9	< 40	Arnold	18600173
18-Oct-85	329	0.12 ± 0.06	AME	18600132					0.9	< 50	Arnold	18600174
19-Oct-85	382	0.14 ± 0.07	AME	18600133					0.9	< 20	Arnold	18600175
21-Oct-85	223	0.1 ± 0.07	AME	18600134								
23-Oct-85	314	0.05 ± 0.04	AME	18600135					0.9	< 20	Arnold	18600176
24-Oct-85	266	0.07 ± 0.05	AME	18600136	0.9	< 30	Grader	18600178	0.6	< 50	Arnold	18600177
28-Oct-85									0.8	< 30	Arnold	18600179
29-Oct-85	388	0.06 ± 0.04	AME	18600137	0.9	< 60	Grader	18600181	0.9	< 40	Arnold	18600180
30-Oct-85	189	0.7 ± 0.2	AME	18600138								
31-Oct-85	217	1.5 ± 0.3	AME	18600139	0.8	< 40	Grader	18600183	0.9	< 40	Arnold	18600182
1-Nov-85	196	0.59 ± 0.17	AME	18600140								
2-Nov-85	260	0.5 ± 0.1	AME	18600141								
4-Nov-85	311	0.11 ± 0.05	AME	18600142								
7-Nov-85	361	< 0.03	AME	18600143								
11-Nov-85	218	0.5 ± 0.4	AME	18600144								
12-Nov-85	298	0.08 ± 0.06	AME	18600145								
13-Nov-85	203	< 0.08	AME	18600146								
14-Nov-85	363	0.19 ± 0.08	AME	18600147	0.6	< 60	Grader	18600184	0.9	< 40	Arnold	18600185
15-Nov-85	352	0.06 ± 0.05	AME	18600148					1.2	< 20	Arnold	18600186
17-Nov-85	344	0.11 ± 0.05	AME	18600149	0.4	< 110	Grader	18600188	1	< 20	Arnold	18600187
20-Nov-85	245	1.2 ± 0.02	AME	18600150	0.8	< 60	Grader	18600189				
21-Nov-85	202	3.7 ± 0.5	AME	18600151	0.4	< 60	Grader	18600190	0.9	< 30	Arnold	18600191
22-Nov-85	326	0.15 ± 0.07	AME	18600152					0.9	< 30	Arnold	18600192
23-Nov-85									0.4	< 70	Arnold	18600193
26-Nov-85	274	1.4 ± 0.3	AME	18600153	0.1	< 250	Grader	18600194	0.9	< 30	Arnold	18600195
27 Nov 85	301	0.5 ± 0.1	AME	18600154	0.1	< 370	Grader	18600196	0.9	< 30	Arnold	18600197

TABLE E-12, continued.

Collection Date	Volume (m^3)	$^{239+240}Pu$ ($fCi\ m^{-3}$)	Location	OEHL Sample Number	Volume (m^3)	$^{239+240}Pu$ ($fCi\ m^{-3}$)	Location	OEHL Sample Number	Volume (m^3)	$^{239+240}Pu$ ($fCi\ m^{-3}$)	Location	OEHL Sample Number
28-Nov-85									0.9	< 30	Arnold	18600198
29-Nov-85					0.9	< 40	Grader	18600199				
30-Nov-85									0.9	< 40	Arnold	18600200
1-Dec-85									0.9	< 40	Arnold	18600201
2-Dec-85									0.8	< 30	Arnold	18600202
3-Dec-85	274	15 ± 2	AME	18600155								
4-Dec-85	312	0.06 ± 0.05	AME	18600156	0.9	< 60	Grader	18600203				
5-Dec-85	388	0.04 ± 0.03	AME	18600157								
6-Dec-85	360	< 0.05	AME	18600158								
7-Dec-85	208	0.7 ± 0.2	AME	18600159								
8-Dec-85	238	0.2 ± 0.1	AME	18600160	0.8	< 50	Grader	18600204	0.9	< 50	Arnold	18600205
9-Dec-85	329	2.7 ± 0.4	AME	18600161	0.9	< 40	Grader	18600207	0.3	< 100	Arnold	18600206
10-Dec-85	311	0.8 ± 0.6	AME	18600162								
11-Dec-85	286	0.16 ± 0.07	AME	18600163	1.3	< 10	Grader	18600209	0.7	< 20	Arnold	18600208
12-Dec-85	292	5.5 ± 0.7	AME	18600164	0.9	< 20	Grader	18600210	1.1	< 10	Arnold	18600211
13-Dec-85					0.9	< 30	Grader	18600213	0.9	< 20	Arnold	18600212
14-Dec-85									0.6	< 40	Arnold	18600214
14-Oct-88	88	4.3 ± 3.3	LE-2	18900168								
15-Oct-88	61	11.0 ± 5.6	LE-2	18900169								
17-Oct-88	77	< 5.1	LE-2	18900170								

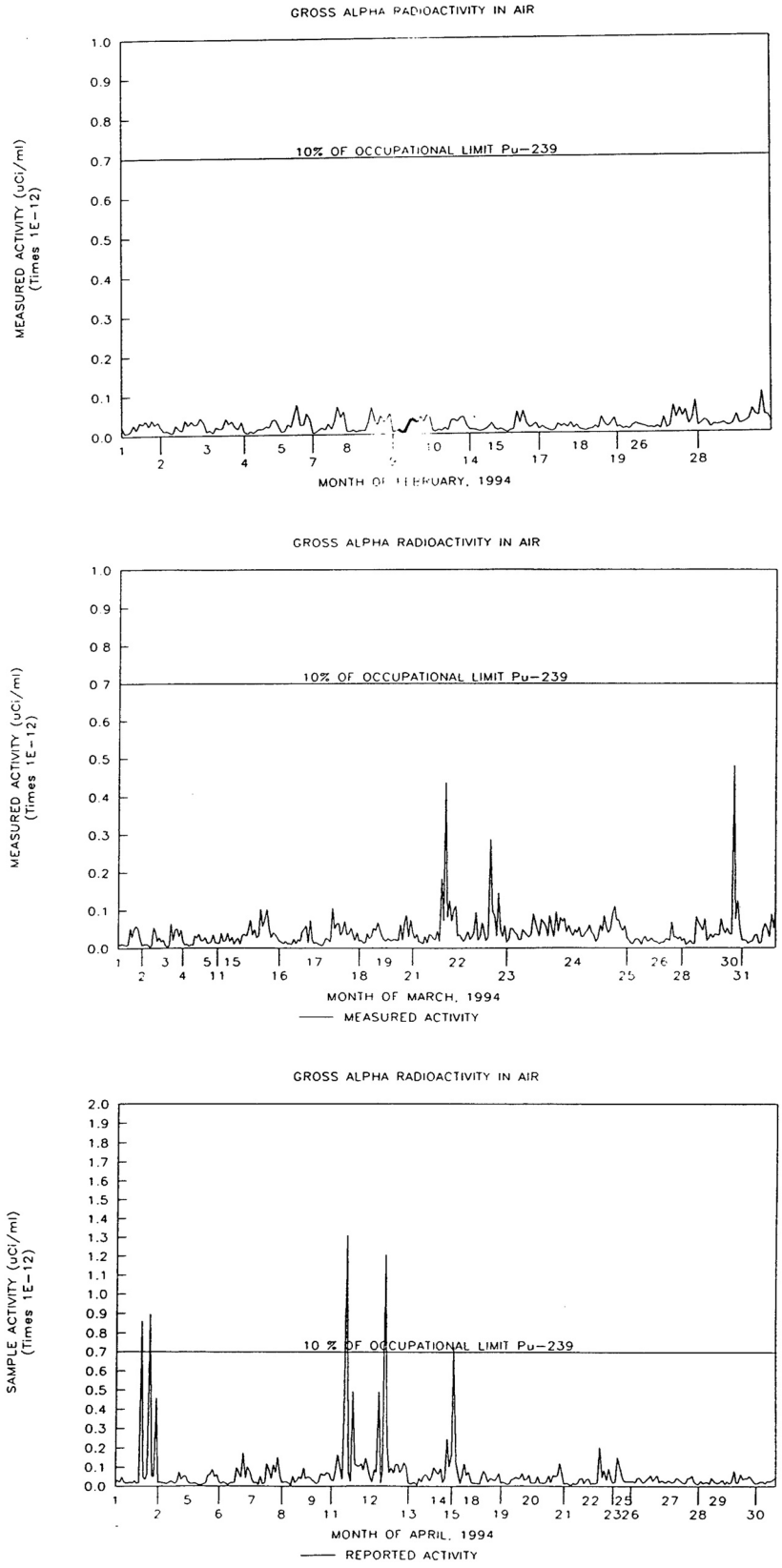


Figure E-17. Air Sampling Results for Work Areas in RCA During Soil Processing, February to April 1994, from Doane (1996).

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Appendix F

Exposure Assessment Data for Individuals Assigned to Johnston Atoll

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TABLE F-1. Respiratory Protection Factors for Solid Aerosols, 10 CFR 20, Appendix A, (NRCb 2014).

Respirator Type	Subcategory	Operating Mode	Assigned Protection Factors
Air Purifying	Facepiece, half	Negative pressure	10
	Facepiece, full	Negative pressure	100
	Facepiece, half	Powered, air-purifying	50
	Facepiece, full	Powered, air-purifying	1000
	Helmut, hood	Powered, air-purifying	1000
Atmosphere Supplying	Facepiece, half	Demand	10
	Facepiece, full	Demand	100
	Facepiece, half	Pressure demand	50
	Facepiece, full	Pressure demand	1000
	Facepiece, half	Continuous flow	50
	Facepiece, full	Continuous flow	1000
	Helmut, hood	Continuous flow	1000
Self-Contained Breathing Apparatus	Facepiece, full	Demand	100
		Pressure demand	10,000
		Demand, recirculating	100
		Positive pressure recirculating	10,000

TABLE F-2. Ingestion Dose Coefficients, ICRP Report 67 (ICRP 1994b).

Organ/Tissue		Committed Equivalent and Effective Doses (mrem μCi^{-1})				
		Am-241	Pu-238	Pu-239	Pu-240	Pu-241
Adrenals		5.55E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
Bladder Wall		5.55E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
Bone Surface		3.40E+04	2.78E+04	3.11E+04	3.11E+04	6.29E+02
Brain		5.55E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
Breast		5.55E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
GI Tract	Stomach Wall	6.29E+01	5.18E+01	5.92E+01	5.92E+01	1.11E+00
	Small Intestine Wall	7.03E+01	5.92E+01	6.66E+01	6.66E+01	1.15E+00
	Upper Large Intestine Wall	1.33E+02	1.18E+02	1.22E+02	1.22E+02	1.44E+00
	Lower Large Intestine Wall	2.78E+02	2.59E+02	2.52E+02	2.52E+02	2.11E+00
Kidneys		1.70E+02	1.18E+02	1.26E+02	1.26E+02	1.85E+00
Liver		2.04E+03	5.92E+03	6.29E+03	6.29E+03	1.26E+02
Muscle		5.55E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
Ovaries		6.66E+02	3.59E+02	4.07E+02	4.07E+02	8.14E+00
Pancreas		5.55E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
Red Bone Marrow		1.15E+03	1.37E+03	1.48E+03	1.48E+03	2.41E+01
Lungs		5.55E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
Skin		5.55E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
Spleen		5.55E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
Testes		6.29E+02	3.66E+02	4.07E+02	4.07E+02	8.14E+00
Thymus		5.55E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
Thyroid		5.55E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
Uterus		5.55E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
Remainder		5.92E+01	4.81E+01	5.55E+01	5.55E+01	1.11E+00
Effective Dose		7.77E+02	8.51E+02	9.25E+02	9.25E+02	1.81E+01

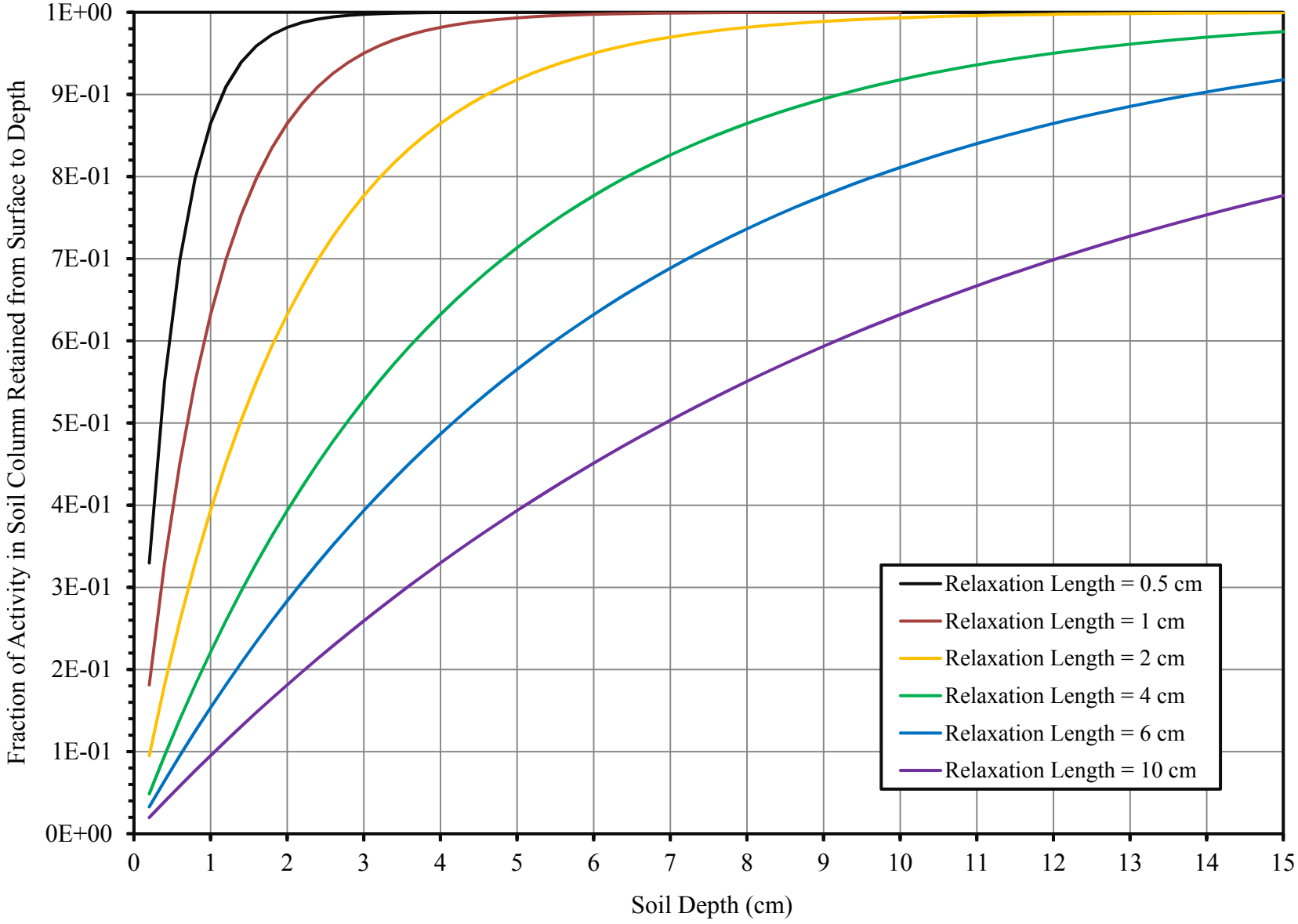

Figure F-1. Fraction of Activity in Soil Column retained from Surface to Depth for Various Relaxation Lengths.

TABLE F-3. Intake Summary Example of Individual Working as Thor Missile Technician for One Year in 1966.

Type of Day	Time Period	Inhalation Volume (m^3)	Airborne $^{238+239+240}Pu$ Concentration ($fCi\ m^{-3}$)	$^{238+239+240}Pu$ Inhalation Intake per Day (pCi)	Soil Concentration for Soil Ingestion ($pCi\ g^{-1}$)	Soil Ingestion Rate per Day (mg)	Ingested Activity per Day (pCi)	Average Days per Week	Exposure Duration (days)	$^{238+239+240}Pu$ Intakes (pCi)	
										Inhalation	Ingestion
Work	Work	15	14	0.210	69.7	50	3.49	6	365	65.7	1090
	Off-duty	13.2	0.57	0.0075	7.8	50	0.39			2.35	122
	Total =	28.2	-	0.218	-	100	3.88		Total =	68.1	1212
Off	Off-duty	26.8	0.57	0.0153	7.8	100	0.78	1	365	0.797	244
									Total =	68.9	1456

TABLE F-4. CED Summary for Example of Individual Working as Thor Missile Technician for One Year in 1966 (ICRP 60/66), $f_1 = 5 \times 10^{-4}$ for Ingestion Intakes.

Inhalation Type		S		M		Inhalation Type		S		M	
Organ/Tissue		CED (mrem)	Inhalation Fraction	CED (mrem)	Inhalation Fraction	Organ/Tissue		CED (mrem)	Inhalation Fraction	CED (mrem)	Inhalation Fraction
Adrenals		0.191	0.51	0.899	0.90	Muscle		0.190	0.51	0.899	0.90
Bladder Wall		0.191	0.51	0.899	0.90	Ovaries		1.45	0.51	7.17	0.90
Bone Surface		108	0.51	504	0.89	Pancreas		0.190	0.51	0.994	0.91
Brain		0.191	0.51	0.899	0.90	Red Bone Marrow		5.02	0.53	23.1	0.90
Breast		0.191	0.51	0.899	0.90	Res Tract	Ex. Th. Air	10.4	1.00	2.49	1.00
GI Tract	Esophagus	0.0975	1.00	0.805	1.00		Lungs	24.1	1.00	8.99	0.99
	St Wall	0.197	0.49	0.905	0.89	Skin		0.190	0.51	0.899	0.90
	SI Wall	0.209	0.47	0.917	0.88	Spleen		0.190	0.51	0.899	0.90
	ULI Wall	0.297	0.33	1.00	0.80	Testes		1.48	0.52	7.10	0.90
	LLI Wall	0.491	0.20	1.20	0.67	Thymus		0.190	0.51	0.899	0.90
	Colon	0.121	0.81	0.828	0.97	Thyroid		0.190	0.51	0.899	0.90
Kidneys		0.351	0.69	1.05	0.90	Uterus		0.190	0.51	0.899	0.90
Liver		21.2	0.52	103	0.90						

TABLE F-5. WGP Activity Fractions and Activity Ratio Relationships Over Time.

Year	α-Radiation Activity Fractions				Activity Ratios - $^{238+239+240}$Pu:		Relative Pu Mass to 1960
	Pu-238	Pu-239	Pu-240	Am-241	^{241}Pu	^{241}Am	
1962	0.021	0.786	0.172	0.021	0.160	47.7	0.9995
1963	0.021	0.778	0.171	0.030	0.168	32.6	0.9993
1964	0.021	0.772	0.169	0.038	0.176	25.0	0.9990
1965	0.020	0.765	0.168	0.047	0.185	20.5	0.9988
1966	0.020	0.759	0.167	0.054	0.194	17.5	0.9986
1967	0.020	0.754	0.165	0.061	0.204	15.3	0.9984
1968	0.019	0.749	0.164	0.068	0.214	13.7	0.9982
1969	0.019	0.744	0.163	0.074	0.224	12.5	0.9980
1970	0.019	0.739	0.162	0.080	0.235	11.5	0.9979
1971	0.019	0.735	0.161	0.085	0.247	10.7	0.9977
1972	0.018	0.731	0.160	0.091	0.259	10.0	0.9975
1973	0.018	0.727	0.159	0.095	0.271	9.48	0.9974
1974	0.018	0.724	0.159	0.100	0.285	9.00	0.9972
1975	0.018	0.720	0.158	0.104	0.299	8.59	0.9971
1976	0.017	0.717	0.157	0.108	0.313	8.23	0.9969
1977	0.017	0.714	0.157	0.112	0.329	7.91	0.9968
1978	0.017	0.711	0.156	0.116	0.345	7.64	0.9967
1979	0.017	0.709	0.155	0.119	0.362	7.39	0.9965
1980	0.017	0.706	0.155	0.122	0.380	7.17	0.9964
1981	0.016	0.704	0.154	0.125	0.398	6.98	0.9963
1982	0.016	0.702	0.154	0.128	0.418	6.80	0.9962
1983	0.0161	0.700	0.1533	0.131	0.438	6.64	0.9961
1984	0.016	0.698	0.153	0.133	0.460	6.50	0.9960
1985	0.016	0.696	0.152	0.136	0.482	6.36	0.9958
1986	0.016	0.694	0.152	0.138	0.506	6.24	0.9957
1987	0.015	0.693	0.152	0.140	0.531	6.13	0.9957
1988	0.015	0.691	0.151	0.142	0.557	6.03	0.9956
1989	0.015	0.690	0.151	0.144	0.584	5.94	0.9955
1990	0.015	0.688	0.151	0.146	0.613	5.86	0.9954
1991	0.015	0.687	0.150	0.148	0.643	5.78	0.9953
1992	0.015	0.686	0.150	0.149	0.675	5.71	0.9952
1993	0.015	0.685	0.150	0.151	0.708	5.64	0.9951
1994	0.014	0.684	0.150	0.152	0.743	5.58	0.9951
1995	0.014	0.683	0.149	0.153	0.779	5.52	0.9950
1996	0.014	0.682	0.149	0.155	0.818	5.47	0.9949
1997	0.014	0.681	0.149	0.156	0.858	5.42	0.9948
1998	0.014	0.680	0.149	0.157	0.900	5.37	0.9948
1999	0.014	0.680	0.149	0.158	0.944	5.33	0.9947
2000	0.014	0.679	0.149	0.159	0.990	5.29	0.9946
2001	0.014	0.678	0.148	0.160	1.04	5.26	0.9946
2002	0.013	0.678	0.148	0.161	1.09	5.22	0.9945

TABLE F-6. Intake Summary Example of Individual Working in General Areas for One Year in 1964.

Type of Day	Time Period	Inhalation Volume (m^3)	Airborne $^{238+239+240}Pu$ Concentration ($fCi\ m^{-3}$)	$^{238+239+240}Pu$ Inhalation Intake per Day (pCi)	Soil Concentration for Soil Ingestion ($pCi\ g^{-1}$)	Soil Ingestion Rate per Day (mg)	Ingested Activity per Day (pCi)	Average Days per Week	Exposure Duration (days)	$^{238+239+240}Pu$ Intake (pCi)	
										Inhalation	Ingestion
Work	Work	15	5.7	0.086	7.8	50	0.39	6	365	26.7	122
	Off-duty	13.2	5.7	0.0752	7.8	50	0.39			23.5	122
	Total =	28.2	-	0.161	-	100	0.78		Total =	50.3	244
Off	Off-duty	26.8	5.7	0.1528	7.8	100	0.78	1	365	7.97	244
									Total =	58.3	488

TABLE F-7. CED Summary for Example of Individual Working in General Areas for One Year in 1964.

Inhalation Type		S		M		Inhalation Type		S		M	
Organ/Tissue		CED (mrem)	Inhalation Fraction	CED (mrem)	Inhalation Fraction	Organ/Tissue		CED (mrem)	Inhalation Fraction	CED (mrem)	Inhalation Fraction
Adrenals		0.113	0.72	0.708	0.96	Muscle		0.113	0.72	0.708	0.96
Bladder Wall		0.113	0.72	0.708	0.96	Ovaries		0.854	0.73	5.54	0.96
Bone Surface		63.6	0.72	397	0.96	Pancreas		0.113	0.72	0.764	0.96
Brain		0.113	0.72	0.708	0.96	Red Bone Marrow		3.05	0.74	18.3	0.96
Breast		0.113	0.72	0.708	0.96	Res Tract	Ex. Th. Air	8.67	1.00	2.08	1.00
GI Tract	Esophagus	0.0819	1.00	0.677	1.00		Lungs	20.1	1.00	7.43	1.00
	St Wall	0.115	0.71	0.710	0.95	Skin		0.113	0.72	0.708	0.96
	SI Wall	0.119	0.69	0.714	0.95	Spleen		0.113	0.72	0.708	0.96
	ULI Wall	0.148	0.55	0.743	0.91	Testes		0.878	0.73	5.57	0.96
	LLI Wall	0.213	0.38	0.808	0.84	Thymus		0.113	0.72	0.708	0.96
	Colon	0.0874	0.94	0.682	0.99	Thyroid		0.113	0.72	0.708	0.96
Kidneys		0.238	0.85	0.810	0.96	Uterus		0.113	0.72	0.708	0.96
Liver		12.8	0.73	82.2	0.96						

TABLE F-8. Intake Summary Example of Individual Working as Technician for one Year in 1964, with Some Duties in RCA.

Type of Day	Time Period	Inhalation Volume (m^3)	Airborne $^{238+239+240}Pu$ Concentration ($fCi\ m^{-3}$)	$^{238+239+240}Pu$ Inhalation Intake per Day (pCi)	Soil Concentration for Soil Ingestion ($pCi\ g^{-1}$)	Soil Ingestion Rate per Day (mg)	Ingested Activity per Day (pCi)	Average Days per Week	Exposure Duration (days)	$^{238+239+240}Pu$ Intake (pCi)	
										Inhalation	Ingestion
Work	Work (1)	3	26.6	0.080	69.7	10	0.70	6	365	25.0	218
	Work (2)	12	5.7	0.068	7.8	40	0.31			21.4	98
	Off-duty	13.2	5.7	0.0752	7.8	50	0.39			23.5	122
	Total =	28.2	-	0.223	-	100	1.40		Total =	69.9	438
Off	Off-duty	26.8	5.7	0.153	7.8	100	0.78	1	365	7.97	244
									Total =	77.9	682

TABLE F-9. CED Summary for Example of Individual Working as Technician for one Year in 1964, with Some Duties in RCA.

Inhalation Type		S		M		Inhalation Type		S		M	
Organ/Tissue		CED (mrem)	Inhalation Fraction	CED (mrem)	Inhalation Fraction	Organ/Tissue		CED (mrem)	Inhalation Fraction	CED (mrem)	Inhalation Fraction
Adrenals		0.153	0.71	0.948	0.95	Muscle		0.152	0.71	0.948	0.95
Bladder Wall		0.153	0.71	0.948	0.95	Ovaries		1.16	0.72	7.41	0.96
Bone Surface		86.1	0.71	531	0.95	Pancreas		0.152	0.71	1.02	0.96
Brain		0.153	0.71	0.948	0.95	Red Bone Marrow		4.13	0.73	24.5	0.96
Breast		0.153	0.71	0.948	0.95	Res Tract	Ex. Th. Air	11.6	1.00	2.78	1.00
GI Tract	Esophagus	0109	1.00	0.905	1.00		Lungs	26.8	1.00	9.93	1.00
	St Wall	0.156	0.70	0.951	0.95	Skin		0.152	0.71	0.948	0.95
	SI Wall	0.161	0.68	0.956	0.95	Spleen		0.152	0.71	0.948	0.95
	ULI Wall	0.202	0.54	0.997	0.91	Testes		1.19	0.73	7.46	0.96
	LLI Wall	0.293	0.37	1.09	0.83	Thymus		0.152	0.71	0.948	0.95
	Colon	0.117	0.94	9.12	0.99	Thyroid		0.152	0.71	0.948	0.95
Kidneys		0.321	0.85	1.09	0.95	Uterus		0.152	0.71	0.948	0.95
Liver		17.3	0.72	110	0.96						

TABLE F-10. Intake Summary Example of Individual Working at JACADS in 1993.

Type of Day	Time Period	Inhalation Volume (m^3)	Airborne $^{238+239+240}Pu$ Concentration ($fCi\ m^{-3}$)	$^{238+239+240}Pu$ Inhalation Intake per Day (pCi)	Soil Concentration for Soil Ingestion ($pCi\ g^{-1}$)	Soil Ingestion Rate per Day (mg)	Ingested Activity per Day (pCi)	Average Days per Week	Exposure Duration (days)	$^{238+239+240}Pu$ Intake (pCi)	
										Inhalation	Ingestion
Work	Work	15	0	0.0	0.0	50	0.0	6	365	0.0	0.0
	Off-duty	13.2	0.1	0.0013	1.4	50	0.07			0.41	22
	Total =	28.2	-	0.0013	-	100	0.07		Total =	0.41	22
Off	Off-duty	26.8	0.1	0.00268	1.4	100	0.14	1	365	0.14	44
									Total =	0.55	66

TABLE F-11. CED Summary for Example of Individual Working at JACADS in 1993.

Inhalation Type		S		M		Inhalation Type		S		M	
Organ/Tissue		CED (mrem)	Inhalation Fraction	CED (mrem)	Inhalation Fraction	Organ/Tissue		CED (mrem)	Inhalation Fraction	CED (mrem)	Inhalation Fraction
Adrenals		0.00522	0.16	0.0112	0.61	Muscle		0.00520	0.15	112	0.61
Bladder Wall		0.00522	0.16	0.0112	0.61	Ovaries		0.0418	0.16	0.0979	0.64
Bone Surface		2.96	0.15	6.31	0.60	Pancreas		0.00520	0.15	0.0135	0.67
Brain		0.00522	0.16	0.0112	0.61	Red Bone Marrow		0.122	0.18	0.267	0.62
Breast		0.00522	0.16	0.0112	0.61	Res Tract	Ex. Th. Air	0.0915	1.00	0.0218	1.00
GI Tract	Esophagus	0.000821	1.00	0.00677	1.00		Lungs	0.217	0.98	0.0846	0.95
	St Wall	0.00555	0.15	0.0115	0.59	Skin		0.00520	0.15	0.0112	0.61
	SI Wall	0.00612	0.13	0.0121	0.56	Spleen		0.00520	0.15	0.0112	0.61
	ULI Wall	0.0105	0.08	0.0165	0.41	Testes		0.0416	0.16	0.0909	0.62
	LLI Wall	0.0191	0.04	0.0251	0.27	Thymus		0.00520	0.15	0.0112	0.61
	Colon	0.00406	0.20	0.0100	0.68	Thyroid		0.00520	0.15	0.0112	0.61
Kidneys		0.00790	0.27	0.0147	0.61	Uterus		0.00520	0.15	0.0112	0.61
Liver		0.533	0.16	1.17	0.62						

TABLE F-12. Intake Summary Example of Individual Working as Thor Missile Technician for one Year in 1964.

Type of Day	Time Period	Inhalation Volume (m^3)	Airborne $^{238+239+240}Pu$ Concentration ($fCi\ m^{-3}$)	$^{238+239+240}Pu$ Inhalation Intake per Day (pCi)	Soil Concentration for Soil Ingestion ($pCi\ g^{-1}$)	Soil Ingestion Rate per Day (mg)	Ingested Activity per Day (pCi)	Average Days per Week	Exposure Duration (days)	$^{238+239+240}Pu$ Intakes (pCi)	
										Inhalation	Ingestion
Work	Work	15	26.6	0.210	69.7	50	3.49	6	365	125	1090
	Off-duty	13.2	0.57	0.0075	7.8	50	0.39			2.35	122
	Total =	28.2	-	0.218	-	100	3.88		Total =	127	1212
Off	Off-duty	26.8	0.57	0.0153	7.8	100	0.78	1	365	0.8	244
									Total =	128	1456

TABLE F-13. CED Summary for Example of Individual Working as Thor Missile Technician for one Year in 1964 (ICRP 60/66), $f_1 = 5 \times 10^{-4}$ for Ingestion Intakes.

Inhalation Type		S		M		Inhalation Type		S		M	
Organ/Tissue		CED (mrem)	Inhalation Fraction	CED (mrem)	Inhalation Fraction	Organ/Tissue		CED (mrem)	Inhalation Fraction	CED (mrem)	Inhalation Fraction
Adrenals		0.273	0.66	1.58	0.94	Muscle		0.272	0.66	1.58	0.94
Bladder Wall		0.273	0.66	1.58	0.94	Ovaries		2.06	0.66	12.3	0.94
Bone Surface		154	0.66	885	0.94	Pancreas		0.272	0.66	1.70	0.95
Brain		0.273	0.66	1.58	0.94	Red Bone Marrow		7.33	0.68	40.9	0.94
Breast		0.273	0.66	1.58	0.94	Res Tract	Ex. Th. Air	19.0	1.00	4.57	1.00
GI Tract	Esophagus	0.180	1.00	1.49	1.00		Lungs	44.1	1.00	16.3	0.99
	St Wall	0.279	0.64	1.59	0.94	Skin		0.272	0.66	1.58	0.94
	SI Wall	0.290	0.62	1.60	0.93	Spleen		0.272	0.66	1.58	0.94
	ULI Wall	0.377	0.48	1.68	0.88	Testes		2.11	0.67	12.4	0.94
	LLI Wall	0.572	0.31	1.88	0.79	Thymus		0.272	0.66	1.58	0.94
	Colon	0.196	0.92	1.50	0.99	Thyroid		0.272	0.66	1.58	0.94
Kidneys		0.551	0.81	1.81	0.94	Uterus		0.272	0.66	1.58	0.94
Liver		30.8	0.66	183	0.94						

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Appendix G

IREP Example Screening Doses

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TABLE G-1. Screening Doses (rem) Calculated with IREP, Cancer of the Liver (including biliary system) [Table 4-7 Excerpts from Kocher and Apostoaei 2007)].

Age at exposure (y)	Time since exposure when cancer was diagnosed (y)					
	5	10	15	20	25	≥ 30
18	15	4.0	5.3	7.3	8.8	11 (11)[d]
20	19	5.2	6.7	8.5	11	13
25	35	8.5	11	14	16	16
30	60	14	17	20	20	20
35	78	18	20	20	20	20
≥ 40	96	22	20	20	20	20

[d]First entry applies at time since exposure of 30 years; second entry in parentheses applies at time since exposure of 32 years or greater (age at diagnosis of 50 years or greater).

TABLE G-2. Screening Doses (rem) Calculated with IREP, Cancer of the Lung – I (including trachea and bronchus) [Table 4-10 Excerpts from Kocher and Apostoaei 2007)].

Smoking status	Age at exposure (y)	Time since exposure when cancer was diagnosed (y)		
		5	10	≥ 15
Never smoker	Any	220	46	44
Former smoker	Any	530	130	130
Current smoker[d]	Any	720	160	150

[d]Screening doses apply when the number of cigarettes smoked per day is unknown. IREP also calculates PC for separate smoking categories of < 10, 10-19, 20-40, and ≥ 40 cigarettes per day; screening doses for these smoking categories are similar to values for former smokers and current smokers with an unknown number of cigarettes smoked per day.

TABLE G-3. Screening Doses (rem) Calculated with IREP, Cancer of the Lung – II (including trachea and bronchus) [Table 4-11 Excerpts from Kocher and Apostoaei 2007)].

Age at exposure (y)	Time since exposure when cancer was diagnosed (y)[c]					
	5	10	15	20	25	≥ 30
18	58	18	26	35	44	52 (54)[e]
	95	23	32	43	54	63 (66)
	100	23	33	44	54	64 (68)
20	76	24	33	44	55	63
	120	30	41	54	65	76
	140	31	42	54	67	78
25	150	45	60	77	90	90
	250	56	71	89	110	110
	250	57	73	91	110	110
30	270	80	100	120	120	120
	420	95	120	140	140	140
	440	97	120	140	140	140
35	360	100	120	120	120	120
	550	120	140	140	140	140
	570	120	140	140	140	140
≥ 40	450	130	120	120	120	120
	680	150	140	140	140	140
	720	150	140	140	140	140

[c]For each age at exposure and time since exposure when cancer was diagnosed, first entry gives the screening dose for never smokers, second entry gives the screening dose for former smokers, and third entry gives the screening dose for current smokers that applies when the number of cigarettes smoked per day is unknown. IREP also calculates PC for separate smoking categories of < 10, 10-19, 20-40, and ≥ 40 cigarettes per day; screening doses for these smoking categories are similar to values for former smokers and current smokers with an unknown number of cigarettes smoked per day.

[e]First entry applies at time since exposure of 30 years; second entry in parentheses applies at time since exposure of 32 years or greater (age at diagnosis of 50 years or greater).

TABLE G-4. Screening Doses (rem) Calculated with IREP, Cancer of the Bone [Table 4-13 Excerpts from Kocher and Apostoaei 2007)].

Age at exposure (y)	Time since exposure when cancer was diagnosed (y)						
	3	5	10	15	20	25	≥ 30
18	33	10	14	21	30	38	45 (48)[d]
20	47	14	19	28	37	47	55
25	96	32	37	51	64	76	76
30	190	61	66	84	110	110	110
35	270	83	84	110	110	110	110
≥ 40	320	110	110	110	110	110	110

[d]First entry applies at time since exposure of 30 years; second entry in parentheses applies at time since exposure of 32 years or greater (age at diagnosis of 50 years or greater).

TABLE G-5. Screening Doses (rem) Calculated with IREP, Lymphoma and Multiple Myeloma [Table 4-30 Excerpts from Kocher and Apostoaei 2007)].

Age at exposure (y)	Time since exposure when cancer was diagnosed (y)					
	5	10	15	20	25	≥ 30
18	96	22	30	38	48	57 (61)[e]
20	120	29	37	47	59	70
25	230	50	64	78	93	93
30	420	88	110	130	130	130
35	520	110	130	130	130	130
≥ 40	690	140	130	130	130	130

[e]First entry applies at time since exposure of 30 years; second entry in parentheses applies at time since exposure of 32 years or greater (age at diagnosis of 50 years or greater).

TABLE G-6. Screening Doses (rem) Calculated with IREP, Acute Lymphocytic Leukemia [Table 4-33 Excerpts from Kocher and Apostoaei 2007)].

Age at exposure (y)	Time since exposure when cancer was diagnosed (y)										
	3	5	10	15	20	25	30	35	40	45	50
18	0.28	0.24	0.91	2.7	6.5	13	24	40	64	110	160
≥ 20	19	16[e]									

[e]Entry applies at all times since exposure when cancer was diagnosed of 5 years or greater.

TABLE G-7. Screening Doses (rem) Calculated with IREP, Acute Myeloid Leukemia [Table 4-34 Excerpts from Kocher and Apostoaei 2007)].

Age at exposure (y)	Time since exposure when cancer was diagnosed (y)										
	3	5	10	15	20	25	30	35	40	45	50
All	6.7	5.8	9.1	14	19	25	29	33	35	38	39

TABLE G-8. Screening Doses (rem) Calculated with IREP, Chronic Myeloid Leukemia [Table 4-32 Excerpts from Kocher and Apostoaei 2007)].

Age at exposure (y)	Time since exposure when cancer was diagnosed (y)										
	3	5	10	15	20	25	30	35	40	45	50
All	1.6	1.4	5.0	12	22	37	57	86	130	180	240

TABLE G-9. Screening Doses (rem) Calculated with IREP, Leukemia, excluding Chronic Lymphocytic Leukemia [Table 4-31 Excerpts from Kocher and Apostoaei 2007)].

Age at exposure (y)	Time since exposure when cancer was diagnosed (y)										
	3	5	10	15	20	25	30	35	40	45	≥ 50
18	2.2	1.9	4.4	9.1	17	28	41	58	78	110	140
20	2.5	2.2	4.8	9.8	18	29	42	59	79	110	140
25	3.4	3.0	6.1	12	20	31	44	59	78	100	130
30	4.5	3.9	7.4	14	22	32	44	57	73	92	120
35	5.7	5.0	8.8	15	23	32	42	53	65	78	94
40	6.9	6.0	11	16	24	31	38	46	53	61	69
45	8.0	7.0	12	17	23	29	34	37	40	43	46
50	9.2	8.0	12	18	23	26	28	29	29	28	27
≥ 55	11	8.8	13	19	22	24	23	21	19	17	15

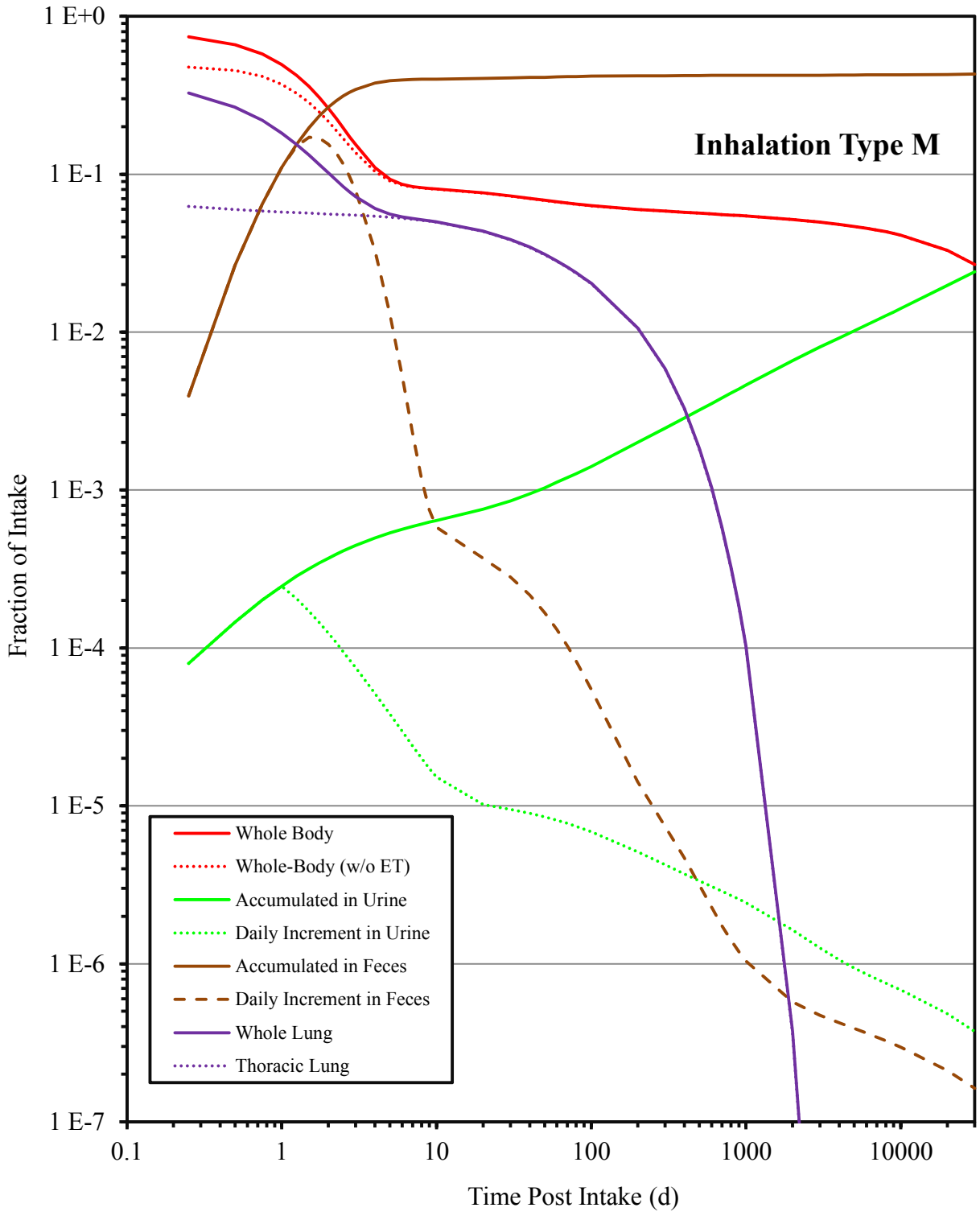

Figure G-1. ICRP 68 Intake Retention Functions for Inhalation of Type M Stable Plutonium, Values from Potter (2002).

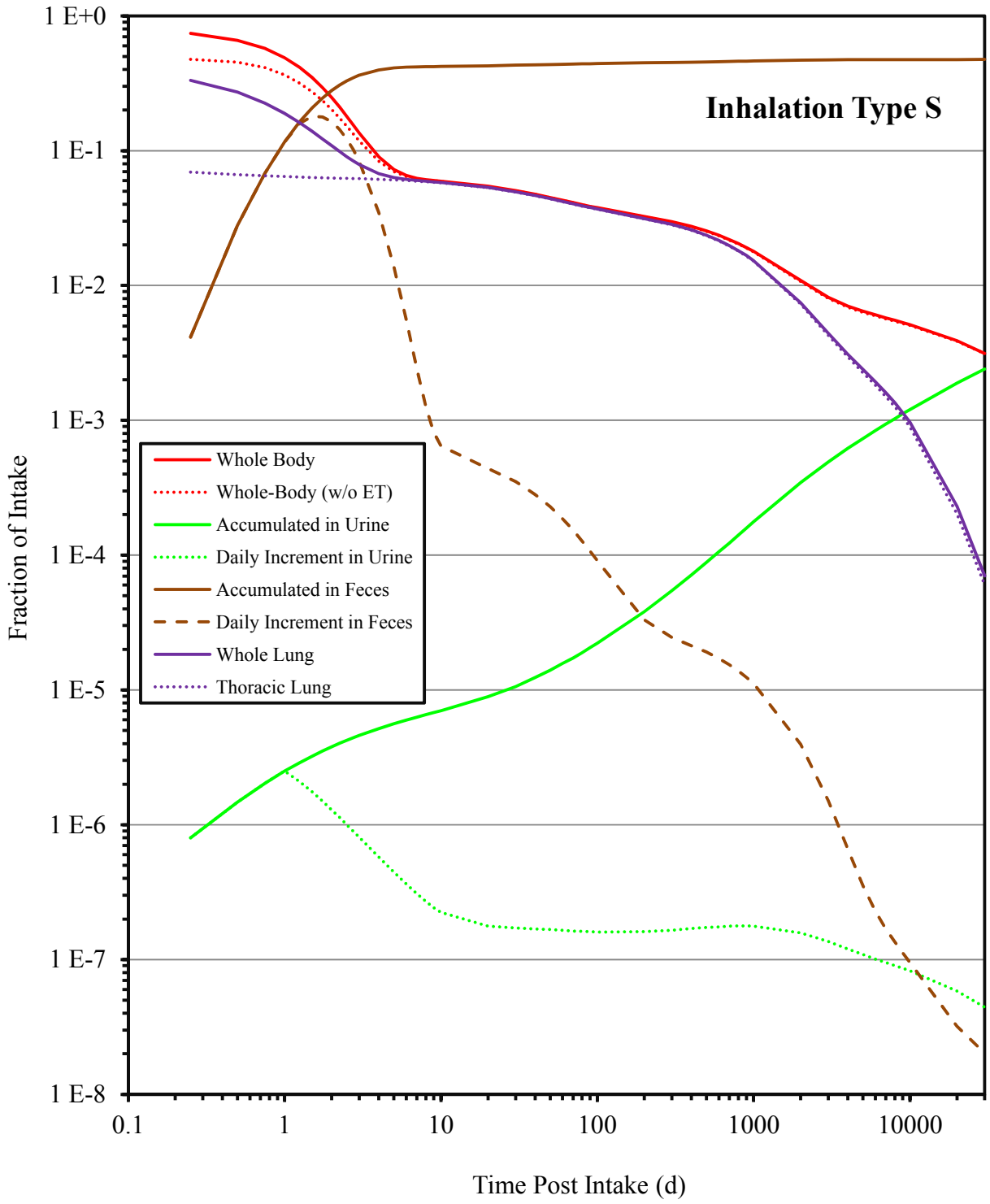

Figure G-2. ICRP 68 Intake Retention Functions for Inhalation of Type S Stable Plutonium, Values from Potter (2002).

TABLE G-10. EEOICPA Internal Target Organ for Metastases of Blood and Lymphatic System for Various ICD-9 Diagnoses Codes.

ICD-9 Diagnosis Codes	Cancer Code Explanation	Cell Type	Site of Incidence vs. Site of Original Radiation Dose	EEOICPA Internal Target Organ (ORAU 2012)
200.0x	Reticulosarcoma	immature lymphoid	Likely linked	Same as for 201.0x
200.1x	Lymphosarcoma			
200.2x	Burkitt's Tumor Lymphoma	B-cell	Uncertain link	LN(TH)
200.3x	Marginal zone lymphoma	B-cell	Uncertain link	LN(TH)
200.4x	Mantle cell lymphoma	B-cell	Uncertain link	LN(TH)
200.5x	Primary central nervous system lymphoma	usually B-cell	Uncertain link	LN(TH)
200.6x	Anaplastic large cell lymphomas	T-cell	Likely linked	Same as for 201.0x
200.7x	Large cell lymphoma	usually B-cell, sometimes T	Likely linked	Same as for 201.0x
200.8x	Mixed lymphosarcoma	immature lymphoid	Likely linked	Same as for 201.0x
201.0x	Hodgkin's paragranuloma	usually B-cell	Likely linked	Dose to highest non-metabolic organ (HNMO), except if site of incidence is spleen, a thoracic lymph node, or a lymph node in the head, where respectively dose to the spleen, LN(TH), or LN(ET) are used
201.1x	Hodgkin's granuloma			
201.2x	Hodgkin's sarcoma			
201.4x	Hodgkin's lymph histiocytosis			
201.5x	Hodgkin's nodular sclerosis			
201.6x	Hodgkin's mixed cellularity			
201.7x	Hodgkin's lymphocyte-depleted			
201.9x	Hodgkin's disease unspecified			
202.0x	Nodular lymphoma	B- or T-cell	Uncertain link	LN(TH)
202.1x	Mycosis fungocides	T-cell	Likely linked	HNMO
202.2x	Sezary's disease	T-cell	Likely linked	HNMO
202.3x	Malignant histiocytosis	immobile macrophages	Likely linked	Same as for 201.0x
202.4x	Leukemia, reticuloendothelialosis	B-cell	Likely linked	Bone marrow
202.5x	Letterer-Siwe Disease (Langerhans cell histiocytosis)	possibly T-cell	Likely linked	LN(TH)

TABLE G-10, continued.

ICD-9 Diagnosis Codes	Cancer Code Explanation	Cell Type	Site of Incidence vs. Site of Original Radiation Dose	EEOICPA Internal Target Organ (ORAU 2012)
202.6x	Malignant mast cell tumors	mast	Likely linked	Same as for 201.0x
202.8x	Lymphomas, not elsewhere classified	B- or T-cell	Uncertain link	LN(TH)
202.9x	Malignancies of lymphoid and histiocytic tissue	B- or T-cell	Uncertain link	LN(TH)
203.0x	Multiple myeloma	plasma cell	Likely linked	Bone marrow
203.1x	Plasma cell leukemia			
203.8x	Other immunoproliferative neoplasms			
204.0x	Acute lymphoid leukemia	B- or T-cell lineage	Likely linked	Bone marrow
204.1x	Chronic lymphoid leukemia		Uncertain link	Special model
204.2x	Subacute lymphoid leukemia		Likely linked	Bone marrow
204.8x	Lymphoid leukemia, not elsewhere classified	B- or T-cell lineage	Likely linked	Bone marrow
204.9x	Lymphoid leukemia, not otherwise specified			
205.0x	Acute myeloid leukemia	myeloid blasts (normally produce mature neutrophils)	Likely linked	Bone marrow
205.1x	Chronic myeloid leukemia			
205.2x	Subacute myeloid leukemia			
205.3x	Myeloid sarcoma			
205.8x	Myeloid leukemia, not elsewhere classified			
205.9x	Myeloid leukemia, not otherwise specified			
206.0x	Acute monocytic leukemia	monoblastic (most cells normally expected to produce monocytes)	Likely linked	Bone marrow
206.1x	Chronic monocytic leukemia			
206.2x	Subacute monocytic leukemia			
206.8x	Monocytic leukemia, not elsewhere classified			
206.9x	Monocytic leuk., not otherwise spec.			

TABLE G-10, continued.

ICD-9 Diagnosis Codes	Cancer Code Explanation	Cell Type	Site of Incidence vs. Site of Original Radiation Dose	EEOICPA Internal Target Organ (ORAU 2012)
207.0x	Acute erythremia	not well understood	Likely linked	Bone marrow
207.1x	Chronic erythremia			
207.2x	Megakaryocytic leukemia	primitive magakayoblasts		
207.8x	Other specified leukemia, not otherwise classified	multiple		
208.0x	Acute leukemia, unspecified cell	typically primitive cell type	Likely linked	Bone marrow
208.1x	Chronic leukemia, unspecified cell			
208.2x	Subacute leukemia, unspecified cell			
208.8x	Other leukemia, unspecified cell			
208.9x	Leukemia, unspecified cell, not otherwise specified			