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OF THE UNITED STATES
DEPARTMENT OF ENERGY

AN IN SITU DETERMINATION OF ^{241}Am ON

ENEWETAK ATOLL

DATE OF SURVEY: JULY 1977 to DECEMBER 1979

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ABSTRACT

An in situ gamma ray spectrometer system was operated at Enewetak Atoll from July 1977 to December 1979 in support of the Enewetak Cleanup Project. The system employed a high purity germanium planar detector suspended at a height of 7.4 m above ground. Conversion factors were established to relate measured photopeak count rate data to source concentration in the soil. Data obtained for ^{241}Am , together with plutonium-to-amerium ratios obtained from soil sample analyses, were used to establish area-averaged surface (0 - 3 cm) transuranic concentration values. In areas which exceeded cleanup criteria, measurements were made in an iterative fashion to guide soil removal until levels were reduced below the cleanup criteria. Final measurements made after soil removal had been completed were used to document remaining surface transuranic concentration values and to establish external exposure rate levels due to ^{137}Cs and ^{60}Co .

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1.0 INTRODUCTION

Under contract to the Department of Energy, EG&G provided an element of that Department's Enewetak Radiological Support Project which supported the Defense Nuclear Agency (DNA) in the cleanup of Enewetak Atoll. EG&G operated an in situ gamma ray spectrometer system at Enewetak from July 1977 to December 1979. This system was used to determine surface (0-3 cm) concentration values of ^{241}Am as one step in the effort to characterize total transuranic surface contamination at Enewetak arising from the nuclear testing program.

A high purity germanium (HPGe) planar detector, suspended 7.4 m above the ground, was used to measure the 60 keV gamma ray from ^{241}Am (a daughter of ^{241}Pu). Conversion factors were established to relate the measured photopeak count rate data to average ^{241}Am concentration in the soil (see Section 5). Using total transuranic to americium ratios established from soil sample data, a statistical interpolation routine was then used to convert the individual ^{241}Am measurements into area-averaged transuranic surface concentration values.¹ These results formed the data base used in deciding whether or not contaminated soil removal was required. Final measurements made after soil removal had been completed were used to document remaining transuranic surface contamination.

Guidelines for the removal of contaminated soil existed for both surface and subsurface contamination. Since the attenuation mean free path for 60 keV gamma rays in Enewetak soil is approximately 2.0 cm, the sensitivity of the in situ system to subsurface ^{241}Am contamination decreases rapidly with depth. For a uniform distribution with depth, approximately 95% of the unscattered 60 keV gamma rays reaching the detector would originate within the top 6 cm of soil and approximately 99% would originate within the top 9 cm. For this reason, the in situ measurements were used to obtain only surface concentration values (defined for the Enewetak cleanup as the average concentration in the top 3 cm). Subsurface soil samples were used to evaluate and quantify subsurface contamination.

2.0 INSTRUMENTATION

The in situ gamma ray spectrometer utilized an HPGe planar detector having a surface area of 19 cm² and a thickness of 1.6 cm. The detector was

mounted inside a cannister suspended at the end of a 9 m retractable pneumatic boom. This boom was mounted at the rear of a small, lightweight, tracked vehicle (the IMP*) specifically selected for its ability to operate in soft sand (Figure 1). The IMP was modified and equipped as a fully self-contained mobile data acquisition and reduction system. Power was supplied by a 4 kW Onan generator mounted in front of the IMP. A roof-mounted air conditioner provided the necessary humidity and temperature environment for the electronic equipment mounted in the rear section of the vehicle. Signals from the preamplifier (mounted on the detector) were fed to a microprocessor-based 4096 channel pulse height analyzer located inside the IMP. At the completion of each measurement, data were transferred from the analyzer to a Hewlett-Packard 9831 calculator for initial field processing. The results of the initial processing were printed out on an HP printer. The data were then stored on cassette tape.

A Pb-Cd collimator was used to limit the detector field-of-view for 60 keV gamma rays to a finite area on the ground (see Section 8.0). The

Figure 1. AN IMP SET UP IN A TYPICAL COUNTING MODE. The HPGe detector is housed inside the cannister at the end of the retractable boom.

*The word IMP and its variations as used in this report were derived from a trademark of the Delorean Manufacturing Company.

collimator consisted of 1.6 mm (1/16") thick soft lead backed by 0.8 mm (1/32") thick cadmium. Both the lead and cadmium were supported on a 1.6 mm thick aluminum cone. The collimator slipped around the detector housing cap and then extended down 12 cm at an angle of 50° from the vertical. A 1.27 cm thick soft lead collar, 2.54 cm long, was placed around the detector housing cap to further reduce background counts in the ²⁴¹Am photopeak window due to air scatter.

In order to adequately support the Enewetak Cleanup Project, it was necessary to fabricate three complete in situ systems, i.e., three IMPs. All three systems were identical. Two systems were routinely deployed in the field: the third system provided a backup.

3.0 DATA REDUCTION PROCEDURES

3.1 Field Processing

The initial stage of the data reduction was performed in the field immediately following each measurement. The main advantage of field data reduction was that the operator could perform quality control checks on the system after each measurement, shortening the data turnaround time. In addition, the program allowed the operator to input certain bookkeeping information through the HP 9831 calculator; e.g., island name, stake number, percent of brush cover, date, time, weather conditions, and the detector serial number. This information and the spectral data were then stored on magnetic tape.

The field program was restricted to analysis of five narrow regions of the spectrum yielding data for ²⁴¹Am, ¹⁵⁵Eu, ¹³⁷Cs, and ⁶⁰Co (⁶⁰Co in two regions). This restriction, and the technique used to extract the photopeak data, enabled the field processing to be completed during the time it took to move between locations.

Photopeak shapes for the four isotopes (five photopeaks) were determined empirically on Enjebi Island (located at the northern end of the Atoll) for the first two HPGe detectors to arrive at Enewetak. Resolution of both units was 1 keV to 1.2 keV full width at half maximum (FWHM) at 59.5 keV under normal field operation conditions. Detailed manual (graphical) analysis was performed on each of the five photopeaks for count rates ranging from background to those of

the calibration sources — tens to hundreds of times background. Peak shapes were constant over the count rate ranges within the limits of recognition imposed by statistics at lower count rates. Careful measurements were then made, using the high count rate data, to determine the points at which the peak rises out of the background. Each region so delineated was used in the program to determine the centroid and net photopeak counts. Symmetrical windows adjacent to the peak region were used to determine (by straight line interpolation) the background under the peak.

To find a peak, a narrow predetermined segment of the spectrum was examined. This method, which contributed greatly to the quickness of the program, was viable because each measurement was analyzed immediately. Consequently, the IMP operator could adjust the gain and zero of the analyzer system, when necessary, to keep the peaks where they belonged. For peak finding, the raw data were first smoothed by a sliding interval filter of near-optimum width. The filtered data were searched for the channel with the most counts. This channel was the peak channel. No further use was made of smoothed data. The central peak region and background windows were positioned with respect to the peak channel as described in the previous paragraph. The peak centroid, background counts, and net peak counts were determined. The one sigma standard deviation was calculated from the total counts (peak plus background) and a statistical counting error was assigned (sigma/net counts). The centroid (in channel number) was converted to energy. Net counts were converted to equivalent soil concentration using a conversion coefficient stored in the library array and the live time measured by the analyzer during spectrum acquisition. The coefficient stored in the library had units of (pCi/g)/cps. Determination of that number is described in Section 5.0. The error assigned to the soil concentration result was the statistical counting error, plus a 10% error to account for uncertainties in the conversion coefficient (see Section 6.0). It should be pointed out that any bump in the spectral region assigned to a photopeak was analyzed and printed out. The net/sigma value and a spectral plot were used to determine if the result was significant.

Below are numbers used for the 59.5 keV (²⁴¹Am) and 86.5 keV (¹⁵⁵Eu) analyses. Slightly wider windows were used for higher energy peaks.

Sliding interval filter:
rectangular, 3 channels wide

Region examined for americium:
ch 155 to 162 (58.1 to 60.75 keV)

Region examined for europium:
ch 227 to 234 (85.1 to 87.75 keV)

Low energy background window:
peak -8 to peak -5 channels

Photo peak:
peak -4 to peak +3 channels

High energy background window:
peak +4 to peak +7 channels

Analyzer gain:
0.375 keV/channel

**Table 1. Initial Detector Efficiency
Calibration Results for ^{241}Am**

Detector Serial Number	Operating Voltage (kV)	Detector Efficiency [cps/($\gamma/\text{cm}^2\text{-sec}$)]
386	-2.0	19.1
393	-2.0	19.3
483	-3.0	17.2
496	-3.0	18.1
513	-2.5	18.7
635	-2.0	17.2

3.2 Laboratory Processing

Several correction factors had to be applied to the ^{241}Am data prior to its use in determining the area-averaged total transuranic surface concentration values. These were all made in the laboratory. The conversion factor used in the field program was the same for all systems. This conversion factor assumed a detector height of 740 cm and a detector efficiency of 19.0 cps per ($\gamma/\text{cm}^2\text{-sec}$). It did not include the possibility of any additional attenuating material between the detector and the ground. Corrections had to be made if any of these assumptions were not valid. Correction factors were routinely applied for attenuation due to vegetation (a maximum 15% correction) and for the different efficiencies of the various detectors used at Eniwetok (Table 1).

4.0 OPERATIONAL PROCEDURES

Prior to making any measurements, the detector system was calibrated to 0.375 keV per channel (approximately 1500 keV full scale) using a combination ^{60}Co , ^{137}Cs , and ^{241}Am calibration source. The calibration was checked periodically and any gain shift was corrected. (Maintaining power to the preamplifier and amplifier on a 24-hour-a-day basis minimized gain shift problems.) The IMP was moved from location to location with the boom fully retracted and the detector securely fastened. At a measurement point the boom was extended to its full length and then inclined at an angle of 20° away from the IMP.

After completing the measurement (a typical acquisition time was 900 seconds), the boom was retracted and the detector secured for movement to the next measurement location. The total time required for each measurement sequence was 20 to 25 minutes.

A five minute calibration run was made every morning, noon, and afternoon when a system was in the field. These data were processed in the same way that a typical measurement was processed. The data were stored on magnetic tape for permanent retention. Although the sources used were not calibrated, the relative response as a function of time provided a means of monitoring for any changes in the detector efficiency.

Figure 2. GEOMETRY USED IN THE DERIVATION OF CONVERSION FACTORS RELATING IN SITU PHOTOPEAK COUNT RATE DATA TO SOURCE CONCENTRATION IN THE GROUND.

5.0 SYSTEM CALIBRATION

5.1 Flux Calculation

The unscattered flux of gamma rays of energy E at a height h above a smooth air-ground interface due to an emitter distributed in the soil is given by (see Figure 2):

$$\phi = \int_0^\infty \int_0^\infty \frac{S_v}{4\pi r^2} \exp \left[-(\mu/\rho)_a \rho_a r_a \right] \exp \left[-(\mu/\rho)_s \rho_s r_s \right] 2\pi x \, dx \, dz \quad (1)$$

where

S_v = the activity per unit volume $[(\gamma/\text{sec})/\text{cm}^3]$,

$r = r_a + r_s$ (cm),

$(\mu/\rho)_a, (\mu/\rho)_s$ = the air and soil mass attenuation coefficients (cm^2/g), and

ρ_a, ρ_s = the air and soil density (g/cm^3).

This expression assumes a source distribution which varies only with depth. A uniform distribution in the horizontal plane is assumed, which leads to results expressed in terms of an area average over the field-of-view of the detector. For fallout activity the distribution after a period of time can be reasonably approximated by an exponential distribution given by:

$$S_v = S_v^0 e^{-\alpha z} \quad (2)$$

where

S_v^0 = the activity per unit volume at the surface $[(\gamma/\text{sec})/\text{cm}^3]$ and

α = the reciprocal of the relaxation length (cm^{-1}).

Rewriting equation (1) in terms of θ and z , combining with equation (2) and integrating over z leads to:

$$\phi = \frac{S_v^0}{2} \int_0^{\pi/2} \frac{\tan \theta \exp \left[-(\mu/\rho)_a \rho_a h \sec \theta \right]}{\alpha + (\mu/\rho)_s \rho_s \sec \theta} d\theta \quad (3)$$

5.2 Detector Calibration

The detector response to a given flux, ϕ , of gamma rays of energy E incident at an angle θ can be given in terms of an effective detector area, A , defined by:

$$A = \frac{N_p}{\phi} \quad (4)$$

where N_p is the net photopeak count rate (sec^{-1}).

The effective area, in general, varies as a function of the gamma ray angle of incidence and is normally written as:

$$A = A_0 R(\theta) \quad (5)$$

where

A_0 = the detector photopeak count rate for a unit flux incident perpendicular to the detector face $[(\text{cps})/(\gamma/\text{cm}^2\text{-sec})]$ and

$R(\theta)$ = the ratio of the detector response at an angle θ to that at $\theta = 0^\circ$

Both A_0 and $R(\theta)$ can be determined experimentally.

5.3 Conversion Factor

Combining equations (4) and (5) with equation (3) leads to an expression which relates the measured photopeak count rate to source activity at the surface.

This is given by:

$$\frac{N_p}{S_V^0} = \left[\frac{A_0}{2} \int_0^{\pi/2} \frac{R(\theta) \tan \theta \exp \left[-(\mu/\rho)_a \rho_a h \sec \theta \right]}{\alpha + (\mu/\rho)_s \rho_s \sec \theta} d\theta \right] \quad (6)$$

The conversion factor N_p/S_V^0 given by equation (6) is in units of cps per $(\gamma/\text{cm}^3\text{sec})$. For a specific isotope the conversion factor is normally changed to units of cps per (pCi/cm^3) . Multiplying the expression in the brackets in equation (6) by the soil density (in g/cm^3) leads to the conversion factor $N_p/(S_V^0/\rho)$ normally given in units of cps per (pCi/g) .

For the Enewetak cleanup, surface contamination was defined as the average concentration within the top 3 cm of soil. In general, the average concentration in the top z cm, S_V^z , for a source distributed exponentially with depth is given by:

$$S_V^z = \frac{1}{z} \int_0^z S_V^0 e^{-\alpha z} dz = \frac{S_V^0}{\alpha z} (1 - e^{-\alpha z}) \quad (7)$$

Combining equations (6) and (7) leads to the final expression for the conversion factor used at Enewetak:

$$\frac{(S_V^z/\rho)}{N_p} = \frac{(1 - e^{-\alpha z})}{\alpha z} B \left[\frac{A_0 \rho_s}{2} \int_0^{\pi/2} \frac{R(\theta) \tan \theta \exp \left[-(\mu/\rho)_a \rho_a h \sec \theta \right]}{\alpha + (\mu/\rho)_s \rho_s \sec \theta} d\theta \right]^{-1} \quad (8)$$

in units of $[(\text{pCi}/\text{g})/(\text{cps})]$, where B converts γ/sec to pCi for a specific isotope.

5.4 Results

In order to evaluate Equation 8, it was necessary first to determine A_0 and $R(\theta)$ for each detector being used, in its normal field configuration. A_0 was determined by placing a known source directly below the detector at a distance great enough to simulate a parallel beam of photons at the detector face. In determining A_0 , it is important to utilize the same method for determining the net counts in the photopeak as that used in the field. A total of six detectors were calibrated for the Enewetak program. Although two of these detectors were purchased for another program, all six were used at one time or another during the cleanup project. Table 1 summarizes the initial ^{241}Am results for these detectors. The detectors were periodically recalibrated at Enewetak to correct for efficiency changes which occurred during the course of the cleanup project.

$R(\theta)$ was measured in detail for gamma ray energies between 60 and 2600 keV, using detector #386. The detector was mounted inside the container used at Enewetak. Measurements were made with and without the Pb-Cd collimator. Calibrated sources were placed at a fixed distance of 1 m from the detector face at angles from 0° to 90° (0° being directly below the detector). Measurements were made at 10° intervals except between 50° and 65° when the collimator was in place, where 2° intervals were used. In order to account for any azimuthal asymmetries which might exist in the detector, the source was rotated about the detector at a rate of 4 rpm during each measurement. Figure 3 shows the results for ^{241}Am . The $R(\theta)$ data were fitted with a Fourier series to the 10th order and folded into Equation 8 for derivation of the conversion factors. Although these measurements were made in detail only for detector #386, the results were checked for ^{241}Am

Figure 3. RELATIVE RESPONSE OF THE HPG6 DETECTOR MOUNTED IN ITS NORMAL FIELD CONFIGURATION (WITH COLLIMATOR) FOR 60 keV GAMMA RAYS AS A FUNCTION OF INCIDENT ANGLE. Zero degrees being directly below the detector.

using several other detectors: no significant difference was observed.

To evaluate Equation 8, it is necessary to obtain experimentally or make assumptions on the source depth distribution and certain properties of the soil. Table 2 gives results for ^{241}Am with the following parameters:

Photons per Disintegration =
0.359

Effective Area (A_e) =
19.0 cps/($\gamma/\text{cm}^2 \cdot \text{sec}$)

Detector Height (h) =
800, 450, 100 cm

Depth Distribution (α) =
0.33, 0.10, 0.05 cm^{-1}

Soil Density (ρ_s) =
2.0, 1.5, 1.0 g/cm^3

Air Density (ρ_a) =
1.30(10^{-3}), 1.15(10^{-3}), 1.0(10^{-3}) g/cm^3

Soil Mass Attenuation Coefficient, $(\mu/\rho)_s$ =
0.333 cm^2/g (for 60 keV gamma rays)

Air Mass Attenuation Coefficient, $(\mu/\rho)_a$ =
0.188 cm^2/g (for 60 keV gamma rays)

Conversion factors are given for the average ^{241}Am concentration in the top 3 cm of soil. The detector angular response, $R(\theta)$, was obtained with the Pb-Cd collimator in place from the data shown in Figure 3.

The final ^{241}Am conversion factor, 8.95 (pCi/g)/cps, was obtained for a detector height of 7.4 m, a soil density of 1.5 g/cm^3 and an air density of 1.15 (10^{-3}) g/cm^3 . A weighted average was used to account for observed variations in the depth distribution. In the following section, each of the input parameters to Equation (8) is discussed in

Table 2. The Conversion Factor (S_v/ρ)/ N_p in (pCi/g)/cps for ^{241}Am as a Function of Detector Height, Air Density, Soil Density and Depth Distribution

h(cm)	$\alpha(\text{cm}^{-1})$	$\rho_a (\text{g}/\text{cm}^3)$	$\rho_s(\text{g}/\text{cm}^3)$		
			2.0	1.5	1.0
800	0.33	1.30	8.33	9.10	10.61
800	0.33	1.15	8.10	8.85	10.33
800	0.33	1.00	7.89	8.63	10.06
800	0.10	1.30	9.17	9.49	9.60
800	0.10	1.15	8.94	9.24	9.35
800	0.10	1.00	8.71	9.01	9.11
800	0.05	1.30	9.35	9.52	9.86
800	0.05	1.15	9.11	9.28	9.60
800	0.05	1.00	8.88	9.04	9.36
450	0.33	1.30	7.45	8.14	9.49
450	0.33	1.15	7.35	8.03	9.36
450	0.33	1.00	7.25	7.92	9.23
450	0.10	1.30	8.22	8.50	8.60
450	0.10	1.15	8.11	8.39	8.48
450	0.10	1.00	8.00	8.27	8.37
450	0.05	1.30	8.38	8.53	8.84
450	0.05	1.15	8.26	8.42	8.71
450	0.05	1.00	8.16	8.31	8.60
100	0.33	1.30	6.67	7.29	8.49
100	0.33	1.15	6.67	7.28	8.48
100	0.33	1.00	6.66	7.27	8.47
100	0.10	1.30	7.36	7.61	7.70
100	0.10	1.15	7.35	7.61	7.70
100	0.10	1.00	7.35	7.60	7.69
100	0.05	1.30	7.50	7.63	7.91
100	0.05	1.15	7.50	7.63	7.91
100	0.05	1.00	7.49	7.63	7.90

detail. Errors in the conversion factor associated with variations in each of these parameters are also discussed.

6.0 VARIABLES AFFECTING THE ^{241}Am CONVERSION FACTOR

6.1 Air Density and Composition

As can be seen from Table 2, the conversion factor for ^{241}Am at a detector height of 7.4 meters is relatively insensitive to large changes in the air density. The IMP conversion factor assumes an air density of $1.15 (10^{-3}) \text{ g/cm}^3$, which corresponds to air at a temperature of 85°F (30°C) and a pressure of 750 mm Hg. There is only a ± 2.5 percent change in the conversion factor by going to the density extremes given in Table 2. A density of $1.30 (10^{-3}) \text{ g/cm}^3$ corresponds to air at a temperature of 41°F (5°C) and a pressure of 780 mm Hg, and a density of $1.00 (10^{-3}) \text{ g/cm}^3$ corresponds to air at a temperature of 125°F (52°C) and pressure of 700 mm Hg. Changes in air density over the ranges of temperature and pressure which actually occur at Enewetak should not contribute more than a 1 percent error to the conversion factor.

The mass attenuation coefficient for 60 keV gamma rays in air ($0.188 \text{ cm}^2/\text{g}$) was derived from standard air composition tables and elemental mass attenuation coefficient tables. Since the corresponding mass attenuation coefficient for water is 0.20, moisture in the air should not significantly affect the air attenuation factor.

6.2 Soil Density and Composition

The in situ, or wet, soil density and soil composition are both required to determine the attenuation factor for gamma rays of a given energy in soil. Soil composition is required to determine the mass attenuation coefficient. The product of the mass attenuation coefficient and the soil density then gives the linear attenuation coefficient, which is the inverse of the attenuation mean free path. The soil density is also required to convert concentration per unit volume to concentration per unit mass.

Soil density and percent soil moisture were obtained using a Troxler Model 3411 nuclear density/moisture gauge. Density is determined by measuring the attenuation of 662 keV gamma rays from a ^{137}Cs source through a given depth of

soil. The moisture content of soil is determined by measuring the moderation, or slowing, of fast neutrons from an Am-Be neutron source. Dry density is obtained by subtracting the moisture content from the wet density. The percent moisture is obtained by dividing the moisture content by the dry density. In the Troxler gauge, both the ^{137}Cs and the Am-Be sources are located in a probe which can be inserted to a given depth in the soil. The gamma ray and neutron detectors are placed on the surface at a fixed lateral displacement of 25 cm from the sources. After placing the sources at a given depth, gamma ray and neutron counts are accumulated for a period of one minute. The resulting counts are converted to wet density and moisture content using calibration curves supplied by the manufacturer.

Measurements were made at 182 locations within 73 different areas over 9 islands. At each location the average wet density and percent moisture were obtained for the top 15 cm, 10 cm and 5 cm of soil. The 5 cm measurements were repeated after rotating the detectors through an angle of 90° . Based on the 364 independent readings taken at the 5 cm depth, the mean wet density obtained was 1.53 g/cm^3 , with a standard deviation of 0.14 g/cm^3 . The mean value for the percent moisture was 16 percent, with a standard deviation of 5 percent.

A wet density of 1.50 g/cm^3 was used for the final conversion factor. This corresponds to an average moisture of 14 percent, which is probably close to the average yearly percent moisture.

The mass attenuation coefficient for Enewetak soil was based on chemical analysis of 124 soil samples obtained from 9 islands during December 1979. These samples were analyzed for organic content as well as elemental composition. Results of the analysis showed that the primary component of Enewetak soil is calcium carbonate. A number of trace elements were also identified. The most significant trace element was magnesium, which contributed approximately 1 to 2 percent by weight. Although the organic content varied from 0.5 to 25 percent by weight, most samples were in the range of 1 to 8 percent, with an average of approximately 4 percent for all samples. The in situ mass attenuation coefficient for each sample was obtained from a weighted average of the water, organic and appropriate elemental mass attenuation coefficients. The water content, by

weight, for each sample was based on the in situ moisture measured with the nuclear density/moisture gauge just prior to collecting the sample. All samples were dried prior to the chemical analysis. The mass attenuation coefficient for organic material was estimated by using the value derived for cellulose. Based on these 124 soil samples, an average value of $0.333 \pm 0.012 \text{ cm}^2/\text{g}$ was obtained for the in situ Enewetak soil mass attenuation coefficient. The average value for the dry, organic-free component was $0.365 \text{ cm}^2/\text{g}$ compared to $0.37 \text{ cm}^2/\text{g}$ for pure calcium carbonate.

Table 3 shows the effect on the ^{241}Am conversion factor due to variations (at the 1 and 2σ level) in the soil density and the soil mass attenuation coefficient. For a fixed mass attenuation coefficient of $0.333 \text{ cm}^2/\text{g}$, a $\pm 2\sigma$ variation in the soil density leads to approximately ± 2 percent change in the conversion factor. For a fixed soil density of 1.5 g/cm^3 , a $\pm 2\sigma$ variation in the mass attenuation coefficient leads to a ± 6.5 percent change in the conversion factor. Since the soil density and the in situ soil mass attenuation coefficient, both vary from location to location, it is more appropriate to examine their combined effect on the conversion factor. As seen in Table 3, the maximum effect occurs with a low soil density combined with a high mass attenuation coefficient or a high density combined with a low mass attenuation coefficient. For the appropriate 2σ limits this case would lead to a ± 9 percent change in the conversion factor. In reality low density areas were found to be those areas having high organic and/or soil moisture content, which would lead to a lower mass attenuation coefficient. Similarly, high density areas generally had a higher mass attenuation coefficient. For this combination the appropriate

2σ limits lead to a ± 5 percent change in the conversion factor. This is more typical of the actual range of uncertainty in the data due to observed variation in the wet soil density and in situ soil composition.

6.3 Depth Distribution

One of the most critical factors in relating an in situ measurement to radionuclide concentration in the soil is a knowledge of the source distribution with depth. This is especially true when attempting to determine the total activity per unit area. For the Enewetak ^{241}Am conversion factor, depth distribution data were obtained from profile measurements made during the 1972 reconnaissance survey.² A total of 108 profile measurements were made on 20 islands from Alice to Wilma. The data for each profile, most taken to a depth of 30 cm, were fit to an exponential distribution, as given in Equation (2), and a value computed for the relaxation length. Of the 108 profiles, 11 had a relaxation length of 3 to 5 cm, 45 had a relaxation length of 5 to 10 cm, 15 had a relaxation length of 10 to 20 cm, and the remaining 37 were best represented by a uniform distribution. The last group included those distributions which were slowly decreasing with depth, slowly increasing with depth, or oscillating up and down with depth. Based on these data, the actual conversion factor was computed from a weighted average of the values obtained for relaxation lengths of 4 cm, 7.5 cm, 15 cm, and 1000 cm (i.e., a uniform distribution).

Figure 4 shows the variation in the ^{241}Am conversion factor for average concentration in the top z cm, with z varying between 0 and 10 cm, for several different depth distributions. As can be seen, the conversion factor can vary

Table 3. Variation in the ^{241}Am Conversion Factor* with Different Values for Soil Density and the Mass Attenuation Coefficient

Mass Attenuation Coefficient (μ/ρ) _s (cm^2/g)		Soil Density $\rho(\text{g/cm}^3)$				
		1.22 (-2σ)	1.36 (-1σ)	1.5 (mean)	1.64 ($+1\sigma$)	1.78 ($+2\sigma$)
0.309	(-2σ)	8.61	8.49	8.38	8.29	8.22
0.321	(-1σ)	8.89	8.77	8.66	8.57	8.56
0.333	(mean)	9.18	9.06	8.95	8.86	8.79
0.345	($+1\sigma$)	9.47	9.35	9.24	9.15	9.08
0.357	($+2\sigma$)	9.75	9.63	9.52	9.43	9.36

* $(S^3/\rho)/N_p$ in units of (pCi/g)/cps with detector height of 7.4 m.

Figure 4. CONVERSION FACTORS FOR ^{241}Am GIVING AVERAGE CONCENTRATION IN THE TOP Z CM AS A FUNCTION OF DEPTH DISTRIBUTION.

significantly with variation in the depth distribution. This variation, however, is minimized when determining the average concentration in the top 2-3 cm. In particular, for the 3 cm average specified in the Enwetak cleanup criteria, the conversion factor varies from a value of 8.63 pCi/g per cps for a relaxation length of 3 cm to a value of 9.00 pCi/g per cps for a uniform distribution, compared to a value of 8.95 pCi/g per cps obtained from the weighted average. Thus, even for the extreme case of the measured depth distributions, there is only a 4

percent error in the conversion factor. For 90 percent of the distributions measured, the uncertainty in the conversion factor due to variations in the depth distribution is on the order of ± 1 percent. For this reason, no effort was made to obtain additional depth profiles during the cleanup project.

6.4 Detector Efficiency

The in situ conversion factor is directly proportional to the detector efficiency, as shown

in Equation (8). Since the conversion factor used in the field program for ^{241}Am assumed a detector efficiency of $19.0 \text{ cps}/(\gamma/\text{cm}^2 \cdot \text{sec})$, it was mandatory to correct the data for detectors whose efficiency differed from this value. Table 1 shows the original values obtained for the detector efficiency for each of the six detectors used at Enewetak.

Several of these detectors showed a significant change in efficiency after the original measurement. One detector suffered a 15 percent decrease in efficiency over a single weekend. The daily calibration measurements made in the field were monitored closely in order to detect any sudden change in efficiency. In addition, starting in July 1978 a remeasurement of detector efficiency (using an NBS cross-calibrated ^{241}Am source) was made every three to four weeks. A new correction factor was applied whenever the efficiency changed by 5 percent or more.

6.5 Detector Height

As can be seen in Table 2, variations in detector height do not significantly affect the ^{241}Am conversion factor. This is due primarily to the assumption made in the derivation that the activity is distributed uniformly in the horizontal plane. It is because of this assumption that an in situ measurement provides a direct method for obtaining an area-averaged value for the activity over the field-of-view of the detector. As the detector height increases, the $1/r^2$ decrease in the gamma ray flux at the detector due to a given source element is compensated by the r^2 increase in the area, or source elements, within the detector field-of-view. The rather minor variations observed are due to slight additional attenuation for gamma rays incident at a given angle due to an increased path length through the soil and air. For the Enewetak ^{241}Am conversion factor, a variation of $\pm 0.5\text{m}$ in the normal detector height of 7.4 m leads to a 1 percent change in the conversion factor.

For some areas, measurements were taken on a 12.5 m grid pattern with the detector at a height of 4.6 m. For this height there is a 7 percent change in the conversion factor. Corrections were made to account for this difference on all measurements taken at 4.6 m.

7.0 OTHER SOURCES OF ERROR

7.1 Shielding by the IMP

A portion of the ground area which is within the detector's field-of-view is shielded from the detector by the IMP. This reduces the flux arriving at the detector by approximately 4 percent. All final ^{241}Am data were corrected to account for this 4 percent shielding factor. For measurements taken at a detector height of 4.6 m, the IMP shielding factor is approximately 13 percent. All data obtained at the 4.6 m detector height were also corrected for this factor.

7.2 Contributions due to ^{155}Eu

One of the residual fission products found at Enewetak, ^{155}Eu , emits a 60 keV gamma ray which interferes with the 59.5 keV gamma ray from ^{241}Am . It is possible to correct for this interference by monitoring one of the two other gamma rays emitted by ^{155}Eu : one at 86.5 keV and one at 105.3 keV. The ratio of 86.5 keV to 60.0 keV gamma rays from ^{155}Eu is 24.3 to 1. For an in situ measurement, the ratio of these two gamma rays at the detector is somewhat dependent on the depth distribution of the europium; this is due to differences in soil attenuation at 60 keV ($\mu/\rho=0.333 \text{ cm}^2/\text{g}$) and at 86.5 keV ($\mu/\rho=0.22 \text{ cm}^2/\text{g}$). A reasonable compromise for field measurements is to assume a ratio at the detector of 30:1. As discussed in Section 3, the field program processed the spectral data for the 86.5 keV photopeak. The contribution of ^{155}Eu to the 60 keV photopeak was obtained by dividing the net counts at 86.5 keV by 30 and subtracting this from the net counts at 60 keV. This correction factor was never more than 3 percent (at a few locations on Pearl) and generally ran between 1 percent and 2 percent. For this reason, although the ^{155}Eu was always monitored, no significant correction was required for the ^{241}Am data.

7.3 Effects of Detector Distortion

The typical symptom of detector degradation (due to icing, vacuum leak, lowered bias, etc.) was reduced resolution, i.e., wider photopeaks. The simple analysis program used in the field could not accommodate such an effect. Photopeak counts would be spread into the background windows resulting in an erroneously low value for net counts and, therefore, soil concentration. Window limits in the program

could have been changed in the field if one cared to analyze peak shapes for a detector that was degraded but stable. The philosophy at Enewetak, however, was to correct the problem rather than attempt to correct the data.

7.4 Brush Correction Factor

Most of the islands surveyed were covered with a heavy layer of *Messerschmidia* and *Scaevola* scrub vegetation, ranging in height from approximately 1 to 4 meters. A series of measurements were performed in October-November 1977 on Pearl to determine the effect of this vegetation on the 60 keV gamma ray from ^{241}Am . Ten representative areas with brush covering 70-80 percent of the IMP field-of-view were measured. The access road cut through the brush accounted for most of the open area. Each area was then carefully cleared of brush by hand to prevent any soil disturbance and the measurements repeated. The results of this experiment gave a brush correction factor of 15 percent for 100 percent brush cover. No correlation was observed between the brush height and the brush attenuation factor. This was ascribed to the fact that the vegetation normally encountered typically grew in the form of a canopy rather than solid cover.

At each measurement location, an estimate of the percent brush cover within the detector field-of-view was made by the operator. This value was then used to provide a correction factor for brush attenuation. The estimate of brush cover was somewhat subjective and could have been in error by as much as 20 percent for some locations. Even a 20 percent error in the brush cover estimate, however, would only introduce a 3 percent error in the ^{241}Am concentration value. Thus, although some uncertainty was inherent in the method used to determine a brush attenuation correction factor, the uncertainty was less than would result from ignoring brush attenuation effects completely.

7.5 Measurement Reproducibility

A repeatability experiment was conducted on Pearl at location 3-N-0.5 in May 1979 to determine if any systematic variation could be observed in the IMP measurements over the course of a typical day. A total of 17 measurements were made, each for the standard 900-sec

measurement time, with the detector fixed in position. The sample standard deviation for the series of measurements was 5 percent of the mean value. For the same set of measurements the average one sigma error due to counting statistics was 6.7 percent. No systematic variation was observed between the early morning measurements, made when the ground was damp due to an early morning rain, and the afternoon measurements made during the hottest part of the day.

One location on Janet was remeasured five times over a two-month period in the fall of 1977. The standard deviation for this set of measurements was 7.8 percent of the mean value. During the same period of time, two locations on Pearl were remeasured three times over a period of one month. The standard deviation was 4.4 percent of the mean for one location and 6.6 percent of the mean for the other location.

These data indicate that the primary source of error in measurement reproducibility was associated with counting statistics, which generally ran from 5 to 7 percent.

8.0 DETECTOR FIELD-OF-VIEW

The detector field-of-view is of some practical concern for an in situ measurement. However, as shown in Figure 3, even with a collimator the detector response does not drop abruptly to zero. Thus the field of view has an edge which is somewhat fuzzy. The field-of-view can only be defined in a practical sense by investigating the fraction of the flux reaching the detector which originates from a given area on the ground. This can be obtained using Equation (3) combined with the relative angular response of the detector given in Figure 3. The results for 60 keV gamma rays are shown in Figure 5. It can be seen that 95 percent of the total flux originates from a circle having a diameter of approximately 21 m, while 99 percent of the total originates from a circle having a diameter of approximately 25 m. Thus a 30 percent increase in area at the edge of the field-of-view only contributes an additional 4 percent to the total flux. In going from a 21m diameter circle to a 30 m diameter circle, the total area is doubled. However, the flux arriving at the detector from this additional area represents only 5 percent of the total. Due to the collimator, all 60 keV gamma rays originating beyond a circle of approximately 30 m in diameter are cut off. It can

Figure 5. FRACTION OF THE TOTAL FLUX REACHING THE COLLIMATED DETECTOR ORIGINATING FROM A CIRCLE OF DIAMETER d DIRECTLY BELOW THE DETECTOR FOR A DETECTOR HEIGHT OF 7.4 m.

also be seen that minor variations in the detector angular response from system to system would not significantly affect the results of the in situ measurement.

On most islands at Enewetak it was necessary to cut roads through the brush to survey in a grid and to allow the IMP access between locations. In many cases the method used to clear away the brush led to significant soil disturbance within the approximately 3 to 4 m wide area of the road.

Figure 5 can be used to estimate the fraction of the total flux which originates from this disturbed area. The detector was routinely suspended directly over the center of the road. From Figure 5 it is seen that approximately 10 percent of the total flux originates from a 3.5 m diameter circle directly under the detector. This entire area was normally within the road. The road also occupies approximately 15 percent of the remaining area which contributes the other 90 percent of the total flux. Thus the disturbed area within the road

contributed about 25 percent of the total flux reaching the detector.

9.0 COMPARISON WITH SOIL SAMPLE DATA

In order to obtain an independent measurement which could be used as a quality control check on the in situ measurements, a soil sampling program was established which attempted to obtain a sample which was representative of the average concentration within the area sampled by the IMP. A total of 109 locations on 17 different islands were compared using both techniques. Two soil sample composites, each comprised of 6 samples, were analyzed for each measurement location. The ratio of the mean of the soil sample results to the mean of the IMP results was 1.05. A difference of approximately 10 percent (based on laboratory soil moisture measurements) was expected since the soil sample results were expressed in terms of dry weight rather than in situ or wet weight as given by the IMP. After correcting for this difference in reporting methodology, the IMP mean value was approximately 5 percent greater than that given by the soil sample data.

There are a number of factors which could account for the measurement difference. Probably the most important is that the soil sample results for each location were based on a measurement of several thousand cm^3 of soil compared to approximately 10 to 15 million cm^3 of soil for the IMP measurement. This fact becomes more important when combined with data obtained on Tilda which indicated there could be a high degree of variability in ^{241}Am activity in both the horizontal and vertical directions within a single IMP measurement location. For many of the locations sampled, the two soil sample composites obtained within the same area gave significantly different results, in some cases by as much as a factor of 2 or 3. This again indicated there could be a high degree of variability within a given measurement location. Because of this, one would not necessarily expect to achieve agreement at any given measurement location between soil sample analysis and an IMP measurement. This was found to be the case. However, based on a large number of comparisons, the overall agreement was considered excellent.

10.0 RESULTS FOR ^{137}Cs AND ^{60}Co

Although the primary function of the in situ measurement system at Enewetak was to obtain surface (0-3 cm) concentration values for ^{241}Am , complete spectral data were obtained at each measurement location for gamma ray energies up to approximately 1500 keV. The rather simple data reduction program used in the field only processed these data for ^{241}Am , ^{155}Eu , ^{137}Cs and ^{60}Co . The ^{155}Eu data were used to correct the ^{241}Am data due to interference from the 60 keV gamma ray of ^{155}Eu , as discussed in Section 7.2. Data for ^{137}Cs and ^{60}Co were used to obtain external exposure rate values for use in the post-cleanup dose assessment. The selection of these particular isotopes for detailed analysis was based on previous data which indicated the primary gamma ray emitting radionuclides at Enewetak were ^{241}Am , ^{137}Cs and ^{60}Co .² Random visual inspection of the complete spectrum tended to support this assumption with the exception of Pearl, where measurable levels of ^{133}Ba were detected.

Conversion factors, in units of pCi/g per cps, can be obtained for these radionuclides, as well as any others which might be present in detectable quantities, by using Equation (8) in Section 5.3 with the appropriate input parameters. Figure 6 shows a typical detector efficiency (A_{θ}) curve for the HPGe planar detectors which were used at Enewetak. Angular response data, $R(\theta)$, were also obtained for a number of gamma ray energies. Figure 7 shows the results for 662 keV gamma rays from ^{137}Cs , with and without the collimator. Although the collimator does have a significant effect on the angular response, it was not thick enough to completely cutoff the higher energies as it did for the 60 keV gamma rays from ^{241}Am (see Figure 3).

Conversion factors are given in Table 4 for ^{137}Cs as a function of source depth distribution. Also shown in Table 4 are conversion factors relating external exposure rate (in $\mu\text{R/h}$ at 1 meter) to photopeak count rate. The exposure rate conversion factors were obtained from data given by Beck, et al³ which relate exposure rate at 1 meter to source distribution in the ground for a variety of radionuclides. It can be seen that, although a knowledge of the source depth distribution can be very critical in determining concentration values, it is not nearly as critical for determining exposure rate values.

Figure 6. A TYPICAL DETECTOR EFFICIENCY VERSUS ENERGY CURVE FOR THE HPGe PLANAR DETECTORS USED AT ENEWETAK

For the post cleanup dose assessment, external exposure rate values for ^{137}Cs were obtained using a conversion factor of $3.6 \mu\text{R/h}$ per cps. For ^{60}Co conversion factors of $20.5 \mu\text{R/h}$ per cps for the 1173 keV peak and $22.3 \mu\text{R/h}$ per cps for the 1333 keV peak were used. In principle, either peak could be used to determine the total external exposure rate due to ^{60}Co . Both should lead to the same result. In practice, however, some measurements showed a slight difference in the

two results. In these cases the average value was used.

Table 5 shows the post cleanup island average values for ^{137}Cs and ^{60}Co exposure rate from the IMP data. Also shown for comparison are the values obtained in November 1972 from an aerial survey.² For comparison, the aerial data have been corrected for radioactive decay to November 1978. The two sets of data agree fairly

Figure 7. RELATIVE RESPONSE OF THE HPGe DETECTOR FOR 662 keV GAMMA RAYS AS A FUNCTION OF INCIDENT ANGLE. Zero degrees being directly below the detector.

well except in the obvious cases where cleanup activities have reduced the levels. It should be noted that the island average values for the aerial survey data were estimated from exposure rate contours while those for the IMP were obtained by numerically averaging discrete data points.

The island average values for ^{137}Cs exposure rate given in Table 5 can be converted to island average concentration values using the data given in Table 4. Although the depth distribution for ^{137}Cs can vary significantly from point-to-point, the profile data obtained in 1972 showed that a reasonable compromise for all the northern islands would be to take an average of values given for a 10 cm and a 15 cm relaxation length. Table 6 gives the results for the average concentration in the top 15 cm based on a conversion factor of 5.4 pCi/g per cps. Shown for comparison are the results obtained from the 1979 fission product data base soil sampling program. In general the results agree quite favorably.

11.0 OPERATIONAL EXPERIENCE

11.1 IMP Operations

The IMP performs in situ gamma ray spectroscopy to measure ^{241}Am and other

gamma emitters and thus functions as a mobile laboratory. Experience in operation of a sophisticated system such as the IMP under remote tropical conditions is limited. Thus this section has been included to discuss the operational problems and their solutions. It was desired to have two IMPs operational at all times. To achieve this, three complete IMPs were provided. It was also desired to have two operating detectors for two of these IMPs, and a third available on-atoll in the Radiation Laboratory for soil sample spectroscopy. Four detectors were procured to satisfy these requirements. The desired mode of operation was not always achieved, however, due to detector repair requirements.

Operating conditions for the IMPs included high temperature, high humidity, and salt spray. Depending on the season, tropical rain storms and high winds were often encountered. During the project, several tropical storms caused major damage to the atoll. During these times the IMPs were secured inside the IMP shed and the detectors lashed inside the IMP cab.

Transportation between islands was by military landing craft or amphibious LARCs. The landing craft ramp angle was usually about 30 degrees. The LARC ramp angle ranged up to 60 degrees.

Table 4. Conversion Factors Relating the Net Photopeak Count Rate for ^{137}Cs to Source Activity in the Soil and to External Exposure Rate, as a Function of Source Distribution, for a Detector Height of 7.4 m.

Relaxation Length	^{137}Cs Conversion Factors		
	Average Activity in the Top z cm		External Exposure Rate at the 1 Meter Level
$1/\alpha$ (cm)	z (cm)	$[(S_z/\rho)/N_p]$ $[(\text{pCi/g})/\text{cps}]$	$[(\mu\text{R/h})/\text{cps}]$
5	0	13	3.6
	5	8.2	
	10	5.6	
	15	4.1	
	25	2.6	
	40	1.6	
	60	1.1	
10	0	10	3.7
	5	7.9	
	10	6.3	
	15	5.2	
	25	3.7	
	40	2.5	
	60	1.7	
15	0	8.8	3.4
	5	7.5	
	10	6.4	
	15	5.6	
	25	4.3	
	40	3.1	
	60	2.2	

Considerable shock and vibration was inherent in any boat operation, and sea conditions sometimes made a fast, rough embarkation mandatory.

Several design measures were taken to minimize the effects of these conditions. The detector was mounted inside a cannister packed with an annulus of foam cushioning (polyurethane). The detector rested on a 1/4-inch, foam-rubber-cushioned metal support ring. The ring itself was spring suspended inside the cannister. The top of the detector dewar was tightly packed using foam cushioning against the top lid of the cannister. The collimator cone was suspended from the bottom of the dewar, so the collimator and dewar (with protruding detector) moved as a

unit. The cannister was suspended from a hinged yoke allowing the cannister to remain vertical as the boom was pushed out to 20-degrees-from-vertical position. A latch-plate locking pin was used to secure the cannister to the boom at all times except while the cannister was elevated to take a measurement.

The IMP data acquisition portion of the cab was air conditioned from a roof-mounted unit. The air conditioner was operated continuously at full cool. The IMP electronics, computer and printer were mounted in a standard shock-mounted instrument rack inside the IMP. The mounting was successful as it allowed use of laboratory equipment during field operation. Maintenance experience was similar for the IMP computers

Table 5. Island Average Exposure Rate Values for ^{137}Cs and ^{60}Co Obtained from the Final Post Cleanup IMP Data and from the 1972 Aerial Survey Data

Island	Average Exposure Rate ($\mu\text{R/h}$ at 1 m)					
	^{137}Cs			^{60}Co		
	Aerial* (Nov 72)	Aerial** (Nov 78)	IMP	Aerial* (Nov 72)	Aerial** (Nov 78)	IMP
Alice	42	37	29.3	36	16	17.4
Belle	61	53	35.8	50	23	15.2
Clara	20	17	18.3	19	8.6	9.2
Daisy	6.8	5.9	4.4	14.4	6.5	7.0
Irene+	14	12	3.3	63	29	13.0
Janet+	25	22	10.2	13	5.9	3.3
Kate	11	9.6	5.0	7	3.2	1.8
Lucy	6	5.2	6.1	7	3.2	2.6
Mary	5.5	4.8	3.1	4	1.8	1.4
Nancy	6	5.2	6.0	5	2.3	2.2
Olive	6.5	5.7	5.1	4.5	2.0	1.9
Pearl+	12	10	4.0	45	20	7.0
Ruby	2	1.7	0.6	12	5.4	3.8
Sally+	3.5	3.0	2.0	3	1.4	1.5
Tilda	4	3.5	2.3	2	0.9	0.7
Ursula	3	2.6	0.9	1.8	0.8	0.3
Vera	2.8	2.4	1.7	2	0.9	0.5
Wilma	1	0.9	0.8	1	0.5	0.3
Yvonne+	5.6	4.9	1.9	22.4	10	4.1

*From NVO-140, Table 9, p. 80 (reference 2)

**Nov. 72 data corrected for radioactive decay to Nov. 78

+Islands where soil was removed during the cleanup

Table 6. Average ^{137}Cs Activity in the Top 15 cm Obtained from the IMP Data (with $1/\alpha = 12.5$ cm) and the 1979 Fission Product Data Base Results

Island	Final IMP Results (pCi/g)	Fission Product Data Base Results (pCi/g)
Alice	44	40
Belle	54	61
Clara	27	22
Daisy	6.6	6.8
Irene+	5.0	6
Janet	15	16
Kate	7.5	7.8
Lucy	9.2	12
Mary	4.7	6
Nancy	10	11
Olive	7.7	7.5
Pearl	6.0	7.2
Ruby	0.9	2.0
Sally	3.0	3.5
Tilda	3.5	3.2
Ursula	1.2	1.2
Vera	2.6	3.0
Wilma	1.2	1.3

+Additional cleanup was performed on this island after the fission product data base samples were obtained.

and the laboratory computers. The pulse height analyzer (PHA) was designed for field use and had a satisfactory maintenance record.

Rain storms initially caused problems of water penetration at cable connectors. These problems were solved by installing a flexible rubber boot over the cables at the cannister entrance and at the feedthrough in the rear of the cab. In addition, the feedthrough was recessed inside the cab wall and partially protected by a door. Thermal insulation was installed around the cab side of the feedthrough plate to avoid condensation problems. The dew point at Enewetak is usually greater than 80°F, so a cold connector (i.e., less than 80°F) caused condensation.

The Onan electrical generator was modified to increase its reliability. The regular fuel pump was exchanged for an electric fuel pump. An oil bath air cleaner was installed. A water separator and improved filter was installed in the gasoline feed line. One of the Onans operated for about 4,400 hours, which is about twice the normal lifetime.

Rust prevention was also a design concern. The inner and outer surfaces of the sheet metal forming the IMP body were coated with zinc chromate primer. Outer surfaces then received a coat of white acrylic enamel. Inside surfaces were coated either with Glyptal varnish or commercial undercoating material, depending on the location. These initial measures were combined with a maintenance grind-and-repaint program. There was considerably less deterioration on the IMPs than on other equipment on-atoll that did not receive this type of preventive maintenance.

11.2 Maintenance Program

Critical spare parts and replacement components were maintained on-atoll. These spares included an Onan electrical generator, air conditioners, air compressors, the extendable mast, and spare parts for the IMP and Onan engines. Electrical spares included the cable harness and detector power supplies. Mechanical and electronic maintenance was performed by the two-man IMP technician crew, assisted by the two Air Force mechanic-drivers who were assigned to the IMP. Occasionally the base operating contractor's vehicle maintenance shop provided a special service, such as welding. The required spare parts and components were selected based on general experience, modified by on-atoll history. Replacements were ordered as parts were used

from the spares inventory, or as failure required a part.

A regular maintenance schedule was established and usually adhered to. One day per six day work week was usually devoted to maintenance for each operating IMP. This was modified based on urgency of survey schedules, and further modified depending upon transportation needs. For example, if an IMP were working a remote island, i.e., not served by a military work boat, and required one or two days to complete the survey, the survey would be completed and maintenance delayed until the third day.

11.3 Liquid Nitrogen

The HPGe detectors used in the IMPs operated at liquid nitrogen temperature. In the early months of the program the liquid nitrogen was air lifted from Honolulu on scheduled MAC cargo flights. Two military surplus 500-gallon containers were used. Shipping regulations required that the pressurized containers be vented outside the aircraft cabin. The condition of the containers, combined with these regulations, resulted in excessive nitrogen loss before delivery at Enewetak. The on-atoll transfer containers were military surplus, wheeled, horizontal 50-gallon liquid oxygen carts, all of which had a high liquid nitrogen loss rate. This system was rather expensive and inconvenient.

A military surplus, trailer mounted liquid oxygen/liquid nitrogen generating plant was obtained, and the base operating contractor had people trained to operate it. About every two weeks, the plant was activated and two of the three on-atoll liquid nitrogen containers were filled. The liquid nitrogen containers, specifically purchased for this program, were more efficient containers than the original containers. The containers were Linde LS-160B models, each holding 160 liters. This program successfully supplied all the IMP and Radiation Lab liquid nitrogen requirements.

11.4 Detector Performance

Three detectors were purchased for use on the project and a fourth was ordered a few months later, when the effects of Enewetak conditions on the detectors were confirmed. Two other detectors had been procured for a similar measurement program at the Nevada Test Site

(NTS). Detectors were assigned by DOE to Enewetak or NTS, based on priority and scheduling of the two projects. Detectors were transferred informally and expeditiously, in response to DOE direction. All six detectors were used at Enewetak at various times.

All detectors used at Enewetak were initially calibrated in Las Vegas. Starting in July 1978, a calibrated ^{241}Am source was available on-atoll and periodic remeasurements of effective detector area were made. These remeasurements were used to provide an effective area correction factor for data handling. Field calibration sources, consisting of ^{241}Am , ^{137}Cs , and ^{60}Co , were used for three-times-daily detector performance monitoring. Field calibration was performed to set the gain of the detector electronics, and to generally track detector behavior. For the field calibration measurements, the percentage standard deviation for the ^{241}Am value was 2 to 5 percent. The mean error in a series of effective area measurements was 1.1 percent.

In the first months of the project, gradual loss of detector resolution with usage was noted. This was traced to water vapor entering the liquid

nitrogen dewar during refilling in the field, causing an ice layer to form at the bottom of the dewar. This in turn partially insulated the detector, causing higher than design operating temperature. The problem was solved by the following maintenance procedure. About once a month, the detector was brought to room temperature, and ethanol was used to remove water from the detector dewar. The dewar interior was then dried using a stream of dry air. The dewar was then refilled with liquid nitrogen.

The average detector life span when installed in an IMP was about four months, with a range of less than a month to over seven months. Causes or symptoms of failure were: preamp corrosion, vibration sensitivity, no signal transmission, wide peaks and noise at low energy, and dewar failure. The last three items listed can probably all be classified as dewar failure, and were ultimately traced near the end of the project to corrosion of the 22 mil beryllium entrance window, or the beryllium-aluminum epoxy seal. At that time an all-aluminum detector housing was ordered for repaired detectors; however, none of this type housing was available in time to be used on the Enewetak project.

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