APPENDIX G

REVIEW OF AERIAL GAMMA RADIATION SURVEYS AROUND THE ROCKY FLATS PLANT

Gamma radiation surveys can be used to characterize the concentrations of gamma-emitting radionuclides in soils. For the Rocky Flats Plant (RFP), the primary radionuclides of concern have been isotopes of plutonium. However, the primary radiations emitted by plutonium are alpha and beta radiations which are difficult to measure, except with laboratory analyses of samples. Thus, direct field measurements of plutonium in soil, using radiation survey instruments techniques, are not feasible. However, ^{241}Pu is present in the plutonium from the RFP, and it decays to form ^{241}Am. The decay of ^{241}Am includes coincident emission of an x-ray of energy about 60 keV, which can be detected by some gamma radiation survey instruments. Concentrations of ^{241}Pu and ^{239}Pu can be calculated from the measured ^{241}Am concentrations and ratios of plutonium to ^{241}Am, obtained from other studies. Gamma radiation surveys may also be useful for investigating other radionuclides of potential concern, including ^{137}Cs and ^{238}U.

Aerial gamma radiation surveys are generally performed to study large areas of land and facilities that may be difficult or costly to survey with other techniques. Such aerial surveys have been routinely performed around many of the U.S. Department of Energy (DOE) nuclear weapons facilities.

In this appendix we briefly summarize results of aerial gamma radiation surveys that have been performed around the RFP. We focus primarily on measured concentrations of ^{241}Am in soil, as these can be related to plutonium concentrations in soil. In addition, Colorado State University may have significant quantities of in situ data around the RFP (Webb 1995). However, we have not evaluated those data, as it was thought that the soil sampling data would be more useful to the project (see also Chapter VIII).

RESULTS OF AERIAL SURVEYS AROUND THE ROCKY FLATS PLANT

Routine aerial surveys of DOE facilities were initiated in 1958 to monitor radiation levels around facilities involved in producing or using radioactive materials. The routine surveys were initially performed by the U.S. Geological Survey, but relatively early in the program EG&G Energy Measurements (as it is now known) began performing the surveys (Popenoe 1995). EG&G Energy Measurements (EG&G/EM) is separate from the EG&G Rocky Flats operating contractor.

We obtained reports describing four aerial gamma radiation surveys of the area around the RFP, performed in 1960 (Popenoe 1965, 1966), 1972 (EG&G 1974), 1981 (Boyns 1982), and 1989 (Boyns 1990). The 1960 survey was a very large area survey (6500 mi^2), focused on the Colorado piedmont, not the RFP. The other surveys covered smaller (though still large) areas (200 mi^2 and less), focused around the RFP. As described below, another survey was apparently performed in 1973, though no report of this survey was issued. These five (four documented by reports and one undocumented by a report) are thought to be the only aerial gamma radiation surveys performed around the RFP.

The four documented aerial surveys were performed for large areas around the RFP, and results were described for plant areas and areas outside the plant. Because we are interested in releases of radioactivity from the plant, we focus on results for areas outside the plant boundary.

The aerial surveys generally attempt to determine radiation contributions from radionuclides in soils and facilities (terrestrial sources), so corrections are made to account for contributions from airborne radioactivity and cosmic radiation.

1960 Aerial Survey of the Denver Area

Two documents report results of the 1960 aerial survey; one is a detailed map with some text describing results (Popenoe 1965) and the other is a formal report with more detailed discussions of methods and results (Popenoe 1966). The following is taken primarily from the formal report (Popenoe 1966). The 1960 survey was performed by the U.S. Geological Survey as part of the Aerial Radiological Measurement Surveys (ARMS-I) program. The survey was conducted from September 15 to October 13, 1960, over about 6500 mi^2 of the Colorado piedmont. The area surveyed includes about 50 mi north and south of the RFP, with the eastern survey boundary along the 104°W longitude meridian, and the western boundary being the front range of the Rocky Mountains. The measurements were taken with six thallium-activated sodium iodide detectors, connected in parallel and fed through a discriminator and pulse shaper to accept only signals from gamma radiations with energy greater than 50 keV. The detectors were carried in an aircraft flying east-west flight lines spaced 1 mi apart at an altitude of 500 ft.

The results of the survey were given in counts per second (cps) gross radiation of energy greater than 50 keV (Popenoe 1966). Maps were provided, which show cps isopleth lines (Popenoe 1965 and Popenoe 1966). A geologic map of the same area was also provided, and the radiation levels were seen to be related to the surface geology. In particular, it was concluded that the higher radiation levels occurred over areas of alluvium derived from crystalline rocks of the front range, due to the higher radioactivity existing in such rock. Along the front range, radiation levels ranged from about 300 to about 1500 cps (Popenoe 1965 and Popenoe 1966). Above the RFP, radiation levels were in the range 600–750 cps. This is slightly greater than levels above the area adjacent to the RFP (mostly 500–600, with some 300–500 cps), but less than levels in many other areas equally close to the front range. The reports do not mention any other reasons (other than geology, that is) for the levels measured above the RFP.

1972 Aerial Survey

The 1972 survey was performed in two stages, with a detailed survey performed in May for an area of about 2 mi (east-west) × 8 mi (north-south), and a larger-area survey performed in October over an area of about 200 mi^2 (EG&G 1974). Both surveys were performed with radiation detectors mounted in a small airplane, flying at altitude of about 500 ft. The detailed-area survey involved flight lines spaced about 0.2 nautical mi apart, while the larger-area survey used spacing of about 1 nautical mi. The radiation detector system consisted of an array of 14 NaI(Tl) scintillation crystals, each 4 × 4 in. (assumed to be diameter × thickness).

Measurements consisted of two types, made simultaneously. The first is gross counts of gamma radiation having energy greater than 50 keV. These gross counts were converted into equivalent radiation exposure rates ($\mu R\ h^{-1}$) at a level 3 ft above the ground surface, by applying corrections to account for background (nonterrestrial) radiation and to adjust from the flight altitude to the 3-foot level. The second measurement type is gamma spectral data (which show the distribution of gamma energies), recorded for the energy range 0.05 to 3.0 MeV (50 to 3000 keV). The gamma spectra could be used to identify particular radionuclides.

Based on results of the larger-area survey, EG&G concluded that "...both the concentration and relative abundance of radioactive isotopes are consistent with normal terrestrial background radiation." The 3-ft exposure rates were generally between 14 and 22 $\mu R\ h^{-1}$. The detailed survey, however, showed elevated exposure rates, from 20 to 100 $\mu R\ h^{-1}$, near or over plant buildings. These elevated exposure rates were thought to be due to the accumulation of fissionable material (this could include uranium or plutonium) in the buildings. The radioisotopes responsible for the elevated exposure rates could not be identified absolutely, due to constraints of aircraft speed and minimum flying altitude.

Plutonium and associated radionuclides were thought to be at least partially responsible for the elevated exposure rates. The EG&G report (EG&G 1974) indicates that another survey of the RFP was conducted in May 1973, using special instrumentation, carried in a helicopter, to determine ^{241}Am concentrations associated with plutonium contamination. The report indicates that the 1973 survey was to be the subject of a separate report. Discussions with workers and former workers at the RFP have indicated that there may have been a report or maps produced which provided results of these ^{241}Am measurements. However, after much searching, we were unable to locate such a report or map. For further followup, we contacted EG&G/EM in Las Vegas and talked to a technical information administrator. This information administrator indicated that the ^{241}Am survey was flown, but the budget was reduced and no results were produced and no report or even letter report was issued (Gordon 1995). Based on this information, we conclude that results of the ^{241}Am survey are probably not available.

1981 Aerial Survey

The 1981 survey was performed in August, over an area of about 93 km^2 (36 mi^2) around the RFP (Boyns 1982). The survey area was roughly 7 mi (east-west) × 5 mi (north-south). The survey used radiation detectors mounted in a helicopter. Flight lines were spaced about 250 ft apart, and were flown at an altitude of about 150 ft. The radiation detector system consisted of 20 NaI(Tl) scintillation crystals, each 12.7 cm diameter × 5.1 cm thick.

The radiation detection capabilities were improved over the 1972 survey, and ^{241}Am could be detected. The minimum detectable activity for ^{241}Am was expressed as the following amounts, any of which would produce essentially the same detector response:

- 5.8 mCi for a point source,
- A surface concentration of 0.8 $\mu Ci\ m^{-2}$ for surface contamination, or
- A concentration in soil of 28.6 $pCi\ g^{-1}$, for a 5-cm thick surface layer of soil, with a particular, assumed exponential distribution with depth.

No specific analyses were reported for ^{137}Cs.

Results of the survey showed ^{241}Am contamination in a "plume" extending eastward from the general area of the 903 Area. This contamination was measureable as far as about 500 m east of the former Pad. Because the exact distribution of contamination with depth was not known, the measurements were not converted into concentrations in soil, but were given as counts per second. However, the report (Boyns 1982) did provide conversion factors for a variety of possible depth distributions. If we apply these correction factors, maximum concentrations within the plume area would be around 50–140 $pCi\ g^{-1}$ (where the range reflects the use of a range of factors for the possible depth distributions). This level of maximum concentration corresponds relatively well with the maximum of about 90 $pCi\ g^{-1}$ seen for the same area in the more recent soil sampling of DOE (1995).

1989 Aerial Survey

The 1989 survey was performed in July 1989, over an area of about 124 km^2 (48 mi^2) around the RFP (Boyns 1990). The survey area was roughly 8 mi (east-west) × 6 mi (north-south). The survey used radiation detectors mounted in a helicopter. Flight lines were spaced about 250 ft apart, and were flown at an altitude of about 150 ft. The radiation detector system consisted of eight NaI(Tl) scintillation crystals, each 2 in. thick × 4 in. wide × 16 in. long.

The radiation detection capabilities for ^{241}Am were improved again over the 1981 survey. For the aerial survey, the minimum detectable activity for ^{241}Am was expressed as the following amounts, any of which would produce essentially the same detector response:

- 2.9 mCi for a point source,
- A surface concentration of 0.35 μCi m^{-2} for surface contamination, or
- A concentration in soil of 11.2 pCi g^{-1}, for a 5-cm thick surface layer of soil, with a particular, assumed exponential distribution with depth.

For this 1989 survey, results were also reported for ^{137}Cs measurements.

Field measurements were also made at ground level in the general area where elevated ^{241}Am was seen in the 1981 survey (Boyns 1990). These in situ measurements used high purity germanium detectors (HPGe), which allow better discrimination of low-energy gamma radiation than do the NaI(Tl) detectors used in the aerial survey. For the field survey, measurements were made on a grid spacing of 200 ft, with the detector about 3 ft above the ground surface. The minimum detectable surface concentration of ^{241}Am was indicated to be 0.006 μCi m^{-2}.

As for the 1981 survey, results of the 1989 aerial survey were presented as counts per second. Conversion factors were again provided, for converting to concentrations in soil, for various depth distributions. A "plume" of ^{241}Am, extending eastward from the 903 Area, was seen, and the activity appeared to be in the same location and to have similar magnitude to that seen in the 1981 survey (Boyns 1990). The area showing measureable ^{241}Am was slightly larger than in the 1981 survey, but this was attributed to the improved sensitivity (lower minimum detectable activity) of the 1989 survey.

Results of the aerial measurements for ^{137}Cs indicated that concentrations were similar to worldwide background concentrations (Boyns 1990). In addition, there was no pattern of ^{137}Cs distribution to suggest emissions from the RFP. In fact, ^{137}Cs concentrations were generally lower over the RFP area, as well as for other recently disturbed areas, such as new housing developments. This is expected, and is consistent with recent soil disturbances causing the dilution of the surface contamination (where it was initially deposited) into the generally less contaminated deeper soils.

Results of the in situ survey were converted to surface concentrations, with the assumption of uniform surface contamination (Boyns 1990). Results indicated surface ^{241}Am concentrations of 0.006–0.84 μCi m^{-2} outside the perimeter fence. These levels were indicated to be consistent with results of the aerial survey.

As part of the in situ survey, coincident in situ measurements and soil samples were taken, to compare results from the different methods (Boyns 1990). The results indicated that in situ measurements could be quite useful for determining soil concentrations of ^{241}Am, and thus plutonium, through the use of plutonium to ^{241}Am ratios. Some concerns were also noted: (1) the field of view of the in situ measurements is much larger than the size of a soil sample; this needs to be accounted for in planning surveys, (2) the plutonium to ^{241}Am ratio must be known if the goal is estimating plutonium concentrations. This ratio can be determined through soil sampling

and analysis, or from considerations of decay and ingrowth, and (3) it is necessary to know the depth distribution of the ^{241}Am (or other radionuclide being measured) so that proper conversion factors can be used to convert from the gamma measurements to estimates of soil concentrations; such distributions can be determined from soil sampling at intervals in depth.

1990 In Situ Survey

Another in situ survey was performed in 1990 (Reiman 1991). Two areas were surveyed: (1) an area around the old landfill, in the southwest part of the RFP production area, and (2) an area east of the 903 Pad. The surveys were conducted on 150-ft square grid patterns using two high purity germanium detectors (HPGe) of type 20%, N-type, coaxial detectors. One detector was used at height 1 m above the ground surface, while the other was used at height 7.5 m above ground.

The survey east of the 903 Pad is most pertinent to our work. The area surveyed was about 2400 ft (east-west) × 1950 ft (north-south), and was mostly east of the 903 Pad. Gamma spectra were collected that allowed the determinations of ^{241}Am, ^{137}Cs, ^{238}U, ^{226}Ra, ^{232}Th, and ^{40}K, though we focus on ^{137}Cs and ^{241}Am results here. Based on the assumption of uniform contamination to a depth of 3 cm, the minimum detectable concentration of ^{241}Am was 0.9 pCi g^{-1}. Cesium-137 concentrations were reported to be consistent with expected levels from worldwide fallout (Reiman 1991). Americium-241 concentrations were seen to fall off with increasing distance east of the 903 Pad and were consistent with results of the 1989 aerial survey.

POTENTIAL PROBLEMS IN EVALUATING AERIAL SURVEY RESULTS

There are two important considerations for evaluating results of aerial radiation surveys, that are not encountered for soil sampling. First is the very large field of view of the radiation detectors, due to their altitude above the ground. For the 1972 survey, the field of view was about ¼ mi wide, for a mean gamma energy of naturally occurring isotopes (EG&G 1974). This field of view would be somewhat smaller for the lower energy radiation from ^{241}Am, and would be smaller at lower altitudes (as in the later surveys). Because of the large field of view, it is difficult to use the results to precisely locate the radiation sources. When isoexposure contours (contour lines of constant exposure rate or radiation count rate) are then drawn, the result is some broadening and averaging of the actual soil radionuclide concentrations. As an example, if there was an isolated “hot spot” of activity on the soil (i.e., a point source), the aerial survey would indicate an elevated area larger than it actually was, and would indicate a lower average concentration in soil. If the exact area of the source was known, correction factors, which are provided (Boyns 1990), can be applied to calculate the actual concentration. In the case of a small source, the *total* activity measured should correspond to the actual total, within analytical uncertainties.

A second difficulty in evaluating results of the aerial surveys arises because the actual distribution of contamination with depth in the soil is unknown. We mentioned above that conversion factors are provided, in the aerial survey reports, to convert gross count rates into estimated concentration of radioactivity in soil. These conversion factors are provided for a number of different potential depth distribution of the radioactivity. For perspective on the variability of these conversion factors, we considered a table given in the 1989 survey report (Boyns 1990) for ^{241}Am. In converting gross counts to an average concentration in the top 5 cm

of soil, the conversion factors have a range of more than a factor of two. For the concentration in the top 10 cm of soil, the conversion factors have a range of a factor of about five. The actual conversion factors vary for different radionuclides (because of gamma energy), different depth distributions in soil, and for different radiation detector systems.

CONCLUSIONS

Based on the four documented aerial surveys reviewed here, some conclusions can be made. First, it is clear that ^{241}Am contamination in soils extends outside the perimeter fence, in a "plume" extending eastward from the 903 Area. This area of contamination appears qualitatively similar to results of soil sampling in the same area (DOE 1995). Maximum concentrations seen in the aerial surveys are also similar to those of the soil sampling study. Though only four aerial surveys have been documented (that we have located), the results of the four are generally consistent. However, detection sensitivities have improved over time, so the more recent surveys have measured somewhat larger areas of contamination, with the outer limits at lower concentrations. There is no information to indicate that the areal distribution of ^{241}Am in soils has changed over time.

The levels of ^{137}Cs measured were generally consistent with worldwide fallout levels, and showed no pattern indicating release from the RFP.

For determining soil concentrations of radionuclides, aerial surveys generally provide a less accurate method than collection and analysis of soil samples. This is due to at least two important factors: (1) the radiation detectors in aerial surveys have a large field of view, which means the locations of contamination cannot be precisely determined, and (2) assumptions must be made about the distribution of contamination with depth, which introduces additional, potentially large uncertainties into the results. However, benefits of aerial and in situ gamma surveys are (1) that a very large area can be monitored, and (2) problems of spatial heterogeneity with soil sampling and analysis are not an issue.

The RFP site contractor has sampled extensively in the area to the east of the 903 Area, with analyses for ^{241}Am, in addition to plutonium and uranium (DOE 1995). The Colorado State University has also performed extensive sampling in this area, for plutonium and ^{241}Am, with particular emphasis on ^{241}Am to plutonium ratios (Schierman 1994; Webb 1996). We conclude that the results of these and other soil sampling studies are more useful for quantitative evaluations of plutonium and americium contamination around the RFP than results of the aerial surveys. However, the aerial surveys are useful for general corroboration of the soil sampling results.

Another aerial survey was performed, in 1973, to examine ^{241}Am concentrations. However, based on our searches for documentation on the survey and a conversation with staff at EG&G/EM, which flew the survey, we conclude that results of the survey are probably not available.

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