RADIOECOLOGY OF NATURAL SYSTEMS

FINAL REPORT

for the period
May 1, 1962 – October 31, 1979

MASTER

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October 31, 1979

prepared for
**THE U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. EY-76-S-02-1156**

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1. INTRODUCTION

This is the final report to the U. S. Department of Energy and its predecessors on Contract EY-76-S-02-1156 with Colorado State University. This project, initiated in May 1962, has carried several titles reflecting changes in activities. Overall however, the title of recent years, "Radioecology of Natural Systems," appropriately encompasses the diverse investigations conducted since the inception of the project. During the first five years of the program, investigations were focused on the accumulation of fallout radionuclides in a well-studied mule deer population in north-central Colorado. Understanding of the accumulation patterns required various studies of an ecological or physiological nature. In 1967, the scope of the program was enlarged to include studies on radionuclide behavior in mountain lake ecosystems, radiation effects on a short-grass plains ecosystem, and the combined effects of radiation and intra-specific competition on the pika (Ochotona princeps). In 1971, studies on the geochemistry of lead in an alpine lake and the foraging impact of grasshoppers were added to the diverse program. The summer of 1972 marked the beginning of the research program which was to dominate the effort for the duration of the contract, namely the behavior of plutonium in the terrestrial environs of the Rocky Flats plutonium facility near Denver, Colorado.

The funding pattern for the contract began with a contract for \$15,000 in 1962, which climbed rather steadily to \$183,000 in 1973. Since 1973, the annual expenditure has steadily decreased to ~ \$50,000 for the final year. The total cost of the project over its 17+ year duration was \$1.25 million. Research productivity was highest during the first several years of the contract and declined thereafter. Major reasons for the decline in

productivity include increased contractual red tape, both in Washington and at Colorado State, and inflation. However, productivity in recent years has still been acceptable in the view of the principal investigator. Some 70 open literature publications, 18 M.S. or Ph.D. theses, and numerous other reports were prepared during the contract. Over 80 formal oral presentations on research conducted under the contract were made. Several additional papers representing work under this contract remain to be published.

Perhaps more important to the field of radioecology than the individual research contributions, are the personnel trained and the development of general concepts. This contract made possible the graduate programs of a substantial number of professionals, most of whom now hold important positions in government, industry and education. Many of these individuals are contributing directly to Department of Energy programs. The program in general has led to the development of many basic concepts of radioecology. Most of these will be presented in a book to be published by CRC Press, Inc. in 1980. The book is authored by F. W. Whicker and V. Schultz and is entitled, "Radioecology: Nuclear Energy and the Environment." In addition, several review articles, bibliographies, and a selected readings volume have been prepared under partial funding from the contract.

This report is a general, qualitative summary of activities and major findings over the entire tenure of the program. The report was prepared with the intent of providing a quickly readable account. Quantitative details are available in the individual publications, reports and theses listed in part IX. While this report is the final formal requirement of the program, it is not the last word as several papers remain to be prepared for ultimate publication.

II. FALLOUT DEPOSITION AND BEHAVIOR

Regional and local variations in radionuclide concentrations in mule deer, forage plants and trout from mountain lakes required study of radionuclide deposition patterns. Deposition of aerosols in complex mountain terrain is influenced by large-scale disruption of the tropopause, orographic precipitation, eddy currents, and near the ground, by vegetation zonation and wind-driven snow accumulation patterns.

Arrival of fresh fission products was monitored very efficiently during the period 1961-1965 by analyzing deer thyroids for ^{131}I . The remarkably high accumulation and rapid response of the thyroid enabled detection of even small, isolated events, some of which went undetected through milk and air monitoring. The thyroid ^{131}I profiles through time yielded information not only on cloud arrival times, but also on the relative duration and magnitude of fallout deposition resulting from test series or isolated tests in some cases. Atmospheric tests by the U.S., U.S.S.R., and China were detected in this manner, as were cratering and some vented underground tests at the Nevada Test Site.

Data on ^{137}Cs in soil, vegetation, and muscle tissues of mule deer and trout lead to the definite conclusion that fallout deposition was highly correlated with elevation. On the eastern slope of the northern Colorado Front Range, fallout deposition approximately doubled between 6,000 feet and 10,000 feet elevation. Depending largely on precipitation patterns and their association with elevation and topography, four-fold or greater variations in world-wide fallout deposition occur within the state of Colorado.

Periodic intrusions of stratospheric air resulting from extreme orographic lee waving occur along Colorado's Front Range. This phenomenon

was largely deduced from surface measurements of ozone and their correlation with air motion patterns. However, during the early 1960's when the stratosphere was enriched with weapons testing debris, there was a positive correlation between ozone and radioactivity in surface air, which served to strengthen the lee waving hypothesis.

One investigation was specifically devoted to the elucidation of fallout deposition on a local scale (2 ha), as influenced by topography, vegetation, and microclimate. It was found that the forest canopy serves to scrub aerosol particles from the atmosphere. This reduces the air concentration and delays the deposition of material on the ground. Fallout impaction on vertical surfaces increased with mean air speed. Thus, protected draws and areas leeward of the prevailing winds are less subject to impaction. However, such areas more efficiently accumulate vertically deposited material than wind-swept sites because debris on the latter is removed more effectively.

In alpine and other relatively barren areas, the overriding factor in fallout deposition is snow drifting. At the higher elevations in Colorado, over 2/3 of the annual precipitation is in the form of snowfall, and snowfall accounts for roughly 3/4 of the total deposition of worldwide fallout. The fallout debris is tied up with snow until melting carries the debris to prostrate vegetation, litter and soil. Open, uneven terrain and wind cause snow drifting and accumulation in lees and draws. As a result, snow depths at the end of winter may range from zero on exposed ridges to 30 feet or more in protected spots. Thus, such protected areas are highly enriched in fallout, while exposed areas are nearly devoid of the material. This phenomenon is a major reason why fallout inputs to alpine lakes protected by steep-walled cirques are comparatively high.

Another factor which can cause "hot spots" of fallout deposition in mountain areas is runoff from large rock slabs, followed by sorption in the vegetation-litter-soil complex at the base of such rock slabs. In the course of making ^{239}Pu measurements at Rocky Flats, we conducted soil sampling in a number of areas remote from the facility in order to estimate the ^{239}Pu contributed by world-wide fallout. In general, the "background" soil levels were < 0.1 dpm/g. At the base of a large rock slab in the Park Range in north-western Colorado, a soil sample contained around 7 dpm/g, or over 70 times the general background level. Other long-lived radionuclides in the same sample, including ^{137}Cs and ^{90}Sr , were elevated to a comparable extent. It is of interest that the plutonium level in the soil from this very pristine location exceeded the state of Colorado standard of 2 dpm/g soil.

III. FALLOUT RADIONUCLIDES IN MULE DEER

The initial 5 years of the program were devoted to the understanding of accumulation of ^{131}I , ^{137}Cs and ^{90}Sr in mule deer that inhabited the Cache la Poudre drainage in north-central Colorado. Deer were selected for this autecological study because of their nationwide importance as a game species consumed by man, the intensive concurrent ecological study of the Cache la Poudre population by D. E. Medin and A. E. Anderson of the Colorado Department of Game and Fish, and the readily measurable levels of fallout radionuclides in deer tissues and other environmental media.

Over a three-year period (1962-1964), an animal was harvested weekly from its natural range, which provided tissues for analysis. In addition, animals were collected annually over a longer time period to elucidate

longer term temporal trends. Short-term variations were studied by obtaining samples from hunters at game check stations. Data on vegetation, climate, behavior, migration, and physiology were systematically collected by Medin and Anderson over the range of the deer population, which was of great value in understanding radionuclide accumulation patterns. A captive colony of hand-reared deer was developed so that controlled studies on the metabolism of iodine, strontium and cesium could be conducted. These studies, along with the observed data from the natural environment, provided the foundation necessary for the development of predictive models of radionuclide concentration in deer.

The target organs, thyroid, bone and muscle were routinely assayed for ^{131}I , ^{90}Sr , and ^{137}Cs , respectively. Liver tissues were also assayed by gamma ray spectrometry and the radionuclides ^{137}Cs , ^{144}Ce , ^{106}Ru , and ^{54}Mn were present in the 1963-64 samples. The radionuclides ^{144}Ce , ^{125}Sb , $^{103,106}\text{Ru}$, ^{137}Cs , ^{95}Zr , ^{54}Mn were commonly found in lung tissues, rumen contents, and forage plants collected on the deer ranges.

Temporal trends in ^{131}I (thyroid), ^{90}Sr (bone) and ^{137}Cs (muscle) were constructed over a period of several years. Each nuclide displayed a different pattern over time, depending primarily on the effective half times in the critical tissues. Being slow to turnover in bone, ^{90}Sr levels rose steadily from early 1962 to the spring of 1964. Owing to the nuclear test ban treaty, no atmospheric tests were conducted after December 1962, except for the relatively low yield events conducted by the People's Republic of China. Thus ^{90}Sr levels in bone declined after the peak in 1964. Cesium-137 concentrations in muscle peaked in late summer of 1963, and declined for about 8 years thereafter with an observed half-time of about 2.3 years. During the period 1962-64, the temporal

pattern for ^{137}Cs in muscle displayed substantial seasonal peaks, corresponding to time of summer range occupancy. This seasonal pattern was not observed for the other radionuclides. Levels of ^{131}I in thyroid tissue fluctuated over several orders of magnitude, depending on current testing of nuclear devices. Levels were non-detectable during periods of no testing. The short effective half time of ^{131}I in the thyroid is reflected in rapid response to fresh fallout deposition, and rapid decline thereafter. This behavior gave rise to unique "signatures" for a number of individual events.

A substantial effort was made to elucidate physiological and ecological factors that modified the observed radionuclide burdens in deer tissues. Sampling of large numbers of deer from the same general area at a given point in time revealed large variations among individuals; in some cases a ten-fold range existed in radionuclide concentrations. Frequency distributions were characterized for ^{131}I (thyroid), ^{90}Sr (bone), and ^{137}Cs (muscle) and all were found to be log-normal. Age-associated physiological factors were responsible for producing much of the variation in ^{131}I and ^{90}Sr among individuals. There was a significant decline in thyroid concentrations of ^{131}I with age. Further, near-term deer fetuses exhibited 10-fold higher ^{131}I levels than their mothers. The age effect for ^{90}Sr in bone was more complex, since the entire intake history is of importance, as well as the age-specific metabolic parameters. Since young deer have a higher bone turnover rate, they will more rapidly reflect changes in ^{90}Sr intake than older animals. Thus when fallout levels were increasing, young animals had significantly higher ^{90}Sr burdens. Under conditions of constant, continuous intake however, the older animals will contain higher burdens, as demonstrated by analysis of stable strontium in bone.

Since the major radionuclide intake pathway was shown to be ingestion of contaminated forage, it is reasonable to expect that variations in forage concentrations and food habits will account for substantial variation in deer tissue burdens. Sampling of 12 important deer forage species revealed an 8-fold difference in ^{137}Cs levels between the highest and lowest concentrators. Further, rumen-reticulum content analysis by D.E. Medin and A. E. Anderson revealed substantial seasonal and individual food preferences. In the case of ^{137}Cs in muscle, food habits were definitely shown to account for much of the variability among individual deer. Although plants were not analyzed for ^{131}I , it is believed that there were species variations which were likewise reflected in thyroid burdens. Food preference appeared to be less important for producing variations in ^{90}Sr burdens in bone. The major reason for this appears to be the greater importance of food habits averaged over longer time periods than just the recent diet. Because of the long residence time of ^{90}Sr in bone, cumulative intake is a stronger determinant than short term fluctuations in intake.

Metabolism studies with ^{131}I , ^{90}Sr and ^{137}Cs were conducted with a colony of hand-reared mule deer in order to quantify uptake, retention, and tissue distribution. Initially, wild-trapped pregnant does were transported to the holding facility on the CSU foothills campus. After birth in the subsequent spring, fawns were taken from their mothers and hand-reared in order to provide animals that could be handled in the metabolism experiments. The experiments involved oral dosing, followed by subsequent whole body counting and daily urine and fecal analysis. This provided the data necessary to calculate assimilation fractions and retention functions. Such parameters were determined as a function of age, sex, diet, season, and activity level.

The metabolic information, coupled with intake functions based on diet and radionuclide levels in forage, provided a basis for construction of radionuclide concentration models. Such models were formulated on the basis of a convolution of the intake and retention functions. This enabled a time-dependent prediction of tissue burdens from measurements of radionuclide burdens in forage plants. The models were validated by comparing predicted tissue concentrations with observed data. In general, the models gave very reasonable predictions and were judged to have considerable utility. An interesting and valuable spinoff from this effort was the ability to estimate food intake rates of free-ranging deer on the basis of observed ^{137}Cs levels in the diet and in muscle tissue. Resolution of the model was sufficient to permit the estimation of consumption rates by season and age group.

The radiation doses to mule deer from ^{90}Sr , ^{137}Cs , ^{144}Ce , ^{54}Mn and ^{106}Ru were of the same magnitude or slightly higher than from natural background radiation. Annual doses to the thyroid from ^{131}I reached 80 times the background level. At the population level, no deleterious radiation induced effects would be expected. However, another aspect of importance is the radiation dose received by humans as the result of deer flesh consumption. The data indicated that consumption of one meal of deer meat alone would likely lead to the ingestion of more ^{137}Cs than from the entire normal daily diet. Furthermore, consumption of liver would result in the ingestion of ^{144}Ce , ^{54}Mn and ^{106}Ru in addition to ^{137}Cs . While the probable intake levels would certainly not lead to specifically identifiable low-level radiation effects, the chance of incurring such effects might be increased if we accept the linear dose-response hypothesis.

IV. FALLOUT BEHAVIOR IN MOUNTAIN LAKES

Studies on the cycling of ^{137}Cs , ^{90}Sr , and stable lead were conducted in montane and alpine lakes in Colorado. The radionuclide studies were conducted from 1965-1975, while the lead investigations were carried out periodically between 1971 and 1979. The radionuclide and lead studies are discussed under separate headings.

A. Radionuclide Studies

These investigations began largely out of curiosity as to the levels of ^{137}Cs in trout as compared to deer muscle. It was quickly determined that ^{137}Cs burdens in muscle tissues of trout from some alpine lakes were as much as an order of magnitude higher than levels in deer during the same time period. This provided the initial impetus to sample a large number of lakes on a systematic basis to determine ^{137}Cs and ^{90}Sr burdens in trout. The lakes sampled were also characterized on the basis of limnology, watershed, location, and effective precipitation in an effort to understand radionuclide concentration patterns and variations. These investigations ultimately led to detailed studies on the cycling of cesium in a particularly interesting montane lake and to measurements of the kinetics of radiocesium in trout and other aquatic biota under controlled conditions in the laboratory.

For the statewide survey, trout were sampled from 51 montane and alpine lakes in 11 major mountain ranges. In addition, several streams and reservoirs at lower elevations were sampled. Burdens of ^{137}Cs in trout muscle varied by a factor of 50 among the montane and alpine lakes. Levels of ^{137}Cs in fish from plains and foothills reservoirs were very low and frequently non-detectable. Trout in the Cache la Poudre river contained non-detectable ^{137}Cs burdens at lower elevations, but the levels

increased with altitude, although not reaching the same degree of concentration as trout from the high mountain lakes. Concentrations of ^{90}Sr in trout bone varied among lakes by a factor of 40 and most of this variation could be accounted for by differences in dissolved calcium concentrations in water.

The variations in ^{137}Cs concentrations in trout could be explained on the basis of sampling date, latitude, elevation, raw precipitation reaching the lake, watershed character, bottom sediment character, and trophic level. Between 1965 and 1970, ^{137}Cs levels declined 5-fold according to a function containing components from the current fallout rate and from cumulative deposition. There was a slight tendency for ^{137}Cs burdens to increase with latitude and a stronger tendency to increase with lake elevation. Lakes in areas receiving particularly heavy snowfall, or those which by virtue of topography accumulated large snow drifts, tended to contain trout with unusually high ^{137}Cs burdens. Watersheds barren of soil and vegetation contributed more ^{137}Cs to lakes from runoff than well-vegetated watersheds because the vegetation-litter-soil complex strongly sorbs ^{137}Cs from runoff. The tendency of ^{137}Cs to recycle to the biota from sediment was dependent on the nature of the sediment. High clay sediments serve as effective sinks for the nuclide, but highly organic sediments in shallow water are ingested by trout to a sufficient degree in some cases to control ^{137}Cs burdens. Large, predatory trout contained about 3 times the ^{137}Cs concentrations as smaller prey fish, which corroborates the concept of a trophic level increase for radiocesium. While the competing ion effect was very important for ^{90}Sr (calcium), there was no evidence that potassium concentrations modified ^{137}Cs burdens.

East Twin, a semi-drainage montane lake was chosen for ecosystem-scale tracer investigations because it did not follow the pattern of

^{137}Cs behavior that was expected from the statewide survey. First, the limnological, watershed, precipitation, and elevational characteristics would have suggested minimal ^{137}Cs levels in trout. However, trout from this system contained relatively high ^{137}Cs levels. Second, the high levels persisted over a period of several years, while other lakes sampled through time showed significant decline in ^{137}Cs burdens in trout. Detailed sampling and analysis of the lake components, as well as laboratory studies showed that trout in this system achieved high and persisting burdens of ^{137}Cs by ingestion of sediments. It is hypothesized that such ingestion is inadvertent and the result of chasing amphipods near the sediment-water interface.

In 1970, 1 kilogram of stable CsCl was introduced to East Twin Lake in lieu of a radiocesium tracer to determine the cesium kinetics of the lake ecosystem. Samples of water, seston, sediment, amphipods, zooplankton, trout, and emergent vegetation were taken over time and the cesium content was determined by neutron activation and subsequent gamma ray spectrometry. Time curves of the cesium content of each lake compartment were constructed, and these were evaluated to estimate the inventory distribution, concentration ratios, and rate constants describing intercompartmental transfers. Within a few days after introduction of the tracer, sediment contained most of the total inventory. Although concentration ratios relative to water of 10^2 to 5×10^3 were observed in the biota, the living components of the ecosystem held only a minor fraction of the total cesium inventory.

Of considerable interest was the finding from the East Twin Lake study that concentration ratios for zooplankton and amphipods increased in late winter when ice thickness was maximal and dissolved oxygen was minimal. This implies that the kinetics of the system are altered by

seasonal limnological changes. In an effort to understand these phenomena, a series of laboratory studies were conducted with amphipods. Ingrowth and retention of radiocesium in amphipods was studied under different regimes of temperature and conductivity; however, the data have been inconclusive. Nevertheless, it is still believed that many constant-coefficient system models could be considerably improved by incorporating time-variable coefficients. Very little progress has been made in this area of radioecology.

Trout also displayed seasonal variation in the concentration ratio at East Twin Lake. In part, this response could be attributed to cesium fluctuations in their major food, Gammarus lacustris. However, intake and retention in trout are influenced by temperature, weight, and growth rate. The interaction of these factors on the retention of cesium was carefully documented in laboratory studies. These relationships were successfully applied to the field situation at East Twin Lake as reflected in a model which accounted for the seasonal fluctuations of cesium in trout. These relationships were also useful in estimating the seasonal food consumption rates of trout from observed data on cesium levels in Gammarus and trout, as well as water temperature and trout weights over time.

The aquatic radioecology studies completed are useful to the development of concepts that can be applied to the assessment of radionuclide releases to aquatic environments. For example, studies at East Twin Lake demonstrated that the biota in some systems maintain radionuclide burdens proportional to cumulative inventory rather than to the rate of introduction. Thus, low-level discharges that may be acceptable for rate-limiting systems may not be acceptable for inventory-limiting systems. The

relatively high concentrations of fallout ^{137}Cs in trout suggest that some aquatic systems can provide a significant pathway to man. For example, a single meal of trout from certain mountain lakes could provide the same ^{137}Cs intake (and dose commitment) as the normal diet over a period of 20-30 days.

B. Stable Lead Studies

Based on a statistically significant correlation between ^{137}Cs and stable lead in trout from 9 remote mountain lakes, it was hypothesized that the geochemical processes governing the transport and behavior of these pollutants had similarities. Further, it seemed likely that the positive correlation between lead and fallout ^{137}Cs was evidence for an atmospheric input of anthropogenic lead. To test these ideas, as well as to obtain basic data on the distribution and dynamics of lead in a remote, pristine alpine lake, a concerted effort was made to elucidate the lead geochemistry of the Snow Lake ecosystem. Much of the data collected during this study is still being analyzed. Therefore, the following account is preliminary. This study should be completed within the next 6 months with a definitive manuscript for publication.

Snow Lake is in the Never Summer Range in north-central Colorado at an elevation of 3511 meters. It is situated in a very steep-sided glacial cirque which forms a rocky watershed almost entirely devoid of soil and vascular plant life. The lake is deep, highly oligotrophic and exhibits water of unusually low conductivity. Trout in this lake exhibited comparatively high concentrations of ^{137}Cs in muscle and lead in liver and bone tissue.

Field work at Snow Lake included morphometry, water turnover, limnological characterization, biomass estimates of zooplankton, trout, and

periphyton, and quantitative measurements of precipitation, including snow depth distributions through the winter and spring months. Samples of precipitation, dust fall, bedrock, water (inflow, lake proper, outflow), sediment (versus depth), periphyton, zooplankton, and trout were taken over a period of several years for analysis of lead by atomic absorption photometry. In addition, mass spectrometry was employed by LFE Environmental Analysis Laboratories to measure the stable isotopes of lead in a limited array of sample types and numbers. This was done in an effort to distinguish anthropogenic fallout lead from the natural lead aerosol and lead weathered from bedrock in the Snow Lake watershed.

Data on lead in precipitation and precipitation amounts provide an estimate of the direct deposition flux. Amounts entering the lake from watershed runoff were more difficult to estimate because of the diffuse and often concealed inflows, but recognizable inflows were sampled. The outflow is sufficiently distinct to permit estimates of lead export from the system. Data on water volume, sediment and periphyton area, and biomass of zooplankton and trout, coupled with lead measurements in these compartments, provide a basis for calculation of concentration ratios and inventory distribution. An overall lead budget, detailing inputs, inventory, and losses will be constructed to illustrate the dynamics of the system as a whole.

The utility of this sort of information will ultimately lie in the environmental assessment of lead in the environment. Lead is known to be chemically toxic at relatively low concentrations. Transportation and industry are releasing tremendous quantities of lead to the atmosphere, where much of it is transported like fallout on a world-wide basis. It is accumulating in various environmental sinks, and lake sediments

represent one type of sink. Whether the lead content of lake biota is governed mostly by current input rates or by cumulative deposition in the sediments can determine whether (and when) in time the material will stress the biota of the system.

Preliminary data suggest that recent anthropogenic lead inputs to the system are significant. The basis for this suggestion is that the lead content of the top layers of sediment are substantially higher than the deeper layers. Current lead input rates from direct precipitation alone appear to be in the range of 500 g per year to the lake, not including watershed runoff, which could be up to 6 times as great as that falling directly on the lake. The other preliminary finding of interest is that lead concentration ratios (relative to filtered water) for the biota are in the range of 10^2 to 10^4 . This suggests that lead is reasonably mobile in aquatic systems, which further justifies research in this area.

V. RADIATION EFFECTS ON NATURAL POPULATIONS AND COMMUNITIES

In addition to studies on the behavior of radionuclides in ecosystems, radioecology includes the effects of radiation on populations and communities. In 1969, an 8,750 Ci ^{137}Cs source was installed in a native shortgrass ecosystem for the purpose of studying the response of the plant community, arthropods, and microorganisms to a large gradient of chronic and short term exposures. In separate investigations, the radiosensitivity of two small mammals were studied under field and laboratory conditions.

A. Shortgrass Plains Vegetation

The installation of the large ^{137}Cs source and physical study plots were designed to provide 2 45° sectors for a gradient of chronic gamma ray exposures, 3 sectors for 30-day seasonal exposures (April, July and December),

and a control (continuously shielded) sector. Permanent plots were established in each sector and these received exposure rates ranging from over 650 R/hr near the source to 7.8 mR/hr in the plots most distant from the source. Periodically following the initiation of radiation exposure, plots were examined for the kinds, numbers, and condition of vascular plants. This permitted the quantification of population attributes such as density and production, and the calculation of the community parameters diversity index and coefficient of community. Such attributes were fitted to a three-dimensional response surface to time and exposure rate.

In the chronically-irradiated sectors, distinct zonation appeared, with an area of complete devastation near the source, an area of graded effects further out, and finally an area exhibiting no effects. The boundaries of these zones regressed away from the source with time, until after a number of years, they stabilized. The time-specific response curves could be evaluated to determine the exposure rates necessary to produce a threshold effect, a 50% reduction from controls, and total killing. From such data, the sensitivity of the shortgrass plains community to chronic exposure could be quantified and compared to other irradiated communities.

In comparison to other communities, the grassland is very resistant to radiation stress, requiring large exposures to produce significant effects. The grassland is roughly comparable to other herbaceous communities studied in terms of radiation response. Only the moss-lichen dominated systems exhibit greater resistance than the grassland. Within the grassland community, there is a wide range of tolerances of plant species to radiation. The woody shrubs and certain herbaceous forbs were the most sensitive; the grasses and certain forbs were the most resistant. Phenology and production were the most sensitive indicators of radiation effects. In the zone

between complete mortality and no effects, the dominant effect of radiation is structural simplification, as reflected by reduction in diversity through selective mortality of the more sensitive species. An interesting phenomenon in this zone was the enhanced vigor of certain resistant species in response to reduced competition from more sensitive species.

Of the sectors receiving short-term seasonal exposures, that irradiated in December was most severely damaged. This initially unexpected result was explained on the basis that winter-dormant cells received a greater total dose than those undergoing rapid division in spring and summer. Also, due to dormancy, repair mechanisms were less effective. The damage in the community irradiated in December was not manifest until the following spring and summer.

Following the development of damage to the seasonally-irradiated communities, succession and repair were observed. In plots severely denuded by high exposures, the dominant revegetation mechanism was invasion by hardy "weed" species commonly observed on disturbed areas. These plants achieved vigorous stands within a year or two following exposure. Further from the source where some species were only partially damaged or killed, the revegetation process was largely dominated by re-sprouting from living propagules. These successional processes and patterns were compared among plots receiving damage from radiation, fire, rototilling, and scraping of aboveground biomass.

These investigations provide the information necessary to establish threshold doses for radiation damage, and a basis for prediction of the possible effects of a disaster such as a major nuclear power accident or nuclear warfare. In addition, it became evident during the study that radiation is a form of stress than can be applied to natural communities

in a highly controlled and quantitative manner. In this sense, the response and comparative resilience of natural communities to various forms of stress can be studied and broadly predicted from radiation exposure.

B. Arthropods and Microorganisms

The only organisms in the ^{137}Cs gamma field besides vascular plants which could be feasibly studied were the arthropods and microorganisms. The ranges of small mammals, reptiles and birds were very large compared to the area receiving biologically significant exposures, and problems of dosimetry and sample size all discouraged studies of such animals. Arthropods, particularly ants, carabid beetles and spiders were studied across the radiation gradient of each chronic and seasonally exposed sectors, as well as the control sector. Relative abundance with respect to location was assessed from pitfall trap data.

None of the arthropods exhibited direct avoidance of the radiation field. In fact, Western harvester ants established a nest at a location continuously receiving 18 R/hr. After two years, the nest mound diameter had continued to increase and the colony was still active. After three years of chronic irradiation, the capture frequency of harvester ants was significantly higher in the irradiated zones than in the control area. This was interpreted as an indirect effect of radiation, in that areas denuded of vegetation by radiation were more easily traveled by these ants and therefore they were more heavily used. Harvester ants also appeared to be attracted to the vegetation that had invaded areas denuded by short-term seasonal exposures. Neither the beetles nor the spiders showed significant differences in use between irradiated sectors and the control. The ant, Myrmica americana, was the only species to exhibit a negative effect

from radiation, in that captures in irradiated sectors were significantly lower than in the control sector. This response was also interpreted as being indirect. This ant is associated closely with grasses of the area, and in fact may tend aphids that utilize the roots of these grasses. The grasses had been killed in the heavily irradiated zones and had not reinvaded the sectors receiving short term exposures.

Abundance of fungi, actinomycetes and bacteria in soil was also studied across the chronic gamma radiation field. The plate count method was used to determine microbe numbers in 10 g of soil. Numbers of fungi and actinomycetes were significantly depressed near the source, but bacterial numbers were essentially unaffected at all exposure rates. Fungi appeared as the most sensitive microbe studied. The depression of fungi and actinomycetes near the source may have been partly responsible for the long persistence of dead plant crowns in the plant-lethal zone. Variations in soil moisture and temperature caused greater microbial fluctuations than radiation exposure.

C. Small Mammals

Radiation sensitivity was studied in two species, the pika (Ochotona princeps) and the Richardson ground squirrel (Citellus richardsonii). These studies were conducted because of the scarcity of data on wild species, and more importantly, because of the suspected difficulty in judging radiation response under field conditions from laboratory work. The $LD_{50(30)}$ was determined on ground squirrels captured near Estes Park, Colorado, and held in captivity. Exposures from ^{60}Co were delivered at 50 R/min. The calculated $LD_{50(30)}$ was 1260 R, and all but one death occurred between 5 and 10 days post-irradiation. This animal was considerably more resistant than most mammals, based on the $LD_{50(30)}$ criteria.

Pikas were captured near the summit of Mount Evans in the central Colorado Front Range at elevations ranging from 3450 to 4340 meters. The $LD_{50(30)}$ was determined on a group held in captivity, and a group released at the site of capture. Pikas released back to the natural environment were irradiated with ^{60}Co the day of capture, ear tagged with color-coded disks, and returned to the capture site the next day. Survival was judged on the basis of visual observation in previously-established territories. This method appeared reasonable as 8 of 9 sham-irradiated pikas were observed 30 days after release. The calculated $LD_{50(30)}$'s were 560 and 380 R for the captive and natural environment groups, respectively. Mean survival time was 9-13 days for irradiated pikas in captivity and 5-7 days for those released. These results indicated that pikas were comparatively sensitive to radiation in spite of its adaptation to the alpine environment; and also that radiation in combination with environmental stresses is more effective than radiation alone. Predation and competition with unirradiated pikas for territories were hypothesized as the major environmental stresses interacting with radiation. In a more carefully designed followup study utilizing artificial enclosures and dens, the hypothesis of intra-specific stress from territorial aggressiveness was strengthened considerably.

The results of the small mammal studies, as well as the work involving higher plants, arthropods and microorganisms, clearly indicate that radiation responses of organisms in nature cannot be accurately predicted from artificial laboratory investigations. A wide spectrum of ecological interactions can modify the radiation response, either upward or downward, depending on circumstances. This not only makes prediction difficult; it also makes radiation effects studies in natural settings most difficult to carry out and interpret.

VI. PLUTONIUM BEHAVIOR IN A GRASSLAND ECOSYSTEM

During the summer of 1972, pilot studies on the distribution, transport, and ecological effects of plutonium in the terrestrial environs of the Rocky Flats nuclear weapons facility near Denver, Colorado were initiated. Because of uncertainties in funding however, the work did not gain much momentum until 1973. By mid-1974, this program was receiving the majority of the effort under the contract and this trend has continued through October 1979.

The Rocky Flats facility, presently operated for the Department of Energy by Rockwell International, has handled large amounts of plutonium for defense purposes since approximately 1950. During the period 1959-1964, drums containing plutonium-contaminated cutting oil were deteriorating and leaking onto the ground of the former barrel storage area. During this period, and until 1969 when all barrels had been removed and the contaminated area had been covered with asphalt, the barrel storage area was a source of contamination of the surrounding area. Physical disturbance of the area and resuspension of contaminated soil by winds are primarily responsible for the initial distributions of plutonium to the environs. Other accidental events and routine releases also caused some contamination of the environs, but these sources were minor in comparison to the barrel storage area. Most of the Pu contamination was deposited to the east and southeast of the source area because of the prevailing directions of the strong winds. Public concern, a lack of knowledge on the environmental behavior of Pu, and its high radiotoxicity all provided justification and impetus for this investigation.

A. Ecosystem Distribution

To determine the distribution of Pu in the terrestrial environment, several sampling areas were established. Three areas were near and downwind

of the source: a 0.25 ha plot 50 m southeast, a 0.75 ha plot 200 m southeast, and a 500 m transect extending from 270 to 770 m southeast. Two other study plots were established; one 1400 m south of the source area, and one in the northwest corner and upwind of the plant. During 1972-1976, samples of soil, litter, vegetation, arthropods, snakes, birds, small mammals, and mule deer were taken from the study plots for Pu analysis and biomass estimates. Samples were analyzed by liquid scintillation counting in our laboratory and by alpha spectrometry by commercial laboratories.

Based on data from the principal study plot 200 m downwind of the source area, the top 21 cm of soil contained over 99% of the ecosystem Pu inventory. About half of this was in the upper 3 cm. Fractions of the total inventory in non-soil compartments were orders of magnitude lower than the soil inventory. The inventory exhibited the following ranking: soil >> litter > vegetation >> arthropods > small mammals > other animals. A major reason for soil so-dominating the Pu inventory is the comparatively insignificant mass/unit area of the other compartments. Although soil contained the highest concentrations of Pu of the materials studied, concentration ratios were reasonably high, especially for litter and vegetation. However, much of this result was due to surficial dust that was not removed from the litter and vegetation prior to Pu assay. Concentration ratios relative to 0-3 cm soil ranked as follows: litter > vegetation > arthropods > small mammals > other animals. While Pu levels in litter, vegetation and arthropods were always readily detectable, levels in small mammals were occasionally non-detectable and levels in other animal tissues were seldom detectable.

Plutonium concentrations in soil varied inversely with distance from the source area, depth of sample, and particle size of dry-sieved samples. Coefficients of variation of Pu in soil samples randomly collected within sampling grids ranged to more than 300%, and frequency distributions were highly skewed with most values lying below the mean and a few being much larger than the mean. The measured plutonium distribution patterns and known characteristics of the source imply the following dispersal mechanisms: (1) the attachment of PuO_2 to soil particles; (2) primary dissemination of the contaminated soil particles by disturbance and wind; and (3) weathering of the contaminated soil particles. The high degree of spatial variability suggests that the most common functional form of the contaminated soil during dissemination was an agglomerated particle containing a large number of individual grains of soil and PuO_2 .

In an effort to more fully understand the problem of sampling heterogeneity, soil samples from the principal study plot were examined microscopically so that plutonium particle sizes and micro-distribution could be investigated. We wanted to explore the idea that occasional high-activity samples were possibly caused by "hot particles" of plutonium. An autoradiographic technique, utilizing nuclear emulsion plates, was used to obtain abundance of, and equivalent size distributions for, plutonium particles in Rocky Flats surface soil. A total of 1700 particles were sized, for which mean $^{239}\text{PuO}_2$ equivalent diameters of 0.29 μm , 0.25 μm , and 0.20 μm were found for 7-, 14-, and 37-day exposures of soil to emulsion plates. A method to scan for particles greater than 1.50 μm equivalent diameter, utilizing Kodak AA Industrial X-Ray film, was also used. The largest particle sized with this procedure was 6.86 μm $^{239}\text{PuO}_2$ equivalent diameter. None of the particles sized was of sufficient magnitude alone to account

for elevated plutonium activity observed in Rocky Flats surface soil samples. Variability in particle concentrations was observed, however, which suggested that heterogeneity in the spatial distribution of plutonium particles in the soil may partially explain observed variability in soil plutonium concentrations. While no "hot particles" (> 1000 dpm) were found, their presence cannot be ruled out because of the limited quantity of soil that can be feasibly examined by the autoradiographic technique.

Based upon data from samples taken across gradients of plutonium contamination, levels of plutonium in litter, vegetation and arthropods were significantly correlated to concentrations in soil. These correlations provided additional evidence that most of the plutonium associated with these samples was actually attached to surficial dust. This study corroborates the idea expressed by other investigators that plutonium moves in the environment principally by physical rather than physiological mechanisms.

Data on ^{239}Pu concentrations in vegetation, small mammals and arthropods were too variable to show statistically significant differences between species or taxonomic groups. It also could not be shown that there were significant differences between collection dates nor types of small mammal tissues. Statistical analyses were exhaustive in that data were log-transformed to reduce heterogenous variance and skewness of distributions, and normal as well as non-parametric procedures were used. It is concluded that the large variability in the data are real, and not the result of poor sampling and/or analytical technique. This kind of variability is probably representative of that likely to be encountered from accidents or single events. Smaller sampling variability for world-wide fallout and routine low-level discharges are more likely because of smaller particle sizes and more opportunity for stochastic mixing processes.

Samples analyzed by alpha spectrometry provided data on the isotopes ^{239}Pu and ^{238}Pu , and thus the opportunity to examine their comparative behavior was afforded. The activity isotopic ratio of ^{239}Pu to ^{238}Pu (IR) for surface soil was about 65. The IR was found to decrease with depth, and IR values for many animal tissues were also substantially lower. The initial interpretation of this observation was that ^{238}Pu must be more mobile than ^{239}Pu . This concept has some experimental basis if the two isotopes occur in separate particles. However, there is no basis for thinking this to be the case in the contamination at Rocky Flats. Individual particles of PuO_2 likely contain both isotopes, and furthermore, there is considerable evidence for monomeric Pu in environmental samples. Further examination of the data indicates that the IR is biased on the basis of total Pu activity present. Above 10 dpm, the IR appears independent of sample activity, but below that value, the IR decreases. This suggests some low-level interference in the alpha peak of ^{238}Pu , and our present hypothesis is that the IR effect is basically an analytical problem.

B. Transport Processes

In an effort to understand the dynamic behavior of plutonium in the environs of Rocky Flats, several studies dealing with transport processes were undertaken. These investigations included measurements of aerial deposition rates, soil erosion, plutonium export initiated by the activities of pocket gophers and mule deer, and mechanisms of plutonium accumulation by vegetation. The construction of a Pu transport model is presently possible, based on the results of these studies, and those of other laboratories at Rocky Flats. However, this has not been accomplished because other efforts have taken priority.

In 1976 and 1977, aerial deposition rates were measured in the principal study plot (macroplot 1) with 21 wet pot collectors. The data were in reasonable agreement with the Rockwell air monitoring data, but there was some indication that conventional deposition from the air column was not the only mechanism involved. Dust generated by vehicular traffic and rain splash-up of surface particles were probably more important mechanisms of deposition in the pot collectors.

Since over 99% of the plutonium in the ecosystem is in soil, erosional processes, both wind and water driven, could disperse significant quantities of the element. These processes can be enhanced considerably by natural phenomena such as animal activity and needle ice formation, and by human disturbance. Attempts were made to measure soil erosion by tracing the location of ^{59}Fe -tagged soil particles and by recording beta counts from sealed ^{90}Sr sources buried at fixed positions beneath the soil surface. These very sensitive techniques gave no indication of measureable soil erosion over the duration of the study in undisturbed, well-vegetated areas. However, in steep or disturbed areas, evidence of erosion was visually observed but not quantified.

The potential of certain animals for dispersing plutonium was investigated in detail for pocket gophers and mule deer, and superficially for arthropods. For example, pocket gophers at Rocky Flats dig tunnels and burrows and form mounds which expose contaminated soil to erosional processes. Quantitative estimates of the amount of soil thus exposed per unit area per year, and the amounts of Pu in mound soil were made. Since most of the mound soil originates from a depth of 10-15 cm, it contains less Pu than the surface soil. The fate of plutonium in exposed mounds was not quantified, but observations indicate that most of the mound soil

and the Pu contained in it remains within a few meters of the original mound. Mule deer ingest plutonium associated with vegetation and soil and transport the material to the surrounding area where most of it is deposited on the ground in fecal pellets. It was estimated that deer transport less than 10^{-7} of the Pu inventory annually, and that most of this is redeposited on DOE-controlled property. Observations indicate that the most heavily contaminated area is utilized only occasionally by deer. Arthropods, because they harbor a larger inventory of Pu than other animals, and because many of them are very mobile and have rapid population turnover rates, probably export considerably more Pu to the surroundings than other animals. However, data indicate that total biological export is very small and probably on the order of 0.001% per decade. Of this, less than 10% is likely to leave DOE-controlled property. In time, plutonium is slowly migrating to deeper soil layers. Thus, it is expected that export, both physical and biological, will diminish through time, assuming that the buffer zone around the plant is protected from disturbance and a good cover of natural vegetation is maintained.

Based on greenhouse studies, transplanted sod blocks in the field at Rocky Flats, and comparison of Pu content of ultrasonicated to unwashed vegetation in field plots, it is concluded that aerial transport and surficial contamination dominates substantially over root uptake from soil. Of the plutonium associated with vegetation, over 90% appears to be surficial, which accounts for the comparatively high concentration ratios obtained in the inventory and distribution phases of the program. However, the point is made that evaluation of plutonium ingestion by herbivores must account for such surficial deposition. Further, such material is of importance from the standpoint of export and possible biological effects.

As plutonium migrates into the soil and as litter and uncontaminated dust accumulate on the soil surface, the aerial transport mechanism for the present Pu inventory should diminish.

C. Ecological Effects

The contamination of a portion of the terrestrial environs of Rocky Flats with substantial quantities of plutonium provided the opportunity to search for possible ecological effects resulting from the presence of the element. Gross population effects from the levels of plutonium present in the environment were not expected on the basis of simple dose calculations and data from laboratory studies. However, prior to our studies, a lack of population effects had not been demonstrated and furthermore, extrapolation from the laboratory to the natural environment is frequently not a valid practice, owing to complexities and interactions which occur in nature but not in the laboratory.

We conducted studies which permitted comparisons of various biological measurements and pathological data between ecologically similar study areas at Rocky Flats of widely varying plutonium levels. Soil in the principal study areas ranged from 100 to over 20,000 dpm $^{239}\text{Pu}/\text{g}$ in the upper 3 cm ($2\text{--}400 \mu\text{Ci}/\text{m}^2$). In addition, comparative data were obtained from control areas, containing only world-wide fallout plutonium of the order of $0.1 \text{ dpm}/\text{g}$ ($0.002 \mu\text{Ci}/\text{m}^2$). Biological measurements such as vegetation community structure and biomass; litter mass; arthropod community structure and biomass; and small mammal species occurrence, population density, biomass, reproduction, and physical size of whole carcass and organs were made. In addition, pathological examinations of small mammals, including x-ray for skeletal sarcomas, microscopy for lung tumors, and necropsy for general pathology and parasite occurrence were carried out.

While minor differences in certain biological attributes between study areas were observed, none could be related to plutonium levels. Pathological conditions and parasites were found in some rodents, but occurrence frequencies between control and contaminated areas were similar. No evidence of cancers or other radiogenic diseases was found. These observations and measurements, combined with intensive field observations over a period of five years, led to the conclusion that plutonium contamination at Rocky Flats has not produced demonstrable ecological changes. Furthermore, the levels of plutonium observed in tissues of plants and animals in contaminated areas were insufficient to produce the doses that would be required to produce obvious biological changes. Subcellular biological changes, such as chromosome aberrations, cannot be ruled out at Rocky Flats. However, even if chromosome aberration frequencies were increased in the more highly contaminated areas, population-level changes would likely not persist because of the surrounding reservoir of normal genetic information, and because of natural selection.

Based on all the plutonium work we conducted in the terrestrial environs of Rocky Flats, there is strong evidence that the element is not likely to pose an ecological hazard unless extremely high levels ($>>1 \text{ mCi/m}^2$) occur. The major reason for this is the extremely low biological mobility of the common chemical forms of the element, amply demonstrated in this and other research. Although uncertainty exists as to possible long-term changes in biological availability of plutonium, we expect gradual soil penetration and dispersion to diminish the present hazard potential with time. Furthermore, if natural thorium is a reasonable geochemical analogue of plutonium as many scientists believe, then the extremely low biological mobility of primordial thorium should be generally indicative of the long term mobility of plutonium.

VII. ANCILLARY INVESTIGATIONS

Understanding of radionuclide transport and effects in the ecological context requires basic knowledge on physiological and ecological processes. This maxim was encountered repeatedly in the course of the project and thus a number of basic studies were conducted as necessary to support the overall program. Some of this basic work was published as such, and a brief synopsis is presented.

A. Mule Deer

A considerable amount of basic work was accomplished on certain aspects of behavior and physiology of mule deer. Of great importance to the radionuclide work was information on food habits and forage intake rates. Food habits were studied both by microscopic analysis of rumen contents and by observing the feeding behavior of tame animals in the field. Feeding behavior studies also included observations and measurements on the ingestion of soil, which can be a major transport pathway for radionuclides. Titanium measurements of fecal material provided a quantitative basis for the conclusion that deer may ingest significant quantities of soil.

Forage intake rates of free-ranging mule deer were estimated on the basis of ^{137}Cs levels observed in forage plants and mule deer tissues and measurements of assimilation and retention of Cs in captive deer. The method of calculation involved a numerical solution of the convolution of intake and retention functions. This permitted estimates of forage intake by sex, season, and age class. While food intake of deer under captive conditions can be easily measured by conventional methods, the application of radionuclide measurements to estimation of forage intake in wild animals proved a novel approach to getting new information on mule deer.

The development and maintenance of a captive tame deer colony provided opportunity to investigate body composition, gastrointestinal physiology, antler and thyroid physiology, and optimal husbandry methods. Body composition was studied by dissection of body parts of animals involved in a variety of radionuclide metabolism experiments. Studies on mean residence time of ingesta and fecal output were made possible by tracers such as ^{51}Cr and findings are relevant to such diverse research efforts as ruminant physiology and census of deer populations. The ^{90}Sr metabolism studies yielded basic information on the calcium dynamics and skeletal physiology of antlered deer. Numerous techniques for raising, maintaining and handling captive deer were developed. Such techniques will be helpful to other investigations involving wild ungulates.

B. Pikas

Studies on the effects of radiation on wild and captive pikas led to the opportunity, and often the necessity, of ancillary observations on behavior and physiological parameters. Field studies at Mount Evans required the development of trapping and handling methods, as well as long hours of detailed observations on behavior, other features of the natural history of pikas, interactions with other alpine species, and the physical environment.

The development of field enclosures for the investigation of intra-specific competition and response to irradiation provided the opportunity to study territorial behavior to an extent unmatched by previous investigators. In such a setting, the numbers of animals, space, and frequency of den sites could be manipulated experimentally to produce varying degrees of aggressive behavior. In addition, the artificial habitat was designed such that other behavioral traits, such as burrowing, and reproduction

could be quantified. The artificial enclosures also provided opportunity to study winter habits of pikas, of which little was previously known due to the severity of the weather in the alpine zone.

C. Trout

Most of the basic information on trout was gathered in conjunction with radionuclide cycling studies at East Twin Lake, and most of this work involved food habits and seasonal feeding rates. Estimations of feeding rates were based on observed ^{137}Cs concentrations in lake invertebrates and trout flesh and on cesium retention. Laboratory studies provided the necessary relationships between cesium retention and water temperature, growth rate, and body weight.

One of the more significant findings on the behavior of trout was the ingestion of bottom sediments. Sediments were identified microscopically in gut contents and the rate of ingestion was calculated on the basis of ^{137}Cs cycling data. It is hypothesized that trout in East Twin Lake ingested sediments inadvertently while foraging on amphipods near the sediment-water interface. As the sediments ultimately constitute the dominant reservoir of most radionuclides in most aquatic systems, the sediment-fish pathway has potential for dominating the long-term flow of radionuclides to biota consumed by man.

D. Other Species

Other species on which basic data were gathered include grasshoppers and coyotes. The grasshopper work involved determination of their foraging impact on grassland plant species. Phosphorus-32 was employed to estimate feeding rates of two grasshopper species common to the shortgrass plains biome. Measurements were also made on the quantities of grass cut but

not consumed by grasshoppers. At Rocky Flats, observations of coyote-deer interactions and coyote foods were made relative to work on the role of mule deer in transporting plutonium. Incidental observations on a number of additional plant and animal species were made, some of which were published. For example, observations on aggressiveness in blue grouse were published as this was a rather unexpected behavior.

VIII. ANCILLARY PROFESSIONAL CONTRIBUTIONS

A. Training of Radioecologists

The training of some 25 radioecologists was made possible through support from project funds. Graduate research assistantship stipends were provided for selected students in return for services to the program. A list of those students receiving support from the contract is provided in Table 1, along with an indication of degrees earned and present employment. Twelve Ph.D. and 11 M.S. degrees were earned by the listed individuals. Twelve are presently employed by governmental agencies or major contractors, 7 by educational institutions and 4 by private firms. Nine of the individuals listed are employed by major DOE laboratories. Twenty of the 25 listed people are presently working in radioecology or a closely related field and have well-established careers in the field. In view of the continuing and projected need for radioecologists, and the very limited production of them, the investment in these people will become increasingly important with time. Collectively, the radioecologists trained under this program will prove to be a far greater resource than the scientific information per se developed under the contract.

Table 1. Individuals who received graduate training under full or partial support from DOE Contract EY-76-S-02-1156.

Name	Degree	Year	Present Employment
F. W. Whicker	Ph.D.	1965	Colorado State University
G. C. Farris	M.S., Ph.D.	1965, 1967	Univ. of Southern Colorado
T. E. Hakonson	M.S., Ph.D.	1967, 1972	Los Alamos Scientific Lab.
C. S. Gist	M.S.	1969	Oak Ridge Associated Universities
A. F. Gallegos	Ph.D.	1969	New Mexico Highlands Univ.
L. Fraley, Jr.	Ph.D.	1971	Colorado State University
O. D. Markham	Ph.D.	1971	Idaho National Engineering Laboratory
S. Sparrow	M.S.	1973	U. S. Dept. of Agriculture
L. L. Cadwell	Ph.D.	1973	Battelle Northwest Labs
R. G. Schreckhise	Ph.D.	1974	Battelle Northwest Labs
D. K. Halford	Ph.D.	1974	Idaho National Engineering Laboratory
C. A. Little	Ph.D.	1976	Oak Ridge National Lab.
R. A. Geiger	M.S.	1977	Michigan State University (student)
L. M. McDowell-Boyer	M.S.	1977	Oak Ridge National Lab.
T. F. Winsor	post-doctoral	1977	Rockwell International (Rocky Flats)
J. A. Bly	M.S.	1977	
G. S. Hiatt	M.S.	1977	Wyoming Game & Fish Dept.
S. Baker	M.S.	1977	Western Nuclear Corp.
N. A. Daugherty	M.S.	1977	Pennsylvania State Univ.
L. Hersloff	Ph.D.	1977	Rocky Mountain Energy Co.
W. J. Arthur, III	M.S.	1977	Idaho National Engineering Laboratory
A. W. Alldredge	Ph.D.	1978	Colorado State University
S. L. Mecker	M.S.	1978	Upjohn Company
L. E. Alexander	M.S.	1979	U. S. Forest Service
K. L. K. Weaver			Colorado Dept. of Health

B. Synthesis of Radioecological Concepts

The breath of findings from different projects, and the collective ideas contributed by students and investigators supported under the contract, has provided foundation for the synthesis of many radioecological concepts. Most of this synthesis effort has been expressed in the form of review articles, bibliographies and selected readings, editorial services, development of graduate courses, and preparation of a book "Radioecology: Nuclear energy and the environment," soon to be published by CRC Press. These contributions could not have been made without the long-term support of the contract, and the enthusiasm and research freedom provided by technical representatives over the tenure of the program.

IX. PUBLICATIONS AND ORAL PRESENTATIONS

The following reports on work wholly or partially supported under DOE Contract EY-76-S-02-1156 have been published or prepared for publication (the recent reprints and pre-prints accompany this report):

- Hanson, W. C., F. W. Whicker, and A. H. Dahl. 1963. Iodine-131 in the thyroids of North American deer and caribou: comparison after nuclear tests. *Science* 140: 801-802. (C00-1156-2)
- Hanson, W. C., A. H. Dahl, F. W. Whicker, W. M. Longhurst, V. Flyger, S. P. Davey, and K. R. Greer. 1963. Thyroidal radioiodine concentrations in North American deer following 1961-1963 nuclear weapons tests. *Health Physics* 9: 1235-1239. (C00-1156-4)
- Whicker, F. W., E. E. Remmenga, and A. H. Dahl. 1965. Factors influencing the accumulation of I-131 in Colorado deer thyroids following 1961-1962 nuclear weapons tests. *Health Physics* 11: 293-296. (C00-1156-8)
- Whicker, F. W., G. C. Farris, A. H. Dahl, and E. E. Remmenga. 1965. Factors influencing the accumulation of fallout Cs-137 in Colorado mule deer. *Health Physics* 11: 1407-1414. (C00-1156-10)
- Whicker, F. W. 1965. Factors influencing the accumulation of fallout cesium-137 in mule deer. Ph.D. Dissertation. Colorado State University, Fort Collins. 230 p. (C00-1156-11)
- Farris, G. C. 1965. Strontium-90 in antlers and selected bones of Colorado mule deer. M. S. Thesis. Colorado State University, Fort Collins. 83 p. (C00-1156-12)
- Whicker, F. W., G. C. Farris, and A. H. Dahl. 1967. Concentration patterns of Sr-90, Cs-137, and I-131 in a wild deer population and environment, p. 621-633. In B. Aberg and F. P. Hungate (Ed.) *Radioecological Concentration Processes*, Pergamon Press, New York. (C00-1156-13)
- Whicker, F. W., R. A. Walters, and A. H. Dahl. 1967. Fallout radionuclides in Colorado deer liver. *Nature* 214: 511-513. (C00-1156-14)
- Whicker, F. W., G. C. Farris, and A. H. Dahl. 1966. Radioiodine concentrations in Colorado deer and elk thyroids during 1964-65. *J. Wildlife Mgmt.* 30(4): 781-785. (C00-1156-16)
- Farris, G. C., F. W. Whicker, and A. H. Dahl. 1967. Effect of age on radioactive and stable strontium accumulation in mule deer bone, p. 93-102. In J. M. A. Lenihan, J. F. Loutit, and J. H. Martin (Ed.) *Strontium Metabolism*, Academic Press, London. (C00-1156-17)
- Whicker, F. W., G. C. Farris, and A. H. Dahl. 1968. Wild deer as a source of radionuclide intake by humans and as indicators of fallout hazards, p. 1105-1110. In W. S. Snyder (Ed.) *Radiation Protection*, Pergamon Press, New York. (C00-1156-18)

- Remmenga, E. E. and F. W. Whicker. 1967. Sampling variability in radio-nuclide concentrations in plants native to the Colorado Front Range. *Health Physics* 13: 977-983. (C00-1156-19)
- Whicker, F. W. and C. M. Loveless. 1968. Relationships of physiography and microclimate to fallout deposition. *Ecology* 49(2): 363-366. (C00-1156-20)
- Nelson, W. C. and F. W. Whicker. 1969. Cesium-137 in some Colorado game fish, 1965-66, p. 258-265. In D. J. Nelson and F. C. Evans (Ed.) *Symposium on Radioecology*. CONF-670503. U. S. Atomic Energy Commission, Division of Technical Information Extension, Oak Ridge, Tennessee. (C00-1156-21)
- Farris, G. C., F. W. Whicker, and A. H. Dahl. 1969. Strontium-90 levels in mule deer and forage plants, p. 602-608. In D. J. Nelson and F. C. Evans (Ed.) *Symposium on Radioecology*. CONF-670503. U. S. Atomic Energy Commission, Division of Technical Information Extension, Oak Ridge, Tennessee. (C00-1156-23)
- Hakonson, T. E. and F. W. Whicker. 1969. Uptake and elimination of cesium-134 by mule deer, p. 616-622. In D. J. Nelson and F. C. Evans (Ed.) *Symposium on Radioecology*. CONF-670503. U. S. Atomic Energy Commission, Division of Technical Information Extension, Oak Ridge, Tennessee. (C00-1156-24)
- Hakonson, T. E. 1967. Tissue distribution and excretion of ^{134}Cs in the mule deer. M. S. Thesis. Colorado State University, Fort Collins. 121 p. (C00-1156-25)
- Farris, G. C. 1967. Factors influencing the accumulation of strontium-90, stable strontium, and calcium in mule deer. Ph.D. Dissertation. Colorado State University, Fort Collins. 189 p. (C00-1156-26)
- Hakonson, T. E. and F. W. Whicker. 1971. Tissue distribution of radio-cesium in the mule deer. *Health Physics* 21(6): 864-866. (C00-1156-27)
- Hakonson, T. E. and F. W. Whicker. 1971. The contribution of various tissues and organs to total body mass in the mule deer. *J. Mammalogy* 52(3): 628-630. (C00-1156-29)
- Gist, C. S. 1969. Iodine-131 retention in mule deer. M. S. Thesis. Colorado State University, Fort Collins. 75 p. (C00-1156-31)
- Markham, O. D. and F. W. Whicker. 1970. Radiation $\text{LD}_{50(30)}$ of pikas (*Ochotona princeps*) in the natural environment and in captivity. *Am. Midland Naturalist*. 84(1): 248-252. (C00-1156-32)
- Markham, O. D., F. W. Whicker, and R. M. Hansen. 1970. Radiation $\text{LD}_{50(30)}$ of Richardson ground squirrels. *Health Physics* 18(6): 731-732. (C00-1156-33)

- Gallegos, A. F. 1969. Radiocesium kinetics in the components of a montane lake ecosystem. Ph.D. Dissertation. Colorado State Univ., Fort Collins. 342 p. (C00-1156-34)
- Nagy, J. G., T. E. Hakonson, and K. L. Knox. 1969. Effects of food quality on food intake in deer. Trans. 34th North Am. Wildl. and Natural Resources Conf. 34: 146-154.
- Allredge, A. W. 1971. Those bottle fawns. Colorado Outdoors 20(3): 19-21. (C00-1156-36).
- Gallegos, A. F., F. W. Whicker, and T. E. Hakonson. 1971. Accumulation of radiocesium in rainbow trout via a non-food chain pathway. Proceedings, Fifth Ann. Midyear Topical Symposium, Health Phys. Soc., Health Physics Aspects of Nuclear Facility Siting II: 477-498. (C00-1156-37).
- Gist, C. S. and F. W. Whicker. 1971. Radioiodine uptake and retention by the mule deer thyroid. J. Wildlife Mgmt. 35(3): 461-468. (C00-1156-38).
- Whicker, F. W., W. C. Nelson, and A. F. Gallegos. 1972. Fallout ^{137}Cs and ^{90}Sr in trout from mountain lakes in Colorado. Health Physics 23(4): 519-528. (C00-1156-39)
- Hakonson, T. E., A. F. Gallegos and F. W. Whicker. 1974. Use of ^{133}Cs and activation analysis for measurement of cesium kinetics in a montane lake. p. 344-348. In D. J. Nelson (Ed.) Proceedings, Third National Symposium on Radioecology, May, 1971, Oak Ridge, Tenn. CONF-710501-P1. (C00-1156-41)
- Gallegos, A. F. and F. W. Whicker. 1974. Radiocesium retention by rainbow trout as affected by temperature and weight. p. 361-371. In D. J. Nelson (Ed.) Proceedings, Third National Symposium on Radioecology, May 1971, Oak Ridge, Tenn. CONF-710501-P1. (C00-1156-42).
- Markham, O. D. and F. W. Whicker. 1974. Intraspecific competition and response of pikas (Ochotona princeps) to radiation. p. 1070-1075. In D. J. Nelson (Ed.) Proceedings, Third National Symposium on Radioecology, May 1971, Oak Ridge, Tenn. CONF-710501-P2. (C00-1156-43).
- Fraley, L., Jr. and F. W. Whicker. 1974. Response of a native shortgrass plant stand to ionizing radiation. p. 999-1006. In D. J. Nelson (Ed.) Proceedings, Third National Symposium on Radioecology, May 1971, Oak Ridge, Tenn. CONF-710501-P2. (C00-1156-44)
- Fraley, L., Jr. 1971. Response of shortgrass plains vegetation to chronic and seasonally administered gamma radiation. Ph.D. Thesis. Colorado State University, Fort Collins. 170 p. (C00-1156-45)

- Schultz, V. and F. Ward Whicker. 1971. A selected bibliography of terrestrial, freshwater and marine radiation ecology. USAEC Report TID-25650. USAEC Division of Technical Information Extension. Oak Ridge, Tenn. 185 p. (C00-1156-46)
- Adams, C. E., D. Lund, and D. Markham. 1971. A chromosome study of the pika, Ochotona princeps. Mammalian Chromosomes Newsletter 12(3): 77-78. (C00-1156-47)
- Markham, O. D. 1971. Effects of ^{60}Co radiation and social interaction of the pika (Ochotona princeps). Ph.D. Thesis. Colorado State University, Fort Collins. 51 p. (C00-1156-48)
- Markham, O. D. and F. W. Whicker. 1972. Burrowing in the pika. J. Mammalogy 53(2): 387-389. (C00-1156-49).
- Markham, O. D. 1971. Observations on an aggressive blue grouse. Colo. Field Ornithologist 10: 6. (C00-1156-50)
- Markham, O. D. and F. W. Whicker. 1973. Seasonal data on reproduction and body weights of pikas (Ochotona princeps). J. Mammalogy 54(2): 496-498. (C00-1156-51)
- Markham, O. D. and F. W. Whicker. 1973. Notes on the ecology of the pika (Ochotona princeps) in captivity. Am. Midl. Naturalist 89(1): 192-199 (C00-1156-52)
- Schultz, V. and F. W. Whicker. 1972. Ecological aspects of the nuclear age: Selected readings in radiation ecology. TID-25978. U. S. Atomic Energy Commission, Technical Information Center, Oak Ridge, Tenn. 588 p. (C00-1156-53)
- Cadwell, L. L. 1973. Colony formation of the western harvester ant in a chronic gamma radiation field. Am. Midl. Naturalist. 89(2): 446-448. (C00-1156-55)
- Hakonson, T. E. 1972. Cesium kinetics in a montane lake ecosystem. Ph.D. Thesis. Colorado State University, Fort Collins. 154 p. (C00-1156-56)
- Whicker, F. W. and L. Fraley, Jr. 1974. Effects of ionizing radiation on terrestrial plant communities. p. 317-366. In J. T. Lett, H. Adler, and M. R. Zelle (Eds.) Advances in Radiation Biology, Vol. 4. Academic Press, Inc., New York. (C00-1156-57)
- Schultz, V. and F. W. Whicker. 1974. Radiation ecology. CRC Critical Reviews in Environmental Control 4(4): 423-464. (C00-1156-58)
- Cadwell, L. L. and F. W. Whicker. Responses of naturally occurring arthropods in a gamma radiation field. Environmental Entomology (In Press), Accepted 9/22/77. (C00-1156-59).

- Fraley, L., Jr. and F. W. Whicker. 1973. Response of shortgrass plains vegetation to gamma radiation: I. Chronic irradiation. *Radiation Botany* 13: 331-341. (C00-1156-60)
- Fraley, L., Jr. and F. W. Whicker. 1973. Response of shortgrass plains vegetation to gamma radiation: II. Short-term, seasonal irradiation. *Radiation Botany* 13: 343-353. (C00-1156-61)
- Alldredge, A. W., J. F. Lipscomb, and F. W. Whicker. 1974. Forage intake rates of mule deer estimated with fallout cesium-137. *J. Wildlife Mgmt.* 38(3): 508-516. (C00-1156-62)
- Hakonson, T. E. and F. W. Whicker. 1975. Cesium kinetics in a montane lake ecosystem. *Health Physics* 28: 699-706. (C00-1156-64)
- Hakonson, T. E., A. F. Gallegos, and F. W. Whicker. 1975. Cesium kinetics data for estimating food consumption rates of trout. *Health Physics* 29: 301-306. (C00-1156-65)
- Sparrow, S. 1973. Chronic gamma radiation stress on soil microorganisms of a grassland. M. S. Thesis. Colorado State University, Fort Collins. 103 p. (C00-1156-66)
- Cadwell, L. L. 1973. Rangeland grasshopper foraging impact. Ph.D. Dissertation. Colorado State University, Fort Collins. 109 p. (C00-1156-67)
- Whicker, F. W., C. A. Little, and T. F. Winsor. 1974. Plutonium behavior in the terrestrial environs of the Rocky Flats Installation. *Environmental Surveillance Around Nuclear Installations, Vol. II. International Atomic Energy Agency, Vienna.* IAEA/SM-180/45. p. 89-103. (C00-1156-68)
- Schreckhise, R. G. 1974. Strontium kinetics in mule deer. Ph.D. Dissertation. Colorado State University, Fort Collins. 76 p. (C00-1156-69)
- Halford, D. K. 1974. A method for artificially raising mule deer fawns. M. S. Thesis. Colorado State University, Fort Collins. 21 p.
- Halford, D. K. and A. W. Alldredge. 1975. Behavior associated with parturition in captive Rocky Mountain mule deer. *J. Mammalogy* 56(2): 520-522. (C00-1156-72)
- Schultz, V. and F. W. Whicker. 1975. Selected bibliography of terrestrial, freshwater and marine radioecology. U. S. Energy Research and Development Administration Report TID-25650-S1. National Tech. Inf. Service, Springfield, Va. 240 p.
- Halford, D. K. and A. W. Alldredge. 1978. A method for artificially raising mule deer fawns. *Am. Midl. Naturalist* 100(2): 493-498. (C00-1156-73)

- Allredge, A. W., F. W. Whicker, and W. C. Hanson. 1976. Environmental impacts associated with Project Rio Blanco. p. 65-73. In Radioecology and Energy Resources - Proc. Fourth National Symposium on Radioecology. C. E. Cushing (Ed.) Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pa. (C00-1156-76)
- Schreckhise, R. G. and F. W. Whicker. 1976. A model for predicting strontium-90 levels in mule deer. p. 148-156. In Radioecology and Energy Resources - Proc. Fourth National Symposium on Radioecology. C. E. Cushing (Ed.) Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pa. (C00-1156-77)
- Cadwell, L. L. and R. G. Schreckhise. 1976. Determination of varying consumption rates from radiotracer data. p. 123-125. In Radioecology and Energy Resources - Proc. Fourth National Symposium on Radioecology. C. E. Cushing (Ed.) Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pa. (C00-1156-78)
- Cushing, C. E., F. W. Whicker, L. Fraley, Jr., et al. (Eds.). 1976. Radioecology and energy resources. Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pa. 401 p.
- Brunson, J. T. and O. D. Markham. Comparison of selected hematological variables between high altitude and translocated pikas, Ochotona princeps. Reviewed by J. Mammalogy and Am. Midl. Naturalist. (C00-1156-79)
- Markham, O. D. 1975. Pika portrait. Colorado Outdoors. July-August 1975: 31-34. (C00-1156-81)
- Dagle, G. E., T. F. Winsor, and R. R. Adee. Besnoitiosis in rodents from Colorado. Reviewed by J. Wildlife Diseases and J. Am. Vet. Assoc. To be resubmitted to J. Mammalogy. (C00-1156-82)
- Little, C. A. 1976. Plutonium in a grassland ecosystem. Ph.D. Dissertation. Colorado State University, Fort Collins. 170 p. (C00-1156-83)
- Geiger, R. A. and T. F. Winsor. 1977. ^{239}Pu contamination in snakes inhabiting the Rocky Flats Plant site. Health Physics 33(2): 145-148. (C00-1156-85)
- Alexander, L. E. 1977. Mother deer. Empire Magazine. 5/8/77 (supplement to the Denver Post). p. 46-48.
- Little, C. A., F. W. Whicker, and T. F. Winsor. Plutonium in a terrestrial ecosystem at the Rocky Flats nuclear weapons plant. J. Env. Quality (under review). (C00-1156-86)
- McDowell, L. M. and F. W. Whicker. 1978. Size characteristics of plutonium particles in Rocky Flats soil. Health Physics 35(2): 293-299. (C00-1156-87)

- Winsor, T. F. and F. W. Whicker. Pocket gophers and redistribution of plutonium in soil. Health Physics (In Press). (C00-1156-88)
- Whicker, F. W. Ecological effects of transuranics in the terrestrial environment. For W. C. Hanson (Ed.). Transuranium Elements in the Environment. TID-22800. U. S. Department of Energy (In Press). (C00-1156-91)
- Little, C. A. and F. W. Whicker. 1978. Plutonium distribution in Rocky Flats soil. Health Physics 34(5): 451-457. (C00-1156-92)
- Arthur, W. J., G. S. Hiatt, and A. W. Alldredge. 1978. Response of mule deer to tape recorded fawn distress calls. Wildlife Soc. Bulletin 6(3): 169-170. (C00-1156-93)
- Ribic, C. A. 1978. Summer foods of coyotes at Rocky Flats, Colorado. Southwestern Naturalist 23: 1. (C00-1156-94)
- Bly, J. A. and F. W. Whicker. 1979. Plutonium concentrations in arthropods at a nuclear facility. Health Physics 37: 331-336. (C00-1156-95)
- Hiatt, G. S. 1977. Plutonium dispersal by mule deer at Rocky Flats, Colorado. M. S. Thesis. Colorado State University, Fort Collins, Colo. 143 p. (C00-1156-96)
- Whicker, F. W. and L. Fraley, Jr. 1977. Overview of Colorado State University terrestrial buffer zone studies. p. 6-9. In D. C. Hunt (Ed.). Transactions of meeting on Rocky Flats buffer zone ecological and environmental research. Rockwell International, Rocky Flats Plant, Golden, Colo. 71 p. (C00-1156-97)
- Little, C. A. 1977. Distribution of plutonium in the terrestrial environment. p. 10-14. In D. C. Hunt (Ed.). Transactions of meeting on Rocky Flats buffer zone ecological and environmental research. Rockwell International, Rocky Flats Plant, Golden, Colo. 71 p. (C00-1156-98)
- Alldredge, A. W., W. J. Arthur, III, and G. S. Hiatt. 1977. Mule deer as a plutonium transport vector. p. 15-19. In D. C. Hunt (Ed.). Transactions of meeting on Rocky Flats buffer zone ecological and environmental research. Rockwell International, Rocky Flats Plant, Golden, Colo. 71 p. (C00-1156-99)
- Arthur, W. J., III. 1977. Plutonium intake by mule deer at Rocky Flats, Colorado. M. S. Thesis. Colorado State University, Fort Collins, Colo. 123 p. (C00-1156-100)
- Winsor, T. F. 1977. Small mammal studies in the buffer zone. p. 20-23. In D. C. Hunt (Ed.). Transactions of meeting on Rocky Flats buffer zone ecological and environmental research. Rockwell International, Rocky Flats Plant, Golden, Colo. 71 p. (C00-1156-101)

- Schultz, V. and F. W. Whicker. Ecological factors in the dispersal of radioactivity in the biosphere. Manuscript prepared for A. Brodsky (Ed.). Handbook of radiation measurement and protection. Vol. III. CRC Press, West Palm Beach, Florida (In Press). (C00-1156-102)
- Watters, R. L., D. N. Edgington, T. E. Hakonson, W. C. Hanson, M. H. Smith, F. W. Whicker, and R. E. Wildung. Synthesis of the research literature. For W. C. Hanson (Ed.). Transuranium elements in the environment. TID-22800. U. S. Department of Energy (In Press).
- Arthur, W. J., III and A. W. Alldredge. 1979. Soil ingestion by mule deer in northcentral Colorado. J. Range Mgmt. 32(1): 67-71. (C00-1156-105)
- Mecker, S. L. 1978. Uptake versus aerial deposition of plutonium in plants at Rocky Flats. M. S. Thesis. Colorado State Univ., Fort Collins. 56 p. (C00-1156-106)
- Little, C. A. Plutonium in a grassland. For W. C. Hanson (Ed.). Transuranium elements in the environment. TID-22800. U. S. Department of Energy (In Press). (C00-1156-107)
- Alexander, L. E. 1979. Mule deer food habits in relation to forage availability at Rocky Flats, Colorado. M. S. Thesis. Colorado State University, Fort Collins. (C00-1156-108)
- Alexander, L. E., A. W. Alldredge and W. J. Arthur. Comparison of mule deer food habits data obtained from bite-count and micro-histological data. J. Range Mgmt. (In Press) (C00-1156-109)
- Alldredge, A. W. and W. J. Arthur. Observations on coyote-mule deer interactions at Rocky Flats, Colorado. Amer. Midl. Natur. (In Press) (C00-1156-110)
- Alldredge, A. W., W. J. Arthur, L. E. Alexander, and G. S. Hiatt. Role of mule deer in plutonium movement at Rocky Flats. In Manuscript. (C00-1156-111)
- Arthur, W. J. and A. W. Alldredge. Seasonal estimates of mule deer fecal pellet and fecal group masses. J. Wildl. Manage (In Press). (C00-1156-112)
- Arthur, W. J. and A. W. Alldredge. Plutonium accumulation by vegetation at Rocky Flats, Colorado. In manuscript. (C00-1156-113)
- Bartman, R., P. N. Neil and A. W. Alldredge. Evaluation of bite count technique in estimating mule deer food habits. In manuscript. (C00-1156-114)
- Johnson, B. K. and A. W. Alldredge. Evaluation of the beta particle attenuation method for measuring standing crop of alpine vegetation. In manuscript. (C00-1156-115)

Nagy, J. G. and A. W. Alldredge. Rate of passage of increasingly fibrous diets through the digestive tract of mule deer (Odocoileus hemionus) and domestic sheep (Ovis spp.). International Congress of Game Biologists, Ireland. (In Press) (C00-1156-116)

The following papers representing work conducted under DOE Contract EY-76-S-02-1156 have been presented orally at scientific meetings or formal seminars at other institutions:

- Whicker, F. W. and A. H. Dahl. 1963. Accumulation of fallout radionuclides in Colorado mule deer. Presented June 13, 1963 at the annual meeting of the Health Physics Society, New York City. P/90. (C00-1156-3)
- Dahl, A. H., F. W. Whicker, and G. C. Farris. 1964. A study of the food chain patterns of Sr-90, Cs-137, and I-131 in a mule deer population. Presented March 10, 1964 at the meeting on Radiation and Wildlife at the North American Wildlife Conference, Las Vegas, Nevada.
- Farris, G. C. 1964. Strontium-90 concentrations in bones and forage plants. Presented April 24, 1964 at the AEC-ARMU Technical Conference at the University of New Mexico, Albuquerque. P/1, Session IV. (C00-1156-6)
- Farris, G. C., A. H. Dahl, and F. W. Whicker. 1964. Accumulation of Sr-90 in selected bones and forage plants of Colorado mule deer. Presented June 18, 1964 at the annual meeting of the Health Physics Society, Cincinnati, Ohio. P/131. (C00-1156-7)
- Whicker, F. W., G. C. Farris, A. H. Dahl, and E. E. Remmenga. 1965. Factors influencing the accumulation of fallout Cs-137 in Colorado mule deer. Presented May 4, 1965 at the Battelle-Northwest Symposium on Radiation and Terrestrial Ecosystems, Richland, Washington. (C00-1156-10)
- Whicker, F. W. 1965. Fallout radionuclides in mule deer. Presented August 9, 1965 at the Central Mountains and Plains Section Conference of the Wildlife Society, Centennial, Wyoming.
- Whicker, F. W., G. C. Farris, and A. H. Dahl. 1966. Concentration patterns of Sr-90, Cs-137, and I-131 in a wild deer population and environment. Presented at the Symposium on Radioecological Concentration Processes, April 25-29, 1966, Stockholm, Sweden. (C00-1156-13)
- Farris, G. C., F. W. Whicker, and A. H. Dahl. Effect of age on radioactive and stable strontium accumulation in mule deer. Presented at the International Symposium on Some Aspects of Strontium Metabolism, May 5-6, 1966, Chapelcross, Scotland. (C00-1156-17)
- Whicker, F. W., R. A. Walters, and A. H. Dahl. Fallout radionuclides in Colorado deer livers. Eleventh Annual Meeting, Health Physics Society, June 27-30, 1966, Houston, Texas. P/79.

- Whicker, F. W., G. C. Farris, and A. H. Dahl. Wild deer as a source of radionuclide intake by humans and as indicators of fallout hazards. Presented at the First International Congress of IRPA, September 5-10, 1966, Rome, Italy. (C00-1156-18)
- Nelson, W. C. and F. W. Whicker. Cesium-137 concentrations in some Colorado game fish, 1965-66. Presented at the Second National Symposium on Radioecology, May 15-17, 1967, Ann Arbor, Michigan. P/54. (C00-1156-21)
- Farris, G. C., F. W. Whicker, and A. H. Dahl. Strontium-90 levels in mule deer and forage plants. Presented at the Second National Symposium on Radioecology, May 15-17, 1967, Ann Arbor, Michigan. P/42. (C00-1156-23)
- Hakonson, T. E. and F. W. Whicker. Uptake and elimination of cesium-134 by mule deer. Presented at the Second National Symposium on Radioecology, May 15-17, 1967, Ann Arbor, Michigan. P/44. (C00-1156-24)
- Hakonson, T. E. Uptake and elimination of cesium-134 by mule deer. Presented at the Institute of Arctic Biology, University of Alaska, College, Alaska, March 22, 1968.
- Farris, G. C., F. W. Whicker, and A. H. Dahl. Factors influencing the accumulation of Sr-90, stable strontium and calcium in mule deer. Presented at the Thirteenth Annual Meeting, Health Physics Society, June 16-20, 1968, Denver, Colorado. P/114.
- Whicker, F. W. and C. M. Loveless. Relationships of physiography and microclimate to fallout deposition. Presented at the AAAS - Ecological Society Meeting, June 24-29, 1968, Logan, Utah. P/36.
- Gallegos, A. F. Curve fitting of biological models to ingrowth type equations. Presented April 26, 1969 at the Student Conference, American Nuclear Society, University of New Mexico, Albuquerque.
- Gist, C. S. and F. W. Whicker. Radioiodine retention in mule deer. Presented May 9, 1969 at the AAAS - Colorado Wyoming Academy of Science Meetings, Colorado Springs, Colorado. P/204.
- Gallegos, A. F. Radiocesium kinetics in a montane lake ecosystem. Presented May 10, 1969 at the AAAS - Colorado Wyoming Academy of Science Meetings, Colorado Springs, Colorado. P/240.
- Whicker, F. W. Investigations in radioecology at Colorado State University. Presented June 6, 1969 at the Institute of Arctic Biology, University of Alaska, College.
- Fraley, L. Response of a shortgrass plains community to ionizing radiation. Presented October 24, 1969 at the IBP Pawnee Site Research Seminar. Southern Colorado State College, Pueblo, Colorado.

Hakonson, T. E. Concepts concerning radioactive materials and their relationship to ecology. Presented December 22, 1969 to the Kiwanis Club, Cottage Grove, Oregon.

Fraley, L. and F. W. Whicker. The effect of ionizing radiation on a shortgrass plant stand. Presented April 22, 1970 at the Meeting of the Southwestern and Rocky Mountain Division of the AAAS, Las Vegas, New Mexico. P/23.

Markham, O. D. and F. W. Whicker. Effect of acute ionizing radiation on pikas (Ochotona princeps) in the natural environment and in captivity. Presented April 22, 1970 at the Meeting of the Southwestern and Rocky Mountain Division of the AAAS, Las Vegas, New Mexico. P/122.

Farris, G. C. and F. W. Whicker. Strontium-90, stable strontium and calcium in mule deer does and their fetuses. Presented April 22, 1970 at the Meeting of the Southwestern and Rocky Mountain Division of the AAAS, Las Vegas, New Mexico. P/123.

Gallegos, A. F., F. W. Whicker, and T. E. Hakonson. Accumulation of radiocesium in rainbow trout via a non-food chain pathway. Presented November 5, 1970 at the Fifth Annual Health Physics Society Midyear Topical Symposium on Health Physics Aspects of Nuclear Facility Siting. Idaho Falls, Idaho.

Hakonson, T. E. and F. W. Whicker. Use of ^{133}Cs and activation analysis for measurement of cesium kinetics in a montane lake. Presented May 11, 1971 at the Third National Symposium on Radioecology, Oak Ridge, Tennessee. P/19. (C00-1156-41)

Gallegos, A. F. and F. W. Whicker. Radiocesium retention by rainbow trout as affected by temperature and weight. Presented May 11, 1971 at the Third National Symposium on Radioecology, Oak Ridge, Tennessee. P/19. (C00-1156-42)

Markham, O. D. and F. W. Whicker. Intra-specific competition and response of pikas (Ochotona princeps) to radiation. Presented May 11, 1971 at the Third National Symposium on Radioecology, Oak Ridge, Tennessee. P/40. (C00-1156-43)

Fraley, L. and F. W. Whicker. Response of a native shortgrass plant stand to ionizing radiation. Presented May 12, 1971 at the Third National Symposium on Radioecology, Oak Ridge, Tennessee. P/163. (C00-1156-44)

Hakonson, T. E. and F. W. Whicker. A stable tracer technique for determining cesium kinetics in a montane lake. Presented August 31, 1971 at the 22nd Annual AIBS Meeting of Biological Sciences, Colorado State University, Fort Collins. P/38.

- Whicker, F. W. Radioecological research at Colorado State University. Presented March 17, 1972, Zoology Department, Washington State University, Pullman, Washington.
- Schreckhise, R. G., A. W. Alldredge, and V. L. Roberts. Facilities for studying tracer kinetics in mule deer. Presented April 27, 1972 at the 48th Annual Meeting of the Southwestern and Rocky Mountain Division of the AAAS, Fort Collins, Colorado. P/120.
- Alldredge, A. W. and F. W. Whicker. A method for measuring soil erosion and deposition with beta particle attenuation. Presented April 27, 1972 at the 48th Annual Meeting of the Southwestern and Rocky Mountain Division of the AAAS, Fort Collins, Colorado. P/122.
- Cadwell, L. L. and F. W. Whicker. The effects of a gamma irradiation field on the structure of a shortgrass plains arthropod community. Presented April 27, 1972 at the 48th Annual Meeting of the Southwestern and Rocky Mountain Division of the AAAS, Fort Collins, Colorado. P/216.
- Whicker, F. W. A prospectus for radioecology. Presented Nov. 1, 1972, Biomedical Division, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
- Whicker, F. W. Behavior of cesium in mountain lakes. Presented Dec. 4, 1972, Biomedical Division, Lawrence Livermore Laboratory, Livermore, California.
- Whicker, F. W., C. A. Little, and T. F. Winsor. Plutonium behavior in the terrestrial environs of the Rocky Flats Installation. Presented Nov. 5-9, 1973 at the Symposium on Environmental Surveillance Around Nuclear Installations, Warsaw, Poland. IAEA/SM-180/45.
- Winsor, T. F., C. A. Little, and F. W. Whicker. Plutonium behavior in the terrestrial environs of the Rocky Flats installation. Presented February 28, 1974 at the 87th Annual Research Conference of Colorado State University, Fort Collins, Colorado. p/91.
- Winsor, T. F., C. A. Little, and F. W. Whicker. Plutonium behavior in the terrestrial environs of the Rocky Flats installation. Presented April 25, 1974 at the 50th Annual Meeting of the Southwestern and Rocky Mountain Division of the AAAS and the 45th Annual Meeting of the Colorado-Wyoming Academy of Science, Laramie, Wyoming. p/80.
- Weaver, K. L. Seasonal kinetics of cesium in a montane lake ecosystem. Presented April 26, 1974 at the 50th Annual Meeting of the Southwestern and Rocky Mountain Division of the AAAS and the 45th Annual Meeting of the Colorado-Wyoming Academy of Science, Laramie, Wyoming. p/64.

Whicker, F. W., C. A. Little, and T. F. Winsor. Plutonium contamination in the terrestrial environs of Rocky Flats. Presented July 9, 1974 at the 19th Annual Meeting of the Health Physics Society, Houston, Texas. p/125.

Whicker, F. W., C. A. Little and T. F. Winsor. Behavior of plutonium in terrestrial ecosystems. Presented July 11, 1974 at the AEC-Sponsored Plutonium Workshop, Estes Park, Colorado.

Fraley, L., C. A. Little and A. W. Alldredge. Plutonium studies in the terrestrial environs of Rocky Flats. Presented October 10, 1974 at the NAEG Information Conference, Las Vegas, Nevada.

Schreckhise, R. G. and F. W. Whicker. A model for predicting strontium-90 levels in mule deer. Presented May 12, 1975 at the Fourth National Symposium on Radioecology, Corvallis, Oregon. p/B-14.

Little, C. A., T. F. Winsor, F. W. Whicker, and L. Fraley, Jr. Plutonium in the grassland at Rocky Flats. Presented May 13, 1975 at the Fourth National Symposium on Radioecology, Corvallis, Oregon. p/A-11.

Winsor, T. F., C. A. Little, and F. W. Whicker. Effects of pocket gopher activity on soil plutonium distribution at Rocky Flats, Colorado. Presented May 13, 1975 at the Fourth National Symposium on Radioecology, Corvallis, Oregon. p/A-20.

Alldredge, A. W., F. W. Whicker, and W. C. Hanson. Environmental impacts associated with Project Rio Blanco. Presented May 13, 1975 at the Fourth National Symposium on Radioecology, Corvallis, Oregon. p/A-28.

Weaver, K. L. and F. W. Whicker. Long-term behavior of cesium in a montane lake. Presented May 13, 1975 at the Fourth National Symposium on Radioecology, Corvallis, Oregon. p/B-36.

Cadwell, L. L., R. G. Schreckhise, and F. W. Whicker. The use of the convolution integral in making consumption rate determinations from radiotracer data. Presented May 14, 1975 at the Fourth National Symposium on Radioecology, Corvallis, Oregon. p/A-48.

Fraley, L., Jr. A comparison of radiation with other artificial stresses on shortgrass vegetation. Presented May 14, 1975 at the Fourth National Symposium on Radioecology, Corvallis, Oregon. p/B-54.

Whicker, F. W., C. A. Little, T. F. Winsor, A. W. Alldredge, S. J. Baker, and J. A. Regnier. CSU radioecological studies at Rocky Flats. Presented June 19, 1975 at the Dow Conference on Rocky Flats Research Programs, University of Colorado, Boulder, Colorado.

Whicker, F. W. Radioecological studies on plutonium at Rocky Flats. Presented July 29, 1975 to the Division of Biomedical and Environmental Research, ERDA, Germantown, Maryland.

- Whicker, F. W. Radioecological studies on plutonium at Rocky Flats. Presented November 12, 1975 at the ERDA-Sponsored Workshop on Environmental Research for Transuranium Elements, Battelle Seattle Research Center, Seattle, Washington.
- Arthur, W. J. Use of tame deer in ecological studies. Presented November 22, 1975 to the Larimer County 4-H Clubs, Fort Collins, Colorado.
- Arthur, W. J. Use of tame deer in ecological studies. Presented December 31, 1975 and July 7, 1976 at the National Wildlife Federation Conservation Summit Program, Estes Park, Colorado.
- Little, C. A. and T. F. Winsor. Statistical experience with environmental plutonium sampling at Rocky Flats. Presented June 27-July 2, 1976 at the 21st Annual Meeting of the Health Physics Society, San Francisco, California. p. Hb/2.
- Arthur, W. J. and L. Alexander. Radioecological studies with mule deer. Presented July 15, 1976 to the Rocky Mountain Nature Association, Fort Collins, Colorado.
- Whicker, F. W. Consequences of transuranics in the terrestrial environment. Presented January 6, 1977 as an invited seminar at Battelle Northwest Laboratory, Richland, Washington.
- Alldredge, A. W., W. J. Arthur, and G. S. Hiatt. Mule deer as a plutonium transport vector. Presented by Arthur February 4, 1977, at Colorado Chapter of The Wildlife Society, Colorado Springs, CO.
- Alldredge, A. W., W. J. Arthur, and G. S. Hiatt. Plutonium movements by mule deer at Rocky Flats, Colorado. Presented February 24, 1977. (Poster Session) 1977 Annual Meeting of the AAAS, Denver, CO.
- Whicker, F. W. and L. Fraley, Jr. Overview of Colorado State University terrestrial buffer zone studies. Presented March 4, 1977 at the Rocky Flats Environmental and Ecological Research meeting, Boulder, CO.
- Alldredge, A. W., W. J. Arthur, and G. S. Hiatt. Mule deer as a plutonium transport vector. Presented March 4, 1977, at the Rocky Flats Environmental and Ecological Research meeting, Boulder, CO.
- Little, C. A. Terrestrial distributions of plutonium. Presented March 4, 1977 at the Rocky Flats Environmental and Ecological Research meeting, Boulder, CO.
- Winsor, T. F. Small mammal studies in the buffer zone. Presented March 4, 1977 at the Rocky Flats Environmental and Ecological Research meeting, Boulder, CO.
- Arthur, W. J. Plutonium intake by mule deer at Rocky Flats, Colorado. Seminar presented March, 1977, at INEL, Idaho Falls, Idaho.

Alldredge, A. W., W. J. Arthur, and G. S. Hiatt. Mule deer as a plutonium transport vector. Presented by Alldredge as an invited seminar, Los Alamos Scientific Laboratory, April 7, 1977. Los Alamos, New Mexico.

Hiatt, G. S. and W. J. Arthur. Mule deer in radioecological studies. Presented April 8, 1977, to Western Wildlife Students Conclave, Fort Collins, CO.

Whicker, F. W. Plutonium studies at Rocky Flats and Summary of Panel on Ecological Consequences of Transuranics. Presented April 19 and 22, 1977, at the ERDA Workshop on Environmental Research for Transuranic Elements, Woods Hole, Massachusetts.

Whicker, F. W. Radioecological problems in uranium mining/milling and nuclear waste management. Presented May 18, 1977, as an invited seminar at Oak Ridge National Laboratory, Oak Ridge, Tenn.

Alldredge, A. W. Measurement of soil erosion and deposition using beta particle attenuation. Invited paper at the Pawnee Soil Science Workshop May 19, 1977. Pawnee Site, CO.

Arthur, W. J. and L. E. Alexander. Mule deer food habits studies - slide talk and field demonstration. Presented July 9, 1977, at National Wildlife Conservation Summit, Estes Park, CO.

Whicker, F. W. Plutonium in the terrestrial environs of the Rocky Flats Plant. Presented November 22, 1977, at a public meeting between Rockwell International and the Colorado State Department of Health, Boulder, CO.

Cadwell, L. L. and F. W. Whicker. Consumption and destruction of range grasses by grasshoppers. Presented February 9, 1978, at the 31st Annual Meeting of the Society for Range Management, San Antonio, Texas.

Alexander, L. E. Use of tame deer in food habits research. Presented May 13, 1978, at the Rocky Mountain Arsenal, Denver, Colorado, to an ecology workshop for Denver area teachers.

Little, C. A. Differential concentration of plutonium isotopes in Rocky Flats biota. Presented June 23, 1978 at the Annual Meeting of the Health Physics Society, Minneapolis, Minn. P/183.

Alldredge, A. W. and L. E. Alexander. Tame deer in food habits research. Presented July 3-9, 1978, to the National Wildlife Federation Conservation Summit, Estes Park, Colorado.

Whicker, F. W. Biological interactions and reclamation of uranium mill tailings. Presented November 21, 1978 at the Symposium on Uranium Mill Tailings. Colorado State University, Fort Collins, Colorado.

Whicker, F. W. Radioecological implications of uranium mining and milling. Presented March 13, 1979 at the Uranium Resource/Technology Seminar II. Colorado School of Mines, Golden, Colorado.

Alldredge, A. W. Mule deer, plutonium, Rocky Flats, and the great wildlife refuge. Presented March 21, 1979 to the Student Chapter of the Wildlife Society. Colorado State University, Fort Collins.

Alldredge, A. W. Role of mule deer in plutonium cycling at Rocky Flats. Presented May 7, 1979 to Rockwell International, Rocky Flats, Golden, Colorado.