U.S. Radioecology Research Programs Initiated in the 1950s

History of the Atomic Projects, The 50s Years:
Sociopolitical, Environmental, and Engineering Lessons Learned

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Introduction

In the early postwar years, beginning in 1949 and extending to the mid-1960s, U.S. Atomic Energy Commission (AEC) research on the fate and effects of radionuclides in the environment was driven by distinct environmental concerns-- the releases of radioactive materials around production sites, fallout from nuclear weapons tests, and radiation effects from both external and internal exposures. These problem areas spawned development of the scientific field of radioecology. To understand the perspectives in the 1950s of the United States on the issues of nuclear energy and the environment, we have reviewed the early research programs. Keeping to the theme of the papers in this environmental session, we will focus on the first area of concern -- the scientific studies to understand the environmental consequences of nuclear production and fuel reprocessing at the three primary production sites: the Hanford Works in the state of Washington, Clinton Laboratories in Oak Ridge, Tennessee, and the Savannah River Plant in South Carolina. The driving environmental issue was the fate and effects of waste products from nuclear fuel production and reprocessing -- concern about entry into environmental pathways. Early operational monitoring and evaluation by health physicists led to realization that additional emphasis needed to be placed on understanding environmental fate of radionuclides. What followed was forward-thinking R&D planning and development of interdisciplinary research teams for experimentation on complex environmental systems. What follows is a review of the major U.S. AEC radioecology research programs initiated during the 1950s, the issues leading to the establishment of these programs, early results, and their legacies for environmental protection and ecological research in the following decades.

The Beginning of the Radioecology Research Programs

At the beginning of the decade of 1950s there was increased awareness of the need for research dealing with the broader aspects of nuclear energy the problems associated with the production and testing of nuclear bombs. Small environmental programs were established at a number of U.S. AEC facilities that produced materials and components for bombs. These

programs were either concerned with the possible problems associated with releases to the local environments (Stannard, 1988). For example, at the Hanford Atomic Works in the state of Washington, an aquatic biology testing facility was established to monitor and assess the possible impact of radionuclides that were being discharged to the Columbia River in water for cooling the giant reactors used in the production of plutonium (Foster, 1972). Here the scientists evaluated the uptake of nuclides, particularly phosphorus-32 and zinc-15 in the Columbia River fish populations as well as other edible marine species such as oysters, clams, and crustaceans in the ocean waters off the mouth of the Columbia River (Foster & Davis, 1956).

Another giant nuclear production facility was built and put into operation in South Carolina in the 1950s (Odum, 1956). Here the AEC, already sensitive to the need for environmental surveillance, contracted with the University of Georgia to carry out preoperational surveys. This project was led by Eugene Odum, already a prominent American ecologist. In this case the Georgia scientists, not yet knowledgeable about radionuclides and their environmental problems, focused on developing background information that would prove useful in understanding possible ecosystem consequences in the vicinity of the facility.

Oak Ridge National Laboratory became a center for development of reactor fuel element reprocessing technology. Reprocessing of fuel elements was necessary to recover the unburned fissile materials, primarily plutonium and uranium-235 which could be reused. At the same time this process resulted in the extraction of waste fission products, created as a result of the fission reaction. Some of the many species of radionuclides produced, because of their long half-lives or their abundance, were recognized as requiring subsequent treatment and disposal in ways that would minimize their release to the environment. Among these elements were strontium-90, cesium-137, cobalt-60, zinc-65, and ruthenium-106. Those with the longest half-lives were of most concern, such as ^{90}Sr, ^{137}Cs, and ^{60}Co (Auerbach, 1993; Whicker & Schultz, 1982).

In the 1950s there were two methods of radioactive waste disposal. The large quantities of high level wastes were stored in specially designed underground tank systems. The wastes containing lesser quantities of radionuclides were, especially at Oak Ridge, either released slowly to a nearby stream after treatment and dilution or placed in large earthen pits (either open

or below ground) and allowed to seep into the nearby soil. This method was predicated on the assumption that the different nuclides would be chemically retained in the surrounding soil column due to chemical fixation of the nuclide species within the exchange complex of the surrounding soil mass. Laboratory studies had shown that these soils had a strong chemical affinity for some of the nuclides, especially ^{137}Cs.

Weapons testing was being conducted in the United States and elsewhere and a number of countries were becoming concerned about world-wide fallout, particularly of ^{90}Sr. Results of surveys of contaminated biota on contaminated islands in the Pacific Proving Grounds were first published in 1956 (AEC, 1956). Meanwhile, agricultural scientists in the U.S. and Great Britain began investigations and field studies on the factors governing uptake of ^{90}Sr and its transport into food chains that led directly to man, especially through milk as well as into major food crops (Klement, 1965). In these countries this research was supported by the respective energy agencies and carried out in the major agricultural research stations (e.g., Beltsville, USA; Agricultural Research Council, UK).

There was also an established network for monitoring and measuring the radioactive fallout from the testing of atomic bombs that had continued into the 1950s. The U.S. Atomic Energy Commission had a broad network of monitoring stations across the U.S. (Eisenbud and Harley, 1953). This program mainly focused on measuring the species and quantities of radionuclides deposited across the U.S. and developed a continuing accounting of the quantities of radionuclides, e.g., ^{90}Sr, ^{137}Cs, and ^{131}I, ^{60}Co, and others that were the fission by-products of nuclear bomb testing.

Awareness of potential and growing ecological problems associated with atomic energy operations and programs began to develop in the 1950s. Perceptive research scientists and health physicists started to worry about the consequences of large-scale radioactive waste disposal activities at atomic energy facilities, especially ORNL (Browder, 1959; ORNL, 1957). At this Laboratory they were already experiencing seepage of wastes from disposal areas into streams and ultimately into the nearby Clinch River. Moreover, they were aware that similar phenomena were occurring at other AEC facilities. They became concerned about the entry of radionuclides

into ecological food chains and the subsequent fate and potential impacts on man through his food stuffs, as well as the effect on the ecology of the landscape.

The combination of airborne releases from world-wide weapons testing and the potential larger scale local releases of radioisotopes from atomic energy research and production facilities resulted in a major concern about the threat not only to man but to the various ecological food chains, populations, and ecosystems that compromise what we recognize as the Earth's biosphere. These concerns being recognized to various degrees in the several countries that were then actively engaged in atomic energy development — both for military and peaceful purposes. It was quickly recognized among the health physicists, biologists, and a small number of ecologists that there was a commonality of issues that would require unprecedented research. In the broad sense the concerns were ecological, although research soon encompassed most aspects of what we now recognize as environmental science.

The Ecological Issues

Throughout the late 1940s and 1950s, the recurrent themes associated with radioactive contamination dealt with various aspects of environmental transport fundamental to understanding both human and environmental health consequences of nuclear energy. The problems of environmental transport involve scores of variables. Research in the field, consequently, involved aerosol physicists, meteorologists, hydrologists, ecologists, agronomists, oceanographers, soil scientists, and geologists who studied these complex environmental systems. Specialists focused on the somewhat distinct components of environmental systems:

- atmospheric transport and disposition
- terrestrial uptake and transport
- surface water transport
- groundwater movement

and focused mainly on tritium and the radioactive isotopes of strontium, cesium, ruthenium, cobalt, iodine, plutonium, and transuranics (uranium and thorium).

Atmospheric dispersion and diffusion addressed both meteorology and topography in estimating both deposition and interception by vegetation, soils, and surface waters. Terrestrial transport included soils, vegetation and animal components, and included organisms as transporters as well as recipients. Surface waters included rivers, lakes, and oceans receiving input from atmospheric input, land runoff or groundwater seepage, and encompassed water chemistry and the aquatic ecological systems (see Parker, these proceedings). Groundwater movement of radionuclides was closely linked to subsurface burial and ground disposal in seepage pits of radioactive wastes (see Stow and Serne, these proceedings).

Critical pathways for movement of radionuclides in the environment had to be determined before more sophisticated experiments on isotope bioavailability and environmental mobility could be conducted. Transfer coefficients for various radionuclides were important for determining ecological fate as well as for potential ingestion exposures to man, and required detailed information on environmental chemistry, biochemistry, and physiology. Much of this information became incorporated into simulation models developed in the following decades which were utilized to evaluate the hazards of environmental contamination from nuclear facilities (Parker, 1956), weapons testing (Tamplin, 1967), or peaceful applications of nuclear energy (Kaye et al., 1971). Enormous efforts of federal and private agencies in surveillance networks for measuring fallout in the environment were fundamental to all these applied studies.

Very early in the development of radioecology it became apparent that the cycling and recycling of radionuclides were unique characteristics of ecological systems, which influenced the ultimate behavior of radionuclides in the environment. Auerbach (1965) described how the recycling phenomenon had focused radioecologists into four lines of investigation: (1) the movement of radionuclides across different trophic levels, (2) linkages in food chains between trophic levels, (3) turnover of radionuclides by different trophic levels, and (4) complete cycles of radionuclides in different ecosystems. These were research topics for radioecologists, who used contaminated environments and experimental tagging with radioisotopes to tease out these complicated interrelationships.

The Early Radioecology Programs

Hanford

Stafford Warren, medical director of the Manhattan Engineer District, raised questions about the impacts of the Plutonium Project on the Columbia River only a few months after the decision to locate at Hanford. In the same year of 1943 that construction began a contract was let to the Applied Fisheries Laboratory of the University of Washington in Seattle to study the effects of x-rays on the developmental of salmon and later, trout. Early research was interrupted by the immediate need to understand the fate and effects of the Hanford pile effluents (Stannard, 1988) and Richard Foster was recruited to Hanford from Seattle to begin work at the site out of the Fisheries Laboratory (Figure 1).

This research group working on the Columbia River and in the northern cold desert of the Great Basin proceeded to investigate two problem areas: (1) exposure of fingerlings to various concentrations of pile effluents and possible biological effects, and (2) uptake and retention of pile effluents. The plant operation and environmental interactions are illustrated in Figure 2. By 1946 studies had shown that the fisheries resources of the Columbia River were not threatened by the plutonium plant and that there was no radiation hazard to the people who used the river or to the fish (Foster, 1972). In fact, process chemicals in the reactor effluent (sodium dichromate) showed greater potential toxicity to aquatic life than the radionuclides discharged and ultimately proved to be the principal toxic hazard to aquatic life.

At the First International Conference on the Peaceful Uses of Atomic Energy in Geneva in 1955, Foster and Davis (1956) summarized the work on aquatic life. Radioactivity ("radioactivity density") was found to vary by an order of magnitude in plankton versus fish. Aquatic plants adsorbed significant quantities of radioactive materials on their surfaces. The scales of fish, followed by bone, liver, and kidney, contained the highest concentrations -- similar to terrestrial organisms. And radioactivity concentrations in plankton, snail, and other aquatic organisms decreased rapidly down river from the Hanford plant. There were some other unexpected ecological findings (Foster, 1979) and these proved to be important discoveries of

the role of food chain accumulation of radionuclides and the importance of understanding the long-term behavior of radionuclides in aquatic environments.

An Unexpected Source of Radioactivity. As the techniques for identification and separation of radioisotopes became more routine, it became apparent that those present in the river were largely products of neutron activation of substances already in the river water and pile components, including activation of natural uranium already present in the river water.

The Importance of Background Radioactivity. A surprise was the finding that radioactivity in fish from the river was substantially higher than was predicted from laboratory exposures to pile effluents. This was explained by the fact that laboratory fish were being fed uncontaminated food while fish in the river were eating food containing natural radioactivity (of greater significance than reactor discharges). This exemplified the importance of the food chain and metabolic processes in determining whole-body concentrations.

The Significance of the Food Chain. Another surprise was the finding of qualitative differences in the elemental composition of radioactivity in laboratory versus river fish. The radioactive body burdens of laboratory fish came from elements such as sodium and other short-lived isotopes that were easily assimilated from the water. In contrast, fish from the river exhibited high concentrations of isotopes such as ^{32}P, which had been concentrated from food resources. Again, the importance of metabolic processes in concentrating some radioisotopes from the environment and the importance of the food chain were demonstrated.

There was also a sizable program in terrestrial ecology underway at Hanford, observed under the broad title of "Biological Monitoring." At the First International Conference on the Peaceful Uses of Atomic Energy, Hanson and Kornberg (1956) showed concentrations and ratios of ^{32}P in adults, eggs, and young birds to the amount in water, with no effect on adult fertility or egg hatchability. They measured the isotopic concentration of swamp water, vegetation, and bird muscle and bone. They reported that ^{131}I concentration factors that could range from 0.2 in vegetation (the food staple) to 1 in insects, 100 in rabbits, and 20 in coyotes. Leo Bustad (1960) at a symposium on radioisotopes in the bisophere gave a summary of the Hanford work in

relation to animal populations (Table 1). He showed the concentrations of eleven isotopes in fish, ^{65}Zn in beef cattle, and accumulation of radioisotopes from drinking water by rats. By the early 1960s Hanson (1963) reviewed nearly every aspect of iodine in the environment illustrating remarkable process in this area of investigation.

Oak Ridge

The Clinton Laboratories had no research program during the war years directed at environmental issues, other than those associated with plant operations which included routine industrial hygiene (health physics) practices and measurements of air and waterborne radioactivity. This laboratory was located in the southern mixed hardwood forests of the ridge and valley province of the south central U.S. in Eastern Tennessee. Karl Z. Morgan, director of the Health Physics Division of Oak Ridge National Laboratory (Clinton Laboratories became Oak Ridge National Laboratory in 1948) became increasing concerned about the possible impacts of contamination released to the environment. The Laboratory's waste disposal practice during the Manhattan Engineer District years was treatment and low-level river discharges. Pit and trench disposal started in 1951 and these were largely unlined impoundments and basins not isolated from the environment. Initial ecological work was contracted to L. A. Krumholz and colleagues of the Tennessee Valley Authority and a program was established in 1950. They could find no evidence of deleterious effects in aquatic or terrestrial populations (Stannard, 1988).

These early negative results, plus the horror in the minds of the physicist leaders at the Laboratory about the complexity, variability, and resiliency of natural ecosystems, almost doomed the future of scientific ecological research in Oak Ridge (Stannard, 1998). Several factors occurred which saved the program: (1) K. Z. Morgan's crusade for continuing the work (Morgan and Peterson, 1999), (2) the Laboratory's decision to drain the White Oak Lake holding basin in 1955 for low-level wastes (Johnson and Schaffer, 1994), and (3) the understanding by Eugene Wigner (former research director of Clinton Laboratories and a future Nobel laureate) that radioactive waste disposal would be a key problem in the development of nuclear power (Stannard, 1998). Morgan transferred Ed Struxness, supervisor of health physics at the Y-12

weapons plant, to Oak Ridge National Laboratory to work on waste management problems. To Struxness this meant research on and in the environment; he soon recruited Orlando Park, professor of Ecology at Northwestern University, to ORNL and his student, Stanley Auerbach, was hired in 1955 as the first ORNL ecologist. Thus the Oak Ridge Ecology Program began with 1.7 man years and a $56,000 budget (Figure 3). The drained White Oak lakebed became the site of Oak Ridge's early experimental ecological research.

The new program was laboratory-based with objectives to establish dose effect relationships for a broad spectrum of forest insect and other arthropod organisms. Laboratory experiments also included the uptake of fission products, particularly ^{89}Sr and ^{90}Sr. Limitations of personnel and funds limited the start of extensive field studies. Early field studies utilized terrestrial microcosms and laboratory experiments to measure the uptake and bioaccumulation of ^{89}Sr by various species of earthworms (Auerbach, 1956, 1958). In the latter part of 1955 two events occurred which changed the direction of the new program. First, the new AEC Environmental Research Branch Manager John Wolfe and his Program Manager Vincent Schultz advised ORNL that the new ecology program should be redirected to a field research effort rather than a laboratory one; furthermore, it should be oriented toward radioactive waste disposal and contamination problems but in the context of ecological science. Second, the 25-hectare impoundment (White Oak Lake), which had been the final settling basin for released low-level quantities of radioactive waste fission products and other chemicals, was drained. This action resulted in a new, highly contaminated terrestrial environment, which contained large quantities of ^{90}Sr, ^{137}Cs, ^{60}Co, and other radioisotopes (Figures 4a - c).

<u>White Oak Lake Bed</u> Prior to the draining of the lake, large (1,000,000-gallon) open earth pits had been dug on the hillside above the lakebed. These pits were considered experimental disposal sites for radwaste products produced from the reprocessing of used reactor fuel elements. ORNL at that time was the major research and development center for chemical engineering studies on techniques for reprocessing used reactor fuel elements. The byproducts included large quantities of fission products, which in the several stages of reprocessing, were segregated into high level wastes and large volumes of lower activity wastes containing principally ^{90}Sr, ^{137}Cs, ^{60}Co, and ^{106}Ru. The high level wastes were siphoned to underground

storage tanks. The lower activity wastes were went to these experimental earthen pits whose soil properties indicated a high exchange capacity for fixing both ^{90}Sr and ^{137}Cs. Ruthenium-106 was found to be mostly non-fixable and seeped out of the pits into small drainages that emptied into the White Oak lakebed.

Even by the standards of that time the White Oak Lake Bed was considered to be highly contaminated. Radiation dose rates at waist level were 10mr/hr to 25mr/hr with some small areas near the waste pits seeps that contained ^{106}Ru as high as 100mr/hr. As the ^{106}Ru decayed the dose rates dropped to the 10mr/hr to 15/mr/hr range. These dose rates resulted largely from the ^{60}Co and ^{137}Cs concentrations in the soil. At that time this small piece of landscape was considered to be one of the most radioactive sites on the earth. We did not know then of the extensively contaminated sites in parts of the former Soviet Union (e.g., Chyliabinsk, Kyshtym, and others). The shift of the ecological research to the lake bed area and the waste pit area in 1956 marked a major change in the ORNL ecological research effort: the combining of ecology with radioactive waste disposal. The White Oak Lake Bed provided a totally new opportunity to approach this problem in an ecosystem context, namely, to study the behavior and transport of radionuclides within the various producer and consumer components of a terrestrial ecosystem (see Auerbach et al., 1958, 1959, 1961). This ecosystem-level approach to understanding and quantifying the accumulations and transfers from one component of an ecosystem (producers) to components that represented primary consumers and predators was a totally new approach and since it combined radioactivity and ecology – the term “radioecology” came into use. Coincidentally, about the same time in the former Soviet Union, an ecological research group led by A. A. Peredel’ski also was studying radioactivity problems from an ecological viewpoint. We did not and still do not know which of the then heavily contaminated Soviet sites this group worked in the 1956-57 period, but he published a paper in 1958 in which he made use of the term "radioecology" (Peredel’ski, 1958).

Prior to establishing research sites, a radiation survey was carried out over the entire lake bed surface (Lee and Auerbach, 1959); based on this information a 2.5 acre (1 hectare) study site was demarcated into a 10x10 meter grid interval system. The research groups then began an intensive mapping and sampling program of the vegetation and insect populations that rapidly developed in this area due to high nutrient status of soils, particularly due to nitrates, phosphates

and other chemicals that composed a major portion of the waste streams released from the Laboratory. Soil sampling and analyses determined the structure, chemistry, and radionuclide content of the study area. The radionuclides of primary concern were ^{90}Sr and ^{137}Cs both because of their abundance in the radioactive wastes and also in fallout from weapons testing.. These factors, plus their long half-lives, made them a primary concern for radiological protection. Figure 5 illustrates the concentrations of these isotopes in the soil and organisms of the lakebed (Crossley, 1963). In the study area, ^{90}Sr concentrations in soil averaged 360-picocuries/gram dry weight. Cesium-137 concentrations were 7300 picocuries /gram dry weight. Although ^{137}Cs was more abundant in soil than was ^{90}Sr, it was less available to vegetation so that the ^{90}Sr concentrations in plants were higher than ^{137}Cs values. Strontium-90 was concentrated above soil levels in plant leaves. Herbivorous insects contained about equal concentrations of the radionuclides, since strontium is eliminated more rapidly than cesium and whole-body equilibrium values thus were much lower than concentrations in the host plants. Predaceous insects had approximately the same concentrations as did herbivorous insects.

From an ecosystem point of view ecologists were interested in the quantities of radionuclides available and their transfer through the food chains on a unit area basis, namely units/ per square meter of soils, vegetation, herbivorous insects, and predaceous insects. These kinds of data provided the ecologists with the capability of calculating not only the uptake of radionuclides but also (using biological half lives and turnover of vegetation biomass) the flow of radionuclides through the ecosystem on an annual basis. With these kinds of data, ecologists were able to project the long-term turnover and cycling of a particular radionuclide through an ecosystem.

This new approach provided a strikingly different perspective of the behavior of radionuclides in the environment (Crossley 1963). When the actual biomasses of the trophic levels involved are included, reduction in the transfer of radionuclides from one trophic level to another is the result (Figure 6). This figure shows the distribution of radionuclides in the soil and biota on a square meter basis. The mass of soil overwhelms the masses of the organisms, so that the soil contained more than 99 percent of the radionuclides in the system. It should be noted that these data do not illustrate the quantities of radionuclides, which pass through the insects feeding

on plants. The concentrations in these organisms rapidly reach steady state equilibrium, so that the quantities of radionuclides ingested are equal to the quantities being eliminated. These data and their implications would not necessarily apply to other food chains, especially those in which organisms whose organ systems and skeleton would serve to accumulate certain radionuclides, e.g., bone structures in bird and mammals. Nevertheless, what was determined then is that the concentration of radionuclides in food chains will depend upon the elimination coefficients and resulting concentration factors in each step or linkage of a food chain.

When the quantities of radionuclides in the ecological trophic levels (e.g. picocuries/m^2) are considered, great reductions of radionuclides occurred during the transfer of radioactive materials from one tropic level to the next higher trophic level. The magnitude of the values at each trophic level was found to be more dependent upon the mass of organisms than upon the concentrations of radionuclides in the organisms. Calculations using the radioisotopes in this lake bed system as tracers also provided the means for calculating the amount of food consumed by these organisms. The insects consumed approximately six percent of the plant biomass during a growing season. A new radiological technique was now available to measure herbivory and predation in natural ecosystems (Reichle, 1967; Reichle and Crossley, 1968).

Waste Pit Studies As noted earlier, in the mid-fifties ORNL experimented with the concept of disposing of large volumes of what was then called intermediate-level wastes. The pits were at the same time operational and experimental. They were experimental in that they were located in a shale formation which had been found to have high sorptive properties for a number of fission products and therefore was being considered for a possible approach to dealing with large volumes of liquid wastes. They were also operational in that they were being used as receiving basins for the large quantities of intermediate level radioactive wastes that were being generated by the fuel element re-processing being carried out at ORNL. Thousands of curies of ^{90}Sr, ^{137}Cs, ^{60}Co, and ^{106}Ru were sent to these pits. With the exception of ^{106}Ru, the other radionuclides were retained to a considerable extent by the soil immediately surrounding the pits.

In 1957 the ecology program was directed by the AEC to carry out an extensive sampling program for radionuclides, particularly ^{106}Ru in the tree stands that grew around the pits. The

purpose was to ascertain if the root systems were absorbing radionuclides that might be leaking from the pits and which could not be detected by other sampling methods. An extensive tree sampling program was carried out in 1957 and 1958 with particular emphasis on the presence and distribution of ^{106}Ru in the forest stands that dominated the waste pit site. Although ^{106}Ru was detected in many of the individual trees, the distribution was highly variable, both within single trees as well as between trees. Analyses of the available data did not yield any correlation between distances from the pits, between individual trees as a function of location, or even within individual trees. Much of the reason for this was because of the limited biological affinity for ruthenium as well as the uncertain knowledge of the subsoil seepage patterns (Auerbach & Olson, 1963). The positive result of this investigation is that it identified and supported the need to carry out forest experiments on the behavior and cycling of fission products using single species of radioisotopes in individual tree species (Witherspoon, 1963). These individual tree experiments ultimately led to the ^{137}Cs forest ecosystem experiment in 1962, where an entire forest ecosystem was experimentally labeled with a radioisotope (Auerbach, Olson, and Waller, 1964).

Savannah River

At the beginning of the decade of the 1950s, the AEC decided that a second major plutonium production site was needed. Two hundred thousand acres in the Piedmont region along the Savannah River in South Carolina was selected. The site was mixed forest, abandoned agricultural land and replanted pine plantations. Without the urgent schedules of the Manhattan Engineer District, there was time to do preliminary ecological work before plant construction, and in 1951 the AEC made arrangements with Eugene Odum at the University of Georgia for an ecological inventory and a plan for ecosystem research. Research was begun "out of suitcases and an abandoned barn" and soon a vacated home was obtained for a field station (Stannard, 1988). This operation ultimately became the Savannah River Ecology Laboratory.

Later in the 1960s following construction and operation of the Savannah River Plant, a diverse radioecology program evolved. There were large quantities of tritium being emitted from the stacks. The usual radionuclides were in waste water streams and the usual problems of

waste disposal existed. In addition, large quantities of warm water were discharged from reactor cooling, introducing the ecological problem of thermal stress. Most of the work on radionuclides focused on assessment of releases (Bebbington, 1973), but the classic ecological research basis had been summarized by Odum (1956) at the First Atoms for Peace Conference in Geneva in 1955. He stressed the importance for understanding the effects of radiation on higher levels of biological organisms - the population, community, and ecosystem. He also hinted at the importance of biogeochemical cycles in the context of the safe disposal of radioactive waste products. He laid out the scientific basis for the developing ecology program at the Savannah River site by calling for studies on radiation effects on trophic structure, productivity, and metabolic properties of ecosystems -- emphasizing the comparison of contaminated and noncontaminated areas. This was state-of-the-art functional ecology with one new variable -- radioactivity. The results of Odum's radioecological research during the late 1950s were reported at the First International Symposium on Radioecology in Fort Collins, Colorado (Odum 1963).

Odum and colleagues began their trophic studies in the Spring of 1957 using phosphorus-32 to isolate individual food chains of intact, natural communities, using an old field ecosystem which had become established five years after abandoned corn and cotton agriculture. Their premise was simply that by labeling foliage of related plants, then any subsequent radiation herbivorous insects found could be determined to be grazers upon those plants, and radioactive predators, in turn, connected to those prey herbivores. While ingenious in concept and simple in experimental design, results were not without exciting findings.

The clearest and most profound result of these experiments was the graphic separation of certain trophic and habitat groups when the concentration of ^{32}P per unit of biomass was plotted against time. Figure 7 illustrates these results for a simple community Rumex acetocella, an annual forb, Oecanthus nigricornus, an orthopteran grazing herbivore, Dorymyrmex pyramicus, an ant, Succinea campestris, a snail occurring on vegetation and on the ground, spiders (primarily Lycosa timuqua and L. carolinesis), and ground-dwelling cryptozoa (Blattids [roaches], Gryllids [crickets], Carabids [ground beetles], Tenebrionids [darkling beetles], and Isopterans [termites]) of mixed trophic structure and probably predominantly saprophagous. The

key in these data were the time intervals required for peak concentrations of ^{32}P to apear, with herbivores first, followed by predators and finally crypotozoa (saprophages). These data also suggested that some species might be omnivorous feeders. A result from other data not illustrated in Figure 7 was that the more common groups of herbivores were not plant specific feeders, and ground-dwelling crypotozoans were feeding above ground at night. Complexity in the trophic structure (herbivore, omnivore, carnivore, saprophage) and diversity in plant host and prey food bases, all served to hint at the complexity of natural ecosystems which radioecologists in the following decades would be challenged to unravel and understand.

Scientific Legacies from the 1950s

Many of the concepts and analytical tools developed very early by the field of radioecology are still pertinent today, and have had a marked influence on both the development of regulatory standards and also scientific progress in the field of ecosystem ecology.

Radiotracers in Ecology

Following the applications of radiotracers in health physics, radiopharmacology, and agriculture, where isotopic tracers were being used to study the dynamics of biological systems, ecologists also began radiotracer applications in ecosystems to study food chain behavior, bioaccumulation, and environmental fate. By the late 1940s, isotopic releases from nuclear operations had already demonstrated the utility of radiotracers for studying mineral nutrition and biogeochemical pathways, and by the early 1950s ecologists were using radioisotopes experimentally in aquatic and terrestrial ecosystems. These early ventures were to open ecology to new areas of experimental study. The pioneering studies of the 1950s were reported in 1960 at the symposium at the University of Minnesota on Radioisotopes in the Biosphere organized by R. S. Caldecott and L. A. Snyder (1959), and in 1963 at the 1st International Symposium on Radioecology organized by Dr. Vincent Schultz and Dr. Alfred Klement, Jr., (1963) at Fort Collins, Colorado in 1961.

Food Chain Dynamics

Radionuclide tracers enabled a whole new field of research on the critical pathways of movement of pollutants in the environment and their potential for food chain discrimination or bioaccumulation in successively higher trophic levels. Sophisticated mathematical equations were developed which permitted calculation of the time dynamic (transient behavior) of whole-body concentrations and equilibrium whole-body burdens from both acute and chronic ingestion. Some isotopes, such as the bone-seeking strontium, were found to have concentration factors much greater than 1.0 (similar to fat soluble and accumulating pesticides such as DDT), the concentration of others equilibrated after the first trophic level exchange, or even decreased (e.g., Reichle, Dunaway, and Nelson 1970). Significant variability also existed in soil-plant uptake, dependent upon soil chemistry and plant nutrition. Nutritional requirements and organismal metabolism of elements, reflected in isotopic turnover (elimination rates and biological half-lives) determines the food chain transient and whole-body concentrations. Food chains inherently neither concentrate nor dilute pollutants, but this phenomenon continues to be misunderstood in the public's perception of the behavior of hazardous materials in the environment. Food chain models have had important application in developing regulatory standards for environmental exposures (ingestion) and in developing risk analysis for chemical releases.

Environmental Protection

While even during the Manhattan Project early research on the health effects of nuclear energy occurred, and soon thereafter the AEC developed an extensive biology program which was in place by the early 1950s (including the "megamouse" genetics program at Oak Ridge), the utility of a broadly based ecology enterprise was not appreciated by many at the AEC. The idea was still widely held that if man was acceptably protected, then his environment would automatically be protected. The fact that man is an "integral part of his environment" had not yet become generally appreciated. Much of the development of radioecology within the AEC , was due to the farsighted vision and encouragement of Charles Dunham, M.D., who became chief of

the Division of Biology and Medicine (DBM) of the AEC in 1955. Some programs were already under way in the early 1950s by Dr. Richard Foster at Hanford, and by the mid-1950s by Dr. Stanley Auerbach at Oak Ridge and Dr. Eugene Odum (University of Georgia) at Savannah River. By 1958 an Environmental Branch was developed within DBM and Dr. John Wolfe, an ecologist, became its director. Support for the large-scale, field-based experimental ecology in both the national laboratories and universities in the United States began with the AEC because of concerns about nuclear energy and the environment, and, only later in the 1970s did the National Science Foundation became a principal research sponsor for ecosystem research.

Regulations and Science

The rapidly expanding base of knowledge about the biological and ecological effects of radiation drove ever more restrictive environmental radiation protection standards, particularly during in the late 1950s. This trend has continued until the present, driven by continued improvement in our scientific understanding of ecological systems, advances in analytic technologies and measurement standards, accelerated federal standards in the 1970s, and expectations for the nuclear industry and R&D laboratories to adhere to ALARA (as low as reasonably achievable) for radiation exposures. Ever increasing restrictions (lowering) of permissible radioactive emissions have made understanding the dynamics of ecological systems even more important (Reichle and Auerbach, 1972). Much more precise information, with less uncertainty, is needed about the fate and behavior of radioactive contaminants in the environment.

The Dynamic Nature of Ecosystems Revealed

It became very clear, very early, that the behavior of radionuclides in the environment was a dynamic phenomenon. Many biological and environmental parameters contributed to the inherent variability of ecological systems. In order to have both a mechanistic and predictive capability for complex behavior in non-linear systems with internal feedback, simulation modeling of ecological systems ultimately became necessary. The foundations for ecological

modeling were laid in the late 1950s and began in earnest in the 1960s (Olson, 1963), contributing to the development of the new field of systems ecology.

The Unfulfilled Promise

The behavior of radionuclides in the environment is governed by a complex and variable set of natural processes and a diversity of ecosystems in which they occur. Almost every component of an ecosystem will have some influence upon the pathways, dynamics, and ultimate distribution of radioactive materials introduced into the system. While applications of radiotracer technology to biogeochemical cycling in ecosystems opened new opportunities to explore elemental dynamics in the environment, there was a pitfall. The ease with which radionuclide tracers could be measured created a wealth of information for different elements in different ecosystems. But, the underlying physical, chemical, and biological variables which controlled elemental dynamics were not adequately quantified. Thus, much knowledge accumulated about the specific behavior of specific radionuclides in specific ecosystems under specific conditions, but the ability to predict the system dynamics under different conditions, for other isotopes or different ecosystems was limited. The most progress was made in soil chemistry, but just as the scientific community began to recognize the importance of obtaining mechanistic, process-level data in the mid to late 1960s the shift and interests in large-scale field radioecological research in the AEC began to wane. Thereafter, these important advances were never realized in the American research program, but were continued later in the 1970s in Europe, with the establishment and support of the European Commission and the establishment of the International Union of Radioecology. The Chornobyl accident on April 26, 1986, has provided an additional stimulus for European radioecology research in recent years.

Table 1. Radioisotopes in tissues of fish from Hanford (After Bustad, 1960).

Isotope	Organ or tissue showing highest concentration	Concentration (µc/g wet weight)
Na^{24}	Bone	2×10^{-3}
Sc^{46}	Spleen	2×10^{-6}
P^{32}	Gut content	7×10^{-3}
Cr^{51}	Blood	5×10^{-4}
Mn^{54}	Bone	5×10^{-5}
Fe^{59}	Gut content	3×10^{-5}
Co^{60}	Spleen	1×10^{-5}
Sr^{80-90}	Bone	8×10^{-6}
Cu^{64}	Gut content	1×10^{-3}
Zn^{65}	Retina	3×10^{-3}
Cs^{137}	Muscle	9×10^{-7}

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Figure Legends

Figure 1 Fisheries Laboratory at the Hanford Site as it appeared in the 1950s. (Courtesy PNNL).

Figure 2 Production of plutonium and radioactive wastes at Hanford. (After Bustad, 1960).

Figure 3 Ecology Laboratory at Oak Ridge National Laboratory in 1956 (temporarily relocated in 1955 to the Y-12 Plant and returned to the ORNL X-10 site in 1961). Shown in the photograph, left to right: Roy Morton, Charles Rhode, Jr. Orlando Park, Manfred Engelmann, Stanley Auerbach, Kurt Bohnsack, James Lackey, Eugene Odum, Ellis Graham, Al Broseghini, and Ed Struxness.

Figure 4a Aerial photograph of drained White Oak Lake bed in 1952.

Figure 4b Naturally revegetated White Oak Lake bed in 1958 where early radioecological studies were conducted. Shown is Stan Auerbach.

Figure 4c Distribution of vegetation with radionuclide concentrations in plants and soils on White Oak Lake bed in 1957.

Figure 5 Transfer of cesium-137 (Top) and strontium-90 (Bottom) from plants to insects on White Oak Lake bed. Values in parentheses are micromicrocuries per gram of dry weight of composite samples. (After Crossley and Howden, 1961).

Figure 6 (Left) Concentrations of radionuclides in soil and organisms of the White Oak Lake bed, 1985, upper value strontium-90, lower value cesium-137, in micromicrocuries per gram of dry weight of a composite sample. (Right) Distribution of radionuclides in soils and trophic levels of the White Oak Lake bed, 1958 (upper value strongium-90, lower value cesium-173, in micromicrocuries per square meter of a composite sample (After Crossley, 1963).

Figure 7 Radiotracer Studies of Food Chains at the Savannah River Site. Quadrat 2 (Rumex). Concentration of phosphorus-32 in six animal populations plotted against time (After Odum, 1963).