Executive Summary

This Report was largely motivated by the fact that ^{137}Cs has often proven to be the most important long-term contributor to the environmental radiation dose received by humans and other organisms as a result of certain human activities. Over the past few decades, ^{137}Cs has been the most important residual radionuclide at many facilities in the nuclear weapons complex of the U.S. Department of Energy (DOE), at nuclear fuel reprocessing facilities, at some nuclear reactor sites, at many radioactive waste disposal sites, in soils worldwide as a result of global fallout from historic nuclear weapon testing, and in the former Soviet Union and other locales in Europe as a result of the Chernobyl accident. In addition, there is concern about the use of ^{137}Cs by terrorists to create a so-called "dirty bomb."

The primary source of ^{137}Cs in the biosphere is atmospheric nuclear weapons testing by the United States and by the former Soviet Union during the 1950s and 1960s. Of the roughly 1 EBq (10^{18} Bq) of ^{137}Cs released to the biosphere, ~90 % was produced by atmospheric testing. Approximately 6 % was produced by the Chernobyl accident and roughly 4 % by nuclear fuel reprocessing facilities. Of the nuclear reactor accidents, the Chernobyl accident on April 26, 1986 in the Ukraine released far more radioactivity, including ^{137}Cs, to the environment than all other nuclear accidents combined.

In addition to its relative abundance, ^{137}Cs has characteristics that enhance its importance as a major contributor to radiation dose. For example, it has a moderately long half-life (~30 y), it emits relatively high energy beta particles, its very short-lived daughter ^{137m}Ba emits a strong gamma ray, and because of its chemical properties, it is readily transported through the environment and food chains. When in solution it can be efficiently taken up by plants and assimilated by animals because of its chemical similarity to the essential nutrient, potassium. The primary deterrent to the transport of ^{137}Cs to humans and other living organisms is its very strong tendency to attach, sometimes irreversibly, to common clay minerals found in most soils and sediments.

It has been ~30 y since the National Council on Radiation Protection and Measurements (NCRP) published a report dealing

specifically with the behavior of ^{137}Cs in the environment. During that period, a great deal of environmental research on radiocesium has been published. Efforts beginning ~20 y ago that were directed at cleanup of DOE's nuclear weapons complex and dealing with the Chernobyl accident, continue today. A report attempting to synthesize a reasonable fraction of the very extensive literature and to summarize knowledge about how this radionuclide behaves in the environment can still be very useful for future risk assessments and for management decisions concerning radioactively-contaminated areas.

The general intent of this Report was to provide a:

- summary of general knowledge on the properties, geographic distribution, and sources of ^{137}Cs in the environment;
- site-specific description of releases, environmental levels, transport pathways, and specific issues relative to ^{137}Cs at three major DOE facilities;
- relatively detailed treatment of the radioecology of ^{137}Cs in terrestrial and aquatic ecosystems, including biogeochemical transport mechanisms and transport modeling concepts; and
- brief summary of the more generic management issues, remediation techniques, and benefit-cost considerations of alternative strategies for lands contaminated with sufficient levels of ^{137}Cs to warrant concerns about public health and environmental quality.

The specific kinds of terrestrial environments considered in this Report include land ecosystems such as agricultural areas with farming or ranching activities, forests, rangelands, arctic and alpine regions, and semi-desert shrub-steppe areas. Freshwater environments considered include streams, lakes or impoundments, swamps, and other types of wetlands. Marine ecosystems, such as estuaries, coastal areas, and the open seas were not specifically included in the scope of this Report because doses from ^{137}Cs to humans and marine biota are generally very small in comparison to pathways involving terrestrial and freshwater systems.

The environmental transport of cesium is governed by many factors, most of which vary over space and time. The accumulation of cesium varies by orders of magnitude between different biological components within a single environment and also among different ecosystems. Much of this observed behavior can be understood

from the chemical properties of cesium and its interactions with soil and sediment particles. The soil or sediment is particularly important because it is the primary reservoir of ^{137}Cs in most ecosystems. The fraction of the ^{137}Cs in ecosystems that is available for biological uptake and transport is largely determined by the strength of its binding to soil or sediment particles. This binding strength is mainly dependent on the clay mineral composition and abundance. Other chemical factors that modify its transport include the soil or sediment cation exchange capacity (CEC) and pH, and the soluble potassium levels in the system. The passage of radiocesium up through animal food chains, unlike the vast majority of other radionuclides, often increases from one trophic level to the next higher trophic level. For example, predatory animals tend to concentrate ^{137}Cs in their soft tissues to a higher degree than do the animals upon which they feed.

The basic radioecology of ^{137}Cs in terrestrial systems, including deposition from the atmosphere, geochemical behavior, dynamics of soil-plant-animal transfer processes and modeling approaches is covered in considerable detail. Various approaches to predictive mathematical modeling and summaries of the various types of transfer coefficients are presented. A similar treatment of the fundamental behavior of ^{137}Cs in freshwater environments is offered. This treatment includes the effects of physical form and environmental chemistry on sediment-water partitioning, sedimentation and remobilization processes, and bioaccumulation processes in aquatic food webs. Various modeling approaches are described for aquatic ecosystems and general approaches to predicting key transport parameter values for ^{137}Cs from basic limnological data are provided. As is the case in terrestrial ecosystems, the behavior of cesium in aquatic ecosystems is governed by properties of the ecosystem itself and by chemical and physical factors that influence the mobility of cesium. There is much evidence for trophic level biomagnification in terrestrial as well as aquatic food chains.

While there is a reasonably detailed treatment in the Report to allow approximations or gain understanding of the levels of ^{137}Cs in plant and animal life, there was no comparable attempt to summarize levels in or estimate radiation doses to humans. Rather, the emphasis in this Report is placed on ^{137}Cs in general environmental components including air, water, soils/sediments, plants and animals other than humans. Information on these components are required by risk assessors to estimate intakes and doses to humans from ^{137}Cs in the environment from the various pathways of inhalation, ingestion and external exposure. Reliable methods of measuring or estimating levels of ^{137}Cs in humans and the resulting

doses are well-developed, and there is a large body of information available. However, this aspect of ^{137}Cs in the environment was not in the scope of this Report. The kinds of information discussed in the Report are, however, essential for the purpose of human risk assessment, and general approaches are briefly described.

DOE facilities examined in this Report were the Savannah River Site (SRS) in South Carolina, the Oak Ridge Reservation in Tennessee, and the Hanford Site in Washington. These sites were chosen for discussion because they all experienced relatively large ^{137}Cs releases to the local environment, and yet these sites differ considerably from one another in terms of climate and characteristic soil types, both of which have very significant influences on the quantitative behavior of radiocesium. Historically, these three sites all had one or more nuclear reactors, nuclear fuel reprocessing facilities, and waste treatment and disposal operations, each of which resulted in environmental releases of radionuclides. The releases at Savannah River and Oak Ridge were largely to aquatic systems, while those at Hanford were primarily to the terrestrial environment. While the climate at Hanford is very dry, that at Savannah River and Oak Ridge is comparatively wet. Savannah River differs from Oak Ridge in the dominant type of soil (very sandy at Savannah River and heavy clay at Oak Ridge), as well as the type of vegetation. Site-specific differences between these facilities have been used to understand how various environmental factors produce rather different patterns of ^{137}Cs distribution and behavior.

A relatively brief summary of alternative approaches and philosophical viewpoints to the management of areas contaminated with ^{137}Cs is provided. This includes a discussion of the "no action" alternative, which may be applied when it can be demonstrated that the costs and ecological damage resulting from engineered remediation are too high to justify when the health and ecological risks of leaving contamination in place are acceptably low. Also included is an examination of certain biological, chemical and physical mitigation or remediation techniques for chemical and radiological contamination, and the extent to which such techniques are likely to be useful for reducing risks from ^{137}Cs. For example, the concepts and experience of using biological approaches, namely phytoextraction and phytostabilization are discussed. A potentially useful physical approach discussed is the application of illite clay to certain ecosystems in order to sequester ^{137}Cs, thus reducing its bioavailability.

The Chernobyl accident in April 1986 provided extensive experience in implementing practical measures to counter the

health impacts of radioactive contamination. The objective of these countermeasures was to reduce the effective dose to people through implementation of practical management strategies. Principles of radioecology that dictate the transport and fate of radionuclides in the environment were clearly demonstrated to govern the success of human-implemented measures to intercept, block or reduce the impacts from radiological accidents. The most immediate countermeasure used by the former Soviet government was the relocation of people from the city of Pripyat and nearby settlements. Discussion on limiting the ingestion of contaminated food and altering agricultural practices is provided. The latter included removing contaminated lands from production, importing uncontaminated feed for cattle, deep plowing of fields to reduce radionuclide concentrations in the soil layer in contact with crop roots, addition of potassium fertilizer to reduce ^{137}Cs uptake by crops, choosing crops that take up less radiocesium, and adding Prussian blue (iron III ferrocyanide) to the diets of cattle which reduces assimilation of radiocesium from the digestive tract. Countermeasures to protect water supplies during the early phase after the accident are described. Urban countermeasures involved, among other measures, decontamination of residences and public buildings and washing roads.

One might assume that any remediation decision concerning management of contaminated lands should be based simply on the ratio of benefits (human health and ecological risk reduction) to costs (monetary and environmental) for the various alternatives. Costs, however, both monetary and environmental, can be difficult to predict, and benefits may in some cases be illusory or restricted to certain groups of people. Irrespective of the source of ^{137}Cs or other forms of contamination of the environment, the subsequent management of the contaminated area can be an extremely complex task. In most situations, the highest levels of contamination are limited to relatively small areas, yet traces of contamination may cover extremely large areas. The decision of how to deal with clearly dangerous levels of contamination that cover relatively small areas is usually a matter of straightforward engineering that is likely to be cost effective and practical. Most of the more complex management decisions are only reached after the analysis of benefits and costs are scrutinized and agreed to by regulatory agencies and other stakeholders, including the organizations responsible, as well as the public. Clearly, however, the science of ^{137}Cs transport in the environment is crucial to credible evaluation of benefits and costs of the various management options for dealing with areas contaminated with this radionuclide.

In terms of the level of detail, this Report provides a reasonably complete treatment of ^{137}Cs in the environment, including its radioecology, and the applications of the scientific aspects of its behavior to the assessment and management of risks to human health and to environmental quality. However, because the literature on ^{137}Cs in the environment is so extensive, diverse and widely scattered, one cannot expect this Report to cover every aspect of knowledge that would logically fit under the broad title of this effort. Furthermore, the Report is too generic to be considered a manual on how to conduct a specific kind of risk assessment. Nonetheless, this Report can serve as general framework of current knowledge for students, professional risk assessors, site remediation specialists and managers, as well as a guide to the very large body of literature on ^{137}Cs in the environment.