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Radionuclide Biological Remediation Resource Guide

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Foreword

Identifying and accessing pertinent information resources that will help site cleanup managers evaluate innovative technologies is key to the broader use of these technologies. This guide is intended to increase awareness about technical information and specialized resources related to phytotechnology, bioremediation and other technologies as they relate to radioactive materials.

Specifically, this document identifies a cross section of information intended to aid users in remedial decision-making, including abstracts of field demonstrations, research documents, and information to assist in the ordering of publications. In addition, the cross reference and look-up format of this document allows the user to quickly scan available resources and access more detailed abstracts.

Please let us know about additional information that could make this guide (and others in the series) more useful to you. It will be recognized that this area of research could be expanded in many ways. We encourage readers to apply these methods or to develop new ones and then add to the body of research papers because expanded use of these methods should improve cleanup strategies. This guide and others listed below are available to the public through http://www.epa.gov/region5superfund, http://www.epa.gov/tio, and http://clu-in.org, and cfpub.epa.gov/si.

Bioremediation Resource Guide
Groundwater Treatment Resource Guide
Physical/Chemical Treatment Technology Resource Guide
Phytoremediation Resource Guide
Soil Vapor Extraction (SVE) Enhancement Technology Resource Guide
Soil Vapor Extraction Treatment Technology Resource Guide

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Introduction

Current Radionuclide Treatment Methods and Rationale for Alternatives

Presently, excavation and shipping to a distant waste disposal site is the most commonly used method for handling soil contaminated with radionuclides. Treatment of surface water or groundwater usually creates sludges or residues that must be treated like soils. This excavation and shipping of soils is very expensive and can be disruptive to the environment in which the contamination is found.

Biological treatment methods, such as phytoremediation and bioremediation, could provide an attractive alternative to the excavation of soil. In some cases, off-site shipment might not be necessary at all, if radioactive decay can be utilized, and in other cases, the volume of shipped material (and, thus, the cost of shipping) could be dramatically reduced. Moreover, these biological methods would minimize the disruption to the environment caused by excavation. Biological treatment methods may also be more efficient and cost-effective than traditional methods in the case of contaminated groundwater or surface water. In many cases, the classes of contaminants which have shown successes in chemical cleanups are the same classes associated with radioactive contaminants (e.g., metals). The primary differences being the latter are isotopic forms of these chemical elements. It is entirely possible that methods successful for chemical elements may be successful for the same radioactive elements.

Background on Biological Remediation

The widespread distribution of environmental pollutants and the need for cost-effective treatment methods have stimulated the emergence of new technologies using biological remediation processes. These new treatment options include phytotechnology – the use of plants for *in situ* remediation of contaminated soil, sludges, sediments, and groundwater through contaminant removal, degradation, or containment; and bioremediation – the use of microbes to sequester contaminants or transform them into a less-toxic state in soil, water and activated sludge systems. Other biological treatment methods include the use of microbial mats, a combination of plant biomass and microbes to immobilize contaminants; the bioaccumulation of pollutants through the use of shellfish; and the use of fungi species for biodegradation processes.

Treatment options such as these utilizing natural processes have been found to be efficient and cost-effective. For example, other well-known natural processes such as in: nutrient cycling of nitrogen, phosphorus, sulfur, carbon dioxide, and water; flow of energy through the various trophic levels of the ecosystems; and natural attenuation of pollutants have served as the underlying template in the sustainability of the ecosystems around the world. By understanding and enhancing these important natural processes, the need for cost-efficiency and sustainability has now emerged as the underlying factors for measuring remediation processes and assessment of environmental quality.

It is in this context, that the efficient natural uptake of nutrients by plants has been utilized in specific remedial-phytotechnological terms such as in: phytostabilization, rhizofilteration, phytoextraction, rhizodegradation, and phytovolatilization. For more information on phytotechnology, please see the glossary on pages 7-9, the U.S. EPA *Phytoremediation Resource*

Guide (http://www.epa.gov/tio/download/remed/phytoresgude.pdf) or the EPA *Citizen's Guide to Phytoremediation* (http://www.epa.gov/tio/download/citizens/citphyto.pdf).

Similarly, the inherent ability of microbes to incorporate chemicals and radionuclides on specific binding sites of their membranes have been adopted in bioremediation applications such as in: biostimulation, mineralization, bioaugmentation, chelation, and sequesterization – indicating the growing importance for a better understanding and use of these emerging biotechnologies. See the glossary on pages 7-9 for a definition of these terms. Additional information on bioremediation technologies can be found at the following web sites:

Bioremediation Resources
http://www.nal.usda.gov/bic/Biorem/biorem.htm
EPA Office of Research and Development (ORD) Bioremediation Documents
http://www.epa.gov/ord/WebPubs/biorem/index.html
http://www.epa.gov/tio/download/citizens/bioremediation.pdf (*A Citizen's Guide to Bioremediation)*
http://www.epa.gov/tio/pubitech.htm
DOE Natural and Accelerated Bioremediation Research (NABIR)
http://www.lbl.gov/NABIR
U.S. Geological Survey
http://www.usgs.gov
http://water.usgs.gov/wid/html/bioremed.html

The other biological treatment methods as described in this guide include studies on fungi, natural attenuation processes, and microbial mats. Fungi represent an important part of the ecosystem and play a major role in nutrient cycling in both aquatic and terrestrial ecosystems. Similar to plant roots, their extensive networks of hyphae, aided by mycorrhizal-plant interactions, have made fungal species a good candidate for remediation of radionuclides in both soil and water.

The long-term restorations of ecosystems and contaminated sites have been attributed to natural attenuation processes. The efficiency of this mode of remediation will vary based on the biological and chemical nature of the contaminated site. For example, the impact of an effluent from uranium mine tailing to groundwater could naturally be mitigated if the soil is rich in carbonate or other reducing agents. Another example of a natural attenuation process is seen in aquatic systems, which serve as a medium for the assemblage of algae, bacteria, and phytoplankton. This kind of assemblage, described in this guide as microbial mats, has been utilized in remediation of chemicals and radionuclides. Additional information on these studies is contained in the DOE Natural and Accelerated Bioremediation Research website: http://www.lbl.gov/NABIR.

Is Biological Remediation Right for Your Site?

Biological remediation is not a viable option for every site. An initial site characterization is highly recommended to determine whether biological remediation will be an effective treatment of choice. Among others tests, a typical site characterization should include the following:

- analysis of nutrient availability to ensure that the site has the necessary nutrient sources (such as nitrates, phosphates, carbon source, and minerals) to support the microbial or plant species
- sequential extraction processes to determine the bioavailability of the pollutant for effective treatment
- analysis of soil acidity/alkalinity to determine if the addition of fertilizers and aeration will be necessary to support the growth of microbes or plants.
- determination of the chemical form of the radioactive species
- identification of the half-life of the radionuclide involved, and
- identification of which plant or microbial species are best suited to the radionuclide-contaminated site

The radiological half-life must be considered, as well. If the half-life is relatively short, it may lead to the effective disappearance of the contaminant in a practical amount of time. Conversely, if the half-life is relatively long, it may necessitate regulated disposal. Furthermore, it is important to ensure that the plants, bacteria, or other organisms that have concentrated radionuclides in their tissue will not be inadvertently transported off-site by wind or water.

In optimal conditions, however, biological remediation methods can be quite effective. In general, phytotechnology works best on large areas of land with low levels of contamination. Given the proper set of conditions, biological remediation can be a welcome alternative to the expensive, traditional methods of remediation. However, because the methods utilize biological modes of cleanup, rather than excavation, phytotechnology and bioremediation can, in some instances, require a longer treatment time than traditional cleanup methods.

Inside this Guide

This *Radionuclide Biological Remediation Resource Guide* outlines various potential phytotechnology and bioremediation methods for treating radionuclide-contaminated sites. Included in this guide are other biotechnologies that show promise at pilot scales and are in need of validation in field demonstrations, such as the use of fungi, microbial mats, and bioaccumulation by shellfish. This current resource guide is part of a series of technology-focused documents prepared by the U.S. EPA, designed in part to address specific contaminants. The U.S. EPA has produced a similar reference in compiling the *Phytoremediation Resource Guide*. This radionuclide guide should serve as a useful reference for EPA Superfund remedial project managers, EPA on-scene coordinators, and EPA health physicists. It may also serve as reference for other federal and state agencies, academic institutions, private contractors, public interest groups, and individual citizens for whom cleanup of radionuclides is an issue and may spur renewed interests in radionuclide research.

Criteria for Selection of Resources

Our goal in this guide is to cite those technologies which, in our opinion, have real practical relevance to the end user in the field. However, we also recognize that there are several other biological remediation research efforts that are in varied degrees of readiness for field deployment. In this context, this document is by no means an exhaustive reference guide. Specifically, we chose to include a particular resource if it met one or more of the following criteria:

- Has gone through a field demonstration
- Has applicability for treating multiple radionuclides
- Has applications for field-based modeling
- Has a high-degree of tolerance of a variety of environmental conditions

Future Research Opportunities

As this guide was being prepared, studies that involved the use of shellfish were reviewed and seemed to be potential options for future biotechnology. A few of the abstracts that described these areas are included on pages 59-62. Although the abstracts did not meet the criteria set for this current guide, perhaps, by including them, new opportunities for future research and field tests in these areas may be explored.

Literature Search

In developing this resource guide, a literature search was conducted on a variety of government databases, commercial databases, and websites including:

Agency for Toxic Substances and Disease Registry
http://www.atsdr.cdc.gov

BIOSIS Previews
http://www.biosis.com

Environmental Protection Agency
http://www.epa.gov

Environmental Sciences and Pollution Management Database
http://www.csa.com

Haz-Map: Information on Hazardous Chemicals and Occupational Diseases
http://hazmap.nlm.nih.gov

The Hazardous Waste Cleanup Information Page
http://clu-in.org

National Center for Environmental Health
http://www.cdc.gov/nceh

National Institute of Environmental Health Sciences
http://www.niehs.nih.gov

National Library of Medicine
- MedlinePlus http://www.medlineplus.gov
  Looked under Health Topics for ***Radiation Exposure***
- PubMed http://www.pubmed.gov

TOXNET: Cluster of databases on Toxicology, Hazardous Chemicals and Related Issues http://toxnet.nlm.nih.gov
- GENE-TOX: Genetic Toxicology (Mutagenicity)
- HSDR: Hazardous Substances Data Bank
- IRIS: Integrated Risk Information System
- ITER: International Toxicology Estimates for Risks
- Toxline: Toxicology Bibliographic Information

U.S. Nuclear Regulatory Commission
http://www.nrc.gov

U.S. Department of Energy
http://www.doe.gov

U.S. Department of Agriculture
http://www.usda.gov

Web of Science
http://www.isinet.com/products/citation/wos

The search terms used included various combinations of the keywords: bioremediation, phytoremediation, phytotechnology, bioremediation, plants, bacteria, fungi, shellfish, remediation, radionuclide, radioisotope, cesium, strontium, radium, plutonium, cobalt, technetium, and uranium.

Glossary

Bioavailability	The degree that a contaminant can be taken up by organisms under specific environmental conditions. In the context of biological remediation, high bioavailability is necessary, and the bioavailability can be increased through various treatment processes.
Bioremediation	The use of naturally-occurring microorganisms or genetically engineered microbes to sequester toxic and radioactive compounds or transform them into less harmful forms.
Biostimulation	The addition of fertilizers and/or aeration to supply nutrients, thus enhancing the growth of indigenous microbes during bioremediation.
Bioaugmentation	The addition of microbes that are known to interact aggressively with a particular contaminant or a pollution site in order to speed-up a bioremediation process
Chelation	The binding of a contaminant to a biological or a chemical molecule, such as a metal binding to a protein. Chelation can change the bioavailability or phytoextraction properties of a metal or radionuclide.
Energy flow	The transfer of energy through an ecosystem. Energy flow starts through the process of photosynthesis by primary producers (such as plants and blue-green algae) and makes energy available through out the various trophic levels of the ecosystem.
Half-life	The time interval whereby radioactive decay reduces the number of atoms of a radioisotope by one-half.
Mineralization	The process by which substances are converted to inorganic compounds.
Nutrient cycling	The movement of nutrients (such as nitrogen, phosphorus, sulfur, carbon, and carbon dioxide in the environment) within an ecosystem, primarily by microorganisms.
Phytodegradation	The breakdown of contaminants by plants, either internally through metabolic processes within a plant, or externally through the release of compounds (such as enzymes) produced by a plant. Pollutants can be degraded, incorporated into the plant tissues, and used as nutrients. Even though chemical forms can be degraded, there is no

way to alter a radionuclide except as it radioactively decays in its own fixed way. Nor can the radioactive decay process be accelerated or decelerated.

Phytoextraction (or phytoaccumulation) — The uptake and translocation of contaminants, either chemical or radioactive, by plant roots into the above ground portions of the plants. Certain plants called hyperaccumulators absorb unusually large amounts of radionuclides in comparison to other plants. One or a combination of these plants is selected and planted at a site based on the type of radionuclides present and other site conditions. After the plants have been grown to a predetermined size, age, or growth stage, they are harvested and tested for radioactive content. The radioactive content of the plant, value of the material, half-life, and regulations determine the appropriate disposal of radioactive plant matter, either into recycling, solid waste, or hazardous waste disposal. In some cases plants may be dried, composted, or incinerated to reduce volume.

Phytostabilization — The use of certain plant species to immobilize contaminants in the soil and groundwater through absorption and accumulation in plant tissues, adsorption onto roots, or precipitation within the root zone. This process reduces the mobility of the contaminant by retarding migration to the groundwater or air and by reducing bioavailability for entry into the food chain. This technique can be used to reestablish a vegetative cover at sites where natural vegetation is lacking due to high radioactivity concentrations in surface soils or physical disturbances to surficial materials. Radioactivity-tolerant species can be used to restore vegetation to the sites, thereby decreasing the potential migration of contamination through wind erosion, transport of exposed surface soils, and leaching of soil contamination to groundwater.

Phytotechnology — The direct use of living plants for *in situ* remediation of contaminated soil, sludges, sediments, surface water, or groundwater through contaminant removal, degradation, or containment.

Phytovolatilization — The uptake and transpiration of a contaminant by a plant, with release of the contaminant or a modified form of the contaminant to the atmosphere from the plant. Phytovolatilization occurs as growing trees and other plants take up water along with the contaminants. Some of these contaminants can pass through the plants to the leaves and volatilize into the atmosphere at comparatively low concentrations.

Rhizodegradation	The breakdown of contaminants in the soil through microbial activity that is enhanced by the presence of a plant's root structure. Rhizodegradation is a much slower process than phytodegradation. Microorganisms (yeast, fungi, or bacteria) consume and digest organic substances for nutrition and energy. Certain microorganisms can digest organic substances such as fuels or solvents that are hazardous to humans and break them down into harmless products through biodegradation. Natural substances released by the plant roots — sugars, alcohols, and acids — contain organic carbon that provides food for soil microorganisms, which enhances their activity. Biodegradation is also aided by the way plants loosen the soil and transport water to the area.
Rhizofilteration	The adsorption or precipitation onto plant roots or absorption into and sequesterization in the roots of contaminants that are in solution surrounding the root zone. The plants to be used for cleanup are raised in greenhouses with their roots in water rather than in soil. To acclimate the plants once a large root system has been developed, contaminated water is collected from a waste site and brought to the plants where it is substituted for their water source. The plants are then planted in the contaminated area where the roots take up the water and the contaminants along with it. As the roots become saturated with radioactive contaminants, they are harvested. This could be followed by incineration or composting to reduce the volume and/or by storage to allow radioactive decay to reduce the volume of contaminated material. Generally, this would be followed by disposal in a regulated landfill.
Sequential extraction	The use of successive applications of various solvents and other chemicals to ensure that the chemical or radioactive contaminant is released from bound surfaces (such as soil particles) so that effective treatment can be achieved. The technique can be used for either diagnostic or treatment purposes.
Sequesterization	The isolation of contaminants in a medium in ways that make them unavailable and less harmful to the environment.
Sustainability	The ability of a system to maintain itself over a prolonged period of time. The quality of a system, biodiversity, and economic status of a system affect its sustainability.

How to Use this Guide

General Information

Within the Abstracts section of this guide, one can find the citations and abstracts, as written by the article's authors, for approximately 100 articles on biological remediation of radionuclides. The abstracts in this guide are organized primarily by technology type (phytotechnology, bioremediation, and other), then by year (most recent to least recent), then alphabetically by the first author's last name. One can look to the top right of the heading on each page to determine the technology type and document numbers assigned to the articles on that page.

Searching the Guide

There are two main ways to identify those resources in this guide that will be most helpful to you:

- Using the Cross-Reference Matrix
- Browsing through the Abstract Keys

Cross-Reference Matrix

The Cross-Reference Matrix, on pages 12-22, provides a way to determine which articles pertain to the contaminants at your site. Each row in the matrix corresponds to one article in the Abstracts section. First the matrix lists the Media Addressed (soil, groundwater, or surface water) in each article, as represented by a dot in the appropriate column. Then, the matrix shows the Radionuclides Addressed (cesium-137, strontium-90, radium-226, plutonium, technetium-99, uranium, thorium, or other) in each article, also represented by a dot in the corresponding column. Less commonly addressed isotopes of the same elements (for example, cesium-134) are listed under "other." Plutonium encompasses plutonium-238, plutonium-239, plutonium-241, or combinations thereof. Uranium refers to the isotopes uranium-234, uranium-235, uranium-238, or combinations thereof or to the Uranium Decay Series. Thorium refers to the isotopes thorium-227, thorium-230 or thorium-232 or combinations thereof or to the Thorium Decay Series. The matrix also shows the Technology Type employed in the article (phytotechnology, bioremediation, or other).

To use this Cross-Reference Matrix, simply look for those rows that address the combination of radionuclides and media that apply at your cleanup site. Look to the right of the row, and you will find the title of the relevant document, the number of the document in the booklet, and the page number on which the document appears. Once you have selected the appropriate documents, use the page number (found at the bottom of each page of abstracts) and document number (preceding each citation at the top of each abstract) to find the full citation and abstract for each document in the abstract listings on pages 23-58.

Abstract Keys

If you already have a preference for the technology type you want to use at your site, you can go directly to the Abstracts section and use the Abstract Keys to find those documents that most effectively address your interests.

Within the abstract listings on pages 23-58, each document has its own Abstract Key located between the citation and the abstract. Here is a sample Abstract Key:

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other
Technology: Phyto.	**Media:** Soil	

A star is placed next to the radionuclides addressed in the articles — in this case, ^{99}Tc. If a less common radionuclide is mentioned, it will be written out in the "other" section. Like the Cross-Reference Matrix, the Abstract Key lists the technology type (in this case, phytotechnology) and the media addressed (in this case, soil). The technology type will be abbreviated as "phyto." for phytotechnology and "biorem." for bioremediation. The media will be abbreviated as "SW" for surface water and "GW" for groundwater.

More information

Within each technology type section, there are some review articles that are very helpful overviews of the work within the field. These are highlighted with an asterisk at the end of the citation, standing for a review article.

In this document, the radionuclides are represented by their chemical symbol. Some of the more common radionuclides mentioned are:

^{137}Cs = cesium-137
^{90}Sr = strontium-90
^{226}Ra = radium-226
Pu = plutonium
^{99}Tc = technetium-99
U = uranium
Th = thorium
^{60}Co = cobalt-60
^{3}H = tritium

In some cases, the abstract may not be available for an article. This will be noted under the Abstract Key.

When available, information on how to obtain the full article will be listed below the abstract. In most cases, this will include a website for the journal in which the article appeared. One can use the citation for the article to find the full text on this website. In most cases, the website will charge a fee for obtaining the full text if you do not have a subscription.

In some cases, a National Technical Information Service (NTIS) order number may be available at the end of the abstract. To obtain one of these documents, call NTIS at (800) 553-6847 or order from their website at http://www.ntis.gov. In other cases, a book number (ISBN) or no other information will be listed. A librarian should be able to help you find these documents or any other documents you have trouble locating.

Cross Reference Matrix

Media Addressed			Radionuclides Addressed								Technology Type	Document Title	Doc. Number	Page
Soil	Ground-water	Surface Water	^{137}Cs	^{90}Sr	^{226}Ra	Pu	^{99}Tc	U	Th	Other				
•			•	•							Phytotechnology	Accumulation of ^{137}Cs and ^{90}Sr from contaminated soil by three grass species inoculated with mycorrhizal fungi	26	32
•			•							General	Other	Application of a dynamic model for evaluating radionuclide concentration in fungi	91	54
•					•			•	•		Bioremediation	Bioremediation of a soil contaminated with radioactive elements	61	45
•			•	•							Phytotechnology	A comparison of ^{90}Sr and ^{137}Cs uptake in plants via three pathways at two Chernobyl-contaminated sites	11	27
•			•								Phytotechnology	A comparison of models for characterizing the distribution of radionuclides with depth in soils	28	33
•			•								Phytotechnology	Dynamics of ^{137}Cs bioavailability in soil-plant system in areas of the Chernobyl Nuclear Power Plant accident zone with a different physico-chemical composition of radioactive fallout	39	37
•										^{134}Cs, ^{85}Sr	Other	Effect of ectomycorrhizae and ammonium on ^{134}Cs and ^{85}Sr uptake into Picea abies seedlings	92	55
•							•				Phytotechnology	Effect of NO_3^- on the fate of $^{99}TcO_4^-$ in the soil-plant system	29	33
•			•	•							Phytotechnology	Environmental processes affecting plant root uptake of radioactive trace elements and variability of transfer factor data: a review	7	25

Cross Reference Matrix

Media Addressed			Radionuclides Addressed								Technology Type	Document Title	Doc. Number	Page
Soil	Ground-water	Surface Water	^{137}Cs	^{90}Sr	^{226}Ra	Pu	^{99}Tc	U	Th	Other				
•										General	Other	Fungal interactions with metals and radionuclides for environmental bioremediation	93	55
•			•								Other	Fungi as potential bioremediation agents in soil contaminated with heavy or radioactive metals	90	54
•			•								Phytotechnology	Generic values for soil-to-plant transfer factors of radiocesium	8	26
•			•					•			Phytotechnology	Identification and validation of heavy metal and radionuclide hyperaccumulating terrestial plant specie	36	36
•										^{65}Zn, ^{54}Mn	Phytotechnology	Incorporating soil structure and root distribution into plant uptake models for radionuclides: toward a more physically based transfer model	6	25
•			•	•							Phytotechnology	Influence of agricultural countermeasures on the ratio of different chemical forms of radionuclides in soil and soil solution	45	38
•			•	•							Phytotechnology	Influence of organic amendments on the accumulation of ^{137}Cs and ^{90}Sr from contaminated soil by three grass species	17	29
•			•	•						^{134}Cs	Other	Influence of soil fungi (basidiomycetes) on the migration of $^{134+137}$Cs and ^{90}Sr in coniferous forest soils	100	57
•										General	Phytotechnology	In-situ remediation of soil contaminated with low concentrations of radionuclides	44	38

Cross Reference Matrix

Media Addressed			Radionuclides Addressed								Technology Type	Document Title	Doc. Number	Page
Soil	Ground-water	Surface Water	^{137}Cs	^{90}Sr	^{226}Ra	Pu	^{99}Tc	U	Th	Other				
●			●	●							Phytotechnology	Long-term study on the transfer of ^{137}Cs and ^{90}Sr from Chernobyl-contaminated soils to grain crops	37	36
●			●								Phytotechnology	Mechanisms of casesium uptake by plants	23	31
●					●						Phytotechnology	Modeling radium and radon transport through soil and vegetation	4	24
●				●							Phytotechnology	Modeling the potential role of a forest ecosystem in phytostabilization and phytoextraction of ^{90}Sr at a contaminated watershed	27	33
●			●								Phytotechnology	An overview of the effect of organic matter on soil–radiocaesium interaction: implications in root uptake	14	28
●						●		●			Phytotechnology	Phytoaccumulation of chromium, uranium, and plutonium in plant systems	32	34
●										General	Phytotechnology	Phytoremediation and reclamation of soils contaminated with radionuclides	35	36
●			●	●							Phytotechnology	Phytoremediation of Chernobyl contaminated land	22	31
●			●								Phytotechnology	Phytoremediation of radiocesium-contaminated soil in the vicinity of Chernobyl, Ukraine	25	32
●										General	Phytotechnology	Phytoremediation of soil contaminated with low concentrations of radionuclides	41	37
●										General	Phytotechnology	Phytoremediation of soils contaminated with toxic elements and radionuclides	42	37

Cross Reference Matrix

Media Addressed			Radionuclides Addressed								Technology Type	Document Title	Doc. Number	Page
Soil	Ground-water	Surface Water	^{137}Cs	^{90}Sr	^{226}Ra	Pu	^{99}Tc	U	Th	Other				
●										General	Phytotechnology	Phytoremediation of toxic elemental and organic pollutants	20	30
●								●			Phytotechnology	Phytoremediation of uranium-contaminated soils: role of organic acids in triggering uranium hyperaccumulation in plants	34	35
●										^{134}Cs	Phytotechnology	Plant uptake of ^{134}Cs in relation to soil properties and time	12	27
●			●		●					^{60}Co	Phytotechnology	Plant uptake of radionuclides in lysimeter experiments	30	34
●			●	●							Phytotechnology	Proceedings of the Chornobyl phytoremediation and biomass energy conversion	33	35
●			●								Phytotechnology	Rhizopheric mobilization of radiocesium in soils	19	29
●								●			Other	Role for lichen melanins in uranium remediation	88	54
●			●							General	Other	The role of fungi in the transfer and cycling of radionuclides in forest ecosystems	84	53
●										General	Phytotechnology	Selection of plants for phytoremediation of soils contaminated with radionuclides	40	37
●			●	●							Phytotechnology	Sequestration of ^{137}Cs and ^{90}Sr from soil by seedlings of Eucalyptus tereticornis	43	38
●							●				Phytotechnology	Soil availability, plant uptake and soil to plant transfer of ^{99}Tc – a review	1	23
●			●	●							Phytotechnology	Soil contamination with radionuclides and potential remediation	24	31

Cross Reference Matrix

Media Addressed			Radionuclides Addressed								Technology Type	Document Title	Doc. Number	Page
Soil	Ground-water	Surface Water	^{137}Cs	^{90}Sr	^{226}Ra	Pu	^{99}Tc	U	Th	Other				
●			●								Phytotechnology	Soil organic horizons as a major source for radiocesium biorecycling in forest ecosystems	10	26
●										General	Other	Soil-fungi radiocesium transfers in forest ecosystems	99	57
●					●						Phytotechnology	Soil-to-plant transfer of ^{226}Ra in a marsh area: modelling application	31	34
●						●					Bioremediation	Solubilization of plutonium hydrous oxide by iron-reducing bacteria	83	51
●			●								Phytotechnology	The true distribution and accumulation of radiocaesium in stem of Scots Pine (Pinus sylvestris L.)	16	28
●			●	●							Phytotechnology	Uptake of cesium-137 and strontium-90 from contaminated soil by three plant species; application to phytoremediation	9	26
●	●									General	Other	Natural attenuation of metals and radionuclides	89	24
●		●								General	Other	Assessment of bioremediation technologies: focus on technologies suitable for field-level demonstrations and applicable to DOD contaminants	95	56
●		●						●		General	Bioremediation	Bioremediation of uranium contaminated soils and wastes	75	49
●		●								General	Bioremediation	Developments in terrestrial bacterial remediation of metals	73	48
●		●					●				Bioremediation	Direct and Fe(II)-mediated reduction of technetium by Fe(III)-reducing bacteria	64	45

Cross Reference Matrix

Media Addressed			Radionuclides Addressed								Technology Type	Document Title	Doc. Number	Page
Soil	Ground-water	Surface Water	^{137}Cs	^{90}Sr	^{226}Ra	Pu	^{99}Tc	U	Th	Other				
●		●								General	Other	Fungal processes for bioremediation of toxic metal and radionuclide pollution	86	53
●		●	●	●				●			Phytotechnology	Metal hyperaccumulation in plants—biodiversity prospecting for phytoremediation technology	5	24
●		●						●			Bioremediation	A procedure for quantitation of total oxidized uranium for bioremediation studies	48	39
●		●						●			Bioremediation	Radionuclide contamination: nanometre-size products of uranium bioreduction	59	44
●		●						●			Bioremediation	Radionuclide immobilization by the formation of crystalline Fe compounds resulting from the bio-oxidation of Fe(II) by Dechlorosoma suillum	55	43
●		●		●				●	●		Bioremediation	Remediation of soils and wastes contaminated with uranium and toxic metals	76	49
●	●	●					●			General	Bioremediation	Bacterial-metal/radionuclide interaction	72	48
●	●	●								General	Bioremediation	Influence of microorganisms on the environmental fate of radionuclides	81	51
●	●	●					●	●		General	Bioremediation	Metals and radionuclide bioremediation: issues, considerations and potentials	60	44
●	●	●								General	Bioremediation	Microbial detoxification of metals and radionuclides	62	45
●	●	●								General	Bioremediation	Microbial interactions with metals/radionuclides: the basis of bioremediation	57	44

Cross Reference Matrix

Media Addressed			Radionuclides Addressed								Technology Type	Document Title	Doc. Number	Page
Soil	Ground-water	Surface Water	^{137}Cs	^{90}Sr	^{226}Ra	Pu	^{99}Tc	U	Th	Other				
●	●	●						●			Bioremediation	Microbial transformations of uranium and environmental restoration through bioremediation	56	43
●	●	●								General	Phytotechnology	Phytoremediation of metals, metalloids, and radionuclides	13	27
●	●	●					●	●			Bioremediation	Reduction of Fe(III), Cr(VI), U(VI), and Tc(VII) by Deinococcus radiodurans R1	63	45
●	●	●								General	Bioremediation	Report on 1st Euroconference on bacterial-metal/radionuclide interactions: basic research and bioremediation	71	48
●	●	●								General	Bioremediation	The role of microorganisms in biosorption of toxic metals and radionuclides	82	51
●	●	●	●	●	●	●	●	●	●	Multiple	Phytotechnology	Trends in phytoremediation of radionuclides	2	23
●	●	●	●	●		●		●		^{3}H	Phytotechnology	The use of plants for the treatment of radionuclides	21	30
	●					●				^{60}Co	Bioremediation	Biodegradation and speciation of PuEDTA by bacterium BNCI	47	39
	●						●				Bioremediation	Effect of electron donor and solution chemistry on products of dissimilatory reduction of technetium by Shewanella putrefaciens	68	47
	●							●			Bioremediation	Microbially mediated redox processes in natural analogues for radioactive waste	58	44
	●							●			Bioremediation	Microorganisms associated with uranium bioremediation in a high-salinity subsurface sediment	50	40

Cross Reference Matrix

Media Addressed			Radionuclides Addressed								Technology Type	Document Title	Doc. Number	Page
Soil	Ground-water	Surface Water	^{137}Cs	^{90}Sr	^{226}Ra	Pu	^{99}Tc	U	Th	Other				
	•							•			Bioremediation	Potential for in situ bioremediation of low-pH, high-nitrate uranium-contaminated groundwater	52	41
	•							•			Bioremediation	Simulating bioremediation of uranium-contaminated aquifiers; uncertainty assessment of model parameters	54	42
	•			•							Bioremediation	Remediation of metal contaminants by microbially mediated calcite precipitation	67	41
	•							•			Bioremediation	Stimulating the in situ activity of Geobacter species to remove uranium from the groundwater of a uranium-contaminated aquifer	51	40
	•	•				•			•	Np	Bioremediation	Biological reduction and removal of Np(V) by two microorganisms	65	46
	•	•						•			Phytotechnology	Removal of uranium from water using terrestrial plants	38	36
		•					•				Phytotechnology	Accumulation of ^{99}Tc in duckweed Lemna minor L. as function of growth rate and ^{99}Tc concentration	18	29
		•				•		•	•	La	Bioremediation	Bioaccumulation of lanthanum, uranium and thorium, and use of a model system to develop a method for the biologically-mediated removal of plutonium from solution	79	50
		•						•			Other	Bioaccumulation of metals by lichens: Uptake of aqueous uranium by Peltigera membranacea as a function of time and pH	87	53

Cross Reference Matrix

Media Addressed			Radionuclides Addressed								Technology Type	Document Title	Doc. Number	Page
Soil	Ground-water	Surface Water	^{137}Cs	^{90}Sr	^{226}Ra	Pu	^{99}Tc	U	Th	Other				
		•					•				Other	Bioremediation of aqueous pollutants using biomass embedded in hydrophilic foam	94	55
		•							•		Other	Biosorption of radionuclides by fungal biomass	101	58
		•								General	Bioremediation	Continuous radionuclide recovery from wastewater using magnetotactic bacteria	74	48
		•								Multiple	Bioremediation	Effect of microbes on the uptake of ^{60}Co, ^{85}Sr, ^{95}Tc, ^{131}I and ^{134}Cs by decomposing elm leaves in aquatic microcosms	80	50
		•						•			Bioremediation	Enzymatically mediated bioprecipitation of uranium by Citrobacter sp.: a concerted role for exocellular lipopolysaccharide and associated phosphatase in biomineral formation	66	46
		•					•	•			Bioremediation	In-situ bioreduction of technetium and uranium in a nitrate-contaminated aquifier	46	39
		•	•				•			^{60}Co	Other	Interactions of microalgae and cyanobacteria with toxic metals and radionuclides	96	56
		•								General	Other	Metal accumulation by fungi: applications in environmental biotechnology	97	57
		•								General	Bioremediation	Metal immobilisation by biofilms: mechanisms and analytical tools	53	42

Cross Reference Matrix

Media Addressed			Radionuclides Addressed								Technology Type	Document Title	Doc. Number	Page
Soil	Ground-water	Surface Water	^{137}Cs	^{90}Sr	^{226}Ra	Pu	^{99}Tc	U	Th	Other				
		•					•				Bioremediation	Microbial reduction of technetium by Escherichia coli and Desulfovibrio desulfuricans: enhancement via the use of high-activity strains and effect of process parameters	70	48
		•				•				Np	Bioremediation	Microbially-enhanced chemisorption of heavy metals: A method for the bioremediation of solutions containing long-lived isotopes of neptunium and plutonium	78	50
		•					•				Bioremediation	Reduction of technetium by Desulfovibrio desulfuricans: biocatalyst characterization and use in flowthrough bioreactor	69	47
		•								General	Bioremediation	Removal and recovery of metals from a coal pile runoff	49	40
		•							•		Other	Removal of thorium from simulated acid process streams by fungal biomass: potential for thorium desorption and reuse of biomass and desorbent	98	57
		•				•				^{241}Am, ^{95}Zr, ^{144}Ce, $^{152+154}$Eu	Other	Sorption of plutonium, americium and fission products from reprocessing effluents using Rhizopus arrhizus	85	53
		•	•								Phytotechnology	Suspended particle adhesion on aquatic plant surfaces: implications for ^{137}Cs and ^{133}Cs uptake rates and water-to-plant concentration ratios	15	28

Cross Reference Matrix

Media Addressed			Radionuclides Addressed								Technology Type	Document Title	Doc. Number	Page
Soil	Ground-water	Surface Water	^{137}Cs	^{90}Sr	^{226}Ra	Pu	^{99}Tc	U	Th	Other				
		•					•				Bioremediation	Technetium reduction and precipitation by sulfate-reducing bacteria	77	49
		•					•				Phytotechnology	Uptake, biotransformation, and elimination of 99Tc in duckweed	3	23

(1) Bennett, R and N Willey. 2003. Soil availability, plant uptake and soil to plant transfer of ^{99}Tc – a review. *Journal of Environmental Radioactivity* 65: 215-231. *

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: The fission yield of ^{99}Tc from ^{239}Pu and ^{235}U is similar to that of ^{137}Cs or ^{90}Sr and it is therefore an important component of nuclear weapons fall-out, nuclear waste and releases from nuclear facilities. There is particular current interest in ^{99}Tc transfer from soil to plants for: (a) environmental impact assessments for terrestrial nuclear waste repositories, and (b) assessments of the potential for phytoextraction of radionuclides from contaminated effluent and soil. Vascular plants have a high ^{99}Tc uptake capacity, a strong tendency to transport it to shoot material and accumulate it in vegetative rather than reproductive structures. The mechanisms that control ^{99}Tc entry to plants have not been identified and there has been little discussion of the potential for phytoextraction of ^{99}Tc contaminated effluents or soil. Here we review soil availability, plant uptake mechanisms and soil to plant transfer of ^{99}Tc in the light of recent advances in soil science, plant molecular biology and phytoextraction technologies. We conclude that ^{99}Tc might not be highly available in the long term from up to 50% of soils worldwide, and that no single mechanism that might be easily targeted by recombinant DNA technologies controls ^{99}Tc uptake by plants. Overall, we suggest that Tc might be less available in terrestrial ecosystems than is often assumed but that nevertheless the potential of phytoextraction as a decontamination strategy is probably greater for ^{99}Tc than for any other nuclide of radioecological interest.

Website: http://www.sciencedirect.com/science/journal/0265931X

(2) Dushenkov, S. 2003. Trends in phytoremediation of radionuclides. *Plant and Soil* 249: 167-175. *

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra ★	Pu ★	^{99}Tc ★
U ★	Th ★	other *Multiple*
Technology: Phyto.	**Media:** Soil, GW, SW	

Abstract: Phytoremediation, a novel plant-based remediation technology, is applied to a variety of radionuclide-contaminated sites all over the world. Phytoremediation is defined as the use of green plants to remove pollutants from the environment or to render them harmless. Current status of several subsets of phytoremediation of radionuclides is discussed: (a) phytoextraction, in which high biomass radionuclide-accumulating plants and appropriate soil amendments are used to transport and concentrate radionuclides from the soil into the above-ground shoots, which are harvested with conventional agricultural methods, (b) rhizofiltration, in which plant roots are used to precipitate and concentrate radionuclides from polluted effluents, (c) phytovolatilization, in which plants extract volatile radionuclides from soil and volatilize them from the foliage and (d) phytostabilization, in which plants stabilize radionuclides in soils, thus rendering them harmless. It is shown that phytoremediation is a fast developing field and the phytoremediation of radionuclides might soon become an integral part of the environment management and risk reduction process.

Website: http://www.kluweronline.com/issn/0032-079X/contents

(3) Hattink, J, AV Harms and JJM de Goeij. 2003. Uptake, biotransformation, and elimination of ^{99}Tc in duckweed. *The Science of the Total Environment* 312: 59-65.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other
Technology: Phyto.	**Media:** SW	

Abstract: Aquatic plants may play an important role in the environmental fate of the long-lived radioactive waste product ^{99}Tc. Aquatic plants show a strong accumulation and retention of Tc, even after they have died. This study focuses on possible bio-organic Tc compounds formed in the water dwelling plant duckweed to possibly explain the accumulation and retention. Moreover, a change in chemical speciation often implies a different fate and behaviour in the biosphere. A mild separation technique was used to distinguish between reduced Tc species and TcO_4^-. Accumulation experiments suggested that reduction of $Tc^{VII}O_4^-$ and subsequent complexation are responsible for the accumulation of Tc in duckweed. A steady state concentration of TcO_4^- in duckweed was reached within 24 h, but the total concentration of Tc increased continuously. Only a small part (at most 5%) of Tc was present as TcO_4^-. Elimination experiments showed that TcO_4^- is the only mobile species. Other Tc species are responsible for the retention of Tc in duckweed. It is known that these species are not bio-available and only slowly re-oxidise to pertechnetate, resulting in a longer residence time in ecosystems.

Website: http://www.sciencedirect.com/science/journal/00489697

*= Review Article

(4) Kozak, JA, HW Reeves and BA Lewis. 2003. Modeling radium and radon transport through soil and vegetation. *Contaminant Hydrology* 66: 179-200.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra ★	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: A one-dimensional flow and transport model was developed to describe the movement of two fluid phases, gas and water, within a porous medium and the transport of ^{226}Ra and ^{222}Rn within and between these two phases. Included in this model is the vegetative uptake of water and aqueous ^{226}Ra and ^{222}Rn that can be extracted from the soil via the transpiration stream. The mathematical model is formulated through a set of phase balance equations and a set of species balance equations. Mass exchange, sink terms and the dependence of physical properties upon phase composition couple the two sets of equations. Numerical solution of each set, with iteration between the sets, is carried out leading to a set-iterative compositional model. The Petrov–Galerkin finite element approach is used to allow for upstream weighting if required for a given simulation. Mass lumping improves solution convergence and stability behavior. The resulting numerical model was applied to four problems and was found to produce accurate, mass conservative solutions when compared to published experimental and numerical results and theoretical column experiments. Preliminary results suggest that the model can be used as an investigative tool to determine the feasibility of phytoremediating radium and radon-contaminated soil.
Website: http://www.sciencedirect.com/science/journal/01697722

(5) Prasad, MNV and HM de Oliveira Freitas. 2003. Metal hyperaccumulation in plants—biodiversity prospecting for phytoremediation technology. *Electronic Journal of Biotechnology* 6. *

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Phyto.	**Media:** Soil, SW	

Abstract: The importance of biodiversity (below and above ground) is increasingly considered for the cleanup of the metal contaminated and polluted ecosystems. This subject is emerging as a cutting edge area of research gaining commercial significance in the contemporary field of environmental biotechnology. Several microbes, including mycorrhizal and non-mycorrhizal fungi, agricultural and vegetable crops, ornamentals, and wild metal hyperaccumulating plants are being tested both in lab and field conditions for decontaminating the metalliferous substrates in the environment. As on todate about 400 plants that hyperaccumulate metals are reported. The families dominating these members are Asteraceae, Brassicaceae, Caryophyllaceae, Cyperaceae, Cunouniaceae, Fabaceae, Flacourtiaceae, Lamiaceae, Poaceae, Violaceae, and Euphobiaceae. Brassicaceae had the largest number of taxa viz. 11 genera and 87 species. Different genera of Brassicaceae are known to accumulate metals. Ni hyperaccumulation is reported in 7 genera and 72 species and Zn in 3 genera and 20 species. Thlaspi species are known to hyperaccumulate more than one metal i.e. T. caerulescence = Cd, Ni. Pb, and Zn; T. goesingense = Ni and Zn and T. ochroleucum = Ni and Zn and T. rotundifolium = Ni, Pb and Zn. Plants that hyperaccumulate metals have tremendous potential for application in remediation of metals in the environment. Significant progress in phytoremediation has been made with metals and radionuclides. This process involves rising of plants hydroponically and transplanting them into metal-polluted waters where plants absorb and concentrate the metals in their roots and shoots. As they become saturated with the metal contaminants, roots or whole plants are harvested for disposal. Most researchers believe that plants for phytoremediation should accumulate metals only in the roots. Several aquatic species have the ability to remove heavy metals from water, viz., water hyacinth (Eichhornia crassipes (Mart.) Solms); pennywort (Hydrocotyle umbellata L.) and duckweed (Lemna minor L.). The roots of Indian mustard are effective in the removal of Cd, Cr, Cu, Ni, Pb, and Zn and sunflower removes Pb, U, ^{137}Cs, and ^{90}Sr from hydroponic solutions. Aquatic plants in freshwater, marine and estuarine systems act as receptacle for several metals. Hyperaccumulators accumulate appreciable quantities of metal in their tissue regardless of the concentration of metal in the soil, as long as the metal in question is present. The phytoextraction process involves the use of plants to facilitate the removal of metal contaminants from a soil matrix. In practice, metal-accumulating plants are seeded or transplanted into metal-polluted soil and are cultivated using established agricultural practices. If metal availability in the soil is not adequate for sufficient plant uptake, chelates or acidifying agents would be applied to liberate them into the soil solution. Use of soil amendments such as synthetics (ammonium thiocyanate) and natural zeolites have yielded promising results. Synthetic cross-linked polyacrylates, hydrogels have protected plant roots from heavy metals toxicity and prevented the entry of toxic metals into roots. After sufficient plant growth and metal accumulation, the above-ground portions of the plant are harvested and removed, resulting the permanent removal of metals from the site. Soil metals should also

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be bioavailable, or subject to absorption by plant roots. Chemicals that are suggested for this purpose include various acidifying agents, fertilizer salts and chelating materials. The retention of metals to soil organic matter is also weaker at low pH, resulting in more available metal in the soil solution for root absorption. It is suggested that the phytoextraction process is enhanced when metal availability to plant roots is facilitated through the addition of acidifying agents to the soil. Chelates are used to enhance the phytoextraction of a number of metal contaminants including Cd, Cu, Ni, Pb, and Zn Researchers initially applied hyperaccumulators to clean metal polluted soils. Several researchers have screened fast-growing, high-biomass-accumulating plants, including agronomic crops, for their ability to tolerate and accumulate metals in their shoots. Genes responsible for metal hyperaccumulation in plant tissues have been identified and cloned. Glutathione and organic acids metabolism plays a key role in metal tolerance in plants. Glutathione is ubiquitous component cells from bacteria to plants and animals. In phytoremediation of metals in the environment, organic acids play a major role in metal tolerance. Organic acids acids form complexes with metals, a process of metal detoxification. Genetic strategies and transgenic plant and microbe production and field trials will fetch phytoremediaition field applications.The importance of biodiversity and biotechnology to remediate potentially toxic metals are discussed in this paper. Brassicaceae amenable to biotechnological improvement and phytoremediation hype are highlighted.

Website: http://www.ejbiotechnology.info

(6) Albrecht, A. 2002. Incorporating soil structure and root distribution into plant uptake models for radionuclides: toward a more physically based transfer model. *Journal of Environmental Radioactivity* 59: 329-350.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other ^{65}Zn, ^{54}Mn
Technology: Phyto.	**Media:** Soil	

Abstract: Most biosphere and contamination assessment models are based on uniform soil conditions, since single coefficients are used to describe the transfer of contaminants to the plant. Indeed, physical and chemical characteristics and root distribution are highly variable in the soil profile. These parameters have to be considered in the formulation of a more realistic soil–plant transfer model for naturally structured soils.

The impact of monolith soil structure (repacked and structured) on Zn and Mn uptake by wheat was studied in a controlled tracer application (dye and radioactive) experiment. We used Brilliant Blue and Sulforhodamine B to dye flow lines and ^{65}Zn and ^{54}Mn to trace soil distribution and plant uptake of surface-applied particle-reactive contaminants. Spatial variation of the soil water content during irrigation and plant growth informs indirectly about tracer and root location in the soil profile. In the structured monolith, a till pan at a depth of 30 cm limited vertical water flow and root penetration into deeper soil layers and restricted tracers to the upper third of the monolith. In the repacked monolith, roots were observed at all depths and fingering flow allowed for the fast appearance of all tracers in the outflow. These differences between the two monoliths are reflected by significantly higher ^{54}Mn and ^{65}Zn uptake in wheat grown on the structured monolith. The higher uptake of Mn can be modelled on the basis of radionuclide and root distribution as a function of depth and using a combination of preferential flow and rooting. The considerably higher uptake of Zn requires transfer factors which account for variable biochemical uptake as a function of location.

Website: http://www.sciencedirect.com/science/journal/0265931X

(7) Ehlken, S and G Kirchner. 2002. Environmental processes affecting plant root uptake of radioactive trace elements and variability of transfer factor data: a review. *Journal of Environmental Radioactivity* 58: 97-112.*

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: Soil-to-plant transfer factors are commonly used to estimate the food chain transfer of radionuclides. Their definition assumes that the concentration of a radionuclide in a plant relates linearly solely to its average concentration in the rooting zone of the soil. However, the large range of transfer factors reported in the literature shows that the concentration of a radionuclide in a soil is not the only factor influencing its uptake by a plant. With emphasis on radiocesium and -strontium, this paper reviews the effects of competition with major ions present in the soil-plant system, the effects of rhizosphere processes and soil micro-organisms on bioavailability, the factors influencing transport to and uptake by roots and the processes affecting long-term uptake rates. Attention is given to summarizing the results of recent novel electrophysiological and genetic techniques which provide a

*= Review Article

physiologically based understanding of the processes involved in the uptake and translocation of radiocesium and -strontium by plants.
Website: http://www.sciencedirect.com/science/journal/0265931X

(8) Frissel, MJ, DL Deb, M Fathony, YM Lin, AS Mollah, NT Ngo, L Othman, WL Robison, V Skarlou-Alexiou, S Topcuoglu, JR Twining, S Uchida and MA Wasserman. 2002. Generic values for soil-to-plant transfer factors of radiocesium. *Journal of Environmental Radioactivity* 58: 113–128.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: This paper describes a generic system for ^{137}Cs, mainly based on a reference soil-to-plant transfer factor which depends solely on soil properties such as nutrient status, exchangeable K-content, pH and moisture content. Crops are divided into crop groups, cereals serving as reference group. The transfer of other crop groups can be calculated by multiplying data for cereals by a conversion factor. Existing data present in the IUR (International Union of Radioecologists) databank and in large part the work of a FAO (Food and Agriculture Organisation)/IAEA(International Atomic Energy Agency)/IUR project on tropical systems provided the basis for the derivation of the conversion factors and reference values.
Website: http://www.sciencedirect.com/science/journal/0265931X

(9) Fuhrmann, M, MM Lasat, SD Ebbs, LV Kochian and J Cornish. 2002. Uptake of cesium-137 and strontium-90 from contaminated soil by three plant species; application to phytoremediation. *Journal of Environmental Quality* 31: 904-909.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: A field test was conducted to determine the ability of three plant species to extract ^{137}Cs and ^{90}Sr from contaminated soil. Redroot pigweed (*Amaranthus retroflexus* L.), Indian mustard [*Brassica juncea* (L.) Czern.], and tepary bean (*Phaseolus acutifolius* A. Gray) were planted in a series of spatially randomized cells in soil that was contaminated in the 1950s and 1960s. We examined the potential for phytoextraction of ^{90}Sr and ^{137}Cs by these three species. Concentration ratios (CR) for ^{137}Cs for redroot pigweed, Indian mustard, and tepary bean were 2.58, 0.46, and 0.17, respectively. For ^{90}Sr they were substantially higher: 6.5, 8.2, and 15.2, respectively. The greatest accumulation of both radionuclides was obtained with redroot pigweed, even though its CR for ^{90}Sr was the lowest, because of its relatively large biomass. There was a linear relationship between the ^{137}Cs concentration in plants and its concentration in soil only for redroot pigweed. Uptake of ^{90}Sr exhibits no relationship to ^{90}Sr concentrations in the soil. Estimates of time required for removal of 50% of the two contaminants, assuming two crops of redroot pigweed per year, are 7 yr for ^{90}Sr and 18 yr for ^{137}Cs.
Website: http://jeq.scijournals.org

(10) Kruyts, N and B Delvaux. 2002. Soil organic horizons as a major source for radiocesium biorecycling in forest ecosystems. *Journal of Environmental Radioactivity* 58: 175–190.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: Here we review some of the main processes and key parameters affecting the mobility of radiocesium in soils of semi-natural areas. We further illustrate them in a collection of soil surface horizons which largely differ in their organic matter contents. In soils, specific retention of radiocesium occurs in a very small number of sorbing sites, which are the frayed edge sites (FES) born out of weathered micaceous minerals. The FES abundance directly governs the mobility of trace Cs in the rhizosphere and thus its transfer from soil to plant. Here, we show that the accumulation of organic matter in topsoils can exert a dilution of FES-bearing minerals in the thick humus of some forest soils. Consequently, such accumulation significantly contributes to increasing ^{137}Cs soil-to-plant transfer. Potassium depletion and extensive exploration of the organic horizons by plant roots can further enhance the contamination hazard. As humus thickness depends on both ecological conditions and forest management, our observations support the following ideas: (1) forest ecosystems can be classified according to their sensitivity to radiocesium bio-recycling, (2) specific forest management

could be searched to decrease such bio-recycling.
Website: http://www.sciencedirect.com/science/journal/0265931X

(11) Malek, MA, TG Hinton and SB Webb. 2002. A comparison of ^{90}Sr and ^{137}Cs uptake in plants via three pathways at two Chernobyl-contaminated sites. *Journal of Environmental Radioactivity* 58: 129-141.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: Foliar absorption of resuspended ^{90}Sr, root uptake and contamination adhering to leaf surfaces (i.e. soil loading) were compared at two Chernobyl-contaminated sites, Chistogalovka and Polesskoye. Although foliar absorption of resuspended ^{90}Sr was quantifiable, its contribution amounted to less than 10% of the plants' total, above-ground contamination. Root uptake was 200 times greater than foliar absorption at the near-field site of Chistogalovka and eight times greater at Polesskoye, where the fallout consisted of the more soluble condensation-type, rather than fuel particles. Strontium's bioavailability exceeded that of ^{137}Cs (analyzed in the same plants) by orders of magnitude when compared using concentration ratios. Simplistic, cumulative effective dose calculations for humans ingesting ^{90}Sr- and ^{137}Cs-contaminated plants revealed that the dose at Chistogalovka was greater from ^{90}Sr (185 mSv vs. 3 mSv from ^{137}Cs), while at Polesskoye the dose from ^{137}Cs (66 mSv) was 30 times greater than from ^{90}Sr (2 mSv).
Website: http://www.sciencedirect.com/science/journal/0265931X

(12) Massas, I, V Skarlou and C Haidouti. 2002. Plant uptake of ^{134}Cs in relation to soil properties and time. *Journal of Environmental Radioactivity* 59: 245–255.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *^{134}Cs*
Technology: Phyto.	**Media:** Soil	

Abstract: ^{134}Cs uptake by sunflower and soybean plants grown on seven different soils and its relation to soil properties were studied in a greenhouse pot experiment. Soil in each pot was contaminated by dripping the ^{134}Cs in layers, and sunflower and soybean plants were grown for three and two successive periods, respectively. ^{134}Cs plant uptake was expressed as the transfer factor (TF) (Bq kg^{-1} plant/Bq kg^{-1} soil) and as the daily plant uptake (flux) (Bq pot^{-1} day^{-1}) taking into account biomass production and growth time. For the studied soils and for both plants, no consistent trend of TFs with time was observed. The use of fluxes, in general, provided less variable results than TFs and stronger functional relationships. A negative power functional relationship between exchangeable potassium plus ammonium cations expressed as a percentage of cation exchange capacity of each soil and ^{134}Cs fluxes was found for the sunflower plants. A similar but weaker relationship was observed for soybean plants. The significant correlation between sunflower and soybean TFs and fluxes, as well as the almost identical highest/lowest ^{134}Cs flux ratios, in the studied soils, indicated a similar effect of soil characteristics on ^{134}Cs uptake by both plants. In all the studied soils, sunflower ^{134}Cs TFs and fluxes were significantly higher than the respective soybean values, while no significant difference was observed in potassium content and daily potassium plant uptake (flux) of the two plants.
Website: http://www.sciencedirect.com/science/journal/0265931X

(13) McGrath, SP, J Zhao and E Lombi. 2002. Phytoremediation of metals, metalloids, and radionuclides. *Advances in Agronomy* 75: 1-56. *

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Phyto.	**Media:** Soil, GW, SW	

Abstract: Phytoremediation is a developing technology that can potentially address the problems of contaminated agricultural land or more intensely polluted areas affected by urban or industrial activities. Three main strategies currently exist to phytoextract inorganic substances from soils using plants:(1) use of natural hyperaccumulators; (2) enhancement of element uptake of high biomass species by chemical additions to soil and plants; and (3) phytovolatilization of elements, which often involves alteration of their chemical form within the plant prior to volatilization to the atmosphere. Concentrating on the techniques that potentially remove inorganic pollutants such as Ni, Zn, Cd, Cu, Co, Pb, Hg, As, Se, and radionuclides, we review the progress in the understanding of the processes involved and the development of the technology. This includes the advances made in the study of

* = Review Article

the physiology and biochemistry of metal uptake, transport and sequestration by hyperaccumulator plants, as well as the investigation of the processes occurring in soil and plant systems subject to the chemical enhancement approach. Enough work has been carried out in the last decade to allow some assessment of the situations and elements in which phytoremediation is likely to be most successful. However, we also identify where there is lack of knowledge. Finally, the likely future directions for research and application are discussed.
Website: http://www.sciencedirect.com/science/bookseries/00652113

(14) Rigol, A, M Vidal and G Rauret. 2002. An overview of the effect of organic matter on soil–radiocaesium interaction: implications in root uptake. *Journal of Environmental Radioactivity* 58: 191–216.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: This paper aims to give an overview of the effect of organic matter on soil–radiocaesium interaction and its implications on soil-to-plant transfer. Studies carried out after the Chernobyl accident have shown that high ^{137}Cs soil-to-plant transfer persists in organic soils over years. In most of these soils, the specific sites in clays control radiocaesium adsorption, organic compounds having an indirect effect. Only in organic soils with more than 95% of organic matter content and negligible clay content does adsorption occur mostly on non-specific sites. After a contamination event, two main factors account for the high transfer: the low solid–liquid distribution coefficient, which is due to the low clay content and high NH_4^+ concentration in the soil solution, and the low K^+ availability, which enhances root uptake. The estimation of the reversibly adsorbed fraction, by means of desorption protocols, agrees with the former conclusions, since it cannot be correlated with the organic matter content and shows the lack of specificity of the adsorption in the organic phase. Moreover, the time-dependent pattern of the exchangeable fraction is related to soil–plant transfer dynamics.
Website: http://www.sciencedirect.com/science/journal/0265931X

(15) Sansone, U, M Belli, Z Jeran, VV Kanivets, J Radojko, M Riccardi and OV Voitsekhovitch. 2002. Suspended particle adhesion on aquatic plant surfaces: implications for ^{137}Cs and ^{133}Cs uptake rates and water-to-plant concentration ratios. *Journal of Environmental Radioactivity* 59: 257–271.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** SW	

Abstract: Suspended particle adhesion on aquatic biota can significantly increase the apparent concentration of radionuclides above their endogenous value, leading to an overestimation of the uptake rate and concentration ratios. This study is an attempt to assess quantitatively the importance of suspended particle adhesion on periphyton samples (biological material coating submerged surfaces). The concentrations of ^{137}Cs and stable Cs (^{133}Cs) in periphyton, suspended particles and filtered water were measured to determine the net water-to-periphyton concentration ratios for ^{137}Cs and stable Cs. The net amount of ^{133}Cs (or ^{137}Cs) taken up by periphyton was calculated by subtracting from the total amount of ^{133}Cs (or ^{137}Cs) on the collected material (periphyton+inorganic particles), the ^{133}Cs (or ^{137}Cs) due to the inorganic particles adhering to periphyton. The mass of suspended particles adhering to the periphyton surface was calculated using scandium as an indicator of the mineral fraction of the suspended particles. The relationship between the concentration ratios for ^{137}Cs and stable Cs and suspended particle adhesion on periphyton external surfaces is discussed.
Website: http://www.sciencedirect.com/science/journal/0265931X

(16) Thiry, Y, F Goor and T Riesen. 2002. The true distribution and accumulation of radiocaesium in stem of Scots Pine (Pinus sylvestris L.). *Journal of Environmental Radioactivity* 58: 243–259.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: The radial and vertical distributions of radiocaesium, potassium and calcium were determined in two Scots pine stands (17 and 58 yr old) similarly affected by the Chernobyl fallout. For both age classes, concentrations are always the lowest in the stemwood, highest in the inner bark and intermediary levels were observed for the outer bark. Due to the cumulative character of its biomass, however, stemwood is a long-term major reservoir of ^{137}Cs. With tree development, changes in the ^{137}Cs radial distribution are well described by variations in the sap ascent pattern and reveal an important transfer between tree rings. It is shown that, both the

biomass evolution and knowledge of the evolution of the ^{137}Cs radial gradient are important to predicting ^{137}Cs accumulation in wood with time. According to the common transfer factor (TF) approach, one would expect a decrease in radiocaesium accumulation with time (from 0.0047±0.0013 to 0.0035±0.0008 m^2/kg for the 17 and 58 yr old trees, respectively). With the wood immobilisation potential (WIP) approach, it was, however, clearly shown that additional annual uptake was highest for the older stand (3.12±0.23 Bq/cm^3 yr for the 58-year-old stand compared to 1.99±0.30 Bq/cm^3 yr for the younger stand). Following the WIP approach, it was moreover possible to distinguish between the ^{137}Cs incorporated via the root uptake process and a possible lasting effect of interception. It is shown that, whereas for the younger stand (5 yr old at the time of the accident) root uptake contributed exclusively to the wood contamination, the former process explained only 48% of the measured total ^{137}Cs content in the wood of the older tree.
Website: http://www.sciencedirect.com/science/journal/0265931X

(17) Entry, JA, LS Watrud and M Reeves. 2001. Influence of organic amendments on the accumulation of ^{137}Cs and ^{90}Sr from contaminated soil by three grass species. *Water, Air and Soil Pollution* 126: 385-398.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: Bahia grass (*Paspalum notatum*), johnson grass (*Sorghum halpense*) and switchgrass (*Panicum virginatum*) were compared for their ability to accumulate ^{137}Cs and ^{90}Sr from three different contaminated soils in the presence and absence of either sphagnum peat or poultry litter amendments. Aboveground plant biomass did not differ between plants that were not exposed to these radionuclides and those that were exposed to soil containing ^{137}Cs or ^{90}Sr. After three harvests, bahia, johnson and switchgrass plants accumulated from 17.2 to 67.3% of the ^{137}Cs and from 25.1 to 61.7% of the ^{90}Sr added to the soil. Poultry litter and peat moss amendments increased aboveground plant biomass, activity of ^{137}Cs or ^{90}Sr in plant tissue, % accumulation of ^{137}Cs or ^{90}Sr from soil and the plant bioconcentration ratio at each harvest compared to the control (no amendment) treatment. The greatest increases in plant biomass, and radionuclide accumulation were observed with poultry litter for each of the three grass species. Johnson grass had greater aboveground plant biomass, activity of ^{137}Cs and ^{90}Sr in plant tissue, % accumulation of ^{137}Cs or ^{90}Sr from soil and bioconcentration ratio in each soil amendment, at each harvest compared to bahia and switchgrass. The greatest accumulation of ^{137}Cs and ^{90}Sr was measured in johnson grass grown in soil that was amended with poultry litter. These results suggest that plant species selection and agronomic practices may need to be considered to maximize phytoremediation of radionuclide contaminated soils.
Website: www.kluweronline.com/issn/0049-6979/contents

(18) Hattink, J and HT Wolterbeek. 2001. Accumulation of ^{99}Tc in duckweed *Lemna minor* L. as function of growth rate and ^{99}Tc concentration. *Journal of Environmental Radioactivity* 57: 117-138.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other
Technology: Phyto.	**Media:** SW	

Abstract: This study focuses on the question of whether short-term studies can be used to forecast the accumulation of the long-lived fission product ^{99}Tc in duckweed, *Lemna minor* L., grown in the field; in other words, are the accumulation parameters independent of changing growth rates typical of natural populations of duckweed. Two processes determine the ^{99}Tc accumulation: (i) uptake and release of $^{99}TcO_4^-$, characterised by a concentration factor, K_d, and (ii) first-order reduction and complexation of Tc^{VII}, characterised by k_{red}. At various ^{99}Tc concentrations, the growth, total Tc and TcO_4^- accumulation were monitored over 10 days; parameters were fitted and compared with earlier results. Both K_d and k_{red} turn out to be independent of time, concentration and growth rate up to a concentration of 10^{-6} mol l^{-1} $^{99}TcO_4$. Concentrations above this level result in toxic effects. The Tc accumulation in field populations of duckweed at Tc concentrations which generally occur in the environment can be forecasted by using the results from short-term experiments.
Website: http://www.sciencedirect.com/science/journal/0265931X

(19) Delvaux, B, N Kruyts and A Cremers. 2000. Rhizopheric mobilization of radiocesium in soils. *Environmental Science & Technology* 34: 1489-1493.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: Though soil-plant transfer is the first step by which radiocesium enters the food chain, it has been scarcely studied in the rhizosphere. Forty-seven soil horizons from 17 pedons with widely varying properties were contaminated with carrier-free $^{137}Cs^+$ and placed into close contact with an active

macroscopic rhizosphere of ryegrass for 4 days. The ^{137}Cs rhizospheric mobilization was strongly correlated with the sodium tetraphenylboron-extractable ^{137}Cs (r = 0.94), supporting that K depletion in the rhizosphere is a capital driving force in ^{137}Cs uptake. The ^{137}Cs soil-plant transfer factor varied from 0.02 to 3.69 g g^{-1} between soil materials and was strongly negatively correlated to the radiocesium interception potential (RIP) (r = -0.88), a common Cs binding characteristic in soil. RIP largely differed between soil materials (13-4861 mol g^{-1}) and was directly related with the soil vermiculite content (r = 0.70). Our results, validated in a wide variety of soils, show that both vermiculitic minerals and plant roots act as competitive sinks for $^{137}Cs^{+}$ in the rhizosphere. They further support that many ^{137}Cs-polluted soils in semi-natural environments can act as a potential source for long-term contamination of the above standing vegetation because they have low K availability.

Website: http://pubs.acs.org/journals/esthag

(20) Meagher, RB. 2000. Phytoremediation of toxic elemental and organic pollutants. *Current Opinion in Plant Biology* 3: 153-162. *

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Phyto.	**Media:** Soil	

Abstract: Phytoremediation is the use of plants to extract, sequester, and/or detoxify pollutants. Phytoremediation is widely viewed as the ecologically responsible alternative to the environmentally destructive physical remediation methods currently practiced. Plants have many endogenous genetic, biochemical, and physiological properties that make them ideal agents for soil and water remediation. Significant progress has been made in recent years in developing native or genetically modified plants for the remediation of environmental contaminants. Because elements are immutable, phytoremediation strategies for radionuclide and heavy metal pollutants focus on hyperaccumulation above-ground. In contrast, organic pollutants can potentially be completely mineralized by plants.

Website: http://www.sciencedirect.com/science/journal/13695266

(21) Negri, MC and RR Hinchman. 2000. The use of plants for the treatment of radionuclides. Pp. 107-132 ***In*** *Phytoremediation of Toxic Metals: Using Plants to Clean Up the Environment.* I Raskin, ed. Wiley-Interscience, John Wiley and Sons, Inc. New York, NY. *

Radionuclides addressed: ★	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu ★	^{99}Tc
U ★	Th	other ^{3}H
Technology: Phyto.	**Media:** Soil, GW, SW	

Abstract: Radioactive contamination has been a problem since the development of nuclear technology in the second half of this century. Causes for radioactive contamination are spills and emissions from all of the operations typical of the nuclear fuel cycle, fallout from nuclear testing, and accidents, like the Chernobyl disaster. The challenges associated with the remediation of soil, groundwater, and wastewater from radionuclides are similar to those associated with the remediation of other inorganic contaminants, with the added radioactive health risk. Also the radioactive decay component may influence, especially for shorter-lived radionuclides, the selection of the most appropriate technology.

A significant amount of literature has been generated since the mid 1960's to describe the chemical behavior in soil and plant uptake of radionuclides of environmental interest. On this basis, phytoremediation has been studied at the bench scale and finally tested in the field at a few sites: for the remediation of uranium-contaminated wastewater and soil at a uranium processing site in Ashtabula, Ohio, and of uranium-contaminated soil from the Fernald site in Ohio. Other field experiments include feasibility studies of the removal of Cesium-137 from soil at Brookhaven National Laboratory, NY, and field trials to remove cesium-137 from soil at Argonne National Laboratory West site, within the Idaho National Engineering and Environmental Laboratory (INEEL). Phytoremediation of both cesium-137 and strontium-90 has been also studied for application at a pond near Chernobyl in Ukraine. Tritiated water is being hydraulically contained by phytoremediation at a field site at Argonne National Laboratory in Illinois.

As in the case of treating heavy metals, phytoremediation has been proven to be most effective and at a more advanced stage of development for treating readily available contaminants and therefore to treat wastewater, surface water and groundwater contamination, including the hydraulic control of tritiated groundwater. Soil-adsorbed radionuclides have been more difficult to treat, and success in soil treatment at this stage depends on the development of specific amendments and treatments that can increase the rate of transfer of the radionuclide into plant-available forms, without further dispersing radionuclides into the environment.

*= Review Article

(22) Victorova, N, O Voitesekhovitch, B Sorochinsky, H Vandenhove, A Konoplev and I Konopleva. 2000. Phytoremediation of Chernobyl contaminated land. *Radiation Protection Dosimetry* 92: 59-64.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: Most of the land within a 10 km radius of the Chernobyl Nuclear Plant is still heavily contaminated by the 1986 accident. In 1998, a 3 year investigation of the potential of willow vegetation systems to stabilise the contaminated land and thereby reduce the dispersion of radionuclides was initiated under the PHYTOR project. During the first year, a number of screening tests were carried out on the contaminated flood plain of the river Pripyat. Survival of new willow plantations was tested at several locations. Except for the predominantly moist peaty soil in the vicinity of Yanov (where survival was nearly 100%), survival was low (0-30%). Notwithstanding, willows are found everywhere on the Pripyat flood plains: 7-8 year old plantations exist on the upper terraces and 1-2 year old saplings cover the newly deposited alluvial sands. For these willows radiocaesium transfer factors ranged from 10^{-4} and 10^{-3} $m^2 kg^{-1}$ and strontium transfer factors from 10^{-3} and 10^{-2} $m^2 kg^{-1}$. Biomass production was low: 70-100 kg ha^{-1} y^{-1}. Therefore, the radionuclide immobilisation in the biomass was insignificant. Even when based on the exchangeable caesium fraction, less then 0.1% for radiocaesium and less than 1% for radiostrontium became incorporated into the wood. Nevertheless, establishment of willow would reduce resuspension and erosion of soil and sediment.
Website: http://rpd.oupjournals.org/cgi/content/abstract/92/1-3/59

(23) White, PJ and MR Broadley. 2000. Mechanisms of casesium uptake by plants. *New Phytologist* 14: 241-256.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: Caesium (Cs) is a Group I alkali metal with chemical properties similar to potassium (K). It is present in solution as the monovalent cation Cs^+. Concentrations of the stable caesium isotope ^{133}Cs in soils occur up to 25 g g^{-1} dry soil. This corresponds to low micromolar Cs^+ concentrations in soil solutions. There is no known role for Cs in plant nutrition, but excessive Cs can be toxic to plants. Studies of the mechanism of Cs^+ uptake are important for understanding the implications arising from releases of radioisotopes of Cs, which are produced in nuclear reactors and thermonuclear explosions. Two radioisotopes of Cs (^{134}Cs and ^{137}Cs) are of environmental concern owing to their relatively long half-lives, emissions of beta and gamma radiation during decay and rapid incorporation into biological systems. The soil concentrations of these radioisotopes are six orders of magnitude lower than those of ^{133}Cs. Early physiological studies demonstrated that K^+ and Cs^+ competed for influx to excised roots, suggesting that the influx of these cations to root cells is mediated by the same molecular mechanism(s). The molecular identity and/or electrophysiological signature of many K^+ transporters expressed in the plasma membrane of root cells have been described. The inward-rectifying K^+ (KIR), outward-rectifying K^+ (KOR) and voltage-insensitive cation (VIC) channels are all permeable to Cs^+ and, by analogy with their bacterial counterparts, it is likely that 'high-affinity' K^+/H^+ symporters (tentatively ascribed here to KUP genes) also transport Cs^+. By modelling cation fluxes through these transporters into a stereotypical root cell, it can be predicted that VIC channels mediate most (30-90 influx under physiological conditions and that the KUP transporters mediate the bulk of the remainder. Cation influx through KIR channels is likely to be blocked by extracellular Cs^+ under typical ionic conditions in the soil. Further simulations suggest that the combined Cs^+ influxes through VIC channels and KUP transporters can produce the characteristic 'dual isotherm' relationship between Cs^+ influx to excised roots and external Cs^+ concentrations below 200 M. Thus, molecular targets for modulating Cs^+ influx to root cells have been identified. This information can be used to direct future genetic modification of plants, allowing them to accumulate more, or less, Cs and thereby to remediate contaminated sites.
Website: http://www.jstor.org/journals/0028646X.html

(24) Zhu, YG and G Shaw. 2000. Soil contamination with radionuclides and potential remediation. *Chemosphere* 41: 121-128. *

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: Soils contaminated with radionuclides, particularly ^{137}Cs and ^{90}Sr, pose a long-term radiation hazard to human

*= Review Article

health through exposure via the foodchain and other pathways. Remediation of radionuclide-contaminated soils has become increasingly important. Removal of the contaminated surface soil (often up to 40 cm) or immobilization of radionuclides in soils by applying mineral and chemical amendments are physically difficult and not likely cost-effective in practicality. Reducing plant uptake of radionuclides, especially ^{137}Cs and ^{90}Sr by competitive cations contained in chemical fertilizers has the general advantage in large scale, low-level contamination incidents on arable land, and has been widely practiced in central and Western Europe after the Chernobyl accident. Phytoextraction of radionuclides by specific plant species from contaminated sites has rapidly stimulated interest among industrialists as well as academics, and is considered to be a promising bio-remediation method. This paper examines the existing remediation approaches and discusses phytoextraction of radionuclides from contaminated soils in detail.

Website: http://www.sciencedirect.com/science/journal/00456535

(25) Dushenkov, S, A Mikheev, A Prokhnevsky, M Ruchko and B Sorochinsky. 1999. Phytoremediation of radiocesium-contaminated soil in the vicinity of Chernobyl, Ukraine. *Environmental Science & Technology* 33: 469-475.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: Remediation of soil contaminated with ^{137}Cs remains one of the most challenging tasks after the Chernobyl 1986 accident. The objectives of this research were to (1) identify extractants that may be used to solubilize ^{137}Cs in soil solution, (2) study the effect of soil amendments on ^{137}Cs accumulation by plants, and (3) evaluate the applicability of phytoextraction for environmental restoration of soil contaminated with ^{137}Cs. The availability of ^{137}Cs to the plants in Chernobyl soil was limited, because this radionuclide was tightly bound to exchange sites of soil particles or incorporated into the crystalline structure of primary and secondary minerals. Out of 20 soil amendments tested to increase ^{137}Cs desorption/solubility in the soil, ammonium salts were found to be the most practical soil amendment that can potentially increase ^{137}Cs bioavailability. Among the screened plants, Amaranth cultivars had the highest ^{137}Cs accumulation. Three sequential crops of Indian mustard grown in one vegetation season at the experimental plot resulted in a small decrease of ^{137}Cs specific activity within the top 15 cm of soil. Further improvements are necessary to make phytoremediation technology a feasible option for restoration of ^{137}Cs-contaminated territories.

Website: http://pubs.acs.org/journals/esthag

(26) Entry, JA, LS Watrud and M Reeves. 1999. Accumulation of ^{137}Cs and ^{90}Sr from contaminated soil by three grass species inoculated with mycorrhizal fungi. *Environmental Pollution* 104: 449-457.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: The use of plants to accumulate low level radioactive waste from soil, followed by incineration of plant material to concentrate radionuclides may prove to be a viable and economical method of remediating contaminated areas. We tested the influence of arbuscular mycorrhizae on ^{137}Cs and ^{90}Sr uptake by bahia grass (*Paspalum notatum*), johnson grass (*Sorghum halpense*) and switchgrass (*Panicum virginatum*) for the effectiveness on three different contaminated soil types. Exposure to ^{137}Cs or ^{90}Sr over the course of the experiment did not affect above ground biomass of the three grasses. The above ground biomass of bahia, johnson and switchgrass plants accumulated from 26.3 to 71.7% of the total amount of the ^{137}Cs and from 23.8 to 88.7% of the total amount of the ^{90}Sr added to the soil after three harvests. In each of the three grass species tested, plants inoculated with *Glomus mosseae* or *Glomus intraradices* had greater aboveground plant biomass, higher concentrations of ^{137}Cs or ^{90}Sr in plant tissue, % accumulation of ^{137}Cs or ^{90}Sr from soil and plant bioconcentration ratios at each harvest than those that did not receive mycorrhizal inoculation. Johnson grass had greater aboveground plant biomass, greater accumulation of ^{137}Cs or ^{90}Sr from soil and plant higher bioconcentration ratios with arbuscular mycorrhizal fungi than bahia grass and switchgrass. The greatest accumulation of ^{137}Cs and ^{90}Sr was observed in johnson grass inoculated with G. mosseae. Grasses can grow in wide geographical ranges that include a broad variety of edaphic conditions. The highly efficient removal of these radionuclides by these grass species after inoculation with arbuscular mycorrhizae supports the concept that remediation of radionuclide contaminated soils using mycorrhizal plants may present a viable strategy to remediate and reclaim sites contaminated with radionuclides.

Website: http://www.sciencedirect.com/science/journal/02697491

(27) Garten, CT, Jr. 1999. Modeling the potential role of a forest ecosystem in phytostabilization and phytoextraction of ^{90}Sr at a contaminated watershed. *Journal of Environmental Radioactivity* 43: 305-323.

Radionuclides addressed:	^{137}Cs	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: The behavior of ^{90}Sr at forest sites in the White Oak Creek watershed, near Oak Ridge, Tennessee, was simulated with a simple, site-specific, multicompartment model that linked biomass and element cycling dynamics. The model was used to predict the role of forest cover in mitigating hydrologic losses of ^{90}Sr from contaminated soils (i.e. phytostabilization) under conditions where contaminant transport is governed mainly by shallow subsurface flow. The model was also used to predict the removal of ^{90}Sr from soil (i.e. phytoextraction) through the growth and harvest of short rotation woody crops over a period of 30 years. Simulations with the model indicated that (1) forest preservation on the watershed is a form of phytostabilization because forest cover helps to minimize hydrologic losses of ^{90}Sr and (2) an attempt to significantly reduce amounts of ^{90}Sr in soil through phytoextraction would be unsuccessful. Over a period of 30 years, and under various management strategies, the model predicted that <15% of the ^{90}Sr initially present in soil at a contaminated site was lost through hydrologic transport and <53% was lost by radioactive decay. Phytostabilization may be important in the management of radioactive land when issues like waste minimization and pollution prevention affect the selection of technologies to be used in environmental restoration.
Website: http://www.sciencedirect.com/science/journal/0265931X

(28) Smith, JT and DG Elder. 1999. A comparison of models for characterizing the distribution of radionuclides with depth in soils. *European Journal of Soil Science* 50: 295-307.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: It is common practice to fit mathematical models to radionuclide activity-depth profiles in soils in order to quantify rates of vertical migration through the soil profile. We have fitted six such models to 21 different activity-depth profiles of radiocaesium (^{137}Cs) derived from Chernobyl and determined relations between the models and the values of their parameters. The advection and dispersion parameters obtained using four solutions to the advection-dispersion equation (each based on different initial and boundary conditions or different simplifications) are in good agreement. We further develop a relation between parameter values obtained using the advection-dispersion models and those determined by a simpler exponential function of the form A^{-Bt} where t is the time and A *and* B are parameters to be estimated. One of the advection-dispersion models proved to be significantly better than the others in terms of goodness-of-fit, versatility and ease of use. A simple model, using calculations based on measured characteristics of the activity-depth profile, was shown to accord well with parameters derived from more complex models based on statistical curve fitting. We have also evaluated the 'residence time' or 'compartmental' model approach to characterizing radionuclide activity-depth profiles. We relate such models to a numerical solution of a simple advection equation, and we show that apparent dispersion in compartmental models is an artefact of numerical dispersion, which can be quantified by the Courant condition. For activity profiles that have a significant advection component, using solutions to the advection-dispersion equation, we have observed a strong positive correlation between advection and dispersion in the profile.
Website: http://www.blackwellpublishing.com/journal.asp?ref=1351-0754

(29) Echevarria, G, Vong, PC and JL Morel. 1998. Effect of NO_3^- on the fate of $^{99}TcO_4^-$ in the soil-plant system. *Journal of Environmental Radioactivity* 38: 163-171.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: This work was undertaken to study the effect of NO_3^- fertilization on the uptake of $^{99}TcO_4^-$ by plants. Ryegrass (Lolium perenne) was grown in a growth chamber on a silty loam soil to which were added increasing quantities of ammonium nitrate (21, 50 and 100 mg N kg^{-1}). Soil samples were then amended with $^{99}TcO_4^-$ at a constant level of 29.6 kBq kg^{-1} dry weight. Total initial NO_3^- content was 43.3, 57.8 and 82.8 mg N kg^{-1}, and total NH_4^+ content was 24.7, 39.2 and 64.2 mg N kg^{-1}. Three cuts were made at 4-week inter-

vals, and aerial biomass was analysed for total ^{99}Tc and N. Results showed that total uptake of ^{99}Tc was decreased by increasing mineral N additions at the first cut, as mineral nitrogen was not a limiting factor for plant growth at this stage. Technetium-99 content in plants varied from 64% of the total applied ^{99}Tc with the lowest NO_3^- content to 31% with the highest. However, at the third cut, cumulative ^{99}Tc uptake reached the same level for the three treatments (80–83%) with no further effect of initial N applications, as NO_3^- was depleted in the soil. Therefore, $^{99}TcO_4^-$ was diluted in the pool of soil NO_3^- and was absorbed proportionally to nitrate by rye-grass.

Website: http://www.sciencedirect.com/science/journal/0265931X

(30) Gerzabek, MH, F Strebl and B Temmel. 1998. Plant uptake of radionuclides in lysimeter experiments. *Environmental Pollution* 99: 93-103.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra ★	Pu	^{99}Tc
U	Th	other *^{60}Co*
Technology: Phyto.	**Media:** Soil	

Abstract: The results of seven years lysimeter experiments to determine the uptake of ^{60}Co, ^{137}Cs and ^{226}Ra into agricultural crops (endive, maize, wheat, mustard, sugarbeet, potato, Faba bean, rye grass) are described. The lysimeter consists of twelve monolithic soil profiles (four soil types and three replicates) and is located in Seibersdorf/Austria, a region with a pannonian climate (pronounced differences between hot and semi-arid summers and humid winter conditions, annual mean of precipitation: 517 mm, mean annual temperature: 9.8°C). Besides soil-to-plant transfer factors (TF), fluxes were calculated taking into account biomass production and growth time. Total median values of TF's (dry matter basis) for the three radionuclides decreased from ^{226}Ra (0.068 kg kg^{-1}) to ^{137}Cs (0.043 kg kg^{-1}) and ^{60}Co (0.018 kg kg^{-1}); flux values exhibited the same ranking. The varying physical and chemical properties of the four experimental soils resulted in statistically significant differences in transfer factors or fluxes between the investigated soils for ^{137}Cs and ^{226}Ra, but not for ^{60}Co. Differences in transfer between plant species and plant parts are distinct, with graminaceous species showing, on average, TF values 5.8 and 15 times lower than dicotyledonous species for ^{137}Cs and ^{60}Co, respectively. This pattern was not found for ^{226}Ra. It can be concluded that ^{137}Cs transfer is heavily influenced by soil characteristics, whilst the plant-specific factors are the main source of TF variability for ^{60}Co. The variability of ^{226}Ra transfer originates both from soil properties and plant species behaviour.

Website: http://www.sciencedirect.com/science/journal/02697491

(31) Martínez-Aguirre, A and R Periáñez. 1998. Soil-to-plant transfer of ^{226}Ra in a marsh area: modelling application. *Journal of Environmental Radioactivity* 39: 199-213.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra ★	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: The Odiel River forms an estuarine system which surrounds a large marsh area. A phosphate fertilizer processing complex releases its wastes into the estuary. The presence of ^{226}Ra in soils and plants (Spartina Densiflora) from the marsh has been investigated. Concentrations up to 700 and 15 mBq g^{-1} have been detected in soil and plant samples, respectively. Soil-to-plant concentration ratios have been calculated and some activity ratios have also been investigated. A model which is able to simulate the dispersion of radionuclides in the marsh has been applied. The model includes the exchange of radionuclides between water and the solid phase (suspended matter and bottom sediments) and the transfer of radionuclides to the plants. Model results are, in general, in good agreement with measurements.

Website: http://www.sciencedirect.com/science/journal/0265931X

(32) Hossner, LR, RH Loppert, RJ Newton, and PJ Szaniszlo. 1998. *Literature Review: Phytoaccumulation of Chromium, Uranium, and Plutonium in Plant Systems.* Amarillo National Resource Center for Plutonium, Amarillo, Texas. 53 pp. *

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu ★	^{99}Tc
U ★	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: Phytoremediation is an integrated multidisciplinary approach to the cleanup of contaminated soils, which combines the disciplines of plant physiology, soil chemistry, and soil microbiology. Metal hyperaccumulator plants are attract-

*= Review Article

ing increasing attention because of their potential application in decontamination of metal-polluted soils. Traditional engineering technologies may be too expensive for the remediation of most sites. Removal of metals from these soils using accumulator plants is the goal of phytoremediation. The emphasis of this review has been placed on chromium (Cr), plutonium (Pu), and uranium (U). With the exception of Cr, these metals and their decay products exhibit two problems, specifically, radiation dose hazards and their chemical toxicity. The radiation hazard introduces the need for special precautions in reclamation beyond that associated with non-radioactive metals. The uptake of beneficial metals by plants occurs predominantly by way of channels, pores, and transporters in the root plasma membrane. Plants characteristically exhibit a remarkable capacity to absorb what they need and exclude what they don't need. But most vascular plants absorb toxic and heavy metals through their roots to some extent, though to varying degrees, from negligible to substantial. Sometimes absorption occurs because of the chemical similarity between beneficial and toxic metals. Some plants utilize exclusion mechanisms, where there is a reduced uptake by the roots or a restricted transport of the metal from root to shoot. At the other extreme, hyperaccumulator plants absorb and concentrate metals in both roots and shoots. Some plant species endemic to metalliferous soils accumulate metals in percent concentrations in the leaf dry matter.

Order Number: NTIS/DE98005257, Report Number: ANRCP-1998-3

(33) Hartley, J and V Tokarevsky. 1998. *Proceedings of the Chornobyl Phytoremediation and Biomass Energy Conversion Workshop.* U.S. DOE Assistant Secretary for Nuclear Energy, Washington, DC. 555 pp.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: Many concepts, systems, technical approaches, technologies, ideas, agreements, and disagreements were vigorously discussed during the course of the 2-day workshop. The workshop was successful in generating intensive discussions on the merits of the proposed concept that includes removal of radionuclides by plants and trees (phytoremediation) to clean up soil in the Chornobyl Exclusion Zone (CEZ), use of the resultant biomass (plants and trees) to generate electrical power, and incorporation of ash in concrete casks to be used as storage containers in a licensed repository for low-level waste. Twelve years after the Chornobyl Nuclear Power Plant (ChNPP) Unit 4 accident, which occurred on April 26, 1986, the primary radioactive contamination of concern is from radioactive cesium (^{137}Cs) and strontium (^{90}Sr). The ^{137}Cs and ^{90}Sr were widely distributed throughout the CEZ. The attendees from Ukraine, Russia, Belarus, Denmark and the US provided information, discussed and debated the following issues considerably: distribution and characteristics of radionuclides in CEZ; efficacy of using trees and plants to extract radioactive cesium (Cs) and strontium (Sr) from contaminated soil; selection of energy conversion systems and technologies; necessary infrastructure for biomass harvesting, handling, transportation, and energy conversion; radioactive ash and emission management; occupational health and safety concerns for the personnel involved in this work; and economics. The attendees concluded that the overall concept has technical and possibly economic merits. However, many issues (technical, economic, risk) remain to be resolved before a viable commercial-scale implementation could take place.

Order number: NTIS/DE98057942, Report Number: PNNL-SA-29991

(34) Huang, JW, MJ Blaylock, Y Kapulnik and BD Ensley. Phytoremediation of uranium-contaminated soils: role of organic acids in triggering uranium hyperaccumulation in plants. *Environmental Science & Technology* 32: 2004-2008.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: Uranium phytoextraction, the use of plants to extract U from contaminated soils, is an emerging technology. We report on the development of this technology for the cleanup of U-contaminated soils. In this research, we investigated the effects of various soil amendments on U desorption from soil to soil solution, studied the physiological characteristics of U uptake and accumulation in plants, and developed techniques to trigger U hyperaccumulation in plants. A key to the success of U phytoextraction is to increase soil U availability to plants. We have found that some organic acids can be added to soils to increase U desorption from soil to soil solution and to trigger a rapid U accumulation in plants. Of the organic acids (acetic acid, citric acid, and malic acid) tested, citric acid was the most effective in enhancing U accumulation in plants. Shoot U concentrations of *Brassica juncea* and *Brassica chinensis* grown in a U-contaminated soil (total soil U, 750 mg kg^{-1}) increased from less than 5 mg kg^{-1} to

more than 5000 mg kg^{-1} in citric acid-treated soils. To our knowledge, this is the highest shoot U concentration reported for plants grown on U-contaminated soils. Using this U hyperaccumulation technique, we are now able to increase U accumulation in shoots of selected plant species grown in two U-contaminated soils (total soil U, 280 and 750 mg kg^{-1}) by more than 1000-fold within a few days. Our results suggest that U phytoextraction may provide an environmentally friendly alternative for the cleanup of U-contaminated soils.
Website: http://pubs.acs.org/journals/esthag

(35) Entry, JA, LS Watrud, RS Manasse and NC Vance. 1997. Phytoremediation and reclamation of soils contaminated with radionuclides. Pp. 299-306 ***In*** *Phytoremediation of Soil and Water Contaminants* Kruger, EL, TA Anderson and JR Coats, eds. American Chemical Society, Washington, DC.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Phyto.	**Media:** Soil	

Abstract: No abstract available.
Book Number (ISBN): 0-8412-3503-1:664 (0)

(36) Kochian, L. 1997. *Identification and Validation of Heavy Metal and Radionuclide Hyperaccumulating Terrestrial Plant Species*. U.S. Department of Energy, Washington, DC. 23 pp.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: This laboratory has been involved in a collaborative project focusing on a range of issues related to the phytoremediation of heavy metal-and radionuclide- contaminated soils. While much of the research has been fundamental in nature, involving physiological and molecular characterizations of the mechanisms of hyperaccumulation in plants, the laboratory is also investigating more practical issues related to phytoremediation. A central issue in this latter research has been the identification of amendments capable of increasing the bioavailability and subsequent phytoextraction of radionuclides. The results described here detail these efforts for uranium and Cs-137. A study was also conducted on a Cs-137 contaminated site at Brookhaven National Laboratory (BNL), which allowed application of the laboratory and greenhouse results to a field setting.
Order Number: NTIS/DE98050572, Report Number: DOE/PC/95701-T9

(37) Krouglov, SV, AS Filipas, RM Alexakhin and NP Arkhipov. 1997. Long-term study on the transfer of ^{137}Cs and ^{90}Sr from Chernobyl-contaminated soils to grain crops. *Journal of Environmental Radioactivity* 34: 267-286.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: The level of ^{137}Cs and ^{90}Sr transfer to four grain crops and the change in transfer with time have been studied on two soils contaminated with fragments of nuclear fuel released during the Chernobyl accident. Field experiments were carried out in 1987–1994 inside the heavily contaminated zone around Chernobyl Nuclear Power Plant. Shortly after the deposition, the rate of ^{90}Sr accumulation by crops was comparable with, or even slower, than that of ^{137}Cs, which is in disagreement with the usual findings. In the following years, ^{137}Cs uptake by plants was reduced by a factor in excess of than 50, whereas the soil-to-plant concentration ratio of ^{90}Sr increased within one order of magnitude, and has remained on approximately the same level since 1991. Changes of the ^{90}Sr and ^{137}Cs concentration ratios for grain crops with time have been used to evaluate the rate of radionuclide leaching from fuel particles and the ageing processes.
Website: http://www.sciencedirect.com/science/journal/0265931X

(38) Dushenkov, S, D Vasudev, Y Kapulnik, D Gleba, D Fleisher, KC Ting and B Ensley. 1997. Removal of uranium from water using terrestrial plants. *Environmental Science & Technology* 37: 3468-3474.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Phyto.	**Media:** GW, SW	

Abstract: Uranium (U) contamination of groundwater poses a serious environmental problem in uranium mining areas and in the vicinity of nuclear processing facilities. Preliminary laboratory experiments and treatability studies indicated that the roots of terrestrial plants could be efficiently used to remove U from aqueous streams (rhizofiltration). Certain sunflower plants were found to have a high affinity for U and were selected for treatment of contaminated water. Almost all of the U removed from the water in the laboratory was concentrated in the roots. Bioaccumulation coefficients based on the ratios of U concentrations in the roots vs U concentrations in the aqueous phase reached 30 000. Rhizofiltration technology has been tested in the field with U-contaminated water at concentrations of 21-874 micrograms/L at a former U processing facility in Ashtabula, OH. The pilot-scale rhizofiltration system provided final treatment to the site source water and reduced U concentration to <20 micrograms/L (EPA Water Quality Standard) before discharge to the environment. System performance was subsequently evaluated under different flow rates permitting the development of effectiveness estimates for the approach.
Website: http://pubs.acs.org/journals/esthag

(39) Fesenko, SV, SI Spiridonov, NI Sanzharova and RM Alexakhin. 1997. Dynamics of ^{137}Cs bioavailability in soil-plant system in areas of the Chernobyl Nuclear Power Plant accident zone with a different physico-chemical composition of radioactive fallout. *Journal of Environmental Radioactivity* 34: 287-313.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: A quantitative analysis of the dynamics of ^{137}Cs bioavailability in soils contaminated following the Chernobyl NPP accident, based on a 6-year (1987–1992) observation period, and a dynamic model describing the behaviour of radiocaesium in meadow ecosystems are presented. It has been shown that the type of deposition and soil characteristics are main factors that significantly affect (up to five times) the changes in bioavailability of this radionuclide in the soil-plant system. The presence of particles, distinguished by their resistance in the environment, can result in an irregular decrease of ^{137}Cs uptake by plants. During the first period after fallout, ^{137}Cs uptake by plants is considerably (up to eight times) influenced by radionuclide distribution between the soil and the mat. The rates of decrease of ^{137}Cs uptake by plants can differ by factor of 3–5, being dependent on soil properties. The effect of these factors depends on the time lapsed after the deposition.
Website: http://www.sciencedirect.com/science/journal/0265931X

(40) Entry, J.A., N.C. Vance, and L.S. Watrud. 1996. Selection of plants for phytoremediation of soils contaminated with radionuclides. *Abstracts of Papers of the American Chemical Society* 212: AGRO 108.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Phyto.	**Media:** Soil	

Abstract: No abstract available.

(41) Entry, JA, NC Vance, MA Hamilton, DZ Zabowski, LS Watrud and DC Adriano. 1996. Phytoremediation of soil contaminated with low concentrations of radionuclides. *Water, Air, & Soil Pollution* 88: 167-177.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Phyto.	**Media:** Soil	

Abstract: No abstract available.

(42) Cornish, JE, WC Goldberg, RS Levine, and JR Benemann. 1995. Phytoremediation of soils contaminated with toxic elements and radionuclides. Pp. 55-63 ***In*** *Bioremediation of Inorganics*. Hinchee, RE, JL Means and DR Burris, eds. Battelle Press, Columbus, OH.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Phyto.	**Media:** Soil	

Abstract: No abstract available.

(43) Entry, JA and WH Emmingham. 1995. Sequestration of ^{137}Cs and ^{90}Sr from soil by seedlings of Eucalyptus tereticornis. *Canadian Journal of Forest Research* 25: 1044-1047.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: The ability of seedlings of Eucalyptus tereticornis Smith to accumulate ^{137}Cs and ^{90}Sr, characteristic radioisotopes of nuclear fallout, from contaminated growth medium was tested. All seedlings were grown for 3 months in 165 cm^3 of sphagnum peat moss - perlite (1:1 v/v) in a growth chamber before treatment with an isotope. After 1 month of exposure, seedlings had accumulated 31.0% of the ^{137}Cs and 11.3% of the ^{90}Sr originally present in the growth medium, with bioconcentration ratios of 54:1 for ^{137}Cs and 13:1 for ^{90}Sr. Accumulation of ^{137}Cs and ^{90}Sr in plant tissue was correlated curvilinearly with increasing time of exposure and with increasing concentration of radioisotope in the growth medium. Because seedlings of E. tereticornis accumulate these radioisotopes rapidly, they may be valuable in remediation of contaminated soils.
Website: http://www.nrc.ca/cgi-bin/cisti/journals/rp/rp2_desc_e?cjfr

(44) Entry, JA, NC Vance, MA Hamilton and D Zabowski. 1994. In-situ remediation of soil contaminated with low concentrations of radionuclides. Pp.1055-1067 ***In*** *In-Situ Remediation: Scientific Basis for Current and Future Technologies*. Gee, GW and NR Wing, eds. Batelle Press, Columbus, Ohio.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Phyto.	**Media:** Soil	

Abstract: No abstract available.
Book Number (ISBN): 0-935470-85-9

(45) Konoplev, AV, NV Viktorova, EP Virchenko, VE Popov, AA Bulgakov and GM Desmet. 1993. Influence of agricultural countermeasures on the ratio of different chemical forms of radionuclides in soil and soil solution. *The Science of the Total Environment* 137: 147-163.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Phyto.	**Media:** Soil	

Abstract: The bioavailability of radionuclides derived from the Chernobyl accident is discussed in terms of their speciation in soils. A scheme representing transformation processes of different chemical forms of these radionuclides in soil and soil solution is proposed. The rate constants of the main transformation processes were obtained experimentally. Various agrochemical countermeasures are evaluated in terms of their influence on the ratio of different radionuclide forms in soil and soil solution. The influence of soil characteristics on the potential effectiveness of countermeasures is discussed. Practically all agrochemical countermeasures currently in use have positive and negative effects. The most effective countermeasures for radiocaesium and radiostrontium were liming of the soil and the application of potassium containing fertilisers at elevated rates.
Website: http://www.sciencedirect.com/science/journal/00489697

Willow and poplar trees removing tritium from the groundwater at Argonne National Laboratory.

Photo: Dr. Victor Ibeanusi

(46) Istok, JD, JM Senko, LR Krumholz, D Watson, LA Bogle, A Peacock, Y-J Chang and DC White. 2004. In situ bioreduction of technetium and uranium in a nitrate-contaminated aquifier. *Environmental Science & Technology* 38: 468-475.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U ★	Th	other
Technology: Biorem.	**Media:** SW	

Abstract: The potential to stimulate an indigenous microbial community to reduce a mixture of U(VI) and Tc(VII) in the presence of high (120 mM) initial NO_3^- co-contamination was evaluated in a shallow unconfined aquifer using a series of single-well, push-pull tests. In the absence of added electron donor, NO_3^-, Tc(VII), and U(VI) reduction was not detectable. However, in the presence of added ethanol, glucose, or acetate to serve as electron donor, rapid NO_3^- utilization was observed. The accumulation of NO_2^-, the absence of detectable NH_4^+ accumulation, and the production of N_2O during in situ acetylene-block experiments suggest that NO_3^- was being consumed via denitrification. Tc(VII) reduction occurred concurrently with NO_3^- reduction, but U(VI) reduction was not observed until two or more donor additions resulted in iron-reducing conditions, as detected by the production of Fe(II). Reoxidation/remobilization of U(IV) was also observed in tests conducted with high (apprx120 mM) but not low (apprx1 mM) initial NO_3^- concentrations and not during acetylene-block experiments conducted with high initial NO_3^-. These results suggest that NO_3—dependent microbial U(IV) oxidation may inhibit or reverse U(VI) reduction and decrease the stability of U(IV) in this environment. Changes in viable biomass, community composition, metabolic status, and respiratory state of organisms harvested from down-well microbial samplers deployed during these tests were consistent with the conclusions that electron donor additions resulted in microbial growth, the creation of anaerobic conditions, and an increase in activity of metal-reducing organisms (e.g., Geobacter). The results demonstrate that it is possible to stimulate the simultaneous bioreduction of U(VI) and Tc(VII) mixtures commonly found with NO_3^- co-contamination at radioactive waste sites.

Website: http://pubs.acs.org/journals/esthag

(47) Bolton, H, D Rai, H Kostandarithes, D Moore and L Xun. 2003. Biodegradation and speciation of PuEDTA by bacterium BNCI. *Abstracts of the General Meeting of the American Society for Microbiology* 103: Q-311.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu ★	^{99}Tc
U	Th	other ^{60}Co
Technology: Biorem.	**Media:** GW	

Abstract: The contamination of DOE sites by plutonium (Pu) is a long-term problem because of its long half-life and low drinking water limit. The synthetic chelating agent EDTA was co-disposed with radionuclides (e.g., Pu, ^{60}Co) in the subsurface at DOE sites and has enhanced the transport of radionuclides in groundwater as the radionuclide-EDTA complex. Biodegradation of EDTA should decrease Pu mobility. One objective was to determine the biodegradation of EDTA in the presence of PuEDTA complexes. The aqueous system investigated at pH 7 (10^{-4} M EDTA and 10^{-6} M Pu) contained predominantly Pu(OH)2EDTA^{2-}. The EDTA was degraded at a faster rate in the presence of Pu. As the total concentration of both EDTA and PuEDTA decreased (i.e., 10^{-5} M EDTA and 10^{-7} M PuEDTA), the presence of Pu decreased the biodegradation rate of the EDTA. It is currently unclear why the concentration of Pu directly affects the increase/decrease in rate of EDTA biodegradation. The soluble Pu concentration decreased, in agreement with thermodynamic predictions, as the EDTA was biodegraded, indicating that biodegradation of EDTA will decrease Pu mobility when the Pu is initially present as Pu(IV)EDTA. A second objective was to investigate how the presence of a second metal will influence the speciation and biodegradation of Pu(IV)EDTA. Preliminary results indicate that the presence of Fe(III) outcompetes the Pu(IV) for the EDTA complex. This indicates that Pu(IV) will not form stable complexes with EDTA for enhanced transport of Pu in Fe(III) dominated subsurface systems. Results from these studies provide mechanistic understanding and approaches to assist in the bioremediate PuEDTA and other radionuclide-EDTA complexes at DOE sites.

(48) Elias, DA, JM Senko and LR Krumholz. 2003. A procedure for quantitation of total oxidized uranium for bioremediation studies. *Journal of Microbiological Methods* 53: 343-353

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Biorem.	**Media:** Soil, SW	

Abstract: A procedure was developed for the quantitation of complexed U(VI) during studies on U(VI) bioremediation. These studies typically involve conversion of soluble or complexed U(VI) (oxidized) to U(IV) (the reduced form which

is much less soluble). Since U(VI) freely exchanges between material adsorbed to the solid phase and the dissolved phase, uranium bioremediation experiments require a mass balance of U in both its soluble and adsorbed forms as well as in the reduced sediment bound phase. We set out to optimize a procedure for extraction and quantitation of sediment bound U(VI). Various extractant volumes to sediment ratios were tested and it was found that between 1:1 to 8:1 ratios (v/w) there was a steady increase in U(VI) recovered, but no change with further increases in v/w ratio. Various strengths of NaHCO3, Na-EDTA, and Na-citrate were used to evaluate complexed U(VI) recovery, while the efficiency of a single versus repeated extraction steps was compared with synthesized uranyl-phosphate and uranyl-hydroxide. Total recovery with 1 M $NaHCO_3$ was 95.7% and 97.9% from uranyl-phosphate and uranyl-hydroxide, respectively, compared to 80.7% and 89.9% using 450 mM $NaHCO_3$. Performing the procedure once yielded an efficiency of 81.1% and 92.3% for uranyl-phosphate and uranyl-hydroxide, respectively, as compared to three times. All other extractants yielded 7.9-82.0% in both experiments. Biologically reduced U(IV) was treated either alone or mixed with uncontaminated sediment slurries to ensure that the procedure was not interfering with subsequent U(IV) quantitation. While U(VI) was recovered, it represented 0.07% of the total uranium alone or 7.8% when mixed with sediments. Total uranium recovered did not change. The procedure was then used to monitor changes in complexed U(VI) levels during uranium-reduction in pure culture and sediments. There was no appreciable complexed U(VI) concentration in pure culture. In sediments however, once soluble U(VI) levels and reduction rates decreased, complexed U(VI) levels began to decrease while U(IV) levels continued to increase. This indicated that once soluble U(VI) was nearly exhausted, sorbed U(VI) became bioavailable and was reduced microbiologically. Typically, uranium is quantified in two steps, soluble U(VI) and U(IV). However, the present study shows that after successive washings with water to remove soluble U(VI), a significant pool of oxidized uranium remains which may be mistakenly quantified as U(IV). This procedure can be used to quantify this pool, does not interfere with U(IV) quantitation, and has an overall efficiency of 95.8%

Website: http://www.sciencedirect.com/science/journal/01677012

(49) Ibeanusi, VM, D Phinney and M Thompson. 2003. Removal and recovery of metals from a coal pile runoff. *Environmental Monitoring and Assessment* 84: 35-44.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Biorem.	**Media:** SW	

Abstract: The removal and recovery of heavy metals from a coal pile runoff water using a mixture of multiple metal-tolerant bacterial strains of ATCC 55673, and ATCC 55674 and a Pseudomonas sp. was investigated. The analysis of elemental composition of metal precipitates recovered from the bacterial biomass by transmission electron microscopy and energy dispersive X-ray analysis revealed the presence of metals originally present in the wastewater. In addition, analysis of metals in culture supernatant and bacterial biomass by inductively coupled plasma emission spectroscopy (ICP-ES) indicated a removal range of 82-100% and a recovery of 15-58% of metals from the wastewater and bacterial biomass, respectively.
Website: http://www.kluweronline.com/issn/0167-6369/contents

(50) Nevin, KP, KT Finneran and DR Lovley. 2003. Microorganisms associated with uranium bioremediation in a high-salinity subsurface sediment. *Applied and Environmental Microbiology* 69: 3672-3675.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Biorem.	**Media:** GW	

Abstract: Although stimulation of dissimilatory metal reduction to promote the reductive precipitation of uranium has been shown to successfully remove uranium from some aquifer sediments, the organisms in the family Geobacteraceae that have been found to be associated with metal reduction in previous studies are not known to grow at the high salinities found in some uranium-contaminated groundwaters. Studies with a highly saline uranium-contaminated aquifer sediment demonstrated that the addition of acetate could stimulate the removal of U(VI) from the groundwater. This removal was associated with an enrichment in microorganisms most closely related to Pseudomonas and Desulfosporosinus species.
Website: http://aem.asm.org/cgi/content/abstract/69/6/3672

(51) Anderson, RT, HA Vrionis, I Ortiz-Bernad, CT Resch, PE Long, R Dayvault, K Karp, S Marutzky, DR Metzler, A Peacock, DC White, M Lowe and DR Lovley. 2003.

Stimulating the in situ activity of Geobacter species to remove uranium from the groundwater of a uranium-contaminated aquifer. *Applied and Environmental Microbiology* 69: 5884-5891.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Biorem.	**Media:** GW	

Abstract: The potential for removing uranium from contaminated groundwater by stimulating the in situ activity of dissimilatory metal-reducing microorganisms was evaluated in a uranium-contaminated aquifer located in Rifle, Colo. Acetate (1 to 3 mM) was injected into the subsurface over a 3-month period via an injection gallery composed of 20 injection wells, which was installed upgradient from a series of 15 monitoring wells. U(VI) concentrations decreased in as little as 9 days after acetate injection was initiated, and within 50 days uranium had declined below the prescribed treatment level of 0.18 M in some of the monitoring wells. Analysis of 16S ribosomal DNA (rDNA) sequences and phospholipid fatty acid profiles demonstrated that the initial loss of uranium from the groundwater was associated with an enrichment of *Geobacter* species in the treatment zone Fe(II) in the groundwater also increased during this period, suggesting that U(VI) reduction was coincident with Fe(III) reduction. As the acetate injection continued over 50 days there was a loss of sulfate from the groundwater and an accumulation of sulfide and the composition of the microbial community changed. Organisms with 16S rDNA sequences most closely related to those of sulfate reducers became predominant, and *Geobacter* species became a minor component of the community. This apparent switch from Fe(III) reduction to sulfate reduction as the terminal electron accepting process for the oxidation of the injected acetate was associated with an increase in uranium concentration in the groundwater. These results demonstrate that in situ bioremediation of uranium-contaminated groundwater is feasible but suggest that the strategy should be optimized to better maintain long-term activity of *Geobacter* species.

Website: http://aem.asm.org/cgi/content/abstract/69/10/5884

(52) Shelobolina, ES, K O'Neill, KT Finneran, LA Hayes and DR Lovley. 2003. Potential for in situ bioremediation of low-pH, high-nitrate uranium-contaminated groundwater. *Soil and Sediment Contamination* 12: 865-884.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Biorem.	**Media:** GW	

Abstract: The potential for stimulating microbial U(VI) reduction as an in situ bioremediation strategy for uranium-contaminated groundwater was evaluated in uranium-contaminated sediment from the FRC, Oak Ridge, TN. Sediment was at low pH (pH 4) and contained high (55 mM) concentrations of nitrate. The addition of organic electron donors resulted in a slow removal of ca. 20% of the nitrate over 120 days with a concurrent increase in pH. Uranium precipitated during nitrate reduction. This precipitation of U(VI) was not due to its reduction to U(IV) because over 90% of the uranium in the sediments remained as U(VI). Studies in which the pH of the sediments was artificially raised suggested that an increase in pH alone could not account for the precipitation of the U(VI) during nitrate reduction. Metal-reducing bacteria were recovered from the sediments in enrichment cultures, but molecular analysis of the sediment demonstrated that the addition of electron donors did not stimulate the growth of these metal reducers. Thus, although U(VI) was precipitated from the groundwater with the simple addition of electron donors, most of the uranium in the sediments was in the form of U(VI), and thus was not effectively immobilized.

Website: http://www.aehs.com/journals/soilcontamination

(53) van Hullebusch ED, MH Zandvoort and PN Lens. 2003. Metal immobilisation by biofilms: mechanisms and analytical tools. *Reviews in Environmental Science and Biotechnology* 2: 9-33.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Biorem.	**Media:** SW	

Abstract: In biofilm environments, heavy metal and radionuclide pollutants are removed by a variety of mechanisms, including biosorption, precipitation as sulfides or phosphates and microbial reductive precipitation. Even if the elemental composition and localization of the precipitate trapped in the biofilm is well described thanks to spectroscopic and microscopic techniques, this review highlights that little is known about metal immobilisation mechanisms in microbial biofilms, i.e., mass transfer of metals, mechanisms involved in (bio)sorption and precipitation and the influence of physico-chemical micro-environments within the biofilm matrix. The review shows the advantage of using a combination of different techniques to evaluate the fate of metals within micro-

bial biofilms. By combining a variety of techniques (e.g., selective extraction, microscopy, spectroscopy and miniaturised sensors), it is possible to gain high-resolution structural and chemical information of biofilms on a level of the individual cell. This approach will facilitate the characterization of the metal immobilisation sites and the metal sorption and (bio)crystallisation mechanisms in biofilms. The results provided by the combination of these techniques will allow to predict the amount of metal accumulation in biofilms as well as their chemical speciation. This review demonstrates that an interdisciplinary approach is required to study metal fate within the biofilm matrix.
Website: http://www.kluweronline.com/issn/1569-1705/contents

(54) Wang, S, PR Jaffe, G Li, SW Wang and HA Rabitz. 2003. Simulating bioremediation of uranium-contaminated aquifiers; uncertainty assessment of model parameters. *Journal of Contaminant Hydrology* 64: 283-307.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Biorem.	**Media:** GW	

Abstract: Bioremediation of trace metals and radionuclides in groundwater may require the manipulation of redox conditions via the injection of a carbon source. For example, after nitrate has been reduced, soluble U(VI) can be reduced simultaneously with other electron acceptors such as Fe(III) or sulfate to U(IV), which may precipitate as a solid (uraninite). To simulate the numerous biogeochemical processes that will occur during the bioremediation of trace- metal-contaminated aquifers, a time-dependent one-dimensional reactive transport model has been developed. The model consists of a set of coupled mass balance equations, accounting for advection, hydrodynamic dispersion, and a kinetic formulation of the biological or chemical transformations affecting an organic substrate, electron acceptors, corresponding reduced species, and trace metal contaminants of interest, uranium in this study. This set of equations is solved numerically, using a finite difference approximation. The redox conditions of the domain are characterized by estimating the pE, based on the concentration of the dominant terminal electron acceptor and its corresponding reduced species. This pE and the concentrations of relevant species are then used by a modified version of MINTEQA2, which calculates the speciation/sorption and precipitation/dissolution of the species of interest under equilibrium conditions. Kinetics of precipitation/dissolution processes are described as being proportional to the difference between the actual and calculated equilibrium concentration. A global uncertainty assessment, determined by Random Sam pling High Dimensional Model Representation (RS-HDMR), was performed to attain a phenomenological understanding of the origins of output variability and to suggest input parameter refinements as well as to provide guidance for field experiments to improve the quality of the model predictions. By decomposing the model output variance into its different input contributions, RS-HDMR can identify the model inputs with the most influence on various model outputs, as well as their behavior pattern on the model output. Simulations are performed to illustrate the effect of biostimulation on the fate of uranium in a saturated aquifer, and to identify the key processes that need to be characterized with the highest accuracy prior to designing a uranium bioremediation scheme.
Website: http://www.sciencedirect.com/science/journal/01697722

(55) Weber KA, SM O'Connor and JD Coates. 2003. Radionuclide immobilization by the formation of crystalline Fe compounds resulting from the bio-oxidation of Fe(II) by Dechlorosoma suillum. *Abstracts of the General Meeting of the American Society for Microbiology* 103: Q-395.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Biorem.	**Media:** Soil, SW	

Abstract: Previous studies examining microbial attenuation of heavy metals and radionuclide (HMR) contamination have demonstrated the potential of nitrate-dependent Fe(II) oxidation for immobilization of HMR in sedimentary environments. Further investigation of the biogenic iron mineral phases produced by Dechlorosoma suillum strain PS in the presence of 100muM U(VI) were analyzed by density gradient centrifugation which resulted in the recovery of five distinct fractions. Differential solubility analysis of 0.5M HCl-extractable Fe and 3M HCl-extractable Fe of each of these fractions indicated a positive correlation between fraction density and crystallinity. Percent of 0.5M HCl-extractable Fe decreased from 100% to 3% with an increase in sucrose concentration (20 to 60%) indicating separation of crystalline Fe ecreased from 100% to 3% with an increase in sucrose concentration (20 to 60%) indicating separation of crystalline Fe compounds. Analysis of total iron content in each fraction revealed that most of the iron (>86%) was present in the more dense crystalline phases. The ratio of 3M HCl- extractable Fe(II) to total Fe (0.68) was also highest in this fraction of which only 1% of the Fe(II) was extractable in 0.5M HCl suggesting crystalline mixed Fe(II)/Fe(III) phases. Analysis of the U(VI) content revealed that the majority (apprx80%) of the U(VI) was also associated with the most dense crystalline phase (3% 0.5M HCl-extractable Fe). These results demonstrate that biogenic crystalline Fe compounds can seques

ter significant proportions of HMR (U(VI)). The formation of a mixed phase crystalline Fe compound sequestering a significant proportion of U(VI) is an ideal remediation strategy as this compound associated with the U(VI) would not be easily re-mobilized by microbial reductive dissolution of Fe.

(56) Francis, AJ. 2002. Microbial transformations of uranium and environmental restoration through bioremediation. Pp. 137-138 ***In*** *Proceedings of the International Workshop 'Uranium Deposits: From Their Genesis to Their Environmental Aspects.'* Kribek, B and J Zeman, eds. Czech Geological Survey, Prague.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Biorem.	**Media:** Soil, GW, SW	

Abstract: Microorganisms present in the natural environment play a significant role in the mobilization and immobilization of uranium. Fundamental understanding of the mechanisms of microbiological transformations of various chemical forms of uranium present in wastes and contaminated soils and water has led to the development of novel bioremediation processes. One process uses anaerobic bacteria to stabilize the radionuclides and toxic metals from the waste, with a concurrent reduction in volume due to the dissolution and removal of nontoxic elements from the waste matrix. In another process, uranium and other toxic metals are removed from contaminated soils and wastes by extracting with the chelating agent citric acid. Uranium is recovered from the citric acid extract after biodegradation/photodegradation in a concentrated form as $UO_3 \bullet 2H_2O$ for recycling or appropriate disposal.

(57) Gadd, GM. 2002. Microbial interactions with metals/radionuclides: the basis of bioremediation. Pp.179-203 ***In*** *Radioactivity in the Environment*. Keith-Roach, MJ and FR Livens, eds. Elsevier Science Ltd., Oxford, UK.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Biorem.	**Media:** Soil, GW, SW	

Abstract: This paper discusses certain microbiological processes which are of significance in determining radionuclide/metal mobility and which have actual or potential applications in bioremediation of metal/radionuclide and metalloid pollution. These include autotrophic and heterotrophic leaching, biosorption (by cell walls and associated components and by free and immobilized biomass), metal reduction and precipitation, metal-binding proteins, polysaccharides and other biomolecules, and metalloid transformation.

(58) Haveman, SA and K Pedersen. 2002. Microbially mediated redox processes in natural analogues for radioactive waste. *Journal of Contaminant Hydrology* 55: 161-174.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Biorem.	**Media:** GW	

Abstract: Natural analogues allow scientists to investigate biogeochemical processes relevant to radioactive waste disposal that occur on time scales longer than those that may be studied by time-limited laboratory experiments. The Palmottu U-Th deposit in Finland and the Bangombe natural nuclear reactor in Gabon involve the study of natural uranium, and are both considered natural analogues for subsurface radioactive waste disposal. The microbial population naturally present in groundwater may affect the redox conditions, and hence, the radionuclide solubility and migration. Therefore, groundwater samples from the two sites were investigated for microbial populations. The total numbers of cells ranged from 10^4 to 10^6 cells ml^{-1}. Iron-reducing bacteria (IRB) were the largest culturable microbial population in the Palmottu groundwater and were present at up to 1.3×10^5 cells ml^{-1}. Sulfate-reducing bacteria (SRB) and acetogens could also be cultured from the Palmottu groundwater. The numbers of IRB and SRB were largest in groundwater with the lowest uranium concentrations. Removal of dissolved U(VI) from solution was concomitant with the growth of IRB enrichment cultures and the reduction of iron. The redox buffer in the Palmottu groundwater consists of iron and uranium species, both of which are affected by IRB. IRB and aerobic heterotrophs were cultured from the Bangombe groundwater, where redox potentials are buffered by iron and organic carbon species. Microbial populations similar to those found at Palmottu and Bangombe are found throughout the Fennoscandian Shield, a potential host rock for subsurface radioactive waste disposal. These results confirm that microorganisms can be expected to play a role in stabilizing radioactive waste disposed of in the subsurface by lowering redox potential and immobilizing radionuclides.

Website: http://www.sciencedirect.com/science/journal/01697722

(59) Yohey, S, SD Kelley, KM Kemner and JF Banfield. 2002. Radionuclide contamination: nanometre-size products of uranium bioreduction. *Nature* 419: 134.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Biorem.	**Media:** Soil, SW	

Abstract: One strategy that is being pursued to tackle the international problem of actinide contamination of soils, sediments and water is to use microbial activity to 'fix' these radionuclides into an insoluble form that cannot be readily dispersed. Here we show that uraninite (UO_2) particles formed from uranium in sediments by bacterial reduction are typically less than 2 nanometres across and that the small size has important implications for uraninite reactivity and fate. Because these tiny particles may still be transported in an aqueous environment, precipitation of uranium as insoluble uraninite cannot be presumed to immobilize it.
Website: http://www.nature.com/nature

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Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U ★	Th	other *General*
Technology: Biorem.	**Media:** Soil, GW, SW	

Abstract: Recent demonstrations of the removal and immobilization of inorganic contaminants by microbial transformations, sorption and mineralization show the potential of both natural and engineered microbes as bioremedial tools. Demonstrations of microbe-mediated mineral formation in biofilms implicate this mode of microbial life in geological evolution and remediation of inorganic contaminants.
Website: http://www.sciencedirect.com/science/journal/13695274

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Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra ★	Pu	^{99}Tc
U ★	Th ★	other
Technology: Biorem.	**Media:** Soil	

Abstract: Some agricultural lands located in the Vromos Bay area, near the Black Sea coast, Southeastern Bulgaria, have been contaminated with radioactive elements (uranium, radium and thorium) and toxic heavy metals (copper, cadmium and lead) as a result of mining and mineral processing of polymetallic ores. Laboratory experiments carried out with soil samples from these lands revealed that an efficient remediation of the soils was achieved by an in situ treatment method based on the activity of the indigenous soil microflora. The treatment was connected with the dissolution of the contaminants in the upper soil horizons and their transfer into the deeply located soil horizons (mainly to the horizon B_2) where they were immobilized as different insoluble compounds. The dissolution of contaminants was connected with the activity of both heterotrophic and chemolithotrophic aerobic microorganisms and the immobilization was due mainly to the anaerobic sulphate-reducing bacteria. The activity of these microorganisms was enhanced by suitable changes in the levels of some essential environmental factors such as water, oxygen and nutrient contents in the soil. On the basis of the above-mentioned laboratory results, the method was then applied under real field conditions in a heavily contaminated experimental plot of land located in the Vromos Bay area. Within 8 months of treatment, the contents of radioactive elements and toxic heavy metals in the soil were decreased below the relevant permissible levels.
Website: http://www.sciencedirect.com/science/journal/0304386X

(62) Lloyd, JR and DR Lovley. 2001. Microbial detoxification of metals and radionuclides. *Current Opinion in Biotechnology* 12: 248-253. *

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Biorem.	**Media:** Soil, GW, SW	

Abstract: Microorganisms have important roles in the biogeochemical cycling of toxic metals and radionuclides. Recent advances have been made in understanding metal–microbe interactions and new applications of these processes to the detoxification of metal and radionuclide contamination have been developed.
Website: http://www.sciencedirect.com/science/journal/09581669

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Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U ★	Th	other
Technology: Biorem.	**Media:** Soil, GW, SW	

Abstract: Deinococcus radiodurans is an exceptionally radiation-resistant microorganism capable of surviving acute exposures to ionizing radiation doses of 15,000 Gy and previously described as having a strictly aerobic respiratory metabolism. Under strict anaerobic conditions, D. radiodurans R1 reduced Fe(III)-nitrilotriacetic acid coupled to the oxida-

*= Review Article

tion of lactate to CO2 and acetate but was unable to link this process to growth. D. radiodurans reduced the humic acid analog anthraquinone-2,6-disulfonate (AQDS) to its dihydroquinone form, AH2DS, which subsequently transferred electrons to the Fe(III) oxides hydrous ferric oxide and goethite via a previously described electron shuttle mechanism. D. radiodurans reduced the solid-phase Fe(III) oxides in the presence of either 0.1 mM AQDS or leonardite humic acids (2 mg ml^{-1}) but not in their absence. D. radiodurans also reduced U(VI) and Tc(VII) in the presence of AQDS. In contrast, Cr(VI) was directly reduced in anaerobic cultures with lactate although the rate of reduction was higher in the presence of AQDS. The results are the first evidence that D. radiodurans can reduce Fe(III) coupled to the oxidation of lactate or other organic compounds. Also, D. radiodurans, in combination with humic acids or synthetic electron shuttle agents, can reduce U and Tc and thus has potential applications for remediation of metal- and radionuclide-contaminated sites where ionizing radiation or other DNA-damaging agents may restrict the activity of more sensitive organisms.
Website: http://aem.asm.org/cgi/content/abstract/66/5/2006

(64) Lloyd, JR, VA Sole, CVG Van Praagh and DR Lovley. 2000. Direct and Fe(II)-mediated reduction of technetium by Fe(III)-reducing bacteria. *Applied and Environmental Microbiology* 66: 3743-3749.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other
Technology: Biorem.	**Media:** Soil, SW	

Abstract: The dissimilatory Fe(III)-reducing bacterium *Geobacter sulfurreducens* reduced and precipitated Tc(VII) by two mechanisms. Washed cell suspensions coupled the oxidation of hydrogen to enzymatic reduction of Tc(VII) to Tc(IV), leading to the precipitation of TcO_2 at the periphery of the cell. An indirect, Fe(II)-mediated mechanism was also identified. Acetate, although not utilized efficiently as an electron donor for direct cell-mediated reduction of technetium, supported the reduction of Fe(III), and the Fe(II) formed was able to transfer electrons abiotically to Tc(VII). Tc(VII) reduction was comparatively inefficient via this indirect mechanism when soluble Fe(III) citrate was supplied to the cultures but was enhanced in the presence of solid Fe(III) oxide. The rate of Tc(VII) reduction was optimal, however, when Fe(III) oxide reduction was stimulated by the addition of the humic analog and electron shuttle anthaquinone-2,6-disulfonate, leading to the rapid formation of the Fe(II)-bearing mineral magnetite. Under these conditions, Tc(VII) was reduced and precipitated abiotically on the nanocrystals of biogenic magnetite as TcO_2 and was removed from solution to concentra tions below the limit of detection by scintillation counting.

Cultures of Fe(III)-reducing bacteria enriched from radionuclide-contaminated sediment using Fe(III) oxide as an electron acceptor in the presence of 25 μM Tc(VII) contained a single *Geobacter* sp. detected by 16S ribosomal DNA analysis and were also able to reduce and precipitate the radionuclide via biogenic magnetite. Fe(III) reduction was stimulated in aquifer material, resulting in the formation of Fe(II)-containing minerals that were able to reduce and precipitate Tc(VII). These results suggest that Fe(III)-reducing bacteria may play an important role in immobilizing technetium in sediments via direct and indirect mechanisms.
Website: http://aem.asm.org/cgi/content/abstract/66/9/3743

(65) Lloyd, JR, P Yong and LE Macaskie. 2000. Biological reduction and removal of Np(V) by two microorganisms. *Environmental Science & Technology* 34: 1297-1301.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu ★	^{99}Tc
U	Th ★	other *Np*
Technology: Biorem.	**Media:** GW, SW	

Abstract: The majority of the radionuclides generated by the nuclear fuel cycle can be removed during established remediation processes. However among the long-lived, alpha-emitting actinides neptunium(V) is recalcitrant to removal from solution by physicochemical or biotechnological methods. The latter include a biocrystallization process, based on the enzymatic liberation of phosphate as a precipitating ligand by a *Citrobacter* sp., which was previously shown to precipitate tetravalent actinides such as Th(IV) and Pu(IV) as their corresponding phosphates. Np(V) was reduced to a lower valence (probably Np(IV)) by ascorbic acid or biologically, using the reductive capability of *Shewanella putrefaciens*, but reduction alone did not desolubilize Np. However Np(V) was removed by the two organisms, *S. putrefaciens* and *Citrobacter* sp. in concert; bioreduction to Np(IV) by *S. putrefaciens*, together with phosphate liberation by the *Citrobacter* sp., permitted bioprecipitative removal of ^{237}Np as well as its daughter ^{233}protactinium. Tests were made possible by a novel technique permitting actinide separation by paper chromatography followed by quantification of the radioactive species using a phosphorImager. This study has implications for the development of methods to remove Np(V) from solution, by the simple combination of two biotechnological methods, which can succeed where chemical treatments are ineffective.
Website: http://pubs.acs.org/journals/esthag

(66) Macaskie, LE, KM Bonthrone, P Yong and DT Goddard. 2000.Enzymatically mediated bioprecipitation of uranium by Citrobacter sp.: a concerted role for exocellular lipopolysaccharide and associated phosphatase in biomineral formation. *Microbiology* 146: 1855-1867.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Biorem.	**Media:** SW	

Abstract: A *Citrobacter* sp. accumulated uranyl ion (UO_2^{2+}) via precipitation with phosphate ligand liberated by phosphatase activity. The onset and rate of uranyl phosphate deposition were promoted by NH_4^+, forming $NH_4UO_2PO_4$, which has a lower solubility product than $NaUO_2PO_4$. This accel decoupled the rate-limiting chemical crystallization process from the biochemical phosphate ligand generation. This provided a novel approach to monitor the cell-surface-associated changes using atomic-force microscopy in conjunction with transmission electron microscopy and electron-probe X-ray microanalysis, to visualize deposition of uranyl phosphate at the cell surface. Analysis of extracted surface materials by ^{31}P NMR spectroscopy showed phosphorus resonances at chemical shifts of 0.3 and 2.0 p.p.m., consistent with monophosphate groups of the lipid A backbone of the lipopolysaccharide (LPS). Addition of UO_2^{2+} to the extract gave a yellow precipitate which contained uranyl phosphate, while addition of Cd^{2+} gave a chemical shift of both resonances to a single new resonance at 3 p.p.m. Acid-phosphatase-mediated crystal growth exocellularly was suggested by the presence of acid phosphatase, localized by immunogold labelling, on the outer membrane and on material exuded from the cells. Metal deposition is proposed to occur via an initial nucleation with phosphate groups localized within the LPS, shown by other workers to be produced exocellularly in association with phosphatase. The crystals are further consolidated with additional, enzymically generated phosphate in close juxtaposition, giving high loads of LPS-bound uranyl phosphate without loss of activity and distinguishing this from simple biosorption, or periplasmic or cellular metal accumulation mechanisms. Accumulation of 'tethered' metal phosphate within the LPS is suggested to prevent fouling of the cell surface by the accumulated precipitate and localization of phosphatase exocellularly is consistent with its possible functions in homeostatis and metal resistance.

Website: http://mic.sgmjournals.org

(67) Smith, RW, DM Cosgrove, JL Taylor, Y Fujita, FS Colwell, TL McLing. 2000. *Remediation of metal contaminants by microbially mediated calcite precipitation.* Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID

Radionuclides addressed:	^{137}Cs	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Biorem.	**Media:** GW	

Abstract: Radionuclide and metal contaminants such as ^{90}Sr are present beneath U.S. Department of Energy (DOE) lands in both the groundwater (e.g., 100-N area at Hanford, WA) and vadose zone (e.g., Idaho Nuclear Technology and Engineering Center at the Idaho National Engineering and Environmental Laboratory [INEEL]). *In situ* containment and stabilization of these contaminants is a cost-effective treatment strategy. However, implementing *in situ* containment and stabilization approaches requires definition of the mechanisms that control contaminant sequestration. We are investigating the in situ immobilization of radionuclides or contaminant metals (e.g., 90Sr) by their facilitated co-precipitation with calcium carbonate in groundwater and vadose zone systems. Our facilitated approach relies upon the hydrolysis of introduced urea to cause the acceleration of calcium carbonate precipitation (and trace metal co-precipitation) by increasing pH and alkalinity and liberating cations from the aquifer matrix by exchange reactions.

$$H_2NCONH_2 + 3H_2O \rightarrow 2NH_4^+ + HCO_3^- + OH^-$$

$$>\mathbf{X}:_2Ca + 2NH_4^+ \rightarrow 2>\mathbf{X}:NH_4 + Ca^{2+}$$

$$Ca^{2+} + HCO_3^- + OH^- \rightarrow CaCO_3(s) + H_2O$$

where >X: is a cation exchange site on the aquifer matrix. Subsurface urea hydrolysis is catalyzed by the urease enzyme, which is produced in situ by native urea hydrolyzing microorganisms. Because the precipitation process tends to be irreversible and many western aquifers are saturated with respect to calcite, the co-precipitated metals and radionuclides will be effectively removed from the aqueous phase over the long-term. Our ongoing research has shown that a) urea hydrolyzing microorganisms are ubiquitous in the Snake River Plain Aquifer underlying the INEEL) b) urea hydrolysis and calcite precipitation are linked, in laboratory and field settings, and c) Sr^{2+} is incorporated into calcite precipitated by urea hydrolyzers with higher distribution coefficients than in abiotic systems. These experimental results and observations have been embodied in a commercially available geochemical and reactive transport computer code that allows field-scale simulations of the urea hydrolysis-calcite precipitation process. The mixed equilibrium-kinetic model accounts for urea

hydrolysis by ureolytic bacteria and calcite precipitation/dissolution using kinetic expressions. Additionally, possible microbial nitrification and its associated consumption of dissolved oxygen and production of acid are accounted for using a kinetic expression. Cation exchange reactions and metal partitioning into the precipitated calcite are treated as equilibrium processes. Simulation of a hypothetical remediation in the Snake River Plain Aquifer using mM levels of urea shows that almost 1 mmole of calcite is precipitated per mmole of hydrolyzed urea, with most of the precipitated cations being derived from exchange of NH_4^+ with the aquifer matrix. Because of the cation exchange reactions and the near absence of NH_4^+ in the groundwater, the long-term persistence of the precipitated calcite is a function of the applied urea concentration and the total cation exchange capacity of the aquifer matrix. Our simulation results suggest that with appropriate urea introduction strategies calcite precipitation can provide for the long term *in situ* sequestration of radionuclides and metals.

Website: http//www.irna.org

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Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other
Technology: Biorem.	**Media:** GW	

Abstract: To help provide a fundamental basis for use of microbial dissimilatory reduction processes in separating or immobilizing ^{99}Tc in waste or groundwaters, the effects of electron donor and the presence of the bicarbonate ion on the rate and extent of pertechnetate ion [$Tc(VII)O_4^-$] enzymatic reduction by the subsurface metal-reducing bacterium *Shewanella putrefaciens* CN32 were determined, and the forms of aqueous and solid-phase reduction products were evaluated through a combination of high-resolution transmission electron microscopy, X-ray absorption spectroscopy, and thermodynamic calculations. When H_2 served as the electron donor, dissolved Tc(VII) was rapidly reduced to amorphous Tc(IV) hydrous oxide, which was largely associated with the cell in unbuffered 0.85% NaCl and with extracellular particulates (0.2 to 0.001 μm) in bicarbonate buffer. Cell-associated Tc was present principally in the periplasm and outside the outer membrane. The reduction rate was much lower when lactate was the electron donor, with extracellular Tc(IV) hydrous oxide the dominant solid-phase reduction product, but in bicarbonate systems much less Tc(IV) was associated directly with the cell and solid-phase Tc(IV) carbonate may have been present. In the presence of carbonate, soluble (<0.001 μm) electronegative, Tc(IV) carbonate complexes were also formed that exceeded $Tc(VII)O_4$ in electrophoretic mobility. Thermodynamic calculations indicate that the dominant reduced Tc species identified in the experiments would be stable over a range of E_h and pH conditions typical of natural waters. Thus, carbonate complexes may represent an important pathway for Tc transport in anaerobic subsurface environments, where it has generally been assumed that Tc mobility is controlled by low-solubility Tc(IV) hydrous oxide and adsorptive, aqueous Tc(IV) hydrolysis products.

Website: http://aem.asm.org/cgi/content/abstract/66/6/2451

(69) Lloyd, JR, J Ridley, T Khizniak, NN Lyalikova, and LE Macaskie. 1999. Reduction of technetium by Desulfovibrio desulfuricans: biocatalyst characterization and use in flowthrough bioreactor. *Applied Environmental Microbiology* 65: 2691-2696.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other
Technology: Biorem.	**Media:** SW	

Abstract: Resting cells of *Desulfovibrio desulfuricans* coupled the oxidation of a range of electron donors to Tc(VII) reduction. The reduced technetium was precipitated as an insoluble low-valence oxide. The optimum electron donor for the biotransformation was hydrogen, although rapid rates of reduction were also supported when formate or pyruvate was supplied to the cells. Technetium reduction was less efficient when the growth substrates lactate and ethanol were supplied as electron donors, while glycerol, succinate, acetate, and methanol supported negligible reduction. Enzyme activity was stable for several weeks and was insensitive to oxygen. Transmission electron microscopy showed that the radionuclide was precipitated at the periphery of the cell. Cells poisoned with Cu(II), which is selective for periplasmic but not cytoplasmic hydrogenases, were unable to reduce Tc(VII), a result consistent with the involvement of a periplasmic hydrogenase in Tc(VII) reduction. Resting cells, immobilized in a flowthrough membrane bioreactor and supplied with Tc(VII)-supplemented solution, accumulated substantial quantities of the radionuclide when formate was supplied as the electron donor, indicating the potential of this organism as a biocatalyst to treat Tc-contaminated wastewaters.

Website: http://aem.asm.org/cgi/content/abstract/65/6/2691

(70) Lloyd, JR, GH Thomas, JA Finlay, JA Cole and LE Macaskie. 1999. Microbial reduction of technetium by Escherichia coli and Desulfovibrio desulfuricans: enhancement via the use of high-activity strains and effect of process parameters. *Biotechnology and Bioengineering* 66: 122-130.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other
Technology: Biorem.	**Media:** SW	

Abstract: *Escherichia coli* and *Desulfovibrio desulfuricans* reduce Tc(VII) (TcO_4^-) with formate or hydrogen as electron donors. The reaction is catalyzed by the hydrogenase component of the formate hydrogenlyase complex (FHL) of *E. coli* and is associated with a periplasmic hydrogenase activity in *D. desulfuricans*. Tc(VII) reduction in *E. coli* by H_2 and formate was either inhibited or repressed by 10 m*M* nitrate. By contrast, Tc(VII) reduction catalyzed by *D. desulfuricans* was less sensitive to nitrate when formate was the electron donor, and unaffected by 10 m*M* or 100 m*M* nitrate when H_2 was the electron donor. The optimum pH for Tc(VII) reduction by both organisms was 5.5 and the optimum temperature was 40°C and 20°C for *E. coli* and *D. desulfuricans*, respectively. Both strains had an apparent K_m for Tc(VII) of 0.5 m*M*, but Tc(VII) was removed from a solution of 300 n*M* TcO_4^- within 30 h by *D. desulfuricans* at the expense of H_2. The greater bioprocess potential of *D. desulfuricans* was shown also by the K_s for formate (>25 m*M* and 0.5 m*M* for *E. coli* and *D. desulfuricans*, respectively), attributable to the more accessible, periplasmic localization of the enzyme in the latter. The relative rates of Tc(VII) reduction for *E. coli* and *D. desulfuricans* (with H_2) were 12.5 and 800 micromol Tc(VII) reduced/g biomass/h, but the use of an *E. coli HycA* mutant (which upregulates FHL activities by approx. 50%) had a similarly enhancing effect on the rate of Tc reduction. The more rapid reduction of Tc(VII) by *D. desulfuricans* compared with the *E. coli* strains was also shown using cells immobilized in a hollow-fiber reactor, in which the flow residence times sustaining steady-state removal of 80% of the radionuclide were 24.3 h for the wild-type *E. coli*, 4.25 h for the upregulated mutant, and 1.5 h for *D. desulfuricans*.

Website: http://www3.interscience.wiley.com/cgi-bin/jhome/71002188

(71) Macaskie, L. Report on 1st Euroconference on bacterial-metal/radionuclide interactions: basic research and bioremediation. *Environmental Microbiology* 1: 185-186.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Biorem.	**Media:** Soil, GW, SW	

Abstract: No abstract available.

(72) Selenska-Pobell, S and H Nitsche, eds. 1999. *Bacterial-Metal/Radionuclide Interaction*. Euroconference of Forschungszentrum Rossendorf, Dresden, Germany. 114 pp.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other *General*
Technology: Biorem.	**Media:** Soil, GW, SW	

Abstract: This issue contains five sessions about radionuclide-bacteria interactions in the presence of metals like uranium and transuranium elements in sediments.

Order Number: DE99749745, Report Number: FZR-252 , CONF-981226,

(73) Stephen, JR and SJ Macnaughton. 1999. Developments in terrestrial bacterial remediation of metals. *Current Opinion in Biotechnology* 10: 230-233. *

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Biorem.	**Media:** Soil, SW	

Abstract: Recent advances in understanding the role and application of bacteria to the remediation of toxic metal and radionuclide contaminated terrestrial environments have come from several avenues. Novel species capable of mobilization and immobilization of metal ions have been discovered. Remediation of toxicity has been accelerated by nutrient amendment, the use of chelating agents and novel methods for phosphate amendment. Major advances in the use of natural and genetically engineered species for bioprotection and remediation of organic co-contaminants have been reported. Construction of wetland function continues to be developed for containment and decontamination of wastewaters.

Website: http://www.sciencedirect.com/science/journal/09581669

(74) Bahaj, AS, IW Croudace, PAB James, FD Moeschler and PE Warwick. 1998. Continuous radionuclide recovery from wastewater using magnetotactic bacteria. *Journal of Magnetism and Magnetic Materials* 184: 241-244.

*= Review Article

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Biorem.	**Media:** SW	

Abstract: Magnetotactic bacteria (MTB) can be magnetically removed and harvested from samples collected from ponds and streams. This is achieved by placing a permanent magnet at the sediment/water interface of a sample container. The bacteria swim along field lines, accumulating at regions close to the pole of the magnet. This is the basic principle of Orientation Magnetic Separation (OMS), where the applied magnetic field is utilised to orientate the bacteria to swim in a specific direction. This paper describes the use of MTB for bioaccumulation and radionuclide removal from wastewater using an OMS system.

Website: http://www.sciencedirect.com/science/journal/03048853

(75) Francis, AJ. 1998. Bioremediation of uranium contaminated soils and wastes. Pp. 340-346 ***In*** *Uranium mining and hydrogeology II*. Merkel, B and C Helling, eds. Koeln, Freibert, Germany.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other *General*
Technology: Biorem.	**Media:** Soil, SW	

Abstract: Contamination of soils, water, and sediments by radionuclides and toxic metals from uranium mill tailings, nuclear fuel manufacturing and nuclear weapons production is a major concern. Studies of the mechanisms of biotransformation of uranium and toxic metals under various microbial process conditions has resulted in the development of two treatment processes: (i) stabilization of uranium and toxic metals with reduction in waste volume and (ii) removal and recovery of uranium and toxic metals from wastes and contaminated soils. Stabilization of uranium and toxic metals in wastes is accomplished by exploiting the unique metabolic capabilities of the anaerobic bacterium, *Clostridium sp*. The radionuclides and toxic metals are solubilized by the bacteria directly by enzymatic reductive dissolution, or indirectly due to the production of organic acid metabolites. The radionuclides and toxic metals released into solution are immobilized by enzymatic reductive precipitation, biosorption and redistribution with stable mineral phases in the waste. Non-hazardous bulk components of the waste such as Ca, Fe, K, Mg and Na released into solution are removed, thus reducing the waste volume. In the second process uranium and toxic metals are removed from wastes or contaminated soils by extracting with the complexing agent citric acid. The citric-acid extract is subjected to biodegradation to recover the toxic met als, followed by photochemical degradation of the uranium citrate complex which is recalcitrant to biodegradation. The toxic metals and uranium are recovered in separate fractions for recycling or for disposal. The use of combined chemical and microbiological treatment process is more efficient than present methods and should result in considerable savings in clean-up and disposal costs.

Report Number: CONF-980981

(76) Francis, AJ and CJ Dodge. 1998. Remediation of soils and wastes contaminated with uranium and toxic metals. *Environmental Science & Technology* 32: 3993-3998.

Radionuclides addressed:	^{137}Cs	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U ★	Th ★	other
Technology: Biorem.	**Media:** Soil, SW	

Abstract: The presence of radionuclides and toxic metals in soils and wastes due to nuclear related activities is a major environmental concern. To restore the contaminated sites, both the radionuclides and toxic metals must be removed. We have developed a comprehensive method to remediate contaminated soils and wastes with the removal and recovery of uranium and toxic metals. The overall process consists of three steps: extraction, biodegradation, and photodegradation. Radionuclides and toxic metals are removed from contaminated soils and wastes by extracting them with citric acid, a natural multidentate complexing agent. Citric acid forms different types of complexes with the transition metals and actinides that may involve the formation of bidentate, tridentate, binuclear, or polynuclear complex species. Several metal-citrate complexes were readily biodegraded by *Pseudomonas fluorescens*, resulting in the bioprecipitation and recovery of the metals, whereas uranyl citrate, which is recalcitrant to biodegradation, upon exposure to light was photodegraded with the precipitation of uranium as $UO_3 \cdot xH_2O$. For example, uranium was removed from contaminated soils and sludge with >85% efficiency. Biodegradation followed by photodegradation of the citric acid extract resulted in >99% recovery of the extracted uranium. In addition, significant amounts of Al, Ca, Co, Cr, Cu, Mg, Mn, Ni, Pb, Sr, Th, and Zn were also removed during biodegradation of the extract. In this process, the toxic metals and uranium are recovered in separate fractions in concentrated form for recycling or disposal.

Website: http://pubs.acs.org/journals/esthag

(77) Lloyd, JR, H-F Nolting, VA Sole, K Bosecker and LE Macaskie. 1998. Technetium reduction and precipitation by sulfate-reducing bacteria. *Geomicrobiology Journal* 15: 45-58.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other
Technology: Biorem.	**Media:** SW	

Abstract: Resting cells of the sulfate-reducing bacterium Desulfovibrio desulfuricans ATCC 29577 were able to precipitate the radionuclide technetium, supplied as the pertechnetate anion (TcO_4^-), under anaerobic conditions by two discrete mechanisms. Sulfidogenic cultures, supplied with sulfate and lactate as an electron acceptor and donor, respectively, precipitated the radionuclide as an insoluble sulfide. Using electron microscopy in combination with energy-dispersive x-ray analysis (EDAX), the precipitate was shown to be extracellular, and contained S as the major element at a fivefold stoichiometric excess to Tc as quantified by proton-induced x-ray emission analysis (PIXE). With hydrogen supplied as the electron donor, the pertechnetate anion was utilized as an alternative electron acceptor in the absence of sulfate. The radionuclide was removed from solution, but in these cultures the precipitate was cell associated, with Tc as the major element detected by PIXE (Tc:S ratio of 2:1). Reduction of the radionuclide in lieu of sulfate was confirmed using XAS. Hydrogen uptake, coupled to metal reduction, was also monitored manometrically, with 1 mol H_2 used to reduce 1 mol TcO_4^-. The implications of these results on Tc mobility in the environment are discussed, and possible biotechnological uses of sulfate-reducing bacteria in bioremediation programs to treat Tc-contaminated waters are highlighted.
Website: http://www.tandf.co.uk/journals/online/0149-0451.asp

(78) Macaskie, LE and G Basnakova. 1998 Microbially-enhanced chemisorption of heavy metals: A method for the bioremediation of solutions containing long-lived isotopes of neptunium and plutonium. *Environmental Science & Technology* 32: 184-187.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu ★	^{99}Tc
U	Th	other *Np*
Technology: Biorem.	**Media:** SW	

Abstract: Immobilized cells of a Citrobacter sp. removed neptunium and plutonium negligibly from solution using an established technique that used biologically-produced phosphate ligand (Pi) for metal phosphate bioprecipitation. Removal of these transuranic radionuclides was enhanced by prior exposure of the biomass to lanthanum in the presence of organophosphate substrate to form cell-bound $LaPO_4$. Polyacrylamide gel-immobilized cells removed little Np and Pu per se, but preloaded LaPO4 promoted the removal of Np and Pu upon subsequent challenge in a flowthrough column. Approximately 2 g of Np was loaded per 1 mL, column, when the experiments were stopped after 10 mL, with maintenance of approximately 90% removal of the input metal. Transuranic element removal by this technique, generically described as microbially-enhanced chemisorption of heavy metals (MECHM), is via a hybrid of bioaccumulative and chemisorptive mechanisms.
Website: http://pubs.acs.org/journals/esthag

(79) Yong, P and LE Macaskie. 1998. Bioaccumulation of lanthanum, uranium and thorium, and use of a model system to develop a method for the biologically-mediated removal of plutonium from solution. *Journal of Chemical Technology and Biotechnology* 71: 15-26.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu ★	^{99}Tc
U ★	Th ★	other *La*
Technology: Biorem.	**Media:** SW	

Abstract: Removal of La^{3+}, UO_2^{2+}, and Th^{4+} from aqueous solution by a Citrobacter sp. was dependent on phosphatase-mediated phosphate release and the residence time in a plug-flow reactor (PFR) containing polyacrylamide gel-immobilized cells. In a stirred tank reactor (STR) lanthanum phosphate accumulated on the biomass rapidly, in preference to uranium or thorium phosphates. Thorium removal was not affected by the presence of uranium but was promoted in the presence of lanthanum. Analysis of the accumulated polycrystalline material by X-ray powder diffraction (XRD) analysis and proton induced X-ray emission (PIXE) suggested the formation of a mixed crystal of lanthanum and thorium phosphate. La^{3+}, UO_2^{2+}, and Th^{4+} are analogues of the corresponding UO_2^{2+} species of Pu^{3+}, PuO_2^{2+}, and Pu^{4+}. The La/U/Th model system was used to identify some potential problems in the bioremediation of wastes containing plutonium and to develop a method for the biologically-mediated removal of plutonium from solution, in a test solution of 239Pu "spiked" with a ^{241}Pu tracer.
Website: http://www3.interscience.wiley.com/cgi-bin/jhome/2517

(80) Bird, GA and W Schwartz. 1996. Effect of microbes on the uptake of ^{60}Co, ^{85}Sr, ^{95}Tc, ^{131}I and ^{134}Cs by decomposing elm leaves in aquatic microcosms. *Hydrobiologia* 333: 57-62.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *Multiple*
Technology: Biorem.	**Media:** SW	

Abstract: We used decomposition of elm leaf discs as a model system to determine the uptake of ^{60}Co, ^{85}Sr, ^{95}Tc, ^{131}I and ^{134}Cs from freshwater by detritus and the role of microbes in this process. Two treatments were used: a microbially enhanced (ME) treatment and a microbially inhibited (MI) treatment. The ME treatment involved the addition of a microbial inoculum, collected from a beaver pond, and nutrients (5 mg P l^{-1} as K_2HPO_4 and 20 mg N l^{-1} as $((NH_4)_2SO_4)$ to the water to enhance microbial growth. The MI treatment involved sterlizing the leaf discs and water with gamma irradiation (1.7 Gy s^{-1} for 4 h) and the addition of a fungicide (100 mg l^{-1} of nystatin) and bactericide (3.0 mg l^{-1} each of streptomycin and penicillin) to the water. The ^{60}Co, ^{95}Tc, ^{131}I, and ^{134}Cs concentrations of the elm leaf discs were greater ($P<0.05$) in the ME treatment than the MI treatment, whereas the ^{85}Sr concentration was higher in the MI treatment. The increase in the ^{95}Tc, ^{131}I, and ^{134}Cs concentration of leaf discs with time in the ME treatment suggests microbes played an important role in uptake. Uptake of these radionuclides by the leaf discs points to the potential importance of detritus in the accumulation of radionuclides. This could subsequently result in the transfer of radionuclides to higher trophic levels by the detritus-food web.

(81) Gadd, GM. 1996. Influence of microorganisms on the environmental fate of radionuclides. *Endeavor* 20: 150-156.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Biorem.	**Media:** Soil, GW, SW	

Abstract: Microorganisms have a significant influence on the environmental fate of radionuclides in aquatic and terrestrial ecosystems with a multiplicity of physico-chemical and biological mechanisms effecting changes in mobility and speciation. Physico-chemical mechanisms of removal include association with extracellular materials, metabolites and cell walls which are features of living and dead organisms. In living cells, some physico-chemical processes are reversible, influenced by metabolism and changing environmental conditions. Metabolism-dependent mechanisms of radionuclide immobilization include sulphide precipitation, transport and intracellular compartmentation and/or sequestration by proteins and peptides. In addition, chemical reduction to less soluble forms can result in immobilization. Microbial processes involved in radionuclide solubilization include autotrophic and heterotrophic leaching, and complexation by siderophores and other metabolites. Such mechanisms are important compoents of biogeochemical cycles for radionuclides and should be considered in any analyses of environmental radionuclide contamination. In addition, several microorganism-based biotechnologies are receiving interest as potential treatment methods.

Website: http://www.sciencedirect.com/science/journal/01609327

(82) White, C, SC Wilkinson and GM Gadd. 1995. The role of microorganisms in biosorption of toxic metals and radionuclides. *International Biodeterioration & Biodegradation* 35: 17-40.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Biorem.	**Media:** Soil, GW, SW	

Abstract: A multiplicity of physico-chemical and biological mechanisms determine the removal of toxic metals, metalloids and radionuclides from contaminated wastes. Physico-chemical mechanisms of removal, which may be encompassed by the general term "biosorption", include adsorption, ion exchange and entrapment which are features of living and dead biomass as well as derived products. In living cells, biosorption can be directly and indirectly influenced by metabolism. Metabolism-dependent mechanisms of metal removal which occur in living microorganisms include metal precipitation as sulphides, complexation by siderophores and other metabolites, sequestration by metal-binding proteins and peptides, transport and intracellular compartmentation. In addition, transformations of metal species can occur resulting in oxidation, reduction or methylation. For metalloids such as selenium, two main transformation mechanisms are the reduction of oxyanions to elemental forms, and methylation to methylated derivatives which are volatilized. Such mechanisms are important components of natural biogeochemical cycles for metals and metalloids as well as being of potential application for bioremediation.

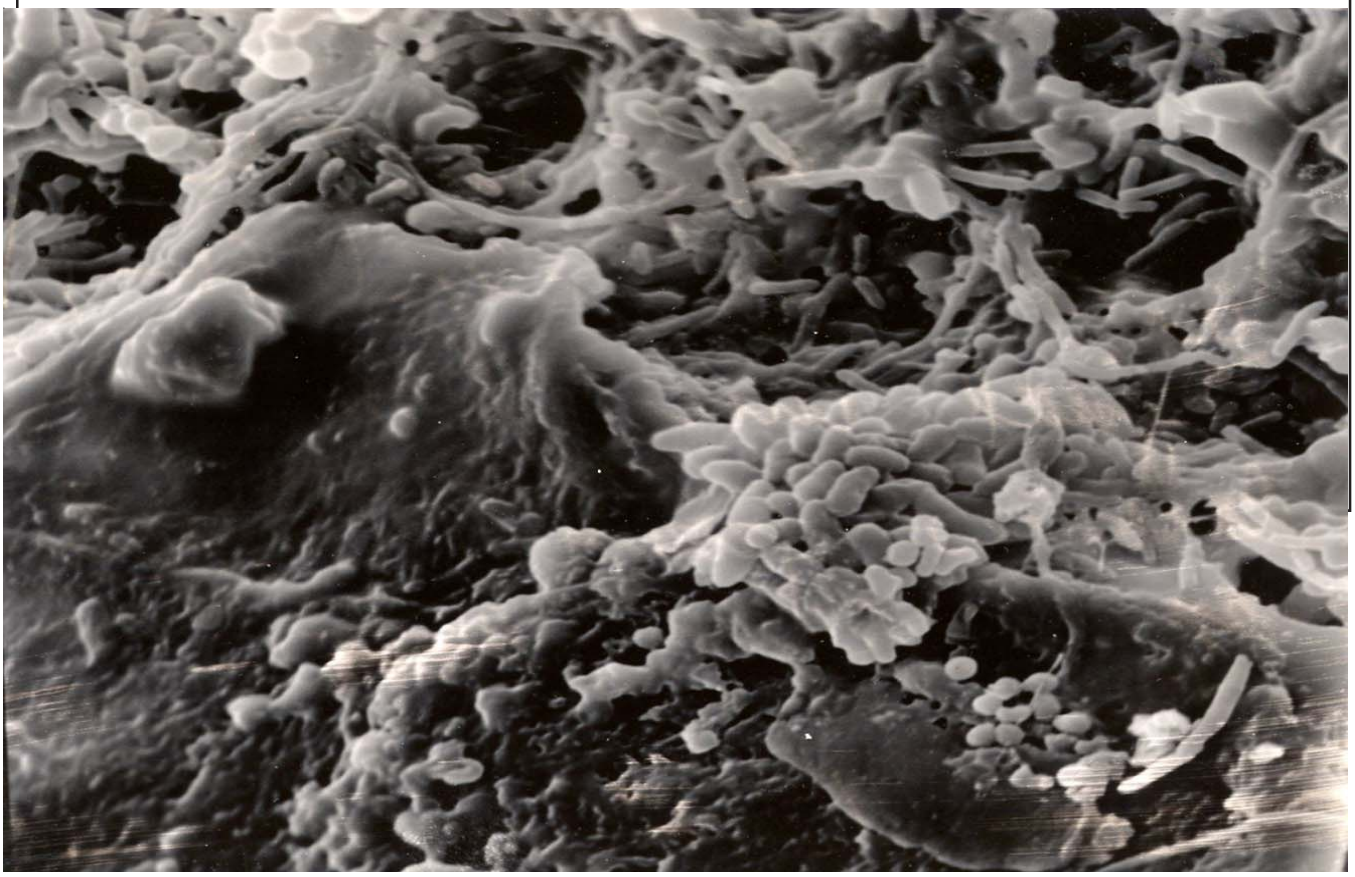
Website: http://www.sciencedirect.com/science/journal/09648305

(83) Rusin, PA, L Quintana, JR Brainard, BA Strietelmeier, CD Tait, SA Ekberg, PD Palmer, TW Newton and DL Clark. 1994. Solubilization of plutonium hydrous oxide by iron-reducing bacteria. *Environmental Science & Technology* 28: 1686-1690.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu ★	^{99}Tc
U	Th	other
Technology: Biorem.	**Media:** Soil	

Abstract: The removal of plutonium from soils is challenging because of its strong sorption to soils and limited solubility. Microbial reduction of metals is known to affect the speciation and solubility of sparingly soluble metals in the environment, notably iron and manganese. The similarity in reduction potential for alpha-FeOOH(s) and hydrous PuO_2(s) suggests that iron-reducing bacteria may also reduce and solubilize plutonium. Bacillus strains were used to demonstrate that iron-reducing bacteria mediate the solubilization of hydrous PuO_2(s) under anaerobic conditions. Up to apprx 90% of the PuO_2 was biosolubilized in the presence of nitrilotriacetic acid (NTA) within 6-7 days. Biosolubilization occurred to a lesser extent (apprx 40%) in the absence of NTA. Little PuO_2 solubilization occurred in sterile culture media or in the presence of a non-iron-reducing Escherichia coli. These observations suggest a potentially attractive, environmentally benign strategy for the remediation of Pu-contaminated soils.

Website: http://pubs.acs.org/journals/esthag



(84) Steiner, M, I Linkov and S Yoshida. 2002. The role of fungi in the transfer and cycling of radionuclides in forest ecosystems. *Journal of Environmental Radioactivity* 58: 217-241. *

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Fungi	**Media:** Soil	

Abstract: Fungi are one of the most important components of forest ecosystems, since they determine to a large extent the fate and transport processes of radionuclides in forests. They play a key role in the mobilization, uptake and translocation of nutrients and are likely to contribute substantially to the long-term retention of radiocesium in organic horizons of forest soil. This paper gives an overview of the role of fungi regarding the transfer and cycling of nutrients and radionuclides, with special emphasis on mycorrhizal symbiosis, Common definitions of transfer factors, soil fungus and soil green plant, including their advantages and limitations, are reviewed. Experimental approaches to quantify the bioavailability of radionuclides in soil and potential long-term change are discussed.
Website: http://www.sciencedirect.com/science/journal/0265931X

(85) Dhami, PS, R Kannan, V Gopalakrishnan, A Ramanujam, S Neeta and SR Udupa. 1998. Sorption of plutonium, americium and fission products from reprocessing effluents using Rhizopus arrhizus. *Biotechnology Letters* 20: 869-872.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu ★	^{99}Tc
U	Th	other *Multiple*
Technology: Fungi	**Media:** SW	

Abstract: Rhizopus arrhizus biomass removed more than 95% of ^{239}Pu, ^{241}Am, ^{95}Zr, ^{144}Ce and $^{152+154}$Eu from different waste streams generated in Purex as well as Truex processes after suitable adjustment of pH.
Website: http://www.kluweronline.com/issn/0141-5492/contents

(86) Gadd, GM, MM Gharieb, LM Ramsay, JA Sayer, AR Whatley and C White. 1998. Fungal processes for bioremediation of toxic metal and radionuclide pollution. *Journal of Chemical Technology and Biotechnology* 71: 364-366. *

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Fungi	**Media:** Soil, SW	

Abstract: No abstract available.
Website: http://www3.interscience.wiley.com/cgi-bin/jhome/2517

(87) Haas, JR, EH Bailey and OW Purvis. 1998. Bioaccumulation of metals by lichens: uptake of aqueous uranium by Peltigera membranacea as a function of time and pH. *American Mineralogist* 83: 1494–1502.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Lichens	**Media:** Soil, SW	

Abstract: Uranium sorption experiments were carried out at approx. 25 degrees C using natural samples of the lichen Peltigera membranacea. Thalli were incubated in solutions containing 100 ppm U for up to 24 h at pH values from 2 to 10. Equilibrium sorption was not observed at less than approx. 6 h under any pH condition. U sorption was strongest in the pH range 4–5, with maximum sorption occurring at a pH of 4.5 and an incubation time of 24 h. Maximum U uptake by *P. membranacea* averaged approx. 42 000 ppm, or approx. 4.2 wt% U. This appears to represent the highest concentration of biosorbed U, relative to solution U activity, of any lichen reported to date. Investigation of post-experimental lichen tissues using electron probe microanalysis (EPM) reveals that U uptake is spatially heterogeneous within the lichen body, and that U attains very high local concentrations on scattered areas of the upper cortex. Energy dispersive spectroscopic (EDS) analysis reveals that strong U uptake correlates with P signal intensity, suggesting involvement of biomass-derived phosphate ligands or surface functional groups in the uptake process.
Website: http://www.minsocam.org/MSA/AmMin/AmMineral.html

* = Review Article

(88) McLean, J, OW Purvis, BJ Williamson and EH Bailey. 1998. Role for lichen melanins in uranium remediation. *Nature* 391: 649-650.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other
Technology: Lichens	**Media:** Soil	

Abstract: Lichens are successful colonizers in extreme terrestrial habitats world-wide, including metalliferous environments. Their ability to accumulate metals has led to their use in monitoring radionuclide fall-out from Chernobyl and uranium uptake from dust resulting from mining. Here we report for the first time a lichen growing directly on uranium minerals and uranium being concentrated within its tissues. Our study suggests that melanin-like pigments, substances previously unreported within lichens, are involved.
Website: http://www.nature.com/nature

(89) Brady, PV and DJ Borns. 1997. *Natural attenuation of metals and radionuclides*. Sandia National Laboratoy, Albuquerque, NM. 250 pp.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Attenuation	**Media:** Soil, GW	

Abstract: Natural attenuation is increasingly applied to remediate contaminated soils and ground waters. Roughly 25% of Superfund groundwater remedies in 1995 involved some type of monitored natural attenuation, compared to almost none five years ago. Remediation by natural attenuation (RNA) requires clear evidence that contaminant levels are decreasing sufficiently over time, a defensible explanation of the attenuation mechanism, long-term monitoring, and a contingency plan at the very least. Although the primary focus of implementation has to date been the biodegradation of organic contaminants, there is a wealth of scientific evidence that natural processes reduce the bioavailability of contaminant metals and radionuclides. Natural attenuation of metals and radionuclides is likely to revolve around sorption, solubility, biologic uptake and dilution controls over contaminant availability. Some of these processes can be applied to actively remediate sites. Others, such as phytoremediation, are likely to be ineffective. RNA of metals and radionuclides is likely to require specialized site characterization to construct contaminant and site-specific conceptual models of contaminant behavior. Ideally, conceptual models should be refined such that contaminant attenuation can be confidently predicted into the future. The technical approach to RNA of metals and radionuclides is explored here.
Order Number: DE98001672/XAB; Report No: SAND-97-2727, CONF-9706209-SUMM

(90) Gray, SN. 1997. Fungi as potential bioremediation agents in soil contaminated with heavy or radioactive metals. *Biochemical Society Transactions* 26: 666-670. *

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other
Technology: Fungi	**Media:** Soil	

Abstract: The origin and impact of heavy metal and radionuclide pollution in soil is discussed and the accumulation of heavy metals and radioactive metals by fungi, particularly the translocation and accumulation of radiocaesium, zinc and cadmium by filamentous fungi are examined and their application to bioremediation is discussed. It is concluded that fungi have a significant potential as bioremediation agents in metal-contaminated soil.

(91) Linkov, I, WR Schell, E Belinkaia and B Morel. 1996. Application of a dynamic model for evaluating radionuclide concentration in fungi. Pp. 752-754 ***In*** *IRPA9: 1996 International Congress on Radiation Protection Proceedings.* Duftschmid, KE, ed. Berger, Horn, Austria.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Fungi	**Media:** Soil	

Abstract: Global fallout from nuclear weapon tests in the 1960s revealed the potential of fungi as an enhanced accumulator of radioactivity. Data derived from Chernobyl fallout sampling has shown fungi to be a major accumulator of radiocaesium and an important food-chain contributor to the human radiation dose. Fungi can significantly affect the ra-

* = Review Article

dionuclide cycling in forests. According to experimental data and estimations, forest microflora, particularly fungi mycelia, could retain up to 40% of radiocaesium. This paper illustrates the application of the dynamic model FORESTPATH to evaluate the contamination dynamics in fungi and the relative importance of fungal species for forest cycling. Only a few studies have been made to model fungi contaminated by radionuclides and these utilize Transfer Factors to describe soil-to-fungi uptake of radionuclides. Such an approach has serious limitations, since equilibrium conditions and specified soil sampling depths must be assumed. The FORESTPATH model uses rate of uptake and residence half-times for radionuclides to describe this process. The model was applied to describe radionuclide dynamics in fungi for the case of chronic deposition and for the accidental release of radionuclides. Experimental measurements of fallout from nuclear weapon tests and from the Chernobyl accident were used to test the FORESTPATH predictions.

(92) Riesen, TK and I Brunner. 1996. Effect of ectomycorrhizae and ammonium on ^{134}Cs and ^{85}Sr uptake into Picea abies seedlings. *Environmental Pollution* 93: 1-8.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *^{134}Cs, ^{85}Sr*
Technology: Fungi	**Media:** Soil	

Abstract: Microorganisms play an important role in the fixation of radionuclides in forest soils. In particular, fungi have the capacity to absorb and translocate radionuclides. The role of the ectomycorrhizal fungus Hebeloma crustuliniformein the uptake of radiocaesium (^{134}Cs) and radiostrontium (^{85}Sr) into seedlings of Norway spruce (Picea abies) was investigated in a pouch test system. Inoculated and non-inoculated seedlings; seedlings inoculated during 8 and 15 weeks; seedlings exposed during 2 and 3 weeks to the radioactive solution; and seedlings grown under low and high ammonium conditions prior to the application of the radionuclides were compared. The final ^{134}Cs and ^{85}Sr activity was determined in fine-roots, main-roots, stems and needles. The results showed that ectomycorrhizae reduced the uptake of ^{134}Cs and ^{85}Sr. The degree of ectomycorrhization was of crucial importance and seemed to be governed by the period during which ectomycorrhizae were allowed to develop and by the ammonium concentration in the nutrient solution. The radionuclide uptake increased with increasing exposure time. Both radionuclides were predominantly accumulated in fine-roots. However, needles proved to describe best the result of net root uptake and translocation to the shoot. The uptake- and translocation-rates of ^{85}Sr were smaller than those of ^{134}Cs. It is assumed that the translocation is coupled with the intensity of water fluxes through the xylem and that ^{85}Sr is more readily adsorbed into mycelium or plant tissue relative to ^{134}Cs. The effect of high ammonium growth conditions was overcome by the effect of ectomycorrhization, except in needles with a very large biomass which behaved as a strong sink and led to a high accumulation of ^{134}Cs.

Website: http://www.sciencedirect.com/science/journal/02697491

(93) Singleton, I and JM Tobin. 1996. Fungal interactions with metals and radionuclides for environmental bioremediation. Pp. 282-298 ***In*** *British Mycological Society Symposium; Fungi and Environmental Change.* Frankland, JC, N Magan and G Gadd, eds. Cambridge University Press, Cambridge, UK.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Fungi	**Media:** Soil	

Abstract: No abstract available.

(94) Wilde, EW, JC Radway, J Santo-Domingo, RG Zingmark and MJ Whitaker. 1996. *Bioremediation of aqueous pollutants using biomass embedded in hydrophilic foam.* Oak Ridge Institute for Science and Education, Tennessee. 261 pp.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other
Technology: Biomass	**Media:** SW	

Abstract: The major objective of this project was to examine the potential of a novel hydrophilic polyurethane foam as an immobilization medium for algal, bacteria, and other types of biomass, and to test the resulting foam/biomass aggregates for their use in cleaning up waters contaminated with heavy metals, radionuclides and toxic organic compounds. Initial investigations focused on the bioremoval of heavy metals from wastewaters at SRS using immobilized algal biomass. This effort met with limited success for reasons which included interference in the binding of biomass and target

metals by various non-target constituents in the wastewater, lack of an appropriate wastewater at SRS for testing, and the unavailability of bioreactor systems capable of optimizing contact of target pollutants with sufficient biomass binding sites. Subsequent studies comparing algal, bacterial, fungal, and higher plant biomass demonstrated that other biomass sources were also ineffective for metal bioremoval under the test conditions. Radionuclide bioremoval using a Tc-99 source provided more promising results than the metal removal studies with the various types of biomass, and indicated that the alga Cyanidium was the best of the tested sources of biomass for this application. However, all of the biomass/foam aggregates tested were substantially inferior to a TEVA resin for removing Tc-99 in comparative testing. The authors also explored the use of hydrophilic polyurethane foam to embed Burkholderia cepacia, which is an efficient degrader of trichloroethylene (TCE), a contaminant of considerable concern at SRS and elsewhere. The embedded population proved to be incapable of growth on nutrient media, but retained respiratory activity. Lastly, the degradative capabilities of embedded G4 were examined. Phenol- or benzene-induced bacteria retained the ability to degrade TCE and benzene. The authors were successful in inducing enzyme activity after the organisms had already been embedded.

(95) Andrews, AM and R Dugan. 1995. *Assessment of Bioremediation Technologies: Focus on Technologies Suitable for Field-Level Demonstrations and Applicable to DOD Contaminants.* Institute for Defense Analyses, Alexandria, VA. 116 pp.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Multiple	**Media:** Soil, SW	

Abstract: Bioremediation is a viable, cost-effective treatment for environmental contaminants. Research activities continue to uncover new bioremediation technologies, increasing the need for field-level demonstrations. The goal of this study is to identify bioremediation technologies that have demonstrated viability in laboratory or pilot studies, but require additional field demonstrations to determine the capabilities and limitations of the technology. In selecting technologies that would be of interest to the DOD, the service-identified research and development priorities for cleanup were considered, and those contaminants amenable to bioremediation were identified. These contaminants included halogenated and non-halogenated hydrocarbons, energetics, and inorganics. Technologies that are promising at either laboratory or pilot scales and are in need of demonstrations for validation under field conditions include bioreactors for the treatment of energetics, in situ anaerobic/aerobic sequential treatment of chlorinated hydrocarbons, constructed wetlands, and white rot fungus. We strongly recommend the first three technologies as candidates for field-level demonstrations; the fourth we recommend less enthusiastically. Beyond our primary recommendations, we make note of two other technologies of interest: microbial mats and systems capable of assessing and monitoring bioremediation activities.

Order Number: NTIS/AD-A301 147/5

(96) Garnham, GW, SV Avery, GA Codd and GM Gadd. 1994. Interactions of microalgae and cyanobacteria with toxic metals and radionuclides. Pp. 289-293 ***In*** *Changes in Fluxes in Estuaries: Implications from Science to Management*. Dyer, KR and RJ Orth, eds. Olsen and Olsen, Fredensborg, Denmark.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other ^{60}Co
Technology: Biomass	**Media:** SW	

Abstract: Accumulation of metals/ radionuclides by microalgae and cyanobacteria may consist of two phases: metabolism-independent binding to cell walls/extracellular polysaccharide (biosorption) followed or accompanied by intracellular uptake which may be energy-dependent. Chlorella salina and Synechocystis PCC 6803 exhibit both uptake mechanisms for cobalt, manganese, zinc and caesium; Chlorella emersonii and Synechocystis PCC 6803 only exhibit a biosorptive phase for technetium. Both phases can be affected by environmental factors, e.g. changes in pH, salinity, nutritional regime and suspended clay minerals. C. salina exhibits multiphasic kinetics for cobalt, manganese and zinc uptake, with a high-affinity mechanism ensuring essential metabolic requirements. Cellular distribution analysis revealed that large amounts of metals/ radionuclides (except Cs^+) are bound to cell walls and to an insoluble intracellular fraction, possibly polyphosphates and/or metal-binding peptides. For Co^{2+}, Mn^{2+}, Zn^{2+}, and Cs^+ the vacuole appeared to play an important role in intracellular compartmentation in microalgae. Accumulation of Cs^+ was via monovalent transport systems for K^+ and/or NH_4^+ and was highly dependent on external Na^+ and K^+ concentrations.

Book Number (ISBN): 87-85215-22-87-85215-22-8

(97) Tobin, JM, C White and GM Gadd. 1994. Metal accumulation by fungi: applications in environmental biotechnology. *Journal of Industrial Microbiology and Biotechnology* 13: 126-130.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Fungi	**Media:** SW	

Abstract: Fungi accumulate metal and radionuclide species by physicochemical and biological mechanisms which include extracellular binding by metabolites and biopolymers, binding to specific polypeptides and metabolism-dependent accumulation. Biosorptive processes have the greatest potential in environmental biotechnology applications. Biosorption consists metabolism-independent accumulation of compounds interactions. The biosorptive capacity of the biomass can be manipulated by a range of physical and chemical treatments with immobilized biomass retaining its biosorptive properties whilst possessing a number of advantages for process applications. Native or immobilized biomass has been used in fixed-bed, airlift, or fluidized bed bioreactors. After biosorption metal/radionuclide species are removed for reclamation and the biomass regenerated by simple chemical treatments.

(98) Gadd, GM and C White. 1992. Removal of thorium from simulated acid process streams by fungal biomass: potential for thorium desorption and reuse of biomass and desorbent. *Journal of Chemical Technology and Biotechnology* 55: 39-44.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th ★	other
Technology: Fungi	**Media:** SW	

Abstract: No abstract available.

(99) Guillitte, O, A Fraiture and J Lambinon. 1990. Soil-fungi radiocesium transfers in forest ecosystems. Pp 468-476 ***In*** *Transfer of Radionuclides in Natural and Semi-natural Environments*. Desmet, G and P Nassimbeni, eds. Elsevier Applied Science, London, UK.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Fungi	**Media:** Soil	

Abstract: The search for soil to fungi radionuclide transfer must take into account macromycetes characteristics and, in particular, the fact that is it impossible to determine in situ the soil part in which the mycelium is located. This study shows that fallout from the Chernobyl nuclear accident made it possible to accurately estimate the depth at which mycelium development occurs and, therefore, to identify factors from the soil layers that are actually colonized by fungi. It is proven that this calculation method of transfer factors provides a more suitable approach to the response of fungal species to radionuclides and greater reliability when interpreting transfers in space and time.

(100) Roemmelt, R, L Hiersche, G Schaller and E Wirth. 1990. Influence of soil fungi (basidiomycetes) on the migration of $^{134+137}$Cs and ^{90}Sr in coniferous forest soils. Pp. 152-160 ***In*** *Transfer of Radionuclides in Natural and Semi-natural Environments*. Desmet, G and P Nassimbeni, eds. Elsevier Applied Science, London, UK.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr ★
^{226}Ra	Pu	^{99}Tc
U	Th	other ^{134}*Cs*
Technology: Fungi	**Media:** Soil	

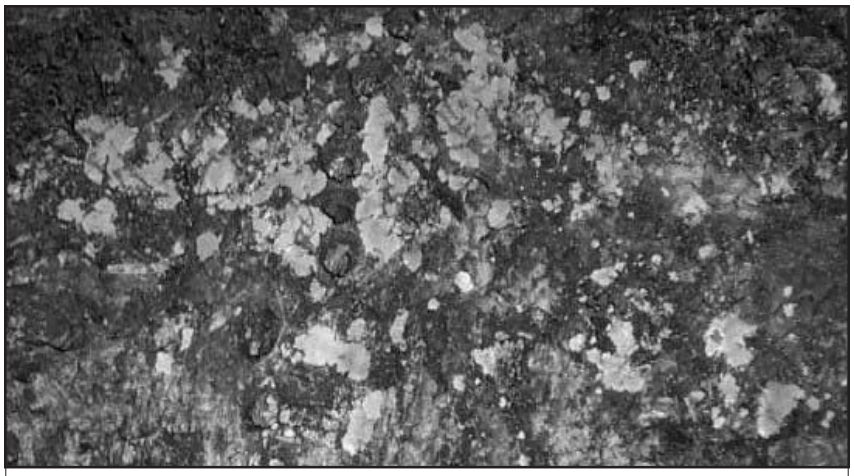
Abstract: During the first three years after the Chernobyl event high $^{134+137}$Cs activities in fruitbodies of basidiomycetes have been measured. A decline of activities with time has not yet been observed. The activities are considerably higher compared to agricultural products from the same area. In order to study the movement of radiocesium in coniferous forest sites, the activities in soil, fungi, and plants have been measured. Based on these results a model to describe the cesium cycling in coniferous forest ecosystems is proposed with special emphasis on the influence of soil fungi and plants on the migration of cesium. As measurements of ^{90}Sr in forest ecosystems are rare this nuclide has been included in the investigations.

(101) White C and GM Gadd. 1990. Biosorption of radionuclides by fungal biomass. *Journal of Chemical Technology and Biotechnology* 49: 331-343

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th ★	other
Technology: Fungi	**Media:** SW	

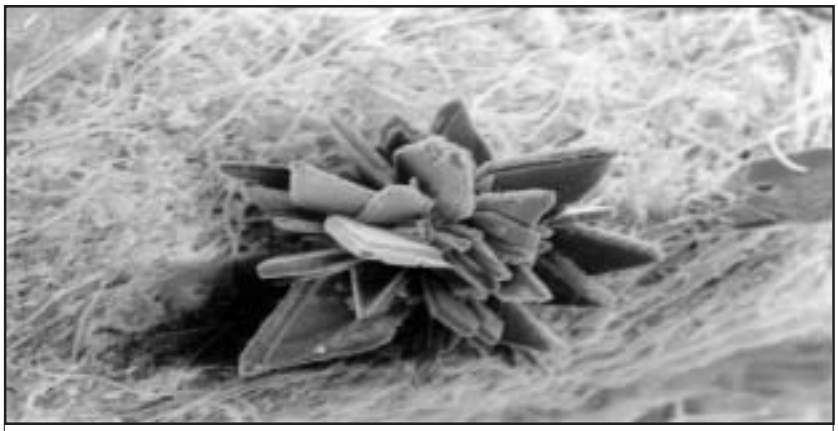
Abstract: Four kinds of bioreactor were evaluated for thorium removal by fungal biomass. Static-bed or stirred-bed bioreactors did not give satisfactory thorium removal probably because of poor mixing. An air-lift bioreactor removed approximately 90-95% of the thorium supplied over extended time periods and exhibited a well-defined breakthrough point after biosorbent saturation. The air-lift bioreactor promoted efficient circulation and effective contact between the thorium solution and the mycelial pellets. Of several fungal species tested, Rhizopus arrhizus and Aspergillus niger were the most effective biosorbents with loading capacities of 0.5 and 0.6 mmol g^{-1} respectively (116 and 138 mg g^{-1}) at an inflow thorium concentration of 3 mmol dm^{-3}. The efficiency of thorium biosorption by A. niger was markedly reduced in the presence of other inorganic solutes while thorium biosorption by R. arrhizus was relatively unaffected. Air-lift bioreactors containing R. arrhizus biomass could effectively remove thorium from acidic solution (1 mol dm^{-3} HNO_3) over a wide range of initial thorium concentrations (0.1-3 mmol dm^{-3}). The biotechnological application and significance of these results are discussed in the wider context of fungal biosorption of radionuclides.

Website: http://www3.interscience.wiley.com/cgi-bin/jhome/2517



Lichen growing on a tree trunk.

Photo: National Oceanic and Atmospheric Administration



A microbial mat remediating contaminants.

Photo: Dr. Victor Ibeanusi

Future Research Opportunities

When there is caution about innovation, it takes a considerable amount of time for emerging technologies to become accepted into the mainstream of activities. This was true for phytotechnology and bioremediation, which were not fully understood two decades ago. However, through research and funding, both technologies have emerged as major alternatives to conventional remediation modalities for environmental cleanups.

As this guide was being prepared, studies that involved the use of shellfish and microbial mats were reviewed and seemed to be potential options for future biotechnology. A few of the abstracts that described these areas are included on pages 60-62. Although the abstracts did not meet the criteria set for this current guide, perhaps, by including them, new opportunities for future research and field tests in these areas may be explored.

(1) Copplestone, D, D Jackson, RG Hartnoll, MS Johnson, P McDonald, and N Wood. 2004. Seasonal variations in activity concentrations of ^{99}Tc and ^{137}Cs in the edible meat fraction of crabs and lobsters from the central Irish Sea. *Journal of Environmental Radioactivity* 73: 29-48.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc ★
U	Th	other
Technology: Shellfish	**Media:** SW	

Abstract: Discharges of most radionuclides into the Irish Sea from the BNFL site at Sellafield have decreased over the past 20 years or so. For a few radionuclides, however, discharges have peaked more recently. Notably, operation of the Enhanced Actinide Removal Plant (EARP) since 1994 has led to an increase in discharges of ^{99}Tc, as a result of the treatment of previously stored waste, with consequent increases in ^{99}Tc activity concentrations in a number of marine species, particularly in crustaceans such as lobsters. Previous research has considered the significance of factors such as sex and body weight on radionuclide concentrations. The current project set out to investigate whether seasonal variations in radionuclide concentrations in crabs and lobsters occur, with particular emphasis on the dynamics of ^{99}Tc and ^{137}Cs. Organisms were obtained from a site off the Isle of Man, where radionuclide concentrations were measurable but the site was sufficiently distant from Sellafield that the radionuclides were well mixed in the water column and not likely to be influenced by the pulsed nature of discharges of ^{99}Tc. Crab and lobster samples were collected monthly, between February 2000 and February 2001. Fifteen or 16 individuals (evenly split as male and female) of each species were collected on each occasion. Seawater samples were also collected over the 12- month period. Activity concentrations of ^{99}Tc in the edible meat fraction (both brown and white meat) ranged from 0.23 to 2.46 Bq kg^{-1} (fresh weight (fw)) in crabs and 124 to 216 Bq kg^{-1} (fw) in lobsters, with no observed seasonal variations. Activity concentrations of ^{137}Cs in both crab and lobster were lower, ranging from <0.16 to 0.85 Bq kg^{-1} for crab meat (fw) and <0.3 to 3.3 Bq kg^{-1} for lobster meat (fw). A statistically significant increase in activity concentrations of ^{137}Cs in the meat was observed in the summer months for both crab and lobster. The cause has not been investigated but may be related to the laying down of energy reserves during the active feeding period over the summer. At all times, uptake of ^{99}Tc is higher in the brown meat fraction of both crabs and lobsters, whilst ^{137}Cs is more uniformly distributed. These results are used to discuss the implications for sampling and monitoring programmes.

Website: http://www.sciencedirect.com/science/journal/0265931X

(2) Bustamante, P, P Germain, G Leclerc and P Miramand. 2002.Concentration and distribution of ^{210}Po in the tissues of the scallop Chlamys varia and the mussel Mytilus edulis from the coasts of Charente-Maritime (France). *Marine Pollution Bulletin* 44: 997-1002.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other ^{210}Po
Technology: Shellfish	**Media:** SW	

Abstract: Polonium-210 (^{210}Po) has been analysed in the soft parts of two bivalves species, the scallop Chlamys varia and the common mussel Mytilus edulis, from the Bay of La Rochelle and Re Island, on the French Atlantic coast. Between those sites, the highest ^{210}Po concentrations have been found in whole scallop soft parts from La Rochelle, reaching 1181 plus or minus 29 Bq kg^{-1} dry weight (dwt), a size effect being related to the highest ^{210}Po concentration in the smallest scallops. The results show a significant difference in concentrations for similar size individuals between species in each site (C. varia > M. edulis) and between sites for each species (Re Island > Bay of La Rochelle). Very high ^{210}Po concentrations have been found in the digestive gland of C. varia, ranging 3150-4637 Bq kg^{-1} dwt. Thus, the digestive gland contains up to 60% of the radionuclide. Subcellular investigations have shown that approximately 40% of the ^{210}Po contained in the digestive gland is in the cytosolic fraction, suggesting a high bioavailability of the ^{210}Po from this fraction to the trophic upper level. Calculations will show that approximately 4 kg of scallops flesh intake would be necessary to reach the annual incorporation limit of 1 mSv.

Website: http://www.sciencedirect.com/science/journal/0025326X

(3) Rapiejko, A, R Rosson, J Lahr, R Garcia and B Kahn. 2001. Radionuclides in Peconic River fish, mussels, and sediments. *Health Physics* 81: 698-703.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U ★	Th	other ^{60}Co, ^{241}Am
Technology: Shellfish	**Media:** SW	

Abstract: For regulatory oversight and quality control of Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) actions, fish, mussels, and sediments

were analyzed from the Peconic River system on Long Island, NY, downstream of the Brookhaven National Laboratory, as well as from control locations. The analyses were for photon-emitting radionuclides (notably ^{60}Co and ^{137}Cs), uranium, plutonium, and americium. Sediments were cored in 4 sections to 0.37 m depth, whole fish were analyzed, and mussels were separated into flesh and shells. Radioisotopes of the cited elements were detected in sediment, some of the fish contained ^{137}Cs, ^{241}Am, and uranium, and mussel flesh contained ^{137}Cs and uranium. All of the ^{60}Co, ^{233}U, and enriched uranium, and some of the ^{137}Cs and ^{241}Am, can most likely be attributed to Brookhaven National Laboratory. The other radionuclides (and some of the ^{137}Cs and ^{241}Am) are believed to have either fallout or nature as their origin. The New York State Department of Health (NYSDOH) evaluated the radiological data in terms of adverse health implications due to consumption of fish with the levels of reported radioactivity. The NYSDOH determined that the added radiation doses likely to result from eating this fish are a small fraction of the radiation dose that normally results from radionuclides present in the body from natural sources.
Website: http://www.health-physics.com

(4) Balint, PJ. 1999. Marine biotechnology: a proposal for regulatory reform. *Politics and the Life Sciences* 18: 25-30.

Radionuclides addressed:	^{137}Cs	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *General*
Technology: Shellfish	**Media:** SW	

Abstract: Biotechnology companies are developing transgenic fish, shellfish, and microorganisms to supplement conventional marine aquaculture and aid in the bioremediation of polluted coastal waters. These products may be ready for open-environment field trials or commercial applications within two to four years. Regulatory authority in the field of marine biotechnology is poorly defined and ill prepared, however, and the science base presently available is not adequate to support credible ecological risk assessment of genetically engineered marine organisms. In response, I offer two specific public policy recommendations: (1) an accelerated program of basic and applied research in marine ecology underwritten by a combination of government and private funds, and (2) the creation of a dedicated unit within the National Marine Fisheries Service responsible for regulatory oversight of transgenic marine organisms. If implemented, these reforms will encourage development in the marine biotechnology industry while laying the groundwork for appropriate ecological risk assessment and management.
Website: http://www.politicsandthelifesciences.org

(5) Hutchins, DA, L Stupakoff, S Hook, SN Luoma and NS Fisher. 1998. Effects of Arctic temperatures on distribution and retention of the nuclear waste radionuclides ^{241}Am, ^{57}Co, and ^{137}Cs in the bioindicator bivalve Macoma balthica. *Marine Environmental Research* 45: 17-28.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *^{57}Co, ^{241}Am*
Technology: Shellfish	**Media:** SW	

Abstract: The disposal of radioactive wastes in Arctic seas has made it important to understand the processes affecting the accumulation of radionuclides in food webs in coldwater ecosystems. We examined the effects of temperature on radionuclide assimilation and retention by the bioindicator bivalve Macoma balthica using three representative nuclear waste components, ^{241}Am, ^{57}Co, and ^{137}Cs. Experiments were designed to determine the kinetics of processes that control uptake from food and water, as well as kinetic constants of loss. ^{137}Cs was not accumulated in soft tissue from water during short exposures, and was rapidly lost from shell with no thermal dependence. No effects of temperature on ^{57}Co assimilation or retention from food were observed. The only substantial effect of polar temperatures was that on the assimilation efficiency of ^{241}Am from food, where 10% was assimilated at 2 degree C and 26% at 12 degree C. For all three radionuclides, body distributions were correlated with source, with most radioactivity obtained from water found in the shell and food in the soft tissues. These results suggest that in general Arctic conditions had relatively small effects on the biological processes which influence the bioaccumulation of radioactive wastes, and bivalve concentration factors may not be appreciably different between polar and temperate waters.
Website: http://www.sciencedirect.com/science/journal/01411136

(6) McDonald, P, MS Baxter and SW Fowler. 1993. Distribution of radionuclides in mussels, winkles and prawns. Part 1. Study of organisms under environmental conditions using conventional radio-analytical techniques. *Journal of Environmental Radioactivity* 18: 181-202.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu ★	^{99}Tc
U	Th	other *Multiple*
Technology: Shellfish	**Media:** SW	

Abstract: Mussels (Mytilus edulis) and winkles (Littorina littorea), collected from Ravenglass, Cumbria, England in the vicinity of the British Nuclear Fuels plc nuclear reprocessing plant at Sellafield, and prawns (Palaemon serratus), landed nearby at Whitehaven, have been investigated to determine the distributions of alpha-emitting (^{210}Po, ^{238}Pu, $^{239+240}$Pu, ^{241}Am) and gamma-emitting (^{95}Nb, ^{95}Zr, ^{103}Ru, ^{106}Ru, ^{137}Cs, ^{241}Am**)** radionuclides in their tissues and organs. Ravenglass mussels exhibited $^{239+240}$Pu concentrations ranging from 43 Bq/kg dry in muscle tissue to 1658 Bq/kg dry in byssal threads, the corresponding ^{137}Cs range being 131-1340 Bq/kg. Although ^{210}Po concentrations were not determined in byssal threads, muscle tissue still displayed the lowest polonium concentration (124 Bq/kg), whilst the viscera (containing digestive gland, stomach and kidneys) contained the highest (596 Bq/kg). Subsequent concentration factor estimates for ^{137}Cs, ^{210}Po and $^{239+240}$Pu in the total soft parts of Ravenglass mussels were, respectively, 9, 25 800 and 1400. In Cumbrian winkles, nuclide concentrations ranged for $^{239+240}$Pu, from 18.5 Bq/kg dry (muscle tissue) to 457 Bq/kg dry (pallial complex); for ^{137}Cs, from 103 (foot tissue) to 1495 Bq/kg (pallial complex) and for ^{210}Po, from 12.2 (muscle tissue) to 145 Bq/kg (digestive gland). Total soft part concentration factors (CFs) were calculated to be 16 for ^{137}Cs, 5500 for ^{210}Po and 5700 for $^{239+240}$Pu.

Website: http://www.sciencedirect.com/science/journal/0265931X

(7) Whitehead, NE, S Ballestra, E Holm and L Huynh-Ngoc. 1988. Chernobyl radionuclides in shellfish. *Journal of Environmental Radioactivity* 7: 107-121. Education, Tennessee. 261 pp.

Radionuclides addressed:	^{137}Cs ★	^{90}Sr
^{226}Ra	Pu	^{99}Tc
U	Th	other *Multiple*
Technology: Shellfish	**Media:** SW	

Abstract: Radionuclides from the Chernobyl accident arrived at Monaco on 30 April, 1986. A sample of Mytilus galloprovincialis collected six days later showed near-maximum levels of most radionuclides. Monitoring continued for seven months thereafter, peak concentrations being transiently as high as 480 Bq kg^{-1} (all soft parts, wet weight) for ^{103}Ru. Other radionuclides detected included ^{132}Te, ^{129m}Te, ^{131}I, ^{106}Ru, ^{134}Cs, ^{137}Cs, ^{110m}Ag, ^{140}Ba, ^{125}Sb, ^{95}Nb and ^{141}Ce. Biological half-lives for elimination in this environment were generally around 10 days or longer and most elimination curves contained a number of components. Radionuclide contents of the mussels were predicted quite accurately from concentrations observed on air filters collected simultaneously, but were not satisfactorily explained relative to total radionuclide concentrations in the seawater even three days after peak air filter activities. The use of concentration factors from the literature did not improve the latter predictions. This suggests that the radionuclides were absorbed very rapidly from the fallout particles, rather than from radionuclides first solubilised from particles. Patella lusitanica specimens contained activities about 20-50 times higher than those in the mussels.

Website: http://www.sciencedirect.com/science/journal/0265931X

Zebra mussels, an invasive species in the US, have potential as future remediation tools.
Photo: United States Geological Survey