
Volume 105 Issue 3 November 2007 ISSN 0013-9351
This Number Completes Volume 105
ELSEVIER
Environmental
Research
A Multidisciplinary Journal of Environmental Sciences, Ecology, and Public Health
Editor-in-Chief: Ellen K. Silbergeld
www.elsevier.com/locate/envres

Available online at www.sciencedirect.com
ScienceDirect
Environmental Research 105 (2007) 316–323
Environmental Research
www.elsevier.com/locate/envres

A model for selecting bioindicators to monitor radionuclide concentrations using Amchitka Island in the Aleutians as a case study

Joanna Burger*

Division of Life Sciences, Environmental and Occupational Health Sciences Institute, and Consortium for Risk Evaluation with Stakeholder Participation, Rutgers University, Piscataway, NJ, USA

Received 1 December 2006; received in revised form 27 March 2007; accepted 3 May 2007
Available online 14 August 2007

Abstract

World War II and the Cold War have left the Unites States, and other Nations, with massive cleanup and remediation tasks for radioactive and other legacy hazardous wastes. While some sites can be cleaned up to acceptable residential risk levels, others will continue to hold hazardous wastes, which must be contained and monitored to protect human health and the environment. While media (soil, sediment, groundwater) monitoring is the usual norm at many radiological waste sites, for some situations (both biological and societal), biomonitoring may provide the necessary information to assure greater peace of mind for local and regional residents, and to protect ecologically valuable buffer lands or waters. In most cases, indicators are selected using scientific expertise and a literature review, but not all selected indicators will seem relevant to stakeholders. In this paper, I provide a model for the inclusion of stakeholders in the development of bioindicators for assessing radionuclide levels of biota in the marine environment around Amchitka Island, in the Aleutian Chain of Alaska. Amchitka was the site of three underground nuclear tests from 1965 to 1971. The process was stakeholder-initiated, stakeholder-driven, and included stakeholders during each phase. Phases included conceptualization, initial selection of biota and radionuclides, refinement of biota and radionuclide target lists, collection of biota, selection of biota and radionuclides for analysis, and selection of biota, tissues, and radionuclides for bioindicators. The process produced site-specific information on biota availability and on radionuclide levels that led to selection of site-appropriate bioindicators. I suggest that the lengthy, iterative, stakeholder-driven process described in this paper results in selection of bioindicators that are accepted by biologists, public health personnel, public-policy makers, resource agencies, regulatory agencies, subsistence hunters/fishers, and a wide range of other stakeholders. The process is applicable to other sites with ecologically important buffer lands or waters, or where contamination issues are contentious.

Keywords: Bioindicator selection; Conceptual model; Environmental; Radionuclides; Amchitka Island; Stakeholder collaboration

1. Introduction

Governmental and non-governmental agencies, Tribal Nations, scientists, conservationists, managers, regulators, and the public are increasingly interested in assessing and monitoring public health and that of species, populations, communities, and ecosystems. This interest has led to the development of assessment tools and biomonitoring plans aimed at determining the overall health of species and ecosystems that both affect human health directly, and are sentinels or indicators of human health. Biota can serve as indicators of potential harm to people living within a system and consuming food from that system (Piotrowski, 1985; Peakall, 1992; DiGuilio and Monosson, 1996; Burger and Gochfeld, 1996, 2001, 2004; Carignan and Villard, 2001; Burger, 2006). Bioindicators and biomarkers need to be developed to fit the specific assessment needs of humans and the environment, within the framework of governmental, Tribal, and public needs. Long-term monitoring programs, and their associated bioindicators, require the interest and support of the general public, as well as governmental acceptance and commitment, since public funds are needed to conduct these programs.

One of the largest biomonitoring tasks facing the Nation is that of assessing and monitoring radiological and other

*Fax: +1 732 445 5870.
E-mail address: burger@biology.rutgers.edu

0013-9351/$ - see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.envres.2007.05.017

hazardous wastes produced by the nuclear weapons complex. The Cold War left the United States, and other Nations, with massive cleanup and remediation tasks for radioactive and other legacy hazardous wastes. The legacy waste complex, administered by the Department of Energy (DOE), has over 100 sites in 34 states (Crowley and Ahearne, 2002). Some of these sites can be cleaned up and returned to other uses, but some have hazardous wastes that will need to be contained in place for centuries, and monitoring tools are required to assure the public of continued safety. Monitoring tools are essential for both contaminated sites, and buffer lands around these sites. While media (soil, sediment, groundwater) monitoring is the usual norm at many radionuclide waste sites, for some situations, where biological resources are critical and recreational or subsistence use is high, biomonitoring may lead to more cost-effective and relevant data, while providing greater peace of mind for local and regional residents (Greenberg et al., 2007). This may be particularly true where local residents distrust the DOE, or feel they have been lied to about these sites (Ahearne, 2001; Thomas, 2001).

This paper provides a conceptual model for developing a biomonitoring plan for radionuclides, using Amchitka Island as a case study. The paper describes a method for developing the plan that is stakeholder-driven and involves stakeholders at every stage. Three underground nuclear tests were detonated on Amchitka Island, and residual wastes will remain in the underground cavities for centuries. It is not feasible to design a groundwater, soil, or sediment monitoring plan because of the depth of the test cavities, and the vast expanse of ocean surrounding Amchitka where there could be radionuclide seepage. It is the biota that are of interest because they form the basis for the Aleut subsistence lifestyle and over 50% of the fish and shellfish consumed in the US comes from the Bering Sea/Northern Pacific Ocean (AFSC, 2003). The NRC (2003) noted that over 40% of all the United States fish and shellfish landings (by weight) derive from the Eastern Bering Sea (including Dutch Harbor). Mito et al. (1999) noted that the total catch of groundfishes on the Eastern Bering Sea shelf and the Aleutian Basin is 2–3 million metric tons per year. Further, although the contamination resides on Amchitka Island itself, it is the potential for off-site movement (in this case into marine waters) that poses the risk. For many DOE sites, and other contaminated places, groundwater, rivers, and other aquatic habitats provide the pathway for possible exposure.

CRESP, a multi-university, multi-discipline Consortium for Risk Evaluation with Stakeholder Participation, was asked to develop an Independent Science Assessment Plan to define and describe the science that would be necessary to assure the public that the subsistence and commercial foods from the marine waters around Amchitka were safe, that the marine environment was not currently impacted, and to provide information that could be used to develop a long-term biomonitoring plan (CRESP, 2003). This paper describes the process of selecting bioindicators for the biomonitoring plan, but other information is described in Burger et al. (2005, 2007a, f) and Burger and Gochfeld (in press) for stakeholder participation, and in Burger et al. (2007b–d) for radionuclide levels. The species selected for bioindicators are described in detail elsewhere (Burger et al., 2007f).

Instead of dealing with the details of radionuclide levels in biota, risk to these organisms or to consumers, and the species selected as bioindicators, this paper focuses on a process of bioindicator selection that can be adapted for other contentious contaminated sites. Most studies of bioindicators present only the species selected as bioindicators, with their justifications, and in rare cases, the contaminant levels used in their selection. While managers, public policy makers and the public can deduce the process, it seems more straightforward to outline a process that can be adapted in other contentious situations.

2. Background on DOE and Amchitka

During and immediately after World War II, the predecessors of US DOE (the Army Corps of Engineers, the Atomic Energy Commission, the Energy Research and Development Administration) obtained many tracts of land for the purpose of developing, producing, and testing nuclear weapons. With the ending of the Cold War, the Nation faced the need to clean up these sites to protect human health and the environment. DOE sites have highly toxic, and long-lived radiological wastes, both in storage facilities and as surface and groundwater contamination (Crowley and Ahearne, 2002). All DOE sites are now subject to regulations of the US Environmental Protection Agency (EPA), Nuclear Regulatory Commission (NRC), appropriate state agencies, and in some cases, Tribal Nations (Bascietto et al., 1990). Amchitka is one of 129 DOE sites requiring long-term stewardship (Wells and Spitz, 2003), and is surely the most remote.

DOE lands have extensive and ecologically valuable resources (Dale and Parr, 1998; Brown, 1998; Burger et al., 2003). The ecological importance of seven of the largest DOE sites was recognized as early as the 1970s through their designation as National Environmental Research Parks (NERPs; DOE, 1994a, b), and much later, by a stewardship program announced in 1994 for the entire complex (DOE order 430.1).

Amchitka Island is a DOE site in the Aleutian chain in the Northern Pacific that was the scene of three underground nuclear tests in 1965 (Milrow), 1969 (Long Shot) and 1971 (Cannikin; Fig. 1). The island was designated a wildlife preserve as early as 1913, but was released for military activity during World War II (Kohlhoff, 2002). Today, it is part of the Alaska Maritime National Wildlife Refuge system under the aegis of the US Fish & Wildlife Service (USFWS). DOE has remediated surface contamination on the island (DOE, 2002), and the Consortium for Risk Evaluation with Stakeholder Participation (CRESP)

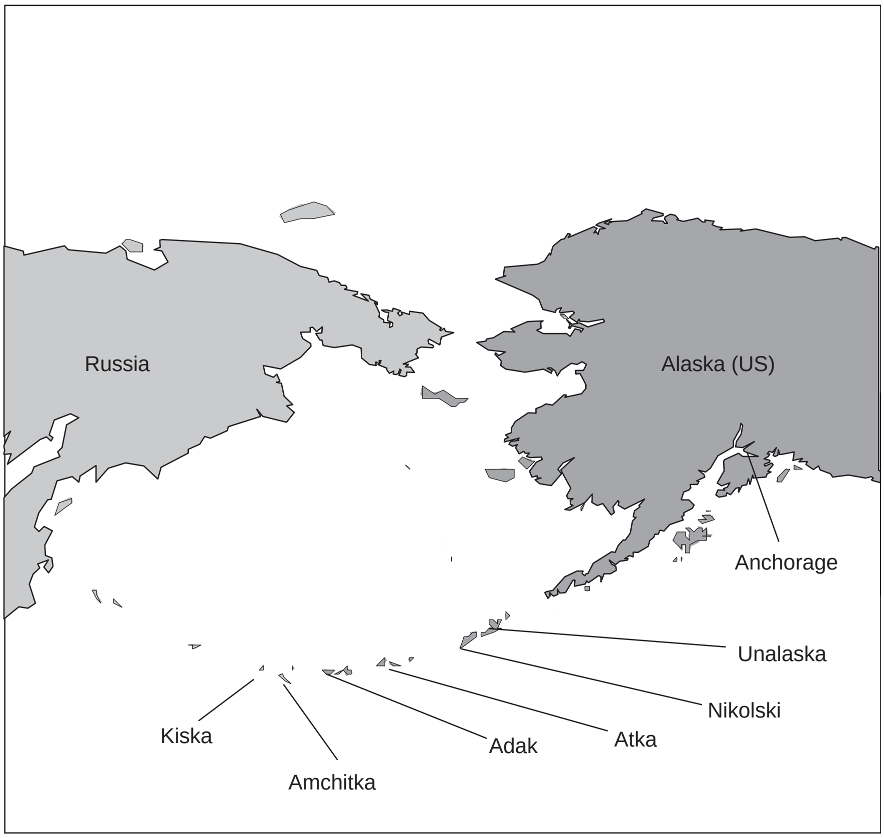

Fig. 1. Map of Amchitka showing the three test shots (Milrow, Long Shot, Cannikin), and the reference site (Kiska Island).

subsequently conducted extensive biological and geophysical evaluations of the radionuclide levels in biota in the marine environment around Amchitka (Powers et al., 2005a, b; Burger et al., 2006). Amchitka has been transferred from DOE's environmental management program, to its Office of Legacy Management (OLM). OLM will retain responsibility for the shot cavities in perpetuity. Legacy waste sites require the approval of a long-term stewardship plan to deal with the radiologic residue that will remain in place in the shot cavities. A long-term stewardship plan requires a monitoring plan that can assure agencies and the public that public health and the environment are protected.

3. Background on the Amchitka independent science assessment

The objective of this paper is to examine the process of selecting bioindicators that involved a full range of stakeholders at several different points (Burger et al., 2005, 2007e). The radionuclide data are presented elsewhere (Burger et al., 2007a–d), and clearly showed that there was no risk to the biota themselves, the food chain, or to humans, from anthropogenic radionuclides. However, the levels found in algae, invertebrates, fish, and birds differed, providing the opportunity to select indicators for future biomonitoring of the marine environment around Amchitka to provide early warning of any potential seepage. There is no potential for remediation since the test cavities are so deep, but early warning could lead to setting exclusion zones around Amchitka to prevent human exposure, although this would not prevent potential harm to marine organisms living there.

In the organisms examined, actinides bioaccumulated in algae and invertebrates, while radiocesium accumulated in higher trophic level birds and fish. Thus, unlike biomonitoring schemes developed for heavy metals or other contaminants, top-level predators were not sufficient to evaluate radionuclide exposure at Amchitka. The process described in this paper resulted in the selection of *Fucus*, *Alaria fistulosa*, blue mussel (*Mytilus trossulus*), dolly varden (*Salvelinus malma*), black rockfish (*Sebastes melanops*), Pacific cod (*Gadus macrocephalus*), Pacific halibut (*Hippoglossus stenolepis*), and glaucous-winged gull (*Larus glaucescens*) as bioindicators (see Burger et al., 2007f). This combination of species included mainly subsistence foods, commercial fishes, and nodes on different food chains.

4. Results: Developing bioindicators

The development of bioindicators was a multiphase, 4-year process that involved two main components: selecting biota and tissues for analysis, and selecting radionuclides for analysis (Fig. 2). Armed with this information, it would then be possible to select bioindicators. The critical first step was developing a

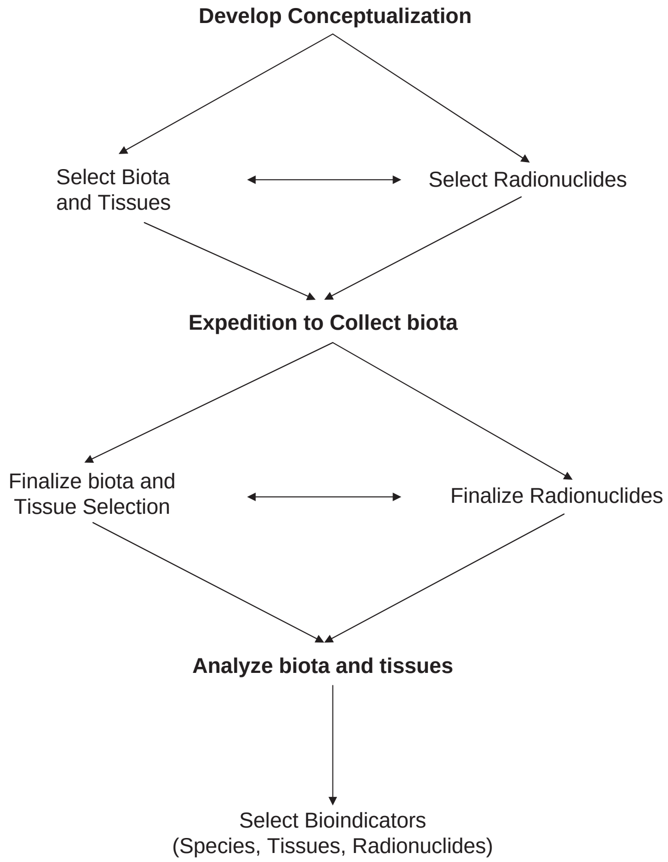

Fig. 2. Schematic showing the relationship between biota species selection and radionuclide selection to derive bioindicators.

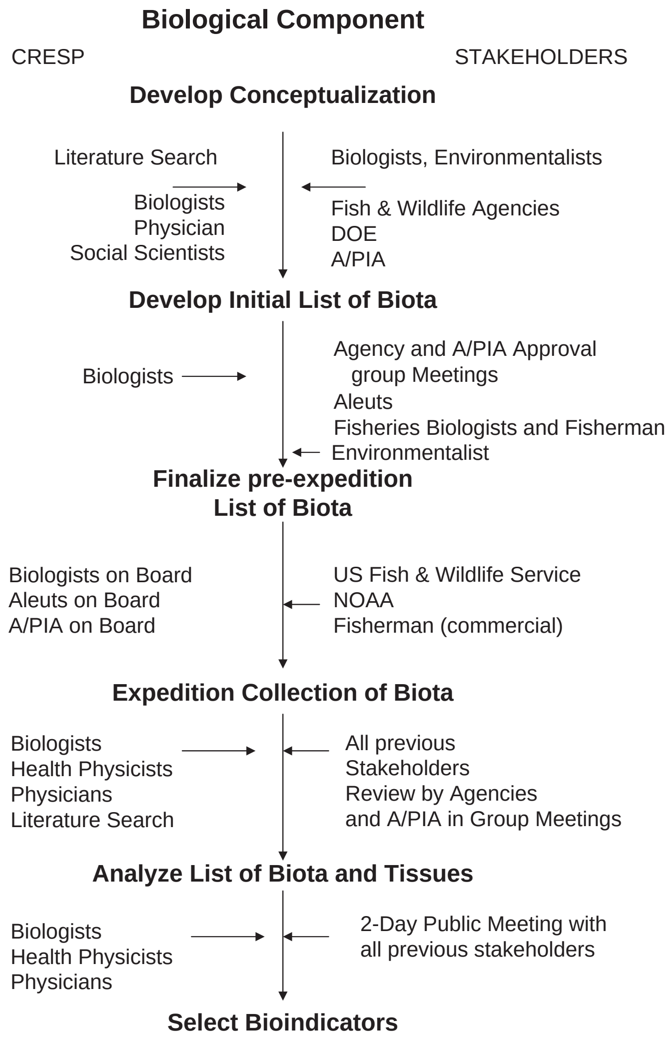

Fig. 3. Schematic showing the biological process of selecting biota for bioindicators. The left indicates the CRESP scientists involved in the process, while the right indicates the involvement of other stakeholders in the decision process.

conceptualization of the key elements for species and radionuclide selection. The approach taken was to determine the major receptors of concern for potential radiation exposure. A public workshop with a range of stakeholders held in Fairbanks in 2002 allowed DOE, the Aleutian/Pribilof Island Association (A/PIA). USFWS, Alaska Department of Environmental Conservation (ADEC), environmental groups, and the public to express their concerns and provide suggestions for the information needed to develop a long-term stewardship plan for Amchitka, including possible indicator species (CRESP, 2002). Throughout the process, A/PIA represented the interests of the Aleuts, NOAA, commercial fishermen, and processing plant managers provided information on fish and shellfish, and the USFWS were most interested in the biota in the marine environment around Amchitka, as is their mandate. From this workshop, CRESP identified three main receptor groups: subsistence people, commercial fisheries, and the marine ecosystem (including different food chains).

While the two components worked in concert throughout the process (Fig. 2), each developed somewhat independently. The process of selecting biota (and tissues) involved several steps: developing an initial list of biota, refining that list prior to the expedition, collecting biota on the expedition, and selecting the subset for analysis (expense precluded analyzing all specimens; Fig. 3), and then using the radionuclide data from these analyses to propose bioindicators. Each phase involved collaborations among different scientists within CRESP, as well as collaborations with different stakeholders. Stakeholders had input through formal workshops and meetings, and during personal conversations. Each step had unique challenges.

4.1. *The biological component*

The development of the initial target species list included literature review, the knowledge of scientists who had developed bioindicators for other sites, and the experiences of scientists who were familiar with the biota of the Aleutian Chain, but not necessarily with the environment directly around Amchitka. Work on the ecology and radionuclides in the Amchitka marine environment had ceased in the late 1970s (Merritt and Fuller, 1977).

Going from the initial list of target biota to the pre-expedition list involved visiting Aleut villages to solicit information about subsistence foods that needed to be included, as well as discussions with resource managers to make sure that we were not collecting species whose populations were declining or in jeopardy, and obtaining the necessary permits to collect organisms.

Once on the ship, the target list was modified by scientific judgements, Aleut and commercial fishermen advice, and availability of organisms. Scientifically, it was essential to collect important subsistence and commercial species, have representatives of different trophic levels, and have these organisms from each of the three test sites and the reference site (Kiska). Since one objective was to obtain species at many different trophic levels, the target species list was initially divided into ecological equivalents, with several species at each level. Ship time and foul weather constraints did not allow us to return to a sample site (e.g. Milrow on the Pacific side of Amchitka or Kiska), making it imperative to collect a broad list of species at the first sampling sites to ensure that ecological equivalents were available from each site. This allowed us to evaluate during the first few days at Amchitka which species might be easiest and most representative to collect. As the expedition progressed the target species list was refined, and the biologists on board concentrated on those species in each trophic level that could be collected at all four sites. While these difficulties were severe because of the remoteness of Amchitka, similar time constraints will impact other indicator work elsewhere.

Species abundance and size affected the target list during the expedition. It proved difficult to collect octopus (*Enteroctopus dofleini*) and Pacific halibut (*H. stenolepis*), but both were important subsistence foods, and the latter was an important commercial species. Octopus could be collected only when encountered during transect dives, and halibut required increased fishing effort, particularly by the Aleut fishermen. Some other species expected, such as king crabs (*Paralithodes camtschaticus*, *Lithodes aequispinus*), were difficult to catch because they remained in water too deep for safe diving (and could not be caught with hook and line by the subsistence fishermen). Some of the subsistence foods, such as limpets (*Tectura scutum*) and mussels (*M. trossulus*), were relatively small, requiring the collecting of greater numbers than initially expected. However, since subsistence foods were of primary importance, as many as possible were collected, recognizing that they would provide special challenges during the analysis phase.

Further, there were differences in how the Aleut subsistence hunters and fishers approached collection of target species compared to the scientists. The scientists on board often collected fish from designated transects while the Aleut fishermen applied their knowledge of habitat use by particular species. Thus, we were able to compare radionuclide levels in fish collected in transects to those collected by fishermen in the traditional manner (there were no differences). Further, the Aleuts collected mussels and other subsistence foods in the exposed intertidal flats, while these organisms were collected by diver-scientists in the intertidal.

The same factors that influenced the initial target list and expedition collection list affected the selection of species (and tissues) for analysis. This phase was also challenging because several factors needed to be considered: receptor group (subsistence, commercial fisheries, trophic level), species group (e.g. invertebrates, birds, fish), age and size, sample size and availability, collector (scientist-divers, biologists, subsistence fishers/hunters), and location (collected near Amchitka by the main expedition or in the NOAA trawls farther offshore). Species that were critical for all three receptor groups (subsistence, fisheries, food chain) had the highest priority for analysis. The second priority was having different species groups within each trophic level. For example, I wanted to have high trophic-level predators in all groups (invertebrates, fish, and birds). The third priority was to analyze species of concern, even if sample sizes were small; this included the bald eagle (*Haliaetus leucocephalus*) and octopus. CRESP was also requested to analyze the Steller sea lion (*Eumetopias jubatus*) taken in a subsistence hunt by the Aleuts. Small species, such as limpets, required dozens of organisms to make a sample, but their subsistence value increased their importance. These factors, important to species selection for Amchitka, would also be important for bioindicator selection elsewhere, and for a range of contaminants.

Tissue selection was relatively straightforward, and involved optimization of the opportunity for detection. That is, in many studies of radionuclides, values fall below the detection limit, making species indistinguishable with respect to use as a bioindicator. Therefore, tissues were analyzed that were known to concentrate particular radionuclides. For example, we analyzed bone for actinides and strontium, and muscle for cesium. My rationale was that if low levels of radionuclides were found in the tissues expected to concentrate them, then the probability of there being levels that could cause significant health effects in other tissues was extremely low.

4.2. The radionuclide selection component

Selecting radionuclides for analysis was only slightly less complicated than selecting biota and tissues (Fig. 4). The list of radionuclides in the Amchitka test cavities remains classified. Therefore, the initial selection of radionuclides for analysis was completed on the basis of radionuclides known to be in other US underground nuclear test cavities (this information has been declassified for some of the underground tests in Nevada), and the radionuclides that were used in the Amchitka groundwater models developed for DOE (by people who did have the classified information about Amchitka; DOE, 2002). The initial list was then presented to a range of stakeholders, some of whom had security clearance and who had seen the list of

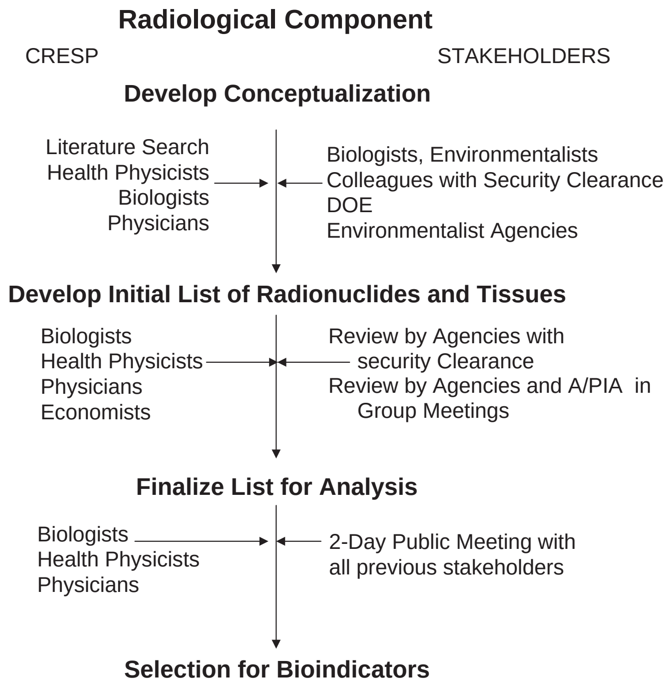

Fig. 4. Schematic showing the process of selecting radionuclides for analysis. The left indicates the CRESP scientists involved in the process, while the right indicates the involvement of other stakeholders in the decision process. *Note*: the 2-day meeting described at the end of the two parallel processes was the same meeting.

radionuclides in the Amchitka test cavities, and they assured CRESP that its list was appropriate. As with the list of biota for consideration, information on target radionuclides was presented at public meetings for comment. In selecting the final list, two other considerations applied: (1) radionuclides were selected that were important for human and ecological health (e.g. cesium-137, strontium-90), and (2) radionuclides were selected that could be indicative of an Amchitka signal (e.g. plutonium), and others that were not (e.g. uranium).

Having selected the radionuclides of interest, health physicists examined known risk levels and human health guidelines for each radionuclide to determine what detection limits were required. This in turn influenced the amount of material that needed to be selected.

Parenthetically, it is of interest to note that all stakeholders, except DOE, were extremely interested in other contaminants in biota, particularly mercury and PCBs (see Burger et al., 2007e). However, DOE was adamant from the very beginning that they were responsible only for radionuclides, and would not fund analysis of other contaminants.

4.3. Combining biota selection with radionuclide selection

The final step was examining the radionuclide data by species and tissue to select bioindicators of radionuclide exposure in the Amchitka marine ecosystem. The objective of this task was to develop bioindicators for a monitoring scheme that would be an integral part of the long-term stewardship plan for Amchitka.

Selection criteria were: (1) to select species that are important subsistence and commercial foods and that are indicative of different trophic levels, (2) to select 1–2 organisms from each trophic level (producers, filter feeders/grazers, primary carnivores, top-level carnivores), (3) to select organisms from different species groups (plants, invertebrates, fish, birds), and (4) to select organisms with the highest detection rates and radionuclide levels. The latter is critical because a bioindicator must provide early warning, and thus accumulate radionuclides before other organisms. Other aspects that guided the deliberations were—(1) sensitivity: the program should detect contamination if it occurs, (2) specificity: the program should continue to provide background results if a major seepage event has not occurred, and (3) predictive value: if elevated radionuclides are detected it should reflect real and significant contamination. Also, the program should be able to detect whether an elevated level is indicative of possible seepage; this requires that some radionuclides will be considered as indicative of an Amchitka nuclear test shot signal (i.e. as a “signature”).

5. Discussion

While the DOE has protocols for developing environmental monitoring plans for its legacy sites (mainly groundwater, soil, and sediment), the need for a biomonitoring plan (and for indicators at Amchitka) came from a wide range of stakeholders, including the State of Alaska. The stakeholders, and indeed the DOE, recognized early that it would be impractical to monitor soil, sediment or groundwater because of the cavity depths and vastness of the marine environment where seepage could occur. A similar need to use biomonitoring, rather than media monitoring, exists at other DOE sites and other hazardous waste sites nationally. Biomonitoring is particularly useful where there is the potential for subsistence, recreational or commercial use of biota from the site (or adjacent habitats), or where there are critical species or habitats in buffer lands around DOE sites. Yet, DOE has not developed methods for biomonitoring as part of their legacy waste management. On the OLM website, there is a listing of the monitoring and surveillance plans currently in use (OLM, 2006); a search of this database indicated that there are 82 reports that list monitoring, none of which list biomonitoring. Some integrated monitoring plans of individual sites have biomonitoring components, but these are usually ecological and involve population numbers, reproductive success, and invasive species (DOE, 2005). There is clearly a need for established protocols to develop bioindicators, and for the development of biomonitoring plans to assure the public of the continued protection of human health and the environment.

There are four principles that should guide the development of bioindicators for long-term stewardship: (1) sustainability, (2) stakeholder involvement, (3) good science, and (4) continued iteration and co-management. Sustainability requires a continued commitment to ensure that the biological resources, food chains, and human foods are protected from harm from radionuclide leakage or seepage. However, sustainability also requires continued funding, ongoing interest, and the ability to provide meaningful results in a cost-effective and timely manner. Any plan should be iterative, and involve co-management among diverse agencies and stakeholders. Stakeholders should be involved in all aspects of the environmental characterization and data collection, and their involvement was critical for CRESP in doing the best science possible.

The process outlined above, however, is both costly and time-consuming. It was 4 years from the initial planning workshop until the writing of the biomonitoring report, and the final long-term stewardship plan is yet to be approved. The process involved hundreds of hours of meetings with diverse stakeholders, in cities, towns, and villages, some of which were remote, hundreds of miles from mainland Alaska, and with populations of well under 100. While most bioindicator selection occurs without such an elaborate species collection and contaminant analysis phase, I submit that it is better to do it right in the first place than to forever be unsure whether the best indicators were selected. Further, the process of involving stakeholders during all phases ensures the incorporation of diverse viewpoints and science, and final buy-in of the species selected. The incorporation of different knowledge bases, in this case of Aleut science, ensured inclusion of the most relevant and site-specific species.

Moreover, embarking on such a process entails commitment to changing plans and incorporating suggestions. Scientists must be willing to listen, appreciate different viewpoints, and make appropriate changes. This was not a paper collaboration, but was a true collaboration among agencies at the state and federal level, governments (US and Tribal), western and Aleut science, and different cultures. It involved trade-offs between subsistence and scientific collecting, different disciplines (biology, ecology, health physics, public health), different species groups, human and ecological receptors, and finally, sample sizes and analytical costs.

More importantly, however, the inclusion of a wide range of stakeholders in the science process from the very beginning made it possible to achieve consensus or agreement on the final list of suggested bioindicators and radionuclides. The process itself, though costly and time-consuming, resulted in acceptance of the radionuclide and biological data, as well as the approach taken. The experience of Amchitka suggests that disagreements about contentious environmental issues, such as contaminated sites and food safety, are amenable to solutions only through stakeholder-driven research that addresses their concerns, as well as those of the relevant governmental agencies responsible for the contaminated sites.

Acknowledgments

Many people contributed to various aspects of this research and thinking about bioindicators over the years, and I thank them now: M. Gochfeld, C. W. Powers, D. Kosson, S. Jewett, R. Patrick, B. Friedlander, L. Bliss, D. Volz, M. Stabin, D. Favret, E.J. Zillioux, M. Greenberg, B.D. Goldstein, K. Cooper, I.L. Brisbin Jr., R. Ramos, C. Dixon, C. Jeitner, S. Burke, C. Safina, T. Shukla, and S. Shukla, and the people of Adak, Atka, Nikolski, and Unalaska, particularly R. Snigaroff, D. Snigaroff, and T. Stamm. The research reported herein was conducted under approved Rutgers University protocols, and was funded by the Consortium for Risk Evaluation with Stakeholder Participation (CRESP) through the Department of Energy cooperative agreement (DE-FC01-06EW07053), NIEHS (P30ES005022), and the Environmental and Occupational Health Sciences Institute. The views expressed in this paper are solely the responsibility of the authors, and do not represent those of the funding agencies.

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