ARTICLE IN PRESS

+ MODEL

Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Journal of Environmental Radioactivity xx (2007) 1–14

JOURNAL OF ENVIRONMENTAL RADIOACTIVITY

www.elsevier.com/locate/jenvrad

A biomonitoring plan for assessing potential radionuclide exposure using Amchitka Island in the Aleutian chain of Alaska as a case study

Joanna Burger [a,b,c,*], Michael Gochfeld [b,c,d], D.S. Kosson [b,e], Charles W. Powers [b,c,d,e]

[a] *Division of Life Sciences, Rutgers University, 604 Allison Road, Nelson Hall, Piscataway, NJ 08854-8082, USA*

[b] *Consortium for Risk Evaluation with Stakeholder Participation (CRESP), Nashville, TN, USA and Piscataway, NJ, USA*

[c] *Environmental and Occupational Health Sciences Institute (EOHSI), Piscataway, NJ, USA*

[d] *Environmental and Occupational Medicine, UMDNJ – Robert Wood Johnson Medical School, Piscataway, NJ, USA*

[e] *Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, TN, USA*

Received 17 January 2007; received in revised form 18 May 2007; accepted 4 June 2007

Abstract

With the ending of the Cold War, the US and other nations were faced with a legacy of nuclear wastes. For some sites where hazardous nuclear wastes will remain in place, methods must be developed to protect human health and the environment. Biomonitoring is one method of assessing the status and trends of potential radionuclide exposure from nuclear waste sites, and of providing the public with early warning of any potential harmful exposure. Amchitka Island (51° N lat, 179° E long) was the site of three underground nuclear tests from 1965 to 1971. Following a substantive study of radionuclide levels in biota from the marine environment around Amchitka and a reference site, we developed a suite of bioindicators (with suggested isotopes) that can serve as a model for other sites contaminated with radionuclides. Although the species selection was site-specific, the methods can provide a framework for other sites. We selected bioindicators using five criteria: (1) occurrence at all three test shots (and reference site), (2) receptor groups (subsistence foods, commercial species, and food chain nodes), (3) species groups (plants, invertebrates, fish, and birds), (4) trophic levels, and (5) an accumulator of one or several radionuclides. Our

* Corresponding author. Division of Life Sciences, Rutgers University, 604 Allison Road, Nelson B-216, Piscataway, NJ 08854-8082, USA. Tel.: +1 732 445 4318; fax: +1 732 445 5870.

E-mail address: burger@biology.rutgers.edu (J. Burger).

0265-931X/$ - see front matter
doi:10.1016/j.jenvrad.2007.06.002

Please cite this article in press as: Burger, J. et al., A biomonitoring plan for assessing potential radionuclide exposure using Amchitka Island in the Aleutian chain of Alaska as a case study, J. Environ. Radioact. (2007), doi:10.1016/j.jenvrad.2007.06.002

major objective was to identify bioindicators that could serve for both human health and the ecosystem, and were abundant enough to collect adjacent to the three test sites and at the reference site. Site-specific information on both biota availability and isotope levels was essential in the final selection of bioindicators. 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 are not sufficient to evaluate potential 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. This combination of species included mainly subsistence foods, commercial fish, and nodes on different food chains.

Keywords: Radiocesium; Actinides; Uranium; Algae; Invertebrates; Fish; Birds; Biological indicators; Amchitka; Marine

1. Introduction

The management of radioactive wastes, and the protection of humans and the environment from residual wastes and nuclear accidents are important elements of radiation protection and public policy. This aspect will become more important if the US and other nations turn to nuclear power to reduce their dependence on oil. Trust, transparency, and sustainability, as well as the public's participation in decision-making, will shape the public policy agenda with respect to nuclear waste in the future (Omenn, 2001; Florid, 2001), and ultimately to nuclear energy. Trust is particularly an issue with chemical and nuclear wastes (Slovic, 1987), and some people feel that the government has lied to them about nuclear safety and risk (Ahearne, 2001; Thomas, 2001).

For the US, at least, conversion to nuclear power will require assuring the public of its continued safety; the public requires peace of mind about nuclear wastes (Greenberg et al., in press). One component of such protection is the monitoring of environmental media or biota. While models are useful in predicting what concentrations might be expected in different biota compartments (Kryshev et al., 2001; Matishov et al., 2001; Hakanson, 2005), measurements of actual concentrations in biota and foods consumed are clearly directly useful in predicting intake rates and ultimately doses, particularly when the public is included in determining what species and foods are tested (Burger et al., 2005, 2006). Further, biomonitoring can provide early warning of potential effects both for people who consume fish and wildlife from the region, as well as of potential food chain and ecosystem effects.

The paper has two aims: (1) to provide a biomonitoring plan for Amchitka Island that can serve as a model of an approach to be used at other nuclear waste sites, and (2) to examine radionuclide levels in a range of biota, including plants, invertebrates, fish and birds, and to select the species that represent the receptors and the concerned stakeholder groups, while providing sufficient information to assess continued human and ecological health. This plan can be used as a model of an approach, and as an indication of the factors to be considered when developing bioindicators for potential radionuclide exposure at other sites. This work is part of a larger multi-disciplinary project by the Consortium for Risk Evaluation with Stakeholder Participation (CRESP) to provide the information to assure the protection of human health

Please cite this article in press as: Burger, J. et al., A biomonitoring plan for assessing potential radionuclide exposure using Amchitka Island in the Aleutian chain of Alaska as a case study, J. Environ. Radioact. (2007), doi:10.1016/j.jenvrad.2007.06.002

and the environment, and to provide a baseline for monitoring in the context of a long-term stewardship plan for Amchitka (Powers et al., 2005, 2006; Burger et al., 2006a).

While there are numerous papers that address the rationale, theory and types of bioindicators (Piotrowski, 1985; Peakall, 1992; Burger and Gochfeld, 2001, 2004; Carignan and Villard, 2001; Burger, 2006), there are few studies that propose specific indicators, or a suite of contaminants, for any given site. Further, most indicator studies deal either with human health or with ecosystem health, although more recently attention has been directed at selecting indicators that can provide information about both (DiGuilio and Monosson, 1996). The guiding principle of the present work was to select bioindicators that provide useful information for both environmental protection and human health protection. Lastly, biomonitoring plans are generally not available to the public, making it difficult for stakeholder groups and resource agencies to obtain the information necessary to provide meaningful input into decisions about long-term stewardship. This paper begins to address these issues.

2. Materials and methods

2.1. Study sites

Amchitka Island (Fig. 1, 51° N lat; 179° E long), in the Aleutian chain of Alaska, is part of the Alaska Maritime National Wildlife Refuge system. It contains important ecological resources (Merritt and Fuller, 1977; Burger et al., 2005, 2006b). The Bering Sea ecosystem provides a large percentage of the fish and shellfish for commercial sale in the US and elsewhere (International Bering Sea Forum, 2007). Dutch Harbor in the Aleutians, the port for commercial fish in the Bering Sea, had the highest tonnage of fish landings in the world in 2003, and provides 17% of Alaska's $811 million fish landings (2.3 million metric tons of fish, NOAA, 2004).

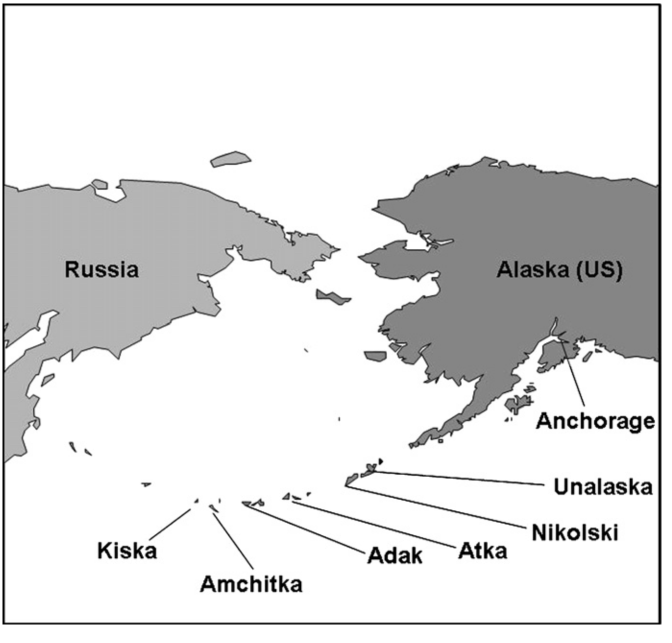

Fig. 1. Map of Aleutians, showing locations of Kiska and Amchitka Islands.

Please cite this article in press as: Burger, J. et al., A biomonitoring plan for assessing potential radionuclide exposure using Amchitka Island in the Aleutian chain of Alaska as a case study, J. Environ. Radioact. (2007), doi:10.1016/j.jenvrad.2007.06.002

Amchitka Island is the only island where the US detonated underground tests, making it far more difficult to assess and technically impossible to remove residual radionuclides. It is unusual among DOE-contaminated sites because of its remoteness, depth below ground surface of the contamination, and the importance of its ecological resources and seafood productivity that could be at risk if there were significant seepages of radionuclides from Amchitka tests to the marine environment. Data on radionuclide residues and conditions in the cavities remain classified. DOE believes that most of the radioactive material from the Amchitka detonations are permanently immobile because it is trapped in the vitreous matrix created by the intense heat of the blast. This, however, is only an assumption, and some model results indicate that breakthrough of radionuclides into the marine environment will eventually occur (DOE, 2002a,b).

2.2. Analysis protocol

Algae, invertebrates, fish and birds were collected under appropriate federal and state permits from both Amchitka and Kiska Islands (reference site) from late June–July 2004, and from a NOAA trawl in July–August 2004. Species names are given in appropriate tables. Following collection of species, specimens were prepared at Rutgers University laboratory, and analyzed at Vanderbilt laboratory and at Idaho National Laboratory (INL). Isotopes analyzed included radioactive cesium (^{137}Cs), iodine (^{129}I), cobalt (^{60}Co), europium (^{152}Eu), strontium (^{90}Sr), technetium (^{99}Tc), americium (^{241}Am), plutonium (^{238}Pu and ^{239,240}Pu), and uranium (^{234}U, ^{235}U, ^{236}U, and ^{238}U).

Our radionuclide analysis design was based on trophic level considerations, and sample availability and quantity. Detection sensitivity was initially determined using lifetime human cancer risk level of 10^{-6}, and sample numbers; quantities and MDAs were selected based on achieving detection levels well below this risk level. However, when we found that a high number of samples were below the MDAs for ^{137}Cs, we used larger quantities of sample and longer counting times to provide results useful for bioindicator selection. Analyses at Vanderbilt and Idaho National Laboratory provided inter-laboratory validation; detailed analytic and quality assurance methods have been previously reported (Powers et al., 2005, 2006).

Gamma emitters (^{137}Cs, ^{152}Eu, and ^{60}Co) were analyzed using homogenized samples loaded into 0.5 L Marinelli beakers and counted on high purity germanium detectors (HPGe) calibrated to the container geometry for 24–72 h. ^{129}I was analyzed with an HPGe detector optimized for low energy counting. The beta emitter, ^{90}Sr, was analyzed via scintillation analysis of its daughter decay product ^{90}Y. Counts were adjusted for background counts, and the Minimum Detectable Activity (MDA) was ± 2 SD background. All values are presented in Bq/kg, wet weight. The actinides (uranium, plutonium, and americium) were quantified using radiochemical techniques and alpha spectroscopy (average MDAs ranged from 0.052 Bq/kg for ^{241}Am to 0.102 Bq/kg for ^{235}U). Initially for gamma emitters 100 g samples were counted for 24 h, but all results were below the MDA; thus to enhance sensitivity, 1000 g samples were analyzed for 72 h. MDAs for ^{137}Cs ranged from 5.57 Bq/kg to 6.25 Bq/kg for 100 g samples and from 0.18 Bq/kg to 0.36 Bq/kg for 1000 g samples.

3. Results

3.1. Principles for species selection

The principles used to select bioindicators are outlined in Tables 1 and 2. Bioindicators are only useful if samples are taken at regular intervals (usually yearly or every five years), and have a similar spatial distribution from year to year. Further, they must be biologically, methodogically, and societally relevant. We adhered to these principles in bioindicator selection. Finally, bioindicators are most helpful if they provide useful information for both environmental protection and human health protection. In this case, they should be indicative of different trophic levels (for environmental health), and be species that people eat.

Please cite this article in press as: Burger, J. et al., A biomonitoring plan for assessing potential radionuclide exposure using Amchitka Island in the Aleutian chain of Alaska as a case study, J. Environ. Radioact. (2007), doi:10.1016/j.jenvrad.2007.06.002

Table 1
Features useful for bioindicator selection (after Burger and Gochfeld, 2004; Burger, 2006; Burger et al., 2006a–c)

Feature	Importance
Biological	*Sensitivity: Does it indicate what it should? *Is it sensitive to change? *Does it change in proportion to the magnitude of contamination? *Specificity: Is it specific to the stressor of concern?
Methodological	*Is it accessible in sufficient numbers? *Can it be sampled by non-experts? *Can it be monitored sustainably?
Sociological	*Is it of interest to and understandable by stakeholders including the Aleut peoples, resource trustees, and agencies? *Is it cost-effective?
Mobility	*Does it represent point source, local, or landscape scale contamination?
Radionuclide accumulator	*Does the species accumulate radionuclides at detectable levels?

The importance of stakeholder involvement in all phases of bioindicator selection cannot be stated too strongly. In this study, stakeholders were an integral part of all phases (Table 2). But even more importantly, stakeholders were involved in the initial development of the *Science Plan* that directed the studies necessary to select and obtain specimens for radionuclide analysis (Burger et al., 2005, 2006a). The most important stakeholders, Aleuts, were included on the ship to collect specimens in the traditional manner (Table 2).

Once we had the analytical results for radionuclide levels in a range of biota, we selected bioindicators using the following criteria: (1) occurrence at all three test shots (and reference site), (2) representative of different trophic levels, (3) representative of different species groups (plants, invertebrates, fish, and birds), (4) applicable to receptor groups (subsistence foods, commercial species, and food chain nodes), and (5) an accumulator of one or several radionuclides. One key characteristic of species selected for indicators was applicability to both human health and the ecosystem. Further details of the selection of biota and radionuclides can be found in Powers et al. (2005, 2006), Burger et al. (2006a) and Burger (in press).

3.2. Species analysis and bioindicator selection

Although we analyzed several isotopes, including radioactive cesium (^{137}Cs), iodine (^{129}I), cobalt (^{60}Co), europium (^{152}Eu), strontium (^{90}Sr), technetium (^{99}Tc), americium (^{241}Am), plutonium (^{238}Pu and ^{239,240}Pu), and uranium (^{234}U, ^{235}U, ^{236}U, and ^{238}U), some were all below the detection levels. There were no samples above the MDA (Minimum Detectable Activity) for ^{129}I, ^{60}Co, ^{152}Eu, ^{90}Sr and ^{99}Tc. The relative number of samples (except for ^{137}Cs all samples generally contained five individuals) with levels above the Minimum Detectable Activity (MDA) are shown in Table 3. This table formed the basis for the following conclusions: (1) there were almost no detectable levels of cesium in non-vertebrates (octopus was an exception), and (2) there were almost no detectable levels of actinides in vertebrates. This dichotomy suggested that we examine vertebrates closely for bioindicators for ^{137}Cs, and algae and invertebrates for the other radionuclides with levels above the MDA.

The species with half or more of the samples above the MDA for ^{137}Cs were glaucous-winged gull, walleye pollock, and Pacific cod (with at least 50% above the MDA), Pacific

Please cite this article in press as: Burger, J. et al., A biomonitoring plan for assessing potential radionuclide exposure using Amchitka Island in the Aleutian chain of Alaska as a case study, J. Environ. Radioact. (2007), doi:10.1016/j.jenvrad.2007.06.002

Table 2
Target species framework

Step	Process
Identify interested and affected parties	*Identify the stakeholders with legal or agency mandates, those who are directly or indirectly affected, and those who are interested *Identify mechanism for stakeholder involvement
Literature review	*Review species present in ecosystem of interest *Review species used as bioindicators in the past for this or similar ecosystems
Expert review and advice	*Hold discussions with natural resource trustees and scientists having unique information about the species in that ecosystem *Solicit resource trustee views on which species are of particular interest to them
Stakeholder review and advice	*Solicit views from interested and affected parties on the species of particular interest to them
Select trophic levels for representation	*Consult with stakeholders above about trophic levels of particular interest *Decide on number of levels or nodes within trophic levels
Array possible species	*Array species in trophic levels *Consider possible food web relationships where the top trophic level may not be a possible candidate for collection
Select organisms within trophic level for initial collection	*Include species whose locations or populations are amenable to collection *Include species of special interest to stakeholders listed above *Consider three major groups: subsistence consumers, commercial fisheries, and food web nodes (including ecosystem effects)
Include flexibility in the form of ecological equivalents	*Recognize that in the field not all organisms might be amenable to collection *Identify ecological equivalents that could serve the same trophic level function

Stages in selection of a suite of biota from which bioindicators of environmental contamination should be selected (depending upon chemical or radionuclide concentrations).

halibut (75% above MDA), and octopus, dolly varden, and black rockfish (100% above MDA) (Table 4). Although there were only 2–5 analyses run for most of these species, they generally represented from 10 to 40 individuals per sample.

For actinides, both algae and invertebrates had a high percent of samples above the MDA, depending upon the isotope (Tables 5 and 6). Among algae, there were significant differences in the mean levels of ^{239,240}Pu, ^{234}U, ^{235}U, and ^{238}U (Table 5). The data indicate that, of the algae species examined, *Alaria fistulosa* and *Fucus* are the best accumulators of the radioisotopes examined. *A. fistulosa* had the highest levels (or the most hits) of ^{239,240}Pu and ^{236}U, the anthropogenic radionuclides of interest. *Fucus* can be collected from the intertidal; *A. fistulosa*, a subtidal species, can be collected by either grappling hooks or by pulling the fronds while in small boats. Since it is likely that this method of collection will result in obtaining largely the top part of the plant, it is important to note that: (1) the whole *Alaria* frond grows in one growing season, and (2) in a series of lab analyses for heavy metals we found that there were no significant differences in the levels of metals as a function of the part of the *Alaria* plant examined for lead and mercury, although cadmium concentrated in the holdfast. In all cases, the differences among parts were usually less than twofold (Burger et al., 2006c).

To determine whether algae or invertebrates (and which invertebrates) would best serve as bioindicators, we compared them (Table 6). There were significant differences in the mean levels of ^{239,240}Pu, ^{234}U, ^{235}U, and ^{238}U. Of the three invertebrates examined, horse mussel had slightly higher levels, but the differences were not great, and in all cases of significant

Please cite this article in press as: Burger, J. et al., A biomonitoring plan for assessing potential radionuclide exposure using Amchitka Island in the Aleutian chain of Alaska as a case study, J. Environ. Radioact. (2007), doi:10.1016/j.jenvrad.2007.06.002

Table 3
Number of composites above the MDA as a function of species and isotope

Species	^{137}Cs	^{241}Am	^{239,249}Pu	^{234}U	^{235}U	^{236}U	^{238}U
Source	A	A	A	N	A	A	N
Primary producers							
Alaria fistulosa	0/4	0/19	6/19	19/19	8/19	2/19	19/19
Alaria nana	0/2	2/21	3/21	21/21	9/21	0/21	21/21
Fucus	0/4	2/14	5/14	14/14	14/14	1/14	14/14
Ulva	0/3	1/12	0/12	12/12	0/12	0/12	12/12
Laminaria (three species)		0/18	3/18	18/18	3/18	0/18	18/18
Grazers/filter feeders							
Sea urchin	0/3						
Giant chiton	0/1						
Rock jingle	0/3	7/21	6/21	21/21	3/21	1/21	21/21
Plate limpet (Chinese hat)	0/2						
Blue mussel	0/2	1/9	0/9	9/9	2/9	0/9	9/9
Horse mussel	0/2	1/8	1/8	8/8	2/8	0/8	8/8
Lower predators							
Dolly varden	3/3						
Atka mackerel	1/3	0/1	0/1	1/1	1/1	0/1	1/1
Rock greenling	0/5						
Yellow Irish lord	1/3	0/3	0/3	3/3	0/3	0/3	3/3
Northern sole	0/2						
Ocean perch	1/3	0/1	0/1	1/1	0/1	0/1	1/1
Eider (adult)	0/2						
Eider (egg)	0/2						
Medium trophic level							
Gulls (adult)	1/2	0/8	0/8	0/8	0/8	0/8	0/8
Gulls (chick)	0/2						
Gulls (egg)	0/2						
Pigeon guillemot		0/3	1/3	0/3	0/3	0/3	0/3
Tufted puffin	0/2	0/3	0/3	0/3	0/3	0/3	1/3
Black rockfish	3/3	1/1	0/1	1/1	1/1	0/1	1/1
Walleye pollock	1/2	1/2	1/2	2/2	1/2	0/2	2/2
Top trophic level							
Octopus	4/4						
Bald eagle	0/2						
Halibut	3/4	0/7	1/7	6/7	1/7	0/7	7/7
Pacific cod	8/14	1/21	0/21	17/21	0/21	0/21	17/21
Sea lion	1/1						

Shown are the number of values above the MDA/total composites analyzed for the key radionuclides examined at Amchitka and Kiska, 2005. Cesium samples included only 1000 g samples. Primary source: A = anthropogenic and N = natural. Scientific names are found in Tables 4–6.
Note: For sea lion, both muscle and liver were analyzed and had values above the MDA. Green sea urchin (*Strongylocentrotus polyacanthus*), limpet (*Tectura scutum*), rock jingle (*Pododesmus macroschisma*), blue mussel (*Mytilus trossulus*) and horse mussel (*Modiolus modiolus*). All other names are given in Table 4 or Table 5.

differences, the algae had higher levels. Since the differences among the invertebrates were small, it seemed prudent to select blue mussels as the bioindicator because they are the preferred subsistence food and they can be gathered in the intertidal (reducing the costs of having divers to obtain horse mussels and rock jingles).

Please cite this article in press as: Burger, J. et al., A biomonitoring plan for assessing potential radionuclide exposure using Amchitka Island in the Aleutian chain of Alaska as a case study, J. Environ. Radioact. (2007), doi:10.1016/j.jenvrad.2007.06.002

Table 4
Examination of predators for use as bioindicators for ^{137}Cs

Species	Number of 1000 g analyses	Percent above the MDA	All values above the MDA
Low trophic level			
Dolly varden, *Salvelinus malma*	2	100	0.70, 0.78
Atka mackerel, *Pleurogrammus monopterygius*	3	33	0.102
Rock greenling, *Hexagrammos lagocephalus*	5	0	–
Yellow Irish lord, *Hemilepidotus jordani*	3	33	0.131
Northern sole, *Lepidopsetta polyxystra*	2	0	–
Ocean perch, *Sebastes alutus*	3	33	0.108
Common eider (adults) *Somateria mollissima*	2	0	–
Common eider (eggs)	2	0	–
Medium trophic level			
Glaucous-winged gulls (adults), *Larus glaucescens*	2	50	0.094
Glaucous-winged gulls (eggs)	2	0	–
Tufted puffin, *Fratercula cirrhata*	2	0	–
Walleye pollock, *Theragra chalcogramma*	2	50	0.46
Black rockfish, *Sebastes melanops*	3	100	0.189, 0.130, 0.111
Top trophic level			
Octopus, *Enteroctopus dofleini*	4	100	0.236, 0.302 0.249, 0.249
Bald eagle, *Haliaetus leucocephalus*	2	0	–
Pacific halibut, *Hippoglossus stenolepis*	4	75	0.190, 0.315, 0.446
Pacific cod, *Gadus macrocephalus*	14	57	0.176, 0.323 0.200, 0.399 0.209, 0.472 0.315, 0.602
Sea lion, *Eumetopias jubatus*	1	100	0.554, 0.405

Given are the values in Bq/kg (wet weight) for 1000 g samples only. For comparative purposes, all predators are listed. Trophic levels were based on previous information; at Amchitka, trophic levels may change slightly, depending upon the food webs. Samples (1000 g) contained from 5 to 35 individuals, depending upon the size of the organisms.

Taken altogether, these data suggest a bioindicator suite for radionuclides at Amchitka (Table 7). Although some of the radionuclides were all below the MDA for the Amchitka data set (^{129}I, ^{60}Co, and ^{99}Tc), the marginal cost of adding them is very small because of the normal analytical stream (and they are important for human health).

4. Discussion

4.1. Species selection

While the selection of biota (and radioisotopes) for bioindicators can be based entirely on radiological and biological factors, we suggest that the inclusion of stakeholders during every part of the process improves the quality of the indicators selected, provides consensus or agreement on their applicability, and ensures stakeholder buy-in to their continued use. The suite of species selected above as bioindicators satisfies the initial criteria of (1) receptor groups, (2) availability at all test shots, (3) species groups, (4) trophic level, and (5) size and age. Size and age are important because larger and older animals generally accumulate higher levels of some contaminants than younger and smaller ones (Lange et al., 1994; Bidone et al., 1997; Burger et al., 2001a,b; Pinho et al., 2002; Green and Knutzen, 2003). For example,

Table 5
Examination of kelp/algae for use as bioindicators for actinides

Isotope	*Ulva*	*Fucus*	*Alaria nana*	*Alaria fistulosa*	*Laminaria*	Chi square, *p* value
Sample size	12	14	21	19	18	
^{241}Am A	0.017 ± 0.019	0.015 ± 0.008	0.018 ± 0.010	0.013 ± 0.006	0.014 ± 0.004	3.22, $p < 0.52$
^{238}Pu A	(0.024, 0.123)			(0.015)		
^{239,240}Pu A	0.0014 ± 0.006	0.031 ± 0.017	0.031 ± 0.018	0.051 ± 0.05	0.020 ± 0.023	19.8, $p < 0.0005$
^{234}U N	0.317 ± 0.121	3.124 ± 1.09	0.986 ± 0.518	1.005 ± 0.557	0.446 ± 0.209	52.3, $p < 0.0001$
^{235}U N	0.008 ± 0.005	0.147 ± 0.052	0.015 ± 0.015	0.052 ± 0.042	0.044 ± 0.041	43.6, $p < 0.0001$
^{236}U A		(0.044)		(0.022, 0.016)		
^{238}U N	0.246 ± 0.137	2.72 ± 0.953	0.843 ± 0.437	0.906 ± 0.484	0.431 ± 0.167	55.2, $p < 0.0001$

Given is the mean (±standard deviation, wet weight) in Bq/kg with the values plus half the MDA. Where there were few values above the MDA for an isotope, the values are listed in parenthesis (no statistical test was performed). A = primarily anthropogenic and N = primarily natural.

mussels are small with a short lifespan, gulls have distinct life stages that are distinguishable (eggs, chicks, and adults that live for 30–40 years), and halibut (very large) and black rockfish (medium sized) live to be over 50 years old. *Fucus* are small while *Alaria* are large and both are short lived. Overall, within any given species, the largest specimens should be selected for analysis to increase the probability of getting detectable levels, and to assure that exposure of top-level predators (including people) is measured. Most of the species are subsistence foods, although some are used more than others. Further, all these species can be collected without resorting to the use of divers, which introduces its own set of health and safety issues, and adds additional costs.

Although sea lion might seem like a potential bioindicator at first glance because of its subsistence value, trophic status, and levels of radiocesium, we did not propose it because their populations are declining, they are difficult to collect without impacting behavior and colony structure, and their foods can be collected as an indication of exposure. Similarly, octopus was not proposed because of the difficulty of obtaining them with reliability.

The key step in species selection is the initial target list of species because this provides the universe for final bioindicator selection once radionuclide data are available. It is at this early stage that a wide range of stakeholders can suggest the inclusion or deletion of species (or tissues), provide local biological information on capture habitats or methods, and provide validation of the list. Finally, bioindicators are most helpful if they provide useful information

Table 6
Comparison of two species of kelp that were the highest accumulators, with invertebrates for use as bioindicators for actinides

Isotope	*Fucus*	*Alaria fistulosa*	Rock jingle	Blue mussel	Horse mussel	Chi square, *p* value
Sample size	14	19	21	9	8	
^{241}Am	0.015 ± 0.008	0.013 ± 0.006	0.021 ± 0.011	0.017 ± 0.004	0.016 ± 0.004	6.56, $p < 0.16$ (NS)
^{238}Pu		(0.015)				
^{239,240}Pu	0.31 ± 0.017	0.051 ± 0.05	0.024 ± 0.012	0.019 ± 0.004	0.022 ± 0.011	8.61, $p < 0.07$
^{234}U	3.124 ± 1.09	1.005 ± 0.557	0.446 ± 0.079	0.598 ± 0.194	0.844 ± 0.804	41.4, $p < 0.0001$
^{235}U	0.147 ± 0.052	0.052 ± 0.042	0.015 ± 0.026	0.021 ± 0.014	0.030 ± 0.048	33.5, $p < 0.0001$
^{236}U	(0.044)	(0.022, 0.016)	(0.011)			
^{238}U	2.74 ± 0.953	0.906 ± 0.484	0.345 ± 0.071	0.558 ± 0.165	0.730 ± 0.646	48.4, $p < 0.0001$

Given are the means (±standard deviation, wet weight) in Bq/kg with the values plus half the MDA for those below the MDA. Where there are very few values above the MDA for an isotope, the actual values are given in parenthesis.

Please cite this article in press as: Burger, J. et al., A biomonitoring plan for assessing potential radionuclide exposure using Amchitka Island in the Aleutian chain of Alaska as a case study, J. Environ. Radioact. (2007), doi:10.1016/j.jenvrad.2007.06.002

Table 7
Proposed bioindicators for Amchitka for ^{137}Cs, ^{129}I, ^{60}Co, ^{99}Tc, $^{239,240}Pu$ and other actinides

Species	^{137}Cs	^{129}I ^{60}Co	^{99}Tc	$^{239,240}Pu$ and other actinides	Rationale
Fucus	X	X	X	X	*Primary producer in intertidal
Alaria fistulosa	X			X	*Primary producer *Intertidal and benthic
Blue mussel	X			X	*Filter feeder *Subsistence food *Intertidal
Dolly varden	X	X			*Low-level predator *Subsistence food *Saltwater fish that spawns in Amchitka lakes
Black rockfish	X	X		X	*Intermediate predator *Subsistence food *Long lifespan *Low mobility
Pacific cod	X	X		X	*Top-level predator *Subsistence food and commercial fish *Intermediate lifespan *Intermediate mobility
Halibut	X	X			*Top-level predator *Subsistence food and commercial fish *Long lifespan *Mobile
Glaucous-winged gull	X	X			*Intermediate level predator *Subsistence food (eggs) *Local *Long lifespan

These are the radionuclides that were detectable, are of interest for human and ecological health in the marine environment, and could be analyzed as a suite to detect any potential risk and for source identification. There are three analytical streams: gamma (^{137}Cs, ^{60}Co, and ^{129}I), beta/gamma (^{99}Tc), and alpha (Pu and U series).

for both environmental protection, and human health protection. In this case, they were indicative of different trophic levels for environmental health (algae, invertebrates, fish, and birds), and were species that people eat.

4.2. Radionuclide selection

Selection of the isotopes for analysis, and for a final biomonitoring plan, was not a trivial task. Radionuclide selection had two important components: selecting the initial list for biota analysis, and selecting the final list for biomonitoring based on a matrix of biota and radionuclide levels. For many sites, such as Amchitka, the source terms may not be available, making selection of the initial isotopes complex. For others, such information may be available, but the relative concentrations may not. Further, even knowing what radionuclides may be present does not in itself lead directly to understanding appropriate radionuclide analysis methodology, such as tissues, species, sample sizes, and counting times.

Please cite this article in press as: Burger, J. et al., A biomonitoring plan for assessing potential radionuclide exposure using Amchitka Island in the Aleutian chain of Alaska as a case study, J. Environ. Radioact. (2007), doi:10.1016/j.jenvrad.2007.06.002

Moreover, although knowledge of the source term for a particular hazardous waste site may lead logically to the analysis of particular isotopes, the public may be interested in a broader range of radionuclides (some of which may derive from atmospheric deposition or other nearby radionuclide point sources). Our experience suggests that a biomonitoring plan could not have been developed for Amchitka without first conducting a detailed analysis of a range of isotopes in a wide range of biota. Site-specific information was essential for both biota and isotopes in order to select appropriate bioindicators.

Selection of bioindicator species, however, is completely dependent upon their ability to bioaccumulate radionuclides. That is, to be useful, the bioindicator species must accumulate radionuclides to a greater extent than other organism within their ecosystems, and they must have levels that are above the MDA.

Finally, and most importantly, the data from Amchitka indicated that a number of diverse species were required to adequately evaluate radionuclide levels. No one species group, or trophic level, was sufficient; actinides bioaccumulated in algae and invertebrates, and radiocesium accumulated in higher trophic levels' birds and fish. Thus, unlike biomonitoring schemes developed for heavy metals, top-level predators are not sufficient to evaluate potential radionuclide exposure at Amchitka.

4.3. Risk balancing and trade-offs

We suggest that bioindicators that represent both human and ecological health have the best chance of long-term public support. Such support is particularly important not only for continued funding that will provide status and trends information, but to provide peace of mind to residents living near hazardous waste sites, particularly nuclear respositories. One aspect of being able to balance risk between humans and ecosystems is having the data to evaluate each. This suggests that biomonitoring schemes should produce status and trends information about both human exposure and ecological receptor exposure. While not every indicator has to represent both humans and ecological receptors, the suite should have some species that do. In the present study, for example, halibut and Pacific cod are top-level predators (and are thus indicative of the health of their food chains), are subsistence foods, and are of considerable commercial interest. Other species fit only two of the receptor categories; octopus and puffins are both top predators and subsistence foods. Still others fit only one category, but are of concern; bald eagles are not eaten, but are top predators of particular interest to the USFWS. Some of the algae are at the bottom of food chains (and thus reflect potential problems for organisms that eat them), are subsistence foods, and are used as a health food and for medicinal purposes by other people.

Not all top-level predators, however, are amenable to collection. We did not collect marine mammals as part of the CRESP protocol because of their declining numbers, vulnerability, and protected status. Instead we chose to analyze their foods as indicators of their exposure; this is the same approach used to determine risk for humans. We examined radionuclide levels in both subsistence and commercial foods as an indication of human exposure.

5. Conclusions

Before the US and other nations can increase their dependence on nuclear power, or deal effectively with nuclear legacy wastes, the public, agencies, and public policy makers must be assured that human health and the environment are adequately protected. One method of assuring peace of mind is to put in place biomonitoring plans that the public feels would provide adequate early warning of any potential problems. Bioindicators, the centerpiece of biomonitoring plans, must be selected to represent the interests of local and regional people, which in the case of Amchitka was subsistence peoples, commercial fisheries, and ecosystem protection. Site-specific information on both available biota and isotope levels was required to select bioindicators for a long-term stewardship plan. Considerable time and effort are required to identify the receptors of interest, and to include relevant stakeholders in the process of indicator selection. However, inclusion of stakeholders leads to empowerment, which in turn results in the selection of indicators that the public supports, and will continue to support for the period of time required to assess status and long-term trends, while providing early warning of the potential for hazardous exposure to people or ecological receptors.

Acknowledgments

We thank the many people who contributed to the development and execution of CRESP's Amchitka Geophysical and Biological Project, especially L. Bliss, B. Friedlander, D. Volz, M. Greenberg, and H. Mayer, and the following for help throughout the project, S. Jewett, D. Barnes, L. Duffy, M. Stabin, A. Morkill, R. Patrick, D. Rogers, D. Dasher, J. Halverson, P. Sanders, J. Alchowiak and the people of the villages of Unalaska, Nikolski, Atka, and Adak in the Aleutians. Technical help was provided by C. Jeitner, S. Burke, M. Donio, D. Favret, S. Shukla, C. Dixon, M. Gray, G. Elias, V. Vyas, and H. Mayer. We thank the entire crew of the *Ocean Explorer*, Captain Ray Haddon, mate Glenn Jahnke, cook Don Dela Cruz, and Bill Dixon, Joao Do Mar, and Walter Pestka, for making our field work possible and pleasant, and for bringing us safely back to port. We also thank the Captain of the *Gladiator* trawler and his crew for aiding our collecting, and M.E. Wilkins for allowing us to participate on the NOAA cruise. This research was funded by the Consortium for Risk Evaluation with Stakeholder Participation (CRESP) through the Department of Energy (DE-FG 26-00NT 40938, DE-FC01-06EW07053) and by NIEHS P30ES005022. The results, conclusions and interpretations reported herein are the sole responsibility of the authors, and should not in any way be interpreted as representing the views of the funding agencies.

References

International Bering Sea Forum, 2007. Available from: <http://www.beringseaforum.org/issues.html> (accessed 12 July 2007).

Ahearne, J.F., 2001. Scientists, policy makers, and the public: a needed dialogue. Health Physics 80, 384–387.

Bidone, E.D., Castilhos, Z.C., Santos, T.J.S., Souza, T.M.C., Lacerda, L.D., 1997. Fish contamination and human exposure to mercury in Tartarugalzinho River, Northern Amazon, Brazil. A screening approach. Water Air and Soil Pollution 97, 9–15.

Burger, J., 2006. Bioindicators: types, development, and use in ecological assessment and research. Environmental Bioindicators 1, 1–18.

Burger, J., Gochfeld, M., 2001. On developing bioindicators for human and ecological health. Environmental Monitoring and Assessment 66, 23–46.

Burger, J., Gochfeld, M., 2004. Bioindicators for assessing human and ecological health. In: Wiersma, G.B. (Ed.), Environmental Monitoring. CRC Press, Boca Raton, pp. 541–566.

Burger, J., Gaines, K.F., Gochfeld, M., 2001a. Ethnic differences in risk from mercury among Savannah River fishermen. Risk Analysis 21, 533–544.

Burger, J., Gaines, K.F., Boring, C.S., Stephens Jr., W.L., Snodgras, J., Gochfeld, M., 2001b. Mercury and selenium in fish from the Savannah River: species, trophic level, and locational differences. Environmental Research 87, 108–118.

Burger, J., Gochfeld, M., Kosson, D., Powers, C.W., Friedlander, B., Eichelberger, J., Barnes, D., Duffy, L.K., Jewett, S.C., Volz, C.D., 2005. Science, policy, and stakeholders: developing a consensus science plan for Amchitka Island, Aleutians, Alaska. Environmental Management 35, 557–568.

Burger, J., Gochfeld, M., Kosson, D.S., Powers, C.W., 2006a. Biomonitoring for Ecosystem and Human Health Protection at Amchitka Island. Consortium for risk evaluation with stakeholder participation, Piscataway, New Jersey.

Burger, J., Jewett, S., Gochfeld, M., Hoberg, M., Harper, S., Chenelot, H., Jeitner, C., Burke, S., 2006b. Can biota sampling for environmental monitoring be used to characterize benthic communities in the Aleutians? Science of the Total Environment 369, 393–402.

Burger, J., Gochfeld, M., Jeitner, C., Gray, M., Shukla, T., Shukla, S., Burke, S., 2006c. Kelp as a bioindicator: does it matter which part of a 5 m long plant is used for metal analysis. Environmental Monitoring and Assessment.

Burger, J., Gochfeld, M., Jewett, S.C., 2006. Selecting species for marine assessment of radionuclides around Amchitka: planning for diverse goals and interests. Environmental Monitoring and Assessment 123, 371–391.

Burger, J. A model for selecting bioindicators to monitor radionuclide concentrations in the marine environment around Amchitka Island in the Aleutians. Environmental Research, in press.

Carignan, V., Villard, M.A., 2001. Selecting indicator species to monitor ecological integrity: a review. Environmental Monitoring and Assessment 78, 45–61.

Department of Energy (DOE), 2002a. Modeling groundwater flow and transport of radionuclides at Amchitka Island's underground nuclear tests: Milrow, Long Shot, and Cannikin (DRAFT). Nevada Operations Office, Las Vegas, Nevada, DOE/NV-11508-51.

Department of Energy (DOE), 2002b. DRAFT screening risk assessment for possible radionuclides in the Amchitka marine environment. Nevada Operations Office, Las Vegas, Nevada, DOE/NV-857.

DiGuilio, R.T., Monosson, E., 1996. Interconnections between Human and Ecosystem Health. Chapman and Hall, London, UK.

Florid, H.K., 2001. Alternative goals and policy mechanisms for radiation protection. Health Physics 80, 397–400.

Green, N.W., Knutzen, J., 2003. Organohalogens and metals in marine fish and mussels and some relationships to biological variables at reference localities in Norway. Marine Pollution Bulletin 46, 362–377.

Greenberg, M., Lowrie, K., Burger, J., Powers, C.W., Gochfeld, M., Mayer, H. Nuclear waste and public worries: public perceptions of the United States major nuclear weapons legacy sites. Human and Ecological Reviews, in press.

Hakanson, L., 2005. A new general dynamic model predicting radionuclide concentrations and fluxes in coastal areas from readily accessible driving variables. Journal of Environmental Radioactivity 78, 217–245.

Kryshev, A.I., Sazykina, T.G., Kryshev, I.I., Strand, P., Brown, J.E., 2001. Radioecology modelling and the computer codes for calculations of doses to marine biota and man in the Arctic. Environmental Modelling Software and Environmental Data News 16, 697–709.

Lange, T.R., Royals, H.E., Connor, L.L., 1994. Mercury accumulation in largemouth bass (*Micropterus salmoides*) in a Florida Lake. Archives of Environmental Contamination and Toxicology 27, 466–471.

Matishov, G.G., Matishov, D.G., Anisimova, N.A., Dzhenyuk, S.L., Zuev, A.N., 2001. Radiation conditions of the environment and biota on the Murmansk Bank in the area of the sunken Kursk nuclear submarine. Oecologia 41, 853–860.

Merritt, M.L., Fuller, R.G. (Eds.), 1977. The Environment of Amchitka Island, Alaska, U.S. Report NVO-79, Technical Information Center, Energy Research and Development Administration, Washington DC.

NOAA (National Oceanic and Atmospheric Administration), 2004. Dutch Harbor – Unalaska, in Alaska, Top U.S. Port for landings in 2003. NOAA report 04–096. Available from: <www.nmfs.noaa.gov/docs/04-096_top_ports.pdf/> (accessed 26 May 2006).

Omenn, G.S., 2001. The new millennium: values, perceptions of risk, and the key roles of science and technology. Health Physics 80, 328–332.

Peakall, D., 1992. Animal Biomarkers as Pollution Indicators. Chapman and Hall, London.

Pinho, A.P., Guimaraes, J.R.D., Marins, A.S., Costa, P.A.S., Olavo, G., Valentin, J., 2002. Environmental Research 89, 250–258.

Piotrowski, J.K., 1985. Individual exposure and biological monitoring. In: Vouk, V.B., Butler, G.C., Hoel, D.G., Peakall, D.B. (Eds.), Methods for Estimating Risk of Chemical Injury: Human and Non-human Biota and Ecosystems. Wiley and Sons, Chichester, UK, pp. 123–135.

Powers, C.W., Burger, J., Kosson, D., Gochfeld, M., Barnes, D. (Eds.), 2005. Amchitka Independent Science Assessment: Biological and Geophysical Aspects of Potential Radionuclide Exposure in the Amchitka Marine Environment. Consortium for risk evaluation with stakeholder participation, Piscataway NJ.

Powers, C.W., Burger, J., Kosson, D., Gochfeld, M., 2006. Additional Radiological Data for Bioindicator Selection. Consortium for risk evaluation with stakeholder participation, Piscataway NJ.

Slovic, P., 1987. Perception of risk. Science 236, 280–285.

Thomas, J.P., 2001. Rebuilding trust in established institutions. Health Physics 80, 379–383.

Please cite this article in press as: Burger, J. et al., A biomonitoring plan for assessing potential radionuclide exposure using Amchitka Island in the Aleutian chain of Alaska as a case study, J. Environ. Radioact. (2007), doi:10.1016/j.jenvrad.2007.06.002