Appendix 3.A

In Press: Journal of Toxicology and Environmental Health

Ecological Risk, Conceptual Site Models, and Long-term Stewardship Where Critical Risk is Off-Site: The Case of the Department of Energy's Amchitka Island Nuclear Test Site

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ABSTRACT/ Managers of contaminated sites are faced with options ranging from monitoring natural attenuation to complete removal of contaminants to meet residential standards. Conceptual Site Models are one tool used by the Department of Energy (DOE) and other environmental managers to understand, track, help with decisions, and communicate with the public about the risk from contamination. CSMs can graphically depict the sources, releases, transport and exposure pathways, and receptors, along with possible barriers to interdict pathways and reduce exposure. In this paper we explore CSMs using Amchitka Island, where the remaining contamination is from underground nuclear test shot cavities containing large quantities of various radionuclides in various physical and chemical forms. Amchitka Island differs from other DOE test shot sites because it is surrounded by a marine environment that is highly productive and has a high biodiversity. The surrounding waters of the Bering Sea and North Pacific ocean are heavily exploited by commercial

fisheries and provide the U.S. and other countries with a significant proportion of its seafood. We propose that the CSMs on Amchitka Island focus the pathways of exposure and critical receptors. Further, CSMs should be incorporated within a larger ecosystem model because of the potentially rapid transport within ocean ecosystems, the large number of migratory species that pass by Amchitka, and the potential for a direct pathway to Aleut food chains and commercial fisheries, remote from the island itself. The exposure matrix for receptors requires expansion for the Amchitka Island ecosystem because of the valuable marine and seafood resources in the region. We suggest CSMs with an expanded exposure/receptor matrix can be used effectively to clarify the conceptualization of the problem for scientists, regulators, and the general public.

Managers are faced with understanding the complex physical, ecological, and contamination conditions of their sites within the context of current and future land uses. Among the tools that are available to managers, Conceptual Site Models can be useful in distilling the essential features of their site for a wide range of stakeholders. Conceptual site models are graphic depictions of exposure conditions on a contaminated site illustrating sources, hazards, environmental transport, pathways and exposure routes, and receptors (Mayer et al. ms). They were first used in the assessment process by the Environmental Protection Agency (EPA) in the late 1980s (EPA 1987, 1988), and were later modified to include quantitative data, off site populations, and land use characteristics (EPA 1991, 1992). They have generally been used where there are a number of remediation decisions or choices, and multiple future land use options.

Since the ending of the Cold War, the public and governmental agencies have been concerned about remediating and reclaiming contaminated land owned or operated by the U.S. Department of Energy (DOE) and Department of Defense (DOD), and converting mo-longer needed land to productive uses. During the process of remediation, both human health and ecological resources require protection, and Conceptual Site Models can clarify the issues. The DOE, DOD, other federal organizations, and the private industrial sector have land holdings that contain chemical and radiological wastes that require remediation, restoration, and return to other land uses. Similarly, many brownfields within urban and suburban areas are in the process of being converted to productive uses (Simons 1998, Powers et al. 2000, U.S. Conference of Mayors 2000, Greenberg et al. 1997, 2001a, 2001b, Miller et al. 2001). Notably, some of the larger federally-owned contaminated sites also contain land that is not contaminated, or is lightly contaminated, as well as areas currently used for recreational, agricultural, or industrial purposes (Greenberg et al. 1997, Solitare et al. 2000, Burger 2000a,b, Carletta et al. in press, Burger et all. in press). While various agencies and stakeholders argue about how contaminated lands should be used, there is little disagreement about the importance of restoring damaged lands (Cairns 1989, Harwell and Kelly 1990, Cairns et al. 1992). Often ecological health takes a back seat to human health concerns, especially during remediation (DOE 1994a,b, 1995, 1996).

For several reasons, not all contaminated land can be restored: 1) the contamination may be too great, 2) suitable or cost effective remediation technologies may not currently be available, 3) remediation may impose too great a risk to established ecosystem or to threatened or endangered species, and 4) remediation itself may pose too great a risk to workers or the public (NRC 2000, DOE 2001)). Further, in some cases it may be deemed appropriate to stabilize the waste and leave the materials in place. In the case of the underground nuclear test shots that the DOE detonated, it is not feasible technically to remediate the below-ground contamination. Moreover, it is believed that most of the radiation is trapped in the vitreous matrix created by the intense heat of the blast, and is therefore permanently immobilized (DOE 2002b). The DOE detonated three underground nuclear tests on Amchitka Island: *Long Shot* (80 kilotons) in 1965, *Milrow* (1 megaton) in 1969, and *Cannikin* (5 megatons) in 1971, the latter being the United States' largest and deepest underground nuclear test (DOE 1995, 2000).

In this paper we develop Conceptual Site Models for Amchitka Island as a method of exploring how hazards and risks can be viewed for a site with long temporal and large spatial scales of hazards, great potential for large-scale exposure if it occurs, and no current technology for hazard elimination or blockage. Amchitka Island, and its surrounding marine ecosystem, is unusual among DOE-contaminated sites because of its remoteness, depth of the contamination, and importance of its ecological resources and seafood productivity. We use Amchitka Island as a case study to explore the use of CSMs for a site where the potential consequences of leakage could be great, the potential for remediation is nil, and some receptors of concern are far away. We suggest that CSMs are particularly critical for long-term stewardship, where contamination is left in place. We argue that CSMs can provide insights on the nature and extent of the receptors at risk.

Background on Amchitka

Amchitka Island is one of over 100 sites in 34 states that comprise the Department of Energy's "Complex" (Crowley and Ahearne 2002). These sites range in size from a few acres to over a thousand square miles, have different degrees of contamination, and are in different stages of remediation. It is costly and technologically challenging to clean up many of DOE's sites, and the degree of cleanup depends partly upon future land uses (NRC 1995, DOE 1996a, b, Leslie et al. 1996). Cleanup decisions should involve a risk-based understanding of the end state, including future land uses, which led DOE to develop a risk-based approach to cleanup (DOE, 2003).

Currently, Amchitka Island is part of the Alaskan Maritime National Wildlife Refuge bordered on the south by the North Pacific and on the north by the Bering Sea (Fig. 1). The marine biological resources in the region are of high value in cultural, commercial, and ecological terms (Merritt and Fuller 1977, NRC 1996). Its marine resources are also potentially important to the subsistence lifestyle of the Aleut/Pribilof Islanders and to commercial fisheries of the region (Patrick 2002). Preserving such DOE lands as ecological preserves recognizes the important ecological resources on these lands (Burger et al. 2003).

In World War II the island served as a military base opposing the Japanese occupation of nearby

Kiska Island. In the 1960s Amchitka was chosen for underground nuclear tests that were too large for the Nevada Test Site, and it was the site of three nuclear tests in 1965, 1969, and 1971. *Cannikin* (1971), the last and largest shot (5 megatons), had an elevator shaft that was over 6,000 feet below the surface, and the blast and resulting chimney collapse formed a new lake (Cannikin Lake) on the island surface. The three Amchitka test shots accounted for about 16 % of the total energy released from the US underground testing program (Robbins et al. 1991, Norris and Arkin 1998, DOE 2000), and Cannikin was the largest U.S. underground blast.

Although there was some release of radiation to the surface, the leaks were not considered to pose serious health risks at the time (Seymour and Nelson 1977, Faller and Farmer 1998). Much of the radiation was probably spontaneously vitrified when the intense heat of the blast melted the surrounding rock. However, the extent of non-vitrified radiation is undetermined, and details regarding the species and amount of radionuclides in the test shot cavities remain classified. The vitrification is believed to minimize the hazard potential by retarding the migration of the radionuclides, which minimizes its hazard potential.

No current technology exists to remediate the test cavities or to inactivate or entrap any radiation. Nor do long term plans envision any attempts to disrupt the shot cavities for remediation purposes. However, Amchitka Island is in one of the most volcanically and seismically active regions of the world (Jacob 1984, Page et al. 1991), and stakeholders are concerned that earthquakes could open subterranean pathways and accelerate the movement of radiation into the sea.

The Bering Sea/North Pacific marine ecosystem around Amchitka Island is rich biologically, and contains a high biodiversity of organisms (Merritt and Fuller 1977; NRC 2000). These organisms exhibit a range of lifestyles: sessile (e.g. kelp, barnacles), largely sedentary (e.g., sea urchins), local movements (e.g. some fish), or are highly mobile (e.g. birds, some marine mammals, some large fish). Thus there is the potential for movement of radionuclides and other contaminants into and out of the marine system surrounding Amchitka (Fig. 2). There is considerable stakeholder interest and concern from several interests, including the Native interests represented by the Aleutian/Pribilof Island Association(A/PIA), the U.S. Fish & Wildlife Service (USFWS), the State of Alaska, and several other health and environment groups.

Stakeholder Concerns

At the time of the nuclear tests, formal protests were made by the State of Alaska, the Aleuts, environmental groups, and the governments of Japan and China (O'Neill 1994, Kohlhoff 2002), and concern continues to this day. In 2001 the DOE removed all structures and remediated the surface contamination, and the surface was closed as part of the Alaska Department of Environmental Conservation's contaminated sites program (DOE 2002a). Although Greenpeace (1996) concluded that surface radionuclide contamination existed, Dasher et al. (2002) did not confirm this. Nonetheless, considerable concern on the part of the State of Alaska, the U.S. Fish & Wildlife Service, the Aleutian/ Pribilof Island Association (A/PIA), and other stakeholders was voiced when DOE's Office of Environmental Management announced plans to terminate its responsibility for the island. The complex and sometimes contentious process of having the major stakeholder parties agree on a path forward toward closure was made possible by an agreement to develope a comprehensive science plan to gather the necessary data to form the basis for biomonitoring and long-term stewardship of Amchitka Island. The development of a Science Plan involved iterations and interactions with multiple agencies and organizations, scientists in several disciplines, regulators, and the participation of Aleuts in their home communities as well as the general public.

The importance of including all parties in all phases of the development of the Science Plan was critical to its acceptance by a broad range of regulators, agencies, resource trustees, Aleut/Pribilof communities, and other stakeholders.

Public concern was substantiated by interpretations of the geology and geophysics of the area, which demonstrated the plausibility that radionuclides could be transported from the shot cavities to the ocean because of seismic activity (Eichelberger et al. 2002). The DOE's own groundwater model predicated that breakthrough into the sea might occur any time from 10 to 1000 years after the blasts (DOE 2002b), although their human health risk assessment indicated negligible human health low risk levels based on non-conservative assumptions (DOE 2002c). However, the absence of recent site-specific data on radionuclide levels in fish and other subsistence foods raised the general level of concern. The Aleuts were equally concerned about the marine ecosystem and its well-being, including species that were not part of their subsistence food chains.

Following the development of the Amchitka Science Plan (CRESP 2003), we (JB, MG) visited several Aleut villages and met with their tribal leaders, conservation/environmental officers, and teenagers to discuss their views on the plan and to solicit dialogue on receptors at risk. Teenagers, who were the main hunters and fishers at some Aleut villages, were particularly interested in the science process and in integrating their life-style concerns with our sampling and analysis work. Stakeholders as far away as Nikolski (about 1000 km from Amchitak) voiced concern that seals they killed might have picked up contamination while residing in Amchitka waters.

Interest in possible radionuclide exposure from the test shots at Amchitka is not limited to the North American side of the Aleutians. One of the authors (CDV) lead a project called "A Community Collaboration in Public Health: A Workshop to Improve Health Promotion and Disease Prevention in Sakhalin" (a partnership of the Magee Women Healthcare International and the

University of Pittsburgh Graduate School of Public Health, sponsored by the US Department of State, Office of Citizen Exchanges). This group explored the public and environmental health threats to the population of Sakhalin Island and the Kuril Islands.

During the environmental training portion of the workshop held in Russia, several obstetricians expressed concern over the rising rates of teratogenesis and spontaneous abortion found in the Oblast region of eastern Russia. There was considerable discussion regarding the possible influence of "radioactive materials" polluting fishing grounds. During a Delphi Focus Group workshop at Pittsburgh, designed to examine environmental issue prioritization, the "radiation material" issue was incorporated into a model of important environmental threats requiring development of interventions. The diet of Sakhalin and Kuril Islanders is rich in seafood; the surrounding seas are among the most productive fisheries in the world.

When the Amchitka Science Plan was presented to the participants there was a wide-ranging discussion. These professionals acknowledged former Soviet Union sources of radionuclides in the Sea of Ohkotsk, as well as potential radionuclide release from Russian submarine decommissioning. They were quite concerned to hear about another possible source of radionuclide release into the Northern Pacific and Bering Sea and effects on common food sources, including crabs and salmon. An indigenous tribe participant from Northern Sakhalin expressed a specific concern that marine mammals, including Steller sea lions, could bioconcentrate "radiation materials" anywhere within their range. Ingestion of these subsistence foods may pose a hazard to indigenous circumpolar peoples. Workshop participants also expressed concern over plans by the Russian Republic to site a large nuclear waste disposal site on one of the Kurile Islands. These islands, like the Aleutians, are subject to high volcanic and seismic activity. This site once operational could affect any CSM of Amchitka Island.

Conceptual Site Models

Conceptual Site Models (CSMs) portray complex physical, ecological, and contamination conditions on sites, and have been used extensively by EPA (EPA 1991, 1992). Complete Conceptual Site Models include sources, environmental media (air, water, soil, food), pathways of environmental transport, indications of any barriers or remedies that exist or are proposed, and pathways to human and ecological receptors. The accompanying text provides failure analyses for these barriers. CSMs should be part of a larger decision support process that includes collection, analysis and interpretation of data within a framework of stakeholder participation, because they clarify and focus the information contained in complex tabular, graphic, and text presentations from risk assessment and environmental impact analysis (Bardos et al. 1996).

There are standard guidelines for developing CSMs for contaminated sites (ASTM 1995). CSMs have the potential to be excellent communication tools for a range of interested parties, from regulators and natural resource trustees, to the general public. Several DOE sites under active environmental remediation have completed CSMs as part of their vision document. DOE's (2003) guidance for developing CSMs noted that sites should provide current CSMs as well as a CSMs depicting the risk-based end state, the latter emphasizing the barriers that will be usedto prevent undue risk. The barriers or blocks include removal, containment, other engineering solutions, and institutional controls. Failure analysis for the blocks is a key feature of the development of CSMs for the DOE (DOE 2003, Mayer et al. ms).

CSMs provide a matrix of exposure routes for human and ecological receptors (DOE 2003), often by listing only worker, public, and ecological, or worker, public, terrestrial, aquatic receptors. We propose that for some sites, an expanded receptor matrix will be valuable for understanding the species at risk, including humans (see below). An expanded receptor matrix allows stakeholders to immediately identify the resources at risk, which may require protection or be part of a long-term biomonitoring plan that is the cornerstone of long-term stewardship.

Conceptual Site Models Role in Environmental Impact Statements and Risk Assessments

The traditional method of evaluating ecological damage or potential damage is to conduct Environmental Impact Statements (EIS). EISs were legally promulgated in the National Environmental Policy Act (NEPA) of 1970, and required that environmental considerations be evaluated in relation to social, economic and technological factors (Hocutt et al. 1992). As an initial stage, a resource inventory is required that also serves as a baseline for future evaluations. Ideally, resource evaluation and baseline studies occur not only before some intervention (i.e. construction activity, remediation), but also after. This latter step is seldom performed, nor is information provided on the probability of damage for the proposed activity. Often the assessments are qualitative, rather than quantitative.

In the last two decades, ecological risk assessment has emerged as the paradigm for evaluating the potential for ecological damage of any disruptive activity, usually quantitatively (NRC 1993). Risk assessment examines the potential risk to target organisms or systems from chemical, physical, or other environmental hazards (Burger and Gochfeld 1997). Often risk assessments require a range of risk characterizations, and population models that incorporate dose-response curves, biotic growth curves, and contaminants information (Lemly 1996, Spromberg et al. 1998), as well as uncertainty analysis (Duke and Taggart 2000). Several government agencies have elaborate policies and guidelines for ecological risk assessment to address their regulatory needs (Bilyard et al. 1993). In general, risk assessment has focused on the technical challenges (Eduljee 2000), but there have been several approaches to integrating the technical aspects of risk assessment into broader environmental management approaches (Burger 1999, Pentreath 2000, Bardos et al. 2000).

We suggest that CSMs, and expanded receptor matrices, will improve both EISs and ecological risk assessments by clarifying and graphically depicting the critical ecological exposure pathways, and potential points of risk reduction. That is, CSMs will focus attention on the critical pathways and associated ecological receptors that require resource identification and risk assessments. Further, CSMs can provide regulators, managers, and the public with a clear depiction of the major ecological resources at risk in the ecosystem, rather than the receptor by receptor approach normally taken. CSMs provide the "big picture" in a simple graphic. We suggest that CSMs, and associated receptor matrices, should be part of both EISs and risk assessments.

Conceptual Site Model and Receptor Matrix for Amchitka

As far as is known, the only nuclear contamination remaining on Amchitka Island is in the underground test shot cavities; surface contamination and debris was removed by DOE, and no surface contamination was found in an extensive study by Dasher et al. (2002). During an underground test, intense heat melts adjacent rock, creating a cavity of molten rock (Laczniak et al. 1996), and rapid cooling turns it into glass. As the rocks cool, some of the radioactive material is trapped in the glass, while other radionuclides reside outside the glass, and are potentially mobile (Smith 1995). The resulting glass is subject to slow dissolution in groundwater and to mechanical breakdown, but it retards the rapid transport of chemicals (Kersting et al. 1999, Haschke et al. 2000). Transport of the material depends upon the physical state of the source, local geochemistry, the extent of fractures or fissures, and local hydrology. Rainfall percolating through the soil is the main vehicle for carrying material from the vicinity of the test cavities, through the rock to the sea (Fig. 3). Rainwater driven downward and outward by hyrdrostatic pressure, dissolves contaminants and carries them through the fractures and fissures, ultimately releasing them into sea.

The marine resources around Amchitka are very rich, in numbers, species diversity, and number of endangered, threatened and species of concern. A high proportion of the commercial fish consumed in the US comes from the northern Pacific and Bering Sea fishery. For example, Dutch Harbor, in the Aleutians, had the highest tonnage of fish landings in the world in 2002. In 2002, Dutch Harbor had 17 % of Alaska's 811 million dollars of fish landings (2.3 million metric tons of fish, NMFS 2004).

In the case of Amchitka, the depth of the shot cavities, and the likely trajectory of movement from the shot cavity means that any leakage would occur into the marine environment (rather than on the surface of the island itself, CRESP 2003). The issue of concern for stakeholders is whether or not radionuclides and other contaminants have already leaked, and if they have (or do in the future), do they provide a risk to marine resources or seafood (CRESP 2003). Although DOEs groundwater models and human health risk assessment suggest there is no cause for concern (DOE 2002b, 2002c), state and federal regulators, the Aleutian/Pribilof Island Association, and other stakeholders are still concerned, and have significant reservations about the uncertainties and assumptions incorporated in these reports.

Part of our objectives in developing CSMs for Amchitka is in providing another tool for understanding risks to the marine environment, and in providing a model for expanded receptor matrices that could be used for other contaminated sites. These CSMs will also be useful risk communication tools regarding Amchitka itself, as more information becomes available. There are three features of Amchitka which are critical to CSM development: 1) if radionuclides leak into the sea, the primary risk is to marine receptors, not to receptors on Amchitka Island itself (other DOE CSMs deal primarily with on-site risks), 2) many marine receptors that live around Amchitka are mobile and highly migratory, and can carry radionuclides and contaminants into and out of the Amchitka system, and 3) many of the marine resources are eaten by the Aleutian people and many species are exploited by commercial fisheries. Thus the potential for off-site movement is expanded to include the entire Aleutian chain, the Pribilof Islands, and the rest of the United States and other nations.

Although the DOE did not develop CSMs or site visions for Amchitka Island, these documents were prepared for other sites where underground nuclear test shots were conducted (e.g. DOE 2004). These CSMs can serve as a model of how DOE views the exposure risks from underground nuclear test shots. Using such models as a starting point, we developed a general CSM that assumes that residual contamination from the test shots is present in groundwater, and that leakage through subsurface fractures and fissures to the sea leads to direct contact or food chain exposure in the marine environment (Fig. 4). Although the possibility is extremely remote that groundwater could contaminate surface water on the island, this pathway is also included. If groundwater were to enter the marine environment three receptor groups would be affected: a stealth resident, terrestrial ecoreceptors (that feed in the marine environment), and marine ecoreceptors. A stealth resident is someone who might live on a remote section of the island for a few months or years without anyone knowing about it. The major pathways would be by direct contact and food chain exposure. Once in the marine environment, exposure routes would be dermal, ingestion, gills, and by food chain bioaccumulation (Fig. 4).

However, this general CSM does not fully identify and explain all of the potential transport and exposure pathways or receptors because it does not consider the interactions and mobility of many ecological receptors that are initially exposed. In reality, leakage or transport to the seafloor can occur in the intertidal/subtidal and benthic regions (with and without sessile organisms such as kelp). The receptors then can be exposed by dermal, gills, ingestion, and through the food chain. The system is interlinked because organisms at all levels not only are exposed to the potential for radionuclides directly (gills, dermal, ingestion of primary producers), but by other organisms at different levels on the food chain. Kelp, for example, are sessile organisms that live in the intertidal/subtidal. Their habitat exposes them to radionuclides mainly if leakage occurs in this zone. In the middle, Atka mackerel live in the deep water and are locally mobile, making them more indicative of local exposure within a narrow geographical range. They reflect food chain exposure. At the other extreme, harbor seals are both mobile and migratory, and live primarily at the surface. Their exposure comes mainly through the food chain, as well as from exposure elsewhere during their migratory phase. They can thus carry radionuclides and other contaminants both into and out of the Amchitka marine ecosystem. Taking it a step farther, humans, such as the Aleut/Pribilof Islanders, may be exposed by eating foods that have bioaccumulated contaminants from the water (gills, dermal), but also through biomagnification up the food chain. These features require an expansion of the pathways and receptors shown by the CSM, and require use of a matrix to depict the resources at risk (Fig. 5).

The Aleutian Islands and adjacent waters contain a wide diversity of wildlife, including fish such as the walleye pollock, Pacific cod, herring, flatfishes (e.g. halibut), rockfishes, Pacific salmon (particularly chum, pink, Coho and sockeye salmon), shellfish, crabs (including snow, red king and brown or golden king crabs), birds (seabirds, waterfowl, and eagles), and marine mammals (Steller sea lions, harbor seals, northern fur seals, orca whales, gray whales, sea otters, and porpoises), to mention just a few. This array of vertebrate species is of great interest to Aleuts, commercial fisheries, resource trustees and the public. It is supported by a diverse food chain base of algae, plankton, small invertebrates and larval fish. Many of these species live on and around Amchitka Island. The productive kelp bed ecosystem around Amchitka supports abundant nearshore fishes (Estes 1978). Recent sampling of freshwater biota on Amchitka Island itself was aimed at examining radionuclides only on the island (Dasher et al. 2002), and there has been relatively little sampling of the marine environment since the 1970s (Merritt and Fuller 1977; CRESP 2002, 2003).

We suggest that CSMs should be accompanied by an expanded receptor matrix (such as Fig. 5) and ecological species matrix (such as Table 1) to provide a more complete picture of the ecotypes and species at risk. Linking the information in Table 1 with the receptor matrix allows managers, regulators, and other stakeholders to understand both the species and risk and the pathways of exposure. While this receptor matrix provides an indication of the types of receptors and major pathways not included in our general CSM, it still fails to identify all of the key risk factors for organisms within the marine environment because they are exposed to contamination from other sources not associated with Amchitka.

Integrating a Conceptual Site Model for Amchitka with the Surrounding Ecosystem

While the CSMs discussed above examine the sources, hazards, pathways of exposure and receptors for Amchitka and its surrounding marine ecosystem, they do not adequately describe the risk to marine resources in the area around Amchitka because of the potential for non-Amchitka contamination to enter the system. This is true partly because marine systems are unbounded and contaminants can enter the system from other sources. Also Amchitka is close to Russian sites of disposal of nuclear submarine wastes. Finally, atmospheric deposition from atmospheric testing, contributed to worldwide radiation exposure. Thus, while the DOE is interested in specific CSMs for Amchitka because of its legal responsibilities for the radionuclides, a broader perspective is needed for stakeholders. The Aleutian and Pribilof Islanders are particularly concerned because their traditional foods could be impacted, even though no one currently resides on Amchitka itself (Patrick 2002).

There are thus two major sources of inputs and outputs in the Amchitka marine ecosystem: movement of contaminants themselves in water and air, and movements of the animals into and out of the system. Understanding the regional ecosystem is critical for Amchitka because the prevailing currents come from the west, potentially bringing radionuclides and other contaminants from the activities of Russian and other countries (shown in Fig. 6). While managers of contaminated sites may not know all the other regional sources of contaminants, it is important to diagram the known sources.

Atmospheric Fallout: Atmospheric deposition from historic nuclear testing, as well as nuclear accidents, can be divided arbitrarily into local (close to source), regional, and global. Global transport has been extensively studied for ^{90}Sr and ^{137}Cs as well as mercury, less well for other radionuclides, and has been measured directly (deposition monitoring) in sea water (Aoyama and Hirose 2003), in soil (Holgye et al. 2004), and in biota (Kirchner and Dailland 2002), including on Amchitka itself (Dasher et al. 2002). Global transport generally confers a uniform distribution within a local area, although regional variations attributable to precipitation regime exist (Simon et al. 2004). A uniform spatial distribution on the local level is often adduced to implicate global rather than local source contributions, reflecting atmospheric testing or accidental releases such as Chernobyl (e.g. Holgye et al. 2004).

Non-Amchitka Radiation:

Radionuclide migration from numerous sources in the Former Soviet Union (FSU) threatens coastal Alaska and especially the Western Aleutian Islands by a complex set of marine transport mechanisms. These pathways must be incorporated into the CSM for Amchitka Island as they may contribute significantly to levels of radionuclides in Amchitka Island seawater, sediment and biota, especially for highly mobile species such as the Stellar sea lion (T.Laughlin, National Marine Mammal Laboratory, Sand Point, Seattle Washington). The factors involved in understanding this cross-Aleutian transport involve knowledge of FSU waste sites and source terms (Suokko and Reicher 1993), the amount of nuclear waste that was directly released into the marine ecosystem, and that waste which was improperly or inadequately contained and will ultimately be released over time into the marine environment (US GAO/RCED 1995). Other important factors include weather patterns, ocean current circulation, sediment flow and transport, fishing fleet activity patterns, the globalization of the seafood markets, and fish and marine mammal range and migration patterns.

From 1965 through 1988 the FSU Nuclear Navy had a policy of marine disposal of reactor vessels, components and spent nuclear fuel (SNF) after encapsulation or containment using different sealants, including a material known as *furfural*. These waste sources were disposed of in three fiords on the east coast of Novaya Zemyla and in the Novaya Zemyla Trough of the Kara Sea. In total, the Soviet Navy dumped into the Kara Sea 16 nuclear reactors from submarines, of which 6 contained spent nuclear fuel (SNF) without full containment and with the screening assembly, and

60% of the damaged SNF from the Number 2 reactor of the *Lenin*, a nuclear powered icebreaker. The contaminated materials and sources were dumped at depths ranging from 12 to 300 meters (Mount et al. 1998).

The Kara Sea is part of the Arctic Ocean. It is located off northern Siberia and lies between the Barents Sea to the west and the Laptev Sea to the east. The salinity of the Kara Sea varies because of large quantities of freshwater it receives from the Ob and Yenisei Rivers, which have carried and will continue to carry radionuclides to the Kara Sea and Arctic Ocean from FSU blast and accident sites, inactive weapons plants, contaminated lagoons, groundwater and active Russian weapons plants. FSU marine radionuclide migration pathways than can potentially contaminate the Western Aleutians also emanate from liquid waste and solid reactor parts disposed of in the Sea of Japan and the Northwest Pacific Ocean, and from disposal of liquid radionuclide waste, east of the Kamchatka Peninsula. A Strontium-90 powered thermoelectric generator was lost at sea by the FSU in the Sea of Okhotsk (Layton et al. 1999).

Russian officials have expressed concern about safety at these decommissioning sites. Russia maintains a fleet of at least 228 nuclear submarines, which need to be maintained and decommissioned. There was an accident at the Vladivostok Naval Nuclear Reactor and Processing Shipyard in 1989, which released significant amountds of radionuclides into the sea (US GAO/RCED 1995). Waste streams associated with current Russian naval operations, the decommissioning of Russian nuclear powered vessels and reactors, and spent fuel reprocessing facilities in the Russian Far East require further refinement of the Amchitka CSM, as communicated by participants in the Workshops.

Discussion and Conclusions

With the ending of the Cold War the DOE, DOD and other agencies worldwide are cleaning up contaminated lands and converting them to other uses, either within the current ownership or with new ownership. The decision process of determining future land use within the context of current and future risk to humans and ecological receptors requires extensive knowledge of not only the pathways of exposure and effective blocks for those pathways, but a complete understanding of the receptors at risk, including humans. CSMs can serve as one tool to better understand graphically the sources of hazards, media and pathways, receptors and blocks to reduce risk. While DOE and others have concentrated on the sources, media and pathways, and the engineering and institutional controls that can block the pathways, we suggest that considerably more attention needs to be devoted to understanding and graphically presenting not only the major classes of receptors at risk, but the ecological attributes that contribute to differences in their exposures.

Specific Relevant Aspects of Amchitka:

The aspects of Amchitka Island which make it imperative to expand the receptor/pathway analysis include the presence of an aquatic environment around the island which ensures rapid transport if there is leakage, the presence of a highly mobile and migratory (for some species) receptor population, and the important and rich seafood source that provides the basis for Aleut/Pribilof Islanders diet and commercial fisheries, both in North America and for circumpolar peoples. The latter point means that potential contaminants are carried to human receptors over a very wide geographical area (in the case of fisheries, all of the U.S. as well as abroad). Thus, the major geographical risk range is very large, while the risk on the island itself is minimal.

Further, the CSMs reveal that there are many levels of exposure pathways. That is, concern is not only for the initial exposure, but for cascading effects to nearly all components of the ecosystem from direct exposure (drinking water, over the gills, foods), but for secondary exposure through organisms which have themselves been exposed through all of the same pathways. Tertiary exposures even occur when intertidal (crabs) and terrestrial species (birds, rats and other mammals) eat carrion, such as large seals or predatory fish that have washed into the intertidal region.

General Applicability:

While Amchitka Island is unique in that it was the site of the largest U.S. underground test shots, and is an island surrounded by cold ocean water, the case for receptor/pathway expansion can be made for a number of DOE and other contaminated sites. As an island, leakage from Amchitka into the sea would undergo rapid transport and dissipation unless trapped by biota. There are a large number of migratory species that can carry radionuclides and contaminants into and out of the Amchitka vicinity; similar conditions can apply elsewhere. For example, at Idaho Engineering and Environmental Laboratory there are a number of migratory or highly mobile species (such as elk) that move through the system, and can carry contaminants with them. Contamination of the Snake River in Idaho would carry radionuclides and other contaminants into the Columbia River, and eventually into the ocean. Similarly, Hanford in the state of Washington has a rich and diverse ecosystem with migratory bird species on site. The Columbia River, with its important salmon populations can also serve as a conduit for the movement of contaminants into and out of the system at the Hanford Site.

While DOE is understandably focusing on remediation and institutional controls to provide blocks to the pathways leading to receptors, we suggest that considerably more attention needs to be devoted to both the complicated ecological receptor matrices, and to differences in the pathways that result from ecological constraints. That is, to an engineer a leaching/transport pathway is sufficient. However, to an ecologist, whether that transport pathway is to the intertidal or the deep ocean benthic environment has different consequences for the receptors, and ultimately for human consumers of marine organisms.

Management Implications:

Developing expanded pathway/receptor matrices based on ecological considerations can aid in identifying more precisely the receptors at risk, making decisions about both remediation and long-term stewardship needs, and presenting the current and future risks more clearly to a range of regulators and other stakeholders. Forcing the responsible agencies, the DOE in the case of Amchitka, to consider the ecological parameters that put species at risk will help identify potential remediation or long-term stewardship needs. Identifying the receptors at risk more specifically will contribute to developing an appropriate biomonitoring plan which will form the basis for an early warning/corrective action should other engineering and institutional controls fail.

Finally, expanded receptor matrices (such as shown in Fig. 5), and expanded landscape pathways (shown in Fig. 6) will provide a better framework for a wide range of stakeholders to understand the potential risks to themselves and ecological receptors, to aid in decision-making about engineering and institutional controls for reducing the risks for each source, and allow stakeholders to consider other risk-reducing strategies. Such decisions can in turn be influenced by regulations (e.g. do not fish commercially within a certain distance of a given facility), public health policy (issuance of consumption advisories), or personal choice (e.g. not eating the fish or other resources from these waters). Having detailed expanded pathways that reflect regional ecosystem inputs and expanded receptors matrices can thus inform regulatory decisions, public policy, and personal choices concerning risk and risk management.

Acknowledgments

We thank the people who contributed to the development of the Science Plan which provided the initial framework for this project, including David Kosson, Barry Friedlander, John Eichelberger, David Barnes, Lawrence Duffy, and Stephen Jewett, as well as Monica Sanchez, Runore Wycoff, and Peter Sanders (Department of Energy, National Nuclear Security Administration, Nevada), Jenny Chapman (Desert Research Institute), Anne Morkill (U.S. Fish & Wildlife Service), Robert Patrick (Aleutian/Pribilof Island Association), Ron King, David Rogers and Doug Dasher (Alaska Department of Environmental Conservation), and the people of the villages of Unalaska, Nikolski, Atka, and Adak in the Aleutians. Over the years our thinking about the characterization of contaminated sites has been influenced by B. D. Goldstein, J. Clark, and A. Upton. This research was funded by the Consortium for Risk Evaluation with Stakeholder Participation (CRESP) through the Department of Energy (AI # DE-FC01-95EW55084, DE-FG 26-00NT 40938). JB and MG were also partially supported by NIEHS ESO 5022. 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.

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Figure Legends

1. Map of Amchitka Island, in the Aleutian chain in the Northern Pacific/Bering Sea ecosystem.

2. Schematic of the marine resources at risk in the marine ecosystem around Amchitka Island. Through the processes of bioaccumulation and biomagnification radionuclides can move through aquatic food chains to higher trophic levels, including human.

3. Schematic of Amchitka showing possible transport to the sea.

4. General CSM for contaminated surface and subsurface soils, modelled after the Department of Energy's CSMs for other underground test shot (after DOE 2004).

5. General CSM for exposure from Amchitka Island with expanded recaptor matrix. The source (residual contamination from underground test shots) and associated pathways to subsurface water is shown in figure 4.

6. Expansion of the CSM to schematically show regional or landscape inputs. This CSM includes the same transport mechanisms as shown in figure 4 and expanded receptor matrix shown in figure 5. Note that the former Soviet Union dumped 16 nuclear reactors into the marine environment, and the encapsulation has the potential for failure.

Table 1. Expanded receptor matrix for marine and seafood resources in the marine ecosystem surrounding Amchitka Island.